Tunable lossless slow and fast light in a four-level N-system

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ABSTRACT

We experimentally investigate a tunable slow and fast light regime for a weak optical pulse propagating controlled with two strong resonant pump fields through a medium of warm Rb atoms in an N-type interaction scheme. We evaluate potential advantages of integrating such a system into an optical gyroscope for improving its performance.

Keywords: coherent resonances, four-wave mixing, group velocity, optical gyroscope

1. INTRODUCTION

Manipulations of group velocity of light by means of atomic coherence have been an subject of many investigations in the recent decades prompted by a wide range of potential applications.[1–3] Recently, interest to fast light peaked due to predictions that a white-light cavity may substantially increase the sensitivity of a laser gyroscope.[4,5] To illustrate the origin of such enhancement, we note that a rotation of an optical cavity can be thought of as a change in the cavity length. Because only certain frequencies resonate within the cavity, a change in the cavity length δL corresponds to a change in the resonant frequencies of a cavity mode:

$$\frac{\delta\nu}{\nu} = -\frac{1}{n_g}\frac{\delta L}{L} = -\left(n + \omega\frac{\partial n}{\partial \omega}\right)\frac{\delta L}{L}. \tag{1}$$

In particular, this equation predicts that if the group index n_g is close to zero then a small change in cavity length (or, in gyroscope case, a rotation rate) results in a larger change of the resonant frequency $\delta\nu$, thus enhancing the output signal.[6,7] The original theoretical analysis predicted that under realistic experimental conditions nearly six orders of magnitude larger frequency shift is expected in such white light cavity gyroscope compared to an empty cavity with no dispersion engineering.[4]

While fast light has been demonstrated in a variety of atomic systems, the need of placing it inside an optical cavity without degrading its performance sets stringent requirements on allowable optical losses. Thus, an ideal system should allow broadband manipulations of its group index around $n_g = 0$ with negligible optical losses. In fact, a gain medium with vanishing group index may be necessary since the expected sensitivity enhancement is expected only for active laser gyroscopes.[4]

A number of interaction configurations have been used to successfully achieved fast light regime;[8–12] however, only a few of them avoid optical losses. One of the possible candidates is a four-level N-scheme, shown in Fig. 1.[13,14] In such system two optical fields - a strong pump Ω_1 and a weak probe Ω_2 - form a single Λ system between two long-lived atomic ground states. In this case atoms are pumped into a non-interacting dark state, resulting in a typical transmission two-photon resonance via electromagnetically induced transparency.[15] An additional strong pump field Ω_3 causes the Autler-Towns splitting of one of the ground-state levels, so that a single EIT resonance is also split into two, producing a dip in the probe field transmission with negative dispersion around zero two-photon detuning δ. Recently, we have theoretically demonstrated[16] that with careful choice of atomic transitions it may be possible to compensate for any absorption and even achieve gain in such

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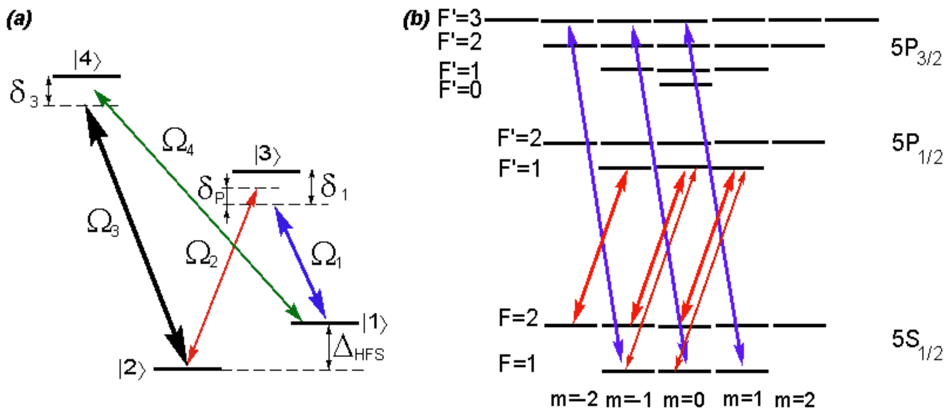

Figure 1. *(a)* Simplified four-level N-scheme, considered theoretically. *(b)* Experimental realization of such scheme using Rb atoms.

system while maintaining negative sign of dispersion if optical transitions between states $|4\rangle$ and $|1\rangle$ is allowed, and a fourth field Ω_4 is generated via the four-wave mixing in a double-Λ system .[17–21]

Here, we report preliminary experimental observations of amplification and negative dispersion of a probe optical field propagating through hot Rb vapor in such an N-scheme.

2. EXPERIMENTAL SETUP

The experimental arrangement is shown in Fig. 2. Two of the required three optical fields — the first pump field Ω_1 and a probe field Ω_2—were derived from a single laser to ensure their mutual phase coherence. For that purpose a laser beam, tuned in the vicinity of D1 line of Rb [as shown in Fig. 1(b)] was phase modulated at the hyperfine ground-state splitting frequency $\Delta_{\rm HFS} = 6.835$ GHz using an electro-optical modulator (EOM). Approximately 1% of the pump intensity was transferred to each of the first-order modulation sidebands. The high-frequency sideband served as a probe field Ω_2, and the unmodulated laser field acted as a pump field Ω_1. Throughout the measurements described below the powers of these two fields were kept constant ($P_{\Omega_1} \approx 0.8\,$mW, $P_{\Omega_2}/P_{\Omega_1} \approx 0.01$). We have verified that lowering or raising the D1 laser power did not produce any qualitative changes in the behavior of the optical resonances described below.

The second strong pump field Ω_3 was produced by an independent laser operating at the D2 Rb line (780 nm), and its power and exact frequency were experimentally optimized as described below. The D1 and D2 optical inputs were combined on a polarizing beam-splitter and circularly polarized before entering the cell. For all reported data we used a 7.5 cm-long ^{87}Rb cell with 5 Torr of Ne buffer gas, magnetically shielded and heated to 50 °C. For detection, we used a fast photodiode (DC to 13 GHz) in a standard heterodyning configuration,[19] in which a fraction of the original laser output played the role of a local oscillator. In order to detect only the weak probe transmission, an acousto-optical modulator (AOM) placed after the EOM shifted the frequencies of the corresponding optical fields by -80 MHz relative to the original laser frequency. Once the frequency shifted optical fields (after interaction with the Rb cell) were mixed with a bypass at the original D1 laser frequency, the beat note between this bypass field and the probe field (the "+1" modulation sideband) occurred at 6.9147 GHz. This signal was easily separated by a spectrum analyzer from any beatnotes between other optical fields, and provided accurate measurements of any variations in the probe field amplitude after interaction with atoms. The beat note between the other "-1" modulation sideband and the bypass optical field happened at 6.7547 GHz. We monitored that channel as well to check a possible effect due to a different four-wave mixing process initiated by the far-detuned interaction of Ω_1 with the 2–3 transition. We found that in the case of "pure" EIT (no D2 field) there was a noticeable modification of the "-1" sideband (that we usually referred to as a Stokes field), as observed in earlier experiments.[19, 20] However, in the presence of the strong D2 laser light, the intensity of the Stokes sideband was completely independent of the probe field's two-photon detuning. Thus, it seems like the

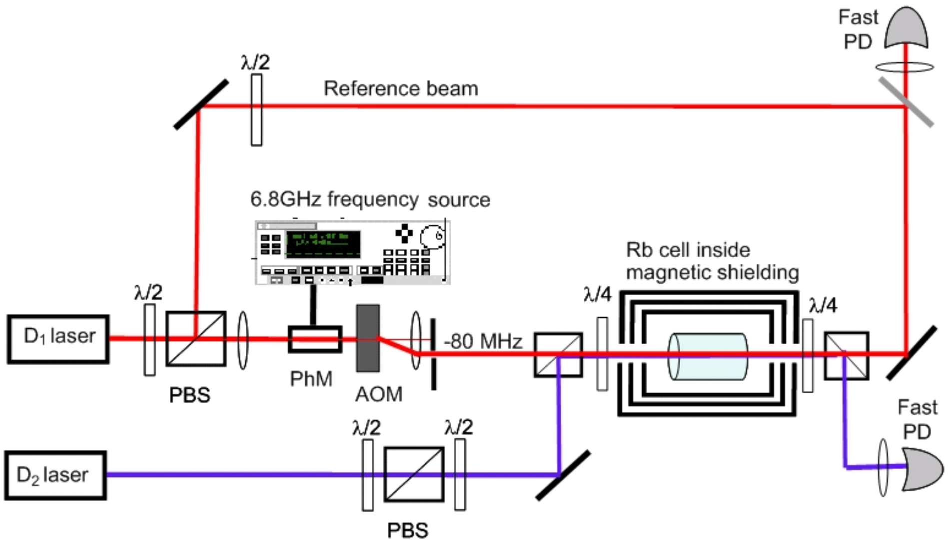

Figure 2. Diagram of experimental setup.

off-resonant action of the pump field does not play a dramatic role, at least in the range of tested experimental parameters.

We also were able to detect and measure the amplitude of the generated four-wave-mixing field Ω_4 by separating Ω_3 and Ω_4 from orthogonality polarized Ω_1 and Ω_2 after the Rb cell using a second polarizing beam splitter, and by detecting the beat note between Ω_3 and Ω_4 at the original modulation frequency 6.8357 GHz using the same fast photodiode.

3. PROBE FIELD TRANSMISSION MEASUREMENTS

We explored a range of optical frequencies for both D1 and D2 lasers, and identified the optimal detuning for the D1 laser to be $5S_{1/2}\, F = 2 \rightarrow 5P_{1/2}\, F' = 1$ and $5S_{1/2}\, F = 1 \rightarrow 5P_{1/2}\, F' = 1$ transition for the pump and probe fields, respectively. In this case to complete N-scheme the D2 laser was tuned in the vicinity of $5S_{1/2}\, F = 1 \rightarrow 5P_{3/2}\, F' = 1$, as shown in Fig. 1(b). Interestingly, if only D1 laser was present, for a circularly polarized probe the transmission was not a typical symmetric EIT resonance, but rather an asymmetric feature with both enhanced absorption and increased transmission (with respect to the background level (i.e. the transmission level at large two-photon detuning δ), as shown in Fig. 3. Yet, for a linearly polarized D1 beam the EIT peak was symmetric; in fact, it was convenient to use this peak to fine-tune the frequency of the laser, since the optimal D1 detuning corresponded to the most symmetric $lin||lin$ EIT resonance.

The presence of the D2 laser in N-configuration strongly modified the probe spectrum, generally increasing the transmission and leading to gain under certain conditions. We observed the strongest gain when the D2 laser was blue-detuned from $F = 1 \rightarrow F'$ transition by 1.0-1.5 GHz, as shown in Fig. 3(a). Under these conditions the spectrum was dominated by a single broad gain peak at the "red" two-photon detuning (i.e. for two-photon detunings below EIT resonance center). As the frequency of the D2 laser was tuned closer to the $F = 1 \rightarrow F' = 2$ transition, the single gain peak moved closer to the zero two-photon detuning, and transformed into a double-peaked structure, as shown in Fig. 3(b). In this transformation the original single gain peak became one of the observed resonances (in this case for smaller δ), as the second peak emerged at higher δ. Observed lineshapes, therefore, are rather similar to the earlier theory predictions[16] for the target regime with tunable zero group index and lossless fast light. Finally, for the red-detuned D2 laser the probe transmission changed back into a single-peak spectrum, although the overall transmission and gain became weaker [Fig. 3(c)], with absorption increasing for larger values of detuning. The transformation of the probe transmission spectrum from a double-peaked feature for the D2 line on resonance to a single peak shifted to one of the sides of the two-photon resonance in accordance with the D2 laser detuning is also similar to the theory predictions.

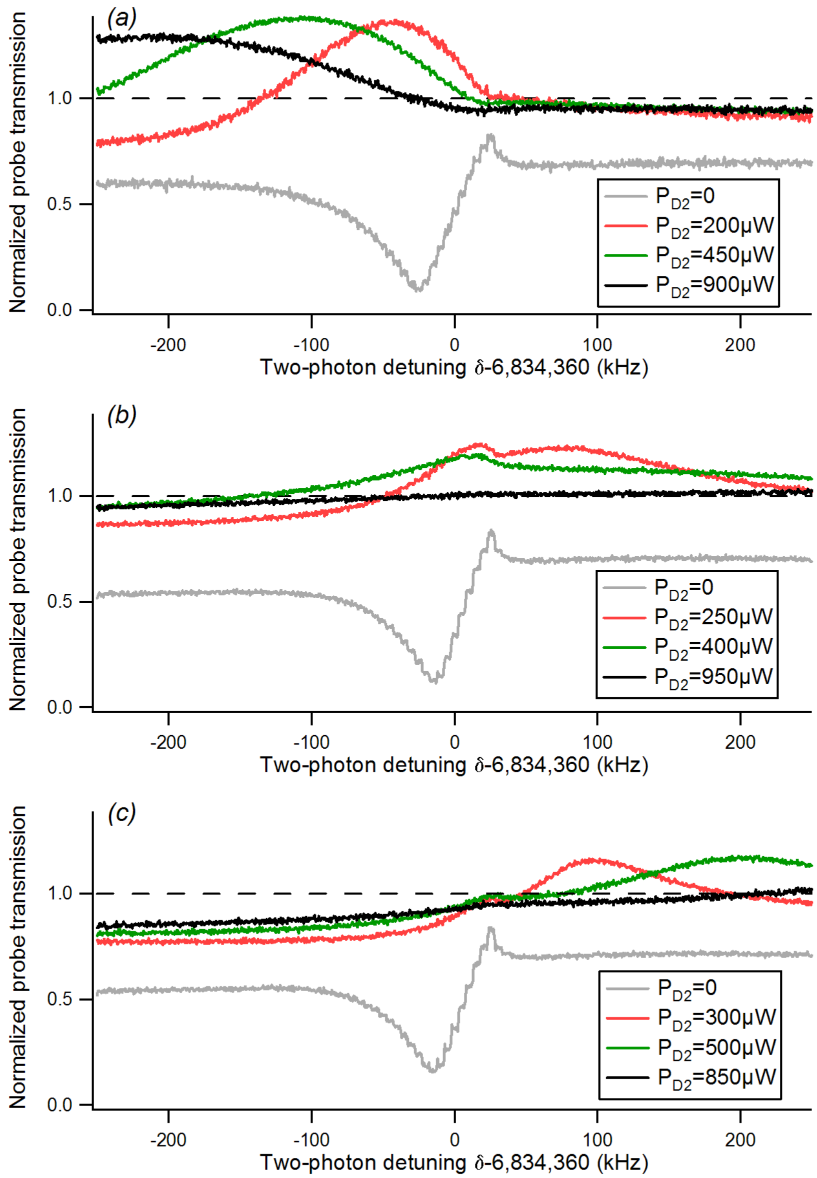

Figure 3. Normalized output probe field spectra at different detunings of the D2 laser: *(a)* blue-detuned at approximately 1 GHz from the center of $F = 2 \rightarrow F'$ transition (maximum four-wave mixing gain); *(b)* on resonance; *(c)* red-detuned by approximately 0.5 GHz).

Fig. 4 shows more details on evolution of the double-peaked probe transmission as the D2 laser power increased. It is clear that the splitting between two observed peaks increased with power, as expected from the original theory.[16] However, we also observed some traits that this theory did not describe. For example, it is easy to see that one of the observed peaks was always narrower and sharper than the other. Also, its position was much less affected by either power or frequency of the D2 pump laser. One of the possible explanation for such behavior is that this peak was due to the contribution of atoms diffusing in and out of the laser beam.[22, 23] Since these atoms spend most of their time outside of the interaction region, they experience much weaker average power broadening and light shift.

Another practical complication in translating the simple four-level theory into real Rb atoms arises from optical pumping of populations into "dark pockets", ground-state sublevels not coupled by either strong pump

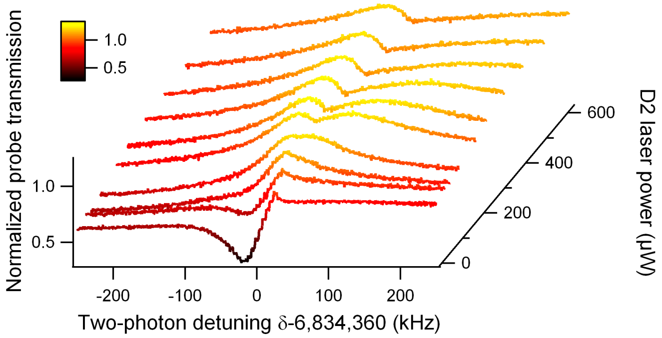

Figure 4. Normalized output probe transmission as a function of frequency difference δ between the probe and D1 pump (i.e. the EOM modulation frequency) and the D2 laser power. Lighter (yellow) coloring marks the spectral regions of positive probe gain.

optical fields. An example of such state is $F = 2, m_F = 2$ state in Fig. 1(b). We observed that for the D2 laser powers greater than 1-2 mW (depending on laser detuning), the probe field was completely transmitted independently of the two-photon detuning [see, for example the black trace (corresponding to 950 μW D2 power) in Fig. 3(b)]. In the future such optical pumping will have to be taken into account when choosing an interaction scheme, since it may potentially limit the pump field powers.

4. GROUP INDEX MEASUREMENTS

Since the absorption spectra looked promising, we then proceeded with measurements of the dispersive properties of this interaction scheme. To do that we added a sinusoidal modulation to the probe field amplitude (by modulating the rf power sent to the EOM), and measured its delay after interaction with atoms with respect to the reference. The frequency of this amplitude modulation was varied from 1 kHz to 100 kHz. Fig. 5 shows the dependence of the group delay and gain as function of modulation frequency for the laser detuning corresponding to Fig. 3(b), at which we have observed a clear double-peaked feature. The measured transmission of the probe signals was uniformly around 90%. The values of delay were measured using either manually by recording and fitting the transmitted traces (for direct confirmation), or by using a lock-in amplifier to detect any phase variations (for better precision). Both methods showed that slow or fast pulse propataion regime strongly depended on the modulation frequency: for higher frequency we observed the probe delay, whereas for the lower frequencies it smoothly changed into advance, passing the zero delay (i.e. zero group index) point. This behavior can be readily understood from the complex shape of the double-peaked transmission resonance [as seen in Fig. 3(b)]: the narrow dip between two peaks affects the probe pulse propagation only in narrow bandwidth, and for higher modulation frequency the broad gain feature dominates the dispersion. We also observed that the range of modulation frequencies corresponding to nearly zero group index (i.e. the boundary between slow to fast light regime) can be controlled by the power of D2 laser: the zero group index was measured at higher modulation frequencies for a higher power. This feature is particularly interesting for development of gyroscopes with controllable bandwidth to accommodate a wide range of detection regimes.

Interestingly enough, we were able to achieve even higher transmission and gain by detuning the D2 laser to approximately 1 GHz to the blue. At this detuning the double-peaked structure was transformed into a single (but stronger) optical gain, as shown in Fig. 3(a). Fig. 6 shows the delay and amplification of the probe field measured in this conditions. The group delay/advance showed similar behavior to the previous resonance case, while maintaining the positive gain for all frequencies, including the point of zero group index. While it is not immediately obvious why we observed such negative delay near the center of the single gain peak, we have reproduced this result in different experimental conditions, including a different vapor cell. This regime will be investigated further, since it seems to be particularly promising for active gyroscope development.

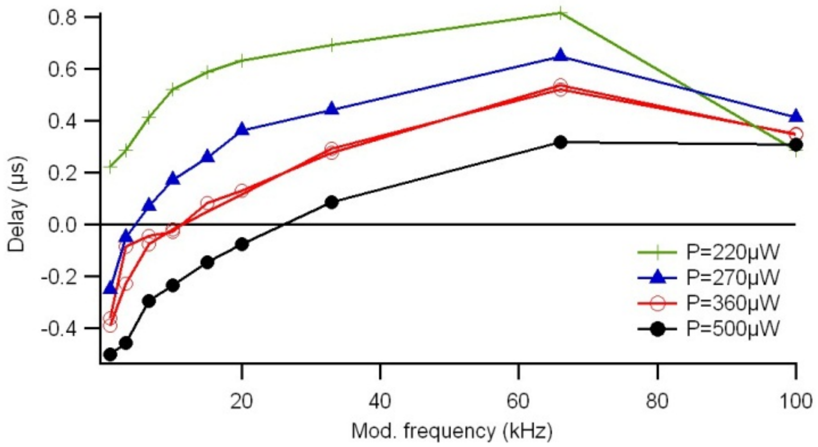

Figure 5. Relative delay of the sinusoidal amplitude modulated probe field with respect to a reference (negative delay indicates fast light regime) as a function of modulation frequency.

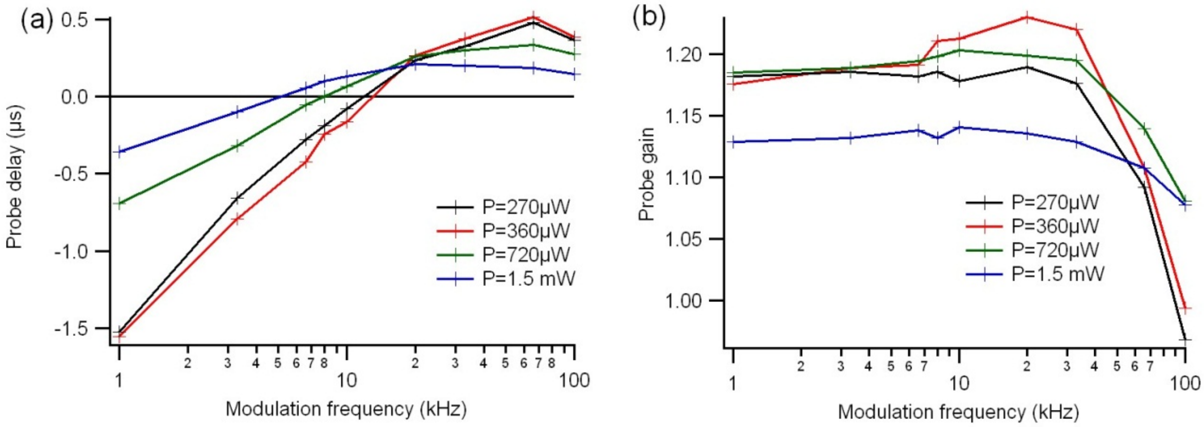

Figure 6. (a) Relative delay of the sinusoidal amplitude modulated probe field with respect to a reference. (b) Relative amplification of the probe field.

5. CONCLUSIONS

Here we report on experimental measurements of amplified optical probe propagation in hot Rb vapor under the four-wave mixing conditions in a double-Λ configuration. We show that with proper choice of powers and detunings of two strong pump fields we can achieve negative dispersion with gain. Moreover, the bandwidth at which zero group index is achieved, can be controlled by adjusting the D2 pump laser power, which makes it attractive for practical gyroscope design.

6. ACKNOWLEDGMENTS

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