Bringing Optical Metamaterials to Reality

By

Jason Gage Valentine

A dissertation in partial satisfaction of the requirements for the degree of Doctor of Philosophy in Engineering – Mechanical Engineering in the Graduate Division of the University of California, Berkeley

Committee in charge:

Professor Xiang Zhang, Chair
Professor Costas Grigoropoulos
Professor Liwei Lin
Professor Ming Wu

Fall 2010
Bringing Optical Metamaterials to Reality

© 2010

By Jason Gage Valentine
Abstract

Bringing Optical Metamaterials to Reality

by

Jason Gage Valentine

Doctor of Philosophy in Mechanical Engineering

University of California, Berkeley

Professor Xiang Zhang, Chair

Metamaterials, which are artificially engineered composites, have been shown to exhibit electromagnetic properties not attainable with naturally occurring materials. The use of such materials has been proposed for numerous applications including sub-diffraction limit imaging and electromagnetic cloaking. While these materials were first developed to work at microwave frequencies, scaling them to optical wavelengths has involved both fundamental and engineering challenges. Among these challenges, optical metamaterials tend to absorb a large amount of the incident light and furthermore, achieving devices with such materials has been difficult due to fabrication constraints associated with their nanoscale architectures. The objective of this dissertation is to describe the progress that I have made in overcoming these challenges in achieving low loss optical metamaterials and associated devices.

The first part of the dissertation details the development of the first bulk optical metamaterial with a negative index of refraction. This metamaterial is shown to overcome the problems of previous metamaterials by reducing the amount of light absorbed in the material. The increased thickness of the bulk metamaterial also allows the first direct experimental observation of negative refraction at optical frequencies. Next, I will describe the design and experimental realization of the first electromagnetic cloak operating at optical frequencies. The cloaking device is designed using quasi-conformal mapping which enables the use of an all dielectric, isotropic metamaterial, allowing the cloak to operate over large bandwidth with low absorption losses, overcoming the problems with previous cloaking proposals. This design methodology and metamaterial system is then extended to realize an optical ‘Janus’ device. The device is designed and experimentally proven to have two different and independent optical functionalities in two separate spatial directions for use in integrated photonics architectures. The last section of the thesis describes several new directions I am pursuing in the field of metamaterials. The first is the experimental realization a photonic black hole. This device functions similar to a gravitational black hole in that it concentrates light into a small spatial area but is realized through a spatial varying index profile. The extension of transformation optics into plasmonic systems is then presented. Experimental work aimed
at realizing a gradient index Luneburg lens is presented utilizing modulations of the surface plasmon mode index though height variations in a dielectric. Finally, a new method for achieving large scale, three dimensional, gradient index metamaterials is presented. Such a method could be employed for achieving large scale cloaks or gradient index lenses for use in photovoltaics.

The findings presented here represent some of the first metamaterial inspired devices at optical wavelengths. It is my hope that this work will help to inspire the next generation of metamaterials and devices with ever increasing functionality.
To my loving parents, without your support none of this would have been possible.
Table of Contents

Table of Contents

List of Figures

Acknowledgements

Chapter 1 Metamaterials
1.1 Metamaterials: What is all the fuss about? 1
1.2 Engineering Material Properties 3
  1.2.1 Effective Media 5
  1.2.2 Negative Refractive Index 7
1.3 Optical Metamaterials 11
  1.3.1 Cut-Wire 12
  1.3.2 Fishnet 13
1.4 Organization of the Dissertation 15
References 16

Chapter 2 Bulk Optical Negative Index Metamaterial
2.1 Introduction 20
2.2 Bulk Fishnet Design 21
2.3 Fishnet Fabrication 25
  2.3.1 Focused Ion Beam Milling 26
2.4 Experimental Results and Discussion 29
2.5 Conclusions and Outlook 34
References 34

Chapter 3 Broadband Optical Cloaking
3.1 Transformation Optics 37
  3.1.1 Electromagnetic Cloaking 38
3.2 Carpet Cloak Design 40
3.3 Carpet Cloak Fabrication 44
3.4 Experimental Results and Discussion 47
3.5 Conclusions and Outlook 52
References 53

Chapter 4 Janus Device
4.1 Introduction 56
4.2 Janus Device Design 57
4.3 Janus Device Fabrication 59
  4.3.1 Reactive Ion Etching 59
4.4 Experimental Results and Discussion 62
4.5 Conclusions and Outlook 67
References 67
Chapter 5 New Directions in Metamaterials
5.1 Photonic Black Holes 70
5.2 Plasmonic Transformations 75
5.3 Scalable 3D Manufacturing 82
5.4 Conclusions and Outlook 86
References 86

Chapter 6 Conclusion and Outlook
6.1 Conclusions 89
6.2 The Future of Metamaterials 90
Figure 1.1. Material parameter space. Optical materials are characterized by the electric permittivity ($\varepsilon$) and the magnetic permeability ($\mu$).

Figure 1.2. Field ratios for effective medium of different shaped constituents. (a) spherical and (b) cylindrical inclusions. These ratios are used in equation 1.5 to compute the effective material properties for both types of constituents where $\varepsilon$ and $\varepsilon_i$ are the matrix and inclusion permittivity, respectively.

Figure 1.3. Left and Right handed triads. (a) While positive index materials are characterized by energy ($S$) and phase ($k$) moving in the same direction, these vectors move in opposite directions (b) in negative refractive index materials.

Figure 1.4. Effective permittivity of a Silver wire composite medium for various filling fractions. The wave is polarized along the wire axis leading to a non-resonant diluted metal. Tuning the filling fraction allows engineering of the effective permittivity.

Figure 1.5. Schematic of the split-ring resonator. (a) Depicts an array of the resonators and the proper polarization of light needed to create an effective magnetic response (b) Unit cell of the metamaterial with annotated dimensions where $P$ is the periodicity of the array. (c) Equivalent circuit of the split-ring where at resonance the internal current ($j$) can induce a magnetic field that is out of phase with the incident light.

Figure 1.6. Permeability of the split-ring metamaterial. The resonator passes through resonance at ~1Ghz wherein a negative effective permeability, Re($\mu$) can be realized. This resonance is accompanied by a loss, Im($\mu$), due to the finite conductivity of the metal.

Figure 1.7. Evolution of the split-ring unit cell as frequencies scale to the optical regime.

Figure 1.8. Cut-wire schematic. (a) Depicts an array of the cut-wires which can lead to a negative index of refraction under the proper polarization. (b) Unit cell of the cut-wire metamaterial where the grey and green wires are made of metal and dielectric, respectively. (c) Circuit model of the cut-wire unit cell depicting the internal $LC$ circuit and current loop.

Figure 1.9. Fishnet metamaterial schematic (a-c) Depict the separate components of the metamaterial which provide both a magnetic (a) and electric (b) response. The silver layers are made of metal and the green layer a dielectric. Combined (c), these constituents form the complete fishnet structure. (d) Unit cell geometry of the metamaterial. (e) Depicts the $LC$ circuit and current loop that form the
magnetic response in the fishnet metamaterial.

**Figure 2.1.** Schematic and electromagnetic response of a single layer fishnet. (a) Schematic of the fishnet design and incident polarization where the dotted line indicates the cross-section of the material analyzed in (b,c). (b) Equivalent circuit of the NIM showing the induced current loop in the material. (c) Finite difference time domain simulation of the electric field within the magnetically resonant portion of the fishnet. The high electric field inside the metal layers is indicated by the strong red / blue color in the electric field plot. The high field, and resulting current, results in absorption of light due to the losses in the metal.

**Figure 2.2** Schematic of the bulk fishnet metamaterial. (a) Schematic of 3 functional layers of a bulk fishnet along the direction of illumination. (b) Unit cell of the fishnet with annotated dimensions. The grey color corresponds to Silver while the green corresponds to Magnesium Fluoride.

**Figure 2.3** Dispersion relations and field plots bulk fishnet structure. In all plots the grey area corresponds to the negative material property regions as determined by simulations. (a) Dispersion relation of the array of metal strips along the magnetic field. The grey area indicates the bandgap where $\mu < 0$. (b) Dispersion relation for the array of metal wires aligned along the electric field. The grey area indicates the region where $\varepsilon < 0$. (c) The dispersion for the 3D fishnet structure. A dispersion curve with negative slope appears (grey region) within the overlapped region of the electric band gap and magnetic band gap if both structures are combined. (d) Magnetic field plot below the band gap. (e) Magnetic field plot above the band gap. The dotted lines in the schematic mark the unit cell size.

**Figure 2.4** Consequences of coupled layers in the bulk fishnet metamaterial. (a) Schematic of a 3 functional layer fishnet showing the cross-section taken in (b,c). (b) Depiction of the cascaded circuit which leads to the magnetic response of the structure. Notice that the current flow on the top and bottom surface of the metal is out phase. (c) Electric field plot of the fishnet generated with FDTD. It can be observed that indeed, the electric field, on the top and bottom of the metal surfaces is out of phase. This leads to the cancellation of the electric field, and thus current, inside the metal, reducing losses due to absorption in the metal.

**Figure 2.5** Refractive index versus number of functional layers. While a large shift is seen when increasing from 1 to 3 layers, subsequent thickness increases have no effect on the index, indicating that the bulk value has been reached.

**Figure 2.6** Schematic of EBL fabrication process. The process starts with spinning and subsequent exposure of the photoresist using the electron beam. The resist is then developed and the device material is evaporated. Finally, the area around the exposure is lifted-off, resulting in positive features on the substrate.
Figure 2.7 Focused ion beam milling schematic and process flow. (a) Schematic of a typical FIB column. The ion gun passes through several lenses and apertures before being focused on the sample. (b) FIB process flow where first a device layer is deposited and then milled with FIB, forming negative features.

Figure 2.8 Schematic and SEM image of fabricated fishnet structure. (a) Schematic of the 21 layer fishnet structure. (b) SEM image of the 21 layer fishnet structure with the side etched, showing the cross-section. The structure consists of alternating layers of 30 nm Ag and 50 nm MgF₂ and the dimensions of the structure correspond to the schematic in (a). The inset shows a cross-section of the pattern taken at a 45° angle. The sidewall angle is 4.3° and was found to have minor effect on the transmittance curve according to simulation.

Figure 2.9 Fabrication procedure and SEM image of the fishnet prism. (a) To fabricate the prism, the multilayer stack was mounted vertically in the FIB and a prism was milled at an angle $\beta \approx 5^\circ$ with respect to the surface. (b) SEM image of a fabricated prism with a 10x10 unit cell fishnet structure milled into the surface. The inset shows a close up view of the prism where the individual metal and dielectric layers are visible.

Figure 2.10 Experimental setup for measuring the index of refraction. (a) Experimental setup for the beam refraction measurement. The focal length of the second lens is $f_2 = 40$ mm. Lens 2 is placed in a 2f configuration, resulting in the Fourier image at the camera position. (b) Geometry schematic of the angle measurement. $\delta$ corresponds to the position difference of the beam passing through a window in the multilayer structure ($n=1$) and prism sample. By measuring $\delta$, the absolute angle of refraction $\alpha$ can be obtained.

Figure 2.11 Fourier plane images and refractive index plot of fishnet metamaterial. (a) Fourier plane images of the beam for the window and prism sample for various wavelengths. The horizontal axis corresponds to the beam shift ($\delta$) and positions of $n = 1$ and $n = 0$ are denoted by the white lines. Image intensity for each wavelength has been normalized for clarity. (b) Measurements and simulation of the fishnet refractive index. The round dots show the results of the experimental measurement with error bars (s.d., $n = 4$ measurements). The measurement agrees closely with the simulated refractive index using the RCWA method (black line).

Figure 2.12 FDTD simulations of passing through the fishnet prism. (a) Simulation of the in-plane electric field component for the prism structure at 1200 nm when the index is positive. Positive phase propagation results in a positive refraction angle. (b) The in-plane electric field component for the prism structure at 1763 nm showing the phase front of the light. Negative phase propagation resulting from the negative refractive index leads to negative refraction angle as measured by the beam shift in the experiment. The bottom figures show a close-up of the time evolution of the field distribution in the unit cell of for both a
positive and negative index of refraction.

**Figure 2.13** Transmission and FOM. (a) Experimental transmittance curve (red line) of a 22 by 22 unit cell fishnet structure (17.6 x 17.6 µm² total patterned area) which has been multiplied by 4x for clarity. The simulated transmittance (black dotted line) was obtained with RCWA. The grey shaded area corresponds to the region of negative refractive index as calculated numerically. (b) FOM versus wavelength for the simulation (dashed line) and experiment (black squares). The lower experimental FOM is due to reduced transmission resulting from fabrication imperfections. The experimental FOM reaches 3.5 at 1775 nm where Re(n) = -1.23.

**Figure 3.1.** Different dimensional forms of cloaking. (a) The most rigorous form of cloaking crushes an object to an infinitesimally small sphere, rendering it invisible from all directions. (b) In 2D cloaking the object is crushed to an infinitesimally thin line, rendering it invisible in 2 directions. (c) In 1D cloaking, the object is compressed into a sheet, which is invisible when viewing the object only within the plane of compression.

**Figure 3.2.** Carpet cloak methodology. The object is first placed on a reflecting surface in free space. Here, the grid represents space where square cells represent isotropic material properties. The object is then surrounded by another reflecting surface, representing the carpet. The area around the carpet is then transformed to crush the bump, or carpet, into a flat sheet. The grid is now deformed, however, within the transformation; each grid point remains nearly square, or isotropic. This transformed space is equivalent to a virtual space with a spatial grid the same as the free space which first surrounded the object.

**Figure 3.3.** Waveguide schematic and refractive index profile. (a) The cloak is created in an Si waveguide sitting on top of SiO₂. TM polarized light is used. (b) The resulting refractive index profile for the cloak. Region C1 is the transformed region with spatially varying refractive index while C2 is the equivalent background with constant refractive index.

**Figure 3.4.** Simulation performance of the cloak. (a) FEM simulation of the curved reflecting surface with no cloak. The curved surface perturbs the beam causing a shadow to be cast. (b) FEM simulation of cloaked surface. The cloak crushes the bump causing the reflecting light to have the same profile as it would have reflecting off of a flat surface. In both simulations the electric field in the z direction is plotted (E_z).

**Figure 3.5.** The carpet cloak design that transforms a mirror with a bump into a virtually flat mirror. (a) Schematic of fabricated carpet cloak showing the different regions where C1 is the gradient index cloak and C2 is a uniform index background. The cloak is fabricated in a SOI wafer where the Si slab serves as a 2D waveguide. The cloaked region (marked with green) resides below the
reflecting bump (carpet) and can conceal any arbitrary object. The cloak will transform the shape of the bump back into a virtually flat object. (b) SEM image of fabricated carpet cloak. The width and depth of the cloaked bump are 3.8 µm and 400 nm, respectively.

Figure 3.6. Fabrication schematic for the carpet cloak. FIB is first used to etch through the Si layer to create the mirror facet, hole profile, and gratings. The Ga is then removed from the sample via rapid thermal annealing and plasma etching. After Ga removal, a cap wafer is placed on top of the sample where the green layer represents PMMA, used to create a good seal on the top of the sample. Directional deposition of Au is then performed to form the reflecting surface. The cap wafer is removed to realize the finished device.

Figure 3.7. Scanning electron microscope image of carpet cloak layout. Light is coupled into the Si slab waveguide via the input grating which has a width of 7 µm and distance from the cloak of 15 µm. After being reflected at the cloaked surface, the beam profile is detected via the output grating which has a width of 40 µm and a distance from the cloak of 55 µm. The inset shows the central region of the cloak. The hole diameter is 110 nm.

Figure 3.8. Optical carpet cloaking at a wavelength of 1540 nm. a-c, The results for a Gaussian beam reflected from (a) a flat surface (b) a curved (without cloak) surface, and (c) the same curved reflecting surface with cloak. The left panel shows the schematics. The middle panel shows the optical microscope images and normalized intensity along the output grating position. The curved surface scatters the incident beam into three separate lobes while the cloaked curved surface maintains the original profile, similar to reflection from a flat surface. The experimental intensity profile agrees well with the intensity profile (|Ez|^2) from 2D simulations (right panel).

Figure 3.9. 2D and 3D simulations for the bump and cloak performed with COMSOL. The (a) 2D and (b) 3D simulations for the bump structure show good agreement as well as the (c) 2D and (d) 3D simulations for the cloak. The 3D simulations are performed with the actual dimensions of the SOI waveguide and the hole pattern.

Figure 3.10. Experimental and simulated performance of the cloak and a control pattern at 1540 nm. The experimental image of the cloak pattern (a) is reproduced here for comparison purposes. The experimental measurement of a control pattern (b) that has been placed around the bump results in an output beam shape similar to a bump only. The control pattern consists of an equally spaced array of holes placed around the bump. The contrast in the two images demonstrates that the resulting single beam exiting the cloak pattern is not simply a result of a regular distribution of holes but is instead from a designed index gradient. The simulated results for both patterns are seen in (c) and (d). There is good agreement between the experimental and simulated results. Plotted on the left of each image is an
intensity plot at the output position.

**Figure 3.11.** Experimental results in the case where the output grating position has been moved to 25 µm from the cloak surface. The cloak pattern (a) and bump (b) show similar results when compared to when the grating is placed 55 µm from the cloak surface as shown in Fig. 3.9.

**Figure 3.12.** Experimental results for the angular dependence of the cloak. (a) The cloak pattern and flat mirror where the input grating is placed at a 60° angle with respect to the reflecting surface. (b) The cloak pattern and flat mirror where the input grating is placed at a 30° angle with respect to the reflecting surface.

**Figure 3.13.** Wavelength dependence of the carpet cloak. a,b, Plotted is the intensity along the output grating for a curved reflecting surface (a) with cloak and (b) without the cloak. The cloak demonstrates broadband performance at 1400 nm – 1800 nm wavelengths. Distinct splitting of the incident beam is observed from the uncloaked curved surface due to the strong scattering of the original beam.

**Figure 4.1.** Single step design for obtaining two functionalities by using transformation optics. Two different metadevices consisting of a horizontal lens with a vertical beam-shifter (a) and a beam-shifter for both directions (b). The virtual/physical space is shown in the left/right panel before/after transformation. Only the area inside the red boundary of the physical space is transformed while the area outside is kept unaltered. Green lines represent the beam directions while the blue lines symbolize wave fronts. On the right are the resulting permittivity profiles resulting from the transformation.

**Figure 4.2.** Metadevice consisting of a focusing element (lens) in horizontal (x-direction) and a beam-shifter in vertical (y-direction). (a) Spatial profile for the permittivity obtained by transformation of the space. The corners have been removed in this case due to spatially overlapping holes in the device. (b) Two-dimensional simulation of the spatial electric field magnitude (|Ez|) for a large beam propagating in the x-direction and a small beam in the y-direction. The white line marks the area of the transformed index region.

**Figure 4.3.** Schematic of the RIE fabrication process. The first step consists of spinning on the photoresist mask material. This mask is the exposed with electron beam lithography and subsequently chemically developed to remove the exposed regions. The wafer is then put in the RIE chamber where a bias is placed between an upper and lower electrode, ionizing the working gases. These gasses accelerated to the surface of the wafer where they react with the device layer, Si in this case. Lastly, the mask layer is removed via a short Oxygen plasma etch.

**Figure 4.4.** Schematic and SEM layout of metadevice. (a) Schematic of device fabricated on an SOI wafer. The TM waveguide mode is excited when
illuminating either of the two input gratings. (b) SEM image of device, showing input and output gratings. Two input / output grating pairs are used to excite the two different directions / functionalities of the device.

**Figure 4.5.** Experimental lens and beam-shifter metadevice performance at a wavelength of 1,500 nm. (a) Scanning electron microscope image of the device whose footprint is 22x22 μm². The inset shows a magnified view of the air holes in the silicon waveguide slab with a hole diameter of 75 nm. (b,c) Optical microscope images with the intensity distribution at the in-couple and out-couple gratings for the lens (horizontal) and the shifter (vertical). Due to the strong back reflection of the excitation beam from the silicon surface the intensities of the output profiles are scaled by 4 times and 8 times, respectively. The white boxes mark the position of the gratings and the hole pattern for the metadevices.

**Figure 4.6.** Experimental dual beam-shifter metadevice performance at a wavelength of 1,500 nm. (a) Scanning electron microscope image of the device whose footprint is 22x22 μm². The inset shows a magnified view of the air holes in the silicon waveguide slab with a hole diameter of 75 nm. (b,c) Optical microscope images with the intensity distribution at the in-couple and out-couple gratings for both the horizontal and vertical shifters, respectively. Due to the strong back reflection of the excitation beam from the silicon surface the intensities of the output profiles are scaled by 8 times. The white boxes mark the position of the gratings and the hole pattern for the metadevices.

**Figure 4.7.** Metadevice performance consisting of a lens and a beam-shifter. (a) Magnitude of the electric field ($|E_z|$) for a 13 μm wide beam traveling from left to right through the focusing element. (b) Measured beam intensity profiles for different distances of the output grating from the center of the device for $\lambda = 1500$ nm. The dotted black line corresponds to a measurement without the optical element between the gratings. The intensities are normalized with respect to the profile for 13 μm distance. (c) Retrieved spot size from the measurements (black) compared to the design values extracted from the simulation (red).

**Figure 4.8.** Metadevice performance consisting of a lens and a beam-shifter. (a) Magnitude of the electric field ($|E_z|$) for a beam propagating from bottom to top through the beam-shifter element. (b) Measured intensity beam profiles for the input and output beams when entering the element at around -6 μm and 6 μm with respect to the center of the device. (c) Beam position of the output beam for various input positions.

**Figure 4.9.** Performance of the dual beam-shifter metadevice. The corresponding input and output beam profiles for the horizontal and vertical direction, respectively. The intensities of the output beam are normalized with respect to the beam profile at 0 μm (center of the device).
**Figure 5.1.** PBH refractive index profile and optical response. (a) Refractive index profile for the PBH structure versus radius with $b = 1.5a = 15\,\mu\text{m}$. The refractive index tends to a singularity at $r = 0$. (b) Magnetic density field plot for the PBH structure. The light is incident at $r = b$ and is trapped into the singularity at the center, resulting in high field intensity.

**Figure 5.2.** Modified PBH schematic and refractive index profile. (a) Schematic of the truncated PBH design. An absorbing core replaces the singularity and is surrounded by a radially varying index profile. (b) Radially varying effective mode index profile of the PBH structure. The center region has an effective mode index of $3.15 + 0.06i$.

**Figure 5.3.** PBH electric field and energy density plots. (a) Electric field plot for a PBH with $b = 1.5a = 30\,\mu\text{m}$. Light is incident at $r = 20\,\mu\text{m}$ and spirals to the core of the structure where it is absorbed. (b) Energy density plot of the same PBH structure demonstrating the path of light in the structure.

**Figure 5.4.** Scanning electron images of the fabricated PBH structure. (a) Overall view of the structure. The extension of the structure at the top of the image is the input waveguide. (b) Close up top view of the pillars used to generate the spatially varying index profile. The pillar diameter is 70 nm. (c) Side view of the pillars composing the structure. The height of the pillars is 500 nm.

**Figure 5.5.** Quantum dot incorporation and imaging schematic. PbS quantum dots (QDs) are deposited onto the fabricated pillars structure using spin casting. The excitation beam (1380 nm) excites the QDs which emit at 1500 nm into free space. The QDs sit within the pillars, allowing excitation from the guided light in the structure. The emission from the QDs is imaged in the far-field via a CCD to map the light flow in the device.

**Figure 5.6.** Electron oscillation schematic and electric field profile of SPPs. An interface separates metal and dielectric semi-infinite media with permittivity $\varepsilon_m$ and $\varepsilon_d$ respectively. The electromagnetic fields are maximum at the interface and decay exponentially in the direction perpendicular to the interface.

**Figure 5.7.** Dispersion relation of a SPP at a Silver-air interface. The dotted line is light propagating in air and the blue line is the SPP dispersion relation. The wave-vector ($k_x$) of the SPP grows as it approaches the frequency approaches the surface plasmon resonance.

**Figure 5.8.** Sandwich structure and effective mode index of the SPP. (a) Sandwich structure consisting of a half space of Gold and air separated by a layer of PMMA with varying thickness ($d$). (b) Effective mode index of the SPP versus PMMA thickness.
Figure 5.9. Plasmonic Luneburg lens schematic and electric field plot. (a) Schematic of the Luneburg lens consisting of a cone of PMMA on top of a Gold film. The red lines represent the energy flow through the lens. (b) Electric field plot of the SPP moving through the lens. A wave with a flat wave front is focused on the opposite side of the lens, whose outer edge is denoted with the white circle.

Figure 5.10. PMMA height and dose correlation. The exposure depth of PMMA is non-linear with dose and must be correlated to allow a designed height profile to be realized. 50k Dalton weight PMMA is utilized to realize a more linear height profile with exposure dose and an atomic force microscope was used to measure the profile.

Figure 5.11. Height profile and SEM image of fabricated Luneburg lens. (a) Atomic force microscope image of the fabricated lens. A well defined linear height profile was realized with a maximum height of 1100 nm. (b) SEM image of fabricated lens with a diameter of 10 µm. The gratings used to excite the lens can be observed at the top and bottom of the image.

Figure 5.12. Experimental results for the plasmonic Luneburg lens at 1500 nm. (a) SEM of overall structure with input and output gratings. (b) Optical image of structure excited outside of lens. (c) Image of illumination at the center of the lens, showing focusing at the back side of the lens and a slightly larger beam at the output. (d) Image of structure illuminated slightly off axis of the lens. The output light can be observed to shift opposite to that of the illumination.

Figure 5.13. PEC Si etching schematic. (a) Optical illumination system for the PEC setup. A DMD provides spatially and temporally modulated light patterns that are projected onto the Si which is place in an etch cell with an HF electrolyte, under bias. The camera allows the etch to be monitored in real-time. (b) Schematic of grey scale Si etching. The light pattern is modulated in a grey scale manner where higher intensities etch the Si at higher pore densities, resulting in a lower refractive index.

Figure 5.14. Schematic of 3D grey-scale index modulation. The illumination pattern is modulated with time, as the etch progresses through the wafer. This results in spatial modulations in the vertical direction. In this case, a radially varying index pattern is demonstrated, as is found for example in a Luneburg lens.

Figure 5.15. SEM of a PEC etched Si wafer. The wafer was etched at 150 W/cm² for 10 minutes in 1:1 HF:Etoh. The resulting Nanoporous region is 160 nm in thickness. The individual pores are too small to resolve in the SEM image.
Acknowledgements

I would like to take an opportunity to thank my co-workers, friends, and family for their support during my graduate studies. It was only through their support that I was able to accomplish what is outlined in this dissertation. The journey through graduate school has been one of the most rewarding experiences of my life largely in part due to the amazing people I have worked with along the way.

Foremost, I would like to thank my mentor, Prof. Xiang Zhang. When I joined ‘xlab’, I knew I would be challenged in both the depth and breadth of my knowledge. However, what I did not realize is how much I would enjoy the challenge. My enjoyment in working hard to tackle difficult problems is in no small part due to Prof. Zhang’s contagious enthusiasm and push to understand the ‘big picture’. His encouragement of my research has allowed me the freedom to formulate and tackle challenging and high impact problems. He has taught me how to think critically and find my way to the front of the field. His guidance in writing scientific papers has also taught me how to communicate these ideas clearly and concisely. Prof. Zhang has been extremely supportive in introducing me to the scientific community by sending me to numerous academic conferences and graciously introducing me to grant managers. His faith in my ability and support over the years is the main reason this dissertation is presented here. I would also like to thank Prof. Costas Grigoropoulos, Prof. Liwei Lin and Prof. Ming Wu for not only serving on my dissertation committee but also my qualification committee. I truly appreciate the time they have invested in my success and it has been a pleasure to get to know them over the years.

I want to especially thank all the members of ‘xlab’. My enjoyment and success in graduate school is a direct reflection of the special environment that exists in the lab. I fear that I will never again have the opportunity to work with such an amazing group of scientists and friends. In particular, I want to thank Dr. Dentcho Genov for guiding me through theory early in my career and Dr. Thomas Zentgraf for teaching me how to be a true experimentalist. I also want to thank Dr. Shuang Zhang, Dr. Jensen Li, Dr. Rupert Oulton, Dr. David Pile and Dr. Yongmin Liu for their continuous guidance and help during my time in the lab. I especially want to thank my fellow graduate students, Dr. Muralidhar Ambati, Chris Gladden, Lee Folk, Ze’ev Abrams, and Erick Ulin-Avila for lively and always interesting discussions but most importantly for their friendship and support over the past five years.

Thanks to all my friends, both in and out of the lab, for making my time at Berkeley truly unforgettable. Particularly, I would like to thank Harrison Moar, Matt Reinthaler and Jay Lynas for always supporting me even if they did not fully understand what I was doing.

Finally, and most importantly, I would like to thank my family and Aleke for their unending love and support. Words cannot describe my appreciation. To my parents, you have not only given me wings, but always encouraged me to fly. This dissertation is dedicated to you.
Chapter 1

Metamaterials

The purpose of this dissertation is to explain the physics, design, and realization of electromagnetic (EM) metamaterials and associated devices. Particularly, this dissertation will focus on metamaterials operating at optical frequencies where plasmonic effects and fabrication limitations are major challenges in realizing such materials and devices. As such, the main emphasis will be placed on overcoming these challenges in the design and experimental realization of such metamaterials. This chapter will serve as an introduction to the underlying physics of metamaterials and describe the brief but fast ascension of the field.

1.1 Metamaterials: What is all the fuss about?

While there is no formal definition of a metamaterial, the broadest and most widely agreed upon description defines them as artificially structured and effectively homogenous materials with properties that arise from the structuring of the material rather than the constituent materials. This definition encompasses materials that have traditionally fallen under the effective medium theory umbrella as well as new types of more exotic materials that exhibit properties not existing in nature. The material properties in question are dynamic responses to time varying fields and as such, the most common areas of implantation are with electromagnetic or acoustic waves. This dissertation will be concerned with electromagnetic metamaterials therefore the properties we will be concerned with are the responses of the material to the electric and magnetic fields of the incident radiation. It is important to emphasize that metamaterials are homogenized composites which dictates that in general the structuring must be at a size scale much smaller than the wavelength of the incident radiation. Therefore, unlike photonic crystals which work by taking advantage of diffraction, light passing through a metamaterial should not diffract, just as if it were to pass through any other homogenous medium.

While not originally deemed metamaterials, the concept of achieving material properties through structuring has existed for quite some time. For example, the idea behind modeling a medium made up of sub-wavelength constituents was first treated by a number of authors in the mid to late 1800’s including Lorentz, Lorenz, Clausius, and Mossoiti [1,2]. Their work has lead to what is now deemed effective medium theory which is primarily concerned with how to model materials, or metamaterials, composed of different types of constituent particles / structuring including spheres, spheroids and cylinders [3]. The metamaterial community has taken effective medium theory one step further by introducing new types of constituents / structures that allow more freedom in creating arbitrary electromagnetic material properties. As such, the main impetus behind the metamaterial community has been the theoretical and experimental demonstration of
unique material properties and devices not readily attainable with naturally occurring materials.

Arguably the two biggest drivers and certainly most publicized endeavors of the metamaterial community have been first, achieving a material with a negative index of refraction and second, achieving a cloaking device. These two directions epitomize the inherent benefits of using physical structures to attain homogenized material responses. The first is the ability to achieve a material with a property not present in naturally occurring materials such as a negative index of refraction and the second is the ability to spatially control the underlying material properties, as we will see is necessary in a cloaking device.

Veselago, in 1968, was the first person to describe the unusual physical phenomena that exist in materials with a negative index of refraction [4]. These unusual phenomena include negative phase propagation, light bending backward at the interface of the material (opposite to that in materials with a positive index of refraction), and the possibility of planar lenses. However, Veselago’s work lay dormant for nearly 30 years due to the lack of availability of such a material. It was not until the concept of metamaterials, and specifically the ability to achieve a high frequency magnetic response, described by Pendry in 1999, that researchers were able to design a material with a negative index of refraction [5]. Smith, in separate experiments in 2000 and 2001, was the first to experimentally realize such a property and was also the one who coined the term ‘metamaterial’ [6,7]. This first experimental demonstration has lead to a plethora of different types of metamaterials including those which exhibit near-zero permittivity [8,9], chirality [10,11], super absorption [12], negative group velocity [13,14], and highly anisotropic material properties [15,16].

The pursuit of negative refractive index materials has been traditionally tied to realizing an imaging device referred to as the so called ‘perfect lens’ proposed by Pendry [17]. In conventional optics, we are ultimately limited by what is referred to as the ‘diffraction limit’ with regards to the resolution by which we can resolve an image. This limit is dictated by the maximum wave-vector that can propagate through free space, which is given by $k_{\text{max}} = \omega / c$. The reason for this limit is that evanescent waves on the surface of an object do not propagate into free space and thus some information about the object is lost. Pendry showed that this resolution limit could be overcome by placing a slab of negative refractive index material in the near-field of the object. This slab of negative index material allows these evanescent waves to be coupled across the metamaterial and imaged on the opposite surface of the slab. Such a slab also allows the propagating waves to be reconstructed, as was proposed in Veselago’s work, thus forming a perfect image which contains all the wave vectors leaving the object. Subsequently, using metamaterials, the perfect lens has been experimentally demonstrated in the microwave region [18] though in the optical region only reduced forms, unable to reconstruct propagating waves, have been realized [19,20].

More recently, new applications for metamaterials have emerged, the most notable of which is the electromagnetic cloaking device, proposed in 2005 [21,22]. Such a device is actually a subset of a design methodology deemed ‘transformation optics’. Transformation optics works by tying Maxwell’s equations to a designed transformation of space [23]. In such transformations, light follows a new coordinate system and, for example, can be caused to flow around an object, rendering it invisible. This coordinate
transformation is realized in a material system by spatial changes in the underlying material properties. Such devices highlight one of the important benefits of employing metamaterials, namely the ability to change material properties in a well designed spatial manner. Another benefit is that such transformations usually require anisotropic material properties which can be designed into metamaterials. However, as we will see, employing spatially changing anisotropic elements can be especially challenging at optical frequencies. The electromagnetic cloak was first realized in 2006 at microwave frequencies [15] and, as will be discussed in this dissertation, has recently been demonstrated at optical frequencies [25]. Using transformation optics as the design methodology and metamaterials as the vehicle; this original cloak work has motivated a myriad of devices such as source transformations [26], electromagnetic black holes [27,28], novel lenses [29], and hybrid optical devices [30].

The remainder of this chapter will devoted to explaining the basic theory behind metamaterials while maintaining a historical perspective. We will focus on using metamaterials to engineer a negative refractive index as it encompasses the most challenging requirements with respect to materials properties. Metamaterials operating at microwave frequencies will be describe first, as they were realized ahead of optical metamaterials. These concepts will then be transferred to the optical regime where imperfect metal properties and fabrication constraints become challenges. We will discuss how these challenges have been addressed as well as outlining the remaining issues when working at optical frequencies.

1.2 Engineering Material Properties

In EM two fundamental material properties describe how light interacts with a material. These two properties are defined as the permittivity (\(\varepsilon\)) and permeability (\(\mu\)) of a medium. The permittivity describes the degree to which a material polarizes in response to the electric field of light while the permeability describes the degree to which a material polarizes in response to the magnetic field. To understand how these properties control propagation of EM waves, we can derive the wave equation for light propagating through any homogeneous medium using Maxwell’s equations. In the absence of free charges and currents these equations,

\[
\nabla \cdot \mathbf{B} = 0, \quad \nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}
\]

\[
\nabla \cdot \mathbf{D} = \rho, \quad \nabla \times \mathbf{H} = \mathbf{j} + \frac{\partial \mathbf{D}}{\partial t}
\]

combined with the constitutive relations,

\[
\mathbf{D} = \varepsilon \mathbf{E} = \varepsilon, \varepsilon_0 \mathbf{E}
\]

\[
\mathbf{B} = \mu \mathbf{H} = \mu, \mu_0 \mathbf{H}
\]

yields the wave equations,

\[
\nabla^2 \mathbf{E} = \mu \varepsilon \frac{\partial^2 \mathbf{E}}{\partial t^2}
\]

\[
\nabla^2 \mathbf{B} = \mu \varepsilon \frac{\partial^2 \mathbf{B}}{\partial t^2}
\]
where the constitutive parameters $\varepsilon_0$ (8.85*10$^{-12}$ F/m) and $\mu_0$ (1.26*10$^{-6}$ H/m) are the permittivity and permeability of free space and $\varepsilon_r$ and $\mu_r$ are the relative permittivity and permeability of a material. These two fundamental EM properties provide a complete description and control of how light interacts with a medium including reflection, transmission, absorption, and refraction. For instance, the impedance of a material is given by $Z = \sqrt{\mu/\varepsilon}$ and refractive index is given by $n = \sqrt{\varepsilon/\mu}$. The wave equations can be solved by assuming some form of a wave, for example a plane wave as,

$$
E(\omega,t) = E_0 e^{i(kr-\omega t)}
$$

$$
B(\omega,t) = B_0 e^{i(kr-\omega t)}
$$

where $\omega$ is the frequency of the wave and $r$ and $t$ the spatial and temporal positions. The wave vector ($k = \frac{\omega}{c}$) dictates the direction of phase advance. It should also be noted that while $\varepsilon$ and $\mu$ are typically defined as scalar values, they are in reality tensors. While very few materials in nature have significant anisotropy, metamaterials on the other hand are generally defined by anisotropic material properties.

In choosing a material for specific application, we are typically confined to using values of $\varepsilon$ and $\mu$ that occur in a naturally occurring materials at a particular frequency. This can be quite restrictive as illustrated in the chart below which categorizes the values of $\varepsilon$ and $\mu$ for all materials.

![Figure 1.1. Material parameter space. Optical materials are characterized by the electric permittivity ($\varepsilon$) and the magnetic permeability ($\mu$).](image)

Region I consists of dielectrics where both the permittivity and permeability of the materials are positive. Region II consists of metals and highly doped semiconductors which have negative permittivity below the plasma frequency but positive permeability. In this region the refractive index, and thus wave vector, have purely imaginary values leading to a lack of wave propagation inside the medium which is the reason, for example,
that metals are opaque. However, regions III and IV have much fewer naturally occurring material candidates. Region IV, where the permeability is negative but permittivity is positive only consists of ferrites that can exhibit negative permeability but only at EM frequencies below the gigahertz range. Region III, on the other hand, where both permittivity and permeability are negative, is devoid of any naturally occurring materials. The main goal of the metamaterial community has been to develop new materials that allow access to any region in Fig. 1.1 and achieve any particular combination of $\varepsilon$ and $\mu$ at any particular frequency.

### 1.2.1 Effective Media

As mentioned earlier, homogenization of structured materials has existed for quite some time under the umbrella of effective medium theory [3]. The field of effective medium theory, in general, seeks to find analytical solutions for the homogenized properties of different structural geometries placed in a background medium. The simplest case of this consists of two constituents, for instance spheres of dielectric constant $\varepsilon_i$ inside a background of dielectric constant $\varepsilon_e$. The modeling of such an effective media has many forms but perhaps the most well known is the Maxwell Garnett theory. While we will discuss permittivity here, the approach is also applicable to a number of material properties including permeability and conductivity. In this treatment, the effective permittivity is derived by defining an average flux density based on averaging the electric fields in both the inclusion and background. The general form of the permittivity takes the form:

$$
\varepsilon_{\text{eff},i} = \frac{f \varepsilon_i A_j + \varepsilon_e (1-f)}{f A_j + (1-f)}
$$

where $f$ is the filling fraction of the inclusion and $A_j$ is the field ratio between the inclusion and background. The subscript $j$ refers to the direction of the electric field in the incident wave.

Such a treatment provides a simple analytical model for determining homogenous properties but has certain limitations. The main limitation is that the inclusions must be much smaller than the wavelength of light so that they are in the quasi-static limit and may be modeled as simple dipoles. The Maxwell-Garnett theory also uses the Lorentz field [1] to derive the electric field present in the inclusion and therefore is inherently non-symmetric in the treatment of the background / inclusion, causing a lack of percolation threshold in the underlying medium. A number of other treatments have been proposed to overcome these shortcomings and provide better agreement with experimental results including the Bruggeman, Coherent potential and unified mixing treatments. However, all these theories are still limited to modeling systems with relatively simple geometries that fall under the quasi-static regime. Despite these limitations, such theories can be quite useful in modeling metamaterials with simple unit cell geometries, as seen in Fig. 1.2.
Figure 1.2. Field ratios for effective medium of different shaped constituents. (a) spherical and (b) cylindrical inclusions. These ratios are used in equation 1.5 to compute the effective material properties for both types of constituents where $\varepsilon_e$ and $\varepsilon_i$ are the matrix and inclusion permittivity, respectively.

Many times, metamaterial unit cells are quite complex and cannot be modeled assuming simplistic unit cell geometry and electric response. Furthermore, metamaterial unit cell dimensions, instead of being much smaller than the wavelength, are typically on the order of the wavelength of light. Under such circumstances, analytical approaches to modeling materials ultimately fail and numerical approaches must be employed to extract material properties. The most popular approach in modeling such complex geometries is the so called ‘S-parameter’ model [31]. In this approach, the scattered waves, or S-parameters, from an inhomogeneous material are used to calculate the homogenized material properties. This model assumes that the scattered waves of the inhomogeneous medium are the same as those of a hypothetical continuous media with the same effective optical properties. The advantage of this approach is that the scattered waves can be calculated directly from simulations as they are the complex reflection ($S_{11}$) and transmission ($S_{21}$) coefficients. This results in the following formula for the refractive index and wave impedance of the material,

$$n = \frac{1}{kd} \cos^{-1} \left( \frac{1 - S_{11}^2 + S_{21}^2}{2S_{21}} \right)$$

$$z = \sqrt{\frac{(1 + S_{11})^2 - S_{21}^2}{(1 - S_{11})^2 - S_{21}^2}}$$

where $d$ is the material thickness and $k$ is the wave vector of the free space wave. The permittivity and permeability can also be extracted as $\varepsilon = n / z$ and $\mu = nz$. The other benefit of this approach is that the scattered waves can be measured experimentally for a material. In doing this though, both the amplitude and phase of the reflected and transmitted light must be measured. This can become difficult at optical frequencies where it is difficult to measure the phase of light due to the short wavelength. One point of contention in this approach is that the material thickness does not necessarily represent the optical thickness of the material. For example, in thin films much smaller than the wavelength, the fields may extend outside of the material at a similar scale to the
thickness of the material itself, yielding an inaccurate index value. Also, as the material thickness approaches that of the wavelength, it becomes difficult to find an unambiguous solution to the equation. However, this approach represents a simple design and experimental tool for metamaterials and has had broad use within the metamaterial community.

1.2.2 Negative Refractive Index

One of the major goals of the metamaterial community has been the desire to engineer a negative refractive index metamaterial (NIM). Such materials fall into region III in Fig. 1.1 where both $\varepsilon$ and $\mu$ are simultaneously negative. Combining equations 1.2 through 1.4, we can find a relationship between the wave vector and the fields in the medium,

$$k \times E = \mu \omega H$$
$$k \times H = -\varepsilon \omega E$$

When both $\varepsilon$ and $\mu$ are positive, we are forced by 1.7 to chose a positive sign for the wave vector and thus refractive index, forming right handed relationship between $E$ and $H$ and $k$ (Fig 1.3a). However, if both $\varepsilon$ and $\mu$ are negative we are forced to chose a negative sign for the wave vector and thus refractive index ($n = -\sqrt{|\varepsilon|/|\mu|}$). This also results in a real value for the wave vector, allowing propagation of light inside the material, unlike materials falling in regions II and III in Fig. 1.1. This forms a left handed relationship between $E$ and $H$ and $k$ (Fig. 1.3b) and is the reason why NIMs are often called left handed materials. It is also important to note that the Poynting vector of light ($S = E \times H$), which dictates the direction of energy flow, remains the same for both cases.

Figure 1.3. Left and Right handed triads. (a) While positive index materials are characterized by energy ($S$) and phase ($k$) moving in the same direction, these vectors move in opposite directions (b) in negative refractive index materials.

In order to realize a NIM we must, therefore, engineer a material with both negative $\varepsilon$ and $\mu$ at the same frequency. For the time being, we will discuss this problem in separate aspects, namely, first engineering a material with a negative electric response or permittivity, and second, engineering a material with a negative magnetic response or permeability. The key goal in both aspects is the fact that each material property should be engineered at the same frequency, which could range from the microwave to the optical regime.
Creating a material with negative permittivity is relatively straightforward. In fact, metals and highly doped semiconductors naturally have a negative permittivity at frequencies below the plasma frequency. This is due to the existence of quasi-free charge in the material which interacts with the electric field of light. The dielectric response of such a metal (at optical frequencies) can be derived using the Drude model [32],

$$\varepsilon(\omega) = 1 - \frac{\omega_p^2}{\omega(\omega - i\gamma)}$$

where $\omega_p^2 = n_e e^2 / \varepsilon_0 m_e$ is the bulk plasma frequency of the metal and $\gamma$ is the damping coefficient of the charge oscillations. At microwave frequencies, where the electromagnetic field does not penetrate into metal, the collisional part of the model is neglected. Therefore, the metal can be modeled as a perfect electrical conductor with a permittivity given by, $\varepsilon(\omega) = 1 - \frac{\omega_p^2}{\omega^2}$. Using simple, naturally occurring materials, we are relatively restricted in the exact value of the permittivity at any one frequency. The choice in the permittivity is limited to a choice of different metals or the doping level of the semiconductor. It should be noted though that semiconductors suffer from a large damping coefficient and therefore are rarely employed in actual metamaterials.

Using the concept of metamaterials though, it is relatively easy to achieve an arbitrary permittivity value at any particular frequency. For example, we can take the case of metallic wires embedded in a dielectric host media, as shown in Fig. 1.2b. Using the analytical approach of Maxwell-Garnett we find that for different volume fractions of the wires we can achieve a well-designed permittivity value, as shown in Fig. 1.4.

![Figure 1.4](image)

Figure 1.4. Effective permittivity of a Silver wire composite medium for various filling fractions. The wave is polarized along the wire axis leading to a non-resonant diluted metal. Tuning the filling fraction allows engineering of the effective permittivity.

This concept has been almost universally adopted in engineering NIMs from the microwave to optical frequencies. It can also be thought of as artificially reducing the plasma frequency of the material or creating a diluted metal. One important note is that
using this technique creates an inherently anisotropic material. While isotropic for TM polarizations, the TE permittivity will have a much different value and in fact contains a resonance when $2\varepsilon_\perp = \varepsilon_\parallel$. This is due to the excitation of localized surface plasmon resonances which are resonant oscillations of the electrons in the metal. Elimination of this anisotropy can be achieved by using a 3D cubic wire grid though this is only employed in the microwave region where fabrication constraints allow more complex architectures [33].

While engineering a material’s permittivity is straightforward, engineering permeability has always been more challenging. The above treatment of wires still applies to permeability but the problem is that naturally occurring materials do not have a high frequency magnetic response, i.e. $\mu(\omega) = 1$ [32]. Therefore, there is no contrast in the background and inclusion in the previous treatment.

In 1999, Pendry proposed that high frequency magnetism could be achieved using small metallic rings by inducing an alternating current, oscillating at the frequency of the electromagnetic wave [5]. Such a current can be generated, for example, by the time-varying magnetic field passing through a conducting coil, simply from Lenz’s law. The induced current, and thus magnetic moment, are normally weak but can be dramatically enhanced by introducing resonances into the coil. Such resonant solenoid structures form the basis for artificially engineered magnetic metamaterials.

**Figure 1.5.** Schematic of the split-ring resonator. (a) Depicts an array of the resonators and the proper polarization of light needed to create an effective magnetic response (b) Unit cell of the metamaterial with annotated dimensions where $P$ is the periodicity of the array. (c) Equivalent circuit of the split-ring where at resonance the internal current ($j$) can induce a magnetic field that is out of phase with the incident light.

The first example of this is the so-called ‘split-ring resonator’. This resonator, shown in Fig. 1.5, is composed of a ring with a single slit at one side. The response of the split ring can be modeled as a simple $LC$ circuit (Fig. 1.5c) where the metal serves as the inductor and the gap as the capacitor. As with all $LC$ circuits, a resonance is achieved at the frequency $\omega_0 = 1/\sqrt{LC}$ where $L$ and $C$ can be estimated by,

$$C = \varepsilon\varepsilon_0 \frac{wt}{g} \quad L = \mu_0 \frac{l^2}{t}$$

In this case, the inductance has been taken from one turn of a wire of area $l^2$. More accurate estimations exist for the inductance [34,35] but the form presented here gives a better intuitive understanding of scaling effects in the split-ring.
At this resonance, a strong magnetic moment is induced in the split rings which give rise to a large effective permeability. The split-ring can be viewed as the inclusion in the conventional effective medium theory where in this case the inclusion’s permeability is no longer equal to 1. Using a field averaging technique, Pendry showed that this effective permeability can be modeled as,

$$
\mu_{\text{eff}} = 1 - \frac{F \omega^2}{\omega^2 - \alpha_0^2 + i \Gamma \omega}
$$

where $F$ is the filling ratio of the SRR ($F = l^2 / P^2$) and $\Gamma$ is the damping term. At resonance, large values of the effective permeability are achieved, with both positive and negative sign. For instance, the permeability is plotted in Fig. 1.6 for a structure having the dimensions outlined in [5].

![Figure 1.6. Permeability of the split-ring metamaterial. The resonator passes through resonance at ~1GHz wherein a negative effective permeability, Re(µ) can be realized. This resonance is accompanied by a loss, Im(µ), due to the finite conductivity of the metal.](image)

With the advent of the split-ring, researchers now had a vehicle to obtain both negative permittivity and permeability. Through proper engineering, the negative regions of both of these constituent properties can be overlapped, forming a band of negative refractive index. In 2000, Smith proposed that this could be done by combining the split-ring unit cell with metallic rods to provide both negative permeability and permittivity, respectively [7]. Using this geometry, Smith demonstrated that split rings alone showed a stop band at ~5GHz (owing to negative $\mu$ but positive $\varepsilon$), while the combination of both constituents opened a pass band at the same frequency (owing to negative $\mu$ and $\varepsilon$). While this first experiment with met with a degree of controversy, the same group later demonstrated a much thicker NIM in which that formed a simple prism from [6]. This allowed them to directly measure the angle of refraction at the surface of the material, unambiguously demonstrated a material with a negative refractive index. Since this first demonstration, numerous groups have validated this concept both theoretically and experimentally.
1.3 Optical Metamaterials

Since the inception of metamaterials, there has been great desire to scale their optical properties to the optical wavelength region. This is due to the fact that many of the unique applications of benefits of employing metamaterials lie in this wavelength region. The optical wavelength region encompasses light with a wavelength from 1.5 µm to 400 nm and therefore includes telecommunications, biological imaging/sensing, lithography, and general spectroscopy. However, scaling metamaterials to optical wavelengths involves both fundamental and engineering problems. Here, we will discuss these issues and the new unit cells researchers have developed to overcome them.

So far, we have dealt with modeling metamaterials in the microwave region where metals can be treated as perfect conductors. This entails that the induced current in the metal is in-phase with the applied field and furthermore, there is no field penetration into the metal. However, at optical wavelengths, as the frequency of light approaches the plasma frequency, plasmonic effects begin to dominate invalidating this assumption [36,37,38]. Plasmonic effects are characterized by increased penetration of the electromagnetic field into the metal and phase lag of the motion of electrons compared to that of the incident electric field. These effects start to show up at optical frequencies and become more pronounced as the frequency approaches the plasma frequency of the metal. At frequencies above plasma frequency, metals have a positive permittivity and thus lose their ‘metallic’ behavior.

In the case of the split-ring the phase lag of the electrons can be incorporated into an additional inductance in the structure, referred to as the self-inductance of the electrons [35,36]. To understand the consequences of this effect, we will continue to model the structure without loss for the time being. The self inductance can be modeled as,

\[ L_e = \frac{4l}{wto_p^2} \]  

(1.11)

where \( 4l \) is the circumference of the split ring and \( w \) and \( t \) are the width and thickness of the wire, respectively. The magnetic resonance of the split-ring now becomes,

\[ \omega_0 = \frac{1}{\sqrt{(L_e + L_s)C}} \]  

(1.12)

where \( L_s \) is the structural impedance derived in section 1.2.2. We can now introduce a geometric scaling factor \( a \), by which all dimensions in the split ring are scaled. From 1.9 and 1.11 we can see that while \( C \) and \( L_s \) scale with \( a \), \( L_e \) scales as \( 1/a \). The resonance frequency can be redefined using this scaling factor as,

\[ \omega_0 = \frac{1}{\sqrt{c_1a^2 + c_2}} \]  

(1.13)

where \( c_1 \) and \( c_2 \) are constants unrelated to the size of the unit cells. At microwave frequencies, the additional inductance is negligible due to the fact that \( c_1a^2 >> c_2 \). At smaller dimensionality, when \( c_1a^2 \approx c_2 \), the self-inductance results in a saturation of the magnetic resonance. The presence of \( c_2 \), which is proportional to \( 1/\omega_p^2 \), demonstrates the fact that as we approach the plasma frequency the inductance of electrons becomes dominate. Based on the above analytical model, FDTD simulations, and experimental
validation, it has been shown that the magnetic resonance frequency of the split-ring geometry indeed saturates at wavelengths below ~1µm [35,36,37,39,40].

In the above treatment, we have not taken into account any losses or penetration of radiation into the metal. It is relatively easy to incorporate this interaction but it has been shown to have a negligible effect on saturation of the magnetic resonance frequency [35]. While not important in the saturation of the response, this effect causes increased losses in the metal due to finite penetration depth of the electric field. At visible frequencies this penetration depth is typically on the order of 25 nm for noble metals such as Silver and Gold. The field inside the metal causes increased interaction with the free electrons which become increasingly damped at high frequencies. This damping is caused by electron-electron and electron-phonon scattering, and thus energy loss to heat generation [32]. In addition to ohmic losses, radiative losses increase due to the fact that imperfections in the metal, due to fabrication, scatter radiation out of the structure. Due to this increased loss at optical wavelengths, the figure of merit of metamaterials is defined as,

$$\text{FOM} = -\frac{\text{Re}(n)}{\text{Im}(n)}$$

This FOM relates how many oscillations a wave will undergo in the material before being completely absorbed. While FOM’s greater than 100 are common in microwave frequencies, eclipsing a FOM of 3 has been a great challenge in the optical wavelength region [41].

1.3.1 Cut-Wire

To push the response of metamaterials into the visible wavelengths, new unit cell geometries have been developed. One such unit cell is made of cut-wires, sometimes referred to as the ‘chop-stick’ geometry [42,43]. The evolution from the split-ring geometry is straightforward, and can be seen in Fig. 1.7.

![Figure 1.7. Evolution of the split-ring unit cell as frequencies scale to the optical regime.](image)

By eliminating one bar of the split ring and opening the gap, we end up with a unit cell with two capacitors in series, each with a smaller capacitance than the original geometry. The reduction in the overall capacitance allows an increase in the magnetic resonance saturation frequency. Such a unit cell is typically fabricated in a vertical orientation, as seen in Fig. 1.8, where electron-beam lithography can be used to define the
cross-section and vertical deposition of the material can be used to easily control the separation distance between the wires.

Figure 1.8. Cut-wire schematic. (a) Depicts an array of the cut-wires which can lead to a negative index of refraction under the proper polarization. (b) Unit cell of the cut-wire metamaterial where the grey and green wires are made of metal and dielectric, respectively. (c) Circuit model of the cut-wire unit cell depicting the internal $LC$ circuit and current loop.

It has been shown that using such geometry allows one to achieve a negative index of refraction without the incorporation of any additional elements [44,45]. However, the problem that arises with the split-wire geometry is that it is not possible to engineer the spectral position of the negative permeability and permittivity band independently. Therefore, while it has been experimentally demonstrated that cut-wires can achieve a negative refractive index down to 1.5 µm [45], these structures are not optimized with respects to the values of the permittivity and permeability, and thus it is difficult to achieve large negative refractive indices. For example, in [45] the refractive index only reached a value of -0.3 with a FOM equal to 3.

1.3.2 Fishnet

To overcome the fact that the cut-wire’s magnetic and electric response are intrinsically linked, the concept of the so called “fishnet” metamaterial was proposed by Zhang [46]. The fishnet takes advantage of the magnetic response induced between two parallel wires but adds an additional component to engineer the spectral position of permittivity (Fig. 1.9).
Figure 1.9. Fishnet metamaterial schematic (a-c) Depict the separate components of the metamaterial which provide both a magnetic (a) and electric (b) response. The silver layers are made of metal and the green layer a dielectric. Combined (c), these constituents form the complete fishnet structure. (d) Unit cell geometry of the metamaterial. (e) Depicts the $LC$ circuit and current loop that form the magnetic response in the fishnet metamaterial.

The first component of the fishnet metamaterial is thick metallic wires oriented along the direction of magnetic field of the incoming light (Fig 1.9a). These metal wires are separated by a dielectric layer, forming the equivalent of the cut-wire structure. This structure provides a magnetic response, or artificial permeability, that is engineered by either changing the dielectric thickness or wire width, thus changing the $L$ and $C$ of the circuit. We can estimate the $LC$ value of the unit cell as (Fig 1.9e) \[ L = \frac{\mu_0 g l}{P_E}, \quad C = \varepsilon \varepsilon_0 \frac{P_E l}{g} \] (1.15)

It should be noted that modeling the capacitance and inductance for such a structure only provides a qualitative design tool. Unlike in the microwave frequencies where metals are nearly perfect and experience little field penetration, at optical frequencies there is significant field penetration causing the $LC$ model to break down. For instance, we can see from 1.15 that the magnetic resonance frequency should depend linearly on $1/l$. However, due to the interaction of fields on both wires (not taken into account in the $LC$ model), the thickness of the dielectric spacer is also equally important in determining the resonance frequency [48]. In reality, either increasing the width of the wire or decreasing the spacer thickness will move the magnetic frequency to longer frequencies and vice-versa.

The second constituent consists of thin metallic wires oriented in the direction of the electric field of the incoming light (Fig. 1.9b). These wires provide an effective permittivity that can be engineered separately from the permeability. Increasing the width of wires, thus increasing the effective metal content, will decrease the permittivity (larger
negative value) while changing the spacer thickness has little influence on the permittivity. These two constituents are combined to form the fishnet metamaterial (Fig. 1.9c,d) where both a negative permeability and permittivity can be engineered at a particular wavelength.

The superposition of responses may seem at first like an oversimplification of the structure. However, simulations and experimental data show that there is relatively little interaction between the two constituents [49,50]. Combining the structures will yield a slight decrease in permittivity due to higher metal content and a slight shift in the magnetic resonance to shorter wavelengths. Due to the small interaction between the constituents, it is still quite useful to model / design the two constituents separately and then combine them to fine tune the frequency of the negative index band.

Due to the increased freedoms associated with designing the fishnet metamaterial it has been used to achieve the highest FOM’s at optical frequencies. The highest figure of merit for a single layer of the structure (one metal / dielectric / metal layer) which has been experimentally measured is 3.0, which was achieved at a wavelength of 1.5 um [50]. The fishnet metamaterial has also been successful at scaling the response into the visible region [51,52], however, such structures still suffer from considerable loss and a low FOM. The lowest wavelength that the fishnet metamaterial has been demonstrated to have a negative index is 580 nm, where a FOM of 0.3 was achieved [53].

While the cut-wire and fishnet structures have had success in scaling the magnetic response to optical frequencies, there are several challenges that remain to be overcome. Firstly, the structures outline so far consist of a single functional (metal / dielectric / metal) layer along the direction of propagation. This is equivalent to an atomic monolayer, making it difficult to assign bulk properties such as the index of refraction. Moreover, due to their resonant nature, these systems suffer substantial loss at optical frequencies, resulting in a low FOM. This severely limits device applications of such materials where thick metamaterials are needed to provide manipulation of light / phase advance across the material. Therefore, it is imperative to realize low-loss bulk optical NIMs in order to unambiguously demonstrate the unique effects associated with negative index of refraction such as negative refraction and phase propagation.

1.4 Organization of the Dissertation

The remainder of this dissertation will be devoted to overcoming the challenges facing metamaterials at optical wavelengths. This includes realizing low loss metamaterials and furthermore, utilizing metamaterials in devices. As such, this dissertation is organized in the following manner.

Chapter 2 will be devoted to the development of a low loss, bulk negative index metamaterial operating at optical wavelengths. The design of the metamaterial will be discussed including the reduction in intrinsic losses related to increasing the thickness. The fabrication and experimental validation of the bulk metamaterial will be presented including the first direct observation of negative refraction in metamaterials at optical wavelengths.

In chapter 3, we will shift to device design and realization using metamaterials. Specifically, transformation optics will be described as well as its use in designing an electromagnetic cloak. Using this design methodology, the first experimental demonstration of cloaking at optical wavelengths will be presented. We will show how
both bandwidth and loss in the cloak can be greatly improved upon by using a non-
resonant, all dielectric metamaterial.

Chapter 4 will be devoted to the expansion of the transformation optics design
methodology into integrated optical devices with multiple functionalities. We will discuss
a new type of device deemed a ‘Janus’ device that incorporates multiple optical devices
into one footprint. The experimental demonstration of the device will be presented as
well as a shift in fabrication methodology that allows more precise dimensionality as well
as possible combination into integrated circuits.

Chapter 5 will describe new directions in metamaterial research and the latest
developments in realizing metamaterial driven devices at optical wavelengths. We will
discuss photonic black holes, plasmonic transformation optics devices, and the
development of a large scale manufacturing method.

Finally, chapter 6 will summarize the main findings discussed in the dissertation
as well as a discussion regarding the outlook for metamaterials and devices. The main
challenges still facing the field as well potential new horizons in metamaterials will be
presented.

References
values of sigma and mu," Soviet Physics USPEKHI-USSR, vol. 10, 1968, pp. 509-
514.
and enhanced nonlinear phenomena," IEEE Transactions on Microwave Theory
Medium with Simultaneously Negative Permeability and Permittivity," Physical
[8] R. Liu, Q. Cheng, T. Hand, J. Mock, T. Cui, S. Cummer, and D. Smith,
"Experimental Demonstration of Electromagnetic Tunneling Through an Epsilon-
100, 2008, p. 023903.
[9] N. Engheta, A. Salandrino, and A. Alù, "Circuit Elements at Optical Frequencies:
95, 2005, p. 095504.
1353-1355.
023901.


Chapter 2

Bulk Negative Index Metamaterials

In this chapter we will discuss the development of the first bulk negative refractive index metamaterial (NIM) [1]. These metamaterials are made of cascaded “fishnet” structures, with a negative index existing over a broad spectral range. We will describe the design of the metamaterial and how cascading of the unit cells can reduce loss in the material. Due to the lowered loss, the metamaterial is able to achieve the highest FOM to date for optical NIMs. A direct observation of negative refraction in the material will be presented by illuminating a prism made of the NIM. Such a demonstration results in an unambiguous observation of negative phase evolution of the wave propagating inside the metamaterial. Furthermore, the material can be readily accessed from free space, making it functional for optical devices. As such, bulk optical metamaterials should open up prospective for studies of the unique effects associated with negative and zero index materials such as the superlens [2], reversed Doppler effect, optical tunneling devices [3,4], compact resonators, and highly directional sources [5].

2.1 Introduction

Since the inception of NIMs in the microwave [6], there has been a constant drive to lower the operating wavelength into the optical regime [7]. The optical regime is particularly interesting due to the presence of several attractive applications of metamaterials including telecommunications, biological imaging / sensing, and lithography. However, as we have seen, there are both fundamental and engineering challenges in scaling such metamaterials to optical wavelengths. On a fundamental level, the increased loss and penetration depth at optical frequencies causes metamaterials to absorb a large amount of the incident light, resulting in a low FOM. Another fundamental challenge arises from the fact that at short wavelengths, we start to approach the plasma frequency of metals, causing saturation in the magnetic response of the structure.

On the engineering level, it becomes difficult to fabricate metamaterials with the proper dimensionality at optical frequencies. For instance, nanoscale imperfections are now at the scale of the incident radiation, causing scattering loss and reduced material performance. This challenging scale level also makes it difficult to fabricate thick metamaterials. The thickness of the material is important as a single layer of NIM acts as a monolayer of atoms. Adding subsequent layers of atoms will cause them to interact, changing the properties of the material where at a certain thickness, the material properties will converge to the bulk value. For instance, we can make an analogy to the difference in the properties of a single layer of graphite (graphene) and that of bulk graphite. In this case, the Raman spectrum of graphene is considerably different from graphite. However, as subsequent layers of graphene are added, the Raman spectrum will converge to that of bulk graphite [8]. Realizing a bulk NIM therefore allows one to assign
a thickness independent measurement of the material properties. Another drawback associated with single layer NIMs is that they do not allow us to truly take advantage of the unique physics associated with a negative index of refraction. This is due to the fact that the thin thickness of such materials does not allow enough phase accumulation within the sample compared to the surrounding medium. For instance, due to the thin thickness of past optical metamaterials it has not been possible to realize a simple prism in order to experimentally observe negative refraction, as was done at microwave frequencies [6].

In this chapter we will discuss how many of these challenges have been overcome by realizing a bulk NIM at optical frequencies. We will show how the bulk NIM is fundamentally different from a single layer metamaterial, allowing one to realize lower intrinsic losses through coupling of layers. We will also experimentally demonstrate the direct observation of negative refraction in such a material by fabricating a prism out of the material.

2.2 Bulk Fishnet Design

In this section we will discuss the design and modeling of the bulk NIM including the consequences of coupling layers. The single layer fishnet design was chosen as a starting point due to its relative ease of fabrication and engineering freedom in tuning the permittivity and permeability independently. The drawback is that the single layer fishnet still suffers from large intrinsic losses at optical frequencies. To get a better understanding for the reason for this loss, we can look at the microscale optical response of such a structure, shown below in Fig. 2.1.

![Figure 2.1](image)

**Figure 2.1.** Schematic and electromagnetic response of a single layer fishnet. (a) Schematic of the fishnet design and incident polarization where the dotted line indicates the cross-section of the material analyzed in (b,c). (b) Equivalent circuit of the NIM showing the induced current loop in the material. (c) Finite difference time domain simulation of the electric field within the magnetically resonant portion of the fishnet. The high electric field inside the metal layers is indicated by the strong red / blue color in the electric field plot. The high field, and resulting current, results in absorption of light due to the losses in the metal.

The electric field plot in Fig. 2.1 was generated with the commercial finite difference time domain (FDTD) solver, Microwave Studio, at an illumination wavelength of 1.5 µm. The intensity of the red and blue color indicates strong electromagnetic fields where the color indicates the phase of the field. From the simulation, it is clear that there
is a large portion of the electric field that penetrates into the metallic layers of the fishnet. At these frequencies, this penetration of field ultimately leads to large loss due to the presence of absorption in the metal layers.

It has been theoretically suggested that stacking up multiple fishnet functional layers along the propagation direction constitutes a promising approach for achieving a bulk optical NIM [9]. As we will see, the coupling of neighboring layers in such a structure can minimize the amount of light absorbed in the metal, thus increasing the FOM. A schematic of a bulk fishnet metamaterial is depicted in Fig. 2.2.

To acquire a clear understanding of the bulk metamaterial’s optical response simulations were performed with a rigorous coupled wave analysis (RCWA). RCWA expands the electromagnetic field into a number of diffraction orders and matches the boundary conditions at each interface. The fishnet was designed to achieve a negative refractive index around 1.5 µm. Silver (Ag) and Magnesium Fluoride (MgF₂) were used as the metal and dielectric (grey and green in Fig 2.2a, respectively). Ag was chosen due to its relatively low intrinsic losses at optical frequencies while MgF₂ was chosen due to its smooth film quality and ease of deposition. The dimensions of the structure, corresponding to Fig. 2.2b, are: \( P_M = P_E = 860\text{nm}, \ l = 565\text{nm}, \ w = 265\text{nm}, \ t_m = 30\text{nm} \) and \( t_d = 50\text{nm} \).

To evaluate the optical response of the bulk structure, an infinite thickness is first assumed for the metamaterial. This allows the eigenmodes of the structure to be solved for, yielding a well defined dispersion relation. We separate the fishnet into two constituents and calculate the dispersion curves. The first constituent is an array of metal strips along the direction of the magnetic field (Fig. 2.3a) in which induced antisymmetric conductive currents across the dielectric layers give rise to a magnetic band gap between 135 THz and 210 THz. This is further confirmed by the plots of the magnetic fields at two frequencies, above (Fig. 2.3d) and below (Fig. 2.3e) the band gap. Below the band gap, the magnetic response is positive, as shown in Fig. 2.3d, where the magnetic field component between the strips is in phase with the external field. Above the band gap, the metal strips have a moderately negative response as shown in Fig. 2.3e, where the magnetic field between the strips is out of phase. The second constituent is an array of metal wires aligned with the polarization direction of the incident electric field (Fig. 2.3b). This array serves as an effective medium with lowered volumetric plasma
frequency (220 THz), below which wave propagation is not allowed due to negative effective permittivity.

Figure 2.3. Dispersion relations and field plots bulk fishnet structure. In all plots the grey area corresponds to the negative material property regions as determined by simulations. (a) Dispersion relation of the array of metal strips along the magnetic field. The grey area indicates the bandgap where $\mu < 0$. (b) Dispersion relation for the array of metal wires aligned along the electric field. The grey area indicates the region where $\varepsilon < 0$. (c) The dispersion for the 3D fishnet structure. A dispersion curve with negative slope appears (grey region) within the overlapped region of the electric band gap and magnetic band gap if both structures are combined. (d) Magnetic field plot below the band gap. (e) Magnetic field plot above the band gap. The dotted lines in the schematic mark the unit cell size.

These two structures are merged to form the bulk fishnet metamaterial, for which the dispersion relation is shown in Fig. 2.3c. A propagation band with negative slope appears in the overlapped region of the forbidden gaps of both electric and magnetic media, demonstrating that the negative index behavior in the bulk cascaded fishnet indeed results from both the electric permittivity and the magnetic permeability being negative.

The cascading of the layers leads to a strong magneto-inductive coupling between neighboring functional layers [10]. The tight coupling between adjacent L-C resonators
through mutual inductance results in a broad band negative index of refraction with low loss, which is similar to the material response of left handed transmission lines [11,12]. In addition, the loss is further reduced due to the destructive interference of the anti-symmetric currents across the metal film, effectively canceling out the current flow in the center of the film [10]. This can be seen below by solving for the electric field in the metal using FDTD software, as was done in Fig. 2.1 for the single layer NIM.

![Figure 2.4.](image)

Figure 2.4. Consequences of coupled layers in the bulk fishnet metamaterial. (a) Schematic of a 3 functional layer fishnet showing the cross-section taken in (b,c). (b) Depiction of the cascaded circuit which leads to the magnetic response of the structure. Notice that the current flow on the top and bottom surface of the metal is out phase. (c) Electric field plot of the fishnet generated with FDTD. It can be observed that indeed, the electric field, on the top and bottom of the metal surfaces is out of phase. This leads to the cancellation of the electric field, and thus current, inside the metal, reducing losses due to absorption in the metal.

In Fig. 2.4b it can be observed that the electric field on the top and bottom surface is out of phase which leads to the current flow on the top and bottom surface also being out of phase. Ultimately this out of phase current destructively interferes inside the metal films, leading to cancellation of the current and field, pulling electromagnetic energy out of the film. This can be observed by the fact that there is no field inside the metal (Fig 2.4c). This strong coupling across the metal film and subsequent current cancellation reduces intrinsic loss within the structure. As we will see, the destructive interference of the field along with the magneto inductive coupling will lead to greatly reduced loss and increased FOM in the bulk fishnet metamaterial.

The other important property of the bulk fishnet metamaterial is that the refractive index should converge. To evaluate the convergence, the refractive index was calculated for multiple thicknesses, ie. number of functional layers, using RCWA. The effective refractive index was found by calculating the complex transmittance and reflectance for the structure and then using the S-parameter approach outlined in chapter 1 [13]. The index versus number of functional layers is plotted below in Fig. 2.5.
Figure 2.5. Refractive index versus number of functional layers. While a large shift is seen when increasing from 1 to 3 layers, subsequent thickness increases have no effect on the index, indicating that the bulk value has been reached.

From Fig. 2.5, a large change in refractive index is observed when increasing the number of functional layers from 1 to 3. However, after 3 layers we see that the refractive index has converged. This demonstrates that 3 functional layers are all that are needed to yield a bulk value for the refractive index. It is important to note that the convergence of the index is highly depended on the specific design of the metamaterial. For instance, if the dielectric layer is thicker, the unit cells will not be coupled as strongly and the convergence will occur for fewer functional layers. However, reducing the coupling will result in increased loss due to lower magneto-inductive coupling.

2.3 Fishnet Fabrication

One of the largest challenges in realizing the bulk fishnet structure is fabricating a thick structure with high aspect ratio. Previous single layer metamaterials have typically been fabricated using electron beam lithography (EBL) using a liftoff process as seen below in Fig. 2.6.

Figure 2.6. Schematic of EBL fabrication process. The process starts with spinning and subsequent exposure of the photoresist using the electron beam. The resist is then developed and the device material is evaporated. Finally, the area around the exposure is lifted-off, resulting in positive features on the substrate.
The liftoff process is a technique that starts by exposing the footprint of the structure in a positive resist, usually poly (methyl methacrylate) (PMMA). The footprint is developed and then the structural material is deposited across the entire wafer. The last step is to liftoff the surrounding film, leaving the structure intact, connected to the substrate. Due to the fact that the footprint of the device material is defined, this process is best employed where relatively small positive device features are needed. While this process is ideal for thin films, it is difficult to fabricate high aspect ratio structures. Typically, the highest aspect ratio (vertical dimension: lateral dimension) possible with a single exposure / liftoff step is 3:1. To make higher aspect structures, researchers must perform multiple exposure / deposition / liftoff steps where each subsequent exposure must be aligned to the first. Using multi-exposure EBL, researchers have made progress fabricating thicker optical NIMs. However, using this technique, only 4 to 5 functional layers are possible due to the build up of inaccuracies in alignment of the layers [14,15]. It is also extremely time consuming to repeat the process multiple times. Ultimately, using this technique researchers have not been able to achieve a sample thick enough for the material properties to converge to the bulk value for the specific metamaterial designs employed [14,15,16].

2.3.1 Focused Ion Milling

Focused ion beam (FIB) milling is a fabrication technique that relies on the selective removal of material rather than a deposition / liftoff step. As suggested by the name, the milling of the material is done by a focused ion source, usually a liquid metal, such as Gallium. A schematic of a FIB is shown below in Fig. 2.7b and is described as follows [17]. The ion gun contains a liquid metal source that is coated onto a field emitter and heated to its melting temperature. The field emitter is then placed under a voltage, usually around 2 to 10 kV, which causes field evaporation of the ionized liquid metal. The evaporated ions are then accelerated by a high voltage, usually 30 to 50 kV, and focused onto the substrate using electrostatic lenses. The focal spot of the ion beam can be adjusted using in-line apertures and can range from several nanometers to a few micrometers. The bombardment of the substrate with ions causes material to be removed by elastic sputtering.
Figure 2.7. Focused ion beam milling schematic and process flow. (a) Schematic of a typical FIB column. The ion gun passes through several lenses and apertures before being focused on the sample. (b) FIB process flow where first a device layer is deposited and then milled with FIB, forming negative features.

The process flow for FIB milling is shown above in Fig. 2.7b. The first step is to deposit the device material which is typically done with electron beam evaporation. The sample is then placed inside the FIB where a beam is rastered in the areas of the film which are to be removed. The process flow is considerably less complicated than EBL and furthermore, is capable of producing features with aspect ratios up to 10:1, enabling thick metamaterial devices with no alignment steps. There are however several drawbacks to the FIB process. The first is that it is relatively slow compared to EBL due to the fact that instead of initiating a chemical change in a photoresist, FIB milling is instead physically removing material. Therefore, FIB is ideal when relatively small negative features are needed in the device material. The second drawback is that a portion of the milling ions, in this case Gallium, are ultimately embedded into the device material. As we will see, this can be problematic for optical devices as Gallium is a lossy metal and causes parasitic absorption.

Despite these disadvantages, the high aspect ratios that are capable with FIB make it the ideal tool to achieve a bulk optical NIM. To create the bulk fishnet metamaterial a multilayer metal-dielectric stack was first deposited. The multilayer stack was deposited by electron beam evaporation of alternating layers of 30 nm Ag and 50 nm MgF2. The final stack consisted of 21 layers with a total thickness of 830 nm resulting in 10 functional layers. The unit cell of the fishnet structure was fabricated with the dimensions outline in Fig. 2.2. The number of functional layers was chosen as it allows a strongly converged refractive index (Fig. 2.5). This large thickness also allows a prism to be created from the metamaterial as will be discussed later in this section.
Figure 2.8. Schematic and SEM image of fabricated fishnet structure. (a) Schematic of the 21 layer fishnet structure. (b) SEM image of the 21 layer fishnet structure with the side etched, showing the cross-section. The structure consists of alternating layers of 30 nm Ag and 50 nm MgF₂ and the dimensions of the structure correspond to the schematic in (a). The inset shows a cross-section of the pattern taken at a 45° angle. The sidewall angle is 4.3° and was found to have minor effect on the transmittance curve according to simulation.

Two different configurations of the fishnet samples were fabricated on the multilayer stack. Samples of the first configuration consist of 22 by 22 in-plane fishnet unit cells and were used for the characterization of the transmittance. A schematic of the 10 functional layer structure as well as a SEM image and a cross-section view (inset), are shown in Fig. 2.8a and Fig. 2.8b, respectively. Samples of the second configuration, which were used to measure the refractive index, consist of a prism fabricated on the multilayer stack, with the number of functional layers ranging from 1 on one side, to 10 on the other side. The prism was formed by placing the sample vertically in the FIB chamber and then tilting the sample at a specified angle $\beta$ with respect to the film surface, as seen in Fig. 2.9a. Once the prism was milled into the surface, the sample was remounted horizontally in the chamber and a 10 by 10 unit cell fishnet pattern was milled into the prism, the SEM image of which is shown in Fig. 2.9b. The exact angle was measured with an atomic force microscope, and was found to be slightly varied for different samples.
Figure 2.9. Fabrication procedure and SEM image of the fishnet prism. (a) To fabricate the prism, the multilayer stack was mounted vertically in the FIB and a prism was milled at an angle $\beta \sim 5^\circ$ with respect to the surface. (b) SEM image of a fabricated prism with a 10x10 unit cell fishnet structure milled into the surface. The inset shows a close-up view of the prism where the individual metal and dielectric layers are visible.

2.4 Experimental Results and Discussion

To experimentally validate the index of refraction of the metamaterial, measurements were carried out by observing the refraction angle of light passing through the prism by ‘Snell’s Law’. This provides a direct and unambiguous determination of the refractive index, as the refraction angle depends solely on the phase gradient the light beam experiences when refracted from the angled output face.

Figure 2.10. Experimental setup for measuring the index of refraction. (a) Experimental setup for the beam refraction measurement. The focal length of the second lens is $f_2 = 40$ mm. Lens 2 is placed in a $2f$ configuration, resulting in the Fourier image at the camera position. (b) Geometry schematic of the angle measurement. $\delta$ corresponds to the position difference of the beam passing through a window in the multilayer structure ($n=1$) and prism sample. By measuring $\delta$, the absolute angle of refraction $\alpha$ can be obtained.

In the experimental setup, light from the optical parametric oscillator (OPO) was focused onto the prism using an achromatic lens (lens 1) while the second lens (lens 2) was placed at its focal position (Fig. 2.10). An Indium Gallium Arsenide (InGaAs) infrared camera was placed at the focal position of lens 2 allowing the light passing through the sample to be imaged at the Fourier plane. The position of the beam at the second lens’s focal distance ($f$) was used to calculate the angle of refraction. Due to limited camera imaging area, only the zero-order Fourier image was recorded. To obtain
the absolute angle of refraction, a window with an area equal to that of the prism was etched through the multilayer stack to serve as a reference. The window’s Fourier image was measured at all wavelengths, giving a reference position corresponding to a refractive index of 1. The centers of the beam spot for both the window and prism samples were determined by fitting the intensity with a 2D Gaussian profile and the total beam shift \((\delta)\) at the position of the second lens was calculated by taking the difference in the beam spot centers. Consequently, the angle of refraction at the surface of the prism \((\alpha)\) is given as:

\[
\alpha = \beta - \tan^{-1}\left(\frac{\delta}{f}\right)
\]

where \(f\) is the focal distance of the second lens (refer to Fig. 2.10a). Snell’s law: \(n = \frac{\sin \alpha}{\sin \beta}\) was then used to calculate the real part of the refractive index of the sample.

Figure 2.11. Fourier plane images and refractive index plot of fishnet metamaterial. (a) Fourier plane images of the beam for the window and prism sample for various wavelengths. The horizontal axis corresponds to the beam shift \((\delta)\) and positions of \(n = 1\) and \(n = 0\) are denoted by the white lines. Image intensity for each wavelength has been normalized for clarity. (b) Measurements and simulation of the fishnet refractive index. The round dots show the results of the experimental measurement with error bars (s.d., \(n = 4\) measurements). The measurement agrees closely with the simulated refractive index using the RCWA method (black line).

Figure 2.11a displays the beam shift \(\delta\) resulting from the light bending at the prism output at different wavelengths, ranging from 1200nm to 1775nm. The measurement was performed on a prism of angle \(\beta = 5.0^\circ\) and the beam shift is plotted along with reference measurements of transmission through a window, without the presence of the prism (left panel). Clearly, as the wavelength increases, the beam shift resulting from the prism refraction is changing from positive to negative, indicating a transition from positive index in the shorter wavelengths to negative index in the longer wavelengths. At a wavelength of \(\lambda = 1475\) nm, the index of refraction is approaching a value of zero, namely, the beam does not acquire any phase while propagating in the metamaterial. Consequently, there is no phase gradient at the angled output face and the
The exiting beam is exactly normal to the output face (see dashed lines in Fig. 2.11a and Fig. 2.12a,b).

Figure 2.11b depicts the measured refractive index of the 3D fishnet metamaterial at various wavelengths. The refractive index varies from \( n = 0.63 \pm 0.05 \) at 1200 nm to \( n = -1.23 \pm 0.34 \) at 1775 nm. The refractive index was determined from multiple measurements of two fishnet prisms with angles of \( \beta = 5.0^\circ \) and \( \beta = 4.7^\circ \) and for wavelengths ranging from 1200 nm to 1800 nm. Although there is a correlation between the beam spot positions shown in Fig. 2.11a and the refractive index in Fig. 2.11b, it should be noted that Fig. 2.11b shows the average of measurements on different prisms with the standard deviation as error bars while Fig. 2.11a shows an individual measurement. The experimental results are found to be in good agreement with the theoretical predictions (black line in Fig. 2.11b) based on RCWA. The measured negative refraction angle is a direct result of negative phase evolution for light propagating inside the sample caused by a negative refractive index. This is illustrated in Fig. 2.12a,b by a numerical calculation of the in-plane electromagnetic field distribution in the fishnet prism at wavelengths of \( \lambda = 1200 \) and 1763 nm where the structure shows a positive and negative index, respectively. Due to the negative phase propagation inside the metamaterial, the electromagnetic wave emerging from the thicker part of the prism experiences phase advance compared to that passing through the thinner parts, causing the light to bend in the negative direction at the exiting interface. We note that the refractive index remains consistent for the fishnet metamaterial with three or more functional layers along the propagation direction which leads to a uniform wave front exiting the prism.
Figure 2.12. FDTD simulations of passing through the fishnet prism. (a) Simulation of the in-plane electric field component for the prism structure at 1200 nm when the index is positive. Positive phase propagation results in a positive refraction angle. (b) The in-plane electric field component for the prism structure at 1763 nm showing the phase front of the light. Negative phase propagation resulting from the negative refractive index leads to negative refraction angle as measured by the beam shift in the experiment. The bottom figures show a close-up of the time evolution of the field distribution in the unit cell of for both a positive and negative index of refraction.

In addition, transmittance measurements were performed on the bulk fishnet metamaterial made of twenty one layers using a Fourier transform infrared microscope (Nicolet Nic-Plan IR microscope). Figure 2.13a shows the measured transmittance spectrum along with the numerically calculated transmittance. The simulation predicts a broad negative index band spanning from 1.45 µm to 2.2 µm (shaded region), which coincides with the high transmission band from 1.5 µm to 1.8 µm. As mentioned previously, this wide band of negative index results from the strong coupling between neighboring layers. The measured transmittance exhibits similar features as the calculation, namely, two peaks imposed over the transmission band which are slightly red-shifted with respect to the numerical results. These features are due to the Fabry-Perot effect, where the impedance mismatch leads to reflectance at the metamaterial/air and metamaterial/glass interfaces. While the peaks are visible at lower refractive index values due to the lower loss, the Fabry-Perot effect cannot be clearly seen in the transmission spectra for larger negative index at longer wavelength where the loss is higher, resulting in broadening and extinction of spectral features.

The transmittance in the negative index band is four times lower than the numerically calculated, which is due to Ga deposition from the FIB. The Ga content in the structure could potentially be removed using high temperature annealing [18], however in this case, the high temperatures would result in melting of the thin Ag films. Therefore, rather than remove Ga an alternative would be to prevent Ga from being deposited in the substrate during the etching process. This could be achieved by using a
FIB with a different source, such as Silicon. Another alternative would be to fabricate the structures on a free standing membrane. In this case, the holes would open into free space, preventing Ga deposition into the substrate below the sample. Nevertheless, our simulations show that the presence of loss in the coupled fishnet metamaterial has a minimum impact on the dispersion relation. This is due to the fact that the bulk fishnet structure operates far from the band edge (see Fig. 2.3) where resonance does not play a significant role. This explains the good agreement between the experimentally measured and simulated refractive indices despite the fabrication imperfections.

Figure 2.13. Transmission and FOM. (a) Experimental transmittance curve (red line) of a 22 by 22 unit cell fishnet structure (17.6 x 17.6 µm² total patterned area) which has been multiplied by 4x for clarity. The simulated transmittance (black dotted line) was obtained with RCWA. The grey shaded area corresponds to the region of negative refractive index as calculated numerically. (b) FOM versus wavelength for the simulation (dashed line) and experiment (black squares). The lower experimental FOM is due to reduced transmission resulting from fabrication imperfections. The experimental FOM reaches 3.5 at 1775 nm where \( \text{Re}(n) = -1.23 \).

We estimate the figure of merit (FOM = |\text{Re}(n)/\text{Im}(n)|) of our fishnet multilayer structure. The material loss [i.e., \( \text{Im}(n) \)] is conservatively estimated from the measured transmittance and reflectance data (Fig. 2.13a) of the twenty one layer sample, assuming a single pass of light through the metamaterial, as \( \text{Im}(n) = (\lambda/4\pi d)\ln[(1-R)/T] \) where \( \lambda \), \( d \), \( R \) and \( T \) are the wavelength, sample thickness, transmittance and reflectance, respectively. The dispersion of the simulated and experimental FOM is plotted in Fig. 2.13b. The FOM = 3.5 at \( \lambda = 1775 \) nm [where \( \text{Re}(n) = -1.23 \)], which is the highest experimentally recorded value to date at optical frequencies [7,19]. For ideal fabrication conditions, the figure of merit could rise to values as high as FOM = 18, as shown in Fig 2.13b. We would like to emphasize that our results are different from recent reports of negative refraction in anisotropic media [20,21,22] with hyperbolic dispersion (equivalent to negative ‘group index’), but positive phase velocity.

The fishnet metamaterial has a period about \( \lambda/20 \) in the vertical direction. The propagation of light traveling along this direction or within some angular range is dominated by this deep sub-wavelength period, and not by the in-plane period, as long as the wave-vector projection on the in-plane directions is small compared to the in-plane reciprocal lattice vector of the fishnet metamaterial. There is only a single propagating
mode in the negative index frequency region, justifying the description of the fishnet metamaterial with an effective index. As the angle of incidence increases, the metamaterial will cease acting as an effective medium as the wavelength will be on the same scale as the periodicity along the propagation. Therefore, the fishnet metamaterial is inherently anisotropic. If higher dielectric materials such as silicon (n~3.6) are used to serve as the dielectric layer, the ratio between the wavelength and in-plane period can be significantly increased because of the larger capacitance in the LC circuit. This would allow the metamaterial to act as an effective medium for a larger range of wavelengths.

It is also important to note that unlike the negative index obtained from photonic crystals [23], the negative index presented here results from simultaneous negative magnetic and electric responses, and shows resemblance to the left handed transmission line due to the tight coupling between the adjacent LC resonators. It should be noted that the negative index occurs in the first propagation band, and with smooth negative phase evolution along the light propagation direction, which differs from the negative refraction obtained in photonic crystals.

2.5 Conclusions and Outlook

In summary, we have experimentally demonstrated the first bulk NIM at optical frequencies and directly measured the refractive index of a NIM prism in the free space. Bulk optical metamaterials may offer the possibility to explore a large variety of optical phenomenon associated with zero and negative refractive index, as well as applications in scaling down of photonics and imaging. It is important to note that the anisotropy present in the refractive index prevents such a structure from being used to achieve a superlens, which must be isotropic. While isotropic metamaterials have been achieved at microwave frequencies, the fabrication constraints at optical frequencies have so far prevented the realization of such a material.

While not isotropic, the bulk fishnets anisotropy is actually advantageous for certain applications. One such application is the electromagnetic cloaking device proposed by Pendry [24]. Such a device requires anisotropy in the underlying material properties and has been achieved at microwave frequencies by using split-ring resonators, which are also anisotropic [25]. However, cloaking requires that the material’s index of refraction be modulated as a function of spatial positions which still remains a serious fabrication challenge. Recent theory though has shown that lower dimensional cloaking is possible with relaxed material properties [26]. This will be the subject of the work presented in chapter 3.

References


Chapter 3

Broadband Optical Cloaking

Recent theories including transformation optics (TO) and conformal mapping have shown that cloaking devices are in principle possible, provided that the appropriate medium can be constructed. The advent of metamaterials has given birth to such a medium and indeed, the first cloaking device has recently been demonstrated in the microwave region. In this chapter we will begin by reviewing TO and how it can be used to design devices, such as the cloak. We also discuss the reasons why an experimental demonstration of cloaking at optical frequencies has remained elusive.

The remainder of the chapter will be devoted to describing the first experimental demonstration of optical cloaking utilizing a form of cloaking deemed ‘carpet cloaking’ [1]. The carpet cloak is designed using a new methodology deemed quasi-conformal mapping which allows simplification of the underlying metamaterials. Such a cloak allows one to conceal an object that is placed under a curved reflecting surface by imitating the reflection of a flat surface. We will demonstrate the fabrication and experimental demonstration of the cloak which consists only of isotropic dielectric materials. This design allows one to achieve broadband and low-loss invisibility at a wavelength range of 1400-1800 nm, overcoming many of the problems in previously proposed cloaking devices.

3.1 Transformation Optics

Transformation optics is a design methodology that enables one to create devices by virtually stretching and compressing space. This is permitted by the fact that Maxwell’s equations are inherently invariant under a spatial transformation. Therefore, any distortion of space created by a coordinate transformation can be realized through spatial changes in the underlying material properties. The form invariance of Maxwell’s equations and its use in manipulating light flow is not an entirely new concept and was in fact realized quite some time ago [2,3]. However, the application of using this technique to design optical devices is a relatively recent development which started with the proposal of the electromagnetic cloak [4,5], which is also when the term ‘transformation optics’ was coined. The fact that Maxwell’s equations can be transformed in such a way is due to the differential form of the equations and is not limited in application to electromagnetic waves. For instance, similar design methodologies have been proposed for elastic [6,7] and matter waves [8] and thus confirmed the general applicability of the method. However, here we will only be concerned with transformations involving electromagnetic waves. To understand how such a transformation is performed, we can first write Maxwell’s equations for a wave of fixed frequency as,

\[ \nabla \times \mathbf{E} + i\omega \mu \mathbf{H} = 0 \]

\[ \nabla \times \mathbf{H} - i \omega \varepsilon \mathbf{E} = 0 \]  

(3.1)
where \( \varepsilon = \varepsilon(x) \) and \( \mu = \mu(x) \) are treated as tensors allowing the possibility that the underlying properties are anisotropic and spatially varying. The spatial matrix \( x \), represents all points in Cartesian space and may also be written as \( x = x' \) where the indices run from 1 to 3, representing \( x, y, \) and \( z \). Maxwell’s equations, under a coordinate transformation given by \( x \rightarrow x'(x) \), will result in the transformed equations [9,10,11],

\[
\begin{align*}
\nabla' \times E' + i\omega \mu' H' &= 0 \\
\nabla' \times H' - i\omega \varepsilon' E' &= 0
\end{align*}
\]

(3.2)

where the rotational symbol in the formula above is the rotational in the new coordinate system which is not the same as the original Cartesian system. The renormalized electric and magnetic fields will now have a new value given by,

\[
E'(x') = (A^T)^{-1} E(x), \quad H(x') = (A^T)^{-1} H(x)
\]

(3.3)

where \( A \) is the Jacobian, given by,

\[
A' = \frac{\partial x'}{\partial x}
\]

(3.4)

We may now derive the new spatially varying material properties, \( \varepsilon'(x') \) and \( \mu'(x') \), that will ultimately cause light to follow the specified spatial transformation. These are now given by,

\[
\begin{align*}
\varepsilon'(x') &= \frac{A\varepsilon(x)A^T}{\det A} \\
\mu'(x') &= \frac{A\mu(x)A^T}{\det A}
\end{align*}
\]

(3.5)

Using this methodology, it is relatively straightforward to manipulate the flow of light in an arbitrary path. All one needs to do is derive the spatial path, or transformation, that the light is intended to take. From that spatial transformation, the values of the underlying constituent parameters naturally follow. This makes transformation optics a quite powerful technique to design complex devices which would be practically impossible to design using a simple ray optics approach. Furthermore, the constituent properties are treated as tensors, allowing anisotropy and increasing design freedoms. However, it is important to note that this freedom in material properties can be a double edged sword. While it allows more complicated devices, it also requires more complicated materials. The concept of metamaterials can be used to realize these complex anisotropic properties, however, as we will see, this becomes more difficult at optical frequencies where fabrication constraints can limit such complexity.

### 3.1.1 Electromagnetic Cloaking

The first and most famous example of a device designed with transformation optics is the electromagnetic cloak [4,5]. The original cloaking proposal by Pendry [5] enacts a spatial transformation that crushes a specified object into an infinitesimally small point. When enacted through spatial changes in the material properties, the crushing causes light to be bent around the object, rendering it invisible in all directions. As there are 3 spatial dimensions, we can in fact choose to crush in the 3 directions independent of one another. Therefore, cloaking in general, can take 3 forms as depicted below in Fig. 3.1.
Figure 3.1. Different dimensional forms of cloaking. (a) The most rigorous form of cloaking crushes an object to an infinitesimally small sphere, rendering it invisible from all directions. (b) In 2D cloaking the object is crushed to an infinitesimally thin line, rendering it invisible in 2 directions. (c) In 1D cloaking, the object is compressed into a sheet, which is invisible when viewing the object only within the plane of compression.

While the original proposal for cloaking was the most rigorous, crushing an object in 3 dimensions (3D), the first demonstration, and highest dimensionality so far achieved, involves crushing an object in 2 dimensions (2D) into an infinitesimally small line [12]. In this case the object is invisible when viewing it in the plane of the crushed line, though it is still visible when looking along the axis of the line. The transformation takes place in cylindrical coordinates due the symmetry of the problem and is then transferred to Cartesian coordinates. In the transformation, two radii are defined, \( R_i \) and \( R_2 \) where \( R_i \) is the radii of the object and \( R_2 \) the radii of the cloak (\( R_i < R_2 \)). All coordinates existing in the region \( r < R_2 \) are then mapped into the region \( R_i < r' < R_2 \) where \( \{r, \theta, z\} \) and \( \{r', \theta', z'\} \) represent the radial, angular, and height coordinates in the original and transformed space, respectively. The mapping between the two can be done through a simple linear transformation squeezing from within a cylinder to within a cylindrical shell. The relation between the coordinate systems is then,

\[
\begin{align*}
    r' &= \frac{R_2 - R_i}{R_2} r + R_i \quad \theta' = \theta \quad z' = z
\end{align*}
\]  

(3.6)

Following the procedure outlined previously, this spatial transformation results in the following material property tensors,

\[
\begin{align*}
    \varepsilon_r &= \mu_r = \frac{r - R_i}{r} \\
    \varepsilon_\theta &= \mu_\theta = \frac{r}{r - R_i} \\
    \varepsilon_z &= \mu_z = \left( \frac{R_2}{R_2 - R_i} \right)^2 \frac{r - R_i}{r}
\end{align*}
\]  

(3.7)

The resulting material properties are both anisotropic and spatially varying. They also involve modifying both the permittivity and permeability simultaneously which makes the engineering requirements quite high. However, by assuming only one polarization of light, these equations can be simplified to only include the components of \( \varepsilon \) and \( \mu \) along the directions of the electric and magnetic field, respectively. Furthermore,
if one discounts the requirement of having a cloak that is perfectly index matched and is only concerned with the spatial dispersion of light inside the cloak, then further simplifications can be made. This is the procedure taken in the first demonstration of the cloak by Smith [12] where the following simplified material parameters are used,

$$\mu_r = \left( \frac{r - R_1}{r} \right)^2 \quad \mu_\theta = 1 \quad \varepsilon_z = \left( \frac{R_2}{R_2 - R_1} \right)^2$$ (3.8)

In this case, both $\mu_\theta$ and $\varepsilon_z$ are spatially invariant while $\mu_r$ must vary as a function of the radius. Using this reduced form, the cloak was realized in the microwave region by employing split-ring resonators which surround a disk where the spatially varying permeability is achieved by spatially varying the dimensions of the split-ring.

One of the largest drawbacks in this original cloaking design is that it requires a magnetic response. This invariably requires the use of resonant elements, such as the split-ring, to achieve the necessary optical properties. This resonance ultimately results in a narrowband operation regime due to the frequency dispersion in the underlying material properties [13,14]. Another problem is that the resonance leads to high intrinsic losses in the materials and saturation in the magnetic response [15,16], as was discussed in chapter 1. While this problem has been partially mitigated with the inception of the bulk fishnet metamaterial at optical frequencies, there is still significant dispersion in the material properties [17].

The largest challenge in scaling this design to optical frequencies is ultimately fabrication constraints. While the fishnet can be used to achieve the required constituent parameters at optical frequencies, it is still not possible to achieve a spatially varying architecture that surrounds an object. In essence, the fishnet metamaterial would have to be wrapped around the cloaked object with the unit cell dimensions changed as a function of radius with respect to said object.

### 3.2 Carpet Cloak Design

Recently, a number of new forms of cloaking have been proposed to relax the requirement of extreme material properties inherent in the original cloaking proposal [18,19,20,21,22]. Of special interest is the carpet cloak, proposed by Li and Pendry [23]. While previous cloak designs either compress the object into a singular point or line, the carpet cloak compresses an object in only one direction (1D) into a conducting sheet. Therefore, invisibility is only achieved when looking at the object within the plane it is crushed. However, the object may still be hidden from view from other directions by carefully choosing its surroundings. For instance, as seen in Fig. 3.2, we start with an object sitting on top of a conducting sheet. We then lay another reflecting sheet top of the object which represents the ‘carpet’ portion of the cloak. This second sheet has a small curve that encloses the object which is invariant in the $z$ direction. This curve is what will be compressed and must have a well defined shape, just as the inner radius of the cylindrical cloak. The area outside of the curved surface is then transformed where the space under the curve is mapped to the outer region, virtually crushing the object into the flat sheet beneath it. Therefore, in virtual space the curved surface is now flat, and the object sitting under the curved reflecting surface appears as if it is the original flat reflecting surface, so it is hidden under the ‘carpet’. In this case the object is not only
hidden within the $x$ plane but also hidden when viewing within entire $x$-$y$ plane, leaving us with a quasi 2D cloak.

![Carpet cloak methodology](image)

**Figure 3.2.** Carpet cloak methodology. The object is first placed on a reflecting surface in free space. Here, the grid represents space where square cells represent isotropic material properties. The object is then surrounded by another reflecting surface, representing the carpet. The area around the carpet is then transformed to crush the bump, or carpet, into a flat sheet. The grid is now deformed, however, within the transformation; each grid point remains nearly square, or isotropic. This transformed space is equivalent to a virtual space with a spatial grid the same as the free space which first surrounded the object.

The unique property of the carpet cloak is that it eliminates singularities and anisotropy in the transformed medium [24], allowing much simpler metamaterials to be employed. The first reason for this is that the topological change of the cloak is less extreme than that in the two or three dimensional cases. Therefore, unlike previous cloaking transformations, it generates a smaller range of values for the material properties. The second reason is that the cloak is designed with a new type of transformation deemed ‘quasi-conformal’ mapping. In the cloak presented in section 1, a simple linear transformation of space was performed. This transformation, while straightforward, puts no restriction on the anisotropy of the underlying material properties. As we have seen, this results in extreme anisotropy even if reduced forms, such as a 2D implementation, are used. Quasi-conformal mapping overcomes this problem by using a well defined function to minimize the anisotropy when performing the spatial transformation. This is done by first defining the covariant metric of the transformation,

$$ g = A^T A $$  \hspace{1cm} (3.9)
where $A$ is the Jacobian matrix ($A_i^j = \partial x^j / \partial x^i$) as defined earlier. This metric can be linked to the underlying anisotropy ($\alpha$) of the medium by,

$$\alpha + \frac{1}{\alpha} = \frac{\text{Tr}(g)}{\sqrt{\det(g)}}$$  \hspace{1cm} (3.10)

where the anisotropy is given by the maximum ratio of the refractive index ($n_i$) in the $x$ and $y$ directions,

$$\alpha = \max \left( \frac{n_x}{n_y}, \frac{n_y}{n_x} \right)$$  \hspace{1cm} (3.11)

The last and most important step in the transformation is to minimize the anisotropy in the transformed media. In the original carpet cloak proposal, Li showed that this can be accomplished by minimizing the Modified Liao Functional [23],

$$\Phi = \frac{1}{hw} \int_0^h d\xi \int_0^w d\eta \frac{\text{Tr}(g)^2}{\det(g)}$$  \hspace{1cm} (3.12)

where $h$ and $w$ are the width and height of the transformed region and $\xi$ and $\eta$ are the $x$ and $y$ coordinates in the transformed system (refer to Fig. 3.2). The result of this transformation is that all the originally square cells (representing the refractive index in the $x$ and $y$ directions) are transformed to rectangles of a constant aspect ratio. While other mappings result in a highly anisotropic cloak profile (rectangles or parallelograms of high aspect ratio), the quasi-conformal mapping makes the transformed cells almost square, so that the anisotropy of the medium is minimized to a point where it can be neglected. This results in a modest range of isotropic indices for the cloak. The approach allows the use of non-resonant elements (e.g., conventional dielectric materials) and offers the possibility to achieve low-loss and broadband cloaking at optical wavelengths. Carpet cloaking was recently realized experimentally at microwave frequencies, utilizing non-resonant metallic elements [25]. However, even with the advances in optical metamaterials [17,26], scaling sub-wavelength metallic elements and placing them in an arbitrarily designed spatial manner still remain challenging at optical frequencies.

Here, we experimentally demonstrate optical cloaking utilizing a dielectric carpet cloak design which is not only isotropic, but also low-loss and broadband. The invisibility is demonstrated within a Silicon (Si) slab waveguide where the cloak region is obtained by varying the effective index of refraction in a 2D space.
The cloak is designed for TM polarization (Fig. 3.3a) so the relevant material tensor components are \( \{ \varepsilon_y, \mu_x, \mu_y \} \) where any anisotropy is manifest in \( \mu_x \) and \( \mu_y \). It should be noted that it is also possible to design the cloak for TE polarization. The rectangular carpet cloak region (region C1 in Fig. 3.3b) is transformed from a background region of the same size via the procedure outlined above and is 7.3 µm x 2.7 µm in size. In the transformation, the anisotropy in \( \mu_x \) and \( \mu_y \) is eliminated and they collapse to \( \mu_x = \mu_y = 1 \) with only spatial variations in \( \varepsilon_z \) remaining, which can be treated as a spatially varying refractive index, \( n(x, y) = \sqrt{\varepsilon_z(x, y)} \). A smooth shape of the bump is chosen in order to reduce the range of refractive indices necessary for the cloak. The shape of the bump is given by,

\[
y_{\text{Bump}} = 400 \cos^2 \left( \frac{\pi}{3800} x \right), \quad -1900nm < x < 1900nm
\]

(3.13)

where all dimensions are in nanometers, resulting in a cloaked area 3.8 µm x 400 nm. Since the cloak is implemented in a waveguide, the refractive index profile of the cloak is generated through the quasi-conformal mapping for the mode dispersion of the Si waveguide slab. The mode index is solved for the case of a 250 nm thick Si layer which is clad on one side by SiO\(_2\) and on the other side by air. The resulting mode index of the cloaking region ranges from 1.50 to 1.94. Since the refractive index must be modulated both above and below the background, we must artificially lower the refractive index of the region around the cloak. To do this, a triangular region with a constant refractive index of 1.58 is placed outside the cloak (C2 in Fig 3.3b). This triangular region should ideally extend to infinity (representing a true background) however, it is has been truncated due to fabrication constraints.
Figure 3.4. Simulation performance of the cloak. (a) FEM simulation of the curved reflecting surface with no cloak. The curved surface perturbates the beam causing a shadow to be cast. (b) FEM simulation of cloaked surface. The cloak crushes the bump causing the reflecting light to have the same profile as it would have reflecting off of a flat surface. In both simulations the electric field in the $z$ direction is plotted ($E_z$).

To validate the performance of the cloak, numerical simulations were performed using a finite element method (FEM) (COMSOL). The simulations of the uncloaked (Fig. 3.4a) and cloaked bump (Fig. 3.4b) are shown above. In the uncloaked case the bump in the reflecting surface perturbates the beam, causing a shadow to be formed in the reflected light. However, once the cloak is placed on top of the bump, this shadow is eliminated, as the bump has been virtually compressed into the flat surface beneath it. Therefore, anything sitting below the bump has effectively been rendered invisible. In these simulations, an effective refractive index is used inside the cloaking region. More rigorous simulations with the employed nanostructuring used to create this effective refractive index are discussed below. We note that the demonstration of the cloaking effect by using an isotropic profile here is in fact closely connected to the optical conformal mapping in [4] but with the phase information also preserved in our case.

3.3 Carpet Cloak Fabrication

The carpet cloak metamaterial was fabricated on a silicon-on-insulator (SOI) wafer consisting of a 250-nm-thick Silicon layer separated by a 3-µm-thick silicon oxide ($\text{SiO}_2$) slab from a Si wafer substrate (Fig. 3.3a, 3.5a). The 250 nm Si layer serves as an optical slab waveguide where the light is confined in vertical dimension and can freely propagate in the other two dimensions.
Figure 3.5. The carpet cloak design that transforms a mirror with a bump into a virtually flat mirror. (a) Schematic of fabricated carpet cloak showing the different regions where $C1$ is the gradient index cloak and $C2$ is a uniform index background. The cloak is fabricated in a SOI wafer where the Si slab serves as a 2D waveguide. The cloaked region (marked with green) resides below the reflecting bump (carpet) and can conceal any arbitrary object. The cloak will transform the shape of the bump back into a virtually flat object. (b) SEM image of fabricated carpet cloak. The width and depth of the cloaked bump are 3.8 µm and 400 nm, respectively.

The index profile within the cloaking region is realized within the Si waveguide by fabricating a 2D sub-wavelength hole lattice with varying density. The required filling fraction of holes is given by the previously discussed Maxwell-Garnett model for cylindrical rods placed in material matrix. This results in a spatially dependent filling fraction,

$$f = \frac{(\varepsilon_{Si} - \varepsilon_{cloak})}{(\varepsilon_{Si} - 1)}$$

(3.14)

The position of the holes are obtained by seeking another coordinate transformation which maps a regular grid of points to the permittivity grid so that every transformed grid point now occupies an area proportional to the reciprocal of the filling fraction of the holes. The holes are thereby situated at every transformed grid point while the value of the constant diameter (which depends on the lattice spacing of the regular grid) can be readily obtained from the same formula after the transformed grid is obtained. The full fabrication procedure for the cloak is shown below in Fig. 3.6.
Figure 3.6. Fabrication schematic for the carpet cloak. FIB is first used to etch through the Si layer to create the mirror facet, hole profile, and gratings. The Ga is then removed from the sample via rapid thermal annealing and plasma etching. After Ga removal, a cap wafer is placed on top of the sample where the green layer represents PMMA, used to create a good seal on the top of the sample. Directional deposition of Au is then performed to form the reflecting surface. The cap wafer is removed to realize the finished device.

The fabrication of sample starts by etching the profile of the reflecting surface through the Si layer and partially through the SiO₂ slab near the edge of the SOI substrate, making the surface accessible for directional deposition of metal from the side. The refractive index pattern is then created by milling holes of constant diameter (110 nm) through the Si layer, again using FIB. This pattern is aligned to the mirror facet and is one of the most challenging aspects of the fabrication process due to beam drift during milling. To compensate for this drift, a custom alignment program was created that allowed re-centering of the pattern several times during milling. Additionally, two gratings were fabricated for coupling the light into and out of the Si-waveguide.

Once the mirror and hole pattern are etched, steps are taken to remove deposited Ga from the sample. Just as with the fishnet [17], Ga deposition in the sample significantly increases the amount of light that is absorbed. In fact, due to the long propagation distance through the etched structure (~15μm), very little light passes through the sample without Ga removal steps. The procedure for Ga removal begins with a rapid thermal anneal at 700°C for 6 minutes. This allows Ga trapped in the sample to aggregate and form droplets on the surface of the structure [27,28]. The wafer is then placed in a reactive ion etcher where a 5 minute Argon plasma etch is used to remove the Ga from the surface of the sample. It was found that this procedure yields up to a 16x improvement in the transmission through the cloaking pattern. The last step is to evaporate metal onto the edge of the reflecting surface, which is done by placing a cap wafer on top of the sample and directionally depositing 100nm of Gold (Au) using
electron beam evaporation. The cap wafer prevents Au from being deposited on the top of the wafer, which would degrade performance.

The overall layout of the sample can be seen below in Fig. 3.7. A beam is launched inside the Si waveguide by illumination of polarized light on the input grating where the polarization is chosen so that only TM mode for the waveguide is launched. The light then reflects off of the reflecting surface and is coupled out of the wafer by the output grating.

![Figure 3.7. Scanning electron microscope image of carpet cloak layout. Light is coupled into the Si slab waveguide via the input grating which has a width of 7 µm and distance from the cloak of 15 µm. After being reflected at the cloaked surface, the beam profile is detected via the output grating which has a width of 40 µm and a distance from the cloak of 55 µm. The inset shows the central region of the cloak. The hole diameter is 110 nm.](image)

### 3.4 Experimental Results and Discussion

To unambiguously prove the carpet cloak, we compare the profile of a Gaussian beam reflected from a cloaked bump to that of a similar beam reflected from (1) a flat surface without a cloak and (2) a surface with bump but without a cloak. For performing the experiment, we used the tunable output of an optical parametric oscillator that produces 200 fs light pulses at a repetition rate of 80 MHz in the near-infrared (NIR). The light was focused on the sample with a 50x/0.42 NIR microscope objective. The average power on the input grating on the sample was approximately 3 mW. An InGaAs charged coupled device (CCD) camera was then used to measure the light coupled out of the waveguide at the output grating position.

Since the input and output gratings have an angle of 90 degrees to each other the polarization of the light from the output grating is rotated by 90 degrees. We used this fact to separate the strong reflected light of the input grating from the light coming from the output grating by utilizing a polarizing beam-splitter, resulting in an increased signal to background ratio on the CCD camera as the original polarization of the incoming light is strongly suppressed. Therefore, the beam profile of the focus at the input grating does not show a Gaussian profile in the camera image (e.g., see Fig. 3.8). The excitation spot
The shape seen in the image is mostly from the cross-polarization terms in the tight focus region and from scattering of the grating.

**Figure 3.8.** Optical carpet cloaking at a wavelength of 1540 nm. a-c, The results for a Gaussian beam reflected from (a) a flat surface (b) a curved (without cloak) surface, and (c) the same curved reflecting surface with cloak. The left panel shows the schematics. The middle panel shows the optical microscope images and normalized intensity along the output grating position. The curved surface scatters the incident beam into three separate lobes while the cloaked curved surface maintains the original profile, similar to reflection from a flat surface. The experimental intensity profile agrees well with the intensity profile ($|E_x|^2$) from 2D simulations (right panel).

Figure 3.8 displays the images for the three configurations as well as the intensity profile at the output grating. As seen in Fig. 3.8a and 3.8b, there is considerable contrast between the reflection from the flat and curved surface. The light reflected from the uncloaked bump shows three distinct spots at the output grating due to the scattering of the bump. The flat surface displays the expected Gaussian beam profile, similar to that of the incident wave. To hide the bump on the surface, the designed cloak pattern was placed around the bump in Fig. 3.8c. Subsequently, the beam profile at the output grating resembles a single reflected beam as is seen with the flat reflecting surface. This demonstrates that the cloak has successfully transformed the curved surface into a flat surface, giving the observer the impression that the beam was reflected from a flat surface. Due to the fact that there is no penetration of light into the bump (through the metal layer), any object could be placed behind it and effectively hidden, making the object invisible.
Both 3D and 2D simulations where performed with a commercial FEM package (COMSOL) to verify the carpet cloak performance. We have used the 2D simulations in order to calculate the far field intensity far away from the cloak in correspondence to the experimental measurement. In the 2D simulations the cloak profile is assumed to have an effective index profile obtained from the quasi-conformal mapping. The simulations (right column, Fig. 3.8) show the magnitude of the electric field component in z-direction and show a good agreement with the experimental results. To verify the quality of the 2D simulation we have also performed a full 3D calculation for the near field region of the cloak area including the waveguide configuration and all microscopic structures (hole pattern). The results for these simulations are shown in Fig. 3.9. Both calculations, 2D and 3D, show good agreement to each other.

![2D and 3D simulations for the bump and cloak performed with COMSOL. The (a) 2D and (b) 3D simulations for the bump structure show good agreement as well as the (c) 2D and (d) 3D simulations for the cloak. The 3D simulations are performed with the actual dimensions of the SOI waveguide and the hole pattern.](image)

As a control experiment, we fabricated a bump together with a pattern that has the same dimensions as the cloak pattern but with a homogeneous distribution of the holes. The results are shown in Fig. 3.10. In the case of the control pattern, the beam profile looks similar to the bump but without cloak (Fig. 3.10b). It shows three spots at the output grating and confirms that the control pattern acts like a homogeneous medium. Only with the correct arrangement of the holes within the cloak pattern the beam gets transformed into a single spot.
Figure 3.10. Experimental and simulated performance of the cloak and a control pattern at 1540 nm. The experimental image of the cloak pattern (a) is reproduced here for comparison purposes. The experimental measurement of a control pattern (b) that has been placed around the bump results in an output beam shape similar to a bump only. The control pattern consists of an equally spaced array of holes placed around the bump. The contrast in the two images demonstrates that the resulting single beam exiting the cloak pattern is not simply a result of a regular distribution of holes but is instead from a designed index gradient. The simulated results for both patterns are seen in (c) and (d). There is good agreement between the experimental and simulated results. Plotted on the left of each image is an intensity plot at the output position.

With a second control experiment, we confirmed that the beam profile for the light passing the cloak pattern maintains a single beam spot as it propagates away from the reflecting surface. We fabricated a second output grating with a shorter distance to the cloak pattern (25 µm) on the same sample. The measurements are shown in Fig 3.11. The results demonstrate that in the case of the cloak the light is propagating as it would if reflected from a flat reflecting surface and not simply being focused at the output grating. The control measurement on the sample with the bump but without the cloak gives again three distinct beams that have closer spacing due to the shorted propagation distance (compared to Fig. 3.8b).

Figure 3.11. Experimental results in the case where the output grating position has been moved to 25 µm from the cloak surface. The cloak pattern (a) and bump (b) show similar results when compared to when the grating is placed 55 µm from the cloak surface as shown in Fig. 3.9.
Due to the nature of transformation optics, the cloak should work for all incident angles. To demonstrate this, samples were fabricated with input gratings placed at 30° and 60° with respect to the reflecting surface (opposed to 45° as in the other experiments). A cloak was placed around the bump and the profile at the output grating was compared to a flat mirror. In both cases, the cloak transforms the light passing through it into a singular beam as in the case for a flat mirror. The results are shown in Fig. 3.12.

**Figure 3.12.** Experimental results for the angular dependence of the cloak. (a) The cloak pattern and flat mirror where the input grating is placed at a 60° angle with respect to the reflecting surface. (b) The cloak pattern and flat mirror where the input grating is placed at a 30° angle with respect to the reflecting surface.

Since the carpet cloak reported here does not rely on resonant elements, it is expected to be nearly lossless and broad-band. Nevertheless, the current nanofabrication technology has a practical limit on the deep sub-wavelength hole size due to the waveguide thickness, causing scattering. Further losses are encountered due to possible residual Gallium left from the FIB. Consequently, the transmission of the carpet cloaking sample was found experimentally to be 58% at a wavelength of 1540 nm. Nonetheless, we emphasize that this reduced transmission is due to experimental imperfections associated with the technique of drilling the holes (FIB) and is not inherent to this cloaking design methodology. For example, electron beam lithography could be used in conjunction with reactive ion etching to completely eliminate the loss associated with Gallium as well as provide for much larger cloaking devices (discussed in chapter 4). In this case, almost perfect transmission should be attainable due to low intrinsic loss of silicon or other dielectrics.
Figure 3.13. Wavelength dependence of the carpet cloak. a, b, Plotted is the intensity along the output grating for a curved reflecting surface (a) with cloak and (b) without the cloak. The cloak demonstrates broadband performance at 1400 nm – 1800 nm wavelengths. Distinct splitting of the incident beam is observed from the uncloaked curved surface due to the strong scattering of the original beam.

To obtain the bandwidth of the carpet cloak, measurements were performed over a wide range of wavelengths. The output intensity profiles for these measurements are plotted in Fig 3.13a. For a broad wavelength range from 1400 nm to 1800 nm the beam profile shows a single peak at the output grating, i.e. the cloak performance is largely unaffected by the wavelength change. At wavelengths below 1400 nm the cloak performance suffers due to the fact that the wavelength in the slab waveguide ($\lambda_0/n_{Si}$) becomes comparable to the hole diameter of the cloak pattern, causing increased scattering and breakdown of the effective medium approximation. The effectiveness of the optical cloak can be improved at wavelengths below 1400 nm by using smaller hole diameter and separation, reducing scattering and extending effective medium approximation to shorter wavelength. Unlike the cloak, the bump alone displays a multi-peak output beam (Fig. 3.13b) which is clearly observed for all wavelengths, indicating the strong perturbation of the beam. The upper wavelength limit for the cloak is ultimately restricted by waveguide cutoff. However, measurements above 1800 nm were not possible due to the CCD sensitivity cutoff.

3.5 Conclusions and Outlook

The experimental demonstration of cloaking at optical frequencies suggests invisibility devices are indeed within reach. The all-dielectric design reported here is isotropic and non-resonance based, therefore promising a new class of broadband and low-loss optical cloaks. This methodology can also be extended into an air background by incorporating non-resonant metallic elements to achieve indices smaller than one. It is interesting to note that nature can provide us with a simple gradient index profile in one direction, or mirage, to bend the light away from the ground. While the mirage effect can distort the image of a distant object, cloaking of an object on the ground requires an index profile varying in two dimensions to fully conceal the scattering from the object.

This approach represents a major step towards general transformation optics [11,29,30] at optical frequencies which has so far remained a challenging endeavor due to increased metal loss and fabrication limitations. In fact, similar carpet cloaks have
subsequently been demonstrated by multiple authors, demonstrating wide spread adoption of the technique [31,32,33]. The application of this design methodology is not only limited to cloaking, but can be extended to a wide variety of devices. The benefit of the design and fabrication methodologies is that they simplify the realization of an arbitrary 2D sub-wavelength effective index profile by using the simple geometry of a hole array with variable density. This allows for easy fabrication and scaling, opening the possibility for a large variety of TO devices at visible and infrared wavelengths. Some of these intriguing applications will be discussed in the subsequent chapters of this dissertation.

References


Chapter 4

Janus Device

In Roman mythology God Janus was depicted with two faces, looking in opposite directions. This led to the phrase 'Janus faced' which is mostly used for a 'two-faced' or deceitful character of a person. Within integrated photonics a concept like Janus can provide a new class of multi-functional optical meta-elements which could be a key ingredient in achieving compact and high speed photonic systems. While there have been great strides in the miniaturization of optical elements, such photonic integration largely consists of combining discrete components at the chip level. Here, we present a new approach of designing a single optical element that possesses simultaneously multiple distinct functions [1]. We will describe how the device was designed using transformation optics to manipulate the space, and light flow, in different spatial directions independently. In the design, quasi-conformal mapping was used, allowing the use of a metamaterial with spatially varying isotropic permittivity. The fabrication and experimental validation of two different devices, both having multiple independent functionalities will be presented, demonstrating the flexibility of this concept. These devices consist of (1) a single optical “Janus” device that acts as a lens as well as a beam-shifter at the same time and (2) a single device that acts as two independent beam-shifters at the same time.

4.1 Introduction

The emerging field of transformation optics (TO) has provided a new design methodology allowing an unprecedented manipulation of light propagation, with the optical cloak as the most prominent example [2,3]. However, transformation optics can also be used to enhance the functionality of conventional optical elements. Traditionally, these conventional elements only involve stretching or compressing the optical space in one direction whereas the remaining dimensions in space are unaltered. For example, an optical lens can be interpreted as a result of a simple wavefront transformation that molds the flow of light in a particular direction. A lens works well in one direction whereas light propagating perpendicular to this direction is strongly perturbed. Since space can be modified in two or three dimensions simultaneously, the additional degrees of freedom provided by TO can be used to spatially imprint elements into a single optical Janus or metadevice. In this chapter, we present a TO design approach together with an experimental demonstration that takes advantage of this dimensionality by integrating multiple, independent optical elements into the same footprint.

Electromagnetic waves passing through a physical space can be caused to experience a predetermined virtual space by modifying the underlying material properties in a spatial manner. This is possible because of the invariance of Maxwell’s equations under a spatial transformation [4,5,6]. Therefore, TO opens the possibility to precisely
control the flow of light in a medium and thus allow to design novel devices for microwave and optical frequencies such as invisibility cloaks [7,8,9], light concentrators [10,11,12,13,14], beam manipulators [15,16,17,18], object transformers [19,20], and even electromagnetic wormholes and blackholes [10,21,22]. On the other hand, TO can also be used to improve conventional optical elements. For example, it is possible to transform a Luneburg lens into a lens with flat focal plane without aberration [23]. The flexibility to control the flow of light at will can also be used to design a new class of optical metadevices that can provide different optical functionalities for different light propagation directions.

We demonstrate this capability of TO by imprinting multiple and dissimilar optical functions into one single optical element. This is done by taking advantage of the fact that TO provides a design methodology by which different directions in space can be manipulated independently by employing a well-defined two dimensional permittivity profile. This is in contrast to conventional optical elements which normally alter the phase front only in one propagation direction, without taking advantage of the fact that the refractive index can be engineered for the entire two dimensional space. As an example of a metadevice, we combine a lens with a beam-shifter, acting perpendicular to it, into the same device. Furthermore, we show the flexibility of the TO approach by replacing the lens of the metadevice with a different functionality, in this case, a second beam-shifter. This level of interchangeable dual-functionality cannot be obtained with conventional optical design. Hence, our scheme paves a new way in designing more compact elements in optical integrated circuits.

4.2 Janus Device Design

The two metadevices are designed by reshaping the boundaries (red lines in Fig. 4.1) of a virtual homogeneous space into a physical inhomogeneous space. The horizontal lens and the vertical shifter (Fig. 4.1a) are created by the compression of the upper and lower boundaries (which originate from the circumference of the same circle) to flat facets. The circle making up these upper and lower boundaries has a radius of 31 µm in virtual space. Due to the fact that rays in the untransformed space must stay perpendicular to the boundaries, the rays have to bend (shown by green color) inside the transformed medium. At the same time, the left and right boundaries are compressed into curved surfaces resulting in a device that can focus a diverging wave into a converging wave, i.e. the element behaves as a lens in the horizontal direction. These left and right surfaces, originally flat, are transformed into surfaces with a radius of 36 µm in real space, yielding a focal length of 20 µm. The same principle is used in the design of the dual beam-shifter as shown in Fig. 4.1b, except that all surfaces are transformed from a circle of radius 31 µm into flat surfaces.
Figure 4.1. Single step design for obtaining two functionalities by using transformation optics. Two different metadevices consisting of a horizontal lens with a vertical beam-shifter (a) and a beam-shifter for both directions (b). The virtual/physical space is shown in the left/right panel before/after transformation. Only the area inside the red boundary of the physical space is transformed while the area outside is kept unaltered. Green lines represent the beam directions while the blue lines symbolize wave fronts. On the right are the resulting permittivity profiles resulting from the transformation.

Normally, such a transformation would require the use of metamaterials with extreme material properties which are in general difficult to realize. However, here we employ quasi-conformal mapping [24], as in the carpet cloak, which reduces the strong anisotropy of the original transformation. The small amount of anisotropy remaining after the transformation is neglected so that only isotropic permittivities are used in the Janus device. Such a map generates an effective permittivity ranging from 0.6 to 5.

The devices are designed to be realized in the Silicon (Si) layer of a Silicon-on-oxide wafer (SOI) by spatially varying the effective refractive index profile for the transverse-magnetic (TM) optical waveguide mode in the Si. Each metadevice is transformed from a background region in the silicon waveguide by taking the dispersion of the TM waveguide mode into account. For the metadevice shown in Fig. 2 the theoretical permittivity profile of the element was translated into a pattern of 75 nm air holes (ε=1) with a spatially dependent density. This approach allows us to cover an effective permittivity range from 2 to 5 for the TM waveguide mode in a 250-nm-thick Si slab. In order to realize the designed permittivity profile, we have to neglect the areas where the permittivity falls below 2, which occur around the four corners of the device. These regions with the highest density of the holes would result in a spatial overlap of the finite holes. However, the light beams rarely access this spatial region so that these parts can be omitted without losing functionality. Furthermore, the abrupt change of the permittivity at the device boundaries leads to reflectivity of ≈5% for each boundary due to the impedance mismatch to the waveguide index. Such a reflection can be efficiently suppressed by adding an additional impedance matching layer or a gradient index profile in the transformation. Although the approximation of the permittivity profile with a discrete pattern can lead to scattering loss and reflection from the device boundary, the overall functionality is preserved.
Figure 4.2. Metadevice consisting of a focusing element (lens) in horizontal ($x$-direction) and a beam-shifter in vertical ($y$-direction). (a) Spatial profile for the permittivity obtained by transformation of the space. The corners have been removed in this case due to spatially overlapping holes in the device. (b) Two-dimensional simulation of the spatial electric field magnitude ($|E_z|$) for a large beam propagating in the $x$-direction and a small beam in the $y$-direction. The white line marks the area of the transformed index region.

The permittivity profile for the lens / beam shifter is shown in Fig. 4.2a where the corners of the device have been removed. The background represents the unstructured / untransformed Si waveguide permittivity. An electromagnetic field plot of a lens / beam-shifter metadevice is shown in Fig. 4.2b. The plot is the magnitude of the electric field in the $z$ direction ($|E_z|^2$) generated with a FEM modeler (COMSOL). In the simulation, two separate beams are incident on the device from the bottom and left of the device. The beam passing the device in the $x$-direction has a waste of 6um and is focused 10 µm from the opposite side of the element. The beam propagating in $y$-direction has a waste of 3um and is shifted by 10 µm when passing through the element.

4.3 Janus Device Fabrication

So far in this dissertation, we have employed FIB to experimentally realize optical metamaterials including the bulk fishnet and cloaking device. While FIB has the advantages of creating high aspect ratio features and is relatively insensitive to different materials (i.e. it can be used to etch dielectrics or metals), it suffers from several disadvantages. The first is that the process is relatively slow as it is serial in nature. This precludes FIB from being used in large scale metamaterials due to a practical limitation in sample area of a few tens of microns. As we have seen, FIB also dopes the wafer with Ga which causes significant optical losses. While annealing and plasma etching can mitigate these problems, it is difficult to fully recover device performance. Ultimately, one of the major goals in the Janus device fabrication was to employ a method that is more scalable and avoids the problem of device degradation during fabrication.

4.3.1 Reactive Ion Etching

Reactive ion etching (RIE) is an attractive alternative to FIB when dealing with typical semiconductor materials such as Si. This is due to the fact that RIE employs a parallel etching process wherein large areas can be patterned at the same time. The technique can also achieve high aspect ratio features with the proper chemistry and etch
masks. Lastly, the technique does not alter the chemistry or properties of the etched materials, avoiding parasitic losses such as those encountered with FIB.

The RIE process, seen below in Fig. 4.3, begins with defining an etch mask on top of the material to be etched, which in this case is Si. The mask may be made of either a soft material such as photoresist (PR) or hard material such as Silicon oxide (SiO₂), often referred to as soft and hard masks, respectively. While the soft mask involves less fabrication steps, it is etched more readily by the gasses employed in RIE and therefore can only be used for relatively low aspect ratio structures. A hard mask is used for higher aspect ratio etches as it etches more selectively with respect to the underlying material. In this case, we employ a soft mask made of the electron beam lithography (EBL) photoresist, poly(methyl methacrylate) (PMMA). Openings in the mask material are then exposed by EBL which defines the areas to be etched in the underlying Si. While EBL is a serial process, it is much faster than FIB as it only induces a chemical change in the PR rather than a physical removal of material. Once the mask is developed, the wafer is placed in the RIE to selectively remove the material beneath the openings in the mask.

Figure 4.3. Schematic of the RIE fabrication process. The first step consists of spinning on the photoresist mask material. This mask is the exposed with electron beam lithography and subsequently chemically developed to remove the exposed regions. The wafer is then put in the RIE chamber where a bias is placed between an upper and lower electrode, ionizing the working gases. These gases accelerated to the surface of the wafer where they react with the device layer, Si in this case. Lastly, the mask layer is removed via a short Oxygen plasma etch.

The RIE process starts by ionizing gases above the wafer which is usually created using a directional source such as an inductively coupled plasma (ICP) or a transformer coupled plasma (TCP). The plasma is biased across the wafer, accelerating the ions onto the surface. The directionality of the source will yield directionality in the etch, allowing one to project the mask pattern through the etched region, yielding anisotropic profiles. The accelerated ions impinge upon the surface of the sample, damaging the material and creating dangling bonds that are highly reactive with the etch gasses. The etch gas then reacts with the dangling bonds, creating volatile species that remove the underlying
material. Since the later process is a chemical reaction, the etch gasses must be carefully chosen in order to ensure removal of the material. In the case of Si, the most common etchants are Cl\textsubscript{2} and SF\textsubscript{6}. Usually, additional gasses are added to passivate the sidewalls of the etch, such as Carbon containing species, which form protective polymer layers. These protective species create a more anisotropic etch as the etch gasses cannot access the sidewall material.

Using RIE, the metadevice was fabricated in a 250-nm-thick crystalline Si device layer of an SOI wafer (Soitec). The device layer is spaced by a 3-µm-thick SiO\textsubscript{2} layer from the Si substrate. This is the same configuration used in the carpet cloak, though here we employ the RIE process instead of FIB (Fig. 4.4a). A PMMA resist layer is spun onto the SOI wafer and electron beam lithography is used to expose the hole pattern into the resist. The metadevices consist of roughly 15,000 holes with a diameter of 75 nm, placed in a 22 µm x 22 µm area with varying density. For a comparison, the carpet cloak consisted of ~2,000 holes and took an hour to etch the pattern. The metadevice, employing almost an order of magnitude more holes, took only ten minutes for exposure of the pattern using EBL. Using FIB, the metadevice fabrication time would be ultimately unfeasible. After development with methyl isobutyl ketone (MIBK), the hole pattern is etched through the underlying Si device layer using a reactive ion transformer coupled plasma etcher with Cl\textsubscript{2}, HBr and O\textsubscript{2} as process gases (Lam Research TCP 9400). The combination of Cl\textsubscript{2} and HBr are used to create a more selective Si compared to the PR mask material while a small amount of O\textsubscript{2} is employed to remove any re-deposited PMMA from the etch areas. Finally, the PMMA resist mask is removed via a short Oxygen plasma etch.

In addition to the hole pattern for the metadevice, four grating couplers are fabricated where a typical geometry for the total structure is shown as an electron scanning microscope (SEM) image in Fig. 4.4b. The gratings are designed to launch a TM mode at 1500 nm into the waveguide and are exposed using EBL in the same step as the hole pattern. However, the finite size of the gratings provides a coupling range over a wide frequency band in the NIR and can be used with slightly lower efficiency for different wavelengths. For the experiment, we utilize the grating coupler not only for launching the light into the waveguide but probing the beam position and shape after passing the element.
Figure 4.4. Schematic and SEM layout of metadevice. (a) Schematic of device fabricated on an SOI wafer. The TM waveguide mode is excited when illuminating either of the two input gratings. (b) SEM image of device, showing input and output gratings. Two input / output grating pairs are used to excite the two different directions / functionalities of the device.

One additional benefit of using RIE is that it allows a straightforward implementation into standard complementary metal–oxide–semiconductor (CMOS) platforms. This is due to the fact that RIE of Si already an integral part of the CMOS process flow and is very well characterized. Such an implementation of transformation optics can bring together the advantages of fast and low loss photonic elements with the superior and highly integrated electronic properties of semiconductor materials like silicon [25,26,27].

4.4 Experimental Results and Discussion

For all optical experiments the light from an optical parametric oscillator (OPAL SpectraPhysics) is focused with a 50x / NA 0.4 near-infrared microscope objective lens. The scattered light from the surface is imaged with the same objective lens to an indium-gallium-arsenide array detector. A close up SEM image of the fabricated metadevice lens (x-direction) / shifter (y-direction) device is shown in Fig. 4.5a. Excitation of the TM waveguide mode, which passes the lens in the x-direction, is performed using a Gaussian beam profile with a spot diameter of 13 µm at the input grating, whereas a small beam spot with a diameter of 2 µm is used for the beam-shifter in the y-direction. It can be seen in Fig. 4.5b that the wide beam size is strongly reduced after passing the metadevice in x-direction. Conversely, if the beam is propagating in the perpendicular direction through the device it is shifted at the output grating from left to right and vice versa (Fig. 4.5c).
Figure 4.5. Experimental lens and beam-shifter metadevice performance at a wavelength of 1,500 nm. (a) Scanning electron microscope image of the device whose footprint is 22x22 µm². The inset shows a magnified view of the air holes in the silicon waveguide slab with a hole diameter of 75 nm. (b,c) Optical microscope images with the intensity distribution at the in-couple and out-couple gratings for the lens (horizontal) and the shifter (vertical). Due to the strong back reflection of the excitation beam from the silicon surface the intensities of the output profiles are scaled by 4 times and 8 times, respectively. The white boxes mark the position of the gratings and the hole pattern for the metadevices.

Using transformation optics as the design methodology not only provides the possibility to incorporate very different functions into a single optical element, but it also allows replacing functionalities without influencing the perpendicular propagation direction. Such a design becomes possible because each device demonstrated here utilizes a transformation that only alters part of the original virtual space boundary (Fig. 4.1). We demonstrate this possibility by replacing the focusing element with a second beam-shifter for the x-direction. Figure 4.6a shows the SEM image of the fabricated pattern for such a dual-shifter metadevice. The device uses the same etched hole size as the lens / shifter element to realize the designed refractive index profile. Both directions of the metadevice act now as a beam-shifter for the x and y-direction as can be seen from the optical microscope images (Fig. 4.6b,c). The overall footprint size is identical for both devices which allows them to be interchangeably used in modular on-chip designs. However, the shape of the device’s footprint can be arbitrarily designed by transformation optics which allows for efficient and flexible integration into specific architectures.
Figure 4.6. Experimental dual beam-shifter metadevice performance at a wavelength of 1,500 nm. (a) Scanning electron microscope image of the device whose footprint is 22x22 µm². The inset shows a magnified view of the air holes in the silicon waveguide slab with a hole diameter of 75 nm. (b,c) Optical microscope images with the intensity distribution at the in-couple and out-couple gratings for both the horizontal and vertical shifters, respectively. Due to the strong back reflection of the excitation beam from the silicon surface the intensities of the output profiles are scaled by 8 times. The white boxes mark the position of the gratings and the hole pattern for the metadevices.

A more detailed analysis of the metadevice consisting of the lens and the beam-shifter is shown in Fig. 4.7. To probe the beam propagation characteristics for the focusing element, out-coupling gratings were fabricated at various distances from the center of the structure and the beam profile was measured at these locations. The results are shown in Fig. 4.7b in comparison to the beam profile measured in the absence of the metadevice. By fitting a Gaussian profile to the experimental beam shapes the size of the beam in the focal region was extracted and compared to the values obtained from the numerical calculation (Fig. 4.7c). We obtain a reasonable agreement in a spot size of approximately 2 µm which represents a reduction of the original beam size by more than a factor of six.
Figure 4.7. Metadevice performance consisting of a lens and a beam-shifter. (a) Magnitude of the electric field ($|E_z|$) for a 13 µm wide beam traveling from left to right through the focusing element. (b) Measured beam intensity profiles for different distances of the output grating from the center of the device for $\lambda = 1500$ nm. The dotted black line corresponds to a measurement without the optical element between the gratings. The intensities are normalized with respect to the profile for 13 µm distance. (c) Retrieved spot size from the measurements (black) compared to the design values extracted from the simulation (red).

In addition to the focusing element of the metadevice, we investigated the performance of the beam-shifter for different positions of the input beam. The beam-shifter is designed to shift a beam perpendicular to its propagation direction without changing its shape and size when passing the device (Fig. 4.8a). The preservation of the beam shape within the device is inherent to the particular transformation. The performance of the beam shifter component of the lens / beam shifter device is shown in Fig. 4.8b for the two cases where the input beam is placed at -6 µm and 6 µm with respect to the center of the device. Although the beam is propagating in total 40 µm to the second grating, its size is preserved as can be seen from the measurement. If the input beam is moved along the input grating the output beam will continuously follow this movement though in the opposite direction (Fig. 4.8c). The maximum beam shift of 10 µm is obtained when the beam enters the device close to the corners of the pattern whereas it is shifted to the opposite corner at the output side of the element.
To further demonstrate the effectiveness of interchanging device functionalities we investigated the performance of the dual beam-shifter device which is shown in Fig. 4.6. For the dual-shifter the focusing function for the light is replaced by a second shifter in $x$-direction. By moving the input beam profile along both in-couple gratings and probing the position and shape of the beam at the output grating we are able to confirm the proper shifting in both directions (Fig. 4.9). Although one can observe a slight asymmetry between shifting the beam from negative to positive positions and vice versa for the horizontal shifter, the measurements clearly demonstrate that both directions provide the desired shifting while maintaining the original beam shape and size. Furthermore, the transmission efficiency for larger beam shifts is reduced. This fact is due to some additional scattering losses when the beam enters and exits the pattern closer to the corners where the index changes abruptly.

**Figure 4.8.** Metadevice performance consisting of a lens and a beam-shifter. (a) Magnitude of the electric field ($|E_z|$) for a beam propagating from bottom to top through the beam-shifter element. (b) Measured intensity beam profiles for the input and output beams when entering the element at around -6 µm and 6 µm with respect to the center of the device. (c) Beam position of the output beam for various input positions.

**Figure 4.9.** Performance of the dual beam-shifter metadevice. The corresponding input and output beam profiles for the horizontal and vertical direction, respectively. The intensities of the output beam are normalized with respect to the beam profile at 0 µm (center of the device).
Since the index profile for the element is made purely from dielectric materials, and does not include resonant metamaterials with metal inclusions, the structures are relatively low loss and potentially broad band. For the 2 µm input spot size we measure 78% transmission which includes the reflection loss of \( \approx 10\% \) from the element boundaries. However, with additional optimization of the element size for a certain beam size and index matching the device boundaries to the silicon, the scattering losses can be further reduced. In addition, the measurement of the shifting performance for several wavelengths shows that the element works over a range of 100 nm for a center wavelength of 1500 nm.

4.5 Conclusions and Outlook

In conclusion, we have experimentally demonstrated that TO can provide a new route for designing and integrating multiple optical functions into a single element. To make optical elements economically feasible for smart integrated devices, they have to be comparable in size to conventional electronic components and compatible with standard semiconductor fabrication technologies. Although, there has been tremendous progress in integrated photonics to enable light propagation on a wavelength scale [28], the footprint of many functional optical devices is still very large compared to their electronic counterparts. Furthermore, the miniaturization of optical elements will be ultimately limited by the diffraction limit of the light which is on the order of the wavelength. Transformation optics can help to overcome this scaling limitation by integrating multiple optical elements into one footprint while preserving their independent functionalities. This type of Janus devices opens a new avenue to achieve a high density of functionality, effectively scaling down the size of photonic systems.

References


Chapter 5

New Directions in Metamaterials

In this chapter, we will discuss some new directions in metamaterial research which are aimed at extending the application of metamaterials and associated devices. The first project that will be discussed is using metamaterials to realize photonic black holes. Such structures are analogous to gravitational black holes as they concentrate light to a singular point. Here, we describe both the theoretical description of the device as well as the ongoing work aimed at achieving such a system by employing a gradient refractive index structure. Due to the concentration of light to a small spatial region, the photonic black hole may find use in photovoltaic concentrator systems.

The second project we will discuss is the extension of transformation optics to plasmonic systems. Surface plasmon polaritons will first be discussed as well as their unique optical properties. We will then present how surface plasmon propagation can be transformed using the same concepts employed in the carpet cloak and Janus device. However, in this case, the mode index of the plasmon is modified by placing a dielectric with spatial variations in thickness on top of a metal film. The theory behind the design of a plasmonic Luneburg lens utilizing such a technique will be outlined as well as the progress in the experimental validation of the design. By modulating the mode index of the plasmon through thickness variations of a dielectric, minimal scattering loss is introduced in the system.

Lastly, we will present a new method for scalable manufacturing of three dimensional gradient refractive index profiles. This method employs a technique called photo-electrochemical etching which allows nanoscale voids to be fabricated within a Silicon wafer. Such nanostructuring occurs on a scale of 5 to 10 nanometers forming an ideal effective medium with minimal loss, allowing long propagation lengths. We will discuss how this technique is being incorporated with a dynamic light pattern to enable three dimensional patterning of gradient index lenses for use in photovoltaic concentrators.

5.1 Photonic Black Holes

By using spatial transformations to design optical paths, transformation optics (TO) allows unprecedented freedoms in the design of new types optical elements. These design freedoms can allow one to realize optical elements that range from exotic applications such as the cloak [1,2,3,4], to more conventional applications such as lenses [5,6], beam-shifters [7] and hybrid Janus devices [8]. While we have so far focused on original device design, transformation optics also allows one to create optical systems that mimic phenomena that occur due to some type of spatial deformation. Perhaps the most interesting types of systems that have been examined are deformations arising from gravitational fields [9,10,11]. Since both gravitational and optical deformations can be
modeled in terms of coordinate transforms, this link is relatively straightforward. For example, celestial events such as wormholes and black holes have been formulated using TO and translated into material systems with spatially varying optical properties [9,10]. Here, we will focus on the proposal of Genov, in which he formulates an optical equivalent to a celestial black hole, referred to as a photonic black hole (PBH) [10]. In this section, the basic theory will be outlined as well as the progress in realizing the system in an experimental setting. The progress and challenges in experimentally validating such a system will also be outlined.

In the general theory of relativity, light motion propagating through a region of curved space-time follows a path given by the Lagrangian,

$$L = \frac{1}{2} g_{00}(x,t)t^2 - \frac{1}{2} g_{ij}(x,t)\dot{x}^i \dot{x}^j$$  (5.1)

where $g_{00}$ represents the dilation in time between the proper time and universal time and $g_{ij}$ represents the spatial change in space. If we are only interested in mimicking the spatial path of light in a black hole, we can take the time invariant case where $g_{00} = 1$. Genov et al. shows that the $g_{ij}$ can be treated as a centrally symmetric metric that can be modeled with an isotropic refractive index that is given by,

$$n = (g / g_{00})^{1/2}$$  (5.2)

where $g_{11} = g_{22} = g_{33}$. At this point, one must find a refractive index profile that mimics the spatial deformation in space existing in a black hole. It was proposed that a two parameter radially varying refractive index profile can fulfill this requirement. This refractive index profile is given by,

$$n = \left( \frac{b}{r} \right)^2 + \left( 1 - \frac{a}{r} \right)^2 \right)^{1/2}$$  (5.3)

Where $a$ and $b$ are constants and $r$ is the radial position within the PBH. In this formulation, the parameter $b$ represents a critical photon trajectory while the parameter $a$ represents an unstable photon sphere. Light entering the structure at $r < b$ will be trapped into the center of the structure, wherein a singularity in the refractive index exists. At a radii $r > b$ light will be deflected and at $r = b$ light will be trapped in an unstable orbit at $r = a$. A field plot of a PBH structure with $b = 1.5a = 15 \mu m$ is shown in Fig. 5.1b with the refractive index profile shown in Fig. 5.1a.
Figure 5.1. PBH refractive index profile and optical response. (a) Refractive index profile for the PBH structure versus radius with \( b = 1.5a = 15 \, \mu \text{m} \). The refractive index tends to a singularity at \( r = 0 \). (b) Magnetic density field plot for the PBH structure. The light is incident at \( r = b \) and is trapped into the singularity at the center, resulting in high field intensity. Field plot is taken, with permission, from [10].

In Fig. 5.1b a Gaussian beam is incident on a PBH at the critical radius causing the light to be funneled to the center of the device wherein in cannot escape, yielding extremely high field intensities. One important aspect of the structure is the singularity in the refractive index at the origin of the device. While this is necessary to achieve an analogous system to a gravitational black hole, it is not possible to realize in a laboratory setting. Therefore, it is necessary to modify this original design in order to experimentally realize a structure demonstrating similar physics. The remainder of this section will be devoted to the progress that has been made in such an experimental realization.

While the truly analogous PBH / gravitational black hole structure requires an infinite refractive index, this region must be replaced if one wishes to experimentally realize the structure. In this case, the center region is replaced with an absorbing region occupying a finite area. Any light reaching this area will be absorbed, preventing it from leaving the center of the device, just as in the original formulation. The device is designed for the TM waveguide mode of a Silicon-on-insulator (SOI) waveguide with a 500 nm Silicon (Si) layer on top of a 2 um Silicon Oxide (SiO2) layer. As in the carpet cloak and Janus device, the PBH is designed for the mode index of the Si waveguide layer, wherein the light is confined. In this configuration, the minimum and maximum effective mode indexes are 1.5 and 3.15, respectively. The device is designed for operation at 1400 nm with \( a = 20 \, \mu \text{m} \) and \( b = 30 \, \mu \text{m} \). The profile of the device is truncated within \( r = 15 \, \mu \text{m} \) and replaced with a constant index region with a complex refractive index of 3.15 + 0.06\( i \). This absorbing core material represents Germanium that has been structured with air holes at a filling fraction of 25%. A schematic of the device as well as a refractive index profile is shown in Fig. 5.2.
Figure 5.2. Modified PBH schematic and refractive index profile. (a) Schematic of the truncated PBH design. An absorbing core replaces the singularity and is surrounded by a radially varying index profile. (b) Radially varying effective mode index profile of the PBH structure. The center region has an effective mode index of $3.15 + 0.06i$.

Finite element method (FEM) simulations (COMSOL) were performed on the truncated PBH structure to better understand light flow in the device. A 1400 nm wavelength Gaussian beam with a full width half maximum of 3 µm is incident on the device. The incident path is chosen to be tangential to the device at $r = a = 20$ µm. The device is truncated at an outer radius of $r = b = 30$ µm due to limitations in fabrication area. An electric field plot ($|E_z|$) of the device is presented in Fig. 5.3a. It can be observed that light is indeed diverted towards the center of the device, where it is absorbed by the core. Unlike in the original PBH proposal, light does not concentrate to a singular point due the truncation in the refractive index. This is also clear from the energy density plot of the device, presented in Fig. 5.3b. It is important to note that if the core of the device is not absorbing, the light will pass through the core and leave the device.

Figure 5.3. PBH electric field and energy density plots. (a) Electric field plot for a PBH with $b = 1.5a = 30$ µm. Light is incident at $r = 20$ µm and spirals to the core of the structure where it is absorbed. (b) Energy density plot of the same PBH structure demonstrating the path of light in the structure.
The PBH structure was fabricated using electron beam lithography (EBL) and reactive ion etching (RIE) in a similar procedure to the Janus device. However, in the case of the PBH, a large region of low index is needed. Fabricating this profile using holes within the Si layer would require long EBL patterning times due to high filling fractions over a large area. Therefore, an inverse process is employed where pillars are etched into the Si instead of holes. This allows the index profile to be created with a smaller number of patterns (cylinders) per area, resulting in the capability to make larger devices. To accomplish this, SiO\textsubscript{2} cylinders are first patterned on the surface of the Si with EBL and an electron beam deposition / liftoff step. These cylinders form an etch mask for RIE of the underlying 500 nm Si layer. Using RIE, these cylinders are etched into pillars within the Si with a radially varying density and thus radially varying refractive index profile. The pillars are fabricated with a diameter of 70 nm and height of 500 nm, as seen in Fig. 5.4. The total number of pillars making up the device with the dimensions outlined above is \( \sim 200,000 \). The center core of the device currently consists of solid Si though this is to be replaced as outlined below.

Several challenges remain to be overcome in experimentally validating the PBH concept. The first challenge is replacement of the center core of the device with an absorbing material. Without this absorbing core, light will simply pass through the center of the device and leave through the opposite side. One method of accomplishing this is to first etch the center Si core away during the RIE process. Once the core is empty, it may be filled using a subsequent deposition step with a material such as Germanium which is absorbing at 1400 nm. However, the Germanium, which has a complex index of \( 4.34 + 0.08i \), must be structured to lower the index down to that of Si to ensure no reflection exists at the boundary of the two materials. This can be accomplished through the use of focused ion beam milling (FIB) or a subsequent RIE step.

The second challenge is experimental validation of the device. The main goal here is to spatially map the flow of light into the core of the device. The first option being pursued is employing near-field mapping of the light using a near-field scanning optical

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig5_4.png}
\caption{Scanning electron images of the fabricated PBH structure. (a) Overall view of the structure. The extension of the structure at the top of the image is the input waveguide. (b) Close up top view of the pillars used to generate the spatially varying index profile. The pillar diameter is 70 nm. (c) Side view of the pillars composing the structure. The height of the pillars is 500 nm.}
\end{figure}
microscope (NSOM). NSOM works by using a sharp probe to locally probe the light propagating along a surface. Therefore, it allows direct observation of light flow inside the structure. Furthermore, by sampling the near-field of light, NSOM is capable of sub-wavelength spatial mapping of the field where the ultimate resolution is dictated by the diameter of the probe’s tip. One practical issue though is that the spatial scan sizes are limited to ~30 µm in our present tool, preventing a continuous map of the full structure. A second method being pursued is coupling a small amount of light out of the structure using emitters placed on top of the device. In this case, PbS quantum dots, with an peak excitation wavelength of 1380 nm, and emission wavelength of 1500 nm, are placed on top of the structure, as seen in Fig. 5.5. Due to the fact that the quantum dots emit light in all directions, a portion of the light will be coupled out of plane and can be imaged in the far-field. This method should allow a spatial map of the field without the complexity of employing NSOM.

![Quantum dot incorporation and imaging schematic. PbS quantum dots (QDs) are deposited onto the fabricated pillars structure using spin casting. The excitation beam (1380 nm) excites the QDs which emit at 1500 nm into free space. The QDs sit within the pillars, allowing excitation from the guided light in the structure. The emission from the QDs is imaged in the far-field via a CCD to map the light flow in the device.](image)

**Figure 5.5.** Quantum dot incorporation and imaging schematic. PbS quantum dots (QDs) are deposited onto the fabricated pillars structure using spin casting. The excitation beam (1380 nm) excites the QDs which emit at 1500 nm into free space. The QDs sit within the pillars, allowing excitation from the guided light in the structure. The emission from the QDs is imaged in the far-field via a CCD to map the light flow in the device.

### 5.2 Plasmonic Transformations

So far, we have dealt with transformations designed for propagating modes in dielectric waveguides. However, this concept can be extended to other optical systems, such as surface plasmon polaritons (SPPs). SPPs are electromagnetic waves which propagate along a metal and dielectric interface wherein the electromagnetic wave is coupled to electron density oscillations in the metal, as seen in Fig 5.6.
Figure 5.6. Electron oscillation schematic and electric field profile of SPPs. An interface separates metal and dielectric semi-infinite media with permittivity $\varepsilon_m$ and $\varepsilon_d$ respectively. The electromagnetic fields are maximum at the interface and decay exponentially in the direction perpendicular to the interface.

In an SPP, the electromagnetic energy is maximal at the surface of the metal and decays exponentially away from the surface. The existence of such waves was first proposed by Ritchie [12] and the application and study of this phenomenon is commonly grouped under the term plasmonics [13]. The existence of such surface waves are a consequence of solving Maxwell’s equations at the metal-dielectric interface and have a unique dispersion relation given by [14],

$$k_{sp} = k_0 \sqrt{\frac{\varepsilon_m \varepsilon_d}{\varepsilon_m + \varepsilon_d}}$$  \hspace{1cm} (5.4)$$

where $\varepsilon_m$ and $\varepsilon_d$ are the values of the permittivity of the metal and dielectric, respectively. This dispersion relation, plotted in Fig. 5.7 results in the wave vector of the SPP deviating from the light line, resulting in a SPP wavelength that is much shorter than that of light propagating in free-space. Due to the mismatch in the wave vector, additional momentum must be provided in order to excite the SPP. This additional momentum is usually generated through the used of prism excitation or by etching a grating in the metal film.
Figure 5.7. Dispersion relation of a SPP at a Silver-air interface. The dotted line is light propagating in air and the blue line is the SPP dispersion relation. The wave-vector ($k_x$) of the SPP grows as it approaches the frequency approaches the surface plasmon resonance.

One of the biggest benefits of the larger SPP wave vector is that it allows tight spatial confinement of light. This confinement has been utilized in a variety of fields including nanolithography [15,16], microscopy [17,18], solar cells [19], and bio-sensing [20]. One of the main goals in plasmonics is to control the flow of light on the surface of the metal. Usually this is done by physically structuring the metal and has been implemented in a variety of applications including Bragg reflectors [21], confined waveguides [22,23], and focusing elements [24,25,26]. However, recently it has been proposed that the concepts of TO can be applied in achieving similar results without the requirement of structuring the metal surface itself [27]. This is possible due to the fact that the SPP wave extends away from the metal surface. Therefore, varying the refractive index outside the metal allows one to modify the effective mode index without modifying the underlying metal.

While the shorter wavelength of SPPs is one of their most useful features, it also makes it more difficult to apply the concepts of TO with spatially varying elements. This challenge arises due to the fact that the shorter wavelength of the SPP will scatter much more readily when encountering discrete changes in the refractive index. Therefore, the scale of the physical structuring employed to achieve a spatially varying refractive index must be much smaller than that for a free-space wave of the same frequency. An alternative to discrete elements is to employ a dielectric cladding layer with varying height, which allows one to smoothly change the mode index of the SPP. This concept was recently proposed by Liu et al. [27] in achieving a SPP Luneburg lens. The remainder of this section will cover the design proposed by Liu and progress in experimental validation of such a lens.

To derive the effective mode index of the SPP a simple system of a metal film covered in two dielectrics is proposed, as seen in Fig. 5.8a. The metal film and upper dielectric (air) are assumed to extend to infinity while the thickness of the sandwiched
dielectric is varied to modify the mode index of the SPP. In this case, Gold is chosen as the metal, Poly (methyl methacrylate) (PMMA) as the sandwiched layer, and air as the upper cladding dielectric. The materials are modeled at a wavelength of 1500 nm. The mode index is solved numerically using a FEM solver (COMSOL) yielding the effective mode index as a function of dielectric spacing layer thickness as seen in Fig. 5.8b.

![Diagram of sandwich structure and effective mode index of the SPP](image)

**Figure 5.8.** Sandwich structure and effective mode index of the SPP. (a) Sandwich structure consisting of a half space of Gold and air separated by a layer of PMMA with varying thickness \(d\). (b) Effective mode index of the SPP versus PMMA thickness.

The Luneburg lens is a spherically symmetric structure with a radially varying index profile that focuses a plane wave incident on one side of the sphere to a point located at the opposite surface of the lens. These lenses are ‘perfect’ in the sense that they have a numerical aperture equal to 1 but are in general hard to realize due to the radially varying 3D index profile. However, a 2D realization is much simpler and still preserves the function of the lens. The lens has an index profile which can be derived from the eikonal equation and is given by [28],

\[
n(r) = \sqrt{2 - \left(\frac{r}{R}\right)^2}
\]

where \(R\) is the radius of the lens and \(r\) is radial position within the lens. Based on the effective mode index, Fig. 5.8b, and 5.5, the refractive index profile can be translated into the SPP mode index by placing a cone of dielectric on top of the metal surface with a linear height profile, as seen in Fig. 5.9a. While this cone could be made out of a variety of dielectrics, it was realized experimentally by fabricating a cone made of PMMA on top of the metal surface. For a working wavelength of 1500 nm, the cone dimensions are: \(R = 5\ \text{um}\) and \(H = 1000\ \text{nm}\), corresponding to Fig 5.9a. An electric field plot of the designed lens is presented in Fig. 5.9b. A SPP wave with flat wavefront is incident on the lens and focused on the opposite surface. The circle represents the boundary of the lens / transformed area.
Figure 5.9. Plasmonic Luneburg lens schematic and electric field plot. (a) Schematic of the Luneburg lens consisting of a cone of PMMA on top of a Gold film. The red lines represent the energy flow through the lens. (b) Electric field plot of the SPP moving through the lens. A wave with a flat wave front is focused on the opposite side of the lens, whose outer edge is denoted with the white circle.

To realize such a profile experimentally, we developed a method of grey scale EBL. In this method, the exposure time of the photoresist (PMMA) is modulated in a position dependent manner to modulate the height of the resist. One difficulty in this procedure is that PMMA (and photoresist in general) is designed to have high contrast and an exposure threshold that is non-linear with dose. Therefore, a lower contrast formulation of PMMA was employed with a molecular weight of 50k Dalton, as opposed to higher contrast formulations with a chain weight of 895k Dalton. This allowed a much smoother grey scale profile to be realized in the resist.

Figure 5.10. PMMA height and dose correlation. The exposure depth of PMMA is non-linear with dose and must be correlated to allow a designed height profile to be realized. 50k Dalton weight PMMA is utilized to realize a more linear height profile with exposure dose and an atomic force microscope was used to measure the profile.

First, a dose test was performed with a linearly varying radial dose change to correlate PMMA height with dose value. The resulting profile is shown in Fig. 5.10.
From the dose test, a dose profile yielding a linear change in PMMA height was generated, yielding the structure seen in Fig. 5.11. Once the lens is defined, focused ion beam (FIB) is used to define gratings in the metal surface to launch the SPP, exciting the lens.

**Figure 5.11.** Height profile and SEM image of fabricated Luneburg lens. (a) Atomic force microscope image of the fabricated lens. A well defined linear height profile was realized with a maximum height of 1100 nm. (b) SEM image of fabricated lens with a diameter of 10 µm. The gratings used to excite the lens can be observed at the top and bottom of the image.

To experimentally validate the lens, a 1500 nm laser beam was incident on one of the gratings, exciting SPP’s traveling on the surface of the metal and through the lens. The SPP was coupled out using a second grating on the opposite side of the device in order to probe the size of the beam. The light was imaged with an InGaAs charged coupled device (CCD). The overview of the device can be seen in Fig. 5.12a with the experimental optical images shown in Fig. 5.12b,c,d. In all cases, the light is incident at the input grating, to the right of the device, and coupled out at the grating to the left of the device.
Figure 5.12. Experimental results for the plasmonic Luneburg lens at 1500 nm. (a) SEM of overall structure with input and output gratings. (b) Optical image of structure excited outside of lens. (c) Image of illumination at the center of the lens, showing focusing at the back side of the lens and a slightly larger beam at the output. (d) Image of structure illuminated slightly off axis of the lens. The output light can be observed to shift opposite to that of the illumination.

In Fig. 5.12b, the SPP is excited outside of the Luneburg lens to gauge the nominal size of the beam at the output grating. In Fig. 5.12c, the SPP is excited through the center of the lens. It can be observed that there is a small focal spot on the back of the lens which diverges and is coupled out of the metal at the output grating. In Fig. 5.12d, the SPP is excited slightly towards the top region of the device, causing the output light to shift towards the bottom of the device, which agrees well with the expected operation of a lens. While these are preliminary results, the lens behaves as expected. However, it is in general desirable to gain more information about light flow in the structure, as in the case of the PBH.

To achieve a more complete experimental validation of the plasmonic Luneburg lens, emitters are currently being added into the PMMA. Unfortunately, the PbS quantum dots employed in the PBH will not solubilized with PMMA at a sufficient loading concentration to enable visualization of the SPP. Therefore, a fluorescent dye with much higher loading concentration in PMMA is currently being employed. The dye, excited by the SPP, will emit in all directions, allowing the light inside the structure to be coupled out of the plane and imaged on a camera. However, the availability of dyes at specific wavelengths dictates that the device be redesigned for operation at 820 nm. While it is general better to work at longer wavelengths due to the longer SPP propagation length, it is difficult to find dyes with excitation wavelength beyond the near-infrared spectrum.
Ultimately, we chose to employ the laser dye, IR-140 (Sigma Aldrich), which has an excitation wavelength of 820 nm and emission wavelength of 850 nm. This dye is premixed with the PMMA before exposure at a concentration of 5 milligrams per milliliter of PMMA. The solution is then sonicated for 30 minutes and then centrifuged to remove aggregates.

Experimental validation of the device is still ongoing at this time utilizing the PMMA solubilized dye. However, this approach looks to be a promising means by which to modulate the propagation of SPPs in a relatively straightforward manner. Furthermore, by modulating the refractive index of the SPP without using discrete elements, it is possible to maintain the minimum amount of loss in the system. This method is not however restricted to SPPs. In fact, one may modulate the refractive index of any waveguide system by varying the height of the guiding dielectric. The grey scale EBL process demonstrated here may be extended to dielectric waveguides to replace physical structuring, providing transformations with less scattering and thus lower loss. If one wants to modulate the index of a higher refractive index waveguide, such as Si, the PMMA profile can serve as a reactive ion etch mask, allowing one to project the spatial height pattern into the Si. This could be particularly useful if one wishes to scale the cloak, Janus device, or PBH to visible frequencies where scattering limits the size of physical structuring. In this case, the Si waveguide could be replaced with a titanium dioxide waveguide which is a transparent, high index material at visible wavelengths.

5.3 Scalable 3D Manufacturing

One of the main challenges facing the metamaterial community is the lack of a technology that allows large scale manufacturing of complex metamaterials with nanoscale feature sizes. It is desirable to scale such materials not only for commercialization means but also to employ metamaterials for devices that must exist on a large scale. For instance, if one wants to realize a cloak capable of hiding a macro scale object, the cloak itself must also exist on a macro length scale. This is due to the fact that the cloak size scales with object size. Another example is employing metamaterials for use in photovoltaics. The design freedoms allowed by metamaterials could be used to design more efficient solar cell concentrators. However, such metamaterials would need to be made on a large length scale in a relatively cheap process. Another challenge is achieving 3D refractive index profiles. So far, in this dissertation we have primarily discussed metamaterial films, such as the fishnet or 2D optical devices such as the cloak. However, it is in general desirable to have the ability to realize 3D profiles to extend the types of metamaterial devices that are realizable.

The commonly employed manufacturing techniques such as FIB and EBL allow precise manufacturing of materials with nanoscale dimensions; however, they are serial processes which are relatively slow, preventing scaling of the overall footprint of the materials. These technologies also only allow 2D materials to be realized, lacking variation in 3D. While we have demonstrated 3D profiles utilizing grey scale EBL, these profiles are only useful though in waveguide geometries where light is confined to a 2D plane. It is therefore necessary to develop new fabrication techniques that allow 3D profiles to be created in a scalable and relatively cheap format.

One potential application of a 3D gradient index profile is lens elements. While we have demonstrated the Luneburg lens on a 2D plane, the lens itself was originally
designed as a spherical element. However, at this point, fabricating the required 3D index profile has not been possible at optical wavelengths due to fabrication constraints. One potential use of such a lens is in photovoltaic concentrator cells. The Luneburg lens is an ideal solar concentrator, approaching the thermodynamic limit for concentration [29]. This is due to the fact it has a numerical aperture of 1 and is also index matched to the surroundings. Recently, it has been shown that, using TO, the lens’s back facet can be flattened [6], allowing easy integration on top of a planar solar cell. In this section we will describe the development of a technology that could not only allow such a lens to be fabricated but furthermore, has the capability of making such an element on a large scale and at low cost.

One technique that has recently been employed for 3D metamaterial manufacturing is direct 2 photon laser writing of photoresist [30,31]. By focusing a high power laser of frequency, $\omega_1$, one can induce 2 photon absorption in a photoresist at $2\omega_1$. The non-linear absorption process combined with the inherent non-linearity in the photoresist significantly decreases the exposure area, yielding features that are sub-diffraction limit in size [32]. Employed in metamaterials, the laser is scanned over the resist in the desired metamaterial pattern. This pattern is subsequently solidified in the resist and can furthermore be exposed in 3D though all parts of the pattern must be supported. If one wishes to incorporate metal into the structure, a chemical vapor deposition of metal can be performed to conformally coat the photoresist pattern. This technique has been employed to realize a range of metamaterials including split-rings [30,31], log-pile structures [33,34] and recently, an optical carpet cloak [35]. However, direct laser writing remains a serial process and is therefore relatively slow. It is also unclear whether such a technique can be used for metamaterials operating at visible wavelengths, where the dimensions need to be on the sub 100 nm length scale.

While precise nanoscale geometries are usually employed in metamaterials, they are not always necessary. In gradient index metamaterials such as the cloak or Janus device, the arrangement of the hole pattern can be relatively arbitrary. One only needs to pay attention to the local filling fraction. Though we have so far used a hexagonal lattice arrangement, this is in fact not necessary. The same structures could be made, for instance, with a sponge like structure where nanoscale pores are etched into the Si in a spatially dependent density, lacking any short range order. In such structures it is also not necessary to create sharp spatial changes in the refractive index. Rather, it is desirable to create smooth index variations with continuous index gradients. This greatly decreases the requirements of the manufacturing technique as we no longer need precise nanoscale placement of structures. We must only ensure that the structuring remains at a scale much less than the wavelength of light and varies smoothly with position. Here, we will discuss a technique that we are currently developing that can achieve such structuring over large areas. We will also describe how this technique can also be used to realize 3D gradient index profiles in the same scalable format.

The technique we are currently developing relies on photo-electrochemical (PEC) etching of Si [36]. In PEC, Si is immersed in an electrolyte typically consisting of hydrofluoric acid (HF) and an organic liquid such as ethanol. The Si is then illuminated at a photon energy above the bandgap and under an applied bias. This illumination generates electrons and holes wherein the bias is chosen to pull the holes to the surface of the wafer, at the interface with the electrolyte. These electronic holes react with the
electrolyte, etching away the Si. The doping level, illumination intensity, and electrolyte concentration can all be used to vary the degree of etching in the Si. For instance, at lower illumination large pores, with a diameter on the order of several hundred nanometers, will form in the Si and follow the crystallographic orientation. These large pores are typically referred to as ‘macropores’ and this technique has been used to create high aspect ratio photonic crystals [37]. At high illumination intensity the pores become much smaller, with a diameter on the order of 5-10 nm in size, and random in their orientation. Such pores are typically referred to as ‘micropores’ and create a sponge like structure. The filling fraction of these nanoscale pores, and thus effective refractive index, can be controlled via the intensity of the illumination. Using this technique, grey scale refractive index patterns have been etched into Si by simply projecting a grey scale optical image onto the wafer [38]. This technique is what we employ here as it provides an excellent effective medium where the refractive index can be modulated spatially.

To enable 3D gradient index patterns, the illumination source must be dynamic such that the etched pattern may be changed with time and thus etch depth. To achieve this, a dynamic micro-mirror device (DMD) is used to modulate the illumination pattern and intensity with time. The DMD is composed of roughly a million individual mirrors that are modulated in time to provide a varying spatial pattern of light. A schematic of the fabrication scheme is shown in Fig. 5.13. Silicon wafers of n-type doping and a resistivity of 10 Ω-cm are used such that illumination of the wafers will generate electronic holes that react with the HF electrolyte. The illumination of the wafer is performed with white light from a DMD projector. Illumination at high intensity will generate pores at a higher filling fraction and thus lower refractive index and vice versa. The DMD is used to project a grey-scale light pattern as seen in Fig. 5.13b and thus grey-scale refractive index profile.
Figure 5.14. Schematic of 3D grey-scale index modulation. The illumination pattern is modulated with time, as the etch progresses through the wafer. This results in spatial modulations in the vertical direction. In this case, a radially varying index pattern is demonstrated, as is found for example in a Luneburg lens.

To generate 3D index patterns, the illumination pattern is changed with time, as seen in Fig. 5.14. Due to the fact that the etch proceeds from the top of the wafer in a time dependent manner, modulation of the illumination pattern with time allows one to project a 3D gradient index pattern into the wafer. An example of a 3D profile is the gradient index lens seen in Fig. 5.14. Such a lens is similar to that of the flattened Luneburg lens proposed in [6].

Figure 5.15. SEM of a PEC etched Si wafer. The wafer was etched at 150 W/cm$^2$ for 10 minutes in 1:1 HF:Etoh. The resulting Nanoporous region is 160 nm in thickness. The individual pores are too small to resolve in the SEM image.

Currently, we are in the progress of establishing PEC Si etching rates and porosity. This is important so that a well designed refractive index profile may be realized based on a prescribed exposure condition. A typical etched sample is shown in Fig. 5.15. The PEC etch was performed in 1:1 HF:Etoh under an illumination of 150 W/cm$^2$ for a duration of 10 minutes. It was observed that that Si etched 160 nm across the pattern in a
uniform manner. In the SEM image it is not possible to observe the individual pores as they are estimated to be at a size between 5 and 10 nm. Optical characterization is currently being used to determine the refractive index of the samples in order to calculate the filling fraction of Si as a function of illumination intensity. Once characterization is complete, 3D gradient lens profiles will be projected into the sample and their optical performance will be characterized.

Ultimately, this large area method should be applicable for a large range of devices and applications. For example, this method could be used to scale the carpet cloak or PBH devices to a size on the order of centimeters. The reduction in local structuring size also allows longer propagation lengths within the structure. If one wishes to move into visible wavelengths, the Si structures formed with this method can be oxidized to SiO2. This SiO2 matrix can be used directly or in-filled with a higher refractive index material such as TiO2 to provide a larger index range or gradient. Furthermore, the parallel and low cost nature of this technique could allow wide adoption in the metamaterial and optics community.

5.4 Conclusions and Outlook

In this chapter we have examined several of the ongoing projects we are pursuing in the area of metamaterials. This work encompasses new applications of metamaterials such as in PBHs and plasmonic transformations as well as an extension in the manufacturing capabilities. The application of metamaterials in achieving PBHs could be potentially useful for energy conversion architectures where small absorber regions are necessary to reduce cost. Such PBH architectures could be fabricated using the scalable 3D manufacturing technique outlined here on a large scale and for low cost. Furthermore, plasmonic transformations should open a new door to manipulating SPPs in a relatively simple manner while maintaining a minimum of scattering loss. The lens transformation presented here could be useful for focusing SPPs into and out of waveguides as well as applications involving field concentration such as in biological sensing.

While metamaterials were originally studied for their unique optical properties, the future of metamaterials relies heavily on the ability to use such materials for useful purposes. By extending the useful applications, the work presented here may further open new doors to broader areas of metamaterial research. In the next chapter, we will elaborate on some of these future directions and challenges.

References


Chapter 6

Conclusion and Outlook

In this dissertation, I have outlined the progress we have made in achieving both new types of optical metamaterials as well as novel devices enabled by such materials. In this chapter I will summarize the findings presented here as well as outline what I believe to be the future of metamaterials and the fundamental challenges facing the field.

6.1 Conclusions

In chapter 2, we described the development of the first bulk negative index metamaterial operating at optical frequencies. We demonstrated how such a structure can overcome the drawbacks in single layer designs by enabling a low loss negative refractive index metamaterial. This is enabled by the coupling of individual layers, resulting in a material that has a refractive index which has converged to the bulk value. Furthermore, using such a thick material, we were able to for the first time at optical frequencies, visualize negative refraction at the material’s interface. The realization of such a thick, low loss material may offer the possibility to explore a large variety of optical phenomenon associated with zero and negative refractive index, as well as applications in scaling down of photonics and imaging.

In chapter 3, we shifted to device design and realization using metamaterials by experimentally realizing the first optical cloaking device. We explained transformation optics and its use in designing an electromagnetic cloak, specifically quasi-conformal mapping. Using this design methodology, the carpet cloak was experimentally realized using isotropic, non-resonant elements. This allowed both large bandwidth and low loss in the cloak, overcoming the problems in earlier forms of cloaking. This approach represents a major step towards general transformation optics at optical frequencies which has so far remained a challenging endeavor due to increased metal loss and fabrication limitations.

In chapter 4, we demonstrated an extension of the quasi-conformal design methodology and isotropic metamaterial system in demonstrating an optical Janus device. We demonstrated how such a device incorporates multiple, independent, optical devices into one footprint. The experimental demonstration of the device was presented as well as a shift in fabrication methodology to reactive ion etching that allowed more precise dimensionality as well as possible combination into integrated circuits. Such a device represents the flexibility in using transformation optics and metamaterials to realize a wide range of optical devices.

In chapter 5 we discussed several new directions in metamaterial research and the latest developments in realizing metamaterial driven devices at optical wavelengths. We discussed the progress in experimentally realizing photonic black holes which mimic their celestial cousins by concentrating light down to a small spatial area. We also discussed the extension of transformation optics to plasmonic systems where the optical
wave is bound to a metal surface. In experimentally realizing plasmonic transformations, a new method of mode index modulation was developed which relies on spatial changes in the height of a dielectric. Such a method avoids scattering losses associated with discrete index changes and could be extended outside of plasmonic systems. Lastly, we described the development of a large scale manufacturing method capable of three dimensional refractive index profiles. Such a method extends the range of possible metamaterial devices; particularly those designed using transformation optics. One potentially useful application of this technique is the fabrication of gradient index lenses for use in photovoltaic concentrators such as the Luneburg lens. Such a lens may in the future be integrated on top of a photovoltaic, avoiding the large and costly parabolic mirror installations currently employed.

6.2 The Future of Metamaterials

While metamaterial research was originally focused on demonstrating unique optical properties, I believe the future of metamaterials research will largely be device driven. For long term continuation of the field, metamaterials must prove to provide useful new device capabilities not possible with conventional materials. I believe the research presented here represents major steps in this direction; however, metamaterial devices are still in their infancy. As such, I will briefly outline some of the areas that represent the most attractive device applications.

The first area of interest is active metamaterials that can be modulated with an external stimulus, allowing reconfigurable devices for manipulating or modulating light flow. One particularly interesting architecture is the incorporation of phase change material, such as Vanadium dioxide (VO₂), into the metamaterial structure. Upon thermal or optical stimulation, VO₂ undergoes a phase transition from a semiconducting state to a metallic state which is accompanied by a large change in the permittivity. Such a material could be incorporated into any of the metamaterials presented here to allow for modulation of the device functionality. Furthermore, the transition of VO₂ is extremely fast, on the order of femtoseconds, allowing fast modulation of the material properties and device function.

I believe another area that will be developed is flexible metamaterials. The unique property of metamaterials is that their optical response is dictated by the underlying structure. While this connection between metamaterial structure and response is the basis of the field, it has to this point not been fully exploited. By utilizing flexible metamaterials, external strain can be mapped out in a spatial and real-time manner by monitoring the optical properties of the underlying film. The most basic employment of this concept would be to fabricate metallic or dielectric metamaterials on top of an elastomeric substrate. The coupling of strain and the metamaterials optical properties could be used, for example, to map the external force exerted by a living cell in a real-time and spatially dependent manner. The coupling of mechanical deformations and optical properties may also lead to new types of transformation optics devices which are created by simply deforming an originally uniform material.

Lastly, I believe that the further development of low loss metamaterials will be a crucial ingredient in device applications and thus the field’s success. While progress in this area has been presented here, I believe that there is still much more to be accomplished. Work is already being performed in incorporating semiconductor gain
material into lossy plasmonic metamaterial structures. However, I believe that a significant amount of work remains to be done in modeling the interaction between the gain medium and metallic elements that comprise the metamaterial. To achieve ideal coupling and mode overlap with the gain material, new metamaterial unit cells will need to be designed to achieve low threshold loss compensation. One interesting area is translation of the dielectric metamaterial designs presented here into an active semiconductor gain medium. In this case, scattering losses from the structuring could be compensated without the problems associated with coupling to metallic elements. Among other things, this could lead to large scale, transparent, optical cloaks.