Slowdown the light speed in an alexandrite crystal

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We have observed a hole in the absorption profile of the homogeneously broadened absorption band of an Alexandrite crystal. With the spectral hole-burning technique that resulting from the periodic modulation of the ground state population at the beat frequency between the pump and the probe fields, we observed the slowdown the light propagation with the group velocity as slow as 12.5 m/s at room temperature. And the group velocity in the Alexandrite crystal depends on the amplitude modulation frequency, the power of laser beam and the orientation of the crystal lattice. The lower frequency or higher power leads to slower group velocity of light.

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With the development of laser technology more and more physical phenomena have been observed, especially in the field of nonlinear optics. And lots of physical laws that describe the nature of interaction between light and material have been acknowledged. All of these made it possibly to change the velocity v_g of light pulses propagating through material system. There has been a flurry of interest in controlled of the velocity of propagation of light pulse through materials, and many experiments have demonstrated that light pulses can be made to propagate superluminal[1,3] or to come to very slow[4−6], even to complete stop[7,8]. In 1999, Hau *et al.*[4] observed a group velocity of 17 m/s in a Bose-Einstein condensate with the technology of electromagnetically induced transparency(EIT)[9]. In 2001, two papers report that they achieved zero speed propagation in materials[5,6], and then in 2003, Boyd's group observed ultraslow light in a ruby crystal and superluminal in an Alexandrite crystal at room temperature[7,8], respectively. All of these show that the study of slow down the light propagation has been an interesting topic in the optical field.

The group velocity of light propagation in media is defined as $v_g = d\omega \frac{d\omega}{dk} = \frac{c}{n_g}$, using this equation we can find the relation between group velocity and the material refractive index:

$$v_g = \frac{c}{n(\omega) + \omega \left[\frac{dn}{d\omega}\right]}.$$

It is clearly that rapid spectral variation of the refractive ($dn/d\omega \gg 1$) will leads to a very slow group velocity. So the key for getting ultraslow light is the material that satisfies the condition. It has been appreciated for quite some time that the refractive index of a resonant optical material has a rapid variation near the material resonance. However, in this situation strong absorption accompanies the rapid variation of refractive index making the experimental observation of these effects very difficult. Most of the recent work on the ultraslow light that happened near the resonant frequency has made use of the electromagnetically induced transparency (EIT) technique to render the material highly transparent while still retaining the strong dispersion. There is another method for produced strong dispersion, the spectral hole-burning effect that was first predicted in 1967 by Schwartz and Tan from the solution of the density matrix equations of motion[10]. The spectral hole is created by the period modulation of the ground state population at the beat frequency between the pump and the probe fields applied to the material. In 1983, Hillman *et al.* observed such a spectral hole with width of 37 Hz in a ruby crystal[11]. Such a narrow spectral hole leads to a rapid spectral variation of refractive index in the medium and then to a very slow group velocity. Using this method we observed ultraslow group velocity of laser pulses propagation in an Alexandrite crystal with 12.5 m/s and the corresponding delay time is 4.06 ms.

Alexandrite crystal belongs to orthorhombic system, and Fig. 1 is this anisotropic crystal's lattice structure. The Al^{3+} ions are octahedral coordinated by the oxygen ions and occur in two different crystal-field sites in this lattice. The Al^{3+} sites lying in the mirror-symmetry planes of the lattice have the site symmetry of the C_s point group, while the other Al^{3+} sites possess inversion symmetry and belong to the C_i point group. The Cr^{3+} ions enter the crystal substitutionally for the Al^{3+} ions, and some replacing Al^{3+} ions in the mirror sites and the rest going into the inversion sites. The Cr^{3+} ions of mirror site experience excited-state absorption and have a population relaxation time of 260 μs, and the inversion-site ions have negligible excited-state absorption and a much longer population relaxation time (~50 ms). With an intensity pump, a very narrow spectral hole will be observed in the absorption spectrum of Cr^{3+} ions at the inversion sites. And this narrow spectral-hole product a very slow group velocity.

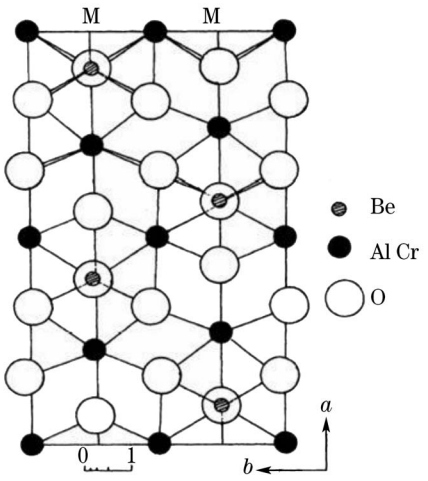

Fig. 1. The crystal lattice structure of Alexandrite looking along the c axis.

In our experiment, we use a single-line argon-ion laser operating at 476 or 488 nm as the source. The beam passes first through an electro-optic modulator which driven by an amplified voltage signal that come from a function generator and then becomes a signal pulses. A glass splitter sent a portion of modulated light to a detector for reference. The central beam was then focused with an 11-cm focal length lens to a 5-cm-long Alexandrite crystal. The power of the beam is 220 mW and the diameter is 3.5 mm. The beam exiting the crystal is incident on a detector, and both the detected signals are stored along on a digital oscilloscope. The finally results were compared on a computer to calculate the relative delay and amplitude of the two signals.

We pump the Alexandrite crystal by the center frequency of the 476-nm laser beam, and probe by its sideband. Because of saturation the center of the beam experienced less absorption than the edge and the beam did not expand significantly in traversing the crystal. As an anisotropic crystal, when we rotating the Alexandrite rod the attenuation transforms periodically. The attenuation as a function of the relative angle is shown in Fig. 2 for modulation frequency of 20 Hz. Here relative angle is the angle between the directions of crystal lattice and the directions of polarization; attenuation is defined as the natural logarithm of the ratio of incident intensity to transmitted intensity.

Moreover, we found that changing the modulation frequency or the relative position of crystal can control delay time. According to the condition of producing spectral hole (the beat frequency smaller than the reciprocal of lifetime), we can predict that the modulation frequency's moving away from the beat frequency will abate the effect of hole-burning. So the signal delay will became smaller. In Fig. 3, we show the measured time delay as a function of modulation for the same condition. The delay has a significant variation: lower frequency has larger delay and higher frequency has smaller delay. In our experiment (beam power: 220 mW, focal length: 11 cm, crystal length: 5 cm), the largest delay-time is 4.06 ms corresponding group velocity is 12.5 m/s.

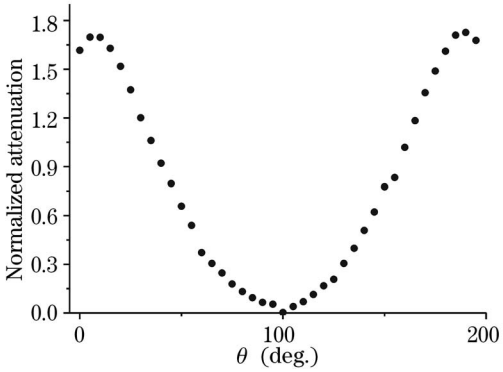

Fig. 2. The attenuation of probe pulse as a function of rotated angle for pump power of 220 mW and modulation frequency of 20 Hz.

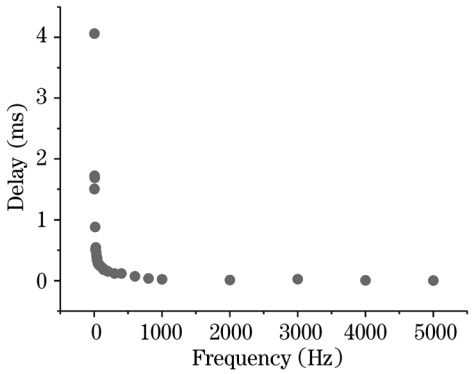

Fig. 3. The time delay as a function of modulation frequency for pump power of 220 mW.

In conclusion, we observed the ultraslow light propagation with single beam in Alexandrite crystal, and the delay time can be controlled by changing the modulation frequency or pump power. The largest delay time in our experiment is 4.06 ms and corresponding group velocity is 12.5 m/s.

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