Dispersion characteristics of silicon nanorod based carpet cloaks

Venkata A. Tamma¹, John Blair², Christopher J. Summers² and Wounjhang Park¹*

¹Department of Electrical, Computer & Energy Engineering, University of Colorado, Boulder, CO 80309-0425, USA
²School of Materials Science & Engineering, Georgia Institute of Technology, Atlanta, GA 30332, USA
*won.park@colorado.edu

Abstract: A wide range of transformation media designed with conformal mapping are currently being studied extensively due to their favorable properties: isotropy, moderate index requirements, low loss and broad bandwidth. For optical frequency operation, the transformation media are commonly fabricated on high index semiconductor thin films. These 2D implementations, however, inevitably introduces waveguide dispersion, which affects the bandwidth and loss behavior. In this paper, for carpet cloaks implemented by a silicon nanorod array, we have confirmed that waveguide dispersion limits the bandwidth of the transformation medium by direct visualizing the cut-off conditions with near-field scanning optical microscopy (NSOM). Furthermore, we have experimentally demonstrated the extension of cut-off wavelength by depositing a conformal dielectric layer. This study illustrates the constraints on the 2D transformation media imposed by the waveguide dispersion and suggests a general technique to tune and modify their optical properties.

OCIS codes: (160.3918) Metamaterials; (230.3205) Invisibility cloaks, (310.1860) Deposition and fabrication

References and links

©2010 Optical Society of America

Received 6 Oct 2010; revised 4 Nov 2010; accepted 5 Nov 2010; published 23 Nov 2010
(C) 2010 OSA
1. Introduction

Transformation optics has rapidly emerged as a new frontier in optics and materials science [1] and has resulted in far reaching new concepts such as the invisibility cloak and more recently the “carpet” cloak. The latter represents a new class of structures which are designed by the quasi-conformal mapping technique and are being investigated extensively because of their low loss and wide bandwidth characteristics. A common practice is to implement them using 2D waveguide geometries but this introduces additional constraints that limit their performance. In this paper, we present an experimental study of the dispersion characteristics of a carpet cloak implemented using a 2D nanorod array medium. It is demonstrated from wavelength dependent near-field scanning optical microscopy (NSOM) measurements and index tuning by atomic layer deposition (ALD) that waveguide dispersion significantly limits the bandwidth of the carpet cloak. These results are applicable to all transformation optics based structures implemented on a 2D thin film geometry and must be considered in the design stage to realize high performance.

In transformation optics, a suitably chosen coordinate transformation is used to deform original space and achieve the desired optical properties. The transformed space is then translated into a distribution of material parameters, permittivity and permeability, in the undistorted space, that result in the same optical properties as the transformed space. The resultant distribution of permittivity and permeability is finally implemented using meta material technologies, in which deep subwavelength scale features are used to generate the desired material parameters. The hallmark application of transformation optics is the cloak of invisibility, a structure that renders an object invisible to outside observers. While there are several different schemes of achieving invisibility [2,3], the transformation optics approach creates an invisibility cloak by opening up an electromagnetically inaccessible region with a suitable coordinate transformation [4]. Unfortunately, the invisibility cloak structure created this way often requires extreme values of optical constants and is thus very difficult to experimentally demonstrate. Many reduction schemes have therefore been proposed to simplify the design and make it more feasible [5–8]. Even the reduced cloak, however, remains difficult to fabricate due partly to the strong anisotropy required for most designs and the experimental demonstration has so far been limited to microwave frequency region. Quasi-conformal mapping provides a way to avoid this difficulty. Recently, a quasiconformal mapping based cloak design was proposed, which makes a curved reflecting surface look flat [9]. Several groups including ourselves implemented the two-dimensional (2D) version of this “carpet cloak” on silicon thin films [10–12]. More recently a three-dimensional (3D) structure was also reported [13].

The carpet cloak has attracted attention because it requires only modest values of permittivity and can be implemented with isotropic materials. This, in fact, is a general characteristic of transformation optical media created by conformal mapping based...
techniques. The use of non-Euclidean geometry in the conformal mapping approach allows one to avoid singularities in the transformed space [14,15]. This, in turn, makes it possible to implement the transformed space with non-resonant dielectric materials and thus achieve low loss operation over a broad bandwidth. This sharply contrasts with earlier transformation optics approaches which typically required the use of sub-wavelength-scale resonators in order to achieve the wide range of optical constants needed for proper implementation. The use of resonators comes at the price of severe frequency dispersion and strong absorption. The resulting structures therefore exhibit extremely narrow bandwidth of operation and large loss. This is particularly problematic for optical frequency operation where noble metals such as silver and gold are often used to create subwavelength-scale resonators based on surface plasmon resonance. However, they, like most metals, become increasing lossy in the near-infrared and visible spectrum, limiting the range of achievable optical constants. The purely dielectric structures possible with conformal and quasi-conformal mapping approach are therefore ideally suited for optical frequency operation. Naturally, there has recently been a surge in studies of this type of structures [16,17] and several novel phenomena and devices such as broadband lens [18], ray optics in the deep subwavelength scale [19], novel waveguide [20], and multifunctional devices [21] have been demonstrated. While the new possibilities the conformal mapping approach brings about are exciting, fabrication is still difficult especially for optical frequency operation, which requires nano-scale features. The most common and straightforward approach is to implement a 2D version on a thin silicon layer, taking advantage of the mature nanofabrication technologies such as electron-beam lithography and focused ion beam milling. Furthermore, the high refractive index of silicon allows the realization of fairly wide range of effective index values. The use of a 2D geometry, however, inevitably introduces additional constraints inherent to any waveguide-based devices, severely affecting their bandwidth and loss behavior.

2. Results and discussion

2.1 Silicon nanorod based carpet cloak design

We designed the carpet cloak based on silicon nanorod array for operations in the near-infrared spectrum for transverse-magnetic (TM, electric field perpendicular to the device layer) polarization. The required index profile was realized by properly varying the nanorod diameters. The silicon nanorod array was fabricated using the electron-beam lithography and reactive ion etching processes on a silicon-on-insulator (SOI) wafer consisting of a 340 nm thick single crystalline silicon device layer on top of a 1 µm thick silicon dioxide (SiO₂) over a bulk silicon substrate. The details of the fabrication process are published elsewhere [22]. The entire device region was comprised of a silicon nanorod array over a 39.6 µm x 39.6 µm area, connected to a 10 µm wide input waveguide and a small output region, as schematically shown in Fig. 1a. The input waveguide is designed to make an incident angle of 45° with the curved reflecting interface of the cloak. Covering an area of 32 µm x 12 µm, the cloak structure is made of a square array of nanorods with lattice constant of 150 nm and varying diameters. The remaining device area is composed of a square array of nanorods with a constant diameter, forming a background medium with effective refractive index of 1.8.
In this paper, we present two nearly identical cloak structures, named A and B, which are later tuned by atomic layer deposition (ALD) of thin dielectric layers. In sample A, the nanorod diameter in the cloak region was varied from the minimum value of 82 nm to the largest value of 150 nm. In the background medium, the nanorod diameter was 97 nm. In sample B, nanorod diameter was varied from 83 nm to 150 nm while it was kept at 97 nm in the background medium region. A low magnification scanning electron micrograph (SEM) showing the entire device structure is presented in Fig. 1b. Higher magnification SEMs are also shown in Figs. 1c and 1d, which reveal there is slight bridging between the largest nanorods.

To obtain effective permittivity generated by the nanorods, we first calculated the effective permittivity of the fundamental TM mode for the air-silicon-oxide slab waveguide: $\varepsilon_{\text{SOI-TM}} = 7.55$ at $\lambda_0 = 1500$ nm. In the long wavelength limit, where the nanorod diameters are sufficiently smaller than the wavelength, the effective permittivity of the nanorod array is given by the simple 2D area average of silicon and air over the 2D unit cell of the nanorod array. Such a simple 2D averaging is an approximate procedure as it does not consider the evanescent mode in the air. However, the validity of this simple averaging rule was confirmed by rigorous 3D photonic band structure calculations. The desired index profile obtained by the procedure given in Ref. 9 was implemented with a 215 x 80 square array of nanorods with various diameters. The periodicity was chosen to be 150 nm or $\lambda_0/10$ for operation at vacuum
wavelength, $\lambda_o = 1500$ nm, which corresponds to $\lambda/5.6$ inside the background medium with refractive index 1.8.

In our previous implementation [10], the cloak was matched to a background medium with refractive index 1.5. This value was very close to the bulk refractive index, 1.46, of silica lower cladding. The small index contrast between the substrate and guiding medium resulted in a weak guiding condition and consequently large propagation loss. The NSOM images reported in the previous paper [10] showed that the light intensity decreases rapidly as it propagates through the background medium. In order to strengthen the guiding condition and reduce the propagation loss, we chose to match the cloak to a background medium with a larger refractive index. In this paper, we present two cloak structures both of which are matched to a background medium with a refractive index 1.80. It should be noted that, although increasing the background medium index has the advantage of improving the light propagation through the nanorod array, it requires larger silicon rod diameters and smaller gaps between the nanorods, thereby making the fabrication much more challenging. In fact, in our previous report [10], a small sublattice in which all feature sizes were doubled was used in order to avoid having to fabricate very small gaps between nanorods. The larger feature sizes, of course, increased the risk of the effective medium theory breaking down and thus the cloak not functioning properly. In the structures presented in this paper, we eliminated the enlarged sublattice and maintained the periodicity of 150 nm throughout the structure, ensuring that the desired effective index profile was created faithfully. This was made possible by carefully optimizing the e-beam patterning and etching conditions, which are reported elsewhere [22]. This is one of the two key improvements made in the current implementation.

The carpet cloak is designed to hide objects behind a curved mirror surface and thus the curved interface should be highly reflecting. In our previous implementation, we relied on natural reflection at the interface between the nanorod array and air (estimated to be ~13%), which inevitably resulted in light leakage through the interface. This implementation greatly simplified the fabrication process but compromised the cloak performance. In order to increase the reflectivity at the nanorod array/air interface and hence improve the cloak performance, a photonic band gap (PBG) structure was added behind the cloak in the current implementation. The PBG structure is composed of 10 x 63 array of silicon nanorods with diameter 312 nm and periodicity 520 nm. This structure exhibits a band gap in the near infrared wavelengths where the experiments were conducted. It is noted that although the PBG structure has much larger rod diameters and periodicity than the cloak structure and thus cannot fit the curved interface exactly, this does not significantly affect the performance of the cloak as shown later by both numerical simulations and experiments.

2.2 Near-field characterizations

For optical characterizations, three fiber-coupled lasers tunable between 1400 and 1604 nm were used as light source. A polarization control paddle was used to set the correct polarization of the laser and the light output from the fiber was butt-coupled into the silicon input waveguide.
The light propagation through the nanorod structure was then directly visualized by NSOM. Figure 2a shows NSOM images taken over various areas from sample B. From the left, the images show, respectively, light propagating in the input waveguide, across the interface between the input waveguide and the background medium, light propagation in the background medium and finally in the cloak region. The carpet cloak is supposed to restore the specularly reflected beam off a flat mirror surface even though the actual reflecting surface is curved. The far right NSOM image in Fig. 2a clearly shows the well-collimated reflected beam just like the reflection off a flat mirror surface, directly confirming the carpet cloak is functioning properly. The observed cloaking behavior is further confirmed by the numerical modeling results obtained by the Finite-Difference Time-Domain (FDTD) simulations. As
shown in Fig. 2b, the nanorod array based cloak structure restores a well-defined single reflected beam. The intensity plot in Fig. 2b is in excellent agreement with the NSOM images in Fig. 2a. It is noted that the far right image is slightly enlarged compared to the other images in Fig. 2a in order to clearly show the definition of the reflected beam in the cloak region. It can be observed from the NSOM images in Fig. 2a and simulation result in Fig. 2b that the reflected beam has a higher intensity core and appears to be narrower than the input beam. Further investigations using FDTD simulations reveal that the introduction of air gap between the curved interface of the cloak and PBG structure results in narrowed reflected beam width. The discretization of curved interface also contributes to this. Also, we note that the simulation and experimental results for the curved interface without carpet cloak have been reported in our previous publication in Ref. 10.

Fig. 3. (a) A schematic of the device structure showing the area from which the NSOM images were taken. (b) NSOM images taken from sample A at various wavelengths and laser power levels. (c) NSOM images taken from sample B at various wavelengths and laser power levels.

As mentioned earlier, one of the greatest advantages of conformal mapping based transformation optics structures is that they can be implemented with non-resonant dielectric materials and therefore exhibit low loss and broad bandwidth of operation. The carpet cloak presented in this paper should, in principle, be capable of low-loss and broadband operation. However, the 2D implementation on SOI wafer imposes the waveguide dispersion inherent to any devices based on a waveguide geometry. This is illustrated in Fig. 3 where NSOM images taken over the cloak region at various wavelengths are presented. As shown in the schematic in Fig. 3a, the scanned area is the cloak region including the curved reflecting interface in the upper right side. Therefore, in all of the images, the light is incident from the bottom, reflected off the curved interface and then propagates towards the left. As shown in Figs. 3b and 3c, samples A and B display almost the same behavior. At shorter wavelengths, strong and well-defined reflected beams are observed. However, as the wavelength is increased, the light intensity decreases. Only a very faint beam is observed at 1520 nm and no light is detected at longer wavelengths. This is the characteristic behavior expected near waveguide cut-off. To model the waveguide dispersion for the background medium, the commercial finite element solver COMSOL was used to calculate the effective index of the slab waveguide mode and the cut-off wavelength was obtained from the plot of the slab effective index as shown in Fig. 6. The cut-off wavelength can also be calculated analytically and the analytical results agree well with those obtained from COMSOL. The cut-off wavelengths for samples A and B were found to be 1600 nm and 1575 nm, respectively. These values are consistent with the experimental observation that the NSOM signal is lost beyond 1520 nm.

2.3 Dispersion engineering by atomic layer deposition

To confirm that the cut-off behavior observed in Fig. 3 was indeed caused by waveguide dispersion and also to investigate if the operating wavelength range could be extended to longer wavelengths, we deposited a 5 nm thick TiO$_2$ layer on sample B and a 10 nm thick
TiO$_2$ layer on sample A using the ALD technique. The details of ALD process have been published elsewhere [23,24]. ALD provides highly uniform and conformal deposition with precise thickness control. Figure 4 shows SEM images taken after the TiO$_2$ depositions by ALD and confirm the formation of highly conformal overlayers of TiO$_2$ with thicknesses of 5 nm and 10 nm, respectively.

![SEM micrographs of (a) sample B conformally coated with 5 nm thick TiO$_2$ layer and (b) sample A coated with 10 nm thick TiO$_2$ layer.](image)

We then performed NSOM on the TiO$_2$ coated samples. Figure 5 shows the NSOM images taken at various wavelengths. The laser power level was kept constant at 10 mW in all measurements. The scanned area was the same as the one in Fig. 3. The 10 nm TiO$_2$ coating significantly increased the cut-off wavelength and, as shown in Fig. 5a, strong and well-collimated reflected beam was observed throughout the entire tuning range of our lasers. For the case of 5 nm TiO$_2$ coating, the effect was less strong. As shown in Fig. 5b, a well-defined reflected beam was observed at 1520 nm but began to diminish as the wavelength was further increased. At 1604 nm, only a very faint reflected beam was detected, similarly to the 1520 nm NSOM image of the uncoated sample. These behaviors are readily understood by considering the cut-off condition for the nanorod array medium. The cut-off condition in a waveguide is reached when the waveguide effective index becomes equal to the cladding index. For a given core index, the guided mode effective index decreases with increasing wavelength because the light spreads more into the cladding which has a lower index than the core. At the cut-off wavelength, the light begins to propagate into the cladding and thus the waveguide no longer supports guided mode. Naturally, the cut-off wavelength will be longer when the core index is higher. In our experiments, the conformally coated TiO$_2$ layers increased the dielectric volume within the unit cell. This, consequently, increased the effective index of the nanorod medium, thereby increasing the cut-off wavelength. For 5 nm thick TiO$_2$ coated sample, the increase in the effective index was small and thus the cut-off wavelength shifted only modestly. The 10 nm thick TiO$_2$ coating resulted in larger increase in effective index and consequently greater shift in the cut-off wavelength.
Fig. 5. NSOM images taken over the cloak region at various wavelengths for (a) sample A with 10 nm TiO$_2$ coating and (b) sample B with 5 nm TiO$_2$ coating. The laser power was constant at 10 mW for all measurements.

For quantitative analysis, we computed the effective index of the guided mode in the background medium for samples A and B with and without TiO$_2$ coating. As shown in Fig. 6, before TiO$_2$ coating, both samples A and B exhibited cut-off near 1.6 μm. This means the input light cannot reach the cloak region at wavelengths greater than ~1.6 μm which is consistent with the experimental observations that an NSOM signal could only be detected up to 1520 nm, as presented in Fig. 3. When TiO$_2$ coating was applied, the additional dielectric layer increased the effective index of the nanorod medium and hence increased the cut-off wavelength. As shown in Fig. 6, a 10 nm TiO$_2$ coating was found to increase the cut-off wavelength to 1.80 μm while a 5 nm TiO$_2$ coating resulted in a cut-off wavelength of 1.67 μm. Again, the dispersion characteristics were consistent with the experimental observations. For sample A with a 10 nm TiO$_2$ coating, the cut-off wavelength was far enough removed from 1604 nm, the edge of our laser tuning range, to exhibit good cloak performance throughout the entire tuning range. For sample B with a 5 nm TiO$_2$ coating the increase in effective index was correspondingly smaller and only a modest increase was observed in the cut-off wavelength. Therefore, at 1575 nm, we began to see a significant decrease in light intensity in the NSOM measurements. At 1604 nm, very little intensity was left in the reflected beam because it was already very close to the cut-off wavelength. ALD coating of TiO$_2$ also changes the effective index profile of the cloak region and could lead to consequent deterioration in cloak performance. However, this effect is not severe in the wavelength range we investigated as the cloak (sample A) still functions normally at 1604 nm as seen in Fig. 5. The major effect of ALD coating is the extension of the cut-off wavelength as seen from the results in Fig. 5.
In addition to introducing cut-off, the waveguide dispersion should also cause deviations in the refractive index profile from the original design values as the wavelength is changed. For example, a nanorod with a diameter 97 nm fabricated on a 340 nm thick SOI wafer should exhibit an effective refractive index of 1.8 at $\lambda_0 = 1500$ nm. The effective index value, however, changes to 1.9 at $\lambda_0 = 1300$ nm and 1.7 at $\lambda_0 = 1700$ nm. It is quite remarkable that despite significant dispersion the current cloak structures function properly throughout the 200 nm tuning range of our experiment. This robustness is one of the strengths of conformal mapping based transformation optics devices. However, waveguide dispersion will at some point begin to compromise the proper cloak operation, defining the upper bound of the frequency bandwidth of the cloak operation.

3. Conclusions

In conclusion, we have presented experimental studies on the dispersion characteristics of a silicon nanorod based carpet cloak structure. Created by quasiconformal mapping, the carpet cloak can be implemented by isotropic dielectric materials, enabling broadband and low-loss operation in the optical frequency region. However, nanorod based carpet cloak designs were
shown to display strong wavelength dependence which was directly visualized by NSOM in the near-infrared frequency region. The wavelength dependence is attributed to waveguide dispersion, which is unavoidable in any 2D geometry. Conformal mapping approach in the transformation optics provides an efficient way to design and implement novel optical devices in the optical frequency range, which are commonly fabricated on a high index semiconductor thin film by the electron-beam lithography or focused ion beam milling. However, whenever a 2D geometry is employed, waveguide dispersion must be properly taken into account to predict and analyze device performance. Since the conformal mapping based design provides potentially very wide bandwidth and low loss, waveguide dispersion and radiation loss will be the major limiting factors in these structures.

Acknowledgements

The authors would like to thank the staff of the GT MIRC for their assistance and support in the fabrication effort outlined in this publication. The work at University of Colorado was supported in part by the National Science Foundation (BES0608934) and Army Research Office (MURI contract 50432-PH-MUR).