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."

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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

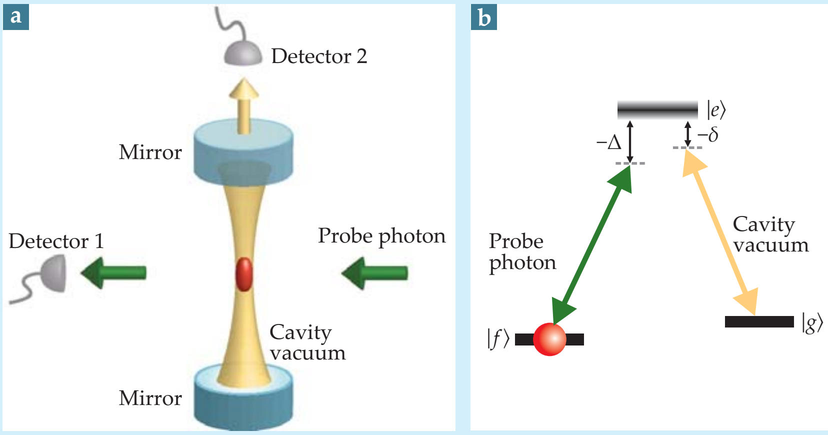

Figure 1. Vacuum-induced transparency. (a) Photons in a probe pulse experience Raman scattering as they interact with a cloud of three-level cesium atoms (red) in an optical cavity. The photons are absorbed and quickly emitted into the cavity, where, after some time delay they are reabsorbed and reemitted collectively—that is, in a way mediated by the response of all the atoms—as an identical probe pulse. Detectors 1 and 2 measure the probe transmission and scattering in the cavity, respectively. **(b)** During the interaction, two transitions from Cs hyperfine states $|f\rangle$ and $|g\rangle$ to an excited state $|e\rangle$ are simultaneously driven by the probe field and the cavity field, respectively. When both fields are either on resonance or detuned from it by the same amount, $\delta \approx \Delta$, coherence between the two hyperfine states cancel the absorption. (Adapted from ref. 2.)

intermediaries. The conceptually simplest approach is to store the photon's state in an atom, or a collection of them, whose coherent response can then subsequently affect another photon.

A single atom, though, simply doesn't absorb a single photon efficiently enough. Placing the atom in a cavity provides an elegant solution. Light that shines along the axis of the cavity repeatedly reflects from its mirrors, and the hundreds of thousands of round trips dramatically increase the atom's absorption cross section. If the mirror spacing is tuned so that the cavity resonates at the frequency of a transition between two electronic states of the atom, the photon and atom become strongly coupled and coherently exchange energy at a rate that exceeds the decay of the system.

At that resonance frequency, atoms normally repeatedly absorb and reemit the photons. Curiously, atoms can fail to absorb radiation when more than two atomic states are involved, a phenomenon discovered by Ugo Fano half a century ago. In atoms that exhibit the effect, destructive interference between two alternate pathways leading to the same excited state eliminates the absorption. In 1991 Field, Stephen Harris (his thesis adviser), Atac Imamoglu (ETH Zürich), and Klaus Boller (University of Twente) showed how to tailor those Fano-type interferences using two optical fields tuned to the separate transition pathways—the EIT technique (see PHYSICS TODAY, May 1992, page 17).

Last year a group led by Gerhard Rempe at the Max Planck Institute of Quantum Optics in Garching, Germany, and, separately, a group led by Dieter Meschede at the University of Bonn implemented the EIT scheme using optical cavities that each contained a single trapped atom—rubidium in one case,[3] cesium in the other.[4] Per the standard protocol, each group pumped its atom along transitions from two neighboring hyperfine ground states to a single excited state: one transition driven by a control laser that "dresses" the excited states and determines the atom's optical response to another, probe laser, incident along the cavity. The control laser could turn on or off the probe's absorption by the atom, and thus the research groups had created the equivalent of an optical transistor.

The vacuum field

In the new work, Vuletić's group opted to squeeze not a single atom into their cavity but a mesoscopic number of them. That decision saved them from a lot of overhead that accompanies work on single atoms, but more importantly, it also allowed them to swap the role of the cavity with that of a control beam.

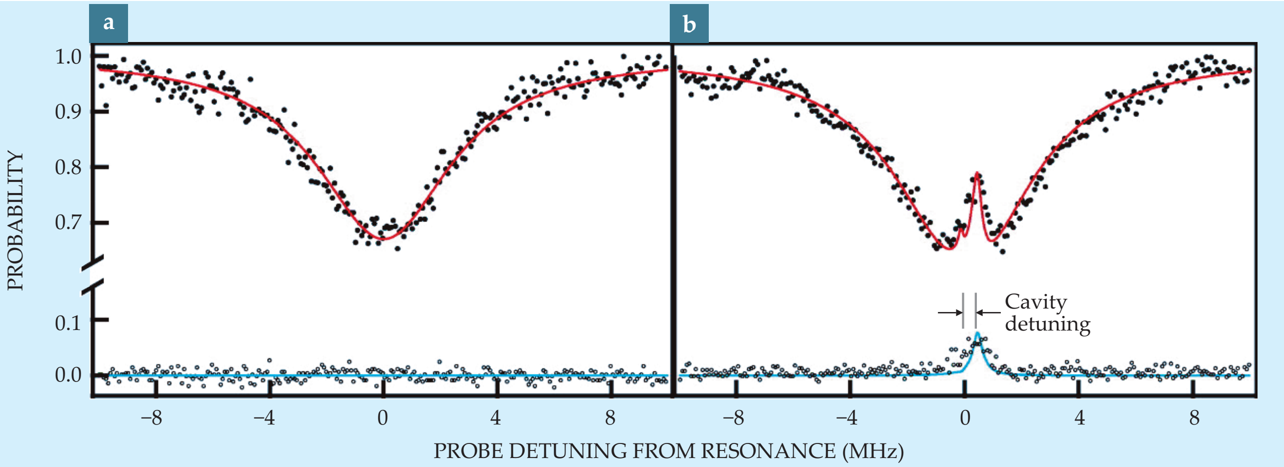

Figure 2. The probabilities of transmission through the cavity (red) and of emission into it (blue) are measured by the two photon-counting detectors sketched in figure 1. **(a)** The spectrum shows a drop in transmission as the probe laser frequency is swept through the resonance frequency of one of the two atomic transitions ($|f\rangle \rightarrow |e\rangle$ in figure 1). When the cavity mode doesn't match the other atomic transition frequency, the probe photons behave as if the mirrors are not there and no photon field builds up between them. **(b)** When the cavity mode is close to the other transition frequency ($|g\rangle \rightarrow |e\rangle$), the vacuum-induced transparency spectrum shows the telltale increase in light transmission in a narrow frequency window. (Adapted from ref. 2.)

Unlike a single atom, which requires a cavity to amplify its influence on the weak probe field, 10^5 atoms are efficient absorbers of a few or even a single photon.

In the MIT approach, a weak probe pulse shines on a cloud of Cs atoms from the side, as illustrated in figure 1. The mirrors' ultrahigh reflectivity traps scattered photons in the cavity, which amplifies their electric field, guarantees strong coupling, and thus ensures that incoming photons are most likely to scatter into a single mode of the resonator. Indeed, that was Field's original prediction: In the strong-coupling regime, fluctuations in the electromagnetic vacuum field are sufficient to induce transparency in the atoms—no control beam required—an effect that's been dubbed vacuum-induced transparency (VIT). Without the vacuum field of the cavity, spontaneous emission from an excited state would send a scattered photon in some random direction where it would be lost in space.

The signature event in VIT, shown in figure 2, is the emergence of a narrow increase in the light transmission when the probe-photon and cavity-vacuum frequencies are both in or near resonance with the two ground state–excited state transitions (figure 1). At those resonance frequencies, the probe absorption and cavity-mode absorption destructively interfere. Crucially, and unlike in EIT, a probe pulse plays dual roles and creates its own transparency: After being absorbed by the atom cloud, a probe photon scatters into the cavity mode, and its reabsorption in that mode by the cloud of atoms renders the cloud transparent to the same probe photon. Eventually, the photon is converted back into the probe pulse, which then exits the system and is detected.

Vuletić's group explicitly measured the influence of the vacuum field on the improvement in the atoms' transparency when the cavity is filled with up to 10 probe photons. The collective improvement increased sublinearly as each photon was added: The transparency was 40% for a single photon, improved to 60% in response to a second one, and went up to 80% when the cavity was filled with all 10 photons.

Photon-number filtering

Although VIT can still serve to switch the state of the atoms from opaque to transparent, if only by detuning the mirror spacing, perhaps, or by introducing a Stark shift, the absence of an external control laser leaves the system without a convenient knob to turn. But the strongly nonlinear effect of low numbers of photons in the cavity, Vuletić argues, provides a way to develop quantum devices such as photon-number filters.[5]

Although the absorption is cancelled by quantum interference, the dispersion of the probe light is not. The presence of the vacuum field induces a delay of 25 ns on the input optical pulse; that corresponds to a light velocity of 1600 m/s. That group-velocity delay experienced by a pulse with a single photon is greater than the delay experienced by pulses with successively higher photon number. The difference will allow researchers to discern how many photons any given laser pulse contains, based on the time it takes each pulse to exit the system.

Similarly, one could focus more than one probe beam at different spatial parts of the cloud, and those probe beams scattering through the cavity should influence each other's group velocity, thanks to their common interaction with the cavity mode. That possibility, comments Harris, opens all kinds of device applications.

Mark Wilson

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