Slow and fast light in photorefractive SBN:60

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Abstract
We demonstrate slow and fast light at room temperature by dispersive phase-coupling in a
photorefractive SBN:60 crystal. Non-degenerated wave-mixing is used to obtain delayed and
amplified pulses with reduced or increased group velocity of $v_g = 0.2$ cm s^{-1} and
$v_g = -1.3$ cm s^{-1}, respectively. The gain spectrum is modulated by using multiple frequency
shifted pumps simultaneously. The complete dispersion of the spectrum is determined via the
phase modulation technique. We compare the experimental results to numerical simulations
based on coupled-wave equations.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

The deceleration of light pulses has numerous potential applications in information processing such as in fiber optical delay lines [1] or increasing the resolution in interferometry [2]. In the last few years, different approaches have successfully demonstrated the slowdown of light pulses. One approach explores dispersion engineering as in photonic band gap structures [3] or coupled resonators [4]. Others take advantage of coherent nonlinear optical processes such as stimulated Brillouin scattering (SBS) [5], liquid crystal light valve systems (LCLV) [6], coherent population oscillation (CPO) [7] or, as the most prominent example, electromagnetically induced transparency (EIT) in ultracold gases, where light was slowed down to 17 m s^{-1} [8].

Recently, Sturman *et al* demonstrated significant deceleration of light pulses by nonlinear two-wave-mixing in a photorefractive BaTiO$_3$ crystal [9]. In this type of photorefractive material, the non-local refractive index response results in a unidirectional transfer of energy and phase between two pumping beams. It has been shown that this process has strong similarities to EIT due to the small gain spectrum that leads to a narrow, highly dispersive phase-coupling effect of only a few hertz width. Compared to slow light based on CPO in ruby crystals [10], gain in photorefractive

materials can be implemented over a broad spectral range. In this article, we investigate the controlled deceleration and acceleration of light pulses in a photorefractive gain doublet induced by a double pump geometry employing a Ce-doped photorefractive strontium–barium niobate (SBN) crystal. This allows the creation of two spectrally separated, independently controllable gain lines in such a way that light pulses can be seamlessly tuned from slow to fast light behavior by detuning the incident pump beam frequencies.

2. Numerical simulation of the double resonance

First we consider the non-degenerated two-wave-mixing case with a single undepleted pump wave as shown in figure 1. The intensity and phase of the signal and the pump are coupled via the refractive index grating induced by the photorefractive effect. Even though the frequencies of signal and pump are different, a volume index grating can still be formed if the fringe pattern moves slowly compared to the characteristic formation time of the medium.

The real (γ) and imaginary (β) parts of the complex coupling constant are given by [11]

$$\gamma(\Omega) = \gamma_0\left(\frac{1}{1 + \Omega^2\tau^2}\right), \qquad \beta(\Omega) = \gamma_0\left(\frac{\Omega\tau}{1 + \Omega^2\tau^2}\right), \tag{1}$$
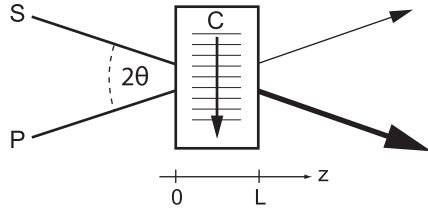
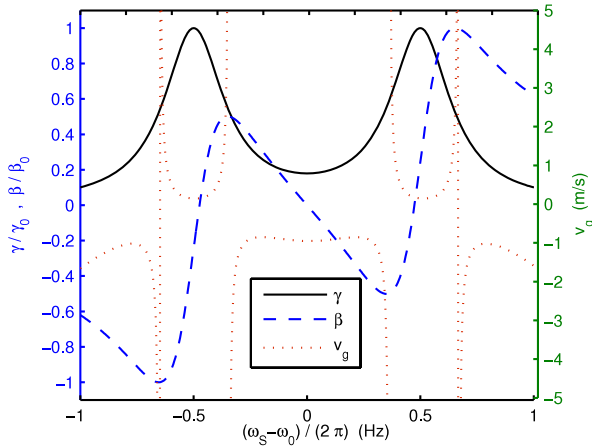**Figure 1.** Schematic of photorefractive two-beam-coupling. S and P are pump and probe, respectively.

Figure 2. Numerical simulation of frequency dependent β, γ, and v_g of a double resonance for diffusion dominated SBN with a non-local response. $\tau = 1$ s; $\gamma L = 7$.

respectively, with $\Omega = \omega_S - \omega_P$ as the frequency detuning between pump and signal, and τ as the risetime of the space–charge field. Since material dispersion is relatively small within the gain bandwidth, group velocity v_g is approximately [12]:

$$v_g(\Omega) \approx c \left(n_0 + c \frac{\partial \beta}{\partial \omega_S} \right)^{-1} \approx \frac{(1 + \Omega^2 \tau^2)^2}{\gamma_0 \tau (1 - \Omega^2 \tau^2)}. \qquad (2)$$

In the widely investigated degenerated mixing case, only a single gain peak occurs in the spectrum, but to achieve a larger degree of control we introduce a second pump with a small frequency offset. This results in a gain profile for the generation of fast light behavior [13].

Figure 2 shows group velocity, intensity- and phase-coupling coefficients versus frequency detuning for two gain peaks with a frequency difference $\Delta\Omega$. At each matched gain frequency a pulse experiences normal dispersion and is amplified since $\gamma > 0$. When the temporal width t_0 of the pulse is in the order of τ, optimum delay to pulse width ratio is achieved [14]. However, in-between the two resonances a pulse with appropriate bandwidth experiences anomalous dispersion.

3. Experimental setup

Our setup is a three-wave-mixing configuration (figure 3). We use Ce-doped SBN with the *c*-axis in the [001] direction and extraordinary polarized beams from a frequency doubled Nd:YAG laser. The beam is split up in one signal beam S
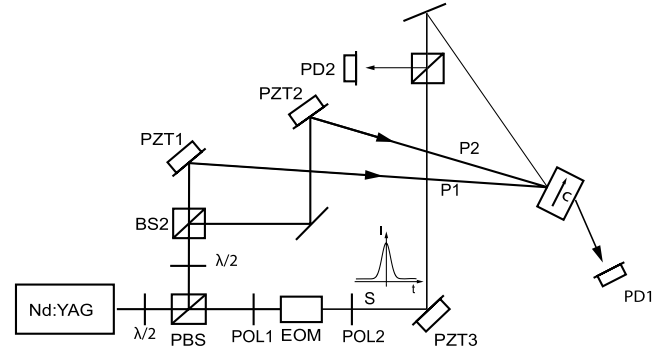

Figure 3. Schematic drawing of the experimental setup. PZT: piezotransducer; PD: photodiode; EOM: electro-optic-modulator S: signal beam; Px: pump beams.

and two pump beams P with equal intensities. The intensity ratio between the pump and the signal is $I_P/I_S \approx 400$ for the undepleted case and the grating period is $\Lambda = 0.77$ μm with a total incident intensity of $I \approx 1$ W cm^{-2}. The signal beam is temporally modulated by an electro-optic-modulator (EOM) with Gaussian shaped pulses and is split up to provide a reference for the delayed pulse. The EOM consists of multiple rotated LiNbO$_3$ crystals and provides a contrast ratio of $I_{max}/I_{min} \approx 400$. After characterization of the EOM response, the dc offset voltage for minimum intensity only transmits a few nanowatts of signal power. No diffraction was observable in the off-state. However, slightly above the offset voltage the modulator response is not completely linear and the transmitted intensity deviates from the electrical drive signal. Additionally, all beams can be shifted in frequency by piezo-mirrors up to some kilohertz.

To measure the frequency dependence of the coupling constant the signal beam is frequency scanned using a sawtooth voltage, and the steady state gain is measured. For determination of the frequency dependent phase-coupling, a low-amplitude (0.2 rad), high frequency (1 kHz), sinusoidal phase shift is applied on the signal beam. The modulation is much faster than the response time, so that it does not affect the recording of the grating. This allows for determination of the phase shift between S and P using the lock-in technique [15]. The received pulses are averaged over several periods.

4. Discussion of spectral properties

Figure 4 shows the experimental result for the frequency dependent coupling with unshifted pumping beams ($\Delta\Omega = 0$). The gain peaks at the central probe frequency and the spectral dependence are in good agreement with the numerics. For $\omega_S - \omega_P = 0$ the curve shows the region of normal dispersion and results in a reduction of the group velocity. The group velocity is directly derived from delay and coupling distance. A transmitted signal pulse is substantially slowed down if the signal matches a part of normal dispersion. Group velocity is calculated according to $v_g = L/\Delta t$. The transmitted pulse experiences a delay of 3 s that yields a group velocity of $v_g = 0.2$ cm s^{-1} for 6 mm coupling length.

The bandwidth depends strongly on the type of crystal used and the experimental conditions, e.g. total incident
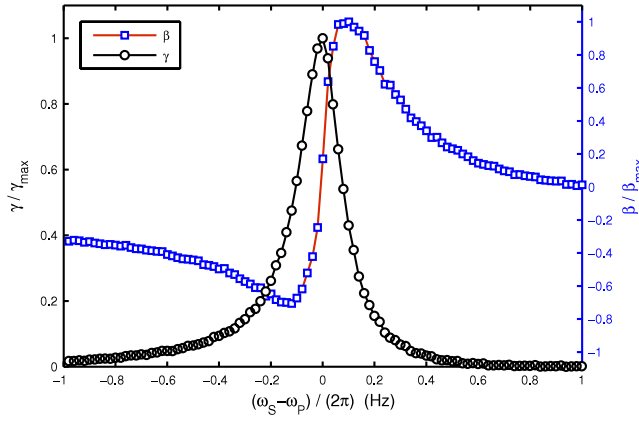
Figure 4. Normalized spectrum of the coupling constants γ and β versus frequency detuning. $\tau = 0.2$ s; $\gamma_{max} = 25$ cm^{-1}.

Figure 5. Measured dispersion spectrum of the gain and phase-response for a double resonance with $\Delta\omega_P = \omega_{P1} - \omega_{P2} = 2.5$ Hz. $\gamma L = 1.5$; $\tau = 0.1$ s; $I_S = 1$ mW cm^{-2}; $I_{P1} = I_{P2} = 280$ mW cm^{-2}.

intensity to decrease the grating build-up time. If the build-up time is increased, shorter pulses can be delayed. In general, photorefractive crystals do not produce gain instantaneously when probe and signal frequencies are matched since the grating is built up and erased with comparable slow time constants. Although τ can be modified to some extent, at low light intensities in SBN it is only available down to the millisecond timescale. However, even small deviations from the pump intensity I_P can change the spectral bandwidth of the coupling and therefore the ratio of t_0/τ and the pulse delay. Similar to slow light in coupled resonators, the delay is bandwidth limited in such a way that the spectral width of the input pulse has to be smaller than the resonance to achieve detectable changes of the group velocity and suppress ringing. With increasing t_0, more spectral components of the pulse fit into the region of normal dispersion and there is an increase in the observed delay time.

Figure 5 shows experimental gain- and phase-response of a double resonance with two 2.5 Hz spaced pumping beams. The double hump gain profile is clearly visible and exhibits the predicted anomalous dispersion slope in-between the two peaks. At the central frequency, intensity coupling is reduced severely. The gain spectrum is not completely symmetric due to the different angles of incidence resulting in a spatial frequency mismatch. Additionally, the sum of the coupling constant deviates from the single resonance and is most likely due to the reduced efficiency of the so-called running holograms.

Figure 6 shows the transmitted Gaussian pulse shapes of the reference signal, unshifted pumps, and detuned pumping beams inserted at the central resonance frequency. The numerical output shape of a Gaussian input pulse with a temporal envelope of $S(0, t) = S_0 \exp(-t^2/t_0^2)$ after a propagation distance d inside the material is obtained by calculating the coupling in frequency space [16]:

$$S(d, \omega) = S_0(0, \omega) \exp\left(\frac{d}{2}(\gamma + 2i\beta)\right). \qquad (3)$$

The theoretical curves are obtained with values of $\gamma L = 1.5$ and $\tau = 0.1$ s obtained from steady state cw measurements.
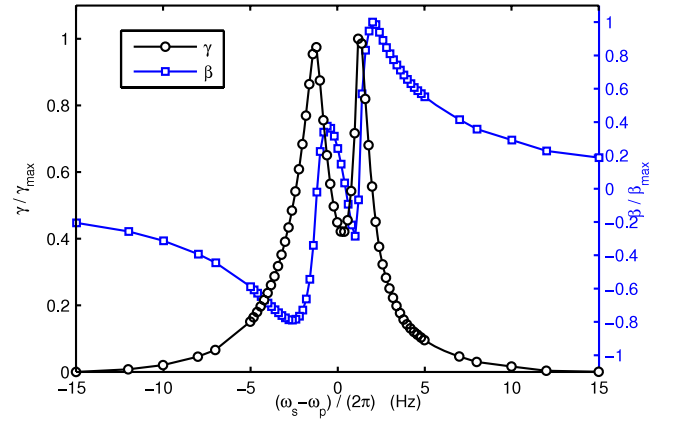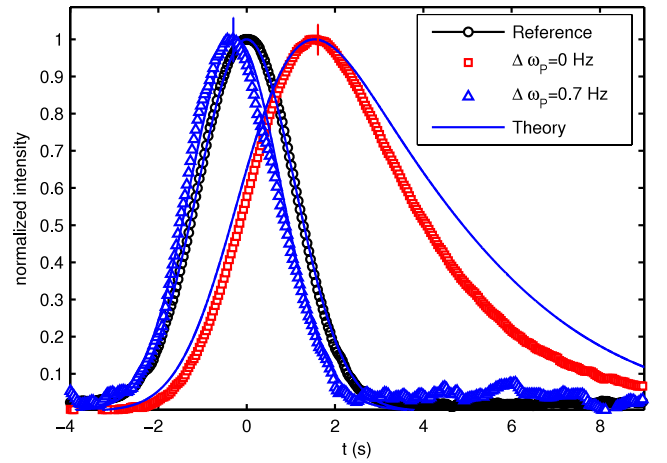

Figure 6. Transmitted pulses through two different gain configurations with zero and 0.7 Hz frequency spacing. $\gamma L = 1.5$; $\tau = 0.1$ s; $I_S = 1$ mW cm^{-2}; $I_{P1} = I_{P2} = 280$ mW cm^{-2}.

The pulse width t_0 is slightly smaller than the response time. Although theory shows good agreement with the experiment, there is a small deviation of the falling edge. This is most likely due to the fact that the EOM is not able to produce perfect Gaussian shaped pulses due to a small nonlinearity near V_π. In this case the sum of squared errors from a perfect Gaussian pulse is 2.05. For unshifted pumping beams the pulse exhibits a behavior as if only a single beam was present. With a coupling length of 5.2 mm a small time advance of $\Delta t = 0.4$ s is observed and results in superluminal propagation with $v_g = -1.3$ cm s^{-1}.

5. Conclusion

We have successfully characterized the complete dispersion spectrum of a single and double gain response in a SBN crystal using the phase modulation technique. The dispersion spectrum is similar to those observed in a dual-frequency pumped Raman gain and can be shifted relative to the probe

frequency, or deformed to create different delay or advance times. The bandwidth of the gain can be regulated by the overall pump field to dynamically change the dispersion spectra.

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