Simultaneous slow and fast light effects using probe gain and pump depletion via Raman gain in atomic vapor

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Abstract: We demonstrate experimentally slow and fast light effects achieved simultaneously using Raman gain and pump depletion in an atomic vapor. Heterodyne phase measurements show opposite dispersion characteristics at the pump and probe frequencies. Optical pulse propagations in the vapor medium confirm the slow and fast light effects due to these dispersions. We discuss applications of this technique in recently proposed rotation sensing and broadband detection schemes.

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Resonant dispersion phenomena originating from optically induced coherence in atomic media have been used to produce both slow and fast light, and have many potential applications[1-7]. Subluminal propagation (or slow light) is observed when the dispersion has a positive slope, corresponding to a reduced group velocity. This has been demonstrated using several approaches, including electromagnetically induced transparency [1,2], coherent population oscillation[8], and photorefractive beam coupling [9,10]. Similarly, controllable anomalous dispersion leading to superluminal propagation (or fast light) has been demonstrated using various techniques, including Raman gain doublets in a vapor medium [4].

Controllable anomalous dispersion has applications in enhancing the sensitivity of a gyroscope [11-13] and in constructing a white light cavity for broadband gravitational wave detection. [14-17]. Here we present a new technique for producing anomalous dispersion, which is better suited than the Raman doublet method for these applications, and for gyroscopy in particular. This technique has the interesting property that while it produces anomalous dispersion for one beam, it simultaneously produces normal dispersion for another.

We recall briefly how the gain-doublet-induced dispersion could be used in realizing a supersensitive gyroscope of the type we have proposed in reference 11. The basic device is a ring cavity containing a gain medium, such as an optically pumped Ti:Sapphire crystal. A rubidium vapor cell is added inside the cavity to serve as the dispersive medium. In the presence of a dual-frequency Raman pump, the cavity field, acting as a Raman probe, would experience gain in the rubidium cell at two different frequencies, each corresponding to the condition where the probe is two-photon resonant with one of the pump frequencies. When the cavity field frequency is near the center frequency between the two peaks, it would experience the negative dispersion necessary for enhancing the rotational sensitivity of the ring laser. In order for this scheme to work, the two pump fields producing Raman gain would each have to be coherent with the probe field, and have a greater intensity than the probe field.

However, in practice, a beam derived from the output of a laser cavity cannot be stronger than the intracavity field. One potential solution is to use the laser output, shifted in frequency by an acousto-optic modulator (AOM), to injection-lock a diode laser, the output of which, after further amplification, could potentially be used to produce pumps stronger than the intracavity field. The experiment reported here presents a simpler alternative to this scheme which uses the weaker laser output beam as the Raman probe and the stronger intracavity beam as the Raman pump. We will describe this alternative approach after presenting the results of the current experiment.

The atomic transitions used in the experiment are illustrated in Fig. 1.

Here, the optical pump produces a Raman population inversion. The probe then experiences Raman gain in the presence of the pump. Single-pass Raman gain with a large gain coefficient and subnatural linewidth can be achieved using a vapor medium with modest atomic density [$N \sim O(10^{12})$] and ground-state dephasing. During the stimulated Raman transition, the pump energy is depleted as the pump photons are converted to probe photons. The gain at the probe frequency is associated with a positive dispersion (subluminal effect), while the depletion at the pump frequency is associated with a negative dispersion (superluminal effect).

Our experiment uses a spatially non-overlapping incoherent optical pump and a moderate intensity Raman pump. For observing gain, an off-resonant Raman excitation is constituted in

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a λ-type configuration using the hyperfine metastable (ground) states and the Doppler-broadened, unresolved hyperfine $5P_{3/2}$ excited state manifold present in the D_2 line in Rb^{85}.

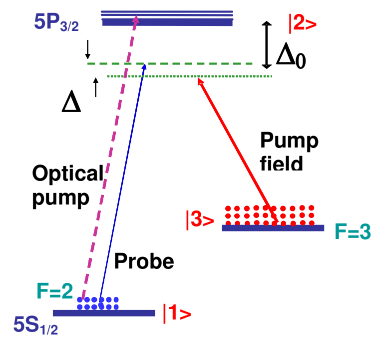

Fig. 1. Energy levels in D2 line of 85Rb used in Raman gain and depletion experiment.

Below, Fig. 2 shows the schematic of our experimental setup. The probe and pump laser beams are obtained using separate accousto-optic modulators (AOMs) after frequency-shifting the beams from a cw Ti:Sapphire laser (line width ~ 1 MHz). The frequency difference between them is matched to the metastable hyperfine state splitting (3.0357 GHz) in Rb^{85} in order to meet the two-photon resonance condition. An incoherent beam from a tapered amplifier diode laser is used as an optical pump to populate the upper metastable state. Raman gain at the probe frequency is observed by scanning its frequency around the two-photon resonance. The pump and probe beams are each linearly polarized, and are orthogonal to each other.

A 10 cm long rubidium vapor cell containing a mixture of 85 and 87 rubidium isotopes is used in the study. The vapor cell is magnetically shielded using two-layers of μ-metal. The cell is heated to a steady temperature of 70 °C using bifilarly wound coils in order to reduce the axial magnetic field due to the coil. All the beams are combined using polarizing and non-polarizing beam splitters at the input end before entering the cell. After passing through the cell, the probe beam is separated from all the other beams by using a high extinction prism polarizer. The spatially non-overlapping optical pump beam does not fall on the detector and therefore does not have to be separated. The optical pump beam is made relatively strong (~ 20 mW) to ensure pumping over a large velocity range of atoms, for efficient Raman population inversion and gain.

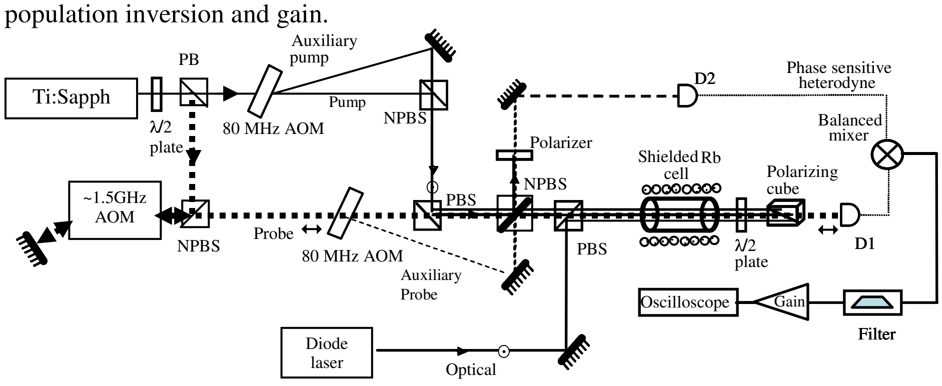

Fig 2. Experimental arrangement. PBS: polarizing beam splitter, AOM: acousto-optic modulator, D: photodiode

While the probe gain is observed, the average frequency detuning Δ_o of the laser fields for the Raman transition is varied by tuning the laser frequency away from the $5S_{1/2}$ (F = 3) - $5P_{3/2}$

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(F′ = 4) transition. Maximum probe gain is observed for a detuning close to 1 GHz below the transition. When this happens, the pump energy is significantly depleted due to transfer of energy from the pump to the probe. As a result, two-photon resonance is also observed in pump depletion. Fig. 3a shows the gain in the probe and a corresponding depletion of the pump beam.

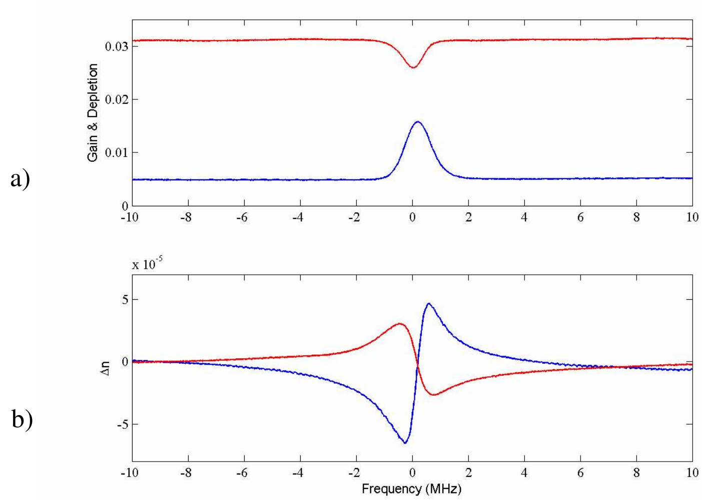

Fig. 3. (a) Measured gain and depletion for Raman Pump (red) and Raman Probe (blue) (b) corresponding dispersions measured using the heterodyne technique

We then use a heterodyne technique to measure accurately the dispersion associated with probe gain and pump depletion (Fig. 3(b)). A non-resonant auxiliary beam is produced by frequency shifting a fraction of the probe beam by 80 MHz, using an AOM. This is then divided in two parts, one of which is combined with the probe that experiences Raman gain and the other with the unperturbed fraction of the probe that does not propagate through the cell. These two heterodyne signals are detected using two fast photodetectors. The phase difference between the two rf signals varies in response to probe dispersion as the probe frequency is scanned around the gain resonance. A mixer with low phase–noise and a low-pass frequency filter are used to demodulate the rf signal from the detectors. The amplitude of the demodulated signal is proportional to the refractive index variation in the dilute atomic medium. A similar heterodyne technique is used to measure the dispersion due to pump depletion in Fig. 3(b), using an auxiliary frequency shifted pump beam shown by the dashed line in Fig. 2. This beam is blocked during probe dispersion measurement, but turned on during the pump dispersion measurement. The polarizer and the half-wave plate in both the unperturbed and the perturbed beam paths are also rotated to measure the pump dispersion using the same experimental arrangement. The dispersion is observed to be negative in comparison with the probe.

Having determined in this way that the theoretical group velocity of a pulse centered at the probe frequency should be less than c_0, due to the positive slope of the dispersion profile at its frequency, and that the group velocity for a pulse at the pump frequency should be greater than c_0 due to the negative slope of the dispersion at that frequency, we next used optical pulses in these beams to show these effects and to measure the group velocities directly.

The beams were pulsed using an RF switch on the voltage controlled oscillator (VCO) which generates the drive frequency for the AOM. Turning the switch off and on with TTL pulses from a digital pulse generator turns the AOM on and off quickly, creating nearly rectangular pulses at the pump and probe frequencies. Such pulses, however, are not suitable for these group velocity measurements since they have many frequency components outside

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the dispersion bandwidth. The VCO output was therefore passed through a mixer and multiplied with a low-pass filtered TTL pulse before being amplified and connected to the AOM transducer. The pulses created had smooth rise and falling edges, and had the two lobed shape which is evident in Fig. 4 and Fig. 5. This two-lobed shape serves the useful purpose of introducing an additional feature into the pulse structure. The shapes of the lobe for the pump pulse and the probe pulse differ because two different frequency mixers were used for the two beams. Fig. 4 shows the delay and gain experienced by the probe pulse in the presence of the pump. The transmission of the probe in the absence of the pump is shown by the black line, and the transmission when the pump beam is on, by the red line. The peak of the pulse clearly emerges later in the presence of gain, and the re-shaped pulse takes longer to fully emerge from the medium, as shown by the long tail on the red line. For reference, we also recorded a pulse which was routed around the cell and experienced no dispersion, shown in blue. The smaller amplitude is due to the imperfect beam splitter used to separate this pulse from the pulse which was sent through the medium.

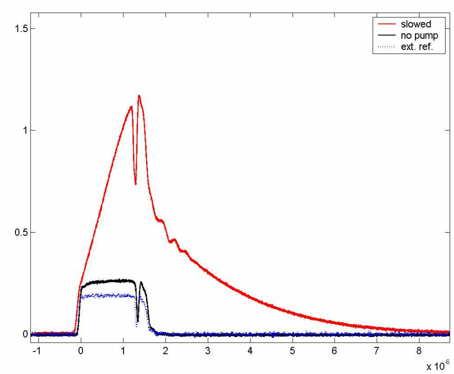

Fig. 4. Slowed probe pulse due to Raman gain induced positive dispersion.

Below, Fig. 5 shows similar data for the pump pulse, but in this case the blue line represents propagation of the pump pulse in the absence of the probe beam, and the red line represents the propagation of the pump when the probe beam is on. Here the difference is less dramatic, but still clear. The solid red line shows the reduction in amplitude due to the depletion of the pump beam, and a very slight advancement at the leading edge, and a more significant one at the trailing edge. The group velocity of this pulse is greater than c_0, due to the anomalous dispersion it experiences.

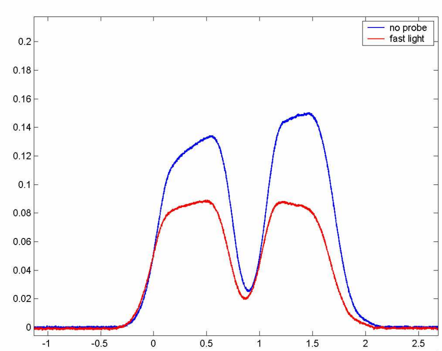

Fig. 5. Advancement of pump pulse (fast light) due to Raman depletion induced negative dispersion.

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This data confirms that the same medium may simultaneously act as a slow light medium for pulses centered at one frequency and a fast light medium for pulses centered at a different frequency. It also points to a simple method of creating steep anomalous dispersion profiles for high power beams with useful applications in rotation sensing and gravitational wave detection, as mentioned earlier.

In our introductory remarks we described a means for creating anomalous dispersion in a laser cavity which required a dual frequency Raman pump stronger than the intracavity (probe) field. However, a more practical approach based on the results presented here is to treat the strong intracavity beam itself as a single-frequency Raman pump, and use a weaker beam as the Raman probe. This weaker beam would be derived from the laser output but dynamically shifted so as to stay at a constant frequency even if the laser output frequency changes. Under these circumstances, the intracavity (pump) field experiences a loss due to depletion by the probe beam when the intracavity frequency is equal to ω_{probe}. This frequency dependent loss creates a controllable anomalous dispersion around ω_{probe}. In this scenario, we might choose the polarization such that the stronger pump beam transmits through the polarizing beam splitters surrounding the cell and then continues around a closed laser cavity path. The depleting probe would be introduced into the cavity by reflecting from one polarizing beam splitter and then rejected from the cavity by reflecting from the next. The auxiliary beams are used only for measuring the dispersion; they are not necessary for the gyroscope operation. This scheme does not require additional lasers for amplification and lends itself naturally to creating dispersion for relatively high powered beams.

Furthermore, if a gain depletion is used in place of a gain doublet, the anomalous dispersion for the depleted pump is accompanied by a normal dispersion for the amplified probe leading to simultaneous slow and fast light propagation in the same medium. This property may be of interest in itself. For instance, with a degenerate pump and probe with orthogonal polarizations, it opens up the possibility of studying polarization rotation accompanied by pulse cleaving and re-merger. However, the experimental demonstration of simultaneous slow and fast light which we present here is intended primarily as a proof-of-principle for the proposed method of creating anomalous dispersion for a laser gyroscope.

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