Ultra-narrow parametric magnetic resonances in a miniature vapor cell

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Multi-photon parametric magnetic resonance in a miniature vapor cell is demonstrated. Much more multi-photon magnetic resonance can be observed when the radio frequency field becomes stronger. The linewidth of the \(n\) photons magnetic resonance equals that of the first-order resonance divided by \(n\), which means that the uncertainty of the magnetic sublevel is reduced by the factor \(n\). The signal-to-noise ratio can be improved when the low-frequency multi-photon resonance takes place, which finds a possible application in precision magnetic field measurement.

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The linewidth is a very important parameter in the field of precision measurement that directly affects the sensitivity or the accuracy of a frequency standard and sensor device. In recent years, much effort has been devoted to developing narrow resonances in atomic clocks, cold atoms, and atomic gyroscopes, and reducing the resonance frequency shift due to effects such as atomic collisions and optical ac-Stark effect at the same time. While the accuracy is the key target for frequency standards and rotation measurements, the sensitivity is much more important for the magnetic field measurement. Then the schemes for narrowing the linewidth are the most studied in atomic magnetometers that measure the magnitude of the magnetic field by measuring Zeeman frequency shifts.

The relaxation time of the Zeeman sublevels is directly related to the linewidth. Filling the buffer gas and wall coating in the cells are two methods to suppress the relaxation processing due to collisions. The spin-exchange relaxation-free magnetometer has very narrow linewidth with a high-pressure buffer gas in a low field strength. A nonlinear magneto-optical rotation magnetometer can obtain a subhertz linewidth by utilizing nonlinear magneto-optical effects and wall coatings. A coherent population trapping magnetometer narrows the linewidth with quantum coherence.

In another viewpoint, no matter what method is used, the only purpose is to suppress the uncertainty of the Zeeman sublevels, i.e., the linewidth. Another way to obtain narrow resonances is keeping the uncertainty fixed, and causing transitions involving multi-photons to take place. The uncertainty of each photon is much less than that of the Zeeman sublevels. Multi-photons then will share the uncertainty of the transition. Let us express this uncertainty in frequency and call it \(\Delta \nu\). A one-photon transition coupling the two states will then have a minimal width of \(2\Delta \nu\). To add the energy of \(n\) photons to drive the transition, one has to change the energy of each photon by \(2\Delta \nu/n\), hence reducing the linewidth. For a compact atomic magnetometer, the small size usually means a limited relaxation time. The multi-photon transition is a physical way to reduce the influence of atomic spin noise. Although the linewidth of the magnetic resonance spectroscopic in frequency becomes narrow, the effective linewidth in magnetic units does not change. The expression of the sensitivity is

\[
\delta B = \frac{\Delta B}{\text{SNR}},
\]

where \(\Delta B\) is the linewidth, and SNR is the signal-to-noise ratio. In the case of multi-photon transition, the resonance is excited by a lower-frequency electromagnetic field. The noise of the circuit could be smaller, and the SNR is then improved. For example, the strength of Earth’s magnetic field is about 0.2–0.7 Gauss, and the corresponding Larmor frequency is 140–490 kHz for rubidium 87 atoms. The frequency ranges of the excited field are 140–490 kHz for single-photon transitions and 14–49 kHz for ten-photon transitions. The voltage-controlled oscillator (VCO) circuits will operate at a much lower frequency. In a typical parametric resonance, the output frequency range of the VCO should be 140–490 kHz for the geomagnetic field. But in a multi-photon resonance, the range is 14–49 kHz for the ten-photon transitions, which is one-tenth of that in a typical parametric resonance. It is obvious that the frequency noise of a VCO with a frequency range of 14–49 kHz is less than that of a VCO with a frequency range of 140–490 kHz. For a narrower modification range, the VCO is less sensitive to the noise of the controlling voltage. Then when we use multi-photon resonance instead of typical one photon...
resonance, the frequency modulation to amplitude noise is then reduced. So the multi-photon magnetic resonance could be candidate for sensitive atomic magnetometer.

In the present work, we study multi-photon parametric magnetic resonance in a miniature vapor cell. Comparing to a micro fabricated vapor cell with micro-electromechanical systems (MEMS) technology\textsuperscript{2,3,15}, our miniature vapor cell has some advantages: 1. the cell is a $5 \text{ mm} \times 5 \text{ mm} \times 5 \text{ mm}$ cube that is produced with six pieces of glass bonded with optical adhesive, so no expensive and complicate instrument is needed; 2. the interaction zone is much larger, and a high SNR can be obtained; 3. antirelaxation coating with mature technology can be used for improving the sensitivity. For achieving a higher sensitivity, we apply a strong radio frequency (RF) field to a parametric magnetic resonance experiment, and then the multi-photon transition that has been extensively studied in the 1960’s takes place\textsuperscript{16}.

The experiment is implemented with a cubic vapor cell filled with rubidium 87 atoms and 10 Torr Neon gas as a buffer gas. The temperature of the cell is stabilized at 40$^\circ$C. As shown in Fig. 1, the cell is placed in a four-layer magnetic shield. A static magnetic field $B_0$ produced by a solenoid and an RF field produced by a pair of Helmholtz coils are along the same direction as the 795 nm light that is emitted by a single-mode vertical-cavity surface-emitting laser (VCSEL). This configuration is a typical parametric magnetic resonance experiment scheme. The RF field is derived from a VCO whose frequency is monitored by a frequency counter (not drawn), and the frequency is modulated by a direct digital synthesizer (DDS). The circularly polarized laser passes through the cell and is detected by a commercial large-area balanced New Focus 2307 photodetector. The signal is then demodulated by a DSP 7280 lock-in amplifier, and the reference signal is from the DDS. Lastly, the demodulated signal is sent to a Tektronix TDS2024C oscilloscope and recorded with its OpenChoice software.

The laser is coupled to the D1 transition $F = 2 \to F' = 2$, and its power is 50 $\mu$W with beam diameter 3 mm. The static magnetic field is 10000 nT, so the corresponding Larmor frequency is 70 kHz. When the amplitude of the RF field is below 2500 nT, a single magnetic resonance peak is observed at 70 kHz, as shown in Fig. 2, and the line width is about 1.4 kHz.

When the amplitude of the RF field is tuned to 5000 nT, several resonance peaks are observed. As shown in Fig. 3, the amplitude of the peaks reduces with resonance frequency, and it can be found that the frequencies obey the relation $\nu = \Delta \nu_1 / n$ and the line widths obey the relation $\Delta \nu = \Delta \nu_1 / n$. The linewidth of the single-photon transition is broadened to 2.3 kHz due to a strong RF field. The number of the multi-photon transitions will increase if the RF field becomes stronger. The weak peaks between multi-photon transition peaks are multi-photon transitions between states whose quantum numbers differ by $\Delta m = 2$. This phenomenon takes place when the nonlinear Zeeman shift is significant, which has been studied in

![Fig. 1. Experiment setup scheme is shown. $\lambda/4$: quarter-wave plate; PC: personal computer.](image)

![Fig. 2. Parametric magnetic resonance signal with a low RF field.](image)

![Fig. 3. Multi-photon parametric magnetic transitions. $n$ is the number of photons involved in transitions.](image)
detail. So, in the experiment, we have observed two type multi-photon transitions at the same time.

These transitions are demonstrated in Fig. 4. The main resonances in Fig. 3 are $\Delta m = 1$ transitions involving absorption of $1, 2, 3, 4, \ldots, n$ photons if the RF field is strong enough. The uncertainty of the Zeeman levels is shared by the photons, and the linewidth is then reduced by $n$.

To certify the linewidth relation, we select five or more photons transitions, as shown in Fig. 5, to compare. The linewidth of the 5-photon transition is 400 Hz, which is a bit smaller than $\Delta \nu_1/5$. It is obvious that the linewidth in magnetic units is not improved. However, the noise in the circuit at 14 kHz could be lower than that at 70 kHz, especially in the situation of a high sample rate. With the different voltage sensitivity of the VCO and other optimized parameters, the noise of the 5-photon transition is about 4 mV and that of the one-photon transition is about 25 mV. The signal of the 5-photon transition is 1.7 V and that of the one-photon transition is 10 V. Then the SNRs are 425 for the 5-photon transition and 400 for the one-photon transition. So multi-photon parametric magnetic resonance is suitable for sensitive atomic magnetometers.

In conclusion, we observe multi-photon parametric magnetic resonance in a miniature rubidium vapor cell and find that high-SNR signals can be obtained without high temperatures. We study the spectroscopic properties and find that the linewidth can be significantly reduced. At the same time, the SNR can be improved when low-frequency multi-photon resonance takes place, which finds a possible application in precision magnetic field measurement.

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References