Ultrashow Light with Coherent Population Oscillations

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June 15, 2007

Abstract

This paper reviews the experiments performed by Bigelow et al on the subject of ultrashow light in room-temperature crystals. A general introduction about methods of creating slow light is given and coherent population oscillations are explained. Further, the results of the research are presented, and two papers that critically review these results and deny the influence of CPO in these experiments are looked into.

1 Introduction

The speed of light in crystalline materials has been subject of research for many years. Fairly recently however, techniques have been developed to control the speed of light in crystals in extreme ways. Group velocities \( v_g \) higher than \( c \) have been reported, leading to the term "fast light" as well as \( v_g \ll c \), called "ultrashow light". Also, light has been successfully stored for short periods of time, where the group velocity is zero.

Bigelow, Lepeshkin and Boyd from the Institute of Optics in Rochester, NY, USA have published two papers about slow light in a room-temperature solid. The first one in Physical Review Letters in March 2003 [1], the second one in Science in July 2003 [2]. The major part of both papers describes the same experiment performed with slow light in a ruby rod, although the article in PRL is much more detailed and in the Science paper an experiment with Alexandrite crystal is added. In this paper I will review both articles. The physics in the articles will be discussed and I will show some of the other research in this field. Finally, I will check if the claims made in the introductions are backed by the results from the article and if the research really is a breakthrough.

2 Slow Light

Slow light occurs when the group velocity of the wavelength at the center of the pulse becomes low. The group velocity is defined as

\[
v_g \equiv \frac{\partial \omega}{\partial k},
\]

where \( \omega \) is the angular frequency and \( k \) the wave number, defined as

\[
k = \frac{\omega}{v_\omega} = \frac{n_\omega \omega}{c}
\]

where \( v_\omega \) is the speed of light of frequency \( \omega \) in the crystal and \( n_\omega \) the index of refraction at that frequency. Rewriting gives

\[
v_g = \frac{c}{n_\omega + \omega \frac{\partial n}{\partial \omega}}
\]

So for high \( \partial \omega / \partial n \), the group velocity becomes small.

Most attempts to create slow light in a crystal are based on electromagnetically induced transparency (EIT). This technique is based on creating a narrow transparent range in the center of an absorption line in a medium, enhancing the strong dispersive properties. In experiments using EIT, three quantum states of the medium material are used, as shown in figure 1. A probe beam is tuned on the resonance frequency of states |1⟩ and |2⟩, while a much stronger pump or coupling beam is tuned on the transition between |1⟩ and |3⟩. The third transition must be a dipole-forbidden transition. The coupling beam causes the material to oscillate between states |1⟩ and |3⟩, thereby reducing the absorption of the probe beam and inducing transparency. Successful experiments have been
performed where the group velocities of pulses have been reduced to \(c/165\) in a Pb vapor cell [3], 17 m/s in a Bose-Einstein condensate [4], 90 m/s in Rb vapor [5] and 45 m/s in a 5 Kelvin Pr-doped \(Y_2SiO_5\) crystal [6].

3 Coherent population oscillations

![Figure 2: Setup used by Bigelow et al to slow down light in a ruby crystal. The electro-optic modulator is used to either create intense pulses, or place a 5% amplitude modulation on the signal, thereby creating side bands that act as probe beams.](image)

The authors of the discussed articles have used a different phenomenon to slow their light down. They make use of coherent population oscillations (CPO) in a ruby rod to reduce the absorption of the light at a small frequency range. A diagram of the setup is given in figure 2. A pump beam pumps the electrons from the \(^4A_2\) ground level (called level a) to the broad \(^4F_2\) level (b). From there, there is fast nonradiative decay to one of the metastable \(^2E\) levels (c) that occurs within a few picoseconds, before radiatively decaying back to the ground state at a rate \(\Gamma_{bc} = 1/50\) ms. The energy level diagram is shown in figure 3.

![Figure 3: I shows a ruby energy level diagram. Due to the fast decay from b to c, the system can be modeled as a simpler two-level model, as shown in II](image)

Figure 3: I shows a ruby energy level diagram. Due to the fast decay from b to c, the system can be modeled as a simpler two-level model, as shown in II. The pump beam is passed through an electro-optic modulator, which places a 5% amplitude modulation on the laser beam. This creates side-bands, that have a difference frequency with the main band that is equal to the modulation frequency. One of these sidebands is used as the probe beam. The interaction between the pump and the probe beam will cause the electrons to oscillate between the ground state and the metastable state. This effect however, will only occur with a significant amplitude if there is time enough for the electrons in the metastable state to decay to the ground state during one oscillation. In other words, only if \(\delta T_{bc} \lesssim 1\), where \(\delta\) is the detuning between the pump and the probe beam, or just the modulation frequency. With a decay time of \(\sim 50\) ms, this means that the modulation frequency must be approximately 200 Hz or lower. The experiment is performed both with an amplitude modulated continuous beam and with intense pulses. A graph showing the relative attenuation versus the modulation frequency for the continuous beam exper-
The population oscillation and the connected susceptibility oscillation causes the monochromatic pump wave to again create sidebands, with one of them exactly equal to the frequency of the probe beam. This light contributes to the intensity of the probe beam, leading to a spectral hole in the probe absorption profile, with a width on the order of $1/T_{bc}$. The shape of the absorption profile is given as

$$\alpha(\delta) = \frac{\alpha_0}{1 + I_0} \left[ 1 - \frac{I_0(1 + I_0)}{(T_{bc}\delta)^2 + (1 + I_0)^2}\right],$$  \hspace{1cm} (4)

where $\alpha_0$ is the unsaturated absorption coefficient and $I_0$ the pump intensity normalized to the saturation intensity. While this effect has similarities to hole-burning in inhomogeneously broadened spectra, it’s not a result from gain depletion, but caused by the interaction of the two waves and therefore a different phenomenon.

According to the Kramers-Kronig relation, this rapid change in absorption must lead to a high change in the refractive index over the same frequency range, which is the way the group velocity is reduced.

In addition to slowing light down, the researchers have also sped up the pulse group velocity. Where a spectral hole in the absorption spectrum leads to slow light, an antihole, a region with enhanced absorption, leads to fast light. The researchers have performed such experiments in Alexandrite crystal. Finally, the researchers have found that it is not necessary to separate the pulse and the probe beams. A single intense pulse was able to provide enough saturation to modify the group index and slow itself. It is claimed that this is the first demonstrated example of an ultraslow pulse that is self-delayed.

## 4 Criticisms

A pulse that is slowed down without the need for a separate pump beam certainly is a breakthrough in the field. But the question remains whether the claims made by Bigelow et al are really backed by their results. No claims are made in the reports that are not supported by their interpretation of the measured data, but recently two papers have appeared that claim that the interpretations of Bigelow et al are wrong. According to Zapskii and Kozlov, the light-pulse delay detected by Bigelow has nothing to do with CPO and is not connected to a reduction of the group velocity [7].

They write that all observations of Bigelow can be explained using a very simple of a two-level saturable absorber. Saturable absorption is a well-known effect in non-linear optics. The simplest form can be modeled by a two-level system with a high dephasing rate $\Gamma_2$ compared to the decay rate $\Gamma_1$ and Rabi frequency $\Omega$. As was shown in figure 3, ruby can also be considered a two-level system.

The intensity of a light beam passed through a saturable absorber $I_{out}$ can be written as

$$I_{out} = \alpha(I, t)I,$$  \hspace{1cm} (5)

where $I$ is the incoming intensity and $\alpha(I, t)$ the transmittivity factor. When the light field varies, the absorption can be described by the following differential equation:

$$\dot{\alpha} = \frac{\alpha_{eq} - \alpha}{\tau}$$  \hspace{1cm} (6)

where $\alpha_{eq}$ is the equilibrium value for the current light intensity, and $\tau$ a time constant in the order of $1/\Gamma_1$. For low light intensities the equilibrium
The absorption value can be written as

\[ \alpha_{eq}(I) = \alpha_0 - \alpha_1 I \]  

(7)

where \( \alpha_1 I \ll \alpha_0 \). The response of the output intensity to a stepwise change in input intensity for a saturable absorber is shown in figure 5. For higher light intensities, bleaching occurs and \( \alpha_1 \) is negative. Using these equations, the response for several input shapes can be calculated. Zapasskiı did so, and found no difference with the results from Bigelow. He points out that the pulse is not really slowed down, but merely that the front of the pulse is absorbed more than the back, because of the saturation of the absorption. This causes the maximum intensity of the pulse to be moved backwards, and after normalization it looks like the pulse is slowed down. Obviously, the maximum 'time delay' must shorter than the temporal length of the pulse. This is also the case for the measurements by Bigelow.

This model can also explain the advancement of the pulse in the Alexandrite crystal. Chromium ions in the metastable excited state absorb light at the wavelength of excitation stronger than those in the ground state. This efficient excited-state absorption causes this crystal to behave as an inverse saturable absorber, with \( \alpha_1 > 0 \). In this case the back part of the pulse is absorbed more than the front part, so the peak moves to the front, giving the impression that the pulse was sped up by the crystal. This model also explains that the effects only occur at low modulation frequencies. The absorption desaturates in a time in order of the decay time of the upper level; so the same calculation applies as for the CPO theory.

In addition to fully explaining the results from the experiments done by Bigelow in a more simple way, Zapasskiı also gives several reasons why the interpretation of Bigelow is wrong. First of all, Bigelow uses a harmonically modulated light beam, represented as three spectral components, of which the central one is the pump beam and the side bands the probe beam. While this approach is in principle correct, the choice of Bigelow et al to analyze the response of the absorber to only one of them and ignoring the second makes the model inadequate, since the second probe component also influences the first one and vice versa. Second, the used definition for group velocity is not usable according to Zapasskiı, since the shape and the spectrum of the pulse would be severely changed under the influence of the strong frequency dependence of the absorption. Finally, it is pointed out that the CPO induced spectral hole can not be detected.
with the lasers used. To detect the hole, the spectral width of the pump and probe beam must be smaller than that of the hole, in the case of ruby that means it must be smaller than 37 Hz. The lasers used have spectra that are multiple orders of magnitude wider.

The results of Zapasskii are confirmed by Selden [8], who has performed a quantitative comparison of the data measured by Bigelow and saturable absorption and found a good agreement. Selden suggests to perform an experiment with a long medium, to increase the delay beyond the upper level decay time and the pulse length, to discriminate between real CPO caused delays and saturable absorption effects. I am not aware of any reaction from Bigelow et al to the findings of Zapasskii and Kozlov or Selden.

5 Conclusion

Coming back to the original questions, it seems that the results done by Bigelow et al, do not definitively demonstrate the slowing down of light due to CPO, but merely show well-known effects of a saturable absorber. These effects do not exhibit the promising features of real slow light, since the pulse delay time is limited by both the temporal length of the pulse and the decay time of the upper level. Also, the high absorption losses are intrinsic to the mechanism and not just a result of a premature technique and eligible for improvement, as is claimed by the researchers.

References


