Abstract: Silicon is an important material for integrated photonics applications. High refractive index and transparency in the infrared region makes it an ideal platform to implement nanostructures for novel optical devices. We fabricated silicon photonic crystals and experimentally demonstrated negative refraction and self-collimation. We also used heterodyne near-field scanning optical microscope to directly visualize the anomalous wavefronts. When the periodicity is much smaller than wavelength, silicon photonic crystal can be described by the effective medium theory. By engineering effective refractive index with silicon nanorod size, we demonstrated an all-dielectric cloak structure which can hide objects in front of a highly reflecting plane. The work discussed in this review shows the powerful design flexibility and versatility of silicon nanostructures.

1. Introduction

Silicon has emerged as an important optical material during the past decades. The large refractive index and transparency in the infrared region make silicon highly attractive for integrated photonics applications. Strongly guided silicon waveguides have dimensions of the order of a few hundred nm. Since the microelectronics is dominated by silicon, the small dimensions of silicon-based optical devices present natural advantage of potential integration with electronic devices. Furthermore, the strong light confinement results in enhanced nonlinear phenomena such as Raman and Kerr effects. This has led to the development of novel chip-scale devices such as laser and wavelength converter.

In addition to the integrated photonics based on strongly guiding silicon waveguides, an exciting pathway to novel optical devices may be found in periodically patterned silicon nanostructures. A material possessing periodic refractive index is often called photonic crystal [1]. Analogous to real crystals in which electronic wavefunction is modulated by the periodic potential, electromagnetic wave propagating in a photonic crystal is similarly modulated, leading to many novel optical phenomena. For example, when the index modulation is sufficiently large, photonic band gap is formed similarly to the electronic energy band gap in semiconductors and insulators. Since no photons are allowed to exist in a photonic band gap, a defect intentionally introduced inside a photonic band gap structure can serve as a strongly confined waveguide or cavity. The strong light confinement provided by photonic band gap can enable, among other things, nano-cavity with extremely high quality factor. Outside the photonic band gap, the light propagation is still strongly modulated by the periodic refractive index. The severe deformation of dispersion surface results in novel phenomena such as self-collimation and negative refraction. Photonic crystal concept has also found great success in nonlinear optics [2] and optical fiber technologies [3]. In all of these phenomena, silicon is one of the most attractive materials because of its high refractive index. The large index contrast in
The important characteristic of this type of solution is that the solutions are identical for various $k$ values that are interrelated by reciprocal lattice vectors. This is the consequence of periodicity in real space leading to periodic Fourier space. From the practical standpoint of solving the wave equation, this means that one has to deal only with the unit cell in both real and Fourier space, which greatly reduces the computational burden.

There are many numerical techniques developed and/or adapted for photonic crystals [4]. Examples include the plane wave method, transfer matrix method, finite-difference time-domain (FDTD) method, and multiple scattering method. They tend to exhibit distinct advantages and deficiencies and therefore a suitable technique must be chosen by carefully considering the nature of the system of interest. Whichever method was used, one should in the end obtain the dispersion relation or photonic band structure in order to have a complete description of the optical properties. Fig. 1 shows a typical photonic band structure for a two-dimensional photonic crystal structure composed of a square array of air holes in silicon. The $xy$ plane represents the normalized in-plane wave vector ($ka/2\pi$) and the vertical axis represents normalized frequency ($\omega a/2\pi c$), where $a$ is the periodicity.

First, in the low frequency limit, the band structure has a conical shape just as a regular dielectric material. The slope of the cone is determined by the effective refractive index, which is given by an average of the indexes of the constituent materials. For example, if the photonic crystal is made of air holes in silicon, the effective index is the volume average of silicon and air indexes. In this long wavelength limit, the feature sizes are much smaller than the light wavelength and thus the light cannot sense the fine details of the structure but only sees an averaged response. Thus, the photonic crystal structure behaves like a homogeneous medium whose effective refractive index can be engineered by the sub-wavelength-scale features. If
the sub-wavelength-scale features happen to exhibit strong resonance, then the effective index will exhibit resonance too. In fact, depending on the nature of the resonance, one can engineer permittivity and permeability of the composite material separately. This is the basic concept of the metamaterial research which has been experiencing explosive growth in recent years (see, for review [5]).

As the frequency is increased, the dispersion curve begins to deform and consequently the photonic crystal structure exhibits unconventional light propagation such as self-collimation and negative refraction as labeled in Fig. 1. In describing light propagation in photonic crystals, it is beneficial to use equi-frequency contour (EFC) which is defined as the collection of allowed wave vectors for a given frequency. In the photonic band structure shown in Fig. 1, EFC is found by simply making a horizontal cut across the band structure. In a homogeneous dielectric material, EFC is circular and the radius is determined by its refractive index.

In the self-collimation region, the EFC is flat. A flat EFC may be considered to as a part of infinitely large circular EFC and thus in this region, the photonic crystal behaves like a dielectric material with infinitely large refractive index. Consequently, irrespective of incident angles, all rays refract toward normal to the interface, i.e. refraction angle is always zero. Also, the light propagating inside the photonic crystal does not experience any diffraction and thus stays collimated even when it is strongly focused. The propagation of tightly focused light without divergence gives the name self-collimation. This phenomenon can be used to build a virtual waveguide network in which light is self-guided without the physical waveguide structures. In the example shown in Fig. 1, self-collimation occurs in two different frequency ranges. In the first photonic band, the self-collimation occurs along the (11) direction whereas in the second photonic band it happens along the (10) direction.

Near the top of the first band, the EFC changes its curvature and has a circular shape centered at the corner of the Brillouin zone. The opposite curvature results in a large walk-off between the phase velocity and group velocity, resulting that they point the opposite directions to each other. This leads to negative refraction in which the light refracts in the wrong direction at the interface. It should be noted that in this case only the group velocity exhibits negative refraction while the phase velocity experiences positive refraction. As will be discussed further later, the photonic crystal in this case behaves like a strongly anisotropic metamaterial whose EFC is hyperbolic.

In the second photonic band, there is another frequency region where the photonic crystal exhibits negative refraction. Because the band is folded by the Brillouin zone formation, the second photonic band has a negative slope. This means the group velocity which is defined as the gradient of the photonic band structure has the opposite sign to the phase velocity. This is the signature of negative refraction. As one approaches the top of the second band, the EFC becomes circular and therefore the photonic crystal behaves like a homogeneous material with a well-defined negative index.

Between the first and second photonic bands, there is a region where there are no allowed modes. This is the photonic band gap. In this frequency region, light propagation inside the photonic crystal structure is prohibited. Photonic band gap can be used to create waveguides and high Q cavities for applications in integrated photonics and semiconductor lasers. This is still an active area of research but will not be discussed in this review. Interested readers are referred to the articles cited in [6]. In the following, we will discuss the recent experimental demonstration of unconventional light propagation in silicon nanostructures.

3. Negative index imaging with silicon photonic crystal

As described in the preceding section, photonic crystals may exhibit negative refraction via two distinct mechanisms: (1) near the top of the first band where EFC has negative curvature and (2) in the second photonic band where the dispersion curve has negative slope. We first describe the experimental demonstration of negative refraction due to negative curvature of EFC [7]. The photonic crystal structure was fabricated on a 300 nm thick silicon-on-insulator (SOI) substrate. It is comprised of a square array of air holes with periodicity 410 nm and hole diameter 295 nm. In this structure, near the wavelength of 1.5 μm, the EFC for transverse-electric (TE, electric field in the device plane) mode has a circular shape centered at the M point \((k_x/2\pi = 0.5, k_y/2\pi = 0.5)\) of the Brillouin zone, thereby exhibiting a negative curvature. Fig. 2
Figure 3 (online color at www.lphys.org) The amplitude, evaluated experimentally in (a) and numerically in (c), and the phase, evaluated experimentally in (b) and numerically in (d), of the field at the slab-photonic crystal interface, where the wave travels from bottom to top (from [7]).

shows the guided wave amplitude measured by the scanning near-field optical microscope (NSOM) overlaid on top of a scanning electron micrograph (SEM). The entire device structure has three regions: 2 μm wide silicon input waveguide, unpatterned silicon area representing a positive index incident medium, and the photonic crystal structure. The 2 μm wide ridge waveguide has a fundamental mode width of 1.5 μm. The mode then diffracts across a 15 μm long region of unpatterned SOI substrate expanding to a width of 6.6 μm. Finally, the beam refracts negatively across the photonic crystal interface, forming an internal focus with a beam waist of 2.6 μm at 3 μm behind the interface. Beyond the internal focus, the beam continues to expand.

The field amplitude image clearly demonstrates the focusing due to negative refraction but misses the phase behavior that occurs at the positive to negative refraction interface and internal focus. In order to retrieve the full complex field of the guided wave, we make heterodyne interferometric measurements with the NSOM [8]. The high resolution amplitude and phase images are shown in Fig. 3a and Fig. 3b, respectively. The geometry of the photonic crystal appears in both amplitude and phase scans, showing that the wave in the photonic crystal is a strongly modulated Bloch wave. Yet in this case, the phase fronts of the wave resemble those of a plane wave because only the first photonic band is excited. More interesting is that we can resolve the curvature of the wavefronts in the phase image across the interface. Upon traversing across the interface from the silicon to the photonic crystal, the curvature of the wavefronts does not change sign. Consequently, inside the photonic crystal, phase fronts do not converge while the amplitude scan clearly shows the focusing. The sign of the curvature does change at the internal focus where the wavefronts change from diverging to converging.

The experimental images are in excellent agreement with numerical simulations shown in Fig. 3c and Fig. 3d. The curvature of the wavefronts may be seen more clearly in the numerical simulation shown in Fig. 3d. The focusing observed in the amplitude scan clearly shows the negative refraction of group velocity. However, the phase velocity refracts positively as can be seen in the phase scan. This is the first unambiguous experimental demonstration of negative refraction due to negative curvature.

Now we describe negative refraction in the second photonic band [9]. In general, the second photonic band exhibits negative slope due to the band folding at the Brillouin zone boundary. If only the second band exists in a given frequency range, the phase of the excited wave progresses backwards and the momentum vector \( \mathbf{k} \), and the fields \( \mathbf{E} \) and \( \mathbf{H} \) form a left-handed set. Near the top of the second band close to the \( \Gamma \)-point (\( k_x a/2\pi = 0, k_y a/2\pi = 0 \)), the EFC is circular, so light refracts isotropically. In this case, \( \mathbf{k} \) is antiparallel to the Poynting vector \( \mathbf{S} \) at all angles, giving the medium a meaningful effective index less than zero. At the top of the second band, the phase velocity is infinite. As the frequency is decreased, the effective index becomes larger in magnitude and more anisotropic.

We designed and fabricated a triangular array of air holes with hole diameter 340 nm and lattice constant 540 nm (from [9]).
Figure 5 (online color at www.lphys.org) 2D finite-difference time-domain (FDTD) simulation of the time-averaged field modulus for (a) TM and (b) TE polarizations. Experimental characterization of the device at an incident wavelength of 1562 nm (c) for TM and (d) for TE. In (c) and (d), the main panels show light collected over the waveguide tip and photonic crystal, and the insets show the output from the photonic wire array. Dotted lines have been imposed on the scattering data to help the reader visualize the device (from [9]).

ter was 340 nm and the lattice constant was 540 nm. In this case, the effective index for the TM polarized light stays nearly isotropic until the second band intersects the air light line, which occurs at a normalized frequency \( \omega_n (\omega_a/2\pi c) \) of \( \omega_n = 0.35 \) in our structure. This indicates a phase index of –1 and defines a phase velocity matching condition between the photonic crystal and air. For a negative index lens, this is the ideal operational frequency. The direction of energy propagation is along the gradient of the EFC. In our structure, the TM polarized light sees a concave dispersion surface and the TE polarization sees a convex dispersion surface. Effectively, this means that the photonic crystal structure spatially collects TM polarized light while spatially dispersing TE polarized light. In general, the high frequency region of the second photonic band is concave and the lower frequency region is convex with respect to the \( \Gamma \)-point. By equating the second derivative of the band structure to zero, a spectral inflection point is defined where the curvature changes sign. This occurs at \( \omega_n = 0.327 \) for TM light and at \( \omega_n = 0.369 \) for TE light. Consequently, because our operating frequency of \( \omega_n = 0.345 \) lies between these values we expect oppositely signed refraction for TE and TM polarizations. That is, TM light will refract negatively while TE refracts positively.

For experimental demonstrations, a 10 \( \mu \)m wide Si ridge waveguide was fabricated with a tapered tip to generate a point-like source. There is a small air gap between the waveguide tip and the photonic crystal, as shown in Fig. 4. The air gap has two important functions. First, it filters out large spatial frequencies which are evanescent in air. Even if the incident frequency only intersects a single photonic band in the first Brillouin zone, incident waves with large transverse \( k \) vectors may excite multiple Bloch waves in the crystal that arise from the intersection with higher order Brillouin zones. Because these diffracted waves do not originate from the same \( \Gamma \)-point, they will not have antiparallel \( k \) and \( S \) vectors and consequently do not have desirable negative index properties. The second important feature of the air gap is that it allows the photonic crystal’s negative effective index to have the same modulus as the surrounding medium. When this occurs, the spatial frequency spectrum supported by the two media is the same. This means that every incident tangential \( k \)-vector is matched across the boundary and therefore there will be no total internal reflection (TIR). While for a flat lens geometry this occurs whenever the background medium has a lower effective index than the photonic crystal, for geometries without parallel interfaces a matched effective
index is needed to avoid TIR at an internal interface. Another benefit of index-matching is that the refracted angle in the photonic crystal always equals the incident angle. If the EFC curve is exactly circular, there will not be any spherical aberration when the index matching condition is satisfied. Furthermore, because there is no optical axis in a flat lens, all off axis aberrations will also be absent.

The finite-difference time-domain (FDTD) simulations in Fig. 5a and Fig. 5b show that this tip geometry produces an internal focus inside the taper with a full width at half maximum (FWHM) of \( \lambda_o/5.9 \), which is close to \( \lambda_o/2n_{eff} \) for the TM light. The light expands to a spot with an FWHM of \( \lambda_o/3.8 \) in air at the end facet of the waveguide. The optical field then propagates in air to the interface of the PC, which consists of a triangular lattice of air holes with the surface normal oriented in the \( J'M \) direction of the PC. The light couples into the second photonic band with an estimated efficiency of 75%, which was calculated by modal field overlap method. In the current slab geometry, however, this value will be modified by the Fabry-Perot resonance and also by the out-of-plane scattering. In any case, we note that the photonic crystal is not expected to exhibit 100% transmission even when the index is perfectly matched. The excited Bloch modes then negatively refract to the back interface of the photonic crystal and couple back out to plane waves in air. For TM polarized light, a well-defined image of the waveguide tip source is produced at a symmetric distance from the back interface of the photonic crystal and is subsequently sampled by an array of 500 nm wide photonic wire waveguides spaced by 1 \( \mu m \) as shown in Fig. 4. For TE polarized light, FDTD shows that the transmission is much lower and the photonic crystal region exhibits higher energy density because the excitation is close to the band edge. The photonic wires are 500 \( \mu m \) long and are fanned out at a small angle so that at the output they are spaced by 5 \( \mu m \), and easily resolvable by an optical microscope. The use of a small fanning angle and the fact that the guides are spaced by twice their width prevents light from coupling into neighboring photonic wires, while still sampling the image at the rate of one data point per \( \lambda_o \).

For optical characterizations, the out-of-plane scattered light was collected and imaged over the waveguide tip and the photonic crystal regions. Also imaged was the output of the fanned photonic wires that sample the image formed by the photonic crystal lens. The latter monitors the light that has propagated through the entire device without being scattered out of plane. Fig. 5c and Fig. 5d show the infrared photographs of the front and back planes of the photonic crystal lens, and the outputs of the fanned-out photonic wires in the insets. For both TM and TE polarizations, we observe a bright spot at the tip of the input waveguide, confirming the formation of a tightly focused and diverging incident field as predicted in Fig. 5a and Fig. 5b. It is clear from Fig. 5c that another bright spot is formed on the back plane of the photonic crystal lens for TM polarization. This demonstrates that the negative index photonic crystal focuses the TM light with high efficiency.

Figure 6 (online color at www.lphys.org) (a) – scanning electron micrograph (SEM) micrograph of self-collimating photonic crystal structure fabricated with a 2 \( \mu m \) wide input waveguide. (b) – the field amplitude in unpatterned silicon slab as measured by a heterodyne NSOM. (c) – the field amplitude in self-collimating photonic crystal slab as measured by a heterodyne NSOM

In contrast, we do not observe any well-defined bright spot for TE polarization. Instead, the light spreads significantly as shown in Fig. 5d. The inset shows that the TM polarization primarily illuminates only a single photonic wire and that this mode is confined strongly enough to permit high transmission for the entire device. In contrast, the TE polarization illuminates 5 photonic wires almost evenly. This experiment represented the first unambiguous demonstration of negative index imaging in the near-infrared region.

4. Self-collimation

The self-collimation region lies just below the negative refraction regime in the first photonic band. In order to observe self-collimation near the wavelength of 1.5 \( \mu m \), we basically use the same photonic crystal structure as shown in Fig. 2 but reduce the lattice constant to 350 nm. The fabricated device consists of a 2 \( \mu m \) wide silicon input waveguide and a 10 \( \mu m \) wide and 50 \( \mu m \) long photonic crystal region. The SEM image of the device is shown in Fig. 6a. For comparison’s sake, we also fabricated a reference sample, in which the photonic crystal region is replaced with unpatterned silicon layer. We then conduct the NSOM measurements to directly image the light propagation inside the device structures. Fig. 6b and Fig. 6c show the NSOM images for the reference sample and self-collimating photonic crystal. When the fundamental mode
Figure 7 (online color at www.lphys.org) (a) – scanning electron micrograph (SEM) of the integrated photonic crystal polarization beam splitter device with input (left) and output (top and right) 5 μm-wide ridge waveguides. (b) – a higher magnification SEM image of the interface between the two photonic crystals. The first (left) photonic crystal has a lattice constant of 353 nm and the second (right) one has a lattice constant of 438 nm and both have the same radius to lattice constant ratio of 0.35. The dark regions in (a) consist of a 300 nm thick silicon layer and the bright regions are where the device layer has been etched down to the underlying 1 μm oxide (from [10]).

Figure 8 (online color at www.lphys.org) Optical images show out-of-plane scattered light collected over the device at 1582 nm. From the scattered intensity it is clear that when illuminated with TM light the transmitted port is bright and when illuminated with TE light the reflected port is bright. The polarization of the incident light is controlled with a polarization controlling paddle and coupled into the device via a fiber coupled laser. The device is illuminated by a lamp to show its geometry (from [10]).

of input waveguide enters the unpatterned silicon region in the reference sample, it diffracts according to the effective index of the silicon layer, which is \( n_{eff} = 3.02 \) for TE polarization. After propagating 50 μm, the beam spreads to a width of 16 μm, as shown in Fig. 6b. In clear contrast, the self-collimating photonic crystal preserves the tightly focused beam throughout the structure. After propagating 50 μm length, the mean waist remains at 2.25 μm, as shown in Fig. 6c.

There is large polarization anisotropy inherent to the slab geometry. We can use the self-collimation and the polarization anisotropy to build a compact, integrated polarization beam splitter [10]. The geometry of the device, as shown in Fig. 7, is similar to a traditional cube beam splitter. A square-shaped region is separated along the diagonal into two different photonic crystal structures that are linearly scaled versions of each other. The first photonic crystal region connected to the input waveguide has a lattice constant smaller by a factor of 0.806 than the second photonic crystal placed on the backside of the hetero-interface. Both photonic crystals are composed of a square array of air holes with the same radius to lattice constant ratio of 0.35 and the same crystal orientation in such a way that the vertical and horizontal interfaces are along the \( \langle 11 \rangle \) direction and the diagonal interface is along the \( \langle 10 \rangle \) direction. At the diagonal interface, the photonic crystal modes...
The response of the device was characterized in the wavelength range of 1520 – 1605 nm. For this entire bandwidth, the TE-like mode is in the region of self-collimation in the first photonic crystal and close or above the band edge in the second photonic crystal. Consequently there is very high reflection at the interface. Furthermore, the beam is self-collimated with very little diffraction before and after the reflection and the field profile incident on the reflected output port waveguide matches well with the field leaving the incident waveguide, as shown in Fig. 8a. On the other hand, the TM-like mode efficiently couples across the diagonal hetero-interface, as shown in Fig. 8b. In the second photonic crystal, the TM-like mode is also close to the self-collimation regime, but the EFC has some positive curvature with respect to the \( I \)-point. The field therefore positively diffracts as it propagates through the photonic crystal structures and does not couple into the output waveguide as well as the TE-like mode does. This can be seen in Fig. 8a by the increased scatter in the vicinity of the output port waveguide. For both polarizations, there occurs very low scatter at the hetero-interface, demonstrating its low loss functionality. We have also measured the extinction ratios of the two ports with an InGaAs photodiode. We used a pinhole to aperture the scattered field and filter out all the light except for that leaving the termination of the port of interest. The power levels could then be accurately measured from each port under illumination with TE and TM light. Extinction ratios are calculated with the expression \( dB = 10 \log_{10} \left( \frac{P_{\text{TM}}}{P_{\text{TE}}} \right) \), where \( P_{\text{TM}} \) is the power in the primary polarization for the port and \( P_{\text{TE}} \) is the power in the cross polarization for the port. At the wavelength of 1582 nm, the response for both ports is the best at 15.7 dB and 16.5 dB for the reflected port and the transmitted port, respectively. In the characterized wavelength range, the best reflection port extinction ratio is 17.9 dB and the best transmission port extinction ratio is 19.7 dB at 1600 nm and 1528 nm, respectively. This follows the general trend in which the performance of the reflection port deteriorates with increasing frequency, as the TM-like mode is increasingly reflected, and the performance of the transmission port improves with increasing frequency, as the TE-like mode has decreasing transmission. To our knowledge, the extinction ratios reported in this work is the best among the photonic crystal based polarization beam splitters.

5. Cloak of invisibility

When the feature size and lattice constant of a photonic crystal become very small, the light no longer “sees” the periodicity in the system but experiences only the averaged response of the structure. The nanostructure then behaves like an effective medium whose optical constants are determined by the details of the structure. It is therefore possible to engineer the optical constants by properly designing the nanostructure. This is the heart of the...
metamaterial concept which has been the subject of extensive research worldwide in recent years (see, for review [11]). The engineered optical constants in metamaterials may reach exotic values unattainable in natural materials, such as negative refractive index (see, for review [12]). The ability to freely engineer optical constants has spawned a new field of transformation optics whose hallmark application is the invisibility cloak, a structure containing an electromagnetically inaccessible region [13,14]. However, experimental demonstration remains a considerable challenge partly because most invisibility cloak designs require strong anisotropy and extreme values of optical constants difficult to achieve even with state-of-the-art metamaterial architecture. Recently, a new cloak was proposed to hide objects in front of a mirror plane [15] and was experimentally demonstrated in the microwave region [16]. This structure does not require extreme values for optical constants nor anisotropy. The modest range of permittivity with minimal anisotropy required for this new cloak design can be implemented with non-resonant dielectric materials. This significantly relieves the issue of loss, thus making this system an ideal candidate for optical frequency operation. Very recently, this new cloak structures were implemented in a silicon-on-insulator wafer and the cloaking effect was observed experimentally by monitoring the scattered light or out-coupled light [17,18]. In our group, we designed and fabricated an invisibility cloak based on a silicon nanorod array. Unlike the two other reports, the light propagation inside the device plane was imaged by the near-field optical microscopy (NSOM). This represented the first direct visualization of cloaking effect in the optical frequency region [19].

The ground plane cloak was designed using a silicon nanorod array fabricated on a 340 nm thick single-crystalline silicon-on-insulator (SOI) wafer. The cloak consists of a 215×80 array of nanorods whose diameters vary from 0.35μm to 0.87μm, where the array periodicity, a, is set to be 150 nm for this specific implementation. Ideally the reflecting interface should be a perfect reflecting mirror but in our structure the high reflectivity at the nanorod-air interface is used to mimic the mirror plane, greatly simplifying the fabrication process. As discussed later, the simulations show the reflectivity is high enough to exhibit cloaking behavior. Also, in the small area in the middle, both the nanorod size and periodicity are doubled in order to avoid extremely small gaps (~20 nm) between the nanorods which are difficult to fabricate accurately with our electron-beam facility. After this modification, the smallest gap dimension was 57 nm. Finally, the background medium with permittivity 2.25 was produced by a uniform array of nanorods with a diameter 0.53μm. The total device region is comprised of a silicon nanorod array over a 39.6×39.6 μm² area, connected to a 10 μm wide input waveguide and a 39.6 μm wide unpatterned silicon output region, as schematically shown in Fig. 9a. The input waveguide is designed to make an incident angle of 45° with the curved reflecting interface of the cloak. The device region contains a 32×12 μm² cloaking structure made of nanorods with diameters ranging from 90.75 nm to 52.18 nm and a uniform spacing of 150 nm. As explained earlier, the cloaking structure also contains a secondary array of 300 nm spaced nanorods with larger diameters in the range of 184.05 nm to 256.18 nm. The cloak area is shown in the SEM micrograph in Fig. 9b.

The performance of this cloak design was investigated by finite-difference time-domain (FDTD) simulations. As shown in Fig. 10a, the cloak produced a well-defined reflected beam exactly analogous to the specular reflection from a flat mirror plane. There is some scattering due to the discretization of the curved interface which is inevitable in the metamaterial implementation. If we decrease the periodicity and nanorod size, the scattering is reduced significantly due both to the more accurately defined reflecting interface and the more precise representation of the
required index profile of the cloak. Also, the design exhibits some light leakage through the reflecting interface due to the less than 100% reflectivity at the interface. The cloak performance will be compromised if the reflectivity becomes too low, however, despite these imperfections, the cloak performs very well. Considering that the middle part of the cloak has nanorod sizes as large as 256 nm, the performance of the current implementation is quite remarkable, showing the robustness of this ground plane cloak design.

The fabricated cloak structures were investigated by NSOM. Three fiber-coupled tunable lasers each of which covers 1410 – 1520 nm, 1528 – 1603 nm, and 1570 – 1603 nm, respectively, were used as light source. Fig. 10b shows the NSOM image for a wavelength at 1500 nm. A well-defined input beam was observed propagating vertically from the bottom of the figure into the cloaking structure. A spot of intense scattering is visible at the reflecting interface. The out-of-plane scattering at the reflecting interface significantly reduces the reflected beam intensity, but is unavoidable in a 2D implementation in which the guiding condition is compromised due to the abrupt interface. Despite losses at the reflecting interface, a clearly defined reflected beam was observed at a reflection angle of 45° with respect to the reflecting interface, as indicated in Fig. 10b. The reflected light beam does not reach the output waveguide, however, due to the propagation loss within the nanorod array region and also because of scattering losses at the reflecting interface. Similar patterns were measured at other wavelengths within the wavelength range accessible with the tunable laser system. This cloak is an all-dielectric cloak made of non-resonant elements and is expected to operate well over a broad range of frequencies. In the current implementation, however, the bandwidth is limited by the waveguide dispersion of the silicon slab. We have also fabricated and measured a reference sample which has the exact same shape and dimensions as the cloak except that the nanorod array is replaced with unpatterned silicon. Naturally, the curved interface generates a complex reflection pattern in clear contrast to the well-defined reflection beam in the cloak sample. The measured NSOM image was in excellent agreement with the FDTD calculations.

6. Conclusions

A review on the recent progress in silicon nanostructures is presented. Silicon nanostructure is a highly versatile system which can be engineered to exhibit a wide variety of novel optical phenomena. In this review, we discussed negative refraction through two different mechanisms and self-collimation, all of which occur near the photonic band edge region. These phenomena rely on the modification of the dispersion surface due to periodicity. Consequently, they occur in the wavelength range comparable to the periodicity, \( a \), or \( a/\lambda = 0.3 – 0.5 \), to be more specific. From the practical standpoint of sample fabrication, achieving near perfect periodicity is very important. Since these phenomena arise from the periodic nature of the system, any disorder in the structure could readily compromise the effect. In this respect, silicon is the best material platform thanks to the mature nanofabrication technologies available for silicon processing.

The invisibility cloak has different physics. In this case, we are operating in the deep sub-wavelength region where \( a/\lambda \) is 0.1 or less. In this so-called effective medium regime, perfect periodicity is not as critical and one only needs to control the size and shape of the individual nanostructures to control the effective optical constants. This greatly relieves fabrication constraints and presents an opportunity for efficient manufacturing. However, the individual feature size has to be made sufficiently small in order to ensure effective medium behavior. This requires the capability of fabricating sub-100 nm scale features for optical frequency operation, which is challenging. Once again, silicon is one of the most suitable candidates for fabricating such nanoscale structures due to the well-developed fabrication technologies.

The concept of using periodic structures to control the light propagation provides a powerful means to manipulate light, potentially enabling highly integrated photonic circuits. The high refractive index, transparency in the infrared region, and availability of mature nanofabrication technologies make silicon an ideal material platform to build novel photonic nanostructures on.

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Dr. Wounjhang Park is an Associate Professor of Electrical, Computer & Energy Engineering at the University of Colorado at Boulder and a Full Member of University of Colorado Cancer Center in Aurora, Colorado. He received his Ph.D. degree from the Georgia Institute of Technology. He then worked at the Georgia Tech Research Institute as a Post-Doctoral Fellow and a Research Scientist until he joined the faculty of University of Colorado in 2001. Dr. Park has a highly productive research career, authoring and co-authoring over 70 peer-reviewed publications. His primary research interests include nanophotonics, biophotonics, nanomaterials synthesis, and fabrication and novel display materials. His recent accomplishments include theoretical design and experimental demonstration of negative index imaging, wavefront reversal and invisibility cloak using silicon-based nanostructures. He is also conducting pioneering work on mechanically tunable photonic crystal, self-assembled metamaterials, and gene detection and delivery using nanoprobes. He is an editorial board member of the Journal of the Computational and Theoretical Nanoscience, a guest editor for the MRS Bulletin, and a 2008 Ruth L. Kirschstein NRSA Senior Fellow in Cancer Nanotechnology Research.