Population- and Coherence-Induced Gain and Self-Oscillations in Alkali Vapor

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Abstract

Gain and oscillations are observed in a 3-level, Λ configuration when Rb atoms are driven with a strong, coherent, laser field and a broadband repumping laser. The system automatically generates an output beam that has a beatnote at the frequency of the ground state hyperfine splitting (6.8 GHz). Gain is due to both population and coherence effects in a Raman configuration. The experimental system is extremely simple and shows promise of providing a compact, Rb-stabilized microwave oscillator.

Large Raman gain signals are observed in the very simple experimental setup diagrammed in Fig. 1. The beam from a single-mode diode laser DL1 (drive laser) is passed through a Rb cell and is then detected on a fast photodiode. DL2 is a solitary diode-laser that can be spectrally broadened by adding noise to the injection current. These two input beams propagate through the cell (either in the same or opposite directions) at a small angle that allows separation of the beams and avoids feedback.

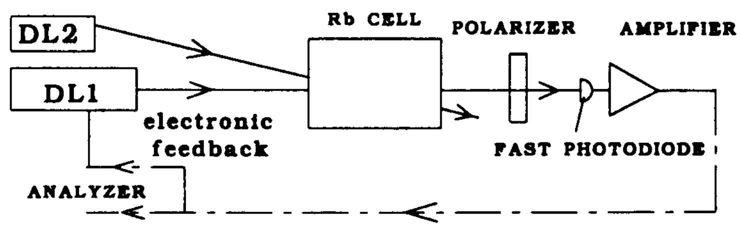

Fig. 1 Experimental setup consists of two diode laser beams, a Rb cell, a fast photodetector, and a microwave spectrum analyzer used to display the signal. The dotted line indicates the electronic feedback path that is used in some of the experiments.

Raman scattering of the drive laser in the Rb vapor generates a beam that is collinear with the drive but is frequency-shifted by the ground state hyperfine splitting (3.0 and 6.8 GHz for Rb^{85} and Rb^{87}). The fast photodiode simply detects the beatnote between the drive laser and the Raman shifted beam. The function of the repumping laser (DL2) is to return the population to the initial ground-state hyperfine level, thus controlling the optical pumping effects of the drive laser. The tuning of the broadband repumping laser is not critical; any

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transition (for example, different P state) that will return population to the initial hyperfine ground state can be used. In this way the repumping laser serves the same purpose as the buffer gas in the earlier Raman laser experiments.{2}

Figure 2 shows a typical signal that is detected with the fast photodiode. In this example the power of the drive laser was ~13 mW, tuned to resonance on the D1, F→F' (2→2') transition; the repumping laser was about 8 mW, broadened to ~500 MHz spectral width and tuned approximately to the D1 (1→2') transition. The spot diameters in the center of the 6 cm long cell were ~500 μm for the drive and ~3 mm for the repump. In this example the beatnote between the self-generated Raman beam and the drive laser has a signal-to-noise ratio of about 40 dB with a detection bandwidth of 300 kHz.

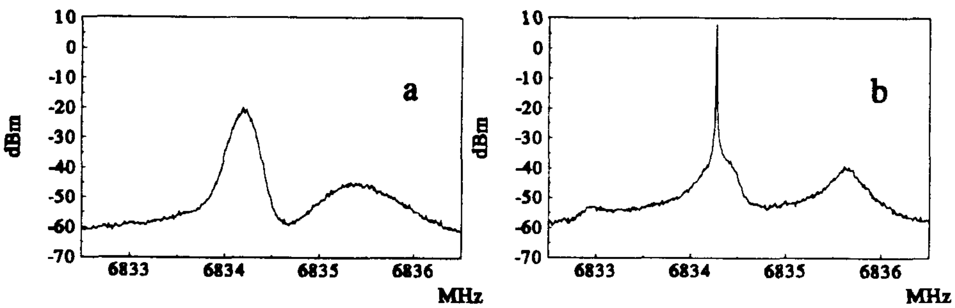

Fig. 2 Signal at 6.8 GHz from the photodetector as displayed on a microwave spectrum analyzer. Part (a) shows the beatnote between the self-generated Raman beam and the drive laser with no electronic feedback, while in (b) the spectrum is narrowed when the electronic feedback at 6.8 GHz causes the system to self-oscillate.

Our approach is reminiscent of the previous work of P. Kumar[1,2] and P. Hemmer,[3] who have demonstrated Raman gain and lasing in Na vapor heat-pipes using optical cavities. Our system is distinguished from previous work in that it does not require an optical cavity, nor a buffer gas. Also, an electronic beatnote signal is generated directly at the hyperfine difference frequency, which can be use to create a narrow self-oscillation at the hyperfine frequency. The system is very simple and in its minimum configuration requires only requires a diode laser, a photodiode and a Rb cell. It does not require a microwave oscillator and it provides a stable oscillation at the frequency defined by the atomic hyperfine splitting.

The gain in this system results from both population and coherence effects, and is remarkably high and robust. We have observed gain in both the Stokes and anti-Stokes configurations, on both the D1 and D2 lines, and within and outside the Doppler profiles. For some configurations the system also shows gain at twice the ground-state hyperfine splitting (13.6 GHz for Rb) which is most likely due to gain in the double-Λ configuration.[3]

Comparison of theoretical and experimental lineshapes is possible for both the microwave spectrum and the optical gain/loss spectrum. A few theoretical models have been used with an attempt to determine the most important physical effects: hyperfine structure, Zeeman structure, optical coherences, propagation, and Doppler broadening. At least for some range of the experimental parameters, the theory reproduces the experimental lineshapes reasonably well.

This simple system generates a signal with a very good signal-to-noise ratio and with a fairly narrow linewidth as a microwave oscillator. An obvious application of the Raman self-oscillator would be as a compact, Rb frequency standard; however a number of questions remain to be answered before this can be realized. In particular, can the problems associated with AC Stark shifts be minimized to the point that the atomically stabilized microwave oscillator has useful stability? Stark shifts resulting from the drive laser power are the main perturbation to the frequency of the Rb self-oscillator. These shifts are complicated by the multilevel nature of Rb, the variation of intensity across and along the laser beam, and their dependence on the detunings of the lasers from resonance. As a baseline test we set up the Rb self-oscillator without any optimization and let it run without any control on the laser frequencies, cell temperature or laser power levels. Using a frequency counter to record the oscillation frequency allows a measurement of the Allan variance of the self-oscillator as shown below.

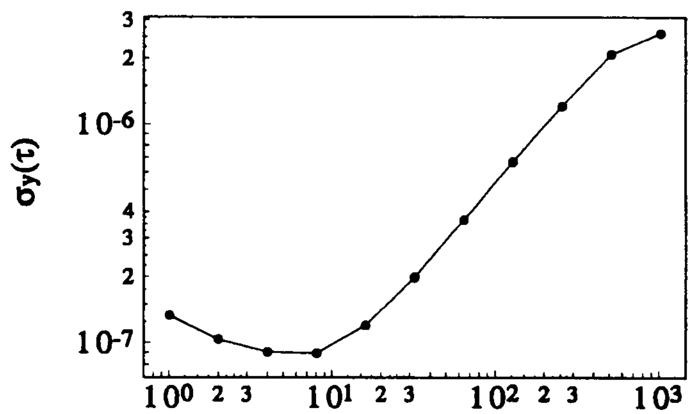

Figure 3. Data shows a typical square-root of the Allan variance of the frequency of the free-running Rb self-oscillator as a function of averaging time (τ) in seconds.

The stability of the frequency is good for a free-running oscillator, but is obviously not of frequency-standard quality in this free-running state. Active control could easily be implemented but with some penalty in complexity. Perhaps there are laser tunings and powers that can be uses to minimize the effects of the AC Stark shift. A potentially important curiosity of the system is that the oscillation frequency does not appear to have first-order sensitivity to acceleration. This may be advantageous in some very high acceleration environments.

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References

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