Conversion of laser-frequency noise to optical-rotation noise in cesium vapor

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We have studied the noise in the optical rotation of a linearly polarized laser beam transmitted through a spin-polarized ^{133}Cs vapor as a function of its frequency detuning from the optical resonance. Our measurements demonstrate the direct conversion of the laser-frequency noise into optical rotation noise by the dispersive response of the atomic vapor. We describe this noise-conversion process in terms of a simple model that can be used to optimize the performance of atomic devices, such as atomic magnetometers, that use optical rotation as their operational signal.

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There has been much recent interest in the conversion of laser frequency noise (FM noise) to amplitude noise (AM noise) by the absorptive response of a resonant atomic vapor [1–5]. This FM–AM noise-conversion process is undesirable, because it degrades the signal-to-noise ratio of atomic devices that rely on optical absorption of the transmitted light as their operational signal [5]. Fluctuations in the laser frequency can also be converted into noise in the laser-light phase shift acquired upon propagation through a resonant medium, and the operational signal of some atomic devices can rely on this phase shift. For instance, phase-shift detection has been the preferred measurement technique in some of the recent work in ultrasensitive optical magnetometry [6]. In this application, the rotation of the polarization plane (optical rotation) of a linearly polarized probe light beam, caused by the phase-shift imbalance of the σ^{+} and σ^{-} components of the transmitted light, serves as the measurement signal of atomic magnetometers capable of achieving sensitivities in the subfemtotesla range [7,8]. The conversion of laser FM noise into optical rotation (OR) noise is of particular concern for the implementation of OR detection in chip-scale atomic magnetometers [9,10], where vertical-cavity surface-emitting lasers (VCSELs), often with high FM noise, are widely used as the light source. In this Letter, we report on the direct conversion of laser FM noise to OR noise in a spin-polarized ^{133}Cs vapor cell.

Previous work on the noise characteristics in OR of linearly polarized probe light has been carried out in the context of nonlinear magneto-optical rotation (NMOR) [11,12]. Here, OR is caused by the birefringence induced by a magnetic field. Noise spectroscopy of NMOR resonances in ^{87}Rb was studied in [11]. A detailed study of noise spectra in NMOR in ^{87}Rb as a function of magnetic field is reported in [12]. In both experiments, the origin of the measured noise can be traced back to the conversion of the probe-laser FM noise to AM noise by the absorptive response of the resonant atomic vapor. Contrary to these experiments, in our study OR is caused by the birefringence induced by a pump optical field. In addition, the measurements reported here show that, for our experimental conditions, the main source of noise in OR is due to the direct conversion of probe-laser FM noise into OR noise, caused by the dispersive response of the resonant medium.

Our experimental setup is shown in Fig. 1. A sample of ^{133}Cs atoms is contained in a millimeter scale ($2\ \mathrm{mm}\times 1\ \mathrm{mm}\times 1\ \mathrm{mm}$) cell. The cell is filled with 173 kPa of N_2 buffer gas to avoid the fast depolarization rate of the ^{133}Cs atoms caused by collisions with the cell walls. The buffer gas also reduces the efficiency of the FM–AM noise-conversion process [5]. The choice of these experimental conditions is motivated by our current efforts to implement chip-scale atomic magnetometers [9,10]. The vapor cell is shielded from magnetic fields in the laboratory and heated to reach atomic densities in the range 1.3×10^{13}–$4\times 10^{13}\ \mathrm{cm}^{-3}$. The ^{133}Cs atoms in the cell are optically pumped by a circularly polarized (σ^{+}) pump beam from a distributed feedback (DFB) laser centered on the pressure-broadened ^{133}Cs D1 optical transition (894.6 nm). The intensity of the pump is attenuated, by a neutral density filter (ND) to yield $\sim$0.7 spin polarization at each atomic density. The dichroism and birefringence of the ^{133}Cs sample is probed by linearly polarized probe light from a VCSEL whose optical frequency is scanned around 894.6 nm. Before entering the cell, the probe light passed through a $\lambda/2$ and a polarizing beam splitter

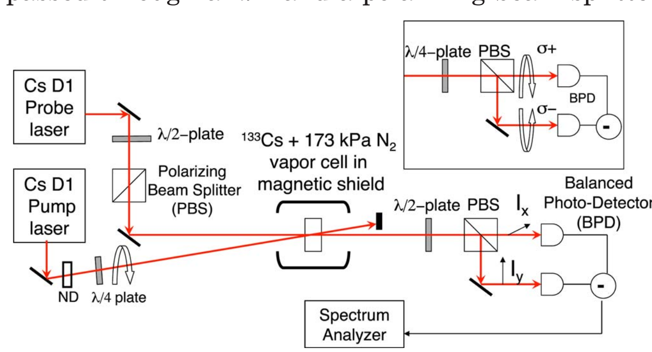

Fig. 1. (Color online) Layout of experimental setup. Inset, polarimeter setup to acquire the I_{+} and I_{-} components of the transmitted probe as indicated in the text.

(PBS) to adjust its optical intensity. Approximate pump and probe optical intensities at the entrance of the cell were 15 mW/cm^2 and 0.5 mW/cm^2, respectively. The cross-section profile of the beams filled the cell window (2 mm^2). A polarimeter consisting of a $\lambda/2$-plate and a PBS analyzed the transmitted probe light's polarization. The intensities of the output beams from the polarimeter, I_x and I_y, are measured by a balanced photodetector (BPD).

The $\lambda/2$-plate is adjusted to balance the polarimeter in the absence of optical rotation (polarimeter zero point). The signal in each of the BPD channels ($S_{x/y}$) is proportional to the intensity of the beam, which can be described by $I_{x/y}=I_+/2 + I_-/2 \pm \sqrt{I_+ I_-}\sin(\Delta\varphi_{\mathrm{OR}}+2\theta_{\lambda/2})$ [13], where $I_\pm$ corresponds to the intensity of the transmitted $\sigma^\pm$ component of the probe, $\Delta\varphi_{\mathrm{OR}}$ is the OR angle, and $\theta_{\lambda/2}$ represents the rotation angle of the $\lambda/2$-plate with respect to the polarimeter zero point. A subtraction of the BPD channels signals yields the OR signal (S_{OR}),

$$S_{\mathrm{OR}} = 2\sqrt{I_+ I_-}\,\sin(\Delta\varphi_{\mathrm{OR}} + 2\theta_{\lambda/2}). \qquad (1)$$

We measured the noise in S_{OR} as a function of probe frequency detuning. From our measurements, we have identified that in the presence of OR, the main source of noise comes from the conversion of laser FM noise to OR noise. In our model, to explain this noise-conversion process, we need to derive the OR angle. The OR angle can be deduced from S_{OR} by dividing out the contributions from absorption that affect $I_\pm$. We first measured S_{OR} as a function of probe light-frequency detuning (blue trace in inset of Fig. 2). The absorption of the circular components of the probe light ($I_\pm$) was obtained by replacing the $\lambda/2$-plate in the polarimeter with a $\lambda/4$-plate (see inset in Fig. 1). By use of Eq. (1) we obtained the OR angle (red trace in inset of Fig. 2). We note that because of the high contribution of pressure broadening from the buffer gas ($\gamma_{\mathrm{BG}} \approx 26$ GHz) to the optical linewidth ($\gamma' \approx \gamma_{\mathrm{BG}}$), neither the ground nor the excited-state hyperfine structure can be resolved. In addition, since the contribution of Doppler broadening

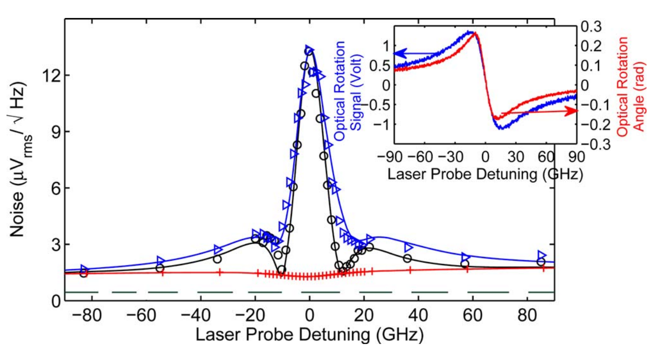

Fig. 2. (Color online) Observed noise as function of probe-light-frequency detuning for OD=0.55. Dashed line, BPD electronic noise; +, data noise in the absence of pump beam; ▷, data noise when the pump beam is present; ○, data noise when the pump beam is present and the polarimeter is balanced at each point, as indicated in text. Solid curves, fit to the noise data. Inset, optical rotation signal (blue trace) and optical rotation angle (red trace).

($\gamma_{\mathrm{Dopp}} \approx 0.4$ GHz) is much smaller than that due to pressure broadening, one can assume that the optical line is homogeneously broadened. Then the OR angle can be approximated by

$$\Delta\varphi_{\mathrm{OR}} = \sigma_o' n l P_z \left(\frac{x}{1+x^2}\right), \qquad (2)$$

where $x=(\nu_L-\nu_o)/(\gamma'/2)$ is the normalized detuning of the probe laser frequency ν_L, P_z is the spin-polarization degree of the ^{133}Cs vapor along the probe propagation axes, $l=1$ mm is the length of the cell along the probe propagation axes, n is the ^{133}Cs atomic density, and σ_o' corresponds to the pressure-broadened optical absorption cross section of the ^{133}Cs D1 transition on resonance.

We used a spectrum analyzer to measure the noise in the OR signal (S_{OR}) at low Fourier frequencies. For the measurements reported here we worked at a Fourier frequency of 385 Hz; this choice was arbitrary, similar noise behavior was observed at different Fourier frequencies. The noise was measured as a function of probe frequency detuning. Depending on the experimental conditions, we identify five main sources of noise in the OR signal: electronic noise, photon-shot noise, laser AM noise, laser FM–AM noise, and laser FM–OR noise. Although other sources of noise were considered, i.e., fluctuations in the spin polarization due to noise in the pump light, they were estimated to be significantly below the electronic noise. The dashed line in Fig. 2 shows the electronic noise, which sets the limit for the smallest change in the signal that can be detected by the BPD. To demonstrate that the BPD is working properly, we show in Fig. 2 (points) the noise in the OR signal as a function of probe-light frequency detuning when the pump beam is blocked, and thus the polarimeter is balanced ($\Delta\varphi_{\mathrm{OR}}=0$) over the entire detuning range. Under these conditions the output beams from the polarimeter have equal intensities and correlated intensity fluctuations that can be eliminated by subtracting the signals from the BPD channels [12]. As expected, in Fig. 2 (points) it is observed that the noise in the signal is dominated by photon shot noise, it is minimum on resonance and increases as a function of frequency detuning owing to higher transmission of the probe.

The behavior of the noise in the OR signal changes drastically when the atomic vapor becomes polarized, causing OR of the probe light. Now the polarimeter is balanced only on resonance ($\Delta\varphi_{\mathrm{OR}}=0$). The hollow triangles in Fig. 2 show the measured noise when the atomic vapor is polarized. We observe that at zero probe-light detuning the noise level is strongly enhanced even though the polarimeter is balanced. This behavior is contrary to what one may expect if the signal were limited by laser AM and FM–AM noise only. The increase in noise on resonance can be explained by the direct conversion of laser FM noise to OR noise by the dispersive response of the resonant medium. As the probe is tuned off-resonance the polarimeter becomes imbalanced, and in addition to photon shot noise and laser FM–OR noise, the OR signal has noise contributions from laser AM and laser FM–AM noise. It is for this reason that the noise does not reach the shot-noise level at the turning points of the OR signal (inset of Fig. 2). To separate the effects of AM noise in the signal we balanced the polarimeter by rotating the $\lambda/2$-plate, to compensate for OR of the probe light, at each measurement point. By balancing the polarimeter, the AM noise in the signal is canceled at each measurement point, and one can clearly see the effects of the FM–OR noise conversion process (hollow circles in Fig. 2).

Fluctuations in S_{OR} due to FM–OR noise can be modeled in a similar way as the conversion of FM–AM noise [4]. Within a linear approximation, the dispersive response of the resonant medium to slow changes in the laser frequency is determined by the slope of its frequency-dependent line shape. Thus in this simple model, when the light frequency is tuned to the zero crossing of the dispersive line, where the dispersive response is steep, the fluctuations in the signal are higher than when the frequency is tuned on the maximum of the dispersive line, where the dispersive response is flat. To test this we take the derivative of the OR signal [Eq. (1)] with respect ν_L to perform a fit of the noise data. We note that when the polarimeter is balanced at each measurement point by the proper adjustment of the $\lambda/2$-plate ($\Delta\varphi_{\mathrm{OR}}+2\theta_{\lambda/2}=0$), changes in S_{OR} due to fluctuations in the laser frequency can be approximated by

$$\delta S_{\mathrm{OR}} = 2\sqrt{I_+ I_-}\left|\frac{\partial \Delta\varphi_{\mathrm{OR}}}{\partial \nu_L}\right|\delta\nu_L. \tag{3}$$

Figures 3(b1) and 3(b2) show the noise measured

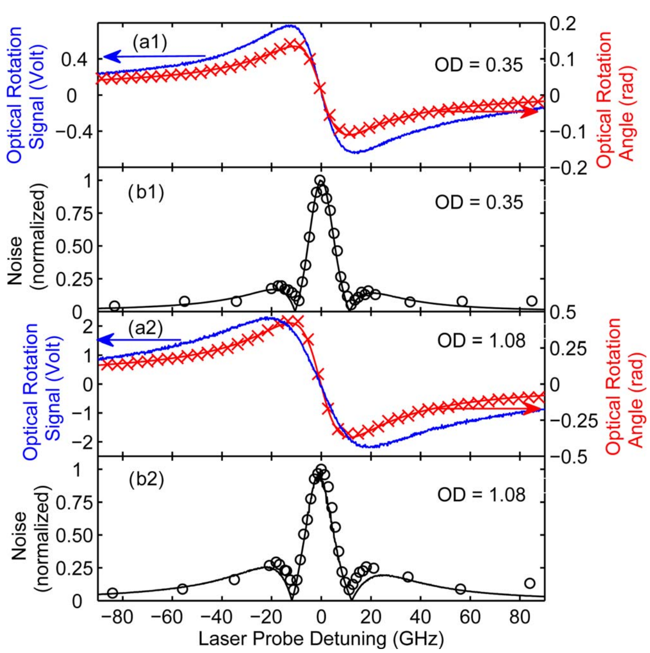

Fig. 3. (Color online) (a1), (a2) Optical rotation signal and optical rotation angle [× data points, line-data fit using Eq. (2)] for OD=0.35 and OD=1.08, respectively. (b1), (b2) Noise density normalized to maximum noise value. Open circles, observed noise. Solid curve, noise level predicted by Eq. (3).

at optical depths on resonance ($\mathrm{OD}=\sigma_o' nl$) of $\mathrm{OD}=0.35$ and $\mathrm{OD}=1.08$, respectively, and the fit of the data according to Eq. (3). For these noise data we have subtracted the contribution from electronic noise and photon shot noise and normalized it to the maximum noise level. Our model can reproduce the main features of the noise data shown in Figs. 3(b1) and 3(b2). It reproduces the enhancement of the noise level at the OR signal zero crossing and the detunings where the FM–OR noise is suppressed. These results show that the FM–OR noise can be reduced by detuning the probe light around the point where the OR *angle*($\Delta\varphi_{\mathrm{OR}}$) is maximum. In general, owing to the competition between rotation and absorption, this detuning does not correspond to the point where the OR signal (S_{OR}) is maximum, as is shown in Figs. 3(a1) and 3(a2). Finally, when the polarimeter is not balanced at every point, laser AM and FM–AM noise should be taken into account to reproduce the noise data (blue curve in Fig. 2).

Despite its simplicity, our model explains the noise in the OR signal and can be used as a guideline to optimize the performance of atomic devices that use OR as their operational signal.

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