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Research paper

Optimization of Sensitivity in an Mx Quantum Magnetometer via Dual-Sideband Modulation in Rubidium Vapor

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Abstract

Atomic magnetometers are one of the most sensitive quantum magnetic sensors that operate at room temperature. Achieving high sensitivity in these sensors requires eliminating various optical and electronic noises in their setup. Various methods have been used for this purpose. Given that these sensors operate in the optical resonance absorption region, one way to achieve high sensitivity is to use dual modulation. In this paper, it is shown that the use of sidebands can be an effective solution to increase sensitivity and overcome the limitations of the sensor's frequency response. By combining the amplitude modulation of the incoming light with the modulation of the magnetic resonance, the sidebands are shifted to higher frequencies. The results show that this dual modulation reduces noise by two orders of magnitude and improves sensitivity from 500pT/√Hz in the unmodulated regime to 1.7pT/√Hz in the dual modulation regime. Therefore, using dual modulation in the magnetic atomic sensor is an effective solution in reducing noise and increasing its sensitivity.

1. Introduction

Atomic magnetometers represent some of the earliest quantum sensors to achieve both commercial availability and practical implementation. They are widely employed in areas such as fundamental physics research, geophysical prospecting, biological signal detection, and the imaging of structural irregularities in materials. All these applications require reducing the noise level in the measurement and achieving high sensitivity. To increase the sensitivity of this sensor, it is necessary to reduce the types of noise present in it. The most important of these noises is thermal noise, shot noise, photon noise, and 1/f noise. In very small fields where the Larmor frequency drops below 1 kHz, 1/f noise has a dominant effect. To reduce 1/f noise, the measurement frequency must be increased. One way to overcome 1/f noise is to use modulation. By modulating the sensor response, the sensor response is based on the modulation frequency, and the received light is demodulated to achieve the response at the output [1, 2]. In this way, if the frequency is high enough, the 1/f noise is greatly reduced. However, in an atomic sensor, the output light is modulated at the Larmor frequency. By modulating the light entering the sensor at a high frequency, a dual modulation condition is created, and the output light exhibits dual modulation. In addition to the modulation frequency, sidebands are also observed at the output.

To understand how sidebands are utilized in this research for magnetic sensing, it is useful to examine magnetic resonance in rubidium vapor briefly. Alkali metals, positioned in the first group of the periodic table, have atomic configurations similar to hydrogen. Rubidium, for instance, has an atomic number of 37, with its outermost electron in the 5s ground state. Optical pumping with a laser beam is a well-established method for altering the atomic quantum state.

Modern tunable lasers enable precise control over the quantum states of neutral rubidium atoms [3, 4]. In rubidium-based magnetometers, circularly polarized light is typically used to redistribute populations among Zeeman sub-levels. The angular momentum of the photon is transferred to the atom, limiting transitions to specific sub-levels. When irradiated with right-handed circularly polarized light, rubidium atoms quickly reach a dark state in which they cease absorbing the laser. Transitions out of this dark state are rare, occurring mainly via dissipative or weak non-optical processes [5].

However, when an RF magnetic field is applied with energy matching the separation between adjacent Zeeman sub-levels, the atoms are driven out of the dark state, leading to renewed absorption of the laser light. This results in the transmitted beam being modulated at the same frequency as the applied RF magnetic field [6].

In type magnetometers utilizing rubidium atoms, the magnitude of the measured magnetic field directly correlates with the rubidium resonance frequency, and therefore with the modulation frequency of the transmitted light [7, 8]. For instance, a 14.27 nT magnetic field corresponds to a resonance frequency of about 100 Hz.

It is important to note that in rubidium-based magnetic field sensing, sensitivity rather than absolute accuracy is the key parameter. The lower the surrounding magnetic field, the more linear and sensitive the sensor becomes. Hence, minimizing the ambient magnetic field is critical for achieving high-performance operation. However, this also necessitates lowering the laser carrier frequency, which, if reduced below a few hundred kilohertz, negatively affects devices like lock-in amplifiers and amplifies 1/f noise.

The dual-modulation technique in quantum magnetometers significantly enhances magnetic field detection sensitivity. By simultaneously modulating the optical frequency and the magnetic resonance of rubidium atoms, the detected signal is shifted to higher frequencies where the (1/f) noise is considerably reduced. This frequency translation enables precise magnetic field measurements even in unshielded environments and improves both the signal-to-noise ratio and the overall stability of the system. Consequently, dual modulation provides an effective pathway for developing compact, low-noise, and ultra-sensitive quantum magnetometers for biomedical, geophysical, and fundamental research applications.

In the present study, we implement a dual-modulation approach to generate controlled sidebands, demonstrating that it is possible to raise the sensitivity of the atomic magnetometer without altering the surrounding ambient magnetic field.

2. Theory

The M_x configuration is the most widely adopted optical arrangement in atomic magnetometry. In this scheme, a circularly polarized pump laser prepares the atomic ensemble with a preferred spin orientation. This net spin polarization is then subjected to a radio-frequency magnetic field applied transversely. The atomic spins process about the static field at the Larmor angular frequency $\omega_l = \gamma B_0$, where γ is the gyromagnetic ratio (the magnetic moment per unit angular momentum) and B_0 denotes the local static magnetic field. The Bloch equations are used to model the temporal dynamics of the spin polarization components (M_x, M_y and M_z) under the influence of the static field (B_0), the transverse driving field (B_{rf} cos (ω_{rf}t)), and the relevant spin-relaxation processes.

$$\frac{d}{dt}\begin{pmatrix} M_x \\ M_y \\ M_z \end{pmatrix} = -\gamma \begin{pmatrix} M_x \\ M_y \\ M_z \end{pmatrix} * \begin{pmatrix} B_{rf}\cos(\omega_{rf}t) \\ 0 \\ B_0 \end{pmatrix} - \begin{pmatrix} M_x/T_2 \\ M_y/T_2 \\ M_z/T_1 \end{pmatrix} \tag{1}$$

These equations incorporate the longitudinal (T_1) and transverse (T_2) relaxation time constants. The detected signal is proportional to M_n, where (n) indicates the orientation of the pump beam relative to B_0. Resonance occurs when a transverse radio-frequency magnetic field is applied with a frequency matching the precession rate of M_n. Under this resonance condition, the magnetometer becomes sensitive to the oscillatory behavior of the atomic magnetic moment. Consequently, the M_x resonance can be observed by monitoring variations in the transmitted light intensity as the RF drive frequency is scanned near the Larmor frequency.

In this configuration, the static magnetic field B_0 is oriented along the z-axis, the RF magnetic field B_{rf} is applied along the x-axis, and the pump beam is positioned at a 45° angle to the z-axis within the yz-plane [9, 10].

Therefore, the pump beam is modulated at the Larmor frequency after passing through the rubidium cell.

If the frequency of the RF field is equal to the Larmor frequency, ω_L, the light intensity on the detector will be as follows:

$$I(t) = I_0[1 + R_{Larmor}sin\omega_L t] \qquad 0 \le R_{Larmor} \le 1 \tag{2}$$

In this case, 1/f noise is also present in the detector and is added to it by converting the above intensity to voltage in the detector. As the field strength decreases, the Larmor frequency decreases, and as a result, the 1/f noise to signal ratio increases. Now, if we modulate the pump light in ω_{mod} frequency, the intensity of the light output from the rubidium cell will be as follows:

$$I(t) = I_0(1 + R_{mod}sin\omega_{mod}t)(1 + R_{Larmor}sin\omega_L t) \tag{3}$$

thus

$$\begin{aligned} I(t) &= I_0(1 + R_{mod}sin\omega_{mod}t \\ &\quad +R_{Larmor}sin\omega_L t \\ &\quad +R_{mod}R_{Larmor}sin\omega_{mod}t\ sin\omega_L t) \\ &= I_0\{1 + R_{mod}sin\omega_{mod}t \\ &\quad +R_{Larmor}sin\omega_L t \\ &\quad +\frac{1}{2}R_{mod}R_{Larmor}[cos(\omega_{mod} - \omega_L)t \\ &\quad -cos(\omega_{mod} + \omega_L)t]\} \end{aligned} \tag{4}$$

As can be seen, there will be ω_{mod} and $\omega_{mod} \pm \omega_L$ frequencies at the output, ω_{mod} which are modulated light, and $\omega_{mod} \pm \omega_L$ are two sidebands around the modulated light due to dual modulation. The magnetic sensor response is generated on the sidebands of the modulation frequency. Since the modulation frequency is far from the DC level, the 1/f noise is almost completely eliminated, and small fields can be measured with higher accuracy.

3. Experimental Setup

The experimental arrangement, illustrated in Figure 1, is centered on a cylindrical vapor cell containing rubidium atoms of the ^{85}Rb isotope. The cell measures 50 mm in length and 25 mm in diameter and is filled with 10 torr of N_2 gas, which serves as a quenching agent for excited rubidium atoms. To reduce spin relaxation from wall collisions, the inner surface of the cell is coated with octadecyltrichlorosilane (OTS). A resistive heating wire is used to maintain the cell at a temperature sufficient to generate the desired rubidium vapor density.

Optical pumping is achieved using a distributed-feedback (DFB) diode laser tuned to the rubidium

D_1 transition at 794.8 nm. The pump beam passes through a sequence of optical components a linear polarizer, an electro-optic modulator, another linear polarizer, and a quarter-wave plate to produce the desired dual modulation before entering the rubidium cell. The electro-optic modulator is driven by a frequency generator and a high-voltage amplifier, operating at a fixed modulation frequency of 70 kHz for this experiment.

In this configuration, the pump beam is directed along the z-axis, while the RF magnetic field B_{rf} lies in the xz-plane, and the external static magnetic field is applied in the yz-plane at an angle of 45° relative to the z-axis.

Radio-frequency coils are used to modulate the spin precession perpendicular to the optical pumping direction. To compensate for the Earth's magnetic field, the rubidium cell is positioned at the center of three orthogonal pairs of Helmholtz coils, enabling precise detection of small residual magnetic-field variations in an unshielded laboratory environment. By applying an oscillating voltage to the coils associated with the radio-frequency (RF) oscillating magnetic field and sweeping its frequency around the Larmor frequency, and by recording the variations of light absorption during its passage through the cell, the in-phase and quadrature components of the detector output are recorded using a lock-in amplifier. The acquisition of these signals, to determine the resonance frequency, is performed using a computer and a program written in the LabVIEW environment. In this program, by applying a radio-frequency sweep command, the detector intensity is recorded and stored as a resonance curve. Finally, the frequency of the lock-in amplifier is locked to the resonance frequency, and the output of the optical detector is recorded for magnetic field measurement.

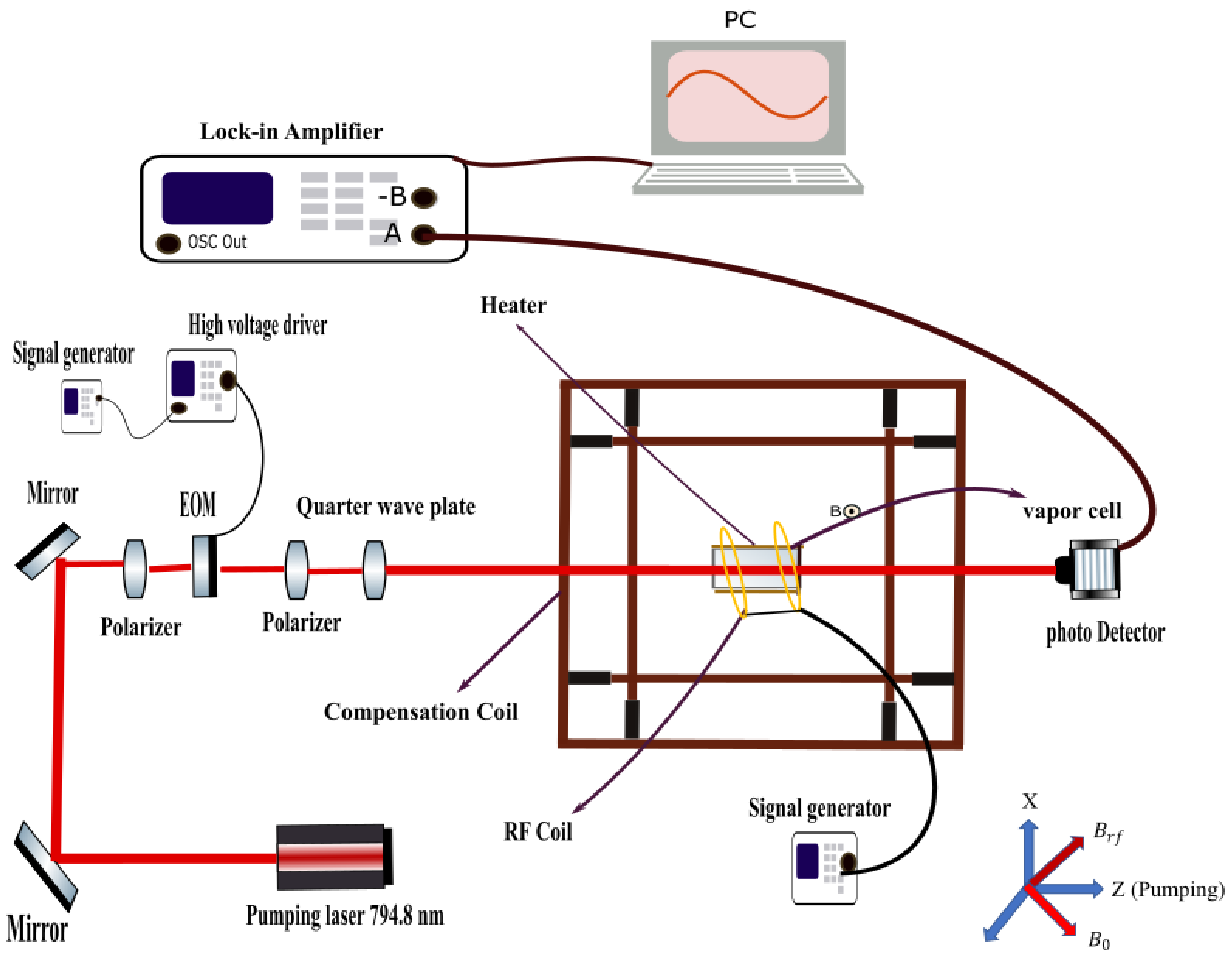

Figure 1. Experimental Setup for Dual Modulation Using Rubidium Magnetic Resonance and Electro-Optic Modulation

4. Discussion and Results

The first stage of the experiment involved capturing the magnetic resonance signal using an unmodulated laser beam, providing a baseline response of the alkali spin system to the external magnetic field. The more prominent resonance peak corresponds to ^{85}Rb, whereas the smaller one originates from ^{87}Rb. The amplitude difference between these two signals reflects the natural isotopic composition of rubidium used in fabricating the vapor cell [11, 12]. Subsequent analysis concentrates solely on the ^{85}Rb resonance, which appears at a frequency of 3900 Hz. When the transmitted laser light through the rubidium vapor becomes modulated by magnetic resonance, the in-phase component of the detected intensity exhibits a Lorentzian profile centered near the resonance frequency. The maximum of this in-phase response occurs at 3900 Hz, corresponding to the strength of the applied magnetic field within the cell. Using the relation $\omega_l = \gamma B$, this resonance frequency translates to a magnetic field magnitude of approximately 556 nT. Any variation in the external magnetic field consequently shifts the resonance frequency proportionally [13]. Figure 2 illustrates the data obtained from dual modulation measurement caused by rubidium magnetic resonance using modulated laser light. As shown, two sidebands appear on either side of the main band. The main band, observed at a frequency of 70 kHz, corresponds to the demodulation of intensity modulation by the electro-optic modulator, which was preset to 70 kHz by the experimenter. Additionally, the two sidebands, as predicted by the mathematical relationships discussed in the theoretical section, are clearly observable in the data. It is important to note that the dependence of each sideband's frequency on the rubidium magnetic resonance frequency means that any change in the external magnetic field around the rubidium cell will result in a frequency shift of the sidebands.

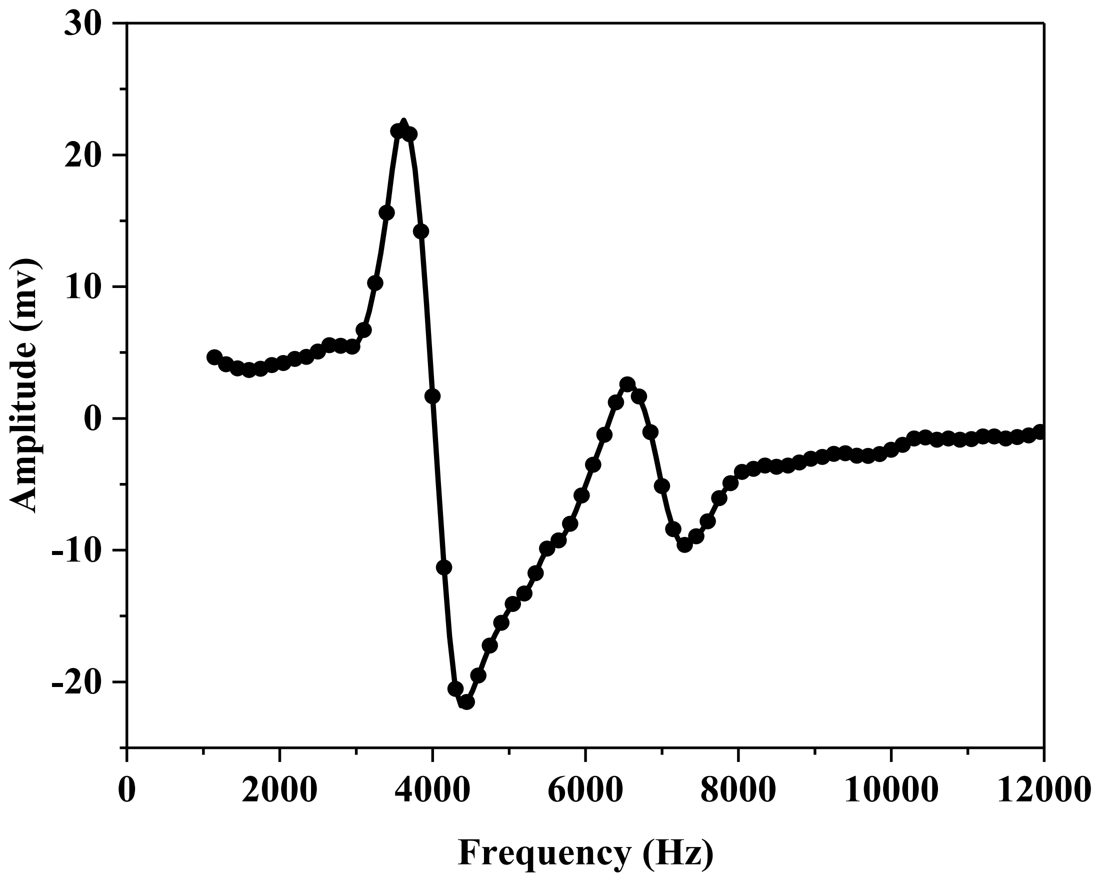

Figure 2. Quantum Sensor Resonance signal

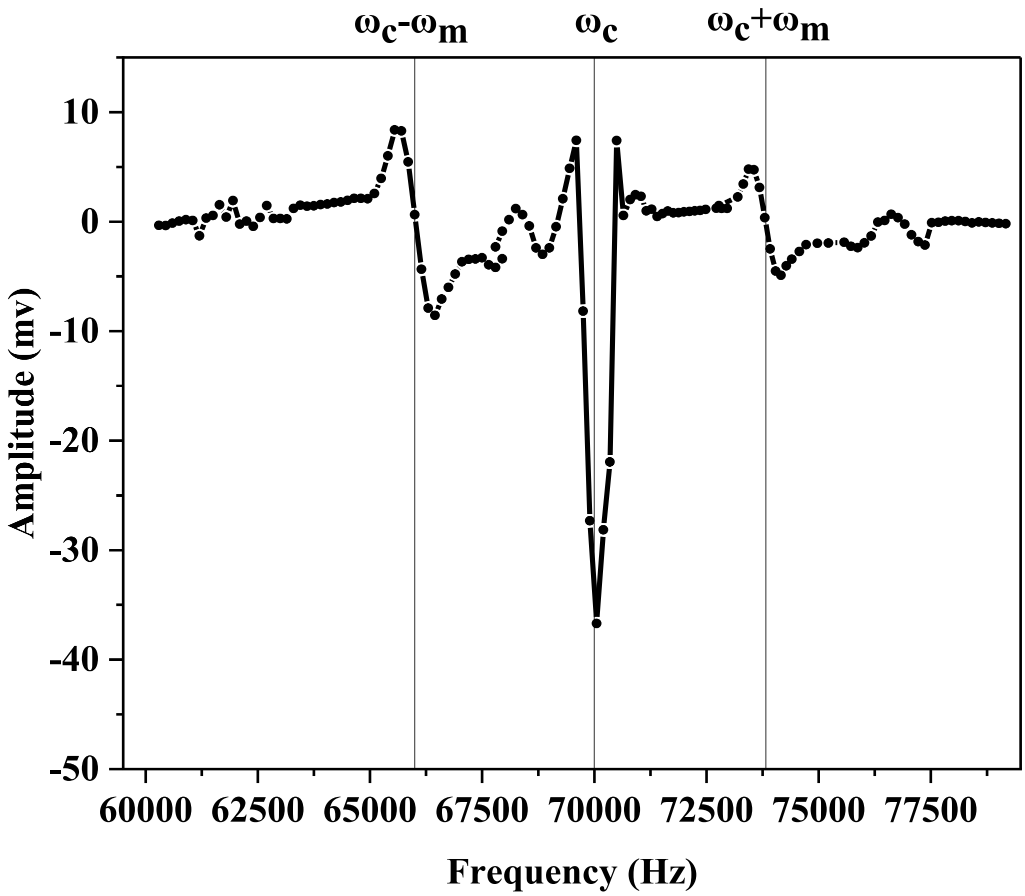

Figure 3. Main Band and Two Sidebands in Dual Modulation

This feature is the main advantage of dual modulation for designing a magnetic field sensing experiment. Specifically, dual modulation enables magnetic field sensing at a much higher frequency than the single-light modulation frequency, which corresponds to the rubidium resonance frequency. Considering the frequency behavior of noise in a measurement, such as the well-known 1/f noise arising from the intrinsic nature of electronic components, the advantage of dual modulation becomes clearer. From the 1/f relationship, it is evident that electronic instruments exhibit less noise at higher operational frequencies. Therefore, dual modulation enables the measurement frequency to be shifted to much higher frequencies, reducing noise while avoiding limitations such as the inadequate response of instruments like lock-in amplifiers at frequencies of a few hundred hertz. However, one of the main drawbacks of dual modulation is the reduction in signal amplitude, as evidenced by comparing the detected voltage levels in Figures 2 and 3. This issue can be addressed by employing amplifiers to enhance the detected signal back to a higher level. The noise spectral density of the quantum magnetometer was evaluated under two operating conditions using both unmodulated and modulated laser light by recording signals at the resonance center. Voltage power spectra were obtained through fast Fourier transformation (FFT), and the corresponding magnetic field noise spectra were derived using dispersion-slope frequency calibration, as illustrated in Figure 4 and Figure 5 [14, 15]. The results clearly show that when the system operates with modulated laser light, the quantum sensor achieves a sensitivity of approximately 1.7pT/√Hz across the analyzed frequency range. This represents a substantial improvement over the unmodulated configuration, which exhibits a sensitivity of about 500pT/√Hz. The obtained sensitivity value reflects the smallest magnetic field noise level detectable by the magnetometer, per the square root of the measurement bandwidth (Hz).

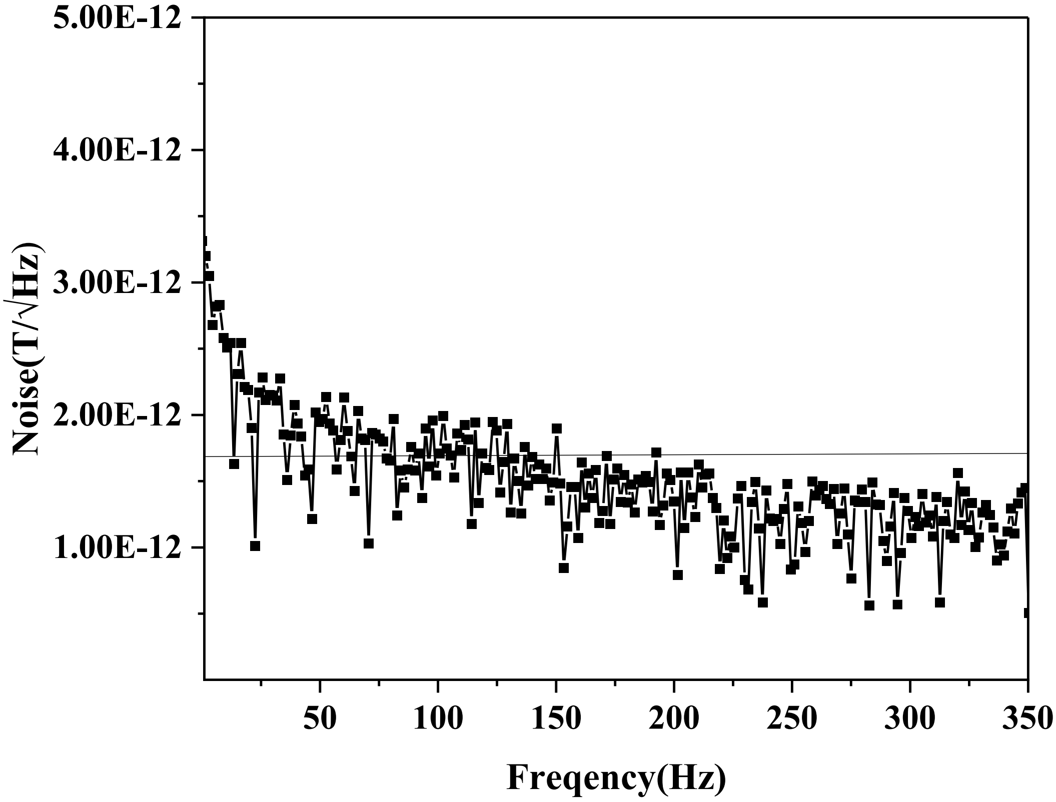

Figure 4. the noise spectral density of the quantum sensor by using modulated laser light

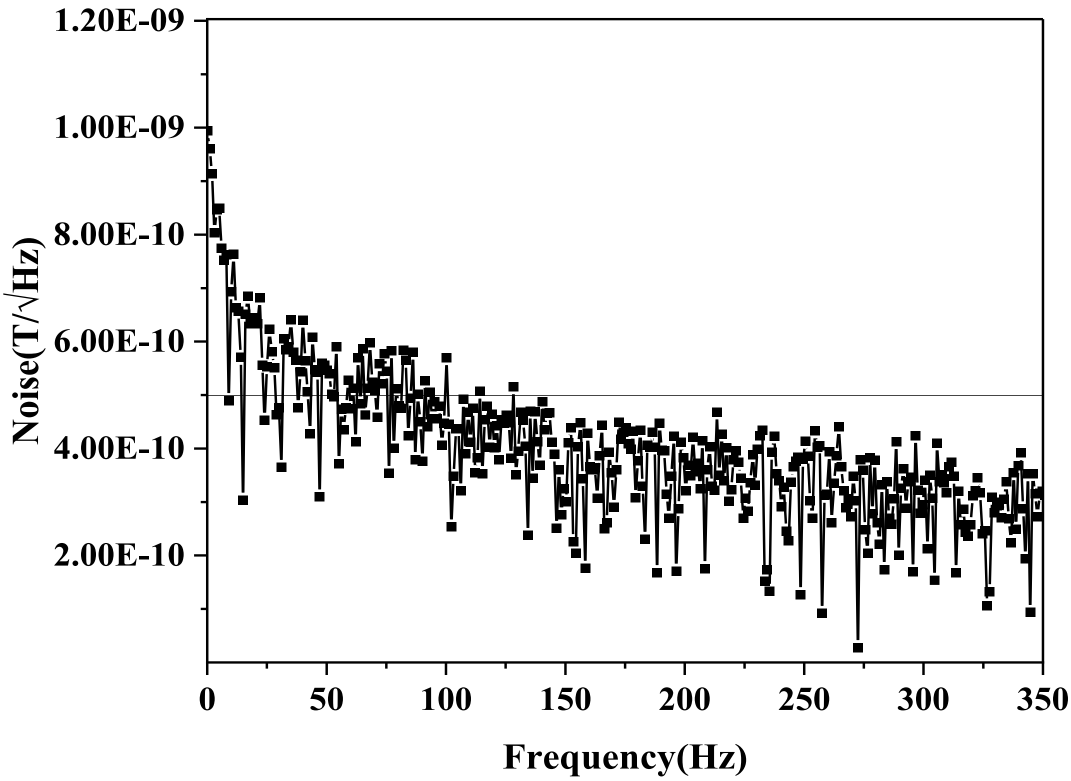

Figure 5. the noise spectral density of the unmodulated laser light quantum sensor

5. Conclusion

In this study, we investigated the impact of dual modulation on the performance of an Mx atomic magnetometer based on rubidium vapor. By simultaneously modulating the optical field and the magnetic resonance, optical sidebands were generated that effectively transferred the magnetic resonance signal from low-frequency regions to higher frequencies. This frequency translation plays a crucial role in suppressing dominant low-frequency noise, particularly 1/f noise, which is a primary limitation in weak magnetic field measurements. As a result, a significant enhancement in sensitivity was achieved. Experimental results demonstrated that the sensitivity improved from approximately 500 pT/√Hz in the unmodulated (conventional) regime to about 1.7 pT/√Hz under dual modulation conditions, corresponding to nearly two orders of magnitude reduction in noise. An important advantage of this approach is that the sensitivity enhancement is achieved without requiring changes to the ambient magnetic field or the fundamental operating conditions of the sensor. This makes the method highly suitable for practical implementations, especially in unshielded environments where low-frequency noise is unavoidable. Furthermore, shifting the detection frequency to higher values improves compatibility with electronic detection systems, such as lock-in amplifiers, which typically exhibit better performance at higher frequencies. In summary, dual modulation provides an efficient and practical approach for improving the sensitivity of atomic magnetometers. Its straightforward implementation, combined with its strong noise suppression capability, makes it a promising solution for a wide range of applications, including biomagnetic measurements, geophysical sensing, and quantum sensing technologies.

Additional Consideration

In this study, the light was modulated using an electro-optic modulator at a frequency much higher than the natural magnetic resonance frequency of rubidium. While this strategy enables shifting the measurement to a higher operational frequency to reduce noise, it also diminishes the influence of the modulated light on the rubidium atoms compared to unmodulated illumination.
Had the modulation frequency of the light been similar to the intrinsic resonance frequency of rubidium, a fundamental alteration in the atomic resonance behavior would be expected, leading to a substantially different experimental response.

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