Diode-laser noise spectroscopy of rubidium

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We report on spectra obtained by measuring the laser intensity noise after a broad-bandwidth diode-laser beam passes through a rubidium vapor cell. The atomic resonance converts laser frequency fluctuations into intensity fluctuations. We compare our experimental spectra with numerically calculated spectra based on a phase-diffusion model of the laser field and find good agreement.

Diode lasers are becoming quite common in atomic physics experiments. The short cavity lengths of diode lasers, however, lead to intrinsic linewidths that are generally broader (≈50 MHz) than atomic resonance widths. In addition to spectroscopic resolution limitations, the frequency fluctuations of diode lasers also lead to reduced signal-to-noise ratios in fluorescence and absorption measurements.[1,2] Methods to reduce the laser linewidth by use of optical feedback have been very successful, so the problem of diode-laser frequency noise can often be avoided.[2] It is important, however, to understand this frequency noise and its consequences better, because the problem, once hidden by optical-feedback linewidth narrowing, may resurface at a higher level of precision. In this Letter we report on spectroscopic experiments to examine the effect that a resonant absorber has on a diode-laser beam with frequency noise. We compare our results with theoretical spectra obtained with a phase-diffusion model for the laser field.

Related frequency noise experiments have been carried out by Anderson *et al.*, who use a synthesized phase-diffusing laser field to observe fluorescence-intensity fluctuations from two-level atoms in an atomic beam.[3] Our experiment is concerned mainly with absorption in a Doppler-broadened vapor. Yabuzaki *et al.* used diode-laser frequency noise to observe Zeeman and hyperfine spectra without scanning the laser.[4] Another form of noise spectroscopy was reported by Dinse *et al.*, who used a carefully synthesized stochastic optical field to perform multiplex spectroscopy.[5]

All these studies are related to frequency-modulation (FM) spectroscopy, wherein a narrow-band laser is frequency modulated to produce upper and lower sidebands in the laser spectrum.[6] Each sideband can mix with the carrier to produce a signal at the modulation frequency, but these signals cancel exactly if there is no absorption since the two sidebands are 180° out of phase. In the simplest form of FM spectroscopy, absorption of one of the sidebands disturbs this exact cancellation and produces a signal. The spectra that we report on differ in that the frequency modulation is stochastic and broadband rather than single frequency, and there is no radio-frequency phase reference for detection. Nonetheless, the basic ideas of FM spectroscopy are useful for an understanding of the origin and shape of our spectra.

In our experiment a broadband diode laser is directed through an absorbing medium and detected with a fast photodetector. The detector output is sent to a spectrum analyzer that is set to a single frequency so that it acts as a tuned receiver. The broadband laser can then be thought of as a carrier with sidebands at the spectrum-analyzer frequency. As in the case of FM spectroscopy, we find that the radio-frequency signal is maximum when the laser center frequency is tuned to the side of the absorption profile and exhibits a minimum when the laser is tuned to resonance. We thus observe spectra with double-peaked profiles similar to those predicted for the case of FM spectroscopy with no radio-frequency phase sensitivity.[6] This simple picture does not take into account the continuum of sidebands that can contribute to a given signal, and it also would predict that the signal strength decreases as the spectrum-analyzer frequency approaches zero, which is not the case.

A more solid theoretical foundation for our observations is found by modeling the diode laser as a phase-diffusing field.[7] The incident laser field is $E_i(x, t) = (1/2)E_i(t)\exp[-i(\omega_L t - kx)] + \text{c.c.}$, with $E_i(t) = E_0 \exp[-i\phi(t)]$, where ω_L is the laser frequency, E_0 is the constant amplitude, and $\phi(t)$ is the phase, which is assumed to be a Gaussian random variable. The field correlation function is $\langle E_i(t)E_i^*(t+\tau)\rangle = E_0^2 \exp(-\Gamma\tau)$, where Γ is the laser half-width. This field will induce a polarization in

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the atomic vapor, which for convenience is assumed to be a two-level system characterized by a resonance frequency ω_0 and a natural linewidth γ (HWHM). For small absorption and for a nonsaturating laser field, the field after traversing the cell of length L is

$$E(t) = E_i(t) - \alpha\gamma L \times \left\{\int_{-\infty}^{t} E_i(t')\exp[-(i\Delta + \gamma)(t - t')]\mathrm{d}t'\right\}_{\mathbf{v}}, \quad (1)$$

where $\Delta = \omega_L - \omega_0 - \mathbf{k}\cdot\mathbf{v}$ is the detuning from resonance for an atom with velocity $\mathbf{v}$, the brackets represent an average over the velocity distribution, and α is the absorption coefficient. This equation can be derived by integration of the Maxwell–Bloch equation in the slowly varying envelope approximation with polarization $P(t)$ obtained from the formal solution for the time-dependent Bloch vector for weak fields. The intensity incident on the detector is then simply $I_D(t) = E(t)E^*(t)$, of which we are only interested in the lowest-order heterodyne part:

$$I_D^H(t) = \alpha\gamma L\,\mathrm{Re}\left(E_i^*(t) \times \left\{\int_{-\infty}^{t} E_i(t')\exp[-(i\Delta + \gamma)(t - t')]\mathrm{d}t'\right\}_{\mathbf{v}}\right), \quad (2)$$

which represents the mixing of the incident field and the field radiated by the induced atomic polarization. By the Wiener–Khintchine theorem, the power spectrum of this heterodyne signal is dependent on the Fourier transform of the intensity autocorrelation function, giving

$$I_S(\omega) = \mathrm{Re}\int_0^{\infty} \exp(i\omega\tau)\langle I_D^H(t)I_D^H(t + \tau)\rangle\mathrm{d}\tau \quad (3)$$

as the expected signal at the spectrum-analyzer frequency ω. Using the well-known properties[7] of the fourth-order correlation functions for the phase-diffusing fields that occur in Eq. (3), we can obtain a simple expression for $I_S(\omega)$. Spectra are finally calculated by a double numerical integration over the Maxwellian velocity distributions in the vapor associated with both $I_D^H(t)$ and $I_D^H(t + \tau)$.

The experiment is performed with a free-running commercial diode laser operating near 780 nm. The diode-laser linewidth is 125 MHz, as measured by observation of the beat note between this laser and a narrow-band (≈150-kHz) diode laser that used optical-feedback stabilization from a diffraction grating.[2,8] The absorbing medium is a room-temperature rubidium vapor ($\alpha L \approx 0.1$), with a Doppler-broadened linewidth of 570 MHz (FWHM). The laser beam is expanded to reduce saturation effects ($I/I_{\mathrm{sat}} \approx 0.3$) and, after passing through the rubidium cell, is focused onto a fast (dc to 3 GHz) photodiode. Part of the laser beam is sent through an auxiliary rubidium cell as a reference.

To record spectra, the spectrum-analyzer frequency is fixed, so it acts as a tuned receiver, and the laser frequency is scanned over the atomic resonance. Figure 1 shows a spectrum of the rubidium D_2 transitions obtained in this mode, the reference absorption spectrum for comparison, and a theoretical noise spectrum of one of the transitions. The peak rms noise voltage (in a 3-MHz resolution bandwidth) is typically 1% or 2% of the dc voltage change caused by the atomic absorption. If the detector signal is observed on a broadband oscilloscope, then the radio-frequency signal is of the same order of magnitude as the absorption signal, which is to be expected since the laser linewidth and the atomic Doppler width are comparable. Each of the double-peaked resonances is slightly asymmetric, which we largely attribute to the multilevel nature of these transitions. Optical pumping of ground-state hyperfine levels causes the Doppler-broadened absorption to be almost exclusively due to the respective cycling transitions, which are labeled in Fig. 1. Each resonance profile is diminished on the side where the noncycling transitions occur. This is to be contrasted with asymmetry caused by correlated amplitude and phase noise, which would generally be on the same side (upper or lower frequency) of the resonance.[3]

To compare our results with the phase-diffusion model, we have concentrated on a single transition. The ^{85}Rb $F = 2$ to $F' = 1$ transition was used, as it has the best combination of signal-to-noise ratio and freedom from interference of nearby peaks. Spectra as a function of laser detuning were taken for values of the spectrum-analyzer frequency from 5 to 1000 MHz. We fitted the reference spectra to a Gaussian function to determine independently the zero-detuning location and the frequency scale of the noise spectra. Each noise spectrum was characterized by the height, width, and center of the low-frequency lobe. The height was taken as the maximum value, the width as the FWHM, and the center as the midpoint of the portion of the peak above 85%. The numerically calculated theoretical curves were treated in the same manner. Figure 2 summarizes the results. For comparison, the theoretical and experimental peak heights were each scaled to 1 at their respective maximum values. The agreement between experiment and theory is quite good, even though we have not attempted to obtain a detailed best fit to the data.

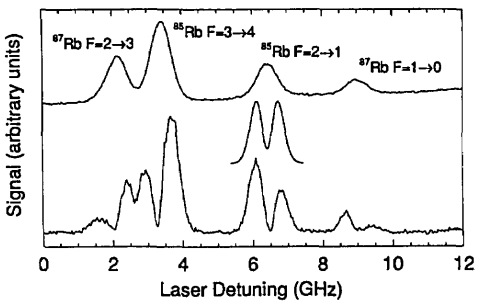

Fig. 1. Laser intensity noise versus detuning (lower trace) and reference absorption spectrum (upper trace) of the rubidium D_2 resonance lines. The middle trace shows a theoretical noise spectrum calculated by use of the experimental parameters. Each resonance is labeled with the appropriate cycling transition. The spectrum-analyzer frequency was 50 MHz for the noise spectrum.

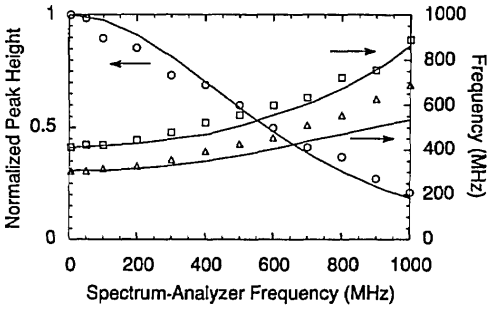

Fig. 2. Peak height (circles), width (squares), and center (triangles) as a function of spectrum-analyzer frequency. The solid curves are the theoretical predictions for the respective parameters.

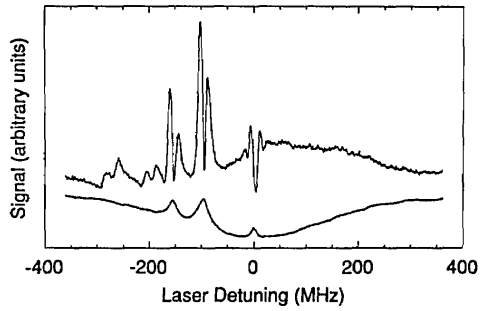

Fig. 3. Doppler-free spectra of the $F = 2$ to $F' = 1, 2, 3$ hyperfine transitions of the D_2 line of ^{87}Rb. The lower trace is a standard saturated-absorption spectrum showing the $F = 2$ to $F' = 3$ transition (at zero detuning) and two crossover resonances. The upper trace is the probe intensity noise measured with the spectrum analyzer set to 25 MHz.

There is a slight discrepancy in the case of the peak centers, which may have several causes. Rubidium is not a two-level atom as the theory presumes, so the optical pumping problem discussed above as well as interference from the nearby ^{85}Rb $F = 3$ to $F' = 4$ transition may shift the observed line.

The phase-diffusion model predicts that the heterodyne signal depends approximately linearly on the laser linewidth. We confirmed this trend by narrowing the linewidth of the laser used above to ≈100 kHz, using optical feedback from an external confocal cavity.[9] The signals were then lost in the noise. In another configuration, however, we used a grating-feedback laser with a measured linewidth of 150 kHz (Ref. 8) to demonstrate that noise spectra can still be detected with narrow-band lasers. In this experiment, we used saturation spectroscopy to obtain a narrow resonance feature. The pump and probe beams were derived from the same laser, and the probe beam was monitored with a detector that had a 100-MHz bandwidth. Figure 3 shows a typical spectrum. In this case, the noise voltage is approximately 0.1% of the saturated-absorption voltage when a 3-MHz resolution bandwidth is used and 1% when detected broadband (100 MHz). We thus find that a factor-of-1000 decrease in the laser linewidth results in a factor-of-100 decrease in the heterodyne signal. This roughly confirms the theoretical prediction, even though our theory has not been extended to the saturation case. The asymmetry in the noise spectrum, which is especially evident in the crossover resonances of Fig. 3, is believed to be caused by correlated amplitude and phase noise inherent in the diode laser.[3] These conclusions regarding the signal size and asymmetry were confirmed by similar results obtained with an optical cavity as the resonant absorber.

In summary, we have shown that the continuum of noise sidebands in a diode laser can be used to perform a variation of FM spectroscopy. We have compared the spectra of a Doppler-broadened vapor with those theoretically predicted by use of a phase-diffusion model of the laser field. Our experiment agrees quite well with this theory. Finally, we have shown that these heterodyne noise spectra are still obtainable with narrow-band lasers, albeit with reduced strength.

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