Superluminal light pulses, subluminal information transmission

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Abstract: We describe optical pulse propagation through a medium where the group velocity exceeds the speed of light in vacuum. The information velocity is observed to be subluminal, consistent with the special theory of relativity.

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1. Introduction

One fundamental characteristic of an optical pulse is its speed of propagation. Unfortunately, it is not possible to assign a single velocity to a pulse when it propagates in an optical material for which the refractive index is a function of frequency because the pulse disperses during propagation. In a situation where the refractive index does not vary too much over the spectrum of the pulse, it is customary to introduce a quantity known as the group velocity that describes approximately the speed of the peak of the pulse. The group velocity is defined as

$$\upsilon_g = \left. \frac{c}{n + \omega \dfrac{dn}{d\omega}} \right|_{\omega=\omega_o} , \tag{1}$$

where c is the speed of light in vacuum, n is the refractive index, and ω_o is the carrier frequency of the pulse. Physically, $\upsilon_g \neq c$ because the speed of each component sinusoidal wave making up the pulse is different in a dispersive material, thereby shifting the location of constructive interference among the waves.

According to Eq. (1), the group velocity can take on unusual values when $dn/d\omega < 0$, as shown in Fig. 1a. It is seen that υ_g is be less than c when the dispersion is normal ($dn/d\omega > 0$), the so-called region of "slow light," or it can be greater than c or even take on negative values in the region of "fast light" when the dispersion is anomalous [1]. In the fast light region, a pulse appears to transit through the medium faster than it would have if it were to travel over the same distance in vacuum. In the case when $\upsilon_g < 0$, the peak of the pulse exits the medium before it passes the entrance face.

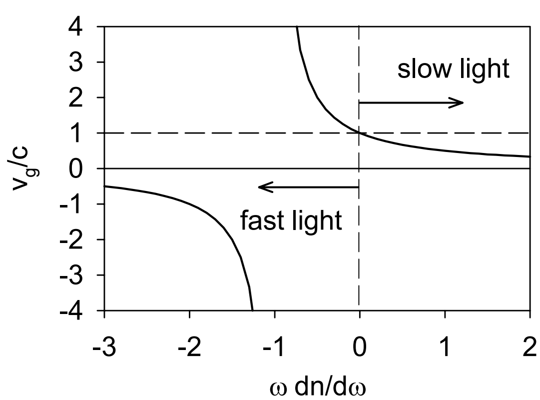

Fig. 1. Regions of fast and slow light. Shown is the group velocity as a function of the chromatic dispersion under conditions when $n(\omega_o) = 1$.

For nearly a century, it was believed that the group velocity loses its meaning when it takes on superluminal values. However, a theoretical investigation by Garrett and McCumber [2] of Gaussian-shaped pulses propagating through a medium with anomalous dispersion indicates that the group velocity does indeed retain a physical significance and accurately predicts the speed of the peak of the pulse. Specifically, they considered pulses propagating through a resonance absorber, and they assumed the "important frequencies" of the pulse fall well within the region of anomalous dispersion. Their prediction was confirmed for the case of pulses propagating through a crystal of GaP:N [3] and a gas of ammonia molecules [4] when the carrier frequency of the pulses was tuned to the center of an absorbing resonance in the material.

More recently, Steinberg and Chiao investigated pulse propagation through a medium possessing two closely spaced amplifying resonances [5]. The dispersion is anomalous between the gain doublet and higher-order dispersion can be minimized by adjusting the frequency separation of the doublet with respect to the widths of the resonances. Figure 2 shows the gain spectrum and refractive index for such a doublet. A gain-doublet fast-light medium has an advantage over a medium with a single absorbing resonance because the pulse experiences amplification rather than attenuation.

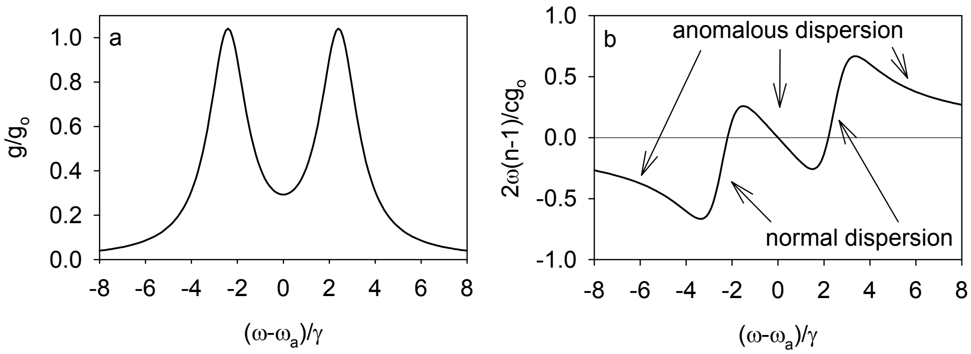

Fig. 2. Characteristics of a gain doublet. a) Gain coefficient g and b) refractive index n as a function of frequency, where g_o is the gain coefficient at the peak of one of the resonances, ω_a is the frequency at the center of the doublet, γ is the half-width at half maximum resonance linewidth. The doublet spacing is set to 9.66γ to minimize higher-order dispersion between the doublet.

2. Using stimulated scattering to achieve large anomalous dispersion

As pointed out by Steinberg and Chiao [5], a gain doublet can be obtained via stimulated Raman scattering when an alkali-metal vapor is driven by an intense two-frequency Raman pump beam. The doublet spacing can be adjusted simply by setting the frequency difference of the bichromatic pump beam. In the scattering process, the intense beam creates a population inversion in the hyperfine-split ground state via optically pumping and simultaneously acts as the Raman pump beam, where the Stokes shift is equal to the hyperfine splitting of the ground state. The process can be very efficient when the pump beam frequency is tuned near a resonance; optical amplification factors of *exp(30)* can be obtained for a few-centimeter-long medium and a pump power of 10's of milliwatts [6].

The first observation of fast-light pulse propagation using the Raman scattering technique was by Wang *et al*. [7], where they studied pulse propagation through a 6-cm-long laser-driven rubidium-metal vapor. They obtained $\upsilon_g = -c/310$ when the carrier frequency of a 2.4-μs-wide (full width at half maximum) Gaussian-shaped pulse was set at the center of the gain doublet, resulting in a pulse advancement of 62 ns in comparison to the situation when an identically-shaped pulse propagated through vacuum. The transit time through the same path in vacuum was only 200 ps, demonstrating that the peak of the pulse exited the medium before it passed the entrance face of the medium. While the group velocity was highly superluminal in their experiment, the pulse advancement relative to the pulse width, denoted by A, was only ~2.6%.

Obtaining large A is a major goal of current research. Possible applications of slow and fast light, such as all-optical adjustable time-delays for data buffers, require $|A| >> 1$. Also, there are unresolved questions as to whether superluminal group velocities constitute a violation of the special theory of relativity, which states that no information can travel faster than c. Large A will make it easier to distinguish between the group velocity of a pulse and the speed on information encoded on an optical pulse.

In a recent study, Stenner and Gauthier [8] showed that A is proportional to g_oL, where g_o is the gain coefficient at the peak of one of the resonances, and L is the length of the medium. The gain path length can be increased by raising the Raman pump power, the atomic number density, and L. Unfortunately, this approach fails because of a modulation instability that occurs when the intense bichromatic field interacts with the atomic vapor. The modulation instability is manifest by an extreme broadening of the spectrum of the input bichromatic Raman pump field as it propagates through the medium. (The same nonlinear optical effect can be used to generate single-cycle optical pulses when the Raman Stokes shift is larger as described in Ref. [9].) Hence, the gain and dispersion properties of the medium at the exit face of the medium are very different than that at the entrance face so that the simple conceptual picture discussed in the previous section is no longer valid. Stenner and Gauthier [8] demonstrated that the modulation instability severely distorts a pulse propagating through the medium, thereby diminishing its use as a fast-light medium.

3. Large fast-light pulse advancement in a dual-zone Raman generator

Fast-light pulse advancement is a linear optical effect and hence it is possible to synthesize the desired dispersion properties, shown in Fig. 2, by cascading two Raman gain media (laser-driven potassium vapor) where each is driven by a distinct *monochromatic* pump field. This dual-zone technique suppresses the modulation instability because the instability arises from the mutual interaction of the two pump frequencies when they are present simultaneously in the medium. Using two 20-cm-long potassium-metal vapor cells in a configuration shown in Fig. 3a, we have demonstrated large A, as shown in Fig. 3b for the case of a 263-ns-long (full width at half maximum) Gaussian-shaped pulse [10]. The pulse is advance by 27.4 ns in comparison to an identical pulse propagating through vacuum, resulting in A = 0.104 and $\upsilon_g = -c/19.6$.

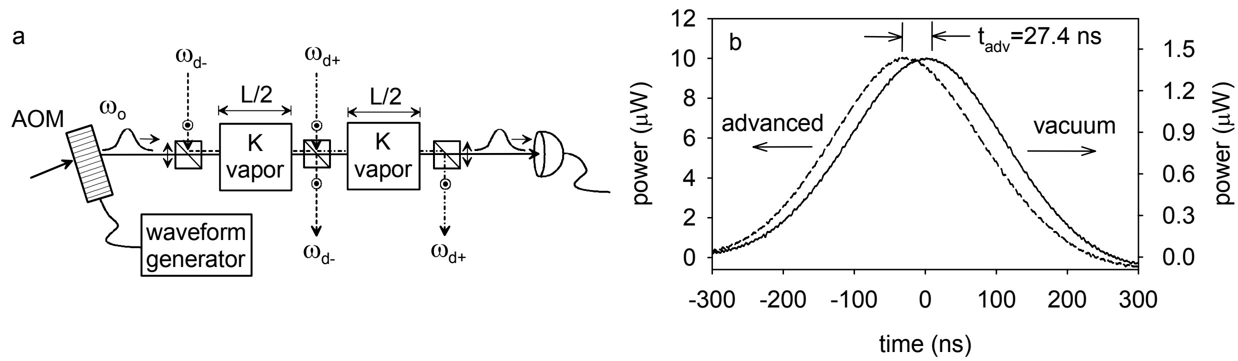

Fig. 3. Fast-light pulse propagation with large relative pulse advancement. a) Experimental setup showing the two-zone Raman amplifiers pumped by distinct monochromatic fields. b) Gaussian-shaped pulse propagating through vacuum (solid line, right-axis scale) and through the two-zone Raman amplifiers (dashed line, left-axis scale). From Ref. [10].

To determine whether the observations shown in Fig. 3b imply superluminal information transfer, we define two optical waveforms that represent distinct symbols in a binary alphabet that can be used transmit a message. By tracking the time at which it is first possible to distinguish between the symbols, we find [10] that the information velocity is subluminal, consistent with the special theory of relativity.

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