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Coherence Effects, Lasing-Without-Inversion and Raman Self-Oscillations in Rb*

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ABSTRACT

We have measured coherence-induced optical-gain and lasing in ^{87}Rb vapor using a V-configuration of laser fields. The dependence of the gain and lasing on various experimental parameters has been investigated and compared with detailed theoretical calculations. In the configuration that theory predicts LWI, we observe robust, CW oscillation. All of our tests of the laser oscillation give results that are consistent with the predictions of LWI. Raman oscillations at the Rb hyperfine frequency have also been observed and studied.

The influence of coherence effects in laser spectroscopy can be profound. Some of these effects are already well known, such as the dark-line resonances that occur in three-level Λ (lamda) systems.[1,2] Recent experiments have also shown dramatic effects such as electromagnetically induced transparency[3], amplification without inversion other coherence induced effects[4,5,6,7,8,9,10]. Suggestions of using coherences to achieve lasing without population inversion (LWI) have stimulated a great deal of activity in this area. A variety of LWI schemes have been proposed and a number of experiments are now underway; but until now, no experimental demonstration of LWI has been successful.

1. V-scheme for Lasing Without Inversion.

Theoretical analysis that includes the effects of upper state coherences predicts that lasing-without-population-inversion (LWI) can be achieved in a simple 3-level V-configuration[11] (Figure 1).

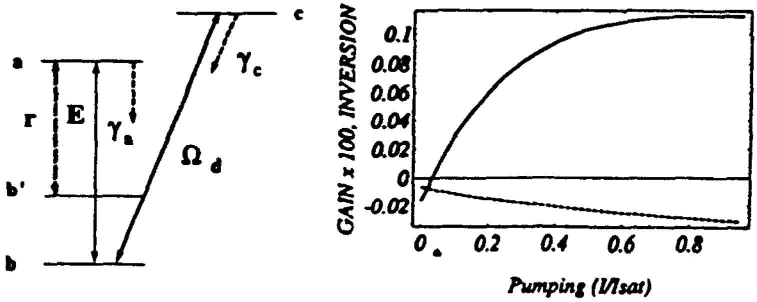

Figure 1. Three level model with a strong coherent driving field (Rabi frequency Ω_d) coupling states b and c. Lasing occurs on a→b with weak incoherent pumping r on b'→a. Graph shows calculations of the gain and inversion for the actual Rb system used in the experiment.

With constraints on field strengths and decay rates, the gain on the transition a→b is

$$Gain \sim \frac{3\lambda^2 NL\gamma_a}{4\pi} \times \frac{(\rho_{aa}-\rho_{bb})+[|\Omega_d|^2/(\gamma_{ac}\gamma_{bc})](\rho_{bb}-\rho_{cc})}{\gamma_{ab}+|\Omega_d|^2/\gamma_{ac}},$$

where ρ_{ii} are the population density matrix elements, γ_{ij} are the relaxation rates of the off diagonal matrix elements ρ_{ij}, N is the atom density, L is the cell length, and λ is the wavelength of the a→b transition. The first term shows the usual gain with population inversion, while the second term (containing the coherence decay product $\gamma_{ac}\gamma_{bc}$) allows gain on the a→b transition but does not require any inversion. It does however, require more population in the ground state (b) than in excited state (c). The V-configuration is particularly interesting because LWI is possible into the atomic ground state. This gives the potential for lasing at shorter wavelengths than might otherwise be possible.

To observe this coherence-induced lasing, we are using the Rb resonance lines. In our case the strong drive field is tuned to the 780 nm F=1→2 and the coherence-induced LWI occurs on the 795 nm F=1→2 transition. We have made a detailed theoretical analysis of this system. The model includes the hyperfine and Zeeman structure (32 levels), laser polarizations, magnetic field, strong drive laser, weak probe field (when used), broadband incoherent pump source, and the laser spectral widths. Population and gain results are then averaged over the atomic velocity distribution.

2. Experimental Results

The experimental system consists of a 4 cm long Brewster window cell, heated to approximately 60 C. The strong coherent drive field comes from a grating-tuned extended-cavity diode laser (ECDL), providing about 25 mW of power with a fast linewidth of less than 50 kHz. A broadband incoherent pumping field put a small amount of population in state (a) and was generated with a solitary diode laser that was modulated with noise. The solitary laser's linewidth could be varied (between about 20 and 500 MHz) by adding broadband electrical noise to the laser's injection current. A separate ECDL provided a low-power (~1 μW) probe beam that was used to measure the gain and the frequency of the LWI signal. To eliminate the possibility of Zeeman coherences a weak magnetic field was applied perpendicular to the plane containing the drive laser's polarization and propagation vector.

With the drive laser tuned to the center of the 780 nm F=1→2 transition, and the incoherent pump tuned to the 795 nm F=2→2 transition, we measure a maximum single-pass gain of about 15% on the 795 nm F=1→2 transition. To achieve laser oscillation using this coherence-induced gain the Rb cell is place inside ring cavity (finesse ~70). A polarizing beamsplitter cube serves as one mirror of the ring cavity, and allows the drive beam into the cell but provides high reflectivity for the lasing field. Figure 2 shows the lasing output from this system.

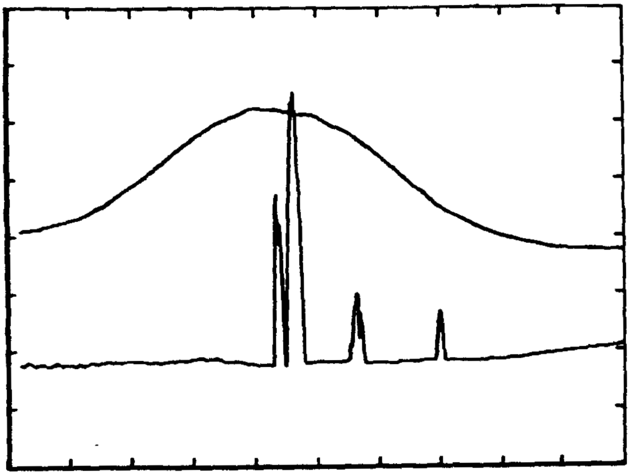

Figure 2. Upper trace shows the Rb absorption profile observed in a separate cell as the drive laser is scanned over the Doppler-broadened 780 nm resonance line. The lower trace, taken simultaneously, shows the laser oscillation at 795 nm that occurs at the resonances of the ring cavity.

This system allows direct comparison of precise experimental measurements with detailed theoretical calculations. We have done numerous experiments to test the theoretical predictions, including: linewidth and frequency measurements of the coherence induced lasing, dependence of the lasing on magnetic field and laser polarization, dependence of lasing on the spectral widths of the lasers etc. In general we find good agreement between the experiment results and the theoretical prediction of coherence-induced lasing without population inversion.

3. Raman self-oscillations.

Using different laser tunings, optical power levels, and Rb densities it was also possible to observe strong stimulated Raman signals that appear at the Rb ground state hyperfine frequencies (3.0 and 6.8 GHz). These signals are similar to those observed by P. Kumar[12] and P. Hemmer[13] in sodium vapor heat-pipes contained in optical cavities. Under certain conditions it is even possible to observe oscillation at twice the hyperfine frequencies (ie. 6.0 and 13.6 GHz). Figure 3 shows a typical Raman signal that appears as a beat note (at 6.835 GHz) on the narrow-linewidth drive laser after it is transmitted through the Rb cell. The Raman signal is ~40 dB above the background noise level and has a 3 db resonance width of about 2 MHz.

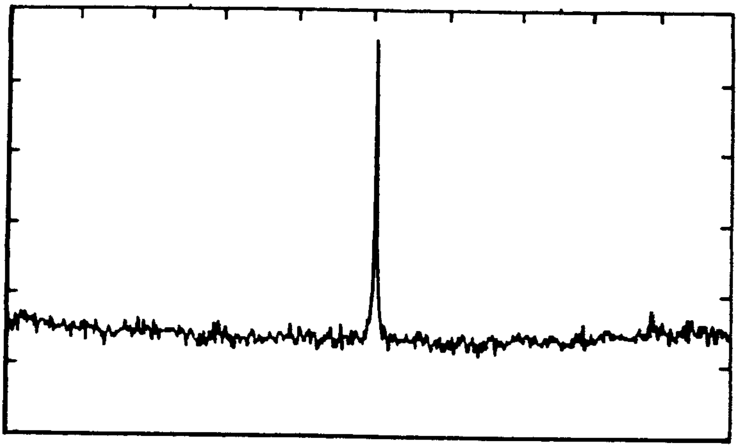

Figure 3. Microwave spectrum analyzer display of a Raman beatnote signal at 6.835 GHz that appears on a narrow-linewidth laser transmitted through the Rb cell. The vertical axis is 10 dB/div, and the horizontal axis is 100 MHz/div with a resolution bandwidth of 300 kHz.

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