is sensitive to just one quadrature—the amplitude, say—squeezing that quadrature reduces the noise; the increased uncertainty of the other quadrature is irrelevant.

From the very beginning, gravitational-wave interferometry was one of the anticipated applications of squeezed light. In 1981, four years before squeezed states were first observed in the lab, Carlton Caves worked out the theory of quantum noise in a gravitational-wave detector.[2] As he showed, the interferometer's shot noise depends critically on the zero-point fluctuations of the vacuum state entering the interferometer's output port (the side of the beamsplitter opposite where the laser light goes in, as shown in figure 1). Injecting a squeezed vacuum state—a state of alternating regions of high and low electric-field uncertainty but with zero average electromagnetic amplitude—affects the quantum fluctuations of the light traversing the interferometer's two arms and can ultimately reduce the noise of the output.

To implement that scheme at GEO600, Schnabel and colleagues needed to vastly improve their light-squeezing capability. Squeezing degrades rapidly as light is attenuated, so squeezing by the usual 3–6 decibels (reducing the electric field variance by a factor of 2–4) would not suffice. The researchers used a squeezing factor of 10 dB—a milestone they'd reached in the lab in 2008—and the squeezing needed to be specially tailored to reduce noise over a broad range of potential gravitational-wave frequencies.

The researchers found that squeezing the vacuum by 10 dB gave an output noise reduction of 3.4 dB as measured by the variance, or a factor of 1.5 as measured by the standard deviation. As figure 2 shows, that factor is nearly constant over the high-frequency part of the band. A planned upgrade to GEO600 should more than halve the optical losses and almost double the benefit of squeezing. And an international team, led by researchers at MIT and the Australian National University and including Schnabel and his group, is working on testing squeezed light at one of the two LIGO detectors.

Of all the envisioned applications of squeezed light, enhancement of a gravitational-wave observatory is the first to be implemented on a large scale. Others, including quantum communication and quantum computation, remain at the proof-of-principle stage. Says Aephraim Steinberg of the University of Toronto, "When I started learning about squeezed light about 20 years ago, I thought the original motivation of improved gravitational-wave sensitivity was a beautiful idea that would probably always remain in the realm of science fiction. This is a landmark paper."

Johanna Miller

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Phase-shifting surfaces bend the rules of ray optics

Researchers have outlined a recipe for fashioning subwavelength optical components from plasmonic antennas.

One way to arrive at Snell's law of refraction is to assume, as Pierre de Fermat did nearly four centuries ago, that light rays travel the fastest path between two points. If the points lie on opposing sides of the interface between optically different materials, then that path likely isn't a straight line.

Richard Feynman likened the problem to that of a lifeguard—presumably a faster runner than swimmer—tasked with rescuing a drowning swimmer. The astute lifeguard, rather than make a beeline to the swimmer, would run toward a point on the shoreline that extends the length of the run in exchange for shortening the length of the swim. Likewise, when a light ray passes from a medium with a low refractive index n_i to one with a high refractive index n_t, its angle of incidence θ_i is larger than its angle of refraction θ_t, as formalized by Snell's law: $n_t \sin\theta_t - n_i \sin\theta_i = 0$. The fastest-path assumption also leads to the law governing the angle of reflection θ_r: $\sin\theta_r - \sin\theta_i = 0$.

Now, Harvard University researchers led by Federico Capasso have posed a question that Fermat, Feynman, and Willebrord Snell likely never considered: How would a light ray's trajectory change if, at the surface of reflection and refraction, it experienced a position-dependent phase shift?

Combining theory and experiments, they've arrived at a conclusive answer: A carefully constructed phase-shifting surface—implementable with plasmonic antennas or other small optical resonators—can bend light in ways that defy the traditional laws of reflection and refraction.[1]

Rethinking Snell's law

Fermat's principle works not because light is in a particular hurry to get from one place to the next, but because the fastest path lies at an extremum, where the derivative of the optical path length with respect to small deviations in trajectory is zero. Light waves that hew closely to the fastest path arrive at their destination at nearly the same time and with nearly the same phase and thus interfere constructively. Away from the extremum, neighboring trajectories of light arrive out of phase and cancel each other.

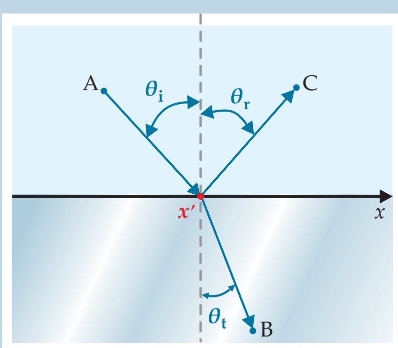

Figure 1. According to Fermat's principle, light that departs from point A refracts and reflects so as to arrive at points B and C with phases ϕ_B and ϕ_C that are constant with respect to small perturbations of the point of incidence x'. By imposing a position-dependent phase shift $\Phi(x)$ along the surface, the location of the paths of stationary phase—and the attendant relationships between the angles of incidence θ_i, refraction θ_t, and reflection θ_r—can be altered arbitrarily. (Adapted from ref. 1.)

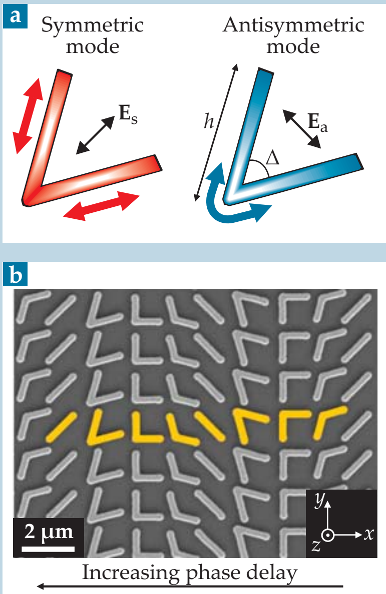

Figure 2. Plasmonic shifts. **(a)** V-shaped plasmonic antennas, with their two resonance modes, can scatter light with a phase delay ranging anywhere from 0 to 2π. Excited plasmons oscillate in the directions indicated by the red and blue arrows and radiate fields oriented along $\mathbf{E}_s$ and $\mathbf{E}_a$. **(b)** By varying the length h of the antenna arms and the angle Δ between them, Harvard University researchers fashioned various V antennas that, arrayed on a silicon wafer in order of increasing phase delay as shown in this scanning electron microscope image, reflect and refract in ways that seem to defy the laws of ray optics. (Adapted from ref. 1.)

Fermat's principle can therefore be recast as a principle of stationary phase. A ray like that depicted in figure 1 reflects and refracts in such a way that light originating at point A arrives at points B and C with phases ϕ_B and ϕ_C that are constant with respect to small perturbations of the point of incidence x'. That is, light travels the path for which $d\phi_B/dx'$ and $d\phi_C/dx'$ are zero.

Adopting that more general interpretation of Fermat's principle, Capasso and his colleagues showed theoretically that a position-dependent phase shift $\Phi(x)$ imposed at the reflecting and refracting surface can alter the location of the path of stationary phase and, along with it, the usual rules of refraction and reflection. They could accommodate the effect with straightforward modifications to Snell's law, $n_t \sin\theta_t - n_i \sin\theta_i = (\lambda/2\pi)d\Phi/dx$, and to the law of reflection, $\sin\theta_r - \sin\theta_i = (\lambda/2\pi)d\Phi/dx$, where λ is the wavelength of light.

"Snell's law assumes that the interface between two media is just a mathematical boundary," lead author Nanfang Yu explains. "By introducing a structured phase delay with a gradient along the surface, it becomes much more than that."

In fact, the Harvard team's equations suggest that reflection and refraction can be altered at will. Negative refraction, multiple critical angles for total internal reflection, and other oddities become possible, as depicted on the cover.

The effect is different from that of metamaterials, which bend light due to

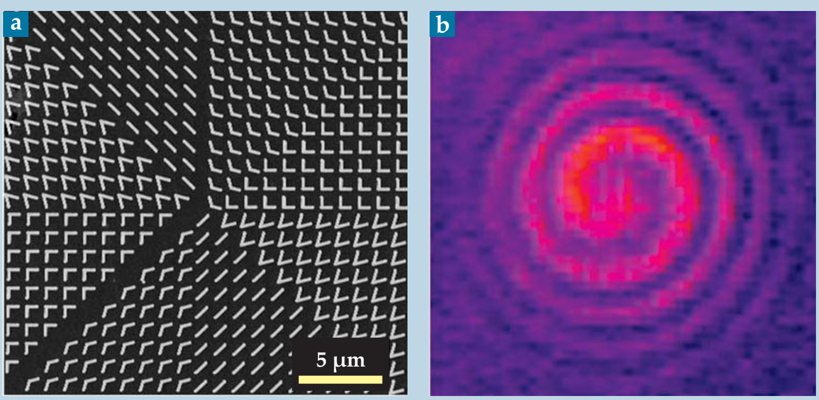

Figure 3. An ultrathin spiral phase plate. (a) The scanning electron microscope image shows plasmonic antennas arranged on a silicon wafer in order of clockwise-increasing phase delay to constitute a spiral phase plate. **(b)** A vortex beam created with the phase plate produces the pattern seen here when it interferes with a Gaussian beam. (Adapted from ref. 1.)

anomalous bulk permittivities. (See the article by Martin Wegener and Stefan Linden, PHYSICS TODAY, October 2010, page 32.) Metamaterials obey Snell's law; they just have unusual indices of refraction. What Capasso and company envisioned are more aptly thought of as metasurfaces.

Plasmonic shifts

Adopting strategies previously used to shape RF wavefronts, the researchers sought to create a metasurface from plasmonic antennas, which scatter light with an amplitude and phase delay that depend on the antennas' resonance properties. (See the article by Lukas Novotny, PHYSICS TODAY, July 2011, page 47.) However, the simplest plasmonic antenna—a straight rod—offers limited control over phase; its phase delay can range only from 0 to π, and the scattering amplitude is appreciable over just half that range.

Coauthor Zeno Gaburro provided a crucial insight—a V-shaped antenna, with its two orthogonally oriented resonance modes, can be designed to scatter light with a phase delay anywhere in the 0 to 2π range. Applying Maxwell's equations, he and his colleagues identified four shapes of V antennas that, along with their mirror images, yield phase delays spanning 0 to 2π in $\pi/4$ increments.

Arrayed in the repeating pattern shown in figure 2, those antennas constitute a discrete approximation to the phase-shifting surface Capasso and company had envisioned with their generalization of Snell's law. The gradient in the phase shift, $d\Phi/dx$, could be adjusted by simply altering the spacing of the antennas. As long as the inter-antenna distance and the antennas themselves are smaller than the wavelength of light, the phase grating behaves like an effective medium.

In a proof-of-principle experiment, the researchers aimed a mid-IR quantum cascade laser at various angles of incidence to their phase-grated wafer. For normal incidence, Snell's law predicts that the angle of refraction should be zero. Indeed, portions of a normally oriented beam passed straight through the wafer, but the portion scattered by the plasmonic antennas refracted with an angle of 40°, in near-perfect agreement with the group's theory. The metasurface proved to be broadband, deflecting light with wavelengths from 5 to 10 μm.

Subwavelength optics

Capasso and his coworkers are already busy dreaming up ways to put their new ideas about reflection and refraction to work. "We have a treasure trove of things to explore—low-aberration lenses, birefringent polarizers, phase plates, you name it," says Gaburro. Among that trove is the phase grating shown in figure 3a, which the researchers created by arranging V-shaped antennas in order of clockwise-increasing phase delay. The subwavelength-thin plate successfully converted a plane wave of IR light into the vortex beam shown in figure 3b.

Nader Engheta of the University of Pennsylvania thinks the work bodes well for low-profile optical devices. "The ability to control the phase of light at will, to shape simple beams into very complex beams, all over subwavelength distances, is a big breakthrough," he says. "It's extremely elegant and beautiful work."

Ashley G. Smart

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Opaque atoms turn transparent in the vacuum field of an optical cavity

A subtle quantum interference effect may offer a path to engineering all-optical logic gates and switches.

Nearly 20 years ago, while working on atomic systems that can lase without inversion, Stanford University doctoral student John Field made a bold prediction. Given a cloud of three-level atoms that are opaque to a light beam, he argued, simply placing the atoms between two closely spaced mirrors can make it transparent to the same beam.[1] A group led by MIT's Vladan Vuletić has now experimentally demonstrated the unusual effect using an exceedingly weak light beam—pulses containing a few or even single photons—focused into an ensemble of about 10^5 cesium atoms.[2] The effect is not small: They see a 40% reduction in absorption probability that appears to emerge out of the quantum blue—induced by the electromagnetic vacuum field in the empty space of an optical cavity. Additional photons injected into the cavity reduce the absorption further still.

The achievement is part of a larger effort over the past couple of years by research groups to combine two workhorse techniques from quantum optics—electromagnetically induced transparency (EIT; see the article by Stephen Harris in PHYSICS TODAY, July 1997, page 36) and cavity quantum electrodynamics. One goal of that effort is to create all-optical logic devices sensitive to single photons.

EIT meets cavity QED

Fast, ubiquitous, and easily detected, photons are ideal carriers of information. Normally they just pass through each other without consequence. So, to tackle a central challenge—controlling the quantum state of one photon using another—researchers turn to atoms as