Scattering reduction at near-infrared frequencies using plasmonic nanostructures

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Abstract: Novel fabrication, detection and analysis approaches were employed to experimentally demonstrate scattering reduction by a plasmonic nanostructure operating at 1550 nm. The nanostructure consisted of a silicon nanorod surrounded by a plasmonic metamaterial cover comprised of eight gold nanowires and was fabricated by a combination of electron beam lithography, focused ion beam milling and dry and wet etching. The optical standing wave pattern of the device in the near-field was obtained using heterodyne near-field scanning optical microscopy. It was found that the spatial curvature of the interference fringes of the optical standing wave pattern was directly related to the scattering reduction of the device. The experiments were in excellent agreement with the theoretical predictions and suggested that the device reduced the scattering by 9.5 dB when compared to a bare silicon nanorod of diameter 240 nm and by 6 dB when compared to a bare silicon nanorod of diameter 160 nm.

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OCIS codes: (250.5403) Plasmonics; (180.4243) Near-field microscopy; (220.4241) Nanostructure fabrication; (290.5820) Scattering measurements; (160.3918) Metamaterials.

References and links

1. Introduction

Recent advances in artificially structured materials and nanofabrication techniques have helped the scientific community realize a variety of invisibility cloaking devices designed using different techniques such as conformal mapping [1,2], quasi-conformal mapping [3–6], scattering cancellation [7,8], transmission line networks [9,10] and anomalous resonances [11,12]. Among them, the scattering cancellation scheme attempts to significantly reduce or completely nullify the scattering cross-section of an object by covering the object with a thin layer of plasmonic material. Since the dielectric core and plasmonic cover have oppositely signed permittivity, they would have mutually opposite dipole moments when illuminated by external light. If the scattering is dominated by the dipole component and the plasmonic cover is designed in such a way that the induced dipole moment exactly cancels that of dielectric core, then there will be no scattering of light, rendering the object invisible to external observers. In this regard, the plasmonic cover may be called an invisibility cloak, although in this scheme the cloak design is highly dependent on the shape and dielectric properties of the object to be cloaked. Also, the condition that the scattering is dominated by dipole moment requires that the entire structure is small compared to the wavelength.

Recently, it was shown that the dominant dipolar contribution to the scattering from a spherical or cylindrical dielectric object could be greatly reduced when coated by a layer of material with negative or very low values of real part of permittivity [8]. It was also shown that the higher order modes could be suppressed albeit substantially more complex design has to be used. Later the theory was extended from isolated spherical or cylindrical objects to collections of closely spaced particles with net size larger than the wavelength of light [13]. This technique is inherently non-resonant and the operational bandwidth of the plasmonic cloak can be quite broad and limited only by the material dispersion of plasmonic cover. It was shown that the operational bandwidth could be further extended by use of multiple layers of plasmonic covers [14]. Recently, cylindrical objects coated with plasmonic covers were studied under broadband non-monochromatic illumination and the cloak performance was evaluated [15]. The scattering cancellation technique has been extended to study plasmonic cloaking of irregularly shaped objects with anisotropic scattering properties [16]. It has also been theorized that instead of covering an object with a plasmonic cloak, similar scattering reduction could be obtained by surrounding the object with suitably designed discrete satellite plasmonic scatterers making the entire system of particles invisible to an observer [17]. Potential applications of plasmonic cloaking include cloaked sensors [18], cloaked near-field probes [19,20] and reduction of optical forces exerted on plasmonic cloaks [21].

For implementation, a natural choice for plasmonic material is a metal, which exhibits negative permittivity values at frequencies below its plasma frequency. However, in the infrared and lower frequency region, most metals tend to exhibit large negative permittivity values. Consequently, an unrealistically thin layer is required to cancel the dipole moment of a dielectric object whose permittivity is typically a small positive number. At optical frequencies, commonly used plasmonic materials are noble metals such as gold and silver. These materials have a negative real part of permittivity at wavelengths above their plasma wavelength. Hence, a sufficiently thin film of these materials could directly be used as a plasmonic cover at visible wavelengths. However, for operation at 1550 nm at which the experiments were conducted, the required thickness would be less than 5 nm. This is extremely difficult to achieve because the natural tendency of crystallization leads to non-continuous, particulate films at these small thicknesses. Hence, suitable plasmonic nanostructures need to be engineered. To achieve effective scattering cancellation, an artificial structure, often referred to as metamaterial, can be used. It has been proposed to use parallel plate metamaterial structures to achieve plasmonic cloaking at both microwave and optical frequencies [22, 23]. It has also been proposed to use concentric shells made up of thin layers of different materials [24, 25] or a shell of nanoparticles [26–28] to surround a spherical or cylindrical object. Experimentally, plasmonic cloaking of a cylindrical object using parallel plate metamaterials in two-dimensional waveguide geometry was demonstrated...
at microwave frequencies [29]. Recently, plasmonic cloaking of a finite cylindrical object in free space was experimentally demonstrated at microwave frequencies [30]. More recently, the scattering cancellation theory was applied to design and demonstrate an invisible metal-semiconductor based detector in the optical frequency range [31]. In this paper, we present an experimental demonstration of scattering reduction by use of plasmonic cover at optical frequencies. In this work, the scattering by a cylindrical object was reduced by a plasmonic metamaterial cover made up of gold nanograting structure. The structure was fabricated using a combination of photolithography, electron beam (e-beam) lithography, focused ion beam (FIB) milling and wet and dry etching.

In addition to the constraints on design imposed by the choice of plasmonic material, the choice of characterization technique also guided the design of the scattering reduction device. In particular, the device was designed in two-dimensional waveguide geometry such that it was amenable to near-field measurements using the Heterodyne-NSOM (HNSOM). Near-field optical microscopy (NSOM) is a powerful technique to map the local fields within photonic devices with a deep sub-wavelength spatial resolution thereby giving insights into the physics of the devices. Due to the sub-wavelength dimensions of the scattering reduction (SR) structure and because the SR structure was designed to reduce scattering for in-plane propagating light only, NSOM is an apt technique to characterize the optical response of the device. Ideally, the most straightforward way to demonstrate scattering reduction is to directly measure scattered light intensity from the device and a control sample. However in many experiments, such a direct comparison of scattered intensity in the far field is simply not possible, like for example, with the waveguide-based devices such as ours due to the inevitable errors introduced by the in- and out-coupling and out-of-plane scattering. Furthermore, it is well known that absolute measurements of intensity are difficult to achieve in the NSOM technique due to the well documented artifacts [32–34]. In addition, in NSOM systems using aperture probes for light collection/illumination, due to the variation of probe collection efficiency [35,36], the measured light intensity could not be compared between multiple samples and probes reliably. Therefore, we search for an alternative technique to characterize the scattering by nanostructures such as the scattering reduction device proposed here. In this work the scattering reduction of the device was estimated by analyzing the curvature of the interference fringes obtained experimentally. It was found that the curvature of the fringes were directly relatable to the scattering cross-section of the device and thereby an accurate estimation of the spatial characteristics of the interference fringes due to the device could be used in conjunction with numerical simulations to evaluate scattering reduction due to the device. Previously, the NSOM technique has been used to obtain high spatial-resolution optical standing wave patterns so as to characterize the whispering gallery modes in microspheres [37], measure dispersion in transmission lines [38], optical waveguides [39], and photonic crystal waveguides [40] among others. In this work, the optical responses of the structure as well as a control sample of bare cylinder with no plasmonic cover were directly visualized using heterodyne near-field scanning optical microscopy (HNSOM) at 1550 nm. The measured characteristics were found to agree well with the simulated results thereby validating the design principle and the present implementation. The novel analysis and fabrication techniques could be useful to further the design, implementation and characterization of such nanophotonic devices.

2. Design and fabrication of scattering reduction device

2.1 Design

We designed a cylindrical scattering reduction (SR) device, based on scattering cancellation theory for operation at 1550 nm for transverse magnetic (TM, electric field perpendicular to the waveguide plane) polarization in a two-dimensional waveguide geometry. The structure was fabricated on a silicon-on-insulator (SOI) wafer consisting of a 340 nm thick single crystalline silicon layer on top of a 1 µm thick silicon dioxide (SiO₂) over a bulk silicon substrate. We designed the plasmonic metamaterial as a gold nanograting structure fabricated
around the circumference of the cylindrical object with a diameter of 185 nm, as shown in Fig. 1.

The grating structure consisted of eight gold nanowires equally spaced around the cylinder and surrounded by 20 nm thick silicon dioxide. The height of the grating structure was fixed at 340 nm by the thickness of the silicon layer. The effective permittivity of the gold grating structure and thereby the operating wavelength of the SR device could be tuned by varying the gold width, thickness or the circumferential periodicity of the gold nanograting structure. Considering the fabrication constraints, we finally chose a design comprised of 8 equally spaced gold nanowires, each of which was 13 nm thick (radial dimension) and 20 nm wide (circumferential dimension).

Fig. 1. Schematic of the entire structure showing the 10 µm wide input waveguide and the scattering reduction device structure located 5 µm from the waveguide edge. The device consisted of a silicon rod surrounded by a gold nanograting structure made of eight equally spaced gold nanowires and both the silicon rod and the gold grating structure were encapsulated in a 20 nm thick layer of silicon dioxide. A 370 nm thick layer of SU8 photoresist was coated over the entire structure and served as the background medium. The legend indicates the materials represented by the various colors.

2.2 Fabrication

Fabrication involved a complex sequence of photolithography, e-beam lithography, localized FIB milling and sputtering with extremely precise alignment, and dry and wet etching. Fabrication details are provided in the Fabrication Methods section (section 2.3). The most challenging procedure was the fabrication of the gold nanograting structure. For this, the sidewall of the silicon rod had to be isotropically coated with 13 nm thick gold film which was subsequently patterned into nanowires to form the required nanograting structure. This required a creative combination of unconventional metal deposition, FIB milling, localized sputtering by FIB, and wet etching, as schematically shown in Fig. 2(a). First, a 13 nm thick gold layer followed by a 10 nm thick chromium layer was evaporated onto the fabricated silicon rod. All exposed surfaces including the sidewall of the silicon rod were coated uniformly with thin gold and chromium films, since the sample was mounted on an off-axis rotating stage during evaporation. The thicknesses of the gold and chromium films on the sidewall were carefully measured and confirmed to be 13 nm and 10 nm, respectively, by comparing the silicon rod diameters before and after metal evaporation. Here, the chromium
layer was added to prevent deformation or melting of gold nanowires during the FIB milling. Since chromium has much higher melting temperature and mechanical hardness than gold, the presence of chromium overlayer made it much easier to define nanostructures using FIB milling. Furthermore, the chromium etchant CR7S could selectively remove chromium, while preserving the gold nanostructures, silicon core and silicon dioxide substrate.

After the gold and chromium deposition, the eight equally spaced gold nanowires were fabricated by directly milling with FIB from top to bottom. It was challenging to make the eight equally spaced FIB cuts in such a tightly squeezed space along the circumference of the rod with a diameter of only 185 nm. The stability of the FIB specimen stage, ion beam stigmation and focus, ion-beam current and milling time had to be controlled with extreme precision. Also, since the milling was done from top to bottom, the upper part of the gold-coated silicon rod was exposed to the ion beam for longer time. This resulted in overmilling of the top part compared to the bottom part, leading to a slightly tapered shape for both the silicon rod and the coated gold nanowires. In order to minimize the tapering of silicon rod and gold nanowires, the ion beam exposure had to be carefully optimized. Figure 2(b) shows the overview of the entire structure including the input waveguide and the SR structure. Figure 2(c) shows the 52°-tilted view of the SR structure after FIB milling, revealing the chromium overcoated gold nanograting structure on the sidewall. Figure 2(d) is the top view of the same structure. Again, the gold nanograting structure on the sidewall is clearly visible. Figure 2(e) shows the top view SEM image of the SR structure after the chromium overlayer was etched and gold nanograting on the sidewall was coated with silicon dioxide protective layer for subsequent etching of gold films on the top surface of the silicon rod and on the silicon dioxide substrate surface. The SEM images, Fig. 2(c) in particular, clearly show the top part of the silicon rod and gold nanowires was milled more than the bottom part. It was difficult to determine the exact dimensions from these images because both the gold nanograting and the sidewall of silicon rod were tapered by the FIB process. We therefore determined the range of the structural parameters from the SEM images and used numerical simulations to identify the dimensions that best fit the experimental data, as described in the following.

2.3 Fabrication methods

The SR structure was fabricated by a combination of photolithography, electron beam lithography, focused ion beam milling, localized silicon dioxide sputtering by FIB and dry and wet etching. The fabrication starts with a silicon-on-insulator (SOI) wafer with top silicon thickness of 340 nm and buried oxide thickness of 1 μm. Silicon input waveguide and alignment marks were patterned by photolithography by using AZ P4210 photoresist. After developing the photoresist, 100 nm thick chromium was evaporated and the pattern was transferred to the chromium layer by lift-off process. By using the chromium alignment marks fabricated by the photolithography, e-beam lithography was carried out and the silicon rod pattern with 185 nm diameter was placed precisely 5 μm away from the edge of the input waveguide end. After developing electron beam resist PMMA A2, chromium (20 nm) was evaporated and the pattern was transferred again by lift-off process. With the chromium layers as the etching mask, the silicon waveguide and the silicon rod were fabricated concurrently by reactive ion etching of silicon with CF\textsubscript{4}/O\textsubscript{2} gas. Then chromium etch mask was completely removed by CR7S chromium wet etchant. Subsequently, a 13 nm thick gold layer followed by a 10 nm thick chromium layer was evaporated onto all surfaces include the sidewall of the silicon rod by using a metal evaporator equipped with off-axis rotating sample mount. Gold grating structure was then fabricated by top to down FIB milling and subsequently the protective chromium layer was selectively removed by CR7S chromium etchant, leaving gold nanograting structure along the sidewall of silicon rod. The FIB based localized sputtering was carried out to deposit silicon dioxide only on the sidewall of the silicon rod, completely covering the gold nanograting structure. Subsequently, gold wet etching was performed to remove all gold films other than the grating structure on the side wall protected by the sputtered silicon dioxide. Finally, 370 nm thick SU-8 was coated everywhere to provide a waveguide medium.
Fig. 2. (a) Schematic illustration of the fabrication process of the SR structure. (b) 52° tilted view SEM image of the SR structure and flat end silicon input waveguide. (c) High magnification SEM image of FIB milled SR structure in 52° tilted view. (d) top view SEM image of the SR structure after FIB milling. (e) top view SEM image of the SR structure after localized silicon dioxide sputtering on the sidewall of the silicon rod.
3. Results and discussions

3.1 Extraction of parameters

Analysis of SEM images of the fabricated SR device revealed variations of the silicon rod diameter and gold nanowire width along the sidewall of the device. The silicon rod diameter and gold nanowire width were measured to be 150 nm and 18 nm at the top of the device and estimated to be 166 nm and 55 nm at the bottom. We then conducted two-dimensional numerical simulations using effective index of guided modes [41] and determined that 160 nm for the silicon rod diameter and 20 nm for the gold nanowire width were the most appropriate average values. More information about the fabricated structures, their dimensions and choice of average structural parameter values are provided in the appendix. All numerical simulations were performed using the commercial finite-element solver COMSOL. The effective refractive index of the 370 nm thick SU8 layer was experimentally measured using the HNSOM to be 1.48 and was used in the two-dimensional numerical simulations. The dielectric constants of bulk silicon and gold were obtained from [42] and [43], respectively. The optical properties of silicon in the two-dimensional geometry were described by the effective index for the TM_{01} mode which was obtained from numerical simulations.

First, the scattering cross-sections (SCS) were calculated for SR devices with constant silicon rod diameters and gold nanowire widths and plotted in Fig. 3(a) in units of meters with the y-axis plotted in logarithmic scale. The numerical simulation used 160 nm for the nanorod diameter, 20 nm for the gold nanowire width and 13 nm for the gold nanowire thickness. In addition to the SCS of the SR devices, the SCS of the bare rods with diameters 160 nm and 240 nm are also plotted in Fig. 3(a) for comparison. Here we chose a diameter of 240 nm for the bare rod because that was the dimension of fabricated reference sample. The actual physical size of SR structure before FIB milling was 211 nm (185 nm silicon rod + 13 nm gold coating). The difference in calculated SCS values between 211 nm and 240 nm silicon rods was 15%, which was much smaller than the scattering reduction achieved by the SR device. It is therefore considered the 240 nm rod is appropriate as reference. As shown in the figure, the SR structure is expected to reduce the scattering by at least 4 times (roughly 6 dB) across the wavelengths range of 1300 ~1700 nm, with a maximum scattering reduction of about 21 dB (roughly 128 time scattering reduction) at 1380 nm. Figures 3(b) and Fig. 3(c) plot the z-component of electric field, |E_z|, at 1550 nm for the SR structure and the bare rod, respectively. The fringes caused by the interference between the incident plane wave and scattered cylindrical wave are clearly seen. The fringes have different curvatures due to the effect of plasmonic cover and also the fringes are less clear in Fig. 3(b) than in Fig. 3(c) due to the reduced scattering by the SR structure.

3.2 Description of analysis technique

As mentioned previously, it is possible to accurately determine the spatial features of the interference fringes using HNSOM. We therefore evaluated the scattering reduction by comparison of key fringe features such as fringe periods and fringe curvature between the SR structure and bare rod samples. In order to justify the validity of this approach, we first establish a clear relationship between SCS and spatial parameters of the interference fringes as the latter could be measured very accurately by HNSOM. Because the interference fringes were formed by the sum of the incident wave and the scattered wave, the spatial features of the fringes are undoubtedly related to SCS. The question is whether SCS can be expressed as a single-valued function of some spatial features of the fringe pattern so that we can determine SCS from the measured fringe pattern. We found that the curvature of the first fringe was an excellent parameter to establish this relationship. To substantiate this claim, we first present a model case of silicon core coated with lossless cover. Analytical calculations using the Mie theory were carried out to obtain the SCS for a silicon rod with diameter 185 nm and coated with a 13 nm thick cover with purely real permittivity. The refractive index of
the background medium was fixed at 1.48 and the calculations were performed for the TM polarization of incident light at a fixed wavelength of 1550 nm.

From these calculations, we extracted the $|E_z|$ field profile and the curves of the first fringe for various cover permittivity values. The curvature $C$ (in units of $m^{-1}$) value was then obtained for each fringe curve at a distance 1 μm from optic axis along the vertical direction (y-direction), as indicated in Fig. 4(d). Plotted in Fig. 4(a) is the SCS of the coated rod, normalized to the SCS (in units of dB) of the bare silicon rod with diameter 240 nm, as a function of the cover permittivity. Figure 4(b) plots the curvature as a function of the cover permittivity over the same range as in Fig. 4(a). Figures 4(a) and 4(b) are then combined into Fig. 4(c) which shows the normalized SCS as a function of the fringe curvature. It can be seen clearly that the SCS is a single-valued function of the fringe curvature and consequently one could determine the SCS by measuring the curvature. This analysis clearly illustrates our rationale of using the spatial information of the fringes to characterize the scattering properties of the SR device. In the realistic structure with complex cover permittivity, analysis becomes more complicated but, as shown later, similar single-valued relationship can be established between SCS and curvature. The plots in Fig. 4(a-c) have been color coded to indicate values of cover permittivity below (red) and above (black) the best matched condition which results in the peak value of normalized SCS. Also, Figs. 4(b) and 4(c) has discontinuities because at the best matched condition the scattering is canceled so much that the fringes are not discernable.

3.3 NSOM measurements

The optical responses of the fabricated SR structure and the bare rod were directly visualized using the HNSOM at 1550 nm. The HNSOM was built around the commercial NSOM head Multiview-2000 from Nanonics. Further details on the HNSOM may be found elsewhere [44] and the details of our measurements are given below. For optical characterization, a fiber coupled laser operating at 1550 nm was used as the light source. A polarization control paddle
was used to set the correct polarization of light and the light was butt-coupled into the input silicon waveguide using an optical fiber. The HNSOM scanning process consisted of three steps. First, the tip oscillation amplitude and phase were set. Then, a section of the 10 μm input waveguide very close to the bare rod or SR device was scanned to verify the proper alignment between the fiber and input waveguide. In the final step, the evanescent field in the SU8 background medium over the desired scan area was directly recorded by metallized cantilevered apertured NSOM probes. The output of the NSOM probe was interfered with a frequency shifted reference to obtain a beat signal which was detected using an InGaAs detector. Different probes with varying aperture diameters were used in the HNSOM experiments leading to variations in probe collection efficiency among various scans.

![Figures 4](#)

Figures 5 show the amplitude (|E_z|) of the measured electric field at 1550 nm for the SR device and the bare rod. Figures 5(a, c) plot the measured |E_z| for the bare rod and SR device, respectively, over an area of 30 μm X 30 μm including both the SR structure (or bare rod) and the edge of the input waveguide. For both scans, the same NSOM probe with aperture diameter 200 nm was used, the lateral resolution was fixed at 200 nm, and the output power of the laser was kept constant at 10 mW. Figure 5(b) shows a higher resolution scan for the bare rod with a scan resolution of 60 nm. The NSOM probe used had an aperture diameter of 150 nm and the output power of the laser was 5 mW. Figure 5(d) plots the measured |E_z| field for the SR device with a scan resolution of about 40 nm. The NSOM probe used had an aperture diameter of 100 nm and the output power of the laser was 10 mW. The measured field data in Fig. 5 visually show the light propagation and scattering in our samples. In Figs. 5(a, c), the light inputted into the silicon waveguide is seen propagating inside the waveguide. Also, the bright vertical lines seen in Figs. 5(a-d) indicate the edge of the input waveguide at which there exists strong out-of-plane light scattering. In the region between the waveguide edge and SR structure (or bare rod), we observe interference fringes due to the interaction.
between incident wave and backscattered wave. As shown in Figs. 5(a, b), the system with the bare rod exhibited clearly visible interference fringes. The figures also show a very distinct forward scattering component, which is shown as the bright area to the right of the bare rod. In contrast, both the interference fringes and forward scattering were not as prominent in the SR structure. To artificially enhance the interference fringes, the SR structure scan data presented in Fig. 5(d) was performed with a larger gain compared to the bare rod scan presented in Fig. 5(c).

![Fig. 5](image)

Fig. 5. Plots of measured $|E_z|$ at 1550 nm for the bare rod sample (a and b) and the SR structure (c and d). (a) and (c) are low magnification images and (b) and (d) are high magnification scans zoomed in on the region between the end of input waveguide and the scatterer. In (a) and (c), white dotted lines were added to help the readers to identify the silicon input waveguide.

3.4 Discussion

We now present the detailed analysis of the experimental data presented in Fig. 5 to show the difference between the bare rod and SR structure. First, the field amplitudes along the optic axis (line joining the center of the input waveguide and the scatterer as shown in the inset of Fig. 6(b)) are presented in Figs. 6(a) and 6(b). The position was measured with respect to the center of SR structure or bare rod. That is, the zero in the $x$-axis of all plots in Fig. 6 corresponds to the center of SR structure or bare rod. Figure 6(a) plots the electric field amplitude extracted from the field data plotted in Fig. 5(d) along with the same data obtained from simulation. The measured data for the first three fringe positions show excellent agreement with the simulation data for the SR device with nanorod diameter 160 nm and nanowire width 20 nm. The dotted lines in Fig. 6(a) indicate the position of the gold nanowires and are marked by the sharp dips in the electric field amplitude caused by the strong attenuation of the field inside gold. The dip in the electric field profile at $x = 100$ nm was clearly observed in both experiment and simulation. On the other hand, the dip at $x =$
−100 nm was not prominent in the experimental data presumably due to the limitations in the NSOM probe resolution. Similarly, Fig. 6(b) plots the electric field profile along the optic axis for bare rod extracted from the experimental NSOM scan in Fig. 5(b) along with the simulation result. In terms of the fringe spacing and positions of peaks and valleys, the experimental data extracted from NSOM scan is shown to agree very well with simulation. Comparing the data presented in Fig. 6, the fringe patterns in SR structure and bare rod samples were clearly different and we attribute these differences to the metamaterial cover in the SR structure, which is shown in the following to result in reduced scattering.

Following the rationale given in the discussion of Fig. 4, the fringe curvatures were analyzed and compared to present quantitative evidence of scattering reduction. For this purpose, we analyzed the first fringe from the SR device or bare rod because it was most clearly observed in the experiments and it also possesses the largest curvature compared to the subsequent fringes as shown in Figs. 3(b) and 3(c). Figure 7 compares the first fringe curvature extracted from the simulations and NSOM scans for the SR device and bare rod. Figure 7(a) plots the fringe curvature extracted from the measured data plotted in Fig. 5(d) along with the simulation result. Once again, the first fringe curve obtained from simulation of the SR device with silicon rod diameter of 160 nm and gold nanowire width of 20 nm overlaps almost exactly with the experimental data. Figure 7(a) also shows the experimental and simulation fringe curves for the bare rod sample, which were in excellent agreement as well. The excellent agreement between the experimentally measured fringe patterns with the simulations as presented in Figs. 6 and 7 gives us the confidence that our simulations accurately describe the experimental data and that the different SCSs of the SR structure and bare rod are reflected in their clearly different fringe patterns. We can now calculate the scattered optical power for the SR structure and bare rod from simulations and determine that our SR structure exhibits a scattering reduction of 9.8 dB compared to the bare rod of diameter 240 nm and by 6.0 dB when compared to a bare rod of diameter 160 nm, which is the diameter of the silicon core in our SR structure.

To further substantiate this claim, the relationship between SCS and fringe curvature taking into account losses in the cover was further investigated. For this, analytical calculations using the Mie theory were carried out to obtain the SCS for a silicon rod with diameter 160 nm and coated with a cover of thickness 13 nm with various complex effective permittivity (ε_{eff}) values. The range of effective permittivity was kept finite for the obvious practical reason of conducting numerical calculations but we made sure the range was wide enough to cover all possible values in our implementation. For example, the effective imaginary permittivity value of 1 or less represents unrealistically small fraction of gold, which could easily be excluded from the SEM images. Real permittivity values larger than −25 were excluded for the same reasons. The opposite limits of highly negative real permittivity and large imaginary permittivity values were similarly determined as they represent extremely high gold fraction which were simply not possible in our implementation. Within the parameter space thus determined, the SCS of the coated rod, normalized to the SCS of the bare silicon rod with diameter 240 nm, was first calculated as a function of both the real part of effective permittivity, Re(ε_{eff}), and the imaginary part of effective permittivity, Im(ε_{eff}). As shown in Fig. 7(b), the SCS is predominantly determined by Re(ε_{eff}) values and rather insensitive to Im(ε_{eff}) for the range of effective permittivity values used in this plot. Furthermore, the SCS was a monotonic function of Re(ε_{eff}) and thus, if Re(ε_{eff}) for the cover is known, then one could determine the expected SCS.

The curvature C (in units of m^{-1}) was then extracted for each fringe curve at a distance 1.3 μm from optic axis along the vertical direction. Such a large distance of 1.3 μm was specifically chosen to remove any interaction between the metal coated NSOM probe and the gold nanogratings covering the silicon nanorod. In Fig. 7(c), we show the curvature as a function of both Re(ε_{eff}) and Im(ε_{eff}) of the cover. It is evident that Im(ε_{eff}) has much more profound effect on the curvature than on the SCS. The curvature surface becomes flatter with increasing values of Im(ε_{eff}), indicating that the curvature is determined primarily by Im(ε_{eff})
when Im(\(\varepsilon_{\text{eff}}\)) is large. For smaller values of Im(\(\varepsilon_{\text{eff}}\)), the curvature is more sensitive to Re(\(\varepsilon_{\text{eff}}\)) as seen from the slope of the surface. The curvature value extracted from the experimentally measured |\(E_z\)| field profile in Fig. 5(d) was \((1.49 \pm 0.04) \times 10^{-5}\) m\(^{-1}\) and, for clarity, only the mean value of \(C = 1.49 \times 10^{-5}\) m\(^{-1}\) is indicated by the horizontal plane in Fig. 7(c). The curvature error range was obtained by analyzing the errors stemming from the finite scan resolutions in the HNSOM images. The contour (black line in the permittivity plane) projected down from the intersection of the surface plot and the horizontal plane is also shown in Fig. 7(c). This line in the complex permittivity plane, which was reproduced in Fig. 7(d) defines the set of complex effective permittivity values which should result in the measured value of curvature, \(1.49 \times 10^{-5}\) m\(^{-1}\). The errors in the experimentally determined curvature are also shown in Fig. 7(d). To show the relationship with the SCS, Fig. 7(d) also shows the contour plot for SCS which are the same data as shown in Fig. 7(b). It is first noted that Fig. 7(d) shows a minimum SCS of 6.8 dB which occurs at the complex permittivity value of \(-35 + 1.0i\). Even if we extend our calculation range to include the imaginary permittivity values smaller than 1, the SCS does not decrease further. Therefore, the measured curvature value of \((1.49 \pm 0.04) \times 10^{-5}\) m\(^{-1}\) indicates that scattering reduction of at least 6.8 dB or higher was accomplished, even if all of the effective permittivity values included in Fig. 7 were possible. As stated before, we set the range of effective permittivity in Fig. 7 deliberately wide in order not to miss any points even remotely possible in our implementation of metamaterial cover consisting of gold nanowires.

Thus, the minimum SCS of 6.8 dB observed in Fig. 7 should be considered a lower bound in SCS and clear evidence showing scattering reduction was accomplished. In order to more precisely determine the value of achieved scattering reduction, we turn to the effective medium theory [45, 46] analysis of the metamaterial cover. From the analysis presented earlier, the metamaterial cover in our SR structure consists of 20 nm wide gold nanowires along the circumference of 160 nm diameter silicon rod, which results in an effective permittivity of \(-30.6 + 3.1i\). This effective permittivity value, which is plotted on the complex permittivity plane in Fig. 7(d) (black circular marker), is located well within the error margin of the complex effective permittivity contour defined by the measured value of curvature extracted from the HNSOM data. From Figs. 7(b), 7(c) and 7(d), this effective permittivity value was found to correspond to scattering reduction of 9.2 dB, which is consistent with the analysis of fringe positions along the optic axis presented earlier. We have also conducted the same analysis for curvature values extracted at a different location and obtained the same.
result. We therefore conclude that the fringe patterns obtained by HNSOM are consistent with the simulations for the SR structure composed of 160 nm silicon rod and 20 nm wide and 13 nm thick gold nanowires and consequently the normalized SCS is 9.5 dB or between 9.2 and 9.8 dB, allowing for the error margin in the experimentally measured curvature. If one chooses to specify the scattering reduction in reference to a bare silicon rod with 160 nm diameter which is the diameter of the core silicon rod in our SR structure, the resulting scattering reduction is 6.0 dB since the SCS of the silicon nanorod of diameter 160 nm is \(-3.5\) dB lower than the SCS of the silicon nanorod with diameter 240 nm.

Fig. 7. Comparison plots of fringe curvature (a) compares the fringe extracted from measured data plotted in Fig. 5 (b, d) and data from simulation results for SR device with nanorod diameter 160 nm and gold nanowire width 20 nm and simulations of bare rod with diameter 240 nm. (b) 3D plot of Curvature (C) as a function of real and imaginary part of the effective permittivity of the coating. The curvature values were calculated at \(d = 1.3\) m along the vertical direction from the optic axis as shown in the inset. Also plotted is a horizontal plane at \(C = 1.49E-5\) and a curve tracing the intersection between the plane and the 3D curve. (c) 3D plot of normalized SCS calculated as a function of real and imaginary part of effective permittivity of the coating along with the contour plots (d) Overlay plots of contours extracted from Fig. 7 (b and c) giving range of possible scattering reduction values. The contour plot extracted from Fig. 7b also contains an error bar indicating the error in obtaining the curvature from experimental data. Also plotted as a black circle is the complex effective permittivity for the gold nanograting structure with grating width of 20 nm.

4. Summary and conclusion

In summary, we presented the experimental demonstration of scattering cancelation device at 1550 nm. From the presented analysis comparing the key spatial characteristics of the fringes extracted from NSOM scans and numerical simulations performed using structural parameters extracted from SEM images, it is clearly seen that the experimental data agree very well with the theoretical predictions for the fabricated structure. In particular, on comparing the fringe patterns at various locations, it is seen that the SR device and bare rod have different scattering cross-sections and that the experimental data for the SR device compares very well
with the theoretical predictions from SR device simulations with silicon rod diameter of 160 nm and nanowire width of 20 nm. Based on these analyses, the scattering reduction device is estimated to have its scattering cross-section reduced by 9.5 dB when compared to a bare rod with diameter 240 nm and by 6.0 dB when compared to a bare rod with diameter 160 nm. The novel analysis and fabrication techniques presented in this work could be useful to further the design, implementation and characterization of such nanophotonic devices.

Appendix

The dimensions of the fabricated SR structure were extracted from the SEM images. Before Cr/Au coating, the silicon rod was slightly tapered and the diameter varied from 160 nm at the top to 200 nm at the bottom. During the FIB milling of the Au/Cr along the sidewall, it was inevitable that a small fraction of the silicon rod was also milled by the ion beam thereby reducing the effective diameter of the core silicon rod. Careful examination of SEM images (Figs. 2(c), 2(d)) yielded that the diameter of the silicon rod core at the top was in the range of 146 nm ~ 152 nm (on average 149 nm). At the bottom, the core silicon rod diameter was estimated by measuring the size of the FIB cuts and then subtracting it from the original bottom diameter of Cr/Au coated silicon rod. The trench depth was determined (Fig. 2(d)) to be in the range of 32.3 nm ~ 47.7 nm (on average 40 nm). Since bare silicon rod diameter was measured to be 200 nm at the bottom and the deposited gold and chromium thicknesses were 13 nm and 10 nm, respectively, the estimated silicon core diameter after FIB milling was $200+2*(13+10)-2*40=166$ nm. Therefore, we concluded that the core silicon rod diameter after FIB milling varied from 149 nm at the top to 166 nm at the bottom. Next, the upper and lower bounds of nanowire widths were determined. First, Fig. 2(c) was used to extract the trench (gap between two adjacent gold nanowires) width at the top. With the resolution of SEM, we were able to determine the trench width at the top of the rod was in the range of 44 nm ~ 46 nm (averaged 45 nm). Since the gold was deposited along the circumference of a 160 nm diameter circle at the top, the gold nanowire width can be readily computed to be 18 nm. It was a little more difficult to determine the trench width at the bottom of the rod due to poorer contrast in Fig. 2(c). It was in the range of 16 nm ~ 28 nm (on average 22 nm). Once again, with the knowledge of circumference, we could calculate the nanowire width to be 55 nm. In summary, the gold nanowire width varied from 18 nm at the top to 55 nm at the bottom.

The analysis of SEM images of the fabricated SR device revealed variations of the silicon rod diameter and gold nanowire width along the sidewall of the device. Instead of conducting computationally expensive 3D simulations incorporating the exact fabricated structural dimensions, we determined the average/effective structural parameters using 2D simulations, which provide correct description for the behaviors of the fabricated structures and use them to highlight and confirm the principles of scattering reduction. For 2D modeling, we need silicon core diameter, gold nanowire width and thickness. The gold thickness could be determined definitively to be 13 nm. Silicon core diameter and gold nanowire width, however, varied along the vertical direction, as discussed before, and we only know of their ranges. Based on the analyses of SEM images, the average silicon rod diameter and gold nanowire width should lie between approximately (150 nm, 18 nm) and (170 nm, 55 nm) where the first number in the parenthesis represents the silicon rod diameter and the second gold nanowire width. We therefore conducted 2D numerical simulations using the parameter values between (150 nm, 18 nm) and (170 nm, 55 nm). Considering that silicon is much more rugged material than gold, it is natural to expect greater non-uniformity for gold nanowire widths and silicon rod diameter. With this reasoning, we expect the average silicon rod diameter should be closer to the median value of the two extremes, 150 nm and 170 nm measured at the top and bottom of the rod, respectively. On the other hand, it is more likely that the gold nanowire width might deviate from the exact median value of the two extreme values, 18 nm and 55 nm, measured at the top and bottom of the rod, respectively. Consistently with these reasoning, after analyzing the simulation results for a variety of structural parameters, we found that the best agreement between the experiment and

#180114 - $15.00 USD  Received 19 Nov 2012; revised 27 Dec 2012; accepted 28 Dec 2012; published 9 Jan 2013
(C) 2013 OSA  14 January 2013 / Vol. 21, No. 1 / OPTICS EXPRESS  1055
simulation was obtained with (160 nm, 20 nm) as seen from simulation results plotted in Fig. 8. First, the field amplitudes along the optic axis (the line joining the center of the waveguide and the scatterer shown in the inset of Fig. 6(b) in the manuscript) extracted from simulations and HNSOM scan are presented in Fig. 8(a) and the simulations were carried out for SR devices with different sets of silicon rod diameters and gold nanowire widths of (160 nm, 20 nm), (185 nm, 35 nm) and (200 nm, 50 nm). As shown, the experimental field amplitude data extracted from the HNSOM scan in Fig. 5(d) agreed the best with the simulation result for (160 nm, 20 nm) case. To obtain a more global view of the electric field profile, the entire first fringe curves were extracted from experimental data and also from the simulation data for the SR device with parameters (160 nm, 20 nm), (160 nm, 30 nm) and (160 nm, 40 nm) and are plotted in Fig. 8(b). The experimental fringe data were once again obtained from the HNSOM scans presented in Fig. 5(d). Once again, the fringe curve corresponding to simulation results for the (160 nm, 20 nm) case was found to match the experimental results the best. Based on the data presented in Fig. 8, the scattering properties of the fabricated SR device are best described by the scattering properties of the simulated ideal SR device with rod diameter 160 nm and gold nanowire width of 20 nm.

![Fig. 8. (a) Comparison of field amplitudes extracted from measured HNSOM data and data from simulation results (b) Comparison of first fringe curves for the fringe data extracted from measured data and data from simulation results.](image)

Acknowledgments

This work is partially supported by Army Research Office (50432-PH-MUR) and Office of Naval Research (N00014-08-1-0874). The authors also gratefully acknowledge Drs. M. Ayache and Y. Fainman for helpful discussion on HNSOM technique and Drs. Kyung-Hak Choi and Jeong-Bong Lee for metal deposition and reactive ion etching. The fabrication work was conducted with the facilities available at the Nanomaterials Characterizations Facility, JILA Keck Laboratory and Colorado Nanofabrication Laboratory.