

Electromagnetically induced transparency in Raman gain for realizing a superluminal ring laser

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Abstract: We describe an approach for realizing a superluminal ring laser using a single isotope of Rb vapor by producing electromagnetically induced transparency (EIT) in Raman gain. We show that by modifying the detuning and the intensity of the optical pump field used for generating the two-photon population inversion needed for generating Raman gain, it is possible to generate a dip in the center of the gain profile that can be tuned to produce a vanishingly small group index, as needed for making the Raman laser superluminal. We show that two such lasers, employing two different vapor cells, can be realized simultaneously, operating in counter-propagating directions in the same cavity, as needed for realizing a superluminal ring laser gyroscope. This technique, employing only one isotope, is much simpler than the earlier, alternative approach for realizing a superluminal Raman laser based on Raman gain and Raman dip in two isotopes [Zhou et. al, Opt. Express 27, 29738 (2019)]. We present both an approximate theoretical model based on four levels as well as the results of a model that takes into account all relevant hyperfine states corresponding to the D1 and D2 transitions in 85Rb atom. We also present experimental results, in good agreement with the theoretical model, to validate the approach.

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1. Introduction

Superluminal lasing can be produced inside a cavity with a negative dispersion gain medium, corresponding to a group index which is much smaller than unity and can approach a value very close to zero [1–4], corresponding to group velocity of light exceeding the vacuum speed of light [5]. It has been shown in previous works that the sensitivity of a ring laser for measuring a cavity length perturbation is enhanced by a factor which is inversely proportional to the group index of the medium [1–4,6–8]. This property makes the superluminal laser highly attractive for various sensing applications, including gravitational waves detection [9,10], navigation [1,2] and measurement of strain [11].

Due to the inherent relation between dispersion and gain/loss dictated by the Kramers-Kronig relations [12], lasing with superluminal group velocity requires the presence of a relatively narrow dip on top of a broad gain spectrum [3]. Over the last decade, different approaches have been studied for realizing the necessary gain profile, such as double Raman gain [5,6,13,14], coupled ring resonators with Brillouin gain [15,16], diode-pumped Alkali Laser (DPAL) medium coupled with a Raman resonance induced depletion [17], Raman gain and depletion using two isotopes of Rb [18], optically pumped Raman gain and a self-pumped Raman depletion [4], and four-wave mixing employing the *N*-Scheme [19–21]. All those approaches are either quite complicated or require the use of many lasers, thus making them challenging for realizing a superluminal laser based sensor in a compact form, as needed for navigation, for example.

In this paper we describe a new approach for realizing a superluminal laser which is simpler than those considered previously. In this technique, only two spectrally uncorrelated lasers are required to realize a superluminal Raman laser. The process requires a Λ -system, in which the populations of the two low-lying states are imbalanced by using an optical pump to couple one of these states to an auxiliary fourth state. An optically detuned Raman pump produces Raman gain for a probe, with the peak gain occurring when the probe and the Raman pump are two-photon resonant. The optical pump, via the Autler-Townes effect [22], produces an electromagnetically induced transparency (EIT), manifested as a dip in the Raman gain profile. As Raman gain is unidirectional, this process is suitable for realizing two independent and counter-propagating superluminal lasers in the same ring cavity, as needed for rotation sensing. This is a distinct advantage of this approach in comparison with the DPAL plus Raman gain technique, which also requires two lasers. Furthermore, unlike DPAL gain, no high pressure buffer gas is necessary.

The technique presented here is also significantly simpler than the approach used in Ref. [4]. To see this, we recall that for the scheme in Ref. [4] three lasers are required to generate a superluminal laser in one direction: a Raman pump and an optical pump to generate the gain using ⁸⁵Rb, and a separate Raman pump to generate the dip using ⁸⁷Rb. Furthermore, the frequencies of the two Raman pump lasers have to be highly correlated. To ensure this correlation, an off-set phase locking technique is used, employing a complex and expensive apparatus. To generate bi-directional superluminal lasers, as required for rotation sensing, one would need additional lasers. In order to avoid mode-locking, it is useful to operate the rotation sensor in a non-degenerate configuration, wherein two different longitudinal modes are used for the clock-wise and counter-clock-wise superluminal lasers. Therefore, it is not possible to share the Raman pump lasers for generating the gain-plus-dip for both directions. However, it is possible to share the optical pump laser. As such, at a minimum, it is necessary to employ five different lasers for such a system, along with two off-set phase locking systems. In contrast, for the scheme described in this paper, only three lasers (two separate Raman pumps, one for each direction, and a single optical pump shared between two directions) are required to make a rotation sensor employing bi-directional lasing. Furthermore, there is no need to make use of off-set phase locking systems.

The rest of the paper is organized as follows. In Section 2, we present an explicit model for implementing this scheme, using transitions in ⁸⁵Rb atoms, and show numerical modeling results of the gain profile for various combinations of operating parameters. In Section 3, we use an iterative model to determine the enhancement in sensitivity of a superluminal laser resulting from this scheme. In Section 4, we show an augmented model where the hyperfine splittings in the excited states are taken into account. In Section 5, we present the experimental configuration used to validate the concept and fittings to the experimental results. In Section 6, we describe how to realize a pair of independent superluminal lasers in a ring cavity for rotation sensing. We summarize the results and present concluding remarks in Section 7.

2. Model using transitions in ⁸⁵Rb atoms

The proposed scheme is illustrated schematically in Fig. 1. Here, the Λ -system consists of the states $|1\rangle$, $|2\rangle$ and $|3\rangle$, and the auxiliary state for optical pumping is labeled as $|4\rangle$. In ⁸⁵Rb, states $|1\rangle$ and $|2\rangle$ correspond, respectively, to the $5^2S_{1/2}$, F=2 and $5^2S_{1/2}$, F=3 states. For simplicity, we modeled the entire $5^2P_{1/2}$ and $5^2P_{3/2}$ manifolds as states $|3\rangle$ and $|4\rangle$, respectively. The Raman pump is applied along the $|2\rangle - |3\rangle$ transition, with a detuning of δ_p . The co-propagating Raman probe is applied along the $|1\rangle - |3\rangle$ transition, with a detuning of δ_s . The optical pumping beam, assumed to be counter-propagating with the Raman pumps and probes, is applied along the $|1\rangle - |4\rangle$ transition, with a detuning of δ_{op} . The Rabi frequencies of the Raman probe, the Raman pump and the optical pump are denoted as Ω_s , Ω_p , and Ω_{op} , respectively. State $|3\rangle(|4\rangle)$ decays at the rate of Γ_a (Γ_b). We assume that each of these states decays equally to the two ground states,

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and that $\Gamma_a = \Gamma_b = 6$ MHz. We also assume that each of the ground states decays collisionally to the other ground state at the rate of Γ_g . For illustrating the basic features of our scheme, we have used a nominal value of 1 MHz for Γ_g . When we compare the model with experimental results, we have used the value of Γ_g as a fitting parameter, with values ranging from 0.3 MHz to 0.5 MHz.



Fig. 1. Left: energy level diagram for ⁸⁵Rb and the applied fields. Here, Ω_s , Ω_p and Ω_{op} are the Rabi frequencies of the probe, pump and optical pump fields respectively, and δ_s , δ_p and δ_{op} are the detuning associated with the same fields. Right: the corresponding Λ system influenced by the optical pump.

We also consider the Doppler broadening, by assuming Maxwell-Boltzmann distribution for the velocities of the atoms, expressed as $w(v) = \sqrt{m/2\pi K_B T} \exp(-mv^2/2K_B T)$, where K_B is the Boltzmann constant, T is the temperature in Kelvin, and m is the atomic mass of ⁸⁵Rb. The frequency of each field as seen by the atoms is shifted as $f = f_0 + \vec{k} \cdot \vec{v}$, where \vec{k} is the appropriate wave vector, \vec{v} is the atomic velocity, and f_0 is the frequency measured in the laboratory frame.

Consider first the case for atoms with zero velocity along the direction of propagation of the beams. The optical pump field produces a population inversion between states $|1\rangle$ and $|2\rangle$. As a result, a detuned Raman pump applied along the $|2\rangle - |3\rangle$ transition produces Raman gain for a probe applied along the $|1\rangle - |3\rangle$ transition. The peak gain occurs when the difference in frequency between the Raman pump and the probe matches the energy difference between states $|1\rangle$ and $|2\rangle$. For a probe with a vanishingly small intensity, the width of the Raman gain spectrum is determined by two factors. The first is the collisional decay rate, Γ_g , of each of the ground states. The second is an additional contribution to the decay rate of state $|1\rangle$, determined by the effective rate of optical pumping from this state to state $|2\rangle$.

In addition to producing the population imbalance, the optical pumping beam affects the effective energy of state $|1\rangle$. If the detuning of the optical pumping beam is large compared to the decay rate of state $|4\rangle$ and the Rabi frequency of the optical pumping is weak ($\Omega_{op} <<\Gamma_b, \delta_{op}$), the energy of state $|1\rangle$ is simply modified by the light-shift [23], given by $\sim (\Omega_{op}^2/4\delta_{op})$. The effective rate of optical pumping from state $|1\rangle$ to state $|2\rangle$ is $\sim (\Omega_{op}^2\Gamma_b/8\delta_{op}^2)$ [24]. However, for $\delta_{op}=0$ and $\Omega_{op} >>\Gamma_b$, the state $|1\rangle$ gets split into two dressed states, via the Autler-Townes (AT) effect [22]. The AT splitting equals the value of Ω_{op} . Such a splitting produces two Raman gain peaks, as a function of the probe frequency, separated by Ω_{op} . This mechanism is equivalent to EIT usually observed in absorption spectra [25–27]. However, in this case, given the population inversion, it manifests as a suppression in the gain. The effective rate of the radiative decay for each of the two dressed states to state $|2\rangle$ is $\sim \Gamma_b/4$. This is because (a) each of these states is an equal superposition of states $|1\rangle$ and $|4\rangle$, and (b) state $|4\rangle$ is assumed to decay with equal probabilities to states $|1\rangle$ and $|2\rangle$, as noted earlier. When the collisional decay rate is taken into account, the net decay rate for each of these dressed states becomes $\sim (\Gamma_b/4 + \Gamma_g/2)$. The linewidth of each of the two Raman gain peaks is expected to be $\sim (\Gamma_b/4 + 3\Gamma_g/2)$, which is ~ 3 MHz.

Consider next the effect of the spread in velocities. For a vapor cell at ~100° C, the Doppler width is ~600 MHz for optical transitions. Since the Raman pump and the probe are copropagating, the location of the peaks in the Raman gain normally experiences a substantially smaller Doppler broadening of ~ 5 kHz, corresponding to the difference frequency of ~3 GHz (the hyperfine splitting in ⁸⁵Rb). However, the optical pumping process is significantly affected by the Doppler broadening. For the zero velocity atoms, the Raman gain spectrum develops two peaks, as noted above. For the atoms with non-zero velocities, the peaks become asymmetric, eventually reducing to a single peak with a light-shift for larger Doppler detunings. When these processes are averaged over the distribution in velocities, the Raman gain spectrum is no longer split between two distinct peaks. Instead the two peaks overlap, with a dip in the center. The properties of this dip can be tuned by adjusting various parameter, in order to produce conditions suitable for a superluminal laser. Next, we construct a concrete model for this system, using density matrix equations, in order to determine the behavior of the gain spectrum more quantitatively.

The equation of evolution for the density matrix which represents the system can be expressed as [28]:

$$\partial \rho / \partial t = -i/\hbar [H\rho - \rho H^{\dagger}] + (\partial \rho / \partial t)_{source}$$
(1)

where ρ is the density matrix and *H* is Hamiltonian, under the electric dipole approximation and rotation wave transformation. The Hamiltonian contains complex terms added to the diagonal elements, in order to account for decays of atomic states as well as the corresponding dephasing of atomic coherences. The second term on the right-hand side in Eq. (1) represents the influx of atoms into a state due to decay from another state. The Hamiltonian is expressed as:

$$H = (\hbar/2)\{[-i\Gamma_g|1\rangle \langle 1| + (2\delta_p - 2\delta_s - i\Gamma_g)|2\rangle \langle 2| - (2\delta_s + i\Gamma_a)|3\rangle \langle 3| - (2\delta_{op} + i\Gamma_b)|4\rangle \langle 4|] + [\Omega_s|3\rangle \langle 1| + \Omega_p|3\rangle \langle 2| + \Omega_{op}|4\rangle \langle 1| + H.C.]\}$$
(2)

The source terms are:

$$\begin{aligned} (\partial \rho / \partial t)_{source} &= \left[\Gamma_g \rho_{2,2} + (\Gamma_a/2)\rho_{3,3} + (\Gamma_b/2)\rho_{4,4} \right] |1\rangle \langle 1| \\ &+ \left[\Gamma_g \rho_{1,1} + (\Gamma_a/2)\rho_{3,3} + (\Gamma_b/2)\rho_{4,4} \right] |2\rangle \langle 2| \end{aligned}$$
(3)

The steady-state solution of Eq. (1) is calculated numerically based on the N-level algorithm [28], and yields the susceptibility of the probe beam as a function of its detuning: $\chi = (\hbar cn/I_{sat}\Omega_s)(\Gamma_a/2)^2 \bar{\rho}_{3,1}$, where *c* is the speed of light in vacuum, $n (=10^{18}m^{-3})$ is the density of atoms, I_{sat} is the saturation intensity for the $|1\rangle - |3\rangle$ transition, assumed to be $120W/m^2$, and $\bar{\rho}_{3,1}$ is the effective matrix element obtained by integrating the results of Eq. (1) over the velocity distribution of atoms.

Figure 2 shows the simulation results for zero atomic velocity and considering atomic velocity distribution. The blue curve represents the gain under the AT splitting. The width of each gain peak is close to 3 MHz, in agreement with the discussion presented earlier. In the presence of velocity averaging, as shown in the red curve, the amplitude decreases, and each of the peaks gets broadened. The asymmetry is due to the fact that the Raman gain pump is detuned above resonance. If the sign of the detuning is reversed, the asymmetry gets reversed as well.

In Fig. 3, we show that it is possible to change the shape of the gain profile from a single peak in (a) to a broad gain with a dip which gets deeper when increasing the optical pump intensity, while the other parameters remain constant. Moreover, the slope of the dispersion in the vicinity of the two-photon resonance frequency changes from a positive to a negative value and can be controlled by modifying this parameter.





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Fig. 3. The gain profiles (blue) and the corresponding dispersions (orange) when varying the optical pump intensity, using the following parameters: $\Omega_s = 0.1\Gamma$, $\Omega_p = 12\Gamma$, $\delta_p = 200\Gamma$, $\delta_{op} = 0\Gamma$; (a) $\Omega_{op} = 1\Gamma$ (b) $\Omega_{op} = 3\Gamma$ (c) $\Omega_{op} = 5\Gamma$ (d) $\Omega_{op} = 7\Gamma$ ($\Gamma = 6MHz$).

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3. Determining the frequency and intensity of the superluminal laser

To find the frequency and the intensity of the laser field developed inside the cavity in the presence of the gain medium described above, we used an iterative algorithm [18,29,30] for solving the semi-classical equations of motion for a single mode laser [31] at steady state. The relevant equations are:

$$v = \frac{\omega_C}{1 + \chi'(\Omega_s, \delta_s)/2} \tag{4}$$

$$\chi''(\Omega_s, \delta_s) = -1/Q \tag{5}$$

where χ' and χ'' are the real part and imaginary part of the susceptibility χ , $\omega_{\rm C}$ is the empty cavity resonance frequency, and Q is the quality factor of the empty cavity. The flow chart of the algorithm is illustrated in Fig. 4.



Fig. 4. Flow chart illustrating the iterative algorithm used to calculate laser output frequency and amplitude

For a certain cavity length, and a fixed set of input parameters, we determine the range of values (denoted as Δ_s) of the probe detuning, δ_s for which the value of $-\chi$ " is greater (1/Q), for an infinitesimally small value of the probe Rabi frequency, Ω_s . We then choose an initial, non-infinitesimal value for Ω_s , and then carry out the outer-most loop of the computation, under which we scan through the values of δ_s within the range Δ_s . For the initial value of Ω_s , we solve the density matrix equations in steady state, yielding the susceptibility (χ ' and χ "), and check to see if Eq. (5) is satisfied, within a chosen level of accuracy. If it is not, we iterate the value of Ω_s until it is satisfied, again within a chosen fraction of accuracy. If it is not, we repeat the process with another value of δ_s . This outer loop is interrupted when both Eq. (5) and Eq. (4) are satisfied, thus yielding the laser frequency and the corresponding Rabi frequency. The saturation intensity for the probe transition is then used to determine the intensity of the laser.

The derivatives $d\nu/dL$ and $d\omega_C/dL$, where L is the length of the cavity, characterize the sensitivity of the laser output frequency relative to cavity length change in a lasing cavity and an empty cavity, respectively. The ratio between these derivatives, $(d\nu/dL)/(d\omega_C/dL)$, represents the sensitivity enhancement factor (SEF), assuming that this quantity has value of unity for a conventional laser. Using the algorithm described above, we find the steady-state solution of the superluminal ring laser for a specific cavity length. To determine the SEF, we introduce a perturbation to the cavity length and find the resulting shift in the lasing frequency. We repeat this process for different values of the cavity length and the corresponding lasing frequency in the absence of the perturbation.

The SEF is plotted Fig. 5, along with the corresponding group index. As can be seen, for a certain set of parameters, the enhancement value can reach a peak value as large as 6×10^4 . It should be also noted that the SEF decreases rapidly if the operating frequency of the laser, in the absence of perturbation, moves too far away from the center of the dip in the superluminal gain profile. This behavior is present in all techniques for realizing a superluminal laser.



Fig. 5. The sensitivity enhancement factor (SEF) and the corresponding group index as functions of the probe detuning obtained using the initial set of parameters: $\Omega_s = 5\Gamma$, $\Omega_p = 12.4\Gamma$, $\Omega_{op} = 5.81248\Gamma$, $\delta_p = -200\Gamma$, $\delta_{op} = -5\Gamma$, $\Gamma = 6 MHz$.

Augmented model taking into account hyperfine splitting in the excited states

For ⁸⁵Rb atoms, as shown in Fig. 6, the $5^2P_{1/2}$ manifold contains two hyperfine levels corresponding to F'=2 and F'=3, separated by Δ =361 MHz, which is less than the Doppler width of ~600 MHz. The $5^2P_{3/2}$ manifold contains four hyperfine levels corresponding to F"=1,2,3,4. However, in the proposed scheme, F"=4 is not allowed to be coupled by the optical pump field due to selection rules. The energy separation between F"=2 to F"=1, and between F"=3 to F"=2 are Δ_{21} =29 MHz and Δ_{32} =63 MHz, respectively, both significantly smaller than the Doppler width. As such, for an accurate modeling of the process, these hyperfine levels need to be taken into account.

We assume that the Raman pump and the probe are each linearly polarized, orthogonal to one another, and the optical pump is also linearly polarized. The complex Hamiltonian and the source terms for the seven-level model are as follows:

$$H = (\hbar/2) \{ [-i\Gamma_g | 1\rangle \langle 1| + (2\delta_p - 2\delta_s - i\Gamma_g) | 2\rangle \langle 2| - (2\delta_s + i\Gamma_a) | 3\rangle \langle 3| - (2\delta_s + i\Gamma_a - 2\Delta) | 4\rangle \langle 4| - (2\delta_{op} + i\Gamma_b) | 5\rangle \langle 5| - (2\delta_{op} + i\Gamma_b - 2\Delta_{21}) | 6\rangle \langle 6| - (2\delta_{op} + i\Gamma_b - 2\Delta_{21} - 2\Delta_{32}) | 7\rangle \langle 7|] + [\Omega_s | 3\rangle \langle 1| + \Omega_p | 3\rangle \langle 2| + \alpha_1 \Omega_s | 4\rangle \langle 1| + \alpha_2 \Omega_p | 4\rangle \langle 2| + \Omega_{op} | 5\rangle \langle 1| + \alpha_3 \Omega_{op} | 6\rangle \langle 1| + \alpha_4 \Omega_{op} | 7\rangle \langle 1| + H.C.] \}$$

$$(6)$$



Fig. 6. Left: description of the system including the hyperfine states and the coupling fields. Right: the coupling ratios among the transitions.

$$\begin{aligned} (\partial \rho / \partial t)_{source} &= \left[\Gamma_g \rho_{2,2} + (\Gamma_a/2)\rho_{3,3} + (\Gamma_a/2)\rho_{4,4} \right. \\ &+ \Gamma_b \rho_{5,5} + (\Gamma_b/2)\rho_{6,6} + (\Gamma_b/2)\rho_{7,7} \right] |1\rangle \langle 1| \\ &+ \left[\Gamma_g \rho_{1,1} + (\Gamma_a/2)\rho_{3,3} + (\Gamma_a/2)\rho_{4,4} \right. \\ &+ \left(\Gamma_b/2)\rho_{6,6} + (\Gamma_b/2)\rho_{7,7} \right] |2\rangle \langle 2| \end{aligned}$$

$$(7)$$

Here, for example, the coefficient α_1 represents the ratios of the probe Rabi frequency for the $|1\rangle - |4\rangle$ transition to the same for the $|1\rangle - |3\rangle$ transition. This is determined by the ratio of the rms value of all the allowed transitions among the Zeeman sublevels of states $|1\rangle$ and $|4\rangle$ to the same for the Zeeman sublevels of states $|1\rangle$ and $|3\rangle$. The other such coefficients, namely α_2 , α_3 and α_4 are determined in a similar manner. Setting Eq. (6) and Eq. (7) in Eq. (1) yields the density matrix equations for these states. Steady state solution of this equation is illustrated in Fig. 7, for different values of the optical pump detuning.



Fig. 7. Gain Profiled computed using the seven-level system, obtained using the following parameters: $\Omega_s=0.1\Gamma$, $\Omega_p=10\Gamma$, $\Omega_{op}=5\Gamma$, $\delta_p=-200\Gamma$, and (a) $\delta_{op}=60\Gamma$, (b) $\delta_{op}=0\Gamma$, (c) $\delta_{op}=-10\Gamma$, (d) $\delta_{op}=-60\Gamma$, $\Gamma=6$ MHz.

As we tune the frequency of the optical pump, we observe a continuous transition of the gain spectrum between a relatively broad gain peak shifted to a lower frequency, as shown in Fig. 7(a), to a different narrower gain peak shifted to a higher frequency, as shown in Fig. 7(d). When the frequency of the optical pump is tuned between these two extrema, we observe a broad gain with a narrow depletion, as shown in Fig. 7(b) and Fig. 7(c).

5. Experimental results

The technique of producing the dip in the Raman gain profile by the optical pump beam was verified experimentally. The configuration for the apparatus used is illustrated schematically in Fig. 8. A vapor cell of naturally occurring Rubidium was heated to $\sim 80^{\circ}$ C. The probe and the pump fields were provided by two independent 795 nm diode lasers, the optical pump beam was provided by another diode laser at 780 nm and was amplified by a tapered amplifier to a maximum power of ~ 800 mW. The optical pump beam was applied to the cell in a counter-propagating configuration relative to the probe and the pump. Saturated absorption spectroscopy (not shown) was used to determine the probe and pump frequencies. Half wave plates (HWP) and polarizing beam was scanned over a range of about 140Γ . It is important to mention that the pump and probe beams were not phase-locked to one another during the experiment. Typically, the beatnote between such a pair of diode lasers is found to be ~250 kHz [32]. As such, the gain spectrum observed experimentally would have an additional broadening by this amount. In the future, we plan to use the technique of off-set phase locking to correlate the frequencies of the pump and the probe laser, thus eliminating this additional broadening.



Fig. 8. Schematic illustration for the experimental configuration.

The probe was polarized horizontally, while the Raman pump and the optical pump were polarized vertically. The polarizing beam splitter at the output was configured in a manner to ensure that only the probe beam would enter the photodetector. However, due to imperfections in the polarization of the Raman pump beam, some of the power from this pump leaked into the detector, creating a significant background signal. Thus, when the probe transmission signal was measured in the DC mode, it was difficult to discern the details of the shape of the dip. In principle, this problem can be overcome by using a chopper wheel to modulate the probe intensity, and demodulating the signal with a lock-in amplifier. Unfortunately, we were not able to implement this technique, and such an approach will be implemented in the near future when the necessary pieces of equipment are in place. As an alternative, we chose to measure the probe transmission signal in the AC-coupled mode.

Figure 9 shows the probe transmission signal (red line with noise) when the optical pump was turned off, and Raman pump was detuned by $\delta_p=120\Gamma$. As such, it represents the conventional electromagnetically induced transparency (EIT), but with optically detuned pump and probe that

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are not phase correlated. The superimposed blue line shows the best fit simulation, where we have neglected the additional broadening (of ~ 250 kHz) due to the relative phase jitter between the Raman pump and the probe, as noted earlier. As can be seen, the agreement between the shapes of the signals is quite good over a broad range of values of the probe detuning. From this result, we can also infer that the collisional decay rate is about 0.3 MHz for a cell temperature of 80° C.



Fig. 9. Blue curve: simulation results for the following parameters: $\Omega_s=2\Gamma$, $\Omega_p=4.5\Gamma$, $\Omega_{op}=0\Gamma$, $\delta_p=120\Gamma$, $\delta_{op}=0\Gamma$ ($\Gamma=6$ MHz), $\Gamma_g=0.3$ MHz. Red curve: the intensity of the probe beam measured in the experiment. Note that gain less than unity corresponds to absorption.

Figure 10 shows (red trace with noise) the probe transmission signal for the case when the Raman pump was detuned farther ($\delta_p = 180\Gamma$), and the optical pump was turned on, with detuning below resonance ($\delta_{op} = -50\Gamma$). The superimposed blue curve represents a theoretical fitting. The dip observed here confirms qualitatively the validity of the model presented above. It should be noted that the experimental results show a somewhat larger degree of asymmetry and broadening than the theoretical fit. We believe that a more accurate model, involving all 39 Zeeman sublevels explicitly, is necessary to improve the agreement. Such an analysis is currently in progress.

In Fig. 11, we show probe transmission (red trace) and the corresponding theoretical fit when the detuning of the optical pump is changed to δ_{op} =-20 Γ . Here, the agreement is quite reasonable over a broad range of the detuning; however, for very large detunings away from the central dip, the model diverges significantly from the experiment. Again, we believe that a more comprehensive model, employing all relevant Zeeman sublevels, is necessary for producing a better fit.

So far, we have illustrated the behavior of the system under various conditions, and shown how the theoretical model is in close agreement with the experimental results. However, it is also important to show that it is indeed possible to get a value of gain that is greater than unity at the center of the dip, since the primary objective of this approach is to realize a superluminal laser. As such, we have adjusted parameters of the experiment to find a set of conditions under which the gain at the center of the dip exceeds unity, as illustrated in Fig. 12(a). Here, the red curve is the experimental data, and the blue curve represents the results obtained using the theoretical model. We see that the agreement is quite reasonable, with the exception that for smaller values of the probe detuning, on the left side of the dip, the model diverges significantly from the experiment. Again, we believe that a more comprehensive model, employing all relevant Zeeman sublevels,





Fig. 10. Blue curve: simulation results for the following parameters: $\Omega_s = 1\Gamma$, $\Omega_p = 10.5\Gamma$, $\Omega_{op} = 10\Gamma$, $\delta_p = 180\Gamma$, $\delta_{op} = -50\Gamma$, $\Gamma = 6$ MHz, $\Gamma_g = 0.5$ MHz. Red curve: the intensity of the probe beam measured in the experiment.



Fig. 11. Blue curve: simulation results for the following parameters: $\Omega_s = 0.66\Gamma$, $\Omega_p = 4.9\Gamma$, $\Omega_{op} = 10\Gamma$, $\delta_p = 180\Gamma$, $\delta_{op} = -20\Gamma$, $\Gamma = 6$ MHz, $\Gamma_g = 0.5$ MHz. Red curve: the intensity of the probe beam measured in the experiment.

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is necessary for producing a better fit. In Fig. 12(b) we show theoretically that it is possible to enhance the gain at the center of the dip significantly, by carefully adjusting the following parameters: cell length, cell temperature, and the Raman pump power. As can be seen, very large gain at the center of the dip can be realized for some combinations of the operating parameters. For example, for the conditions corresponding to the yellow curve in Fig. 12(b), the gain at the center of the dip is ~3.6. In the near future, we will implement conditions with such large gains as we pursue the realization of a rotation sensors based on a pair of counter-propagating superluminal lasers.



Fig. 12. (a) Blue curve: simulation results for the following parameters: $\Omega_s = 2.2\Gamma$, $\Omega_p = 12.5\Gamma$, $\Omega_{op} = 10\Gamma$, $\delta_p = 177\Gamma$, $\delta_{op} = -55\Gamma$, $\Gamma = 6$ MHz, $\Gamma_g = 0.5$ MHz, L = 7.5 cm, $T = 80^{\circ}C$ (L is the length of the Rb cell). Red curve: the intensity of the probe beam measured in the experiment. (b) Simulation results for the same parameters when varying the cavity length, cell temperature, and Raman pump power to enhance the gain.

For the results presented in Figs. 9 through 11 above, we used the following approach. For each of the relevant parameters, such as the Raman pump detuning, the optical pump detuning, the Rabi frequencies for the Raman pump, the optical pump, the probe, and the temperature of the cell, we determined an approximate upper bound and lower bound of the values used in the experiment. We then varied these parameters, within these bounds, until the best qualitative fit to the shape of the experimental data was obtained. The vertical scale used for the gain in the plots are based on the results of the theoretical model. For the result presented in 12 above, we again used the same approach, with the exception that we also recorded the peak value of the gain experimentally, using the DC-coupled mode. The peak value of the gain established from the theoretical fit was found to be in close agreement with the same determined experimentally.

Experimental configuration suitable for realizing a pair of counter-propagating superluminal lasers

One of the most important applications for a superluminal laser is rotation sensing via the Sagnac effect. In order to realize such a rotation sensor, it is necessary to realize a pair of counter-propagating superluminal lasers using a single cavity, in order to suppress common-mode perturbations. Figure 13 depicts a conceptual experimental configuration, employing the scheme described above, for realizing such a system. Specifically, the system employs two Rb vapor cells placed in a ring cavity. Each cell is used to generate a superluminal Raman lasing in the direction of the corresponding Raman pump: one clockwise and the other counter-clockwise. The Raman pump beam for each laser is brought into the cavity for the corresponding gain cell

using polarizing beam splitters (PBSs) and are ejected out of the cavity after a single transition through the cell using another PBS. Thus, the Raman pump for one cell does not interact with the other cell. The optical pump beam for each laser, with the same polarization as that of the Raman pump, is applied and ejected in the same manner, while propagating in the direction opposite to that of the Raman pump. A superluminal Raman laser is then created in each cell in the presence of the Raman pump and the optical pump. A fraction of each of the two lasing beams pass through the output coupler, and the beat between these two lasers can be measured to infer the rate of rotation in the direction perpendicular to the plane of the cavity.



Fig. 13. Illustration of the experimental configuration for realizing a pair of counterpropagating superluminal lasers, employing the same cavity, as needed for rotation sensing via the Sagnac effect.

It is important to note that the Raman laser in one direction does not experience gain from the other cell. This is because Raman gain in a warm vapor cell is unidirectional. For co-propagating Raman pump and probe, the Doppler shift is very small (~4.8 kHz), corresponding to the frequency of the ground state splitting of ~3 GHz. This is substantially narrower than the typical linewidth of the Raman gain profile. On the other hand, if the probe is propagating in a direction opposite to that of the pump, the Doppler shift is effectively doubled (~1.2 GHz), which is much larger than the typical Raman gain linewidth. As such, the gain experienced by the Raman probe is vanishingly small in this case. The potential cross-talk can be suppressed further by making the frequencies of the two Raman laser non-degenerate, corresponding to two different longitudinal modes of the cavity. This concept has the additional advantage of eliminating the so-called lock-in effect that occurs in a conventional ring laser gyroscope.

7. Discussion and conclusions

We have described the scheme for realizing a superluminal ring laser by generating a dip in the Raman gain produced by an optical pump field. We have shown that by increasing the optical pump intensity we can continually control the shape of the gain spectrum from a single and narrow Raman gain to a wide Raman gain with a narrow dip. By optimizing the optical pump intensity and detuning, we can achieve vanishingly small group index and very large enhancement in the sensitivity with which the frequency changes as a function of a change in the cavity length, by a factor of more than four orders of magnitude. We have also shown preliminary experimental

results, in reasonable agreement with simulations, to validate this scheme. Furthermore, we have shown how such a system can be used to realize a pair of counter-propagating superluminal lasers in the same cavity, for realizing a high-sensitivity rotation sensor.

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Disclosures

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