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Demonstration of a phase conjugate resonator using degenerate four-wave mixing via coherent population trapping in rubidium

D.S. Hsiung [a], Xiao-Wei Xia [a], T.T. Grove [a,*], M.S. Shahriar [a], P.R. Hemmer [b]

[a] *Research Laboratory of Electronics, Massachusetts Institute of Technology, Building 26, Room 368, Cambridge, MA 02139, USA*
[b] *Air Force Research Laboratory, Hanscom AFB, MA 01731, USA*

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Abstract

We demonstrate a ring cavity laser using the gain mechanism of a four-wave mixing process, mediated by two-photon Zeeman coherence resulting from coherent population trapping in a rubidium vapor cell. The cell acts as an amplifying phase conjugate mirror at one corner of the ring cavity. Even though the fundamental process requires non-degeneracy between the probe and the conjugate in the atom's frame, they are degenerate in the laboratory frame, via selection of a moving band of atoms for the gratings. As such, no frequency shifting is necessary in the cavity. The polarization orthogonality of the probe and the conjugate is compensated by an intra-cavity quarter wave plate.

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Optical phase conjugation (OPC) is of interest for many applications [1] such as optical resonators, high speed turbulence correction, and the production of the squeezed vacuum state. Recently, we have been developing various types of phase conjugators using atomic vapor. In this work, we report the demonstration of a ring laser where a rubidium vapor cell provides the gain in addition to acting as a phase conjugate mirror [2,3] (PCM).

In previous work, we have demonstrated a double-Λ system in sodium vapor to be an efficient optical phase conjugator [4,5]. This OPC used a coherent population trapping [6,7] (CPT) based grating that produced a conjugate at low pump intensity (1 W/cm^2) with high reflectivity (>50) and fast response time (<1 μs). The sodium double-Λ system has been used to correct high speed turbulence, thus demonstrating the potential for using an atomic vapor as a practical non-linear material [8]. While this conjugator performs well, it requires a large detuning (matching the hyperfine splitting in the ground state) between the pump and the probe beams, representing a serious impediment to extending these techniques to other resonant media.

To eliminate this constraint, we reproduced the CPT-based conjugator using Zeeman sublevels of a single hyperfine ground state and polarized light [9]. This particular experiment used rubidium, and matched the sodium system in performance. The transition frequencies and required power levels are also within the range of diode lasers for this rubidium system, potentially allowing inexpensive and practical systems in the future. While this scheme is much simpler than the one employed in sodium, it is still necessary to introduce a detuning (typically 80 MHz) between the two pump beams, in order to provide the symmetry-breaking necessary for this process. Aside from the experimental inconvenience, this non-degeneracy renders this conjugator unsuitable for applications such as phase conjugate resonators.

* Corresponding author. E-mail: ttgrove@mit.edu

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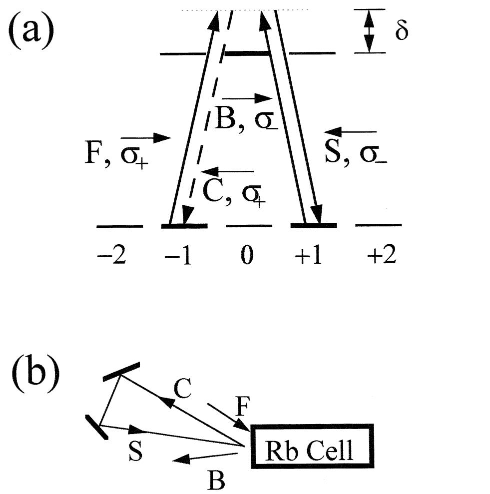

Fig. 1. (a) Level diagram of the rubidium atom and the individual fields. F is the forward pump beam, B is the backward pump beam, S is the signal beam, and C is the conjugate beam. δ is determined by the pump laser detuning relative to a zero velocity atom and Δ results from the Doppler shift. (b) General method we use to create a ring cavity laser based on OPC.

Recently, we have demonstrated how this conjugator can be produced with degenerate frequencies, by writing the gratings in a band of atoms moving with non-zero velocities, without compromising performance [10]. The optical transitions involved in this process are illustrated in Fig. 1a. Here, F and B are the forward and backward pumps, respectively, S is the signal, and C is the conjugate. To illustrate the mechanisms at work in this OPC, consider, without loss of generality, the situation where all the beams are collinear, propagating in the direction $\pm z$. The Raman resonance condition for F and S (as well as for B and C) is satisfied for all values of v_z, the velocity of an atom in the z-direction. However, the laser intensity needed for producing the dark state coherence grows quadratically with v_z. For the low laser intensity used, only a band of atoms with a small range of $|v_z|$ contribute to the grating formation. The width of this band is directly proportional to the power-broadening-limited linewidth of the Raman resonance, which is typically about 2 MHz. For the experiment reported in Ref. [9], this band is centered around $v_z = 0$. Thus, the frequency difference between the forward (F) and backward (B) pumps in the frame of the atoms is the same as in the laboratory frame. In the experiment reported here, we make F and B degenerate. In order to provide for the required non-degeneracy between F and B mentioned above, the band of atoms that participate in the conjugation process are now centered around a non-zero value of v_z such that the differential Doppler shift of F and B add up to the non-degenerate frequencies used in Ref. [9].

Since the forward pump beam (F) and the signal beam (S) are Raman resonant, the atoms get pumped into a dark state, forming a grating in the coherence between the two ground states of the Raman transition. Here, the two ground states are Zeeman sublevels of the same hyperfine ground state. Thus, we have oppositely polarized forward pump (σ_+) and signal (σ_-) beams. The backward pump (B) diffracts off this grating and forms the conjugate beam (C). The backward beam and the conjugate beam are also Raman resonant, and form a grating. The forward pump diffracts off this grating, creating an amplified signal beam. By feeding the output conjugate beam back into the system

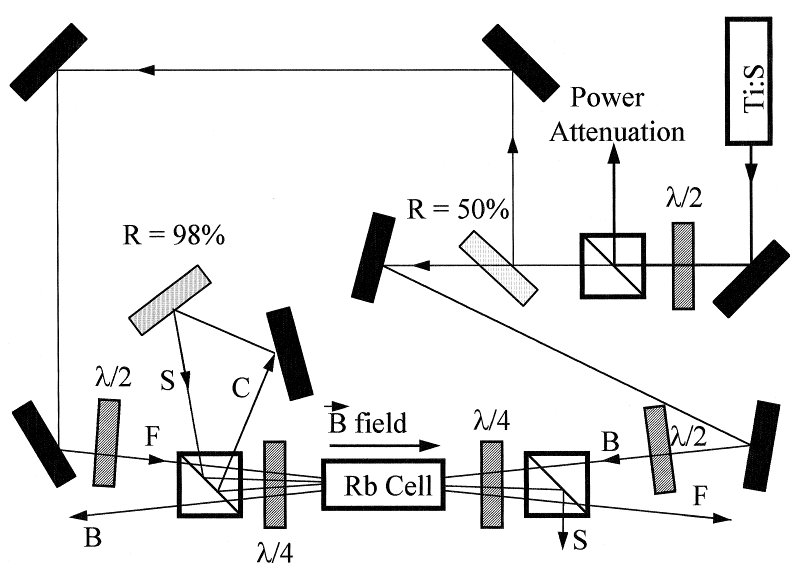

Fig. 2. General experimental set up. The pump beams (F and B) are derived from a Ti:sapphire laser and beam splitters. The resonator cavity cycles the conjugate back into the system as the signal beam.

as a signal beam (using a $\lambda/4$ waveplate to correct the polarization), we create an optical resonator cavity, as shown in Fig. 1b.

The experimental set up is shown in Fig. 2. A single Ti:saphire laser produces both pump beams via beam splitters. Each of the pump beams has a FWHM of 1.0 mm, and the angle between any of the beams is less than 5 mrad. The rubidium vapor is produced inside a heat pipe oven, with Helmholtz coils to provide a magnetic field. The oven and the coils are then boxed in a μ-metal to eliminate stray magnetic fields. A ring cavity is produced when one considers the PCM created by the four-wave mixing as part of the resonator cavity. We use a 98% reflector in the cavity as an output coupler. However, we also have an effective output coupler in the amplified signal beam. In practice, we found that the signal shapes produced by these different methods yield virtually identical results.

Fig. 3 shows the output power of the laser as a function of the pump beam frequency. The maximum occurs to the blue of the ^{87}Rb $5^2S_{1/2}$, $F=2$ to $5^2P_{1/2}$, $F=1$ transition. There is 162 mW in the forward pump and 91 mW in the backward pump. As we showed before [11], the open-loop gain has a single Gaussian shape, with three dips, two corresponding to the two resonances (vertical dashed lines), and one corresponding to a detuning exactly halfway between the resonances. The four peaks corresponding to the three dips would imply that we should get four peaks in the laser. The line shape observed in Fig. 3 indicates that only the first two of these peaks (located around the first resonance) had a gain large enough for lasing to occur.

The output power after the 98% reflector is 0.02 mW while the amplified signal output is around 1 mW. Taking into account the loss in the system due to other factors, we can estimate the internal intensities to be approximately 0.85 mW for the incident beam, and 1 mW for the reflected one. This indicates a saturated gain in the PCM of around 1.2. The linear gain during the lasing build-up is of course much higher (about 40, as reported in Ref. [11]). Note that in a PCM laser of this form, the output power (observed as the amplified signal) is greater than the power circulating in the cavity.

Fig. 4 demonstrates the lasing dependence on the magnetic field produced by the Helmholtz coils. By using the Zeeman shift, we are able to change the effective detunings the atom sees from both the forward pump and signal beams. As the Zeeman shift is opposite for these two beams (see Fig. 1), increasing the magnetic field takes the atom away from Raman resonance. As can be seen from Fig. 4, the lasing width is quite narrow (<0.5 MHz FWHM). Under the open-loop conditions [9,10], we have observed this linewidth to be of the order of 2 MHz. The smaller linewidth observed here is again due to the fact

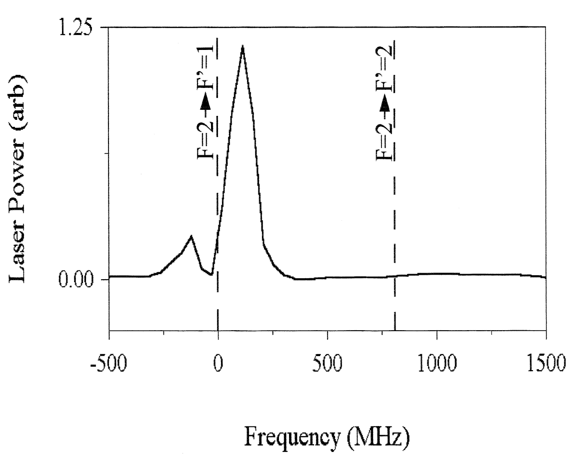

Fig. 3. Pump frequency dependence of the ring laser. The largest peak occurs blue shifted to the ^{87}Rb $5^2S_{1/2}$, $F=2$ to $5^2P_{1/2}$, $F=1$ transition.

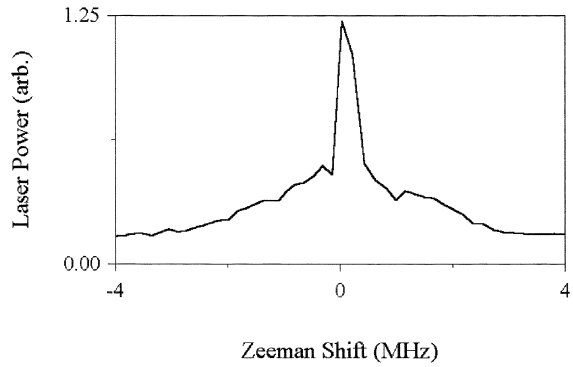

Fig. 4. Lasing dependence on magnetic field. The narrow sharp peak is attributable to a Raman resonance.

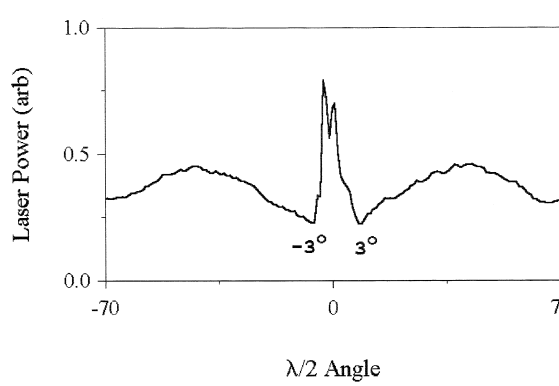

Fig. 5. Lasing dependence on polarization. By inserting a $\lambda/2$ plate between the backward pump's $\lambda/4$ plate and beamsplitting cube, we can give the backward pump any polarization. The sharp peak indicates the need for a well polarized system to maintain the Λ configuration.

that the gain has to be larger than a threshold value in order for lasing to occur.

Fig. 5 demonstrates how the output power of the laser depends on the backward pump polarization. By inserting a $\lambda/2$ plate between the backward pump's $\lambda/4$ plate and beamsplitting cube, we can produce a backward pump with any polarization. As can be seen from the figure, the lasing is highly dependent on the polarization of the backward pump. Consistent with our model, the peak output occurs when the polarization is left circular (σ_-).

In conclusion, we have demonstrated a ring cavity laser using the gain mechanism of a four-wave mixing process, mediated by two-photon Zeeman coherence resulting from coherent population trapping in a rubidium vapor cell. The cell has been used as an amplifying phase conjugate mirror at one corner of the ring cavity. The pump power required is low enough for a semiconductor laser. This paves the way for using the rubidium vapor cell as a conjugator for practical applications.

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