A Carpet Cloak for Visible Light

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ABSTRACT: We report an invisibility carpet cloak device, which is capable of making an object undetectable by visible light. The cloak is designed using quasi conformal mapping and is fabricated in a silicon nitride waveguide on a specially developed nanoporous silicon oxide substrate with a very low refractive index (n<1.25). The spatial index variation is realized by etching holes of various sizes in the nitride layer at deep subwavelength scale creating a local effective medium index. The fabricated device demonstrates wideband invisibility throughout the visible spectrum with low loss. This silicon nitride on low index substrate can also be a general scheme for implementation of transformation optical devices at visible frequencies.

KEYWORDS: Optical metamaterials, invisibility cloak, transformation optics, nanofabrication

Invisibility cloaks, a family of optical illusion devices that route electromagnetic (EM) waves around an object so that the existence of the object does not perturb light propagation, are still in their infancy. Artificially structured materials with engineered EM properties, known as metamaterials,1,2 have been used to control the propagation of EM waves. Metamaterials have been applied to cloaking using the transformation optics design methodology3 to control the propagation of optical4 and more recently plasmonic5–8 waves. The invariance of Maxwell’s equations under coordinate transformation3 allows the space to be reshaped such that the light can propagate in the desired manner. Such transformations usually require EM properties with extreme values that are only achievable in metallic metamaterials and have been experimentally demonstrated for cloaking at microwave frequencies.12,13 Because of the significant metallic loss at optical frequencies, the implementation of invisibility cloaks for visible light has been difficult. Recently another innovative strategy was developed based on exploiting uniaxial crystals.14,15 These devices have demonstrated cloaking in visible frequencies for a certain polarization of light based on intrinsic anisotropy in the crystals.

As an alternative, conformal mapping,16 in which an inverse transformation of the electrical permittivity and magnetic permeability leads to a spatially variable refractive index profile, can be applied to cloaking.17 A two-dimensional (2D) quasi conformal mapping (QCM) technique can be employed to numerically minimize the anisotropy in the index profile which results from the optical transformation. 2D QCM is the basis for the carpet cloak,18 in which an object is hidden under a reflective layer (the carpet). To achieve cloaking, the raised protrusion (the bump) created in the reflective layer is mapped to a flat plane and the resulting 2D index profile forms a carpet cloak device. In contrast to resonant optical structures,19,20 QCM carpet cloak provides a broadband loss-less design and may be invariably extended in the third dimension with some limitations,21 experimentally demonstrated to operate for a range of viewing angles.19 The relatively modest material requirements dictated by QCM enabled the implementation of the cloaking devices in the infrared20,21 using a silicon waveguide. The index variation in these systems is realized through a spatial modulation of the filling fraction of dielectrics at subwavelength dimensions, providing a weighted average index according to the effective medium approximation.

At shorter wavelengths however, devices reported so far suffer from significant scattering from surfaces within a unit cell as the feature sizes become comparable to wavelength. More importantly, the silicon device layer employed in the infrared becomes lossy due to absorption at visible frequencies. To realize cloaking at visible frequencies, the unit cell size must be reduced and a new material system is required that provides both transparency and sufficient index contrast. We demonstrate here a visible light carpet cloak device made of silicon nitride on a specially prepared nanoporous silicon oxide with very low index of <1.25. This unique substrate increases the available index modulation and enables the implementation of transformation optics for guided visible light.

The optical transformation is designed so that a bump centered at the origin and defined analytically as $y = h \cos^2(\pi x/w)$ with a height $h$ of 300 nm and a width $w$ of 6 μm is compressed in the $y$ direction (inset of Figure 1a). QCM of the transformed space results in the relative index variation shown in Figure 1a. The smallest index values occur at the corners of the bump and the maximum index appears around the top of the curved region.

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Image 421x453 to 546x553
We report an invisibility carpet cloak device, which is capable of making an object undetectable by visible light. The cloak is designed using quasi conformal mapping and is fabricated in a silicon nitride waveguide on a specially developed nanoporous silicon oxide substrate with a very low refractive index (n<1.25). The spatial index variation is realized by etching holes of various sizes in the nitride layer at deep subwavelength scale creating a local effective medium index. The fabricated device demonstrates wideband invisibility throughout the visible spectrum with low loss. This silicon nitride on low index substrate can also be a general scheme for implementation of transformation optical devices at visible frequencies.
Away from the bump, the index converges to the relative background index of 1. The actual index variation $\Delta n$ and the background index in the final device depend on the materials used. Figure 1b shows the index modulation and the substrate index required to achieve cloaking, highlighting the requirements to implement the carpet cloak in the visible spectrum. It is important to note that the silicon oxide substrate index fails to provide enough contrast for waveguiding at visible frequencies. To achieve the required index contrast, we consider silicon nitride (SiN) waveguide on a specially developed low index substrate made from nanoporous silicon oxide. The inset in Figure 1b shows the approximate unit cell size requirement for the scattering-free operation of the effective medium. In order for the device to operate throughout the visible spectrum, feature sizes should be on the order of 65 nm half pitch.

In visible frequencies, our SiN has a bulk refractive index of approximately 1.9 and the nanoporous silicon oxide substrate has an exceptionally low refractive index of $\sim1.25$ and both are transparent. To modulate the index of the SiN waveguide, variable-sized holes were drilled in a 2D hexagonal lattice with 130 nm pitch, thereby changing the filling fraction of air/SiN mixture. A waveguide thickness of 300 nm is chosen to achieve single mode propagation while maintaining sufficient index contrast for strongly confined modes at longer wavelengths. This will result in the fundamental transverse electric mode index varying from 1.83 to 1.74 for wavelengths of 400 nm to 700 nm. Thus the background index calculated for the transformation in Figure 1a was projected to approximately 1.5. Figure 2a shows a cross-sectional schematic of the device with the hole size pattern generated to achieve the required index modulation. As expected, the largest holes are located at the corners of the bump and the smallest holes appear right above the peak of the bump. Additionally, an area of constant hole size surrounding the cloak device is required to provide a uniform background index.

The device fabrication process begins with the preparation of the low index substrate. A crystalline silicon wafer is electrochemically etched in an acid/organic (1:1 hydrofluoric acid/ethanol) solution to produce a porous network that penetrates several micrometers into the top surface. The porosity of this network is increased by oxidizing several atomic layers of silicon.
on the internal surfaces at 300 °C and subsequently removing this oxide layer by selective etching. By repeating the oxidation and etching several times, the solid silicon is slowly consumed, leaving solid filling fractions as low as 15%. Once the desired porosity is reached, the entire silicon network is converted to a porous silicon oxide medium by oxidizing at high temperature (800 °C). Because of expansion during oxidation, the resulting medium turns into an approximately 65% porous glass, where the pores range in size from 2 to 20 nm (shown in the inset of Figure 2a). The resulting substrate has a refractive index below 1.25, as confirmed by optical interference measurement in the near-infrared, and has a smooth surface with roughness less than 3 nm rms. A 300 nm SiN slab waveguide is deposited on the low index substrate using plasma-enhanced chemical vapor deposition (PECVD).

To fabricate the hole pattern introduced in Figure 2a, we use a two step pattern transfer process. The waveguide is first covered with a 100 nm thick PECVD silicon oxide to act as a hard mask for etching. ZEP520A electron beam resist is then spun on the oxide layer with a thickness of 120 nm, and the generated hole pattern is written on the resist by electron beam lithography. Figure 2b shows an atomic force microscope (AFM) image of the developed resist with the hole sizes varying from 65 to 20 nm. The resist is used as a mask to transfer the pattern to the 100 nm oxide layer by reactive ion etching (RIE). The resist is then ashed and the pattern is transferred to the nitride waveguide using a selective RIE process, followed by removal of the oxide mask. A low pressure (18 mTorr) RIE etch was developed for directional pattern transfer to the nitride, for which close to 90° sidewall was confirmed by cross sectional imaging. Figure 2c shows an overall scanning electron microscope (SEM) image of the fabricated structure excluding a triangular region defining the background index. To achieve a reflective bottom plane for the device, the area under the bump is opened to the edge of the die using focused ion beam (FIB) milling. The structure is then mounted at 90° to the experimental results shown in Figure 4c, the reflection from the mirror in the ultraviolet region. Also, the waveguide confinement of the beam reduces the mode index, creating a waveguide cutoff in the infrared. Although the waveguide test structure and coupling gratings were designed for demonstration of the cloaking effect using light with transverse electric polarization, in principle the QCM transformation applies for both polarizations.8,19,20

Figure 3. (a) Optical characterization setup; the half-wave plate rotates the polarization of the laser output as desired; the out-coupled light polarization is rotated 90° due to the reflection from the mirror in the sample, and the output polarizer is used to partially filter out the scattered input beam. Inset shows an SEM image of the gratings; the area behind the cloak has been etched by FIB and a silver layer has covered the back of the bump. (b) Dark-field image of the cloak device with the input and output gratings. The input grating and beam path are highlighted by the green circle and the green arrows respectively. (c) Dark-field image of the in coupling laser and the out-coupled light. The yellow dashed triangle defines the region containing the cloak. The red dashed rectangle indicates the out-coupling grating, which is the region of interest for the results presented in Figure 4.
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