Efficient low-intensity optical phase conjugation based on coherent population trapping in sodium

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We have observed optical phase-conjugate gain (>50) in sodium vapor, using low-intensity pump lasers (1 W/cm^2), with a response time of the order of 1 μs. Coherent population trapping is experimentally identified as the phase-conjugate mechanism. A theoretical model is presented that supports these observations by showing that coherent population trapping can write large-amplitude nonlinear-optical gratings at laser intensities well below those needed to saturate the optical transitions.

Four-wave mixing and optical phase conjugation (OPC) have long been known to have potential applications to optical image amplification, processing, and aberration correction.[1] However, widespread application of these techniques has so far been limited because of the slow response and/or low efficiency of existing nonlinear-optical materials at laser intensities achievable with compact cw lasers. For example, previous research in sodium vapor shows fast response,[2–5] but phase-conjugate gain is observed only at high pump intensities (near 100 W/cm^2).[6,7] In this Letter we demonstrate high-efficiency OPC in sodium for pump intensities near 1 W/cm^2, with a response time of the order of 1 μs. If sodium were replaced by rubidium or cesium,[8] a similar performance could be achieved at intensities accessible with cw diode lasers, offering the possibility of the development of portable high-speed four-wave-mixing devices.

The key to efficient low-power OPC in resonant systems is to use coherent population trapping[9–11] (CPT) to write a grating in the ground-state coherence of the atom. Since CPT is an optical pumping process it is possible to saturate the optical nonlinearity at an intensity below that needed to saturate the optical transition, permitting a trade-off of response time for intensity without loss of efficiency, even for low pump intensities. Previously we achieved a factor-of-50 reduction in the pump intensity required for efficient self-pumped OPC in sodium vapor in which CPT was the proposed (but not explicitly verified) mechanism.[12] Here we examine externally pumped OPC in sodium and find not only a similar reduction in threshold intensity but also more than an order-of-magnitude increase in efficiency. Moreover, we verify experimentally the coexistence of CPT and high-gain OPC at low pump intensity.

To see how CPT can be used to perform OPC, we consider the four-level double-Λ system[13] of Fig. 1(a) in the traditional phase-conjugation geometry of Fig. 1(b). The two Λ subsystems are assumed to be separate. For simplicity, consider only the case in which F and S saturate the two-photon transition and B and C are weak. Here the Λ subsystem involving F and S and states $\{|a\rangle, |b\rangle, \text{and } |e\rangle\}$ optically pumps into a transparent superposition state (called the dark state, $|-\rangle$), which is decoupled from the excited state $|e\rangle$. For noncopropagating F and S, as in the case of our OPC geometry, this superposition state is given by

$$|-\rangle = \frac{1}{\Omega_{SF}}[\Omega_S \exp(i\mathbf{k}_S \cdot \mathbf{r})|a\rangle - \Omega_F \exp(i\mathbf{k}_F \cdot \mathbf{r})|b\rangle], \tag{1}$$

where $\Omega_i = \mu_i \mathcal{E}_i/\hbar$ is the Rabi frequency associated with field $i \in \{F, B, S, C\}$, μ_i and $\mathcal{E}_i$ are the relevant

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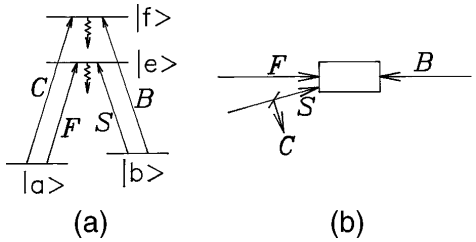

Fig. 1. (a) Schematic of the four-level double-Λ system. (b) Corresponding four-wave mixing geometry.

dipole-moment matrix elements and electric-field amplitudes, respectively, and $\Omega_{SF} = (|\Omega_S|^2 + |\Omega_F|^2)^{1/2}$. When all the atoms are in the dark state, the ground-state coherence is simply given by

$$\rho_{ab} = -\frac{\Omega_S \Omega_F^*}{\Omega_{SF}{}^2} \exp[i(\mathbf{k}_S - \mathbf{k}_F) \cdot \mathbf{r}], \qquad (2)$$

where ρ denotes the atomic density matrix. Thus CPT writes a purely sinusoidal grating in the phase of the ground-state coherence ρ_{ab}. For example, if the states $|a\rangle$ and $|b\rangle$ are the Zeeman sublevels of the ground state, the coherence grating is a spin orientation grating.

The important property of this grating is that it can be saturated at optical intensities well below those needed to saturate the individual optical transitions. In practice one can determine the minimum required pump intensity by equating the ground-state dephasing rate Γ_{gs} to the optical pumping rate into the dark state $\Omega_{SF}{}^2/\Gamma$ (assuming that $\Omega_S, \Omega_F \ll \Gamma$). For example, in low-pressure sodium vapor, atom transit time determines the effective ground-state dephasing time, in which a sodium atom traversing a 1-mm-diameter laser beam at a rms velocity of 6×10^4 cm/s (200 °C) has a 1.7-μs transit time. We note that, unlike for other multilevel nonlinear-optical interactions,[14,15] there is no ground-state population grating present in either the dressed-atom or bare-atom bases. The nonlinear coherence grating is also transparent to the write beams S and F, even for resonant excitation, and remains sinusoidal when fully saturated.

To produce the conjugate beam C (see Fig. 1), the read beam B scatters off of the grating formed by F and S. For the special case in which all lasers are resonant with the excited states, the conjugate wave amplitude C increases until the four-level closed-loop transparency condition is approached.[16] After this, B and C propagate as though the medium were transparent.[17] In the more general case, off-resonant lasers and strong forward and backward pumps F and B, preliminary calculations show that high gain is possible. In the case of a pure three-level system (i.e., when level $|f\rangle$ does not exist) this scheme would still work as long as B and S were nondegenerate.[18] Otherwise, CPT would write a grating transparent to all three beams. The proposed mechanism would also work for a collection of double-Λ (or Λ) subsystems, such as that expected among the various magnetic sublevels of sodium, provided that the ground-state splitting for each double-Λ system is identical.

The experimental apparatus used to perform OPC by use of CPT is schematically shown in Fig. 2. The sodium-vapor cell is a heat-pipe oven operated at ~200 °C with 5 mTorr of helium buffer gas and a variable interaction length of 6–12 cm that is magnetically shielded to better than 100 mG. Two ring dye lasers generate the forward and backward pumps F and B, as shown. Both lasers are tuned approximately to the D_1 transition. The signal beam S is derived from F by use of an acousto-optic modulator (A/O) configured for upshifting and driven with a rf signal of 1.77 GHz having ~1 kHz of frequency jitter, ensuring that the laser jitters of F and S are correlated as required for efficient CPT.[19] Laser beams F and S typically enter the active medium with a 4-mrad angular separation. In addition, the backward pump B is also aligned ~3 mrad away from counterpropagating with F in a direction perpendicular to the F and S plane. This prevents optical feedback of one laser into the other while maintaining the Bragg angle. Typical spot sizes in the cell are ~1.6 mm FWHM for B, 1.0 mm for F, and 1.0 mm for S. Pump intensities (F and B) are near 1 W/cm^2. All the beams are detected in transmission through the cell by photodiodes (DETS. in Fig. 2). Finally, the frequency reference is provided by an atomic beam (not shown).

Figure 3(a) shows a scan of the conjugate gain R (reflected power/input signal power) and transmitted signal gain T as a function of the frequency of the forward pump laser F. Note that the frequency of laser S is also scanned since S is generated from F with the acousto-optic modulator. As shown, high gains are observed, in both reflection and transmission. Here the peak conjugate gain of 55 occurs when F is blue detuned ~200 MHz (±175 MHz) from the $F = 2 \rightarrow F' = 2$ transition frequency, S is upshifted from F by 1774 MHz, and B is red detuned ~600 MHz from the $F = 1 \rightarrow F' = 2$ transition. For these data the optical intensities of the forward and backward pumps F and B are 1.2 and 0.5 W/cm^2, respectively, and the signal beam S has an intensity of 3.5 mW/cm^2. These data show a factor-of-16 increase in reflectivity over those in previous sodium-vapor experiments,[6,7] at ~1% of the pump intensity. For these data the shortest interaction length of 6 cm is used. Using a longer interaction length of 12 cm and higher pump intensities (5 W/cm^2), we observe conjugate reflectivities well above 100 (not shown). Laser polarization measurements show maximum gain when laser beams F and S have crossed linear polarizations[20]

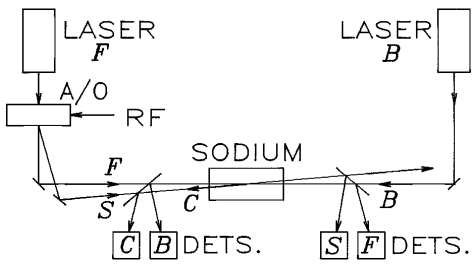

Fig. 2. Schematic of the experimental setup. Laser beam S is derived from F with an acoustic-optic modulator (A/O) driven with a stable rf source.

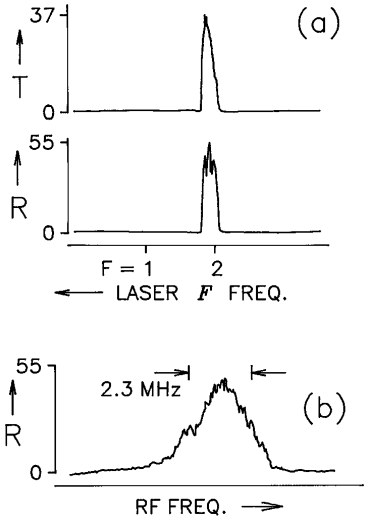

Fig. 3. (a) Signal gain T and phase-conjugate gain R versus laser F frequency. The frequency scale is labeled by the transition frequencies corresponding to the $F = 1$ and $F = 2$ ground-state hyperfine components. (b) Phase-conjugate gain R versus rf frequency driving the acousto-optic modulator.

and show zero gain for parallel linear polarizations. The linearly polarized read beam B can have any orientation (gain is a factor of 2 smaller when B and F are cross polarized), but the conjugate C is always observed to be crossed polarized to B. Finally, we measure response time by switching the rf signal to the acousto-optic modulator and monitoring the phase-conjugate reflection. We find that the response time is no slower than 1.4 μs, the measurement being limited by the speed of the rf switching electronics.

Figure 3(b) shows a scan of the conjugate gain R as a function of the frequency detuning of S relative to F, which we obtained by scanning the rf frequency applied to the acousto-optic modulator (see Fig. 2) while compensating for alignment changes. All other conditions correspond to the peak gain in Fig. 3(a). The observed difference-frequency width of the gain is ~2.3 MHz (centered near 1774 MHz), which is to be compared with the 10-MHz natural linewidth of sodium. This subnatural rf frequency linewidth provides evidence of Raman CPT.[12,21,22] Frequency measurements of the conjugate beam C show that it is downshifted from the backward pump B by 1774 MHz. When B and C are combined on a fast photodiode, a narrow 2-kHz beat note is observed, even though beams F and B are derived from independent lasers, each having ~50 MHz of absolute frequency jitter.

We also performed experiments in a well-separated double-Λ system wherein one Λ subsystem is on the D_1 transition and the other is on the D_2 transition (excited-state splitting of 0.5 THz). With F and S on D_1 and B and C on D_2, conjugate reflectivities of 120% are observed (not shown). With all lasers tuned to D_2, even lower reflectivity is observed (not shown). The poor reflectivities obtained when the D_2 transition is used are probably due to the presence of the strongly absorbing $F = 2 \leftrightarrow F' = 3$ transitions, which do not become transparent because the $F' = 3$ state does not couple to the $F = 1$ ground state.

In summary, we have observed high phase-conjugate gain ($R \approx 50$) in sodium vapor at low pump intensities (~1 W/cm^2), with a fast response time (~1 μs). Raman coherent population trapping has been experimentally identified as the physical basis of the conjugate generation process. This excellent performance offers the possibility of developing practical, portable, high-gain optical signal processing devices based on optical phase conjugation or four-wave mixing.

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