Faster than a speeding photon

Jon Marangos

The textbooks say nothing can travel faster than light, not even light itself. New experiments show that this is no longer true, raising questions about the maximum speed at which we can send information.

Can a light pulse travel faster than the speed of light? This question has intrigued physicists for many years because such an event could violate Einstein's theory of special relativity and the principle of causality (that 'cause' always precedes 'effect'). Together these imply that no object or information can travel faster than the speed of light, $c = 3 \times 10^8\ \mathrm{m\,s^{-1}}$. For nearly two decades, physicists have been sending certain light pulses faster than c over short distances (so-called superluminal propagation), but the light pulses have always been distorted in the process so interpreting these experiments has been difficult[1–3].

In May this year, Mugnai *et al.*[4] reported superluminal behaviour in the propagation of microwaves (centimetre wavelengths) over much longer distances (tens of centimetres) at a speed 7% faster than c. A report by Wang *et al.*[5] (page 277 of this issue) now demonstrates a very large superluminal effect for pulses of visible light, in which a pulse propagates in a specially prepared medium with a negative velocity of $-c/310$: that is, not only faster than a pulse travelling in a vacuum, but so fast that the peak of the pulse exits the medium before it enters it!

A negative velocity can be understood by comparing the times it would take for identical pulses of light to cover some distance L in a vacuum (travelling at velocity c) and in a superluminal medium (travelling at velocity v). The difference in transit times $\Delta T = L/v - L/c$ is a negative quantity if the velocity is superluminal. If v has a negative value then ΔT can become sufficiently negative that the peak of the pulse emerges from the medium at an instant earlier than when the peak of the pulse enters. This brings to mind Arthur Buller's well-known limerick with relativistic overtones:

There was a young lady named Bright,
Whose speed was far faster than light;
She set out one day,
In a relative way,
And returned home the previous night.

But Wang *et al.*[5] claim that, unlike the heroine of this rhyme, their light pulses do not violate causality. They argue that their superluminal pulses are the result of the wave nature of light itself (fortunately, making it impossible for an object with mass to travel faster than c) and that no actual information, or signal, is transmitted faster than c. They use smooth, well-defined light pulses, so that the peak of the pulse at the output results from the forward rising edge of the input pulse, which occurs far earlier in time, making it consistent with causality. An abrupt feature in the light pulse would not be able to travel faster than c. This means that even if the 'effect' appears to precede the 'cause', you still can't send useful information — such as news of an impending accident — faster than c.

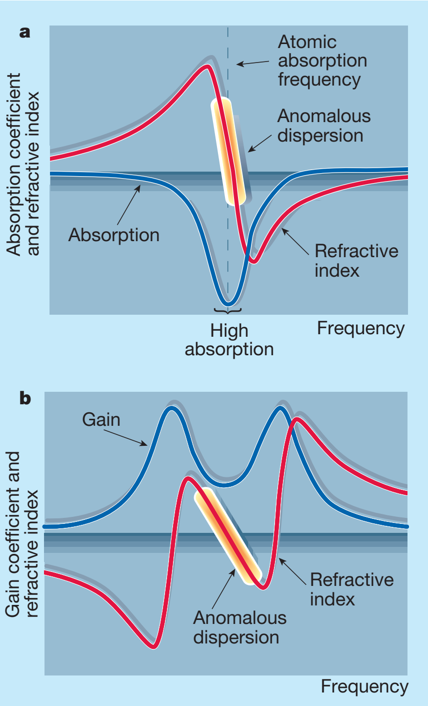

Figure 1 **Sending photons faster than light.** a, **How light absorption and refractive index of a dispersive material change rapidly with wavelength when the wavelength of the light pulse is near an atomic absorption band. The anomalous-dispersion region (where the group velocity of light can be negative) coincides with a region of strong light absorption.** b, **How the gain and refractive index of caesium gas changes with wavelength when there is a 'gain doublet' (two closely spaced peaks) in the amplification of light. Wang *et al.*[5] show that in this case the anomalous-dispersion region can be used to make a pulse of light travel faster than *c*.**

A light pulse has a finite duration, and it is a well-known theorem in physics (the bandwidth theorem) that, to create a pulse of finite duration, an infinite number of waves of different frequency must be added together. The shorter the desired pulse, the larger the bandwidth of frequencies that must be used. All light pulses are therefore formed by a packet of waves of different frequency, each of which has a different amplitude and phase. There is a distinction between the speed of individual waves, called the phase velocity, v_p, and the velocity at which the peak of the wavepacket propagates, known as the group velocity, v_g. In a vacuum the phase and group velocities are the same, but in a highly absorbing or dispersive medium they are usually different. A negative group velocity results when the phases of the different frequency components are shifted by the medium through which they travel, so that the wavepacket they form at the exit is brought forward in time compared with the same pulse travelling through a vacuum.

One way to achieve negative velocity is to modify the refractive index of the medium through which the light passes. Last year scientists at Harvard[6] and elsewhere succeeded in modifying the refractive properties of a cloud of ultracold atoms to generate very slow light pulses with group velocities of a few metres per second. To create the opposite effect — superluminal pulses of light — you need a medium in which the refractive index changes rapidly, for example near an atomic absorption frequency (Fig. 1a). The only problem is that the so-called anomalous dispersion region in Fig. 1a, where v_g can be negative[3], is also in a region where there is increased light absorption. In experiments with such highly absorbing materials, the light pulses are either strongly distorted or absorbed, making any faster-than-light claims difficult to interpret.

A more promising approach to making superluminal light pulses is to work with an atomic medium where there is gain (amplification of light waves) at the atomic transition frequency. This is achieved in a laser-type medium by creating a 'population inversion', whereby a higher population of atoms are in the excited than in the lower-energy atomic state[7]. In this case, anomalous dispersion occurs at frequencies lower than the transition frequency. But close to the transition frequency, where the effect is largest, the rapidly changing gradient in the refractive index causes severe pulse distortion. One way round this problem is to use a gain doublet[8] — that is, two closely spaced regions of gain where the zone between has steep anomalous dispersion but without strong pulse distortion (Fig. 1b). This is what Wang *et al.*[5] have now achieved.

The experiment by Wang and co-workers creates this type of gain doublet in a six-centimetre cell containing caesium gas by using two laser fields closely spaced in frequency (see Fig. 1a on page 277). They first measured the refractive index of the caesium using a third 'probe' laser, and produced a dispersion curve similar to Fig. 1b, with a steep gradient in the anomalous dispersion region corresponding to an expected $v_g = -c/330$. When they sent a 3.7-microsecond light pulse through the medium, it appeared at the exit of the cell before it arrived at the entrance. Although the pulse itself is only shifted forward in time by a modest fraction (1.7%) of its width, this corresponds to the wavepacket leaving the cell 62 nanoseconds before it arrives — in other words, travelling nearly 20 metres away from the cell before the incoming pulse enters it. Compared with the time to travel six centimetres in a vacuum (about 0.2 nanoseconds), the 62-nanosecond lead means that the group velocity of the pulse inside the medium is $-c/310$, close to the predicted value.

In this experiment, each of the different frequency components making up the pulse experiences a slightly different dispersion in the medium. The relative phases between them are therefore changed and the pulse shape is shifted to bring the pulse wavepacket (or group velocity) forward in time. So the anomalous dispersion leads to interference between different frequency components of the pulse that produce the superluminal effect. Although amazing, this type of superluminal pulse propagation does not violate the principle of causality.

There remains, however, some debate about what is the true speed at which information is carried by a light pulse. Traditionally the signal velocity of a light pulse is defined as the speed at which the half peak-intensity point on the rising edge of the waveform travels; in this experiment, this is clearly superluminal. In contrast, some researchers argue that the true speed at which information is carried by a light pulse is not the group velocity of a smooth pulse, but rather the speed at which a sudden step-like feature in the waveform travels, which so far has not been shown to exceed *c*. Superluminal effects are especially interesting in the case of light pulses consisting of only a few photons, in which it could be argued that the group velocity is the same as the velocity of the individual photons. The type of superluminal behaviour discussed here is also predicted to apply to single photons[8], which might have implications for the transmission of quantum information. ■

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1. Steinberg, A. M., Kwiat, P. G. & Chiao, R. Y. *Phys. Rev. Lett.* **71,** 708–711 (1993).
2. Balcou, Ph. & Dutriax, L. *Phys. Rev. Lett.* **78,** 851–854 (1997).
3. Chu, S. & Wong, S. *Phys. Rev. Lett.* **48,** 738–741 (1982).
4. Mugnai, D., Ranfagni, A. & Ruggeri, R. *Phys. Rev. Lett.* **84,** 4830–4833 (2000).
5. Wang, L. J., Kuzmich, A. & Dogariu, A. *Nature* **406,** 277–279 (2000).
6. Hau, L. V., Harris, S. E., Dutton, Z. & Behroozi, C. H. *Nature* **397,** 594–598 (1999).
7. Chiao, R. Y. *Phys. Rev. A* **48,** R34–R38 (1993).
8. Steinberg, A. M. & Chiao, R. Y. *Phys. Rev. A* **49,** 2071–2075 (1994).

Biophysics

Science in motion

Philip Ball

'If it moves, it's biology', goes the saying, but the moment one asks how it moves, physics intervenes. Between the release of chemical energy and the buzz of a fly's wing there is a host of minor mechanical miracles. At the other end of the scale, co-operative motions of groups of organisms ranging from bacteria to fish and humans can influence the movements of individuals. Can it be a coincidence that both fish and slime mould cells swarm in the same patterns (Fig. 1)? A workshop* in Budapest last month showed how physical and biological sciences can collaborate to explain these miracles of motion.

Motion in biology is a cascade of mechanical transduction processes, from the molecular scales of time and length upwards. At every level in this hierarchy, biological motion provides perhaps the ideal testing ground for the current migration of physicists towards biological problems. At the molecular level, the two have long been blended in conventional biophysics, which has been revitalized by single-molecule probe techniques. It is hard to imagine how, without these, one could unravel the secrets of muscle proteins such as titin — the spring that gives relaxed muscle its elasticity. For example, the inequivalence of stretching and contracting in individual titin molecules can be attributed to rapid unfolding and slow refolding of repetitive protein domains (M. Kellermayer, Pécs Univ., Hungary).

But whereas the movements of motor proteins like myosin and kinesin and springs like titin are being decoded residue by residue, it appears that something else may be needed to convert protein movements into the motion of whole cells. Migrating cells are central to embryo development and wound healing.

Myosin typically collects at the trailing edge of the cell to pull it in the direction of motion, whereas a polymerizing network of actin pushes the leading edge forward (G. Borisy, Univ. Wisconsin-Madison). How can actin, a relatively limp filamentary polymer, develop any force to push on the cell membrane? The answer, it seems, is that repeated branching of the polymers, at an angle close to 70°, ensures a constant supply of short filaments at the front edge of the network. These are stiff enough to generate the necessary force. The branching is initiated on the inside of the membrane itself by a membrane-bound protein called Wasp, which activates a second protein, Arp 2/3, to secure itself to actin and provide a junction for a branching filament.

But how do new actin monomers add to the advancing tip if it is pushing against the membrane? Here help is on hand from physics, specifically from George Oster's idea

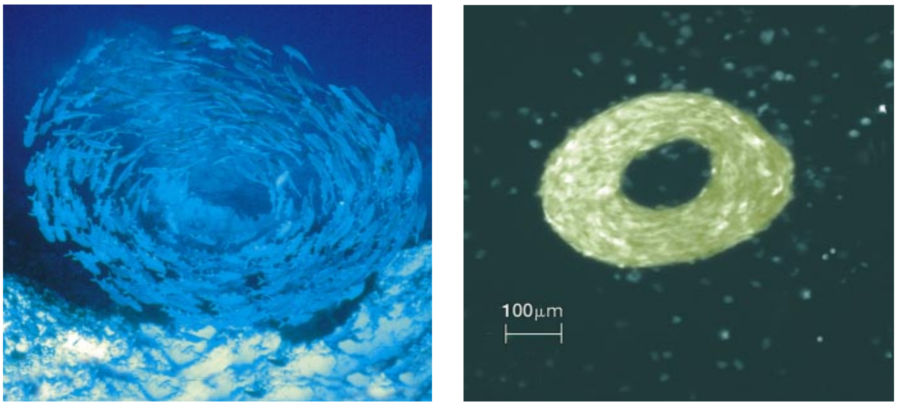

Figure 1 **Swirling vortex motion is a mode of collective swarming behaviour exhibited by both fish (left) and slime mould cells (right).**

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