8 May 2001

ELSEVIER

Optics Communications 191 (2001) 347–351

OPTICS COMMUNICATIONS

www.elsevier.com/locate/optcom

Polarization selective motional holeburning for high efficiency, degenerate optical phase conjugation in rubidium

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Received 9 October 2000; received in revised form 2 January 2001; accepted 7 February 2001

Abstract

We have observed high reflectivity (>40) optical phase conjugation for a low pump intensity (100 mW/mm^2), using degenerate four-wave mixing in rubidium vapor. The polarization of the beams were selected such that the diffracting grating was formed in the Zeeman sublevel coherence. We find that only a selected band of atoms moving at non-zero velocities contribute to this process, by forming, in the atom's frame, a non-degenerate double-Λ system. This observation makes it possible to construct a simple, compact, and highly efficient phase conjugator using a semiconductor laser, without any modulators, for many applications, without any concern resulting from frequency mismatch between the probe and the conjugate.

Keywords: Phase conjugator; Aberration correction; Optical resonators

Optical phase conjugation (OPC) is of interest for many applications such as optical resonators, high speed turbulence correction, and the production of the squeezed vacuum state. In the interest of practical implementation of OPC, a great deal of work has been done in the search for materials that have a fast response time, high gain, and a low power requirement. One promising candidate is an atomic vapor, because of the high degree of non-linearity near resonance. Early efforts at performing OPC in a vapor were designed to treat the atoms as two level systems. In order to avoid absorption losses, it was necessary to operate off-resonance, thus requiring a very high intensity [1].

To circumvent this problem, we previously demonstrated the use of coherent population trapping (CPT) [2,3] as a mechanism for creating a large non-linearity using low power. This technique allows one to obtain a suitable combination of pump power and speed. For example, we demonstrated in sodium vapor [4,5] a conjugate at a pump intensity of 1 W/cm^2, with reflectivity greater than 50, and a response time of less than 1 μs. As an application, we have also used this conjugator to compensate for aberrations caused by high speed turbulence [6]. While this conjugator

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0030-4018/01/$ - see front matter
PII: S0030-4018(01)01101-4

performed well, it required a large detuning between the pump and the probe beams, representing a serious impediment to extending this 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 [7]. This 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, potentially allowing inexpensive and practical systems in the future. While this scheme was much simpler than the one employed in sodium, it was 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.

In this work, we demonstrate how this conjugator can be produced with degenerate frequencies, by writing the gratings in a band of atoms moving with non-zero velocities, without greatly compromising performance. In addition this work also demonstrate polarization selective motional hole burning. To illustrate the mechanisms at work in this OPC consider first the role of atomic velocities. Fig. 1 shows a $j = 1$ to $j' = 1$ atom (with no magnetic field) moving with respect to the laser beams. The Doppler shift seen by each atom is

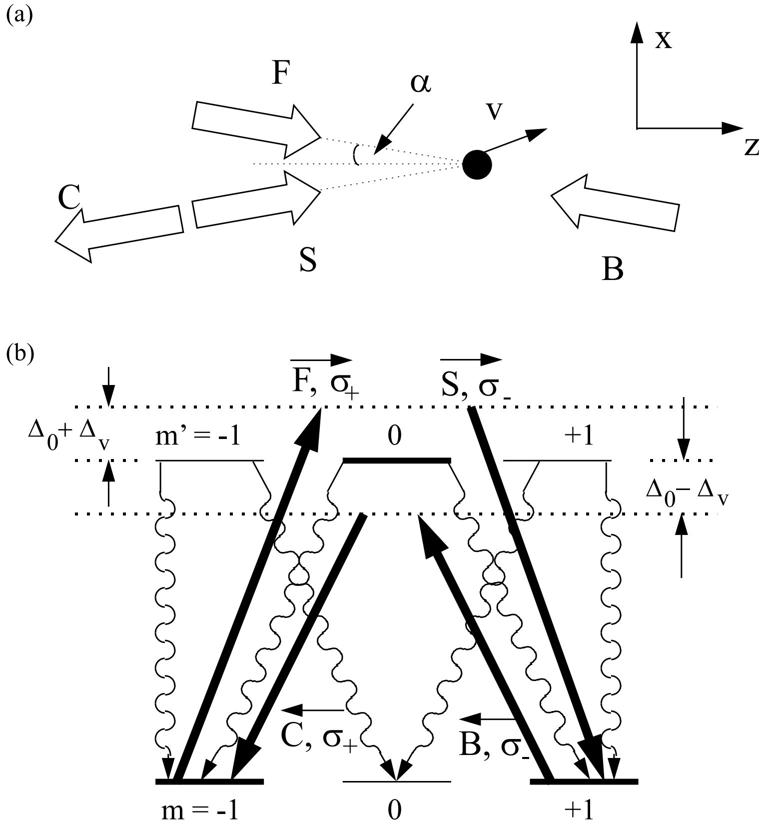

Fig. 1. (a) The orientation of the beams involved in the four-wave mixing process; F: forward pump, B: backward pump, S: signal, C: conjugate. (b) The magnetic sublevels involved in the interaction. Here, Δ_0 is the laser detuning, and Δ_v is the Doppler shift for an atom moving with velocity v in the z-direction. The fields are all degenerate in the laboratory frame.

$$\Delta_F = -kv_z \cos\alpha + kv_x \sin\alpha$$

$$\Delta_S = -kv_z \cos\alpha - kv_x \sin\alpha$$

$$\Delta_F - \Delta_S = 2kv_x \sin\alpha$$

If $|\Delta_F - \Delta_S|$ is small enough, we satisfy the Raman resonance condition (between F and S) and coherently trap the atom in a super-position of the ground states Zeeman sublevels (CPT). Since the degenerate Zeeman sublevels correspond to different orientations of angular momentum, it can be shown that there is a sinusoidally varying angular momentum grating formed by F and S (Ref. [7]). This gratings spacing is inversely proportional to sin α. The backward pump beam, B, diffracts off the grating and forms the conjugate beam, C. If α is increased, the Doppler shifts from F and S become different for more and more atomic velocity groups; hence, more and more atomic velocity groups are no longer Raman resonant. As such, only a band of atoms within a range of velocities centered around $v_x = 0$ contribute to the conjugation process.

All values of v_z satisfy the Raman resonance condition. 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 line width of the Raman resonance, which is typically about 2 MHz. For the experiment reported in Ref. [7] 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. Now the Doppler shift from a $v_z \neq 0$ group of atoms, provides the effective frequency difference between F and B. However, using a non-zero velocity group reduces the density of atoms which are active in the conjugation process compared to the non-degenerate experiment. Thus, the degenerative frequency case reported is not expected to have the same efficiency as the optical conjugator reported in Ref. [7]. We point out that coherences between Zeeman sublevels were used in many experiments [8,9] but not for the process reported here. An application of this process is the phase-conjugate ring resonator demonstrated in Ref. [10].

The experimental setup is shown in Fig. 2. A Ti-sapphire laser and beam splitters provide all of the input beams: F, B and S. Polarizing beam splitting

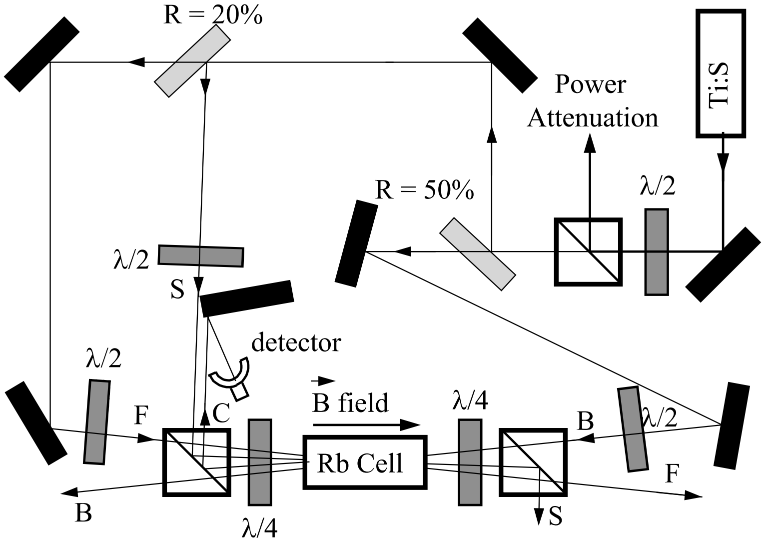

Fig. 2. Schematic illustration of the experimental setup. The rubidium cell is a heat-pipe oven, and the pump is a Ti:sapphire laser. $\lambda/2$ is a half-wave plate, and $\lambda/4$ is a quarter-wave plate.

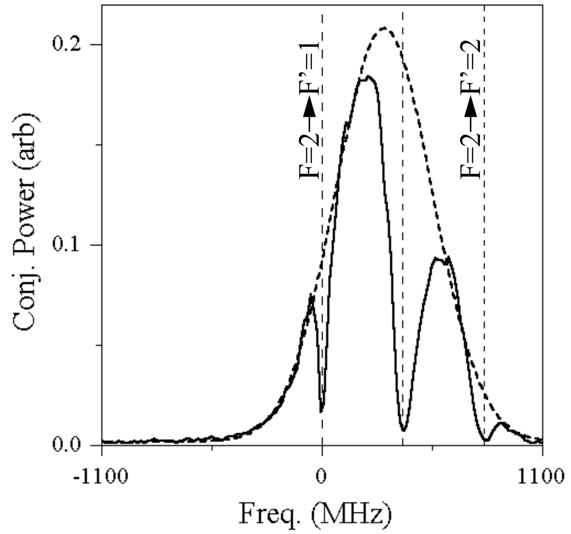

Fig. 3. The conjugate power as a function of the laser frequency. The vertical dotted line on the left (right) corresponds to the $5^2S_{1/2}(F=2)$ to $5^2P_{1/2}(F=1)$ ($5^2S_{1/2}(F=2)$ to $5^2P_{1/2}(F=2)$) transition of the D_1 manifold in ^{87}Rb .

cubes are used to combine the beams, and quarter wave plates are used to create the proper polarizations. The angle between S and F is about 5 mrad. The natural mixture of rubidium vapor consisting of 72.7% of ^{85}Rb and 27.3% of ^{87}Rb is produced inside a heat pipe oven (1 in. long), with Helmholtz coils to produce a magnetic fields. The oven is made of stainless steel and it operate at ≈142°C. In order to eliminate stray magnetic field, the oven and the coils are fully boxed inside a magnetic shield, made of mu-metal cylinder. With this arrangement the effect of stray magnetic field on the DFWM efficiency is negligible.

Fig. 3 shows the reflectivity of the conjugate, as a function of the laser frequency. Here, the first dotted line corresponds to the $5^2S_{1/2}(F=2)$ to $5^2P_{1/2}(F=1)$ transition and the second dotted line corresponds to the $5^2S_{1/2}(F=2)$ to $5^2P_{1/2}(F=2)$ transition of the D_1 manifold, in ^{87}Rb. Consider first the envelope of the conjugate reflectivity, denoted by the dashed lines. The peak of this curve corresponds to a blue detuning above the $F=2$ to $F=1$ transition. Consider the three dips in the reflectivity curve. The first and third dips correspond to the situations when the laser frequency is exactly on resonance with the $F=2$ to $F=1$ transition and the $F=2$ to $F=1$ transition, respectively. The second dip corresponds to the laser frequency being exactly half way between these two transitions. For all three of these conditions, the symmetry breaking is minimized, for atoms at all velocities. The reduction in conjugate reflectivity at these three locations is therefore consistent with our proposed model.

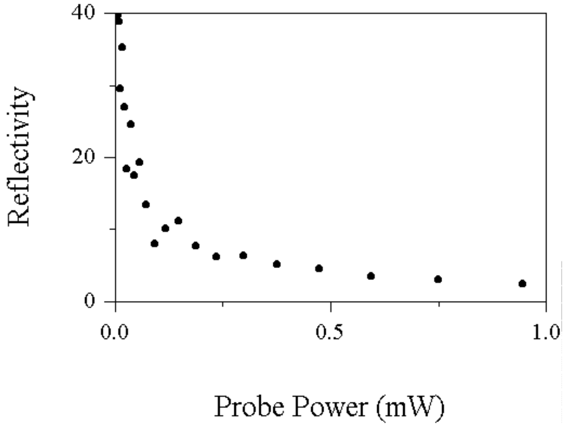

Fig. 4. The conjugate reflectivity as a function of the probe power, showing saturation as the probe becomes stronger.

Fig. 4 demonstrates the dependence of the conjugate reflectivity on the input signal power. As demonstrated in previous work [7], the conjugate is mainly in the σ_+ polarization component, which is approximately 400 times stronger than the σ_- component. F has a power of 84 mW, and B has a power of 24 mW. The pump intensity imbalance again is consistent with the idea that the conjugation favors asymmetry. The laser frequency is kept on the largest peak shown in Fig. 3. We observe a reflectivity as high as 40, saturating to lower values as the probe strength is increased.

The results in Fig. 5 show magnetic field response of the conjugate. For small magnetic fields this is equivalent to detuning the frequency between F and S via the Zeeman shift; hence this is a measurement of the Raman transition width. The FWHM is ≈1 MHz compared to 2.4 MHz in the non-degenerate case [7]. Both of these results are well below the natural line width of 5.9 MHz. If we assume that the optical pumping rate has the dominant effect on the line width, we find that the response time is approximately 160 ns.

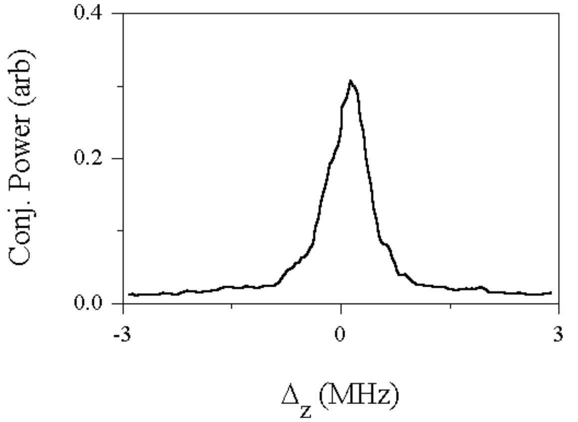

Fig. 5. The conjugate reflectivity as a function of two-photon detuning between F and S (Δ_z is the Zeeman shift). The subnatural line width of about 1 MHz (FWHM) is consistent with CPT.

We also examined the dependence of the conjugate on the backward pump polarization (not shown). A $\lambda/2$ plate placed directly before the $\lambda/4$ plate controls the polarization, with the backward beam becoming σ_+ polarized when the $\lambda/2$ plate is rotated 45°. Consistent with predictions, the conjugate beam does not form when the pump beam is incorrectly polarized.

In conclusion, we have observed high reflectivity (>40) OPC for a low pump intensity (10 W/cm^2), using degenerate four-wave mixing on $5^2S_{1/2}(F=2) \rightarrow 5^2P_{1/2}(F=1)$ transition of ^{87}Rb. The work presented in this paper is not only the demonstration of the novel mechanism but it also give insight into polarization selective motional hole burning (Fig. 3). An important application of the physical process demonstrated here is the CPT based laser resonator [10]. For this work the transition $5^2S_{1/2}(F=2) \rightarrow 5^2P_{1/2}(F=1)$ was particularly selected because it offers advantage of large hyperfine splitting of 812 MHz for its excited state. This results in spectrum without the complications introduced by the Doppler broadening. The Doppler width of Rb at 142°C is about 588 MHz. All the transitions for the D_2 line of both isotopes of Rb lies within the Doppler envelop complicating the interpretation of the spectrum. Two other transitions viz. $5^2S_{1/2}(F=3) \rightarrow 5^2P_{1/2}(F=2)$ and $5^2S_{1/2}(F=3) \rightarrow 5^2P_{1/2}(F=3)$ of ^{85}Rb also give very good contrast CPT at the Zeeman sublevels [11]. Although these transitions are expected to yield high efficiency DFWM but since the excited state hyperfine splitting of 362 MHz for these transitions is less than the Doppler width these transitions cannot be resolved.

Acknowledgements

We acknowledge helpful discussions with Prof. Shaoul Ezekiel of MIT. This work was supported in part by AFRL grant no. F30602-97-C-0136, and AASERT grant no. F49620-96-1-0305.

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