Broadband Light Bending with Plasmonic Nanoantennas

Xingjie Ni, Naresh K. Emani, Alexander V. Kildishev, Alexandra Boltasseva, Vladimir M. Shalaev*

The phase of a light wave can be controlled by using bulk optical elements like lenses and mirrors to modify the wavefront of the propagating light. These elements introduce an additional spatially nonuniform phase in the incoming wave, thereby affecting its propagation characteristics. However, the amount of phase change is limited by the optical properties of the materials, and an appreciable change typically requires a propagation length comparable to or larger than the wavelength. Although metamaterials can be fabricated that are capable of bending light in unusual ways and have enabled many fantastic applications, such as negative refraction (*1*), super-resolution lenses (*2*, *3*), and cloaking (*4*), the capabilities of phase control and light bending are still dictated by the material parameters as governed by the conventional Snell's law. However, the newly discovered generalized version of Snell's law ushers in a new era of light manipulation (*5*):

$$\sin(\theta_t)n_t - \sin(\theta_i)n_i = \lambda\nabla\Phi/2\pi \quad (1)$$

$$\sin(\theta_r) - \sin(\theta_i) = n_i^{-1}\lambda\nabla\Phi/2\pi \quad (2)$$

These expressions indicate that a gradient in a phase discontinuity, $\nabla\Phi$, along an interface between two media with refractive indices n_t and n_i can modify the direction of the refracted and the reflected waves by design and that this can occur in a very thin layer. Another more general interpretation of this is that $\nabla\Phi$ is essentially an additional momentum contribution that is introduced by breaking the symmetry at the interface; hence, in order to conserve momentum, the light wave has to bend accordingly. Note that when there is no phase gradient $\nabla\Phi$ along the interface, Eqs. 1 and 2 reproduce the conventional Snell's law. This is conceptually different from the diffraction formula for a periodic grating because the bent light is caused by a unidirectional phase discontinuity, which is not a particular order of diffraction. Thus by designing and engineering a phase discontinuity along an interface, one can fully control the bending of a light wave beyond what the conventional Snell's law predicts. Such an interface has been realized at a wavelength of 8 μm (*5*). We extend that work and demonstrate wavefront control in a broadband wavelength range from 1.0 to 1.9 μm, accomplished with a relatively thin 30-nm (~λ/50) plasmonic nanoantenna interface.

We used a plasmonic nanoantenna array similar to that in (*5*) and consisting of V-shaped gold antennas (Fig. 1A) to introduce an abrupt phase discontinuity at the interface. This type of antenna supports antisymmetric modes, which provide a tunable phase delay for cross-polarized light (whose polarization is perpendicular to the incident polarization) by appropriately choosing the design parameters. A unit cell of the nanoantenna array consists of eight antennas providing a phase shift from 0 to 2π in the *x* direction. Full-wave finite element method simulation results indicate that the designed antennas have the desired phase change (from 0 to 2π with π/4 intervals) for cross-polarized scattered light (*6*).

We fabricated a nanoantenna array sample on a double-sided polished silicon substrate with standard electron-beam lithography and lift-off processes. The height of the nanoantennas was about 30 nm, and the arm width was 40 nm. Four large arrays with different periods were fabricated on the same substrate (Fig. 1B). We measured the sample by using an ellipsometer, and the experimental measurements indicate that the reflection and refraction of the cross-polarized light are both "negative" in a broad range of incidence angles (Fig. 1, C and D, and fig. S2). In addition, wavelength-dependent measurements showed the broadband behavior of the observed phenomenon for wavelengths from 1.0 to 1.9 μm. All the experimental data match quite well with the theoretical predictions given by the generalized Snell's law, Eqs. 1 and 2, and the three-dimensional full-wave simulation results of the entire array (*6*).

The designed plasmonic interface consisting of a nanoantenna array provides a phase shift and enables us to modify the optical wavefront within an extremely thin layer. Hence, designers can now have unparalleled control of anomalous reflection and refraction, including negative refraction. The design works for a rather broad range of wavelengths, from 1.0 to 1.9 μm. This technique could lead to a variety of applications, such as spatial phase modulation, beam shaping, beam steering, and plasmonic lenses, and it also could have an impact on transformation optics and on-chip optics.

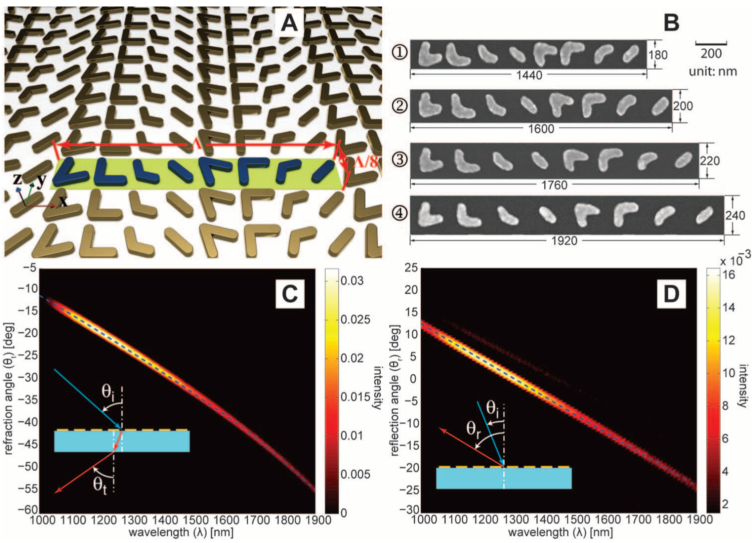

Fig. 1. (**A**) Schematic view of a representative antenna array. The unit cell of the plasmonic interface (in blue) consists of eight gold V-antennas of 40-nm arm width and 30-nm thickness, repeated with a periodicity of Λ in the *x* direction and Λ/8 in the *y* direction. The phase delay for cross-polarized light increases along the *x* axis from right to left. (**B**) Scanning electron microscope images of the unit cells of four antenna arrays with different periodicities fabricated on a single silicon wafer. (**C** and **D**) The false-color maps indicate the experimentally measured relative intensity profiles for the antenna array labeled ① [in (B), Λ = 1440 nm] with *x*-polarized excitation. The dashed line shows the theoretical prediction of the peak position using the generalized Snell's law. (C) Refraction angle θ_t versus wavelength λ for cross-polarized light with 30° incidence angle θ_i. (D) Reflection angle θ_r versus wavelength for cross-polarized light with 65° incidence angle.

References and Notes

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School of Electrical and Computer Engineering and Birck Nanotechnology Center, Purdue University, West Lafayette, IN 47907, USA.

*To whom correspondence should be addressed. E-mail: shalaev@purdue.edu