First, fast, and faster

April 6 2012, By Paul Lett

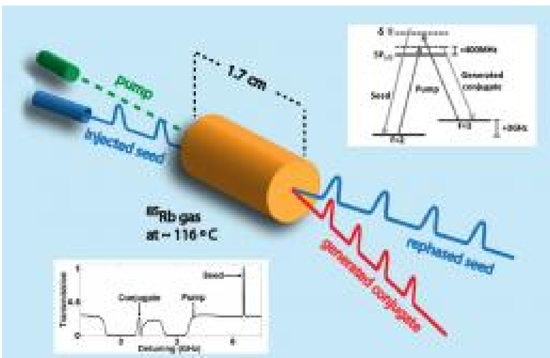

Figure 1. Schematic diagram of the fast light experiment in PML's Laser Cooling and Trapping Group. Inset at top right shows the rubidium energy levels relevant to the experiment. Inset at bottom left shows the relationship between frequency detuning and gain.

(Phys.org) -- Scientists in PML's Quantum Measurement Division have produced the first superluminal light pulses made by using a technique called four-wave mixing, creating two separate pulses whose peaks propagate faster than the speed of light in a vacuum.

Laser Cooling and Trapping Group researcher Paul Lett and colleagues report in a forthcoming paper in Physical Review Letters that this new method of generating "fast light" has resulted in a pulse that travels up to 50 ns faster over the length of a 1.7-cm cell than it would if it were moving through a vacuum.

The findings could have a significant impact on optical communications systems in which signal quality may be improved by speeding up or slowing down pulses. In addition, investigation of the quantum-mechanical correlations between the seed and conjugate pulses will provide fundamental insights into quantum coherence, with potential implications for future quantum information-processing.

Many methods of generating faster-than-light pulses involve sending a pulse composed of multiple wavelengths into a non-linear gain medium. The dispersion properties of the medium (that is, the way it changes a wave's phase velocity depending on its frequency) rearrange the pulse components so that the pulse peak is shifted forward, producing apparent superluminal velocity for the entire group of waves. Conversely, "slow light" pulses can be generated by adjusting conditions so that the peak is shifted backward.

In the PML four-wave mixing experiment (see Figure 1), researchers send "seed" pulses of laser light into a heated cell containing the gain medium, atomic rubidium vapor, along with a separate "pump" beam at a different frequency from the seed pulses. In the medium, the seed pulse is amplified and its peak is shifted so that it becomes superluminal. At the same time, photons from the inserted beams interact with the medium to generate a second pulse, called the "conjugate" because of its mathematical relationship to the seed. Its peak too, the scientists found, can travel faster than an unaltered reference pulse would in a vacuum. Or it can be tuned to travel slower.

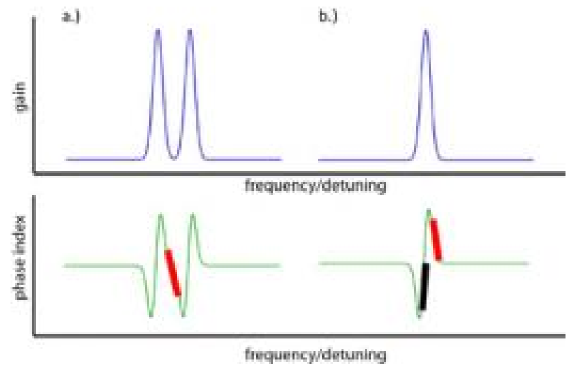

Figure 2. To create fast light, previous experiments have used the double gain features shown in (a.), leading to the linear dispersion region highlighted in red. The NIST experiment uses a gain feature as in (b.), where the region highlighted in red would produce fast light, while the region highlighted in black would produce slow light.

Figure 2a shows the effects of variable dispersion graphically. Sections of the line with a negative slope correspond to conditions in which different frequency components of a pulse “see” a different change in the index of refraction as the pulse moves through a medium. That causes re-phasing, re-forming the pulse ahead of where it would have been. It is that phenomenon that makes it appear that the pulse travels faster than a reference pulse. Researchers can produce this dispersion by pumping a gain medium with the right frequencies. The problem with this method, Lett says, is that the gain features are often so far apart that the dispersion slope is not very steep, resulting in light that is not that much faster than normal.

Instead, the group’s postdoctoral researchers, Ryan Glasser and Ulrich Vogl, used a method more similar to that used to generate slow light, shown in Figure 2b. A single gain feature results in a dispersion with a strong negative slope at the center of a narrow frequency range, causing an increase in the index of refraction for the pulse and slowing it down.

By tuning the frequency of the laser off the center of the gain peak, they were able to access a different part of the dispersion curve that has a steep, positive slope, again generating fast light instead of slow light. Because this slope is steeper than those generated by two gain features, the pulses are sped up more.

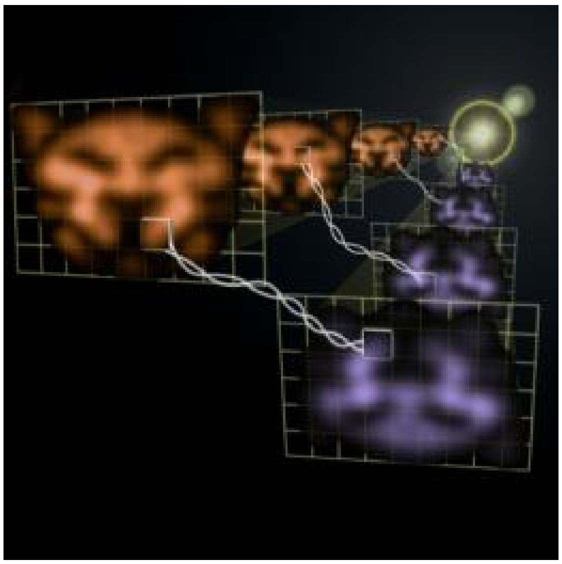

Figure 3. Previous work with writing quantum information onto a beam of light showed how the image of a cat's face - produced by sending light through a mask - could be transmitted, resulting in correlated images with entangled photons. The 4-wave mixing amplifies the original image and generates the second image with local intensity and phase correlations to the first image.

Communications researchers have proposed that slow light could act as a sort of controllable delay line, or storage medium, for light carrying quantum information. Alternatively, the fast conjugate pulse that Lett's group has observed might act as a way to advance the detection of quantum information, should the fast light retain quantum coherence. (NIST scientists emphasized that, while the information detection could be advanced, no information could actually travel faster than the speed of light and that, consequently, principles like causality in special relativity were always respected in these experiments.)

The group has already demonstrated the transmission of an image by passing the seed beam through a mask before injecting it into the cell. (See Figure 3.), In the new work, the injected image traverses the cell faster than a reference image, but has distortion in space and time. Lett attributes this distortion to variations in the intensity of the seed beam and the vapor cell itself. “Different regions of the image actually see different advance,” he says.

One possible way to improve the conjugate image quality is to lessen the temperature variation within the vapor cell itself. Lett and Glasser, however, think that increasing pump laser power and creating a more uniform beam would remove this distortion.

Additionally, the scientists have to determine how much the reality of the experimental equipment will distract from the quality of the information in the light. High-frequency and low-frequency components of the seed pulse fall outside the frequency range that causes fast light, as shown in Figure 2, and will cause distortion of the pulses. This means that the researchers need to set a condition to define when the relevant pulse-containing information has arrived at their detector.

Their solution is to use smooth pulses that fit into the spectral region, but to look at the signal-to-noise ratio of the spatial information contained in the image. Lett is still hopeful about the result: “We can look at it and see that [we] can push the information detection forward and … say that with a real detector and real pulses, [we] can detect the information arriving earlier.”

One major challenge the experiment faced was the stability of the pump laser frequency. Glasser says they struggled with “tweaking the laser to behave properly and be single-mode across the frequencies of interest. That was probably the most frustrating aspect." Additionally, at these frequencies, they were unable to find a commercially-available laser system that provided them with as much optical power as they would have liked.

One immediate application that the group would like to explore for this system is quantum discord. Quantum discord mathematically defines the quantum information shared between two correlated systems – in this case, the seed and conjugate pulses. It is possible that speeding up or slowing down the light could introduce noise into the system, which would destroy quantum coherences that are required for entangling two systems. By performing measurements of quantum discord between fast beams and reference beams, the group hopes to determine how useful this fast light could be for the transmission and processing of quantum information.

More information: "Stimulated generation of superluminal light pulses via four-wave mixing," Ryan T. Glasser, Ulrich Vogl, and Paul D. Lett, forthcoming in *Physical Review Letters*.

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