Ultraslow Light Pulse Propagation Observed in Atoms—Both Cold and Hot

The high density and extremely slow motion of atoms at nanokelvin temperatures can be exploited to alter radically the optical properties of the atoms. Clever tricks at room temperature and above can work, too.

Earlier this year, Lene Hau (Rowland Institute for Science and Harvard University) and her coworkers captured the media spotlight with their announcement[1] of having slowed the speed of light pulses through a Bose–Einstein condensate to a mere 17 m/s, down by a factor of nearly 20 million from light's speed in vacuum. (See PHYSICS TODAY, April 1999, page 9.) Marlan Scully and his colleagues at Texas A&M University, the National Institute for Standards and Technology in Boulder, Colorado, and the Harvard-Smithsonian Center for Astrophysics have recently reported comparable results[2] using an ensemble of rubidium atoms that, at a temperature of 360 K, are a billion times hotter than Hau's sodium atoms. And Dmitry Budker's group at the University of California, Berkeley has seen even slower speeds in rubidium at room temperature. Accompanying the slow speeds are extremely nonlinear optical properties, as well.

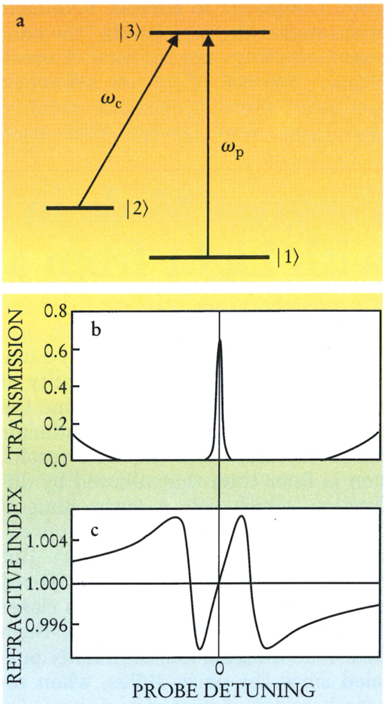
Origins in EIT

All these results have been achieved using the quantum interference effects responsible for electromagnetically induced transparency (EIT). Laser light passing through a medium—clouds of sodium or rubidium atoms in these experiments—is normally absorbed if its frequency is near the transition between one of the ground state's hyperfine levels and one of the first excited states (states $|1\rangle$ and $|3\rangle$ in the accompanying figure). However, as demonstrated in 1991 by Stephen Harris and his coworkers at Stanford University, it is possible to turn off this absorption using a second laser that is tuned to a neighboring transition between a slightly higher hyperfine level (state $|2\rangle$) of the ground state and the same excited state. (See the article by Harris on EIT in PHYSICS TODAY, July 1997, page 36.)

The second laser, called the coupling laser, produces a coherence between states $|1\rangle$ and $|2\rangle$. This coherence, in turn, results in nearly perfect destructive interference for absorbing photons from the first laser (called the probe). Thus the probe beam can pass through with substantially reduced absorption (see part b of the figure). For example, Hau and company report that without the coupling laser, the probe beam was totally absorbed by their sodium atoms at 450 nK; with the coupling laser on, a substantial fraction (about 15%) of the light was transmitted.

Whereas the absorption is canceled in the coherent state produced by the coupling laser, the dispersion is not; the resulting frequency dependence of the index of refraction n is sketched in part c of the figure. The very steep variation that can be created is the cause of the drastically slowed pulse propagation and of remarkable nonlinear optical effects.

Light can be slowed down from its speed c in vacuum just by passing it through a medium with $n > 1$. That's *not* what's going on in these experiments, however. The index of refraction remains close to 1 throughout the transmission window opened up by EIT (as seen in the figure), and the propagation speed—the phase velocity, given by c/n—of a monochromatic beam of light is essentially unchanged from its speed in vacuum.



ELECTROMAGNETICALLY INDUCED TRANSPARENCY (EIT) in a cloud of atoms can produce pronounced delays in light pulse propagation and extreme nonlinear effects. **(a)** To generate EIT, a coupling laser of frequency ω_c is tuned to the transition between the upper hyperfine level $|2\rangle$ of the ground state and an excited state $|3\rangle$. A probe laser pulse is applied at the frequency ω_p of the transition between the lower hyperfine level $|1\rangle$ of the ground state and state $|3\rangle$. **(b)** Calculated transmission window produced by EIT, shown as a function of the detuning of the probe from the $|1\rangle$—$|3\rangle$ resonance. **(c)** The very steep dispersion that is produced in the index of refraction leads to drastically reduced group velocities and to enhanced nonlinear effects. (Adapted from ref. 1.)

But a pulse of light will contain several Fourier components at different frequencies, and the small variations in phase velocity for each frequency can add up to make a big effect. Because the frequency components travel through the medium at slightly different speeds, they get out of phase with each other, with the net result that the envelope of the pulse travels much more slowly than the individual frequency components. The pulse speed, or group velocity, is inversely proportional to the slope of $n(\omega)$ for steep dispersion. Earlier EIT studies[3] measured a group velocity of $c/165$, and group velocities from $c/3000$ to $c/30\,000$ can been inferred from other measurements of dispersion profiles.[4]

Ultracold sodium atoms

Hau and her colleagues observed their dramatically slower group velocities using clouds of sodium atoms cooled to temperatures near or below the transition temperature $T_c = 435$ nK for Bose–Einstein condensation (BEC). The coupling laser is applied transversely to the oblong-shaped atom cloud. A probe laser pulse is then applied orthogonally, along the long axis of the atom cloud. The probe pulse is drastically slowed in the cloud, typically taking 10 μs to traverse the cloud's 100–200 μm length. (Similar delays in an optical fiber would require lengths of over a mile.)

The extremely cold ensemble of atoms has immediate benefits for EIT-induced optical effects. At these very low temperatures, the thermal motion of the atoms is essentially eliminated. "In all geometries, there is no Doppler shift," explains Hau, "and so we can use very low coupling powers." The steepness of the refraction dispersion, and the resulting effects such as reduced group velocity, actually increase with decreased coupling laser power, as long as the coupling laser is strong enough to overcome any Doppler broadening. The experimenters therefore saw their greatest effects with their smallest coupling laser power and their coldest temperature, 50 nK. Also to their advantage is the high number density of the atoms at these low temperatures, on the order of 10^{12}–10^{14} atoms/cm^3. The steepness of $n(\omega)$ is proportional to the density.

Hau and her coworkers saw significant effects above the BEC transition temperature, with group velocities of about 100 m/s for temperatures of a few μK. As the temperature is lowered past T_c, though, there is a marked decrease in the group velocity due to the increase in atom density when the condensate is formed.

Some like it hot

The ultracold temperatures that Hau and her colleagues achieved with their sodium atoms are not necessary for achieving such dramatic optical effects, if one accepts restrictions on the experiment's geometry and carefully controls other experimental parameters. Through such means, both Scully and his coworkers and Budker's group have seen results like Hau's at room temperature and above.

At such warm temperatures, Doppler broadening of the atomic transitions can kill the effects. To overcome this hurdle and obtain the desired steep dispersion, the probe and coupling lasers must be collinear and have nearly the same frequency. Then, because the physics is mostly governed by the difference in the coupling and probe frequencies seen by the moving atoms, the response is essentially independent of the atoms' velocities. Thus most of the effects of Doppler broadening on the EIT resonance can be avoided.

Scully and his coworkers use a rubidium vapor whose density is comparable to Hau's, a few times 10^{12} atoms per cubic centimeter. They also carefully control the amount of neon buffer gas in their sample and the size of their laser beams to reduce the ground state decoherence rate. With this preparation, they have observed a propagation delay of 0.26 ms for an amplitude-modulated probe beam passing through the 2.5 cm length of their sample, which corresponds to a group velocity of about 100 m/s.

Budker's group has achieved an even slower group velocity, 8 m/s, in a rubidium vapor at room temperature. In their experiments, the states $|1\rangle$ and $|2\rangle$ are degenerate but couple to different laser polarizations. A brief rotation of the linear polarization of the coupling laser has the effect of sending in a probe pulse of orthogonal polarization. The coupling and probe beams are therefore inherently collinear. A paraffin coating on the walls of the sample cell makes the ground state coherence very long-lived by suppressing relaxation during atom–wall collisions. Although the rubidium number density is low, Budker and colleagues have observed pulse delays of up to 13 *milliseconds.* They are restricted, however, to very long pulses, which limits the pulse delay to a small fraction of the pulse width. The nonlinear optical processes in the EIT medium, says Budker, are closely related to nonlinear magneto-optic (Faraday) rotation, the primary focus of investigation of his group.[5]

A unique nonlinear medium

The remarkable optical properties of these ensembles of atoms have additional appeal due to the nonlinear effects produced by the dispersion, recently discussed by Harris and Hau.[6] "These are the largest nonlinearities ever produced," explains Harris. With them, it may be possible to perform nonlinear optics at the single-photon level. Compared to current nonlinear optics materials, says Scully, "the nonlinear couplings are millions of times larger." Because of its low efficiency, nonlinear optics at present requires very large laser powers. With such greatly improved efficiencies, the energy density requirements may drop down to the order of nJ/cm^2. (For comparison, the energy density of current optical fibers is about 1 J/cm^2.) Using milliwatt diode lasers, Scully and his colleagues have already produced one example: A new field, coherently generated by wave mixing within their EIT medium, had an amplitude comparable to the transmitted probe beam.

The steepness of the dispersion opens the door to new ways of controlling and monitoring optical properties. For instance, Hau and her coworkers demonstrated in their sample a giant Kerr nonlinearity, in which the phase of one laser beam is controlled by the amplitude of another. This ability could form the basis for an all-optical switch. The steepness may also lead to magnetometers of greatly improved sensitivity.

In addition to being slowed upon entering an EIT medium to a fraction of the speed of light in vacuum, light pulses are compressed spatially by the same fraction. Thus the length of the 2.5 μs pulses of Hau and company was reduced to as short as 40 μm in their sample. Hau notes that such pulses may find application in the probing and manipulation of Bose–Einstein condensates. RICHARD FITZGERALD

References

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Progress Made in Near-Field Imaging with Light from a Sharp Tip

> Recent experiments, on realistic samples, take us further toward the goal of studying details smaller than 10 nm in objects that either emit light or absorb it.

Researchers are striving to image objects optically at smaller and smaller scales. For example, they'd like to determine the chemical identity of individual molecules and examine the optical properties of semiconductor nanostructures. The required resolution is finer than that allowed by diffraction, which sets a lower limit of half the wavelength of light (hundreds of nanometers for visible light). But much higher resolution can be achieved by viewing objects at distances closer than the wavelength of light. Such near-field imaging has been hotly pursued since the early 1990s, when researchers demonstrated its promise for imaging single molecules (see PHYSICS TODAY, May 1994, page 17 and November 1997, page 67). As Dieter Pohl (University of Basel) puts it, "Imagine the potential of microscopy that combines the resolving power of an electron microscope with the enormous spectral resolving power of light."

The standard way of accomplishing near-field microscopy is currently to