Stimulated generation of superluminal light pulses via four-wave mixing

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(Dated: December 13, 2011)

We report on the four-wave mixing of superluminal pulses, in which both the injected and generated pulses involved in the process propagate with negative group velocities. Generated pulses with negative group velocities of up to \( v_g = -\frac{1}{50}c \) are demonstrated, corresponding to the generated pulse’s peak exiting the 1.7 cm long medium \( \approx 50\text{ns} \) earlier than if it had propagated at the speed of light in vacuum, \( c \). We also show that in some cases the seeded pulse may propagate faster than \( c \), and that the generated conjugate pulse peak may exit the medium even earlier than the amplified seed pulse peak. We can control the group velocities of the two pulses by changing the seed detuning and the input seed power.

PACS numbers: 42.65.-k,42.65.Hw,42.65.Ky,42.50.Nn

There has been substantial recent interest in modifying the group velocity of optical pulses, resulting in slow, stopped, and superluminal light [1]. Experiments have resulted in extremely slow light with very small group velocities [2–7], while others exhibit the ability to store and retrieve optical pulses [8–11]. It is also possible to generate a dispersion relation that results in negative group velocities [12–24]. In such cases when the group velocity of light in a material is negative, the exiting pulse’s peak can appear to exit the medium before the peak of the input pulse enters. The peak that exits the medium does not correspond point-to-point to the peak of the input pulse. Rather, the phenomena of re-phasing allows for different frequency components of the input pulse to propagate at different velocities, which results in the apparent pulse peak advancement seen in fast light experiments [25, 26].

We report the stimulated generation of light pulses that propagate with a group velocity faster than the speed of light in vacuum, via four-wave mixing (4WM) in hot rubidium vapor. The 4WM process employed here involves injecting one weak beam into the medium and pumping with a beam at a different frequency, as seen in Fig. 1. A beam at a third frequency is generated via the process, as photons from the pump beam are converted into photons in the injected seed and generated conjugate modes. The amplified seed pulse is shown to have a negative group velocity due to the 4WM dispersion, and stimulates the generation of the conjugate pulse that may appear to propagate even faster, as seen in Fig. 2. The anomalous dispersion results from asymmetric gain and absorption lines at the seed and generated conjugate pulse frequencies. We show that it is possible to manipulate the group velocities of the two modes relative to one another, to some extent, by detuning the seed pulse or varying the input seed intensity. The scheme could be applicable to a variety of optical communications scenarios, where the correction of pulse jitter by advancing or delaying pulses may be necessary. The present results will allow us to investigate the effects of superluminal group velocities on quantum entanglement and squeezed light, both of which may be produced via the 4WM process [6, 27].

The first experiments to produce fast light used absorption lines [12, 13, 28], which exhibit strong negative dispersion at the center of the line, but the dispersion is accompanied by significant attenuation of the input pulses. More recently, schemes using gain doublets have been shown to produce fast light ([1, 14, 16] and references therein). All previous experiments involving fast light, to our knowledge, involve injecting a pulse into the fast light medium, and observing that it appears to exit the medium faster than a reference pulse traveling at the speed of light in vacuum. In our experiment, we show not only that the injected pulse propagates with a negative group velocity, but also that a second pulse at another frequency in a separate spatial mode is generated by the 4WM process, which may appear to propagate faster than a vacuum-traversing reference pulse as well. In contrast to some previous 4WM experiments [6], the group velocities of the seed and conjugate modes under the fast light conditions in the present experiment exhibit little coupling due to the large differential absorption between the two modes. The gain line for the generated conjugate frequency sits inside the edge of an absorption line, resulting in conjugate pulses with a significantly weaker amplitude than the amplified seed pulses which are far off-resonance. Previous theoretical investigations involving four-level atomic systems to generate fast light have been performed in which the probe field is co-propagating with the coupling field [23]. Additional theoretical work has shown that the double-lambda scheme and EIT may result in slow and fast light for two input probe beams [29]. Experimental work has been done in which Raman gain of an input probe results in slow light, while pump depletion results in anomalous dispersion at the pump
frequency (heterodyne detection was used to resolve the different frequency components) [22]. The present experiment differs from these theoretical and experimental investigations in that we generate a conjugate pulse in a separate spatial mode that may propagate superluminally, in addition to the seed pulse. This also has the benefit of allowing for direct detection of both pulses, rather than having to use heterodyne detection to resolve the separate frequency modes.

For the generation of a strong anomalous dispersion we use the 4WM process shown schematically in Fig. 1. The gain line that the input seed pulse experiences results in negative dispersion at the gain line edges, giving rise to superluminal propagation of the injected pulse. The generated conjugate pulse experiences a broad region of negative dispersion due to the gain and absorption line profile resulting from this 4WM process, which is asymmetric (see Fig. 1) and exhibits absorption on the high frequency side of the gain line [6, 27]. Here the seed and conjugate pulses sample independent dispersion features approximately 6 GHz apart, in contrast to the gain-doublet scheme that is sometimes used to create a single dispersion feature [14].

The 4WM process involves the annihilation of two pump photons, and the creation of a single probe and conjugate photon, as is evident when examining the simplified phenomenological interaction Hamiltonian,

$$\hat{H}_I = \chi \hat{a}^{\dagger 2} \hat{b} \hat{c} + \chi^* \hat{a}^{\dagger 2} \hat{b}^{\dagger} \hat{c}^{\dagger} \tag{1}$$

[30, 31]. Here, the modes $\hat{a}$, $\hat{b}$ and $\hat{c}$ correspond to the pump, injected seed and generated conjugate, respectively, and $\chi$ is the effective interaction strength. Combined with energy conservation, this results in the constraint on frequencies such that $2\omega_{\text{pump}} = \omega_c + \omega_p$. The generated conjugate pulses in the present experiment experience both strong absorption and gain, whereas the seed pulses experience only gain, as seen in Figure 1.

The 4WM process is pumped with a strong ($\approx 220$ mW) continuous-wave linearly polarized laser detuned $\approx 400$ MHz to the blue of the Rb D1 line $|5s_{1/2}, F = 2\rangle \rightarrow |5p_{1/2}\rangle$, at $\lambda \approx 795$ nm (see Fig. 1). Weak input seed pulses with peak powers of $\approx 5$ $\mu$W with a full-width at half-maximum (FWHM) of 200 ns and a frequency bandwidth of $\approx 5$ MHz, orthogonally polarized and detuned $\approx 3$ GHz to the blue of the pump beam, are injected at an angle of $\approx 1^\circ$ relative to the pump. The injected seed pulse frequency is varied by changing the operating frequency of a double-passed 1.5 GHz acoustooptic modulator, which is used to generate the seed from part of the pump beam. The pump and probe are focused into the center of the cell with focal spot sizes of $\approx 800$ $\mu$m $\times$ 1000 $\mu$m and $\approx 700$ $\mu$m $\times$ 700 $\mu$m, respectively. A conjugate pulse is created which propagates at the same angle as the seed relative to the pump, but in the opposite azimuthal direction. The $^{85}$Rb cell is 1.7 cm long and is held at a temperature of $\approx 116^\circ$C. The seed and generated beams are spatially filtered with irises after the cell in order to select only the central spots of the 4WM beams and filter out residual pump light. Approximately 2/3 of the pulse power is detected. The pulses are then detected with a high-gain avalanche photodiode and fed directly to an oscilloscope and averaged 512.
times. Reference pulses are obtained by measuring the seed pulses when the pump beam is blocked, and serve as a measure for the vacuum propagation speed of the pulses for each experimental run. The reference pulses were also measured with the RB cell removed, to ensure that they propagate at the same speed with and without the cell present (when the pump is blocked) to within our experimental time resolution.

Most previous experiments involving fast light use absorption lines, single gain lines, or double gain lines that are Lorentzian in shape to generate the desired dispersion [1, 12, 14, 16]. In the present experiment, the generated conjugate experiences an asymmetric gain line with an absorption dip on one of the wings, while the seed experiences only a gain line, as seen in Fig. 1 [6]. Modeling the line shape for the generated conjugate mode as a Lorentzian for the gain and a second Lorentzian for the absorption results in:

$$k(\omega) = \frac{\omega}{c} + \frac{1}{2} \left( \frac{\alpha_g \gamma_g}{(\omega - \omega_g) + i\gamma_g} + \frac{\alpha_a \gamma_a}{(\omega - \omega_a) + i\gamma_a} \right)$$

Here $n_0$ is the background index, and $\alpha_g$ and $\alpha_a$ are the coefficients of the gain and absorption components, respectively, with $\alpha_g < 0$ resulting in gain. The operating frequency and the center frequencies of the gain and absorption lines are denoted by $\omega$, $\omega_g$, and $\omega_a$. The linewidths of the gain and absorption lines are $\gamma_g$ and $\gamma_a$, respectively. Due to the large absorption present at the detuning frequency and the center frequencies of the gain and absorption lines are denoted by $\alpha_g$ and $\alpha_a$, respectively, with $\alpha_g = -175$, $\gamma_g = 20$ MHz, $\alpha_a = 95$ and $\gamma_a = 23$ MHz. The group velocity $v_g$ is defined by

$$k_1 = \frac{dk}{d\omega} = \frac{1}{v_g} = \frac{n_0}{c} \frac{\alpha_g \gamma_g}{2(\omega - \omega_g) + i\gamma_g} + \frac{\alpha_a \gamma_a}{2(\omega - \omega_a) + i\gamma_a},$$

where $k_1$ is the first term in the power series expansion of $k(\omega)$ about the central frequency. The resulting expected time delays and advancements from this model are shown in Fig. 3, with the inset showing a comparison between the measured and modeled conjugate lineshape. Both the magnitude and detuning dependence of the pulse advancement/delay fit the experiment remarkably well. The seed gain line is modeled as a single gain lineshape that has an asymmetric lineshape, as measured (modeled as the sum of several Lorentzians to account for the asymmetry). We speculate that the modeled relative advancements for the seed pulses do not fit the measured data very well due to the steep dispersion of the seed gain line. This results in the seed pulse’s bandwidth exceeding some regions of “linear” dispersion, making higher order terms in the power series expansion of $k(\omega)$ contribute more significantly.

Experimentally the group velocity is determined by the arrival time of the pulse peak relative to a reference pulse propagating at $c$. The next order term is the lowest-order term that contributes to pulse reshaping, as it describes dispersion in the group velocity. The sub-luminal generated pulses in this experiment exhibit some reshaping relative to the reference pulses. The amount of pulse reshaping is sensitive to various experimental parameters such as beam waists, cell temperature and input pulse width. In the present experiment we operated with parameters that allow for minimal reshaping, but consequently sub-optimal pulse advancement.

When the strong pump beam is present, it is possible for both the injected seed and generated conjugate pulses to exhibit negative group velocities, depending on the pump and injected seed detunings. A negative group velocity can be understood by considering its relation to a pulse’s arrival time delay, $\Delta T = \frac{\delta T}{v_g} - \frac{\delta}{c}$, after propagating some distance $L$. When the group velocity is negative, so is the time delay, which corresponds to the pulse peak exiting the medium at a time $-\Delta T$ sooner than if a similar pulse had traversed the same distance in vacuum. With a cell length of 1.7 cm, we obtain a maximum pulse peak advancement of 50 ns for the generated pulse, which corresponds to a group velocity of
Relative advancement is only 2% as a function of the logarithm of the input seed power.

At the largest detunings the generated pulse exhibits significant reshaping relative to the seed.

The generated pulse and amplified seed pulse advancements versus injected seed power are shown in Fig. 4. As can be shown from Eq. 1, the output photon number in both the seed and conjugate modes is proportional to the input seed photon number. The gain is proportional to $\exp(-\alpha_gL)$, where $\alpha_g$ is the gain coefficient (which is negative). The relation of the input seed intensity to the relative pulse arrival time delay is then $\Delta T \propto \frac{1}{\alpha_g} \propto -\ln(I_{in})$.

Since a negative time delay corresponds to advancement, the relative pulse peak advancement of the seeded and generated pulses is proportional to the natural logarithm of the input seed power, as shown in Fig. 4. This situation is unusual in that the intensity of the beam influences its own group velocity. This is somewhat analogous to a Kerr medium in which the intensity-dependent index of refraction alters the phase velocity. The generated conjugate pulse advancement is also controllable by varying the input seed power, resulting in a tunable advancement.

We have shown that a superluminal seed pulse can stimulate the creation of an additional superluminal conjugate pulse by the 4WM interaction. This generated pulse can propagate even faster than the superluminally-propagating seed pulse, with relatively small distortion. The pulse peak advancements of the two pulses are tunable by changing the input seed detuning and power. This could have applications in optical communication schemes in which pulse jitter may be compensated for by advancing or delaying pulses accordingly. Due to the multi-spatial-mode nature of 4WM in atomic vapors, the present results suggest that the superluminal propagation of images may be possible in future experiments. Additionally, due to the high level of squeezing obtainable via 4WM, and the fact that fast light may be obtained at a relatively low gain (and added noise), one may be able to use the quantum correlations between the twin beams to further investigate the details of superluminal light pulse propagation in such media. In particular, one can hope to use the quantum correlations to examine experimentally which part of the input pulse is causally linked to the peak of the output pulse.

Acknowledgments

This work was supported by the Air Force Office of Scientific Research. This research was performed while Ryan Glasser held a National Research Council Research Associateship Award at NIST. Ulrich Vogl would like to
thank the Alexander von Humboldt Foundation.