Gain-assisted superluminal light propagation

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Einstein's theory of special relativity and the principle of causality[1–4] imply that the speed of any moving object cannot exceed that of light in a vacuum (c). Nevertheless, there exist various proposals[5–18] for observing faster-than-c propagation of light pulses, using anomalous dispersion near an absorption line[4,6–8], nonlinear[9] and linear gain lines[10–18], or tunnelling barriers[19]. However, in all previous experimental demonstrations, the light pulses experienced either very large absorption[7] or severe reshaping[9,19], resulting in controversies over the interpretation. Here we use gain-assisted linear anomalous dispersion to demonstrate superluminal light propagation in atomic caesium gas. The group velocity of a laser pulse in this region exceeds c and can even become negative[16,17], while the shape of the pulse is preserved. We measure a group-velocity index of $n_g = -310(\pm 5)$; in practice, this means that a light pulse propagating through the atomic vapour cell appears at the exit side so much earlier than if it had propagated the same distance in a vacuum that the peak of the pulse appears to leave the cell before entering it. The observed superluminal light pulse propagation is not at odds with causality, being a direct consequence of classical interference between its different frequency components in an anomalous dispersion region.

When a light pulse of frequency ν and bandwidth $\Delta\nu$ enters a dispersive linear medium of an optical refractive index $n(\nu)$, the light pulse propagates at the group velocity $v_g = c/n_g$, where $n_g = n(\nu) + \nu dn(\nu)/d\nu$ is the group-velocity index. If the group-velocity index remains constant over the pulse bandwidth $\Delta\nu$, the light pulse maintains its shape during propagation. In recent experiments involving electromagnetically induced transparency (EIT)[20–22], the group-velocity index was greatly enhanced using the lossless normal dispersion region between two closely spaced absorption lines. Thus the group velocity of light was dramatically reduced to as slow as 8 m s^{-1} (refs 23–25). Conversely, between two closely spaced gain lines[16], an anomalous dispersion region appears where $\nu dn(\nu)/d\nu$ is negative and its magnitude can become large. In this situation, the group velocity of a light pulse can exceed c and can even become negative[16,17].

A negative group velocity of light is counterintuitive but can be understood as follows. For a medium of a length L, it takes a propagation time $L/v_g = n_g L/c$ for a light pulse to traverse it. Compared with the propagation time for light to traverse the same distance in a vacuum, that is, the vacuum transit time L/c, the light pulse that enters the medium will exit at a moment that is delayed by a time difference $\Delta T = L/v_g - L/c = (n_g - 1)L/c$. When $n_g < 1$, the delay time ΔT is negative, resulting in an advancement. In other words, when incident on a medium with group-velocity index $n_g < 1$, a light pulse can appear on the other side sooner than if it had traversed the same distance in a vacuum[5,15]. Furthermore, in contradiction to traditional views that a negative group velocity of light has no physical meaning, when the group-velocity index becomes negative, the pulse advancement $-\Delta T = (1 - n_g)L/c$ becomes larger than the vacuum transit time L/c. In other words, it appears as if the pulse is leaving the cell even before it enters. This counterintuitive phenomenon is a consequence of the wave nature of light.

The principle of the experimental realization of a lossless anomalous dispersion region and hence gain-assisted superluminality (GAS) is illustrated in Fig. 1a. In a gaseous medium of atoms each of which has three levels: an excited state $|0\rangle$ and two ground states $|1\rangle$ and $|2\rangle$, we first prepare all atoms to be in a ground state $|1\rangle$ by optical pumping. For simplicity, we first ignore the Doppler shift and assume that the atoms are at rest. We apply two strong continuous-wave (CW) Raman pump light beams E_1 and E_2 that propagate through the atomic medium. The frequencies of E_1 and E_2, ν_1 and ν_2, are different by a small amount 2Δ and both fields are detuned from the atomic transition frequency ν_{01} ($|0\rangle$ to $|1\rangle$) by a large average amount Δ_0. Since the Rabi frequencies associated with the fields E_1 and E_2 are small compared with the common detuning Δ_0, the atoms mostly remain in state $|1\rangle$. When a probe light beam E_p is introduced, a Raman transition can occur, causing an atom to absorb a Raman pump photon from the fields E_1 or E_2 and emit a photon into the field E_p while making a transition from $|1\rangle$ to $|2\rangle$. Obviously, there are two frequencies where the gain in the probe field is maximized. The maximum gain occurs when the probe field is resonant with the Raman transitions caused by either of the two pump fields E_1 and E_2. The optical susceptibility of the probe field can thus be derived as

$$\chi(\nu) = \frac{M_1}{\nu - \nu_1 + i\gamma} + \frac{M_2}{\nu - \nu_2 + i\gamma} \qquad (1)$$

Here $M_{1,2} = \frac{|\mu_{02}|^2}{4\pi\hbar\epsilon_0}\frac{|\Omega_{1,2}|^2}{\Delta_0^2}N$ with μ_{02}, $\Omega_{1,2}$ and N being the dipole moment of the $|0\rangle$ to $|2\rangle$ atomic transition, the Rabi frequencies of the Raman pump fields E_1 and E_2 and the effective atomic density difference of states $|1\rangle$ and $|2\rangle$, respectively. γ is the Raman transition inverse lifetime. The refractive index and the gain coefficient obtained using the susceptibility given in equation (1) are shown in Fig. 1b. In the region between the two gain lines, an anomalous dispersion region appears.

However, in a gaseous atomic medium, there is Doppler broadening: for atoms moving at different velocities in the light propagation direction, the common detuning Δ_0 is shifted. The effects of Doppler broadening are twofold. First, the M-factors in equation

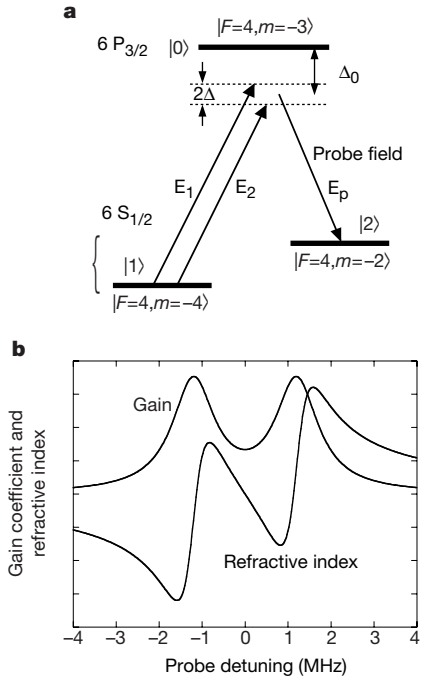

Figure 1 Gain-assisted anomalous dispersion. **a**, Schematic atomic level diagram. **b**, Frequency-dependent gain coefficient and refractive index obtained from equation (1) for a probe light beam propagating through an atomic medium with its level structure shown in **a**.

(1) are replaced by

$$M_{1,2} = \frac{|\mu_{02}|^2}{4\pi\hbar\epsilon_0}\int dV \frac{|\Omega_{1,2}|^2}{(\Delta_0 + vV/c)^2}N(V) \qquad (2)$$

Here $N(V)$ is the effective density of atoms in the velocity group V. The common detuning Δ_0 is replaced by the Doppler detuning $\Delta_0 + vV/c$. However, the quadratic dependence of the coefficient M on the Doppler detuning prevents cancellation. Second, inside the Doppler profile, the expression for M given above appears to become singular when the detuning $\Delta_0 + vV/c$ vanishes. This is automatically avoided in practice because for atoms with detuning $\Delta_0 + vV/c$ that is less than a certain linewidth containing contributions from the natural linewidth and power broadening, the Raman pump beams act like reversed optical pumping beams that deplete these velocity groups. For atoms in the velocity group where the effective detuning $\Delta_0 + vV/c$ vanishes, $N(V)$, the atom number difference also vanishes. Finally, the atoms that are pumped away from the level $|1\rangle$ act as a weak broadband absorber. This compensates for the small residual gain in the region between the two Raman gain lines shown in Fig. 1b.

The experiment was performed using an atomic caesium (Cs) vapour cell at 30 °C and the main set-up is shown in Fig. 2. The caesium atoms are confined in a 6-cm-long Pyrex glass cell coated with paraffin for the purpose of maintaining ground-state spin polarization. The atomic cell is placed in a small (1.0 G) uniform magnetic field parallel to the light propagation direction. In region I, two laser beams optically pump the atoms into the ground-state hyperfine magnetic sub-level $|F = 4, m = -4\rangle$ that serves as state $|1\rangle$ (Fig. 1a). One left-hand ($\sigma-$) polarized laser beam from a narrow linewidth diode laser is tuned to the 852-nm D_2 transitions to empty the $6S_{1/2}$ $F = 3$ hyperfine ground state. We further apply a second laser ($\sigma-$) to optically pump the atoms into the $|F = 4, m = -4\rangle$ state via the D_1 transitions to the $6P_{1/2}$ hyperfine excited states. When atoms collide with the paraffin-coated glass walls, they change their velocities inside the Doppler profile while remaining in the ground state $|F = 4, m = -4\rangle$ and hence the majority of the caesium atoms inside the cell are prepared into this state. In region II, three light beams derived from the same laser propagate co-linearly through the cell. Two strong CW Raman pump beams are right-hand circularly polarized ($\sigma+$) and are frequency-shifted by 2.7 MHz using two acousto-optical (A/O) modulators. The linewidths of the A/O modulators are 20 kHz. A third light beam, the probe beam, is left-hand polarized ($\sigma-$) and by using another A/O can be tuned in frequency and operate either in CW or pulsed mode. In the experiment, the pre-emptied hyperfine magnetic sublevel $|F = 4, m = -2\rangle$ serves as the Raman transition final state $|2\rangle$. The intermediate Raman transitional state $|0\rangle$ is served primarily by the hyperfine sublevel $|F = 4, m = -3\rangle$ of the $6P_{3/2}$ excited state with additional contributions from transitions through $|F = 3, m = -3\rangle$ and $|F = 5, m = -3\rangle$ hyperfine sublevels.

First, we operate the Raman probe beam in a tunable CW mode to measure the gain and refractive index of the atomic system as a function of the probe frequency detuning. Figure 3 shows the measured gain coefficient and the refractive index. In order to obtain the gain coefficient, we first measure the intensity of the transmitted probe beam as a function of probe frequency. We then extract the gain coefficient. The refractive index is measured using a radio-frequency interferometric technique. The superimposed curve is obtained from equation (1) using parameters obtained from the gain measurement. From Fig. 3, we see that a negative change of $\Delta n = -1.8 \times 10^{-6}$ in the index occurs over a narrow probe frequency range of $\Delta\nu = 1.9$ MHz between the two gain lines. Using the expression of the group-velocity index, we obtain the result $n_g = -330\,(\pm 30)$ in that frequency region. The 10% error reflects the accuracy of the phase measurement.

Next, a pulsed Raman probe beam is employed to observe the superluminal propagation. A near-gaussian probe pulse with a 3.7-μs full-width at half-maximum (FWHM) is generated by applying an electronic pulse to the probe beam A/O modulator. A portion of the pulsed probe beam is divided at a beam-splitter before the atomic cell and aligned onto photodiode D1 as a reference. Because the total number of atoms in the probe volume limits the maximum net energy gain of the probe pulse, we use a very weak probe beam (<1 μW) in order to avoid saturation and hence to optimize the anomalous dispersion. A high-sensitivity avalanche photodiode, reverse-biased below breakdown, serves as detector D2 to measure the weak probe pulse that propagates through the atomic cell. The photoelectric current produced by detector D2 is converted to a voltage signal using a 500-Ω load resistor and recorded by a digitizing oscilloscope using a synchronized output signal from the pulse generator as the trigger. Pulses from detector D1 are also recorded.

In order to measure the pulse propagation time, we first tune the diode laser that produces the Raman pump and probe beams far off-resonance from the 852-nm caesium D_2 lines (by 2.5 GHz) to

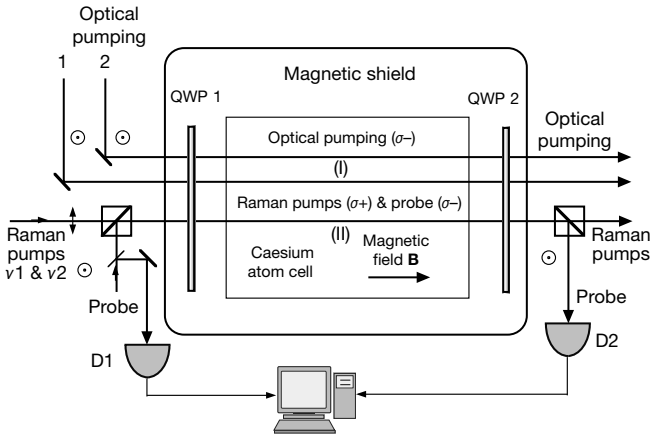

Figure 2 Schematic experimental set-up. Two optical pumping beams tuned to the caesium (Cs) atomic D_1 and D_2 transitions prepare the atoms in its ground-state hyperfine sublevel $|F = 4, m = 4\rangle$. Two Raman pump beams and a Raman probe beam derived from a common narrow linewidth diode laser propagate co-linearly parallel to a small magnetic field **B** through the atomic cell. Two λ/4 plates (QWP1&2) are used to prepare the three light beams into the corresponding circular polarization states and then separate them for analysis.

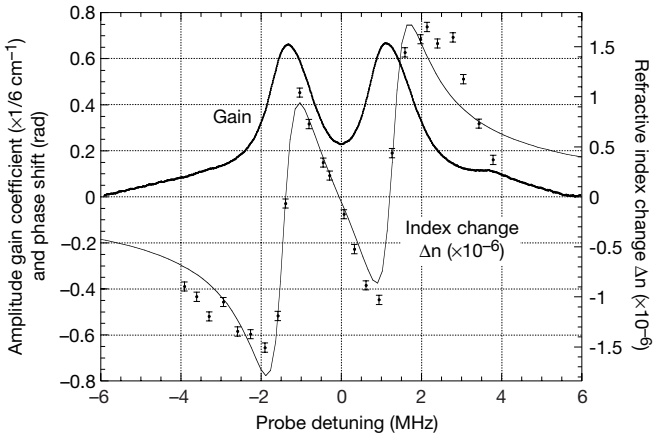

Figure 3 Measured refractive index and gain coefficient. The superimposed curve over the index data is obtained using equation (1) with parameters ν_1, ν_2 and γ obtained experimentally.

measure the time-dependent probe-pulse intensity. When the laser is placed far off-resonance, the atoms have no effect and the probe pulse propagates at speed c inside the cell. We then tune the diode laser back to within the Doppler absorption profile and lock the laser on its side. Using the same synchronized pulse generator output signal as the trigger, we record the time-dependent probe-pulse intensity measured by detector D2. We verify that no systematic drift is present by tuning the laser off-resonance again by the same amount and record the probe-pulse signal; the two off-resonance pulses are identical to within less than 1 ns. Probe pulses both on and off-resonance are shown in Fig. 4. Probe pulses on resonance show a 40% transmittance and this is due to the broad-band absorption of those atoms reverse-pumped away from the $|F = 4, m = -4\rangle$ state. It is evident that there is almost no change in the pulse shape. The front edges and the trailing edges of the pulses are shown in the insets; both edges are shifted forward by the same amount. Using a least-squares fitting procedure, we obtain a pulse advancement shift of 62 ($\pm$1) ns. Compared with the 0.2-ns propagation time for light to traverse the 6-cm length of the atomic cell in vacuum, the 62-ns advancement gives an effective group-velocity index of $n_g = -310\ (\pm 5)$. The small discrepancy with the group-velocity index inferred from the refractive index data is due to experimental errors. The pulses measured with detector D1 are also recorded in the sequence of the off-, on-, off-resonance pulse-propagation measurements and are found to be identical to within 1.5 ns.

Here we note that the physical mechanism that governs the observed superluminal light propagation differs for the previously studied anomalous dispersion associated with an absorption or a gain resonance[5–17]. Specifically, in the anomalous dispersion region of a single gain resonance, the superluminal propagation of a pulse has been viewed as the result of the amplification of the pulse front edge and absorption of its tail[5]. In the present experiment, the 3.7-μs FWHM probe pulse has only a 120-kHz bandwidth (FWHM) that is much narrower than the 2.7-MHz separation of the two gain lines and the probe pulse is placed in the middle of these gain lines spectrally. The probe pulse thus contains essentially no spectral components that are resonant with the Raman gain lines to be amplified. Therefore, the argument that the probe pulse is advanced by amplification of its front edge does not apply. The superluminal light propagation observed here is the result only of the anomalous dispersion region created with the assistance of two nearby Raman gain resonances. We emphasize that the observed superluminal light propagation is a result of the wave nature of light[2]. It can be understood by the classical theory of wave propagation in an anomalous dispersion region where interference between different frequency components produces this rather counterintuitive effect.

Finally, we note that the observed superluminal light pulse propagation is not at odds with causality or special relativity. In fact, the very existence of the lossless anomalous dispersion region given in equation (1) is a result of the Kramers–Kronig relation which itself is based on the causality requirements of electromagnetic responses[3,5]. Remarkably, the signal velocity[4] of a light pulse, defined as the velocity at which the half point of the pulse front travels, also exceeds the speed of light in a vacuum, c, in the present experiment. It has also been suggested[4,16] that the true speed at which information is carried by a light pulse should be defined as the "frontal" velocity of a step-function-shaped signal which has been shown not to exceed c (ref. 4). The implications of the present experiment on signal propagation and its speed will be further analysed, particularly for the case when the light pulse consists of only a few photons. □

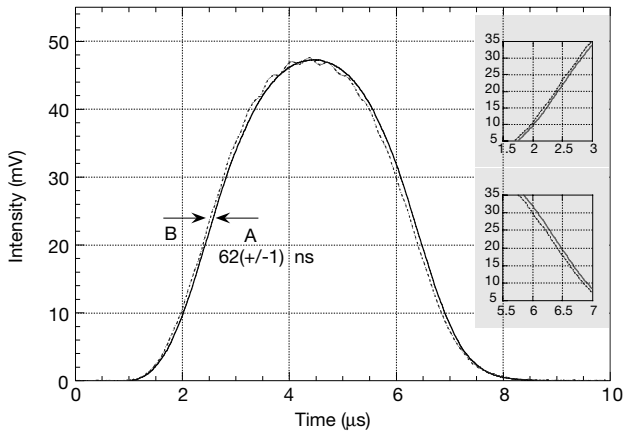

Figure 4 Measured pulse advancement for a light pulse traversing through the caesium vapour in the gain-assisted superluminality state. A indicates a light pulse far off-resonance from the caesium D_2 transitions propagating at speed c through 6 cm of vacuum. B shows the same light pulse propagating through the same caesium-cell near resonance with a negative group velocity $-c/310$. Insets show the front and trailing portions of the pulses. Pulses A and B are both the average of 1,000 pulses. The off-resonance pulse (A) is normalized to the magnitude of B.

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