below the 150 K condensation temperature for water, and thus most water exists as ice on grains. Spectroscopic features from water ice have been seen (*3*, *4*), but these techniques have only been applied to a few objects with favorable viewing geometries. Observations of the water isotope HDO (D is deuterium) in the gas phase of the outer disk led to models of ultraviolet photons from the central star desorbing water molecules from the icy grains back into the gas phase (*5*). The observations of Hogerheijde *et al*. are consistent with this cycle. Their calculations show that a large population of icy grains, equivalent to several thousand Earth oceans, is necessary to maintain the observed level of water vapor on the surface of the disk.

Water can also play a critical role in the formation and final surface composition of planets. Ice enhances the solid material in the cold outer part of a protoplanetary disk, which promotes the formation of cores of gaseous planets (*6*). The disk radius where ice can condense is often termed the "snow line," and the location of this line is a property of the stellar mass and disk evolutionary state (see the figure). The location and evolution of this snow line may affect the formation rate of large planets (*7*).

The distribution of water ice in the circumstellar disk can also help address the issue of where Earth's water originated. While forming, Earth is believed to have been too hot to have liquid water and would have retained little water vapor from the gaseous component of the disk. Thus, the water we have now arrived later, most likely from ice-covered comets or asteroids from the outer parts of the solar system. In addition to the water abundance, the spectra obtained by Hogerheijde *et al*. allow determination of the spin isomer ratio, where the spin refers to the alignment of the hydrogen proton spin vectors (that is, the ratio of the amount of para- to ortho-hydrogen in the water molecules). They found a ratio much lower than that measured for solar system comets, suggesting that material from multiple locations in the TW Hydrae disk is mixed before incorporation into larger bodies. Evidence for such radial transport in the early solar system includes results from the Stardust mission that returned comet samples containing material formed at high temperatures (*8*).

As the number of planets discovered around other stars expands to include many systems with multiple planets, it is clear that the universe includes many planetary system architectures very different from that of our own solar system. To constrain models of planet formation, including the chemical composition, we need to understand the distribution and evolution of molecules in the disk, including water, a key catalyst for life on Earth. The next several years will provide many opportunities to progress in this study as Herschel and other observatories will make spectroscopic observations of a much larger sample of disks covering a range of stellar age and mass. Also, new facilities, such as the Atacama Large Millimeter Array, will greatly expand on the current sensitivity levels to allow spatially resolved observations of molecules in the disk.

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APPLIED PHYSICS

Antenna-Guided Light

Compact arrays of gold nanoantennas can be used to create optical structures that bend the path of light in unusual ways.

Nader Engheta

The bent appearance of a stick half-submerged in water is caused by the difference in refractive indices of air and water—light travels more slowly in water than in air (see the figure, panel A) and refracts and reflects off the air-water interface. Snell's law (*1*) lets us calculate the bending angle if we know the geometry and the refractive indices. In complex optical instruments, where several lenses, mirrors, and other components may be present, designers control the bending by keeping track of the phase shifts imposed along the wavefront of the light; for example, a light beam can be focused by different phase shifts that occur along a curved lens. These optical components are much larger than the wavelength of light, which limits the minimum size of devices. On page 333 of this issue, Yu *et al*. (*2*) show how arrays of structures smaller than the wavelength of light, V-shaped nanoantennas made of gold, bend light by creating abrupt phase shifts through the excitation of resonances. The authors show that these compact "metasurfaces" follow a more general version of Snell's law that accounts for the bending of a light beam in unconventional but potentially useful ways.

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Conventionally, the bending of light may occur at an abrupt interface of two media (e.g., air and water), or through a gradual change of refractive index (e.g., air above the hot desert roads causes mirage; see the figure, panel B). However, it is possible to obtain the desired phase shift along the wavefront by tailoring planar interfaces. One of the early examples is the Fresnel lens, in which a set of concentric lenses are cut to different curvatures and impose different phase shifts. Although a Fresnel lens is much thinner than an equivalent conventional lens, its thickness is still far greater than the wavelength of light.

Light does not always simply pass through a medium; it can also excite resonances that can lead to absorption and emission. For the much longer wavelengths of "light" used in radio and microwave communications, antennas called reflectarrays (*3*) and transmitarrays (*4*) contain multiple antenna elements that act as resonators to control the direction in which signals are received or broadcast. However, the resonant elements responsible for the required phase shift and their arrangement in periodic arrays are still comparable in size to the wavelength of operation (*3*–*5*). These devices often operate over only a narrow range of frequencies.

For shorter-wavelength light, such as infrared and visible light, plasmonic phenomena—the excitation of collective oscillations of electrons in materials such as gold and silver—can allow subwavelength objects to undergo resonance responses in the scattering process. Yu *et al*. designed subwavelength

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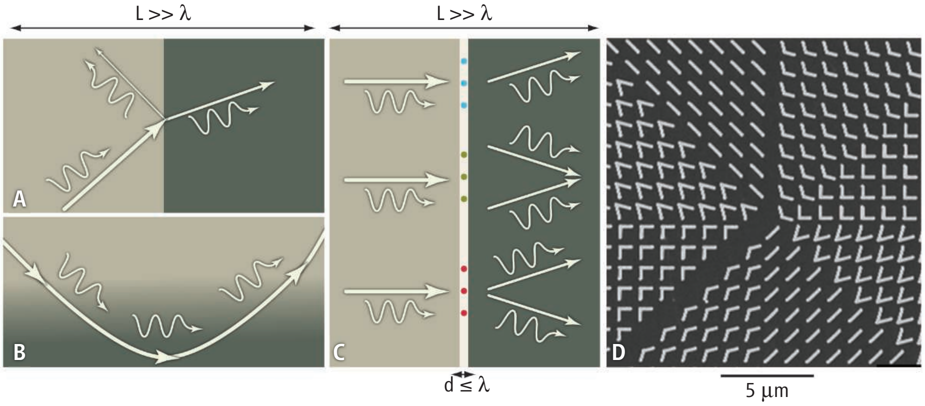

Bending light, big and small. Several mechanisms for bending light are depicted. The optical structures shown in (**A**) and (**B**) are much larger than the wavelength of light. In (A), an interface between two media with two different indices of refraction bends light. In (B), light is bent by a material that gradually changes refractive index with distance. Yu *et al*. caused the bending of light in unusual ways (**C**) with thin metasurfaces. These metasurfaces contain distributed arrays of gold nanoantennas (**D**) that are smaller than the wavelength of light. In such arrays, the proper patterns of phase changes created by resonant nanostructures lead to bending effects not anticipated by conventional laws of reflection and refraction in optics.

gold antennas with a V shape; they varied the scattering of light by changing the length of the arm and the angle and the orientation of these "V's." The phase difference between the scattered and incident fields is tailored over a small distance along the light's path, that is, the structures are optically thin.

Yu *et al*. printed planar arrays of such V-shaped nanoantennas in suitably designed patterns on a silicon wafer and demonstrated several intriguing light-bending scenarios at these metasurfaces, including unconventional reflection and refraction angles, total internal reflections with two critical angles (rather than only one), and reflected light becoming evanescent (diminishing in amplitude with distance away from the interface, rather than propagating) at certain angles. None of these effects are predicted from the conventional Snell's law, but they do follow a generalized version derived by the authors that allows for desired variations of the change of phase on the interface.

These arrays of nanoantennas, which could include movable sections, could be used to design photonic components such as lenses and mirrors that are ultrathin, conformal (angle-preserving), and even deformable. Reconfigurable couplers and waveguides, which could be driven by electric, magnetic, or optical stimuli, may be envisioned that could guide and mix light beams through almost arbitrary paths chosen along a surface. Yu *et al*. have also created optical vortices with orbital angular momentum (*6*) by impinging a beam at normal incidence on the specially designed planar metasurface of these V-shaped nanoantennas. Such vortices could find use in applications such as optical tweezers.

Metasurfaces (*7*) are the planar version of metamaterials that are engineered to control and tailor the light interaction in unconventional ways (for example, creating materials with optical band gaps that completely reflect light over a given frequency range). In the three-dimensional metamaterials, it can be difficult to engineer a structure that maintains its designed performance and avoids performing like a bulk material. Metasurfaces may offer advantages in this regard because their constituent resonant elements are all distributed in a planar surface and more readily assembled. This type of two-dimensional structure will add another tool to the field of transformation optics (*8*, *9*), in which a prescribed change (such as a phase shift or amplitude variation) is designed into the light path for applications such as cloaking, or where metasurfaces are used to creating highly confined cavity modes (*10*, *11*) of potential interest in quantum optics.

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OCEANS

Eddies Masquerade as Planetary Waves

Dennis J. McGillicuddy Jr.

Variabilities in sea-level and upper-ocean chlorophyll reveal the systematic influence of nonlinear eddies.

The advent of satellite-based remote sensing of ocean color in the late 1970s (*1*) provided the first large-scale views of chlorophyll distributions in the upper ocean. These distributions are a proxy for the biomass of phytoplankton, which drive oceanic productivity. More recently, ocean color measurements have been combined with satellite data on sea-surface height (SSH) and other physical properties of the ocean to elucidate the processes that regulate primary production in the sea. On page 328 of this issue, Chelton *et al*. (*2*) further advance this field by showing that ocean eddies exert a strong influence on near-surface chlorophyll.

Initial comparisons (*3*, *4*) of satellite ocean color measurements and SSH data showed that some of the variability in ocean color was associated with large-scale SSH patterns that propagate westward in extratropical latitudes. The authors attributed these patterns to planetary or Rossby waves, which are freely propagating modes of large-scale variability in the ocean. Four basic processes have been proposed to explain the observed relations, including lateral

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