

## Researchers Stop, Store, and Retrieve Photons— or at Least the Information They Carry

We've had two years to get used to the idea of light pulses crawling along at no greater than highway speeds (see *PHYSICS TODAY*, July 1999, page 17). Maybe we should have anticipated that the next step would be to stop light pulses dead in their tracks, although it was not so obvious to everyone that the feat could be done. Now, two experimental groups, both based at Harvard University, have shown that it can be: The teams have effectively stopped and stored pulses of light for times on the order of milliseconds before regenerating the light and sending it on its way.<sup>1,2</sup>

The secret is to couple the light to an atomic system—in this case, a dense gas of three-level atoms—and to imprint the information carried by the photons onto the atoms, specifically as a coherent pattern of atomic spins. The procedure is reversible, and the information stored in the atomic spins can later be transferred back to the light field, reconstituting the original pulse. The accomplishment has brought increased interest in using photons to transmit information to and from atomic systems as part of quantum communication and quantum computation schemes. A further challenge along those lines will be to store reversibly nonclassical states such as squeezed light or single photons. It's already been shown that one can map a quantum-correlated squeezed state of light onto an ensemble of atoms.<sup>3</sup>

One of the two experiments was done by Lene Vestergaard Hau and her group from the Rowland Institute for Science and Harvard University,<sup>1</sup> using a cold cloud of sodium atoms just above the transition to a Bose-Einstein condensate. The same group, together with Steve Harris of Stanford University, had shown in 1999 that light could be decelerated<sup>4</sup> to speeds as low as 17 m/s. The other experiment was done on a vapor of warm rubidium atoms by a group from the Harvard-Smithsonian Center for Astrophysics (CfA), led by Ronald Walsworth

How do you hold a moonbeam in your hand? Two research groups at Harvard have found the answer.

(CfA) and Mikhail Lukin of the CfA's Institute for Theoretical Atomic and Molecular Physics (ITAMP).<sup>2</sup>

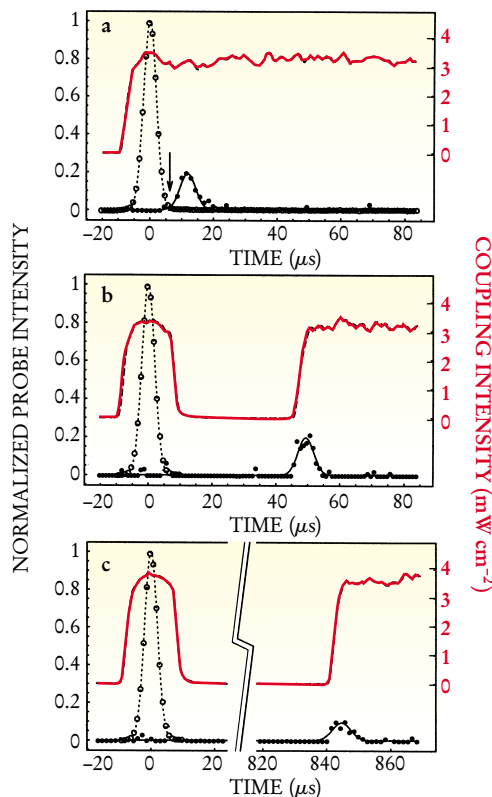
### Transferring information

Perhaps it's a stretch to talk of stopping light because individual photons are not really halted. Rather, the excitation carried by the signal pulse, involving such properties as its angular momentum and pulse shape, is transferred into a collective atomic spin excitation. That's done with the help of a second, coupling beam having in general a different polarization and frequency from the signal pulse. This spin excitation has negligible energy and linear momentum compared to the light pulse; during the trapping operation, those are transferred into the coupling beam and subsequently leave the cell. After some storage time, other coupling

photons are sent through the cell. The information stored in the spin excitations is transferred back to the radiation field, and the original signal pulse is reconstituted. This reversible process depends on the formation of a coupled excitation of light and matter known as a dark-state polariton. (A dark state is one that cannot radiate light.) The information is transferred from purely photonic to purely atomic excitations under the control of the coupling laser.

Hau likens the writing process to the formation of a holographic phase grating on the atomic medium; to read it out, they turn on the coupling laser and the original light pulse comes out. Marlan Scully of Texas A&M University suggests the analogy of quantum teleportation, in which an atom having a state vector at one point in space is reproduced at another point in space; in this case it would be a photon state reproduced at a later time.

In the present method of storing light, the signal light intensity goes to zero as its information is stored in the atomic excitations. But that need not be the case. Scully and his group at Texas A&M have proposed a method that essentially involves shifting to a reference frame in which the atoms move opposite to the light but at the same speed.<sup>5</sup> They propose to accomplish that by Doppler shifting the coupling laser frequency so that it will do its magic only on those atoms within the thermal distribution that are traveling toward the slowed light. Scully told us they also have preliminary results from an experiment that stores a light pulse using a similar



**FIGURE 1.** LIGHT PULSES STORED in cold atoms, shown for various delay times. Pulses transmitted through a cloud of sodium atoms are filled circles fitted with solid lines. The open circles fitted to dotted curves indicate a reference pulse transmitted through a vacuum. (a) Signal pulse delayed by 11.8  $\mu\text{s}$  but not stored. (b) and (c) Pulses stored for 44.3  $\mu\text{s}$  and 839.3  $\mu\text{s}$ , respectively. Light is stored when the intensity of the coupling beam (shown in red) is turned off. (Adapted from ref. 1.)

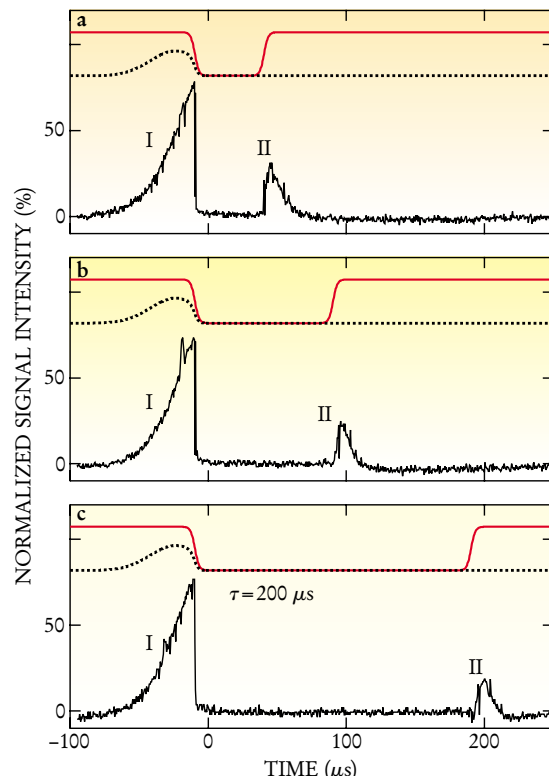
arrangement to that of the CfA group—but reads it out on another light pulse that has a different frequency and that travels in a direction opposite to the original signal pulse.

In the two Harvard experiments, the technique for forming the coupled photon–atom system is electromagnetically induced transparency (EIT), which is a way to render a normally opaque gas transparent to light of a certain wavelength. (See the article by Harris in *PHYSICS TODAY*, July 1997, page 36.) In a simplified picture, the gas is composed of three-level atoms, that is, atoms with two hyperfine or Zeeman ground states and one excited state. Such atoms will normally absorb light from a signal laser pulse whose frequency is just right to raise them from either of their ground states to their excited state. But in EIT one shines in another laser (the coupling laser) whose frequency couples the second ground state also to the excited state. The net result is a destructive interference that prevents the signal laser beam from being absorbed into the excited state.

When the conditions of EIT are met, the index of refraction has a very steep dependence on light frequency. Because of this steep slope, components of the probe beam with slightly different frequencies propagate at different speeds and soon get out of phase. The phase velocity of individual photons does not change but the group velocity is greatly reduced. The slow group velocity is accompanied by a very large spatial compression. For example, in the experiments by Hau and collaborators, a pulse that is 3.4 km long in free space is compressed by a factor of  $10^7$  to a length of 340  $\mu\text{m}$ .

## Stopping light

One might expect that the EIT technique could take the group velocity all the way to zero. But there appeared to be a fundamental problem: To reduce the velocity more, it was thought, one first must make the coupling laser weaker. But reducing the coupling laser intensity also reduces the bandwidth, or frequency spread, of the incoming signal light that can be affected by EIT. If the probe beam has a wider bandwidth, much of it will be absorbed by the atomic medium and not slowed. As the coupling intensity approaches zero—the condition for zero group velocity—the allowed bandwidth for the incoming signal beam is zero,



**FIGURE 2.** LIGHT PULSES STORED in warm atoms, delayed by times of (a) 50  $\mu\text{s}$ , (b) 100  $\mu\text{s}$ , and (c) 200  $\mu\text{s}$  in a cell of 70–90°C rubidium atoms. Pulse I is part of the light pulse that passes through the cell before the coupling laser intensity (red) is turned off. Pulse II is the part of the pulse stored in the cell. Dotted line shows the calculated input signal pulse. (Adapted from ref. 2.)

and no light can be slowed.

About a year ago, Lukin and his colleagues, Susanne F. Yelin of ITAMP and Michael Fleischhauer of the University of Kaiserslautern, Germany, made a key realization.<sup>6</sup> The coupling laser intensity should be taken to zero *after* rather than before the signal pulse has entered the atomic medium. Once the light pulse has been slowed and compressed within the gas, one can continue to reduce the coupling intensity without inducing absorption because the bandwidth of the pulse will continue to narrow in such a way that it always remains within the transparency window. Lukin and his colleagues were inspired in their work by a 1997 proposal by Ignacio Cirac (University of Innsbruck) and others proposing that atomic states might be mapped onto a photon state for transmission to a spatially distant atom.<sup>7</sup> While Lukin and colleagues work with a system of many atoms, Cirac and colleagues have considered the

case of strong coupling between single atoms and single photons in the context of cavity quantum electrodynamics.

## The experiments

To store light pulses, Hau and her colleagues used a gas of sodium atoms having a density of about  $10^{13} \text{ cm}^{-3}$  and a temperature of 0.9  $\mu\text{K}$ . The low temperature minimizes thermal motions, which can smear the relative phase during the storage time. Figure 1 shows the pulses revived after storage times of about 44 and 839  $\mu\text{s}$ . The longer the storage, the smaller the amplitude of the stored pulse as the signal gets dephased with a time constant of about 1 ms. Hau points out that they can shut off the coupling pulse arbitrarily fast.

In the CFA experiment, light pulses were stored in a warm rubidium vapor with atom densities of  $10^{11}$ – $10^{12} \text{ cm}^{-3}$  and temperatures of 70–90°C. Walsworth and his group followed the lead of two groups that had slowed light in a system of warm atoms, despite the complications introduced by the Doppler motion.<sup>8,9</sup> Figure 2 shows light pulses stored for 50, 100, and 200  $\mu\text{s}$ , respectively. The CFA group reported being able to resolve regenerated pulses for storage intervals up to 0.5 ms.

While the pulse in the cold-atom experiment fit entirely within the gas cell, in the CFA experiment, the leading edge of the pulse train passed out of the cell before the coupling laser was taken to zero. This leading edge (peak I in figure 2) was not affected by the storage operation, but that loss was compensated by lower overall losses of the input signal.

Neither experimental group has fully explored the ultimate storage limitation caused by dephasing. Such loss of phase coherence can occur when atoms wander out of the region of the coupling laser or, at high densities, when they have spin-exchange collisions. Studies of decoherence and how to reduce it are under way.

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## Ultrafast X-ray Diffraction Tracks Molecular Shape-Shifting

**I**f you want to understand function, study structure,” exhorted Francis Crick. But knowing a molecule’s static structure is often only the first step toward unraveling how the molecule works, especially in the world of biology. The molecular grappling hook that HIV uses to latch onto its cellular prey, for example, depends on a change of structural shape to initiate infection.

The structural changes that accompany chemical reactions have been studied with fast spectroscopy for the past 50 years. And since the mid-1980s, ultrafast lasers have been the tool of choice in this approach (see PHYSICS TODAY, December 1999, page 19). But with spectroscopy, structure has to be inferred, which is tough to do without a deep and robust understanding of the physics linking spectra to three-dimensional structure.

X-ray diffraction yields structural information directly. In 1982, Ben Larson (Oak Ridge National Lab) and

The molecular workings of photosynthesis, vision, and other light-driven processes can now be studied on the time scales on which they occur.

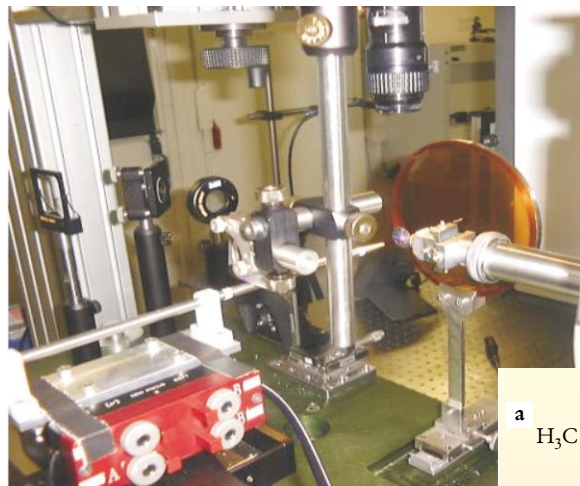
Denny Mills (Argonne National Lab, but then at Cornell University) became the first to couple a nanosecond laser with a synchrotron x-ray source (the Cornell High Energy Synchrotron Source). Their aim was to settle a controversy about the physical mechanism behind the laser annealing of silicon.

In the two decades since that pioneering experiment, the x-ray pulses produced by synchrotrons have become briefer and more intense, lasers have become faster, and the clocks that synchronize the pumping lasers and the probing x rays have become more precise. Exploiting all those developments, Simone Techert, Friedrich Schotte, and Michael Wulff have used ultrafast x-ray diffraction to follow how an organic molecule changes shape in response to light on a time scale of tens of picoseconds.<sup>1</sup> Measuring such rapid confor-

mational changes is “really a tremendous step forward,” says Philip Coppens, who studies laser-generated molecular states at SUNY Buffalo.

Techert’s team did its experiment last year at the ID09 station of the European Synchrotron Radiation Facility in Grenoble, France. At that time, Techert was a postdoc at ESRF (she’s now at the Max Planck Institute for Biophysical Chemistry in Göttingen) and Schotte was a graduate student at the University of Düsseldorf (he’s now at the National Institute of Diabetes and Digestive and Kidney Diseases in Bethesda, Maryland). Wulff developed and directs the ID09 station.

ID09 was built for time-resolved (and high-pressure) studies. After the station’s various insertion devices have intensified, filtered, and focused the bunched x-ray beam, a rotating chopper picks out one 150-ps pulse every revolution of the beam, creating a train of pulses separated by 1.1 ms. Keeping track of the x-ray pulses is a so-called bunch clock, which also controls a femtosecond laser. With a timing accuracy of 3 ps, the bunch clock triggers the laser pulses to excite the



▲ **FIGURE 1. EXPERIMENTAL SETUP** at the European Synchrotron Radiation Facility’s ID09 station. The thin metal pipe is the x-ray collimator; above it are the laser optics. The goniometer holds the sample (a small purple disk), above which is an optical microscope. The amber disk is a beam stop, which protects the image plate detector behind it from high x-ray fluxes. (Courtesy of Simone Techert.)

▼ **FIGURE 2. THE SHAPE** of *N,N*-dimethylaminobenzonitrile ( $C_9H_{10}N_2$ ) changes in response to light. In the nonexcited state, the two methyl groups remain tilted out of the plane of the benzene ring, as shown here from above the molecule (a) and from the side (b). When the molecule absorbs a photon, the methyl groups undergo both an inversion, in which their out-of-plane tilt decreases (c), and a torsion (d), in which they twist about the molecule’s long axis. (Adapted from ref. 1.)

