Towards a high-density squeezed-light magnetometer

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Increasing the sensitivity of alkali-based magnetometers is an active area of interest [1]-[3], with potential applications ranging from space science to medical diagnosis. Quantum-non-demolition (QND) measurements to generate spin squeezing [4, 5] and squeezed light techniques [6]-[8], have both enabled magnetic sensitivities beyond their respective standard quantum limits in such instruments. In theory these techniques are synergistic, although they are yet to be combined in a single instrument. At the same time, they have not been applied to high-atomic-density sensors [7], which are used in micro-fabricated [9] and SERF magnetometers [10], and in which spin noise is more prominent. Squeezed-light-enhanced vapor-cell magnetometers reached nT/(Hz) sensitivity in 2010 [6] and 2 pT/(Hz) in 2011 [7]. Here we report a high-density magnetometer with sensitivity below 100 fT/(Hz) in an instrument that is simultaneously limited by optical shot noise and spin projection noise. This makes the instrument an attractive candidate, not just for the highest-sensitivity quantum-enhanced magnetometer, but also as a test bed for combining optical and atomic squeezing.

In contrast to previous squeezed-light magnetometers, based on spin-alignment [6]-[8], we use a magnetometer architecture based on spin-orientation of the atoms and use phase-sensitive detection to extract the magnetometer signal. This approach allows us to implement features not found in previous squeezed light magnetometers: We probe the spin orientation of the atomic ensemble via the optical Faraday effect, which is an efficient technique for QND measurements, and employ Bell-Bloom excitation, which allows us to work at frequencies of 10s of kHz, where detectors and squeezed-light sources can easily be shot-noise limited. This magnetometer architecture is simple and it is amenable for squeezed light probing. In fact, the same setup used for spin noise spectroscopy our group achieved squeezing of 3.2dB in unpolarized Rb vapor [11].

By operating our magnetometer at an ambient field of $4\mu T$, corresponding to Rb87 Larmor precession of 28kHz, we are able to operate at a regime of minimum technical noise. Figure 1a shows the power spectral density of the phase sensitive signal recorded under these conditions. From the spin noise spectrum obtained at the same conditions we estimate the contributions of fundamental quantum noise and distinguish frequency ranges in which the spin or photon shot noise are dominant, as well as a transition region. The use of squeezed light probing is predicted to have beneficial effects in each region: directly lowering the magnetic noise floor for high frequency signals, for which photon shot-noise dominates, giving stronger QND measurements for low-frequency signals, for which atomic projection noise dominates, and increasing the effective bandwidth of the sensor in the transition region.

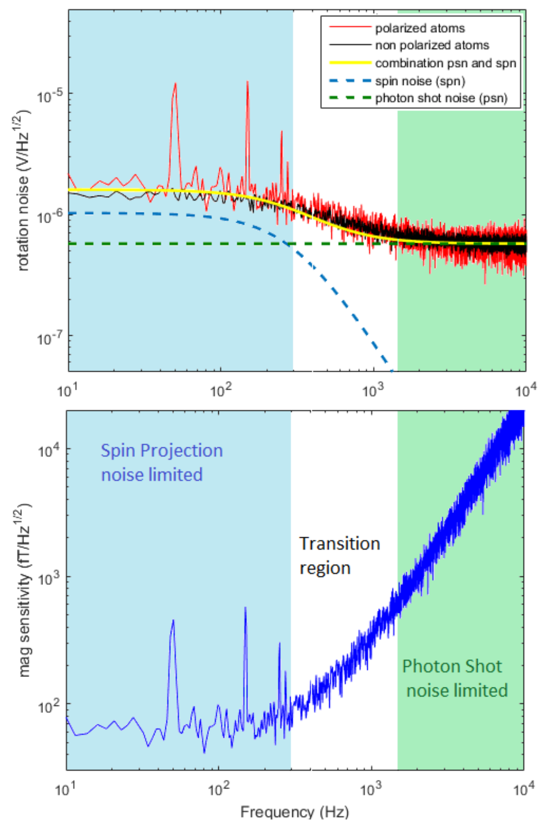

Figure 1: (a)Power spectral density of the Lock in Signal obtained with probe power at $500\mu W$ and pump power $40\mu W$ (b) Experimentally observed magnetic field noise spectral density accounting for the frequency response of the magnetometer.

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