Evanescent wave magnetometer

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The authors describe an atomic magnetometer, the evanescent wave magnetometer, which uses an evanescent wave to measure the Larmor frequency of Rb atoms near the cell surface. The submicron penetration depth of the probe beam allows the evanescent wave magnetometer to achieve a spatial resolution of several tens of microns or better, and greatly reduces the inhomogeneous broadening due to magnetic field inhomogeneities. Its noise density in the present experiment is $\sim 100 \text{pT/Hz}$ for frequencies between 1 and 10 mHz, and decreases to less than $10 \text{pT/Hz}$ as the frequency increases to 25 Hz. © 2006 American Institute of Physics. [DOI: 10.1063/1.2424657]

Atomic magnetometers determine the magnetic field by measuring the energy separation between the Zeeman levels (Larmor frequency) of the ground state alkali metal atoms. They have recently attracted much interest due to their potential of achieving ultrahigh sensitivity, surpassing that of the superconductor quantum interference devices long considered to be the most sensitive magnetometer. Also of great current interest is the miniaturization of atomic magnetometers, e.g., the development of the chip-scale atomic magnetometer, which has a measurement volume of alkali metal vapor of $1 \times 10^{-3} \text{cm}^3$, a few orders of magnitude smaller than conventional atomic magnetometers, and a sensitivity of $5 \text{pT/Hz}$ between 1 and 100 Hz.

Evanescent wave has been studied for a long time and has been used in many studies of atom-surface interactions. Magnetic resonances probed by evanescent wave have been used to study the depolarizing properties of surfaces. The purpose of the present work is to explore the usefulness of evanescent wave in developing ultrasmall atomic magnetometers. We demonstrate the operation of an atomic magnetometer, which we shall refer to as the evanescent wave magnetometer. It uses an evanescent wave to measure the Larmor frequency of Rb atoms within a distance $\sim 10^{-4} \text{cm}$ from the cell surface, and therefore has a very small measurement volume of alkali metal vapor, which in our experiment is $\sim 1 \times 10^{-6} \text{cm}^3$. Thanks to the small penetration depth of the evanescent wave, the evanescent wave magnetometer can achieve a spatial resolution of a few tens of microns or better, comparable to that of the sensor based on Bose-Einstein condensates.

In the following we will describe the operation of the evanescent wave magnetometer in the locked oscillator mode. The cylindrical Pyrex glass cells of diameter 2.5 cm and various thickness contain isotopically enriched Rb (98.3 at. % $^{87}\text{Rb}$) and $\text{N}_2$ gas of various densities. To achieve high polarization at submicron distance from the cell surface, it is crucial to use cells coated with antirelaxation coatings. The experimental setup is shown in Fig. 1. The cell is mounted inside an aluminum box, which is surrounded by an outer box made of thermal insulation material. Hot air flows in the space between the two boxes and heats the inner box and the cell. Zeeman polarization near the cell surface is produced by two right circularly polarized ($\sigma^+$) laser beams, A and B, from single-mode diode lasers operated in the free-running mode. The linewidth of the lasers is 45 MHz. The $1/e^2$ diameters of beam A and beam B are respectively 0.8 and 2.0 mm. The frequency of beam A is tuned to the transitions $5^2 S_{1/2} F=2 \rightarrow 5^2 P_{1/2} F'=1,2$, and that of beam B to the transitions $5^2 S_{1/2} F=1 \rightarrow 5^2 P_{1/2} F'=1,2$. The two excited levels $5^2 P_{1/2} F'=1,2$ are not completely resolved due to Doppler and collisional broadenings. The two beams are incident on the cell surface at the same spot and at angles larger than the critical angle $\bar{\theta}_c = \sin^{-1}(1/n_1)$, where $n_1$ is the index of reflection of the glass. They undergo total internal reflection at the interface between the cell surface and Rb vapor. Beam A and beam B have slightly different incidence angles and their penetration depths are respectively 0.7 and 2.5 $\mu\text{m}$, so that they are spatially separated outside the cell. Both beams being in the same plan of incidence, their evanescent waves propagate in the same direction ($x$ axis). The $z$ axis is normal to the cell surface, pointing into the Rb vapor. A constant magnetic field along the $x$ axis is produced by three pairs of orthogonal

![Evanescent wave magnetometer](image-url)
sensitivity is $\frac{1}{H_{11003}}$. The rf field amplitude is 3 mG. The powers of beam A and beam B are respectively 20 $\mu$W and 2.7 mW. Unless stated otherwise, all the data presented in this letter were taken with a lock-in time constant of 100 ms and a low pass filter roll off of 24 dB/octave.

Helmholtz coils. A pair of radio frequency (rf) coils inside the inner box is used to generate a radio frequency field along the $y$ axis. To use phase-sensitive detection method, the rf field is amplitude modulated by a square wave at 400 Hz. The intensity of the totally reflected beam A, which also serves as a probe beam, is monitored by a silicon photodiode, the output of which is fed into a lock-in amplifier. When the radio frequency matches the Larmor frequency of $^{87}$Rb atoms, the longitudinal Zeeman polarization along the $x$ axis is diminished, causing a decrease in the intensity of the reflected beam A. We scan the radio frequency across the Larmor frequencies of $^{87}$Rb atoms. The output of the lock-in amplifier yields a resonance curve, from which the magnetic field is determined.

Shown in Fig. 2 is a representative rf resonance curve. The linewidth is mainly due to spin exchange collisions. The rf power broadening is 0.14 kHz. Similar magnetic resonance curves were taken in five cells filled with 0.006 amagat N$_2$ gas, and at a temperature of 115 °C. The rf field inhomogeneities in the direction normal to the propagation direction of the evanescent wave makes the evanescent wave magnetometer less susceptible to field inhomogeneities in the direction normal to the propagation direction of the evanescent wave than conventional atomic magnetometers. Shown in Fig. 4 is a representative rf resonance curve for the evanescent wave magnetometer in an inhomogeneous magnetic field. The field at the cell is about 0.3 G and along the $x$ axis. The field gradient is 0.57 G/cm, pointing in the positive $x$ axis. The rf resonance curve for a conventional atomic magnetometer with a cell size of $\sim 1$ mm in such a field would have an inhomogeneous broadening of a half-width at half maximum (HWHM) of about 20 kHz, and the resonance curve would be symmetric. It is interesting to note that the rf resonance curve for the evanescent wave magnetometer is asymmetric (Fig. 4). The low frequency side is Lorentzian with a HWHM of 2.9 kHz. This asymmetry is not due to overlapping of multiple Zeeman resonances, because the separation between adjacent Zeeman resonances is insignificant according to the Breit-Rabi formula. It is due to the diffusion of Rb atoms into the measurement volume from outside, and occurs when $(\omega L/D)^{1/2}L = 1$, where $\omega = 2\pi \gamma dB/dz$ is the Larmor frequency gradient, $D$ the diffusion coefficient, and $L$ the cell thickness. The basic physical picture is the following. Due to diffusion of polarized Rb atoms, the Zeeman polarization, produced by the evanescent waves in a thin (micrometer) layer next to the surface, can extend well beyond the pumped region. Now consider a small volume $\Delta V$ of Rb vapor outside the measurement volume. The Larmor frequency of the Rb atoms in $\Delta V$ depends on the position of $\Delta V$. When the rf coincides with this Larmor frequency, the Zeeman polarization in $\Delta V$ oscillates at the modulation frequency of the rf field, and, as a result of diffusion, modulates the Zeeman polarization in the measurement volume at the same frequency, yielding a signal. Because the field gradient points into the cell, the inhomogeneous broadening due to diffusion is on the high frequency side of the rf resonance curve. A quantitative study of this asymmetric line shape will be reported elsewhere.

The spatial resolution $\delta z$ of a magnetometer is defined as the half-width in the coordinate space of the response curve of the magnetometer, i.e., signal decreases by a factor of 2.
when the position of the magnetometer is changed by a distance $\delta z$. For the evanescent wave magnetometer, the half-width $\Delta \omega_{1/2}$ of the Lorentzian side of the rf response curve is used in determining the spatial resolution. For the data in Fig. 4, the Larmor frequency gradient $\omega' / 2 \pi = 400$ kHz/cm, and therefore the half-width of 2.9 kHz corresponds to a $\delta z$ of 73 $\mu$m. The half-width $\Delta \omega_{1/2}$ is given by $\Delta \omega_{1/2} = \Gamma_{1/2} + C(\omega'^2 D)^{1/3}$, where $\Gamma_{1/2}$ is the half-width in the homogeneous field, and the second term is the additional broadening due to inhomogeneous field, $C$ being a constant that depends on the surface interactions of Rb atoms and is approximately equal to 0.5 in our experiment. For large field gradient, the inhomogeneous broadening dominates, and the half-width is proportional to $\omega'^2$. This is in contrast with the conventional atomic magnetometer, the half-width of which for large field gradient is linearly proportional to $\omega'$. The two-thirds power dependence of the half-width on $\omega'$ has an interesting consequence. It leads to a spatial resolution of $\delta z = C(D / \omega')^{1/3}$, which improves with increasing field gradient. This is due to the fact that as the field gradient increases, the mode corresponding to the lowest eigenvalue becomes more and more concentrated near the surface. It is also interest-

ing to note that the spatial resolution of the evanescent wave magnetometer, being proportional to the cubic root of $D$, can be improved by increasing buffer gas pressure.

Evanescent wave magnetometer can be operated in the free precession mode to eliminate rf power broadening. Due to the unique property of evanescent wave, i.e., its propagation direction being parallel to the cell surface, the evanescent wave magnetometer can naturally accommodate two orthogonal beams that cross in the cell, which is needed in the free precession mode and could be challenging to implement in a miniature wafer-level fabricated conventional atomic magnetometer.

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11. For experimental convenience we used circularly polarized incident beams. The evanescent waves are therefore elliptically polarized [see, for example, Max Born and Emil Wolf, Principles of Optics, 6th ed. (Pergamon, New York, 1980), pp. 47-51]. For example, the projection of the end point of the electric vector of the probe beam on the $yz$ plane is an ellipse, which is characterized by a point on the Poincaré sphere that has a latitude of 68° and a longitude of 153°.