Broadband Light Bending with Plasmonic Nanoantennas

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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).

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. 1C 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.

**References and Notes**

6. See supporting online material available on Science Online.

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Materials and Methods
Figs. S1 and S2

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