Quantum Enhanced Magnetometer with Low Frequency Squeezing

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We report the demonstration of a magnetometer with broadband noise-floor reduction below the shot-noise level. This magnetometer, based on a nonlinear magneto-optical rotation effect, is enhanced by the injection of a squeezed vacuum state into its input. The noise spectrum shows squeezed noise reduction of about 2 dB spanning from close to 100 Hz to several megahertz. We also report on the observation of two different regimes of operation of such a magnetometer: one in which the detection noise is limited by the quantum noise of the light probe only, and one in which we see additional noise from the light-atom interaction.

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Optical magnetometers now reach the subfemtosela/√Hz level of sensitivity [1], surpassing superconducting quantum interference device (SQUID) magnetometers [2]. Ultimately, such magnetometers are limited by quantum-mechanical noise sources, in particular by the light shot-noise at detection, spin projection atomic noise, and the back action of light noise onto atoms [1–3]. The former noise source can be addressed with injection of polarization-squeezed light states [4], while the spin projection noise can be suppressed via the use of atoms prepared in spin-squeezed states [2] or with quantum nondemolition measurements [5, 6].

In this manuscript, we demonstrate a quantum-enhanced, all-atomic optical magnetometer based on a nonlinear magneto-optical (Faraday) rotation (NMOR) [7–13], with the injection of a vacuum-squeezed state into the polarization orthogonal to that of the probe field. We also demonstrate the transition from a shot-noise-limited magnetometer at lower atomic densities, to a region where the magnetometer is affected by back action of the light noise onto the atoms at higher atomic densities. In contrast to a previously reported magnetometer with squeezing generated via parametric down conversion in a nonlinear crystal [4], our setup uses an atomic squeezer based on the polarization self-rotation (PSR) effect [14–20]. Unlike its crystal counterpart, the PSR squeezer does not require a powerful pump laser, but uses a pump laser with only several milliwatts of power in a single-path configuration. Our squeezer generates about 2 dB of squeezing starting from close to 100 Hz and ranging up to several megahertz. This is the lowest frequency quantum noise sideband suppression generated at a wavelength of 795 nm to date. This unique squeezer allows for a quantum enhanced all-atomic magnetometer with improvements to the signal-to-noise ratio for measurements in the same range of frequencies. This is potentially useful for gravitational wave detectors [21], geophysics, astronomy, biophysics, and medical applications. It is particularly useful for detecting low-frequency magnetic signatures against a background of constant field.

The setup of our experiment is depicted in Fig. 1. It contains two important components: the squeezer, which prepares the polarization squeezed probe beam, and the magnetometer, which can be probed with either the squeezed or shot-noise-limited (unsqueezed) beam.

The operation of this squeezer is discussed in detail in Ref. [20]. The output of a DL100 Toptica external cavity semiconductor laser (tuned to D1 line F2 \( \rightarrow \) F1 = 2 transition of \(^{87}\)Rb) passes through a single-mode polarization-maintaining fiber, \( \lambda/2 \) is half-wave plate, \( \lambda/4 \) is quarter-wave plate, PBS is polarizing beam splitter, GP is Glan-laser polarizer, BPD is balanced photodetector.

![Experimental setup](image-url)

**FIG. 1.** Experimental setup. The squeezer prepares an optical field with reduced noise properties which is used as a probe for the magnetometer. SMPM fiber depicts single-mode polarization-maintaining fiber, \( \lambda/2 \) is half-wave plate, \( \lambda/4 \) is quarter-wave plate, PBS is polarizing beam splitter, GP is Glan-laser polarizer, BPD is balanced photodetector.
ters experimentally to be optimal for noise suppression (squeezing) of about 2 dB with respect to the shot-noise level at frequencies in the range of 100 Hz to 1 MHz (see Fig. 5). After the first cell, we make a collimated beam with a waist size of 900 μm. This beam has a squeezed-vacuum field in the polarization orthogonal to the pump field, but in a reference frame where we choose the main polarization axis to be at 45° with respect to the initial polarization, the beam can be treated as polarization-squeezed [4, 19]. We use this polarization-squeezed beam as the probe field for our magnetometer, with a power of 6 mW after absorption loss in the squeezing cell.

The magnetometer itself consists of a similar cell of isotopically enriched ⁸⁷Rb with the addition of 2.5 Torr Ne buffer gas. The cell is also enclosed in the magnetic shielding, but a solenoid with its axis parallel to the direction of probe beam propagation controls the magnetic field inside the cell. We also vary the magnetometer cell temperature to see what density of atoms provides an optimal magnetometer response.

After the magnetometer cell, we have a detection scheme to measure the polarization rotation angle of the probe through the atoms. The scheme consists of a polarizing beam splitter (PBS) set to 45° with respect to the probe light polarization, which splits the probe field at a 50/50 ratio and directs it to the balanced photodetector (BPD). The signal from the BPD is sent to an SRS SR560 voltage preamplifier and then to a Lecroy 640Zi oscilloscope to analyze the response of the system to the magnetic field and also measure the quantum noise spectrum. We tilt the quarter-wave plate after the squeezer (set so that the axis of birefringent material coincides with the light polarization) to create a phase shift between orthogonal polarizations and adjust the squeezing angle of the vacuum field relative to the probe field. In this way we can choose the phase-angle to achieve the maximum quantum noise suppression.

We can remove the squeezed vacuum field from the probe beam by inserting a polarizing beam splitter before the magnetometer, which rejects squeezed vacuum and thus creates a shot-noise-limited, unsqueezed, coherent probe light polarization, which splits the probe field (set so that the axis of birefringent material coincides with the light polarization) to create a phase shift between orthogonal polarizations and adjust the squeezing angle of the vacuum field relative to the probe field. In this way we can choose the phase-angle to achieve the maximum quantum noise suppression.

When we apply a longitudinal magnetic field to the magnetometer cell, the polarization of the probe field rotates due to the NMOR effect and the photodiodes detect a signal proportional to the angle of rotation (for small angles) and the incident intensity of the light. We fix the intensity of light, thus the BPD signal is proportional only to the angle of rotation. A characteristic response curve is depicted in Fig. 2. The broad S-like response is governed by the Zeeman splitting of the ground-state magnetic sublevels and their decoherence time (time of flight of atom in the probe beam in our case) subject to power broadening. The narrow resonance at zero magnetic field is due to velocity changing collisions and repeated interaction of the atoms that diffuse away from the laser beam and then return back to the beam [13, 22]. For such atoms, the effective lifetime in the beam is significantly longer resulting in a narrower spectral feature. We note that if we reduce the power of the probe beam below 1-2 mW, the narrow resonance disappears. The smallest detectable magnetic field (i.e. sensitivity) of the magnetometer is inversely proportional to the slope of this curve; the slope is measured on the steepest part of the response curve on the left side of the narrow peak. This narrow resonance thus increases the response of the magnetometer to very small magnetic fields, and so we maintain the intensity of the probe light at the level of several milliwatts. An easy way to boost the response of the magnetometer is to increase the number of interacting atoms in the magnetometer cell (i.e. increase the cell temperature). The magnetometer response grows linearly for small atomic densities (see Fig. 3) but then tends to saturate since with increased atomic density the probe beam is attenuated which leads to a weaker signal at the BPD [23]. If the density is increased even further, the probe light will eventually be totally absorbed and no response will be detected.

The ultimate sensitivity is governed by the signal-to-
noise ratio (we use SNR=1 as a benchmark everywhere in this paper) and the noise level is set by the quantum noise floor. We compare noise floors of our magnetometer under two experimental conditions: first, when we probe with unsqueezed coherent light, which sets the shot-noise limit, and second, when we use the polarization-squeezed light probe. We conduct this comparison at different temperatures/atomic densities and the results are depicted in Fig. 4. During this measurements we modulate the internal longitudinal magnetic field at various frequencies to ensure that noise floor of the magnetometer is unaffected by the presence of alternating magnetic field. Modulation was set at 30 kHz for data presented in Fig. 4 and 220 Hz for data in Fig. 5.

At lower temperatures, when atomic noise does not contribute much into the overall noise budget, we see broadband noise suppression of about 2 dB from hundreds of hertz to several megahertz, which is independent of atomic temperature and mirrors the input squeezed state noise spectrum (see for example Fig. 5). High resonance-like peaks are due to resonant spikes in electronic dark noise of the BPD and the electronic noise of our solenoid current source. Note that in Fig. 4, one can see an increase of the noise below 10-20kHz. This is due to residual intensity noise (RIN) of our laser which is shot-noise limited only above 20 kHz. This RIN can be suppressed at lower frequencies by careful balancing of the BPD (Fig. 5). However, it increasingly difficult with higher temperatures since the RIN seems to couple into the atomic noise. We choose several noise spectral frequency components from Fig. 4 to better illustrate this situation in Fig. 6. Note that at lower atomic densities, the squeezing level is best and nearly independent of noise sideband frequency. At higher densities, laser noise (RIN) couples into the noise spectra, raising the noise levels for lower sideband frequencies, but at higher sideband frequencies, (>20 kHz) where our laser is shot-noise limited, the quantum noise floor of the magnetometer is independent of noise frequency.

![FIG. 4](image1.png)

**FIG. 4.** (Color online) Magnetometer quantum-noise-floor spectra with polarization-squeezed (light trace) and shot-noise-limited probe (dark trace) fields taken at different temperatures/atomic densities of the magnetometer. (a) 25°C, (b) 35°C, (c) 50°C, (d) 55°C, (e) 60°C, (f) 70°C. Spectrum analyzer resolution bandwidth is 28.6 Hz, the resulting trace is averaged over 500 traces.

![FIG. 5](image2.png)

**FIG. 5.** (Color online) Magnetometer quantum noise spectrum with (a) polarization-squeezed and (b) shot-noise-limited probe fields taken at magnetometer cell temperature of 35°C. The insert shows the low frequency part of the noise spectrum (0 to 1 kHz). The arrow marks the frequency of magnetic field modulation at 220 Hz.

![FIG. 6](image3.png)

**FIG. 6.** (Color online) Noise suppression level vs atomic density normalized to shot-noise level for several noise frequencies.

However at these higher temperatures, we see that light noise back action onto the atoms starts to contribute into the quantum noise budget, and we see that broadband noise starts to increase even for the unsqueezed probe field. Moreover, atoms interact with the squeezed
light quantum state and decrease the amount of squeezing, eventually raising the squeezed noise level above shot-noise for the higher atomic densities (see Fig. 4(f) and 6).

Due to the increased atomic noise contribution, the NMOR magnetometer does not benefit from polarization squeezing at all atomic densities/temperatures as we show in Fig 7. However, benefits of the polarization-squeezed state probe are clearly visible at lower atomic densities.

We demonstrated an all-atomic quantum enhanced NMOR magnetometer with sensitivities down to about 1 pT/√Hz. To the best of our knowledge, this is first demonstration of a squeezer at 795 nm capable of noise suppression below shot-noise levels at low frequencies starting from a few hundred hertz. This brings such a quantum-enhanced magnetometer into the realm of practical applications in medicine, biology, and gravitational wave detection where the characteristic magnetic signatures are at sub-kilohertz frequencies. We also note that any DC magnetic field can be up-converted to the detection band of this device if one spins the overall setup to generate a modulation of the magnetic field at the desired frequency. This may not be very practical for an Earth-based setup, but could be quite simple for a space-based setup, where the overall rotation is easy to achieve at frequencies of hundreds of hertz. So our magnetometer is of potential use in astrophysics and space exploration programs. We also believe that the increase in noise below 100 Hz frequencies in our squeezer is not fundamental, and most likely can be improved with the use of a quieter laser and an improved design of the BPD. We would like to mention that our enhancement works for any shot-noise-limited detection, and address a common argument against squeezing that “it is always possible to increase the SNR by increasing the light power, making squeezing unnecessary.” While this is correct the injection of squeezing increases the SNR even further on top of the power-boost improvement.

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