

Spectroscopy with diode-laser noise

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Received 21 July 1997; accepted 19 August 1997

Abstract

Conversion of laser frequency noise to amplitude noise via interaction with a resonant medium is described. Both experiment and theory show an asymmetric M-shaped noise intensity as a function of laser frequency. We also observe features corresponding to ground state atomic hyperfine structure in the rf spectrum of the noise for the case of K vapor. A calculation of the intensity correlation function of the transmitted light yields an rf spectrum which has the qualitative features observed in the experiment. © 1998 Elsevier Science B.V.

Recently, there have been a number of reports of high resolution spectroscopy performed with the judicious use of laser noise. In particular, Yabuzaki et al. [1] reported that the radio frequency spectrum of the noise of a diode laser, operated so as to have a very low amplitude noise, when propagated through a resonant atomic medium, possessed features at frequencies corresponding to the excited state hyperfine transition frequencies of the atoms. The hyperfine structure of the excited states of Rb and Cs atoms was thus observed in the rf noise spectrum. The ground state hyperfine splitting for these atoms, however, was too large to be observable with the detectors used in the experiment. In other experiments, using Rb [2] and Cs [3] atoms, the frequency noise to amplitude noise conversion taking place in the atomic medium was studied by examining the dependence of the total amplitude noise intensity on laser detuning from resonance. Theoretical predictions and calculations for the noise intensity and the noise spectrum have also been reported [4–8].

In this Letter, we present our observation of both the total noise intensity as a function of laser detuning from resonance and the spectrum of the noise, obtained when a solitary, low amplitude noise, diode laser propagates through a cell containing potassium vapor. For potassium, the hyperfine splitting of the ground state is 462 MHz which is low enough to be observed in the noise spectrum with our shot noise limited detector. The excited state hyperfine structure splittings are so low, however, that our detection noise limits at these low frequencies do not allow us to make meaningful measurements. We also present a theoretical model which successfully predicts most of the observed features in both the total noise intensity as a function of laser detuning from resonance and the rf spectrum of the noise for a given laser detuning.

The physical basis for the effects that we observe can be understood if one considers a diode laser driven by a very low noise current source. Since the noise statistics of the injection current can easily be made sub-Poissonian and for a typical diode laser the current to light conversion efficiency is very high, the stream of photons emanating from the diode laser has sub-Poissonian statistics once the laser is operating sufficiently above threshold. Such a stream of photons, when detected by a shot noise limited

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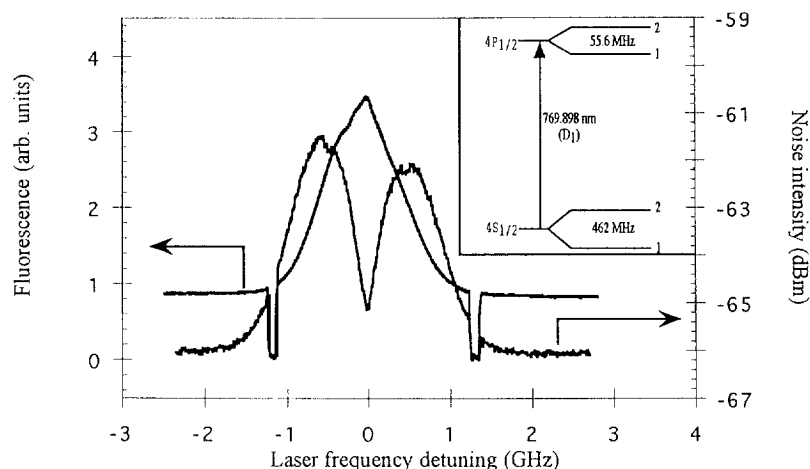


Fig. 1. Noise intensity as a function of laser detuning from the D₁ resonance of K. Also shown is the resonance fluorescence from the laser excited atoms in the Doppler broadened cell and in the inset the energy levels of the K atom under investigation. Experimental parameters are described in the text.

detector, will produce a photocurrent possessing noise which will be predominantly the shot noise produced in the detection process. Thus, if n photons are detected, one ideally observes a noise corresponding to \sqrt{n} photons. The frequency, or phase noise of the diode laser, however, remains significantly high, and for a typical diode laser results in a ~ 25 MHz diode laser linewidth but the detector is insensitive to such noise. When such a laser is propagated through an atomic medium while it is near or at resonance with the atoms, the frequency dependent interaction (absorption and reemission) of the laser with the atoms will act to convert the laser frequency noise to amplitude noise which can be observed with a shot noise limited detector.

A useful picture of what is happening can be obtained by considering the laser as consisting of a central carrying optical frequency, with a distribution of sidebands extending over the laser linewidth. When propagating through the atomic medium, typical FM spectroscopy beats occur, as all the various sidebands beat against each other. One thus expects the noise to increase as one tunes the laser central frequency towards resonance from either side of the transition due to the difference in absorption of the various sidebands. The noise intensity should dip to a local minimum when the laser frequency is at the line center, where the now symmetrically placed noise sidebands are equally absorbed and their beats tend to cancel each other. One thus expects the noise intensity as a function of laser frequency to be M shaped, just as in ordinary FM spectroscopy [9,10].

A typical M shaped plot of the noise intensity versus laser frequency, obtained for a diode laser propagating through a 22 mm long K vapor cell, maintained at 60°C, is shown in Fig. 1. Also shown in the figure is the K atom fluorescence emitted perpendicular to the propagation of

the laser. The total absorbed power in the cell is experimentally observed to be negligibly small, and in the calculations we will assume it to be zero. To obtain this data, we stabilized the injection current of the diode laser so that when the laser intensity was measured by our detector, the dominant observed noise was the shot-noise of the detection process. The laser², operating near the shot-noise limit, at ~ 1.0 mW of power, was focused to a diameter of ~ 50 μm at the center of the cell which corresponds to a Rabi frequency of 730 MHz at cell center and to ~ 220 MHz at the cell windows. The detector noise at any given rf frequency (for which the 490 MHz spectra is a representative example) was measured by an rf spectrum analyzer, as the laser frequency was tuned across the Doppler broadened D₁ resonance of K, at 770 nm. The two sharp dips at -1.2 and $+1.3$ GHz correspond to the laser being blocked and were used to synchronize the sweep of the laser frequency with the rf spectrum analyzer sweep and the fluorescence signal. As can be seen, the noise intensity in these cases drops to -66.2 dBm, which corresponds to the detector/amplifier dark noise.

The asymmetry in the M shape shown in the figure can be understood by considering the energy level diagram of the K atom shown in the inset of Fig. 1. The Doppler broadened D₁ line of K consists of two nearly resolved components separated by the ground state hyperfine splitting of 462 MHz where we ignore the smaller, excited state splitting of 55 MHz. Since the dipole moments of these two transitions are not identical, the M shape becomes asymmetric. A similar M shaped noise structure is observed as one varies the rf frequency of the spectrum analyzer up to the frequency response cutoff of the detec-

² 30 mW (nominal) Mitsubishi laser diode Model ML-6412N.

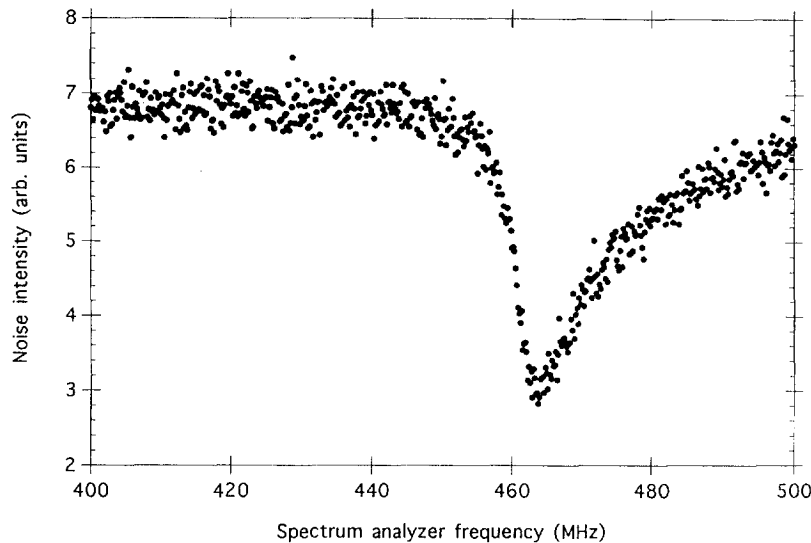


Fig. 2. The rf spectrum of the noise showing the decrease in the noise at the ground state hyperfine transition frequency of 462 MHz. The laser was detuned from the center of the D_1 resonance by ~ -800 MHz. This detuning corresponds to the higher peak of the asymmetric M shaped resonance shown in Fig. 1. The scale is linear and is corrected for the detector/amplifier response. The spectrum analyzer had a resolution bandwidth of 1 MHz and a video bandwidth of 1 kHz. The total decrease in the noise at 462 MHz is ~ 2.5 dBm. Other experimental parameters are described in the text.

tor/amplifier at ~ 520 MHz. At low frequencies, the M shape persists down to the lowest frequencies for which the detector/amplifier combination in our experiment remains shot-noise limited.

When the laser detuning from resonance is held constant, the rf spectrum of the detected noise can be measured by sweeping the spectrum analyzer rf frequency. Such an experiment can reveal an asymmetric dip in the noise spectrum at the K ground state hyperfine transition frequency of 462 MHz, as shown in Fig. 2, where the experimental conditions are similar to those for Fig. 1. This feature could only be observed, however, provided the following conditions are met: (i) the incident laser is tightly focused, (ii) circularly polarized, and (iii) the laser detuning is to the red side of the center of the resonance. The circular polarization in our experiment was obtained by a linear polarizer and a $\lambda/4$ plate between the laser and the K cell, which also acted as an optical isolator to prevent feedback into the diode. There was no polarization selection on the detected light. We note that the M shaped noise shown in Fig. 1 can be observed for any laser polarization. The feature shown in Fig. 2 was obtained for a laser detuning of ~ -800 MHz, corresponding to the laser detuned to the higher peak of the M shape shown in Fig. 1. On the blue side of resonance, that is for $+800$ MHz detuning from resonance, the 462 MHz hyperfine feature in the noise spectrum was very small.

To model these observations, we consider a phase diffusing light field interacting with a model multi-level system corresponding to the D_1 transition of K. The

solution of the problem for the full sixteen level $\{F, m_F\}$ system is too complex, and we therefore approximate it by a four-level system. These four levels, shown in Fig. 3, consist of a three-level A-system interacting with the laser and a fourth trapping level, not interacting with the laser, whereby we can adjust the populations to account for optical pumping by the circularly polarized light. The laser field amplitude was considered to be constant while the phase diffused, changing the laser frequency over a width b , which was one of the free parameters in the theory. The atomic density was assumed to be low enough so that the

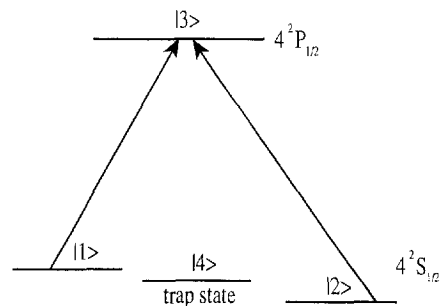


Fig. 3. Schematic four level energy diagram used in the calculation. States $|1\rangle$ and $|2\rangle$, separated by 462 MHz, are simultaneously pumped by the laser. The two calculational models considered used different relaxation models to the trap state, $|4\rangle$, and approximated the transition moments, $|1\rangle-|3\rangle$ and $|2\rangle-|3\rangle$ of the A-system, differently as described in the text.

transmitted intensity could be assumed to be nearly equal to the incident intensity, as it is in the experiment.

Two different four-level models (see Fig. 3), yielding similar results, were used in the calculation. In both models a single laser pumps both the levels $|1\rangle$ and $|2\rangle$ which are separated by the 462 MHz hyperfine splitting, to the upper state, $|3\rangle$. The laser is shown in the figure as if in resonance with both transitions due to Doppler broadening. In the first model, the transition matrix elements and Rabi frequencies of the Λ -system were obtained by averaging over all possible Λ -systems possessing $\{F, m_F\}$ quantum numbers coupled by circularly polarized light and the upper state, $|3\rangle$, was allowed to relax back to any of the three lower states with the appropriate spontaneous emission rates. All possible inelastic transitions between the lower three levels were allowed. In this way, leakage between the trap state, $|4\rangle$, and the interacting Λ -system was included.

For the second model, we solved the sixteen level Bloch equations for σ^+ , circularly polarized light and thus determined which set of four $\{F, m_F\}$ states were preferentially populated on interaction with the light. Therefore in this scheme we use the appropriate transition matrix elements where levels $|1\rangle$ and $|2\rangle$ correspond to the $\{2,1\}$ and $\{1,1\}$ ground states respectively and level $|3\rangle$ corresponds to the $\{2,2\}$ excited state. The trap state, $|4\rangle$, corresponds to the $\{2,2\}$ ground state. Again relaxation from $|3\rangle$ was allowed to all lower lying levels, but in this model, the relaxation between all of the lower states was accomplished by assuming contact with a thermal bath which was used in our model to simulate the effect of a uniform repopulation of the lower levels. This feature of the model allows the resonance fluorescence to be calculated.

The stationary intensity correlation spectrum is generally defined as [5]

$$S_{1,2}(\nu) = \lim_{t \rightarrow \infty} 2 \operatorname{Re} \int_0^\infty e^{-i\nu\tau} \langle\langle I_1(t+\tau), I_2(t) \rangle\rangle d\tau, \quad (1)$$

where $\langle\langle \rangle\rangle$ indicates a stochastic average over the fluctuating field. From this, we can then write the correlation function for the transmitted field which is proportional to that of the absorbed field for the case of pure phase fluctuations and very weak absorption. We thus obtain

$$S_{\text{out,out}}(\nu) = (\alpha L)^2 \{S_{\text{abs,abs}}(\nu; \nu_1, \nu_2)\}_{\nu_1, \nu_2}, \quad (2)$$

where $S_{\text{abs,abs}}$ is the correlation spectrum of the absorbed intensity as defined in Ref. [5], and $\{ \}_{\nu_1, \nu_2}$ indicates the extremely computer intensive double Doppler average.

The measured total noise intensity as a function of laser detuning, which gave the M shape shown in Fig. 1, is just the $S_{\text{out,out}}$ calculated in Eq. (2) when evaluated at a particular rf frequency, ν . The spectrum of the noise, as seen by the spectrum analyzer and shown in Fig. 2, is also given by $S_{\text{out,out}}$ calculated as a function of ν at a particular value of the detuning.

From Eqs. (1) and (2) it can be seen that the rf spectrum of the noise on the transmitted beam is proportional to the correlation function of the absorbed intensity, I_{abs} . This in turn is proportional to a sum over the density matrix elements of the active transitions multiplied by their respective Rabi frequencies, $\sum_{i=1,2} \Omega_{i3} \operatorname{Im}(\rho_{i3})$ (see Fig. 3).

As can be seen from the Bloch equations [5], these density matrix elements are coupled to the two photon coherence, ρ_{12} . We can therefore anticipate that a feature will be obtained in the rf spectrum of the noise at the corresponding hyperfine structure splitting frequency. Furthermore, for a Λ -system, Doppler broadening does not alter the frequency position of the feature. This is the feature that is predicted by Walser and Zoller [5] at the hyperfine frequency, with a splitting proportional to the Rabi frequency corresponding to the upper level splitting in the presence of the laser field. The absence of a splitting in the observed rf spectra is probably due to the fact that the calculation did not take into account Doppler averaging and in addition in the experiment a wide range of Rabi frequencies are present due to the focusing and inhomogeneity of the laser beam.

In Fig. 4, we show both the Doppler-broadened $S_{\text{out,out}}$ (proportional to the noise intensity) and Doppler-broadened resonance fluorescence as a function of the detuning at an rf frequency of 500 MHz, calculated using the second version of the four-level scheme. The Rabi frequency for this calculation was 400 MHz which is intermediate between the experimental values experienced by the atoms in the cell. We see that the basic M-shape is accompanied by a number of additional peaks which are also visible in the experimental results. These peaks vary in number and amplitude as a function of the Rabi frequency and rf frequency as well as other experimental parameters and will be discussed in a future publication.

When we calculate the rf spectrum of the noise without Doppler averaging in Eq. (2) both theoretical models yield

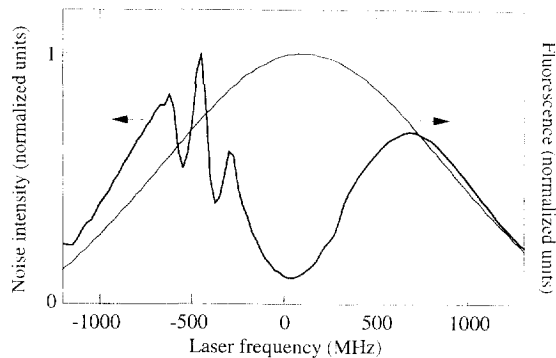


Fig. 4. Calculated noise intensity and resonance fluorescence as a function of laser detuning from the D_1 resonance of K. The second model described in the text was used for the calculation, with a Rabi frequency of 400 MHz.

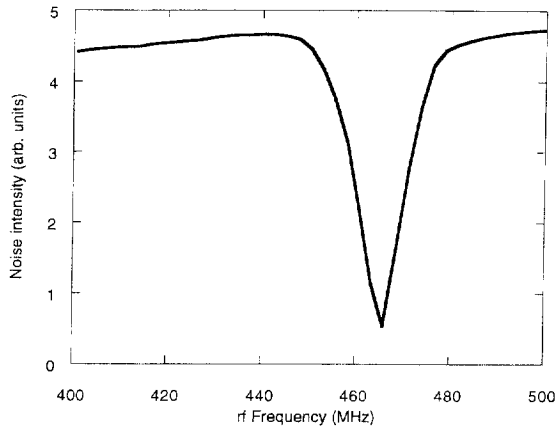


Fig. 5. The calculated rf spectrum of the noise for a detuning of -50 MHz from the center of the resonance and a Rabi frequency of 50 MHz.

similar spectra, with a sharp dip at the hyperfine splitting frequency. To obtain calculated spectra which are similar to the experimental spectra shown in Fig. 2, however, we have to assume an unrealistically large laser linewidth of 300 – 500 MHz, which is more than ten times the actual laser linewidth. A different approach to the calculation of the rf noise spectrum using Monte Carlo methods has also been reported [7]. In this calculation, Doppler averaging was not performed, and thus, to obtain features in the rf spectrum at the hyperfine frequencies, a broad pedestal laser linewidth had to be invoked, similar to the results obtained by us.

When the double Doppler average indicated in Eq. (2) is performed, however, which we did for the second model we considered, reasonable rf spectra are obtained also for a much more realistic, narrower laser linewidth, as shown in Fig. 5 for a laser linewidth of 50 MHz. This calculation also assumed a Rabi frequency of ~ 50 MHz and a detuning of ~ -50 MHz to the red side of the resonance. In calculations of the rf spectrum for higher Rabi frequencies, the dip in the noise spectrum broadens and shifts in a

way that was not observed in the experiments. When calculating the rf spectrum for a laser detuned to the blue side of the resonance, the dip in the noise became much smaller, which corresponds to the experimental observations.

In summary, we have observed frequency noise to amplitude noise conversion in the beam of an amplitude stable diode laser propagated through a K cell. The noise as a function of laser frequency is measured and compares well to a calculation based on calculations using Bloch equations. We also observe a structure in the noise spectrum at the ground state hyperfine frequency which is also qualitatively predicted by the calculation of the intensity correlation function of the transmitted light.

Acknowledgements

The support of the US–Israel Binational Science Foundation is gratefully acknowledged.

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