


Field-Polarization Sensitivity in rf Atomic Magnetometers

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We demonstrate the sensitivity of a sensor based on an optically pumped radio-frequency (rf) atomic magnetometer to the polarization state of the detected rf magnetic field and measure > 36 dB difference in amplitude sensitivity for opposite circular-field polarizations. This sensitivity could be used to create sensors that would allow signal detection while suppressing unwanted rf fields using polarization rejection, in contrast to traditional gradiometry configurations. Additionally, such a sensor will be orientation-sensitive, as the phase of the detected signal is shown to depend on the angle between the sensor's detection axis and the direction to the transmitter.

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I. INTRODUCTION

Optically pumped atomic magnetometers (OPMs) reach impressive sensitivities at subfemtotesla levels when measuring dc [1] or radio-frequency (rf) [2] magnetic fields and compete with state-of-the-art detectors based on superconducting quantum-interference devices (SQUIDs) [3]. These devices are typically used in heavily shielded environments—for example, in multilayer magnetically shielded rooms—or rely on active coils for ambient-noise suppression. In an unshielded environment, the performance of the OPMs operating in the dc regime is degraded by several orders of magnitude due to the ambient magnetic-field noise [4]. Such situations can be remedied to some extent by averaging or by the use of gradiometry techniques [5]. The situation is better for the case of rf atomic magnetometers because the ambient noise, caused by geomagnetic, atmospheric, or urban activities, is outside the bandwidth of interest [6]. Nevertheless, noise-suppression techniques are still required [2,7].

The ultimate intrinsic sensitivity of the state-of-the-art magnetic-field sensors in the presence of noise can be reached using two or more OPMs or OPM channels. The noise-suppression techniques rely on the different distance to the signal and noise sources compared to the gradiometer baseline (the distance between the sensors). Early examples of distant source detection include magnetic-anomaly detection and exploration of the Earth's magnetic field [5], as well as magnetic fields in space [8], while detection of local signal sources includes measurements of faint biomagnetic signals [9].

In this work, we develop a two-channel optically pumped atomic rf magnetometer capable of detecting

low-frequency (below 1 MHz) magnetic-field signals. The quantum properties of the rf magnetometer are explored to construct balanced detection schemes for the measurement or suppression of unwanted linearly polarized rf signals (noise). The schemes do not rely on gradiometer methods and are expected to be largely immune to the relative distance between the signal and noise sources. The proposed schemes rely on the quantum-mechanical laws of conservation of angular momentum. They exploit the sensitivity of an rf atomic magnetometer to the polarization state of an rf magnetic signal [10,11] in a way that is demonstrated theoretically and experimentally in this work, achieving > 36 dB rejection of the unwanted circular polarization of the rf field.

Preferential circular polarization detection is widely used in applications such as interference-effects mitigation in microwave transmission [12] and improvement of the detection sensitivity in MRI systems [13,14]. The measured rf magnetometer sensitivity to the polarization of the detected rf signal can be evaluated in terms of the axial ratio characterizing circularly polarized antennas. The difference in the sensitivity to rf fields with opposite circular polarization corresponds to an axial ratio of 0.14 dB in the limited magnetometer bandwidth of approximately 1 kHz. Direct comparison of the rf magnetometer with other types of circularly polarized antennas is beyond the scope of this work.

A quantum sensor that includes suppression of linearly polarized noise, based on the results of this work, is proposed. This work mainly focuses on the application of the sensor for communication using artificial low-frequency magnetic signals in the presence of strong absorption [15] and ambient (geomagnetic, atmospheric, urban) magnetic-field noise that exhibits some degree of linear polarization, but it might be possible to use some of the results for

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different applications such as low-field NMR spectroscopy [2,16] and magnetic-induction imaging [17].

II. THE TWO-CHANNEL RF MAGNETOMETER

To study the sensitivity of the rf magnetometer to the polarization of the low-frequency magnetic fields, a two-channel rf magnetometer with an active volume of 27 mm^3 is constructed. Figure 1(a) shows the optical-cell assembly of the rf magnetometer. The cubic ($3 \times 3 \times 3 \text{ mm}^3$ internal volume) Pyrex vapor cell (Triad Technology, Inc. [18]) contains enriched ^{87}Rb and 500 Torr nitrogen as a buffer gas. The thickness of the cell's optical-quality windows is 0.5 mm. Two $\lambda/4$ wave plates ($2 \times 2 \times 0.2 \text{ mm}^3$) are epoxied side by side on the front window (in the x - y plane) of the cell. The slow axes of the wave plates are orthogonal and at $\pm 45^\circ$ with respect to the y axis.

A linearly polarized 4 mm diameter pump laser beam at $\lambda = 794.99(1) \text{ nm}$ (on resonance with the $6s \ ^2S_{1/2} \rightarrow 6p \ ^2P_{1/2}$ pressure-shifted D_1 atomic transition) propagating along the z axis passes through the wave plates, creating two separate sections of the cell with pump light of opposite circular polarizations. The reduced ^{87}Rb diffusion

due to the buffer gas spatially separates the atoms pumped with light of the opposite circular polarization.

A linearly polarized probe beam at $\lambda = 780.12(1) \text{ nm}$ (blue-detuned from the $6s \ ^2S_{1/2} \rightarrow 6p \ ^2P_{3/2}$ pressure-shifted D_2 atomic transition by $>50 \text{ GHz}$) propagates through the cell along the negative x axis. The incoming probe beam initially propagates along the z axis and is directed in the vapor cell with an aluminum-coated 3 mm prism [see Fig. 1(b)]. After the cell, a second identical prism sends the probe beam in the negative z direction through a polarimeter for balanced detection. The linear polarization of the probe beam experiences optical rotation in the presence of an atomic polarization precessing in the polarization plane of the probe beam [19].

The optical-cell assembly shown in Fig. 1(b) is mounted in a 50-mm-long, 26-mm-diameter cylindrical oven made of machineable glass ceramic. The oven accommodates the optical-cell assembly and provides optical access for the pump and probe beams. It also allows the cell to be heated to approximately 100°C using a nonmagnetic resistive heater driven by a dc current. The oven is mounted in the center of a 3D-printed coil assembly that is used to generate the static bias magnetic field B_0 parallel to the z axis and the two mutually orthogonal linearly polarized rf magnetic fields $B_{\text{rf}}^x(t)$ and $B_{\text{rf}}^y(t)$ that are perpendicular to the bias-field direction. The 3D coil assembly is housed in a three-layer magnetic-shield chamber.

The bias field B_0 is created by a pair of $100 \times 100 \text{ mm}$ square coils in Helmholtz configuration by passing approximately 40 mA of low-noise dc current through them in series. The rf magnetic fields $B_{\text{rf}}^x(t)$ and $B_{\text{rf}}^y(t)$ are created by two rf coil pairs identical to the bias-field coil pair. The current used to drive the rf magnetic fields is generated by an ac voltage applied across a $200 \text{ k}\Omega$ resistor connected in series with the pair of rf-field coils. The voltage is generated by a two-channel function generator that allows precise phase control of the $B_{\text{rf}}^x(t)$ and $B_{\text{rf}}^y(t)$ signals.

III. THE MAGNETOMETER RESPONSE AS A FUNCTION OF THE BIAS MAGNETIC FIELD

In this section, we present results demonstrating the rf magnetometer tunability and noise floor. The measurements are performed before the quarter-wave plates are installed. A broad circularly polarized pump beam is used, optically pumping the entire cell active volume of 27 mm^3 . The magnetometer bias field B_0 is chosen to correspond to three discrete Larmor precession frequencies (3, 20, and 50 kHz, corresponding to B_0 values of 0.42, 2.85, and $7.14 \mu\text{T}$). For each of the three values of the bias field B_0 , a magnetic signal $B_{\text{rf}}^x(t)$ is applied at a specific frequency and a spectrum analyzer is used to measure the response of the balanced polarimeter. The frequency of the $B_{\text{rf}}^x(t)$ signal is changed in 1 kHz steps. The measurement results are shown in Fig. 2. The rf magnetometer

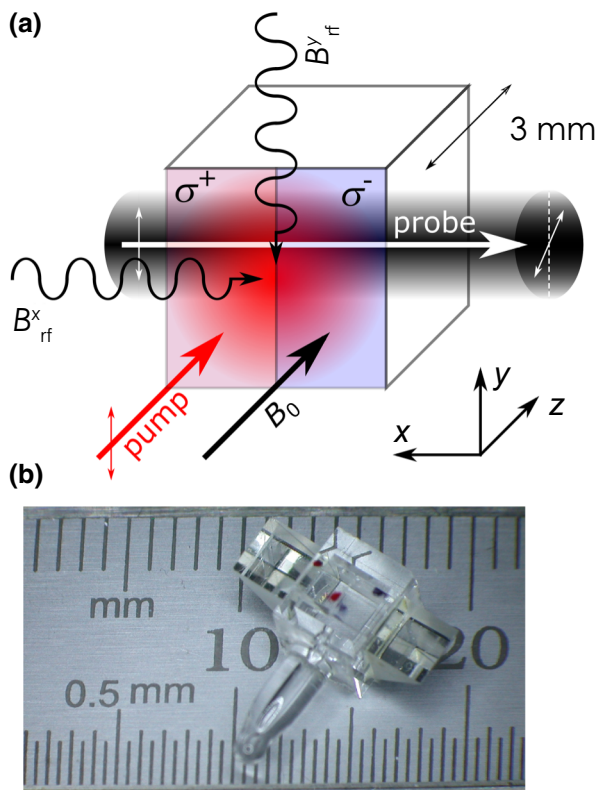


FIG. 1. (a) A diagram of the two-channel optically pumped rf magnetometer. (b) A photograph of the actual optical-cell assembly. The two right-angle prisms [not shown in (a)] steer the probe-beam direction before and after it passes the vapor cell to be parallel to the pump beam for convenience.

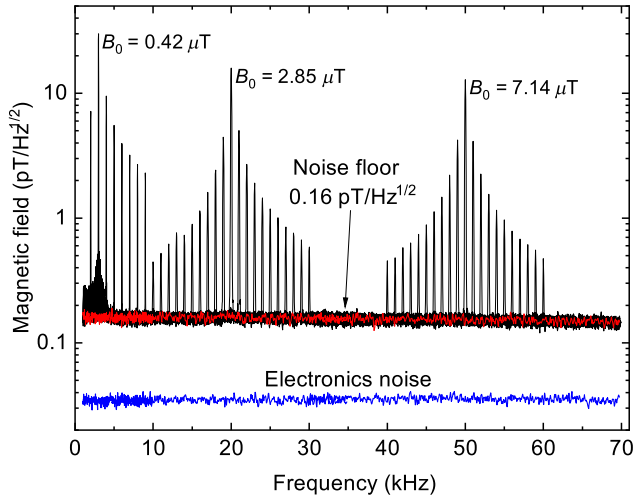


FIG. 2. Tuning of the rf magnetometer with the value of the bias field B_0 . The black traces are spectrum-analyzer data with an applied rf magnetic signal of a different frequency. The red curve (overlapping with the spectrum-analyzer data away from the rf signal) shows the noise of the probe light in the absence of pump laser light. The blue trace shows the residual polarimeter electronics noise in the absence of light. The discrete signal peaks are separated by 1 kHz, the steps of the $B_{\text{rf}}^x(t)$ signal.

has a full width at half maximum bandwidth of 1.45 kHz and a noise floor of $160 \text{ fT/Hz}^{1/2}$, limited by the probe-light noise. The polarimeter-detection-electronics noise (when the probe light is blocked) is measured to be below $40 \text{ fT/Hz}^{1/2}$.

IV. THE POLARIZATION STATE OF THE RF MAGNETIC-FIELD SIGNAL—THE BLOCH VECTOR PICTURE

We first analyze the response of an rf magnetometer to a resonant rf magnetic-field signal of different polarization. We consider the orientation of the bias field B_0 that determines the magnetometer's frequency response, the direction of the circular polarization of the pump laser light, and the state of polarization of the rf magnetic field (linear or circular). In our two-channel rf magnetometer, we can implement all of the possible configurations that are shown in Fig. 3.

The rf magnetometer's principle of operation can be intuitively described by considering the atomic polarization as a vector obeying the Bloch equations of motion. First, consider a coordinate system with a quantization axis along the z axis and use the rotating-wave approximation to transform into a system rotating with the Larmor precession frequency (determined by the value and the direction of B_0 as well as the atomic gyromagnetic ratio) in the corresponding Larmor precession direction [20].

Next, assume that a σ^+ circularly polarized laser beam creates an atomic polarization in the stretched atomic state

$m_F = F$ that is aligned along the z axis, where F is the total angular momentum of the quantum system and m_F is its projection along the quantization axis. A resonant rotating magnetic rf field B_{rf} with a frequency equal to the Larmor precession frequency will be stationary in the coordinate system rotating in the direction of the Larmor precession and will tilt the atomic polarization away from the quantization axis, creating an atomic-polarization component in the plane orthogonal to the quantization axis (the x - y plane). This atomic polarization will start precessing around the quantization axis. The same mechanism for driving the spin precession by an rf magnetic field is used in the classical optically pumped M_x magnetometer [21]. In our example [see Fig. 3(a)], the instantaneous atomic polarization in the laboratory frame is shown in the x direction with an arrow. In the stationary coordinate system, the atomic-polarization component will precess at the Larmor frequency in the x - y plane in a counterclockwise direction. A linearly polarized probe beam propagating in the same plane will experience a corresponding polarization rotation modulated at the Larmor frequency that can be detected with a polarimeter.

If the direction of the bias magnetic field B_0 is reversed [see Fig. 3(b)], the direction of the Larmor precession reverses. In a coordinate system rotating in the direction of the Larmor precession, the rotating rf magnetic field \vec{B}_{rf} will no longer be stationary in the rotating frame and will not cause a resonant tilt of the atomic polarization away from the quantization axis. The atomic-polarization component in the x - y plane will be negligible compared to the case of an oppositely oriented bias field B_0 and no signal will be detected by the polarimeter. This situation can also be understood from the point of view of conservation of angular momentum. The atoms are prepared in a stretched state with a maximum value of the projection quantum number $m_F = F$ and are not allowed to absorb a photon from the circularly polarized rf magnetic field that would increase the value of m_F .

For a linearly polarized rf magnetic field B_{rf} , the situation is different [see Figs. 3(c) and 3(d)]. The linear-field polarization can be decomposed into two in-phase circularly polarized field components rotating in opposite directions. For both possible orientations of the bias field B_0 , there will be an rf magnetic-field component that is stationary in the coordinate system rotating in the direction of the Larmor precession and corresponding polarimeter signals. In both cases, a photon belonging to the corresponding circularly polarized rf field would lead to an allowed decrease of the value of m_F and the corresponding signals will be out of phase.

If we construct a two-channel system, with each channel having opposite orientation of the bias magnetic field B_0 , the sum of the polarimeter signals from the two channels will give a signal in the case of circularly polarized rf magnetic field B_{rf} [Figs. 3(a) and 3(b)] and no signal for

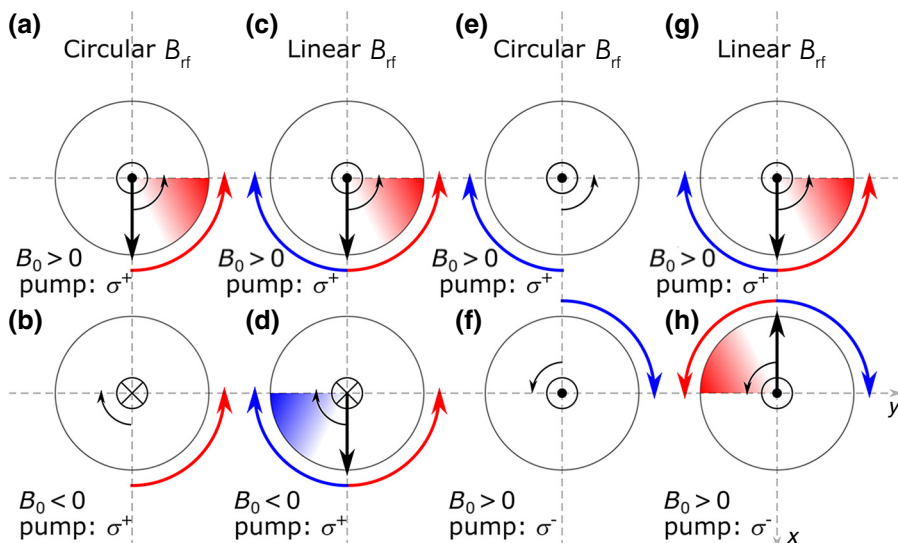


FIG. 3. The configurations for the bias-magnetic-field B_0 direction (positive, black dot; negative, cross), the polarization of the rf magnetic field B_{rf}^y (circular or linear), and the pump-light circular polarization (pump: σ^+ or σ^-). The rotation direction of the rf field is shown with a large arc and the Larmor precession direction with a small arc. The initial atomic-polarization component in the x - y plane is shown with a solid arrow and its precession with a shaded segment.

the case of linearly polarized field B_{rf} [Figs. 3(c) and 3(d)]. Such a noise-suppression scheme relies on detecting a circularly polarized rf magnetic signal and rejecting a linearly polarized noise.

Another possibility offered by the rf magnetometer is to use the direction of the circular polarization of the pump light while keeping the direction of the bias field B_0 the same. If the rotation direction of a circularly polarized rf magnetic field does not coincide with that of the Larmor precession, there is no polarimeter signal for either pump circular polarization orientation [Figs. 3(e) and 3(f)]. If the rf magnetic field is linearly polarized, the field component rotating in the direction of the Larmor precession is going to tilt the atomic polarization away from the z axis.

The atomic polarization in the x - y plane will either be in the direction of the x axis for σ^+ circularly polarized pump light [Fig. 3(g)] or in the opposite direction for σ^- circularly polarized pump light [Fig. 3(h)] at a given instant. In such a situation, the difference between two channels results in either no signal [Figs. 3(e) and 3(f)] or twice the noise [Figs. 3(g) and 3(h)], because there is a π rad phase difference for the atomic polarizations driven by a linearly polarized noise and for the σ^+ and σ^- circularly polarized pump beams. This channel configuration thus leads to a measurement of only the linearly polarized noise, rejecting the circularly polarized rf magnetic-field signal. The measured noise could then be subtracted from the output of an independent channel that measures both signal and noise.

It should be mentioned that the use of an rf field with the opposite circular polarization to that of cases (e) and (f) of Fig. 3 would result in atomic polarizations rotating out of phase with each other but in the same direction, as the bias field and Larmor precession directions are the same for both cases (e) and (f). This is essentially the same situation as encountered in cases (g) and (h). Using the difference between two such channels would result in twice

the signal but also in twice the contribution of the linearly polarized noise.

V. SENSITIVITY TO THE POLARIZATION AND DIRECTION OF THE RF MAGNETIC FIELD—THE DENSITY-MATRIX APPROACH

A simple theoretical model is developed to capture qualitatively the concepts outlined in Sec. IV and illustrated in Fig. 3. The model considers the ground-state manifold of the ^{87}Rb atom, with the energy of the Zeeman states of the $F = 2$ ground-state hyperfine component determined by the Breit-Rabi formula [22]. The energy splitting between the Zeeman states is determined by the value of the static magnetic field B_0 chosen parallel to the quantization z axis. The atomic system is described by a 5×5 density matrix, as all microwave transitions connecting the $F = 1$ and $F = 2$ components of the ground-state hyperfine manifold are neglected here.

The total Hamiltonian of the system includes the atomic Hamiltonian H_0 in the presence of a static magnetic field B_0 , as well as an interaction Hamiltonian H_{rf} in the presence of an rf magnetic field,

$$\begin{aligned} \vec{B}_{\text{rf}}(t) &= B_{\text{rf}}^x(t) + B_{\text{rf}}^y(t) \\ &= B_{\text{rf}}^x \cos(2\pi \nu t) + B_{\text{rf}}^y \cos(2\pi \nu t + \varphi), \end{aligned} \quad (1)$$

confined to the x - y plane. The phase delay φ between the x and y components $B_{\text{rf}}^x(t)$ and $B_{\text{rf}}^y(t)$ of the rf field controls the field's polarization stage.

The time evolution of the atomic system is calculated using the von Neumann equation:

$$i\hbar \frac{d\rho(t)}{dt} = [(H_0 + H_{\text{rf}}), \rho(t)]. \quad (2)$$

For simplicity, the atomic system evolution describing the rf magnetometer operation is broken down to three steps.

First, the optical-pumping process is taken into account by setting the proper initial conditions for the density matrix $\rho(0)$. For optical pumping with σ^+ circularly polarized light, the diagonal matrix element of $\rho(0)$ corresponding to the $|F=2, m_F=2\rangle$ atomic state is set to 1, while all others are set to zero. This corresponds to the situation in which the laser light pumps all the atoms into the stretched state $m_F=F$. For the opposite circular polarization σ^- of the optical-pumping light, only the diagonal element of the initial density matrix $\rho(0)$ corresponding to $|F=2, m_F=-2\rangle$ is set to 1, while all others are set to zero.

Second, the von Neumann equation given in Eq. (2) is solved numerically. We select the following example values: $B_0 = 7 \mu\text{T}$, $\nu = B_0(g_J + 3g_I) \mu_B / (8\pi\hbar)$, $B_{\text{rf}}^x = B_{\text{rf}}^y = 9 \text{ nT}$, and the duration of the time evolution $\tau = 100/\nu$. The Landé factor $g_J = 2.002\ 331\ 13(20)$ for the ^{87}Rb ground state and the nuclear g -factor $g_I = 0.000\ 995\ 141\ 4(10)$ are taken from [23].

Third, the final state of the atomic system $\rho(\tau)$ is used to calculate the atomic polarization along the x direction:

$$P_x = \text{Tr}(\rho(\tau) \hat{S}_x), \quad (3)$$

and in the x - y plane,

$$P_{xy} = \sqrt{[\text{Tr}(\rho(\tau) \hat{S}_x)]^2 + [\text{Tr}(\rho(\tau) \hat{S}_y)]^2}, \quad (4)$$

where \hat{S}_x and \hat{S}_y are the total angular-projection operators in the x and y directions, respectively.

The rotation of the detection-light polarization is proportional to the component of the atomic polarization P_x along the probe beam (the x axis). The expression for the polarization rotation angle of the D_2 probe-light field is [16,24]:

$$\varphi = \frac{1}{4} L r_e c f_{D_2} n_{\text{Rb}} D(\nu) P_x, \quad (5)$$

where L is the vapor cell length, $r_e = 2.3 \times 10^{-15} \text{ m}$ is the classical electron radius, c is the speed of light, $f_{D_2} = 0.696$ is the oscillator strength of the D_2 optical transition with frequency ν_{D_2} , n_{Rb} is the Rb density, $D(\nu) = (\nu - \nu_{D_2}) / [(\nu - \nu_{D_2})^2 + (\Gamma_L/2)^2]$ is the dispersive optical profile, ν is the probe-light frequency, and Γ_L the full width at half maximum of the pressure-broadened D_2 optical transition.

Equation (5) reflects the fact that the Rb optical transitions are broader than both the excited and ground-state hyperfine splitting at a buffer-gas pressure of 500 Torr. It allows us to compare the calculated temporal evolution of the atomic polarization P_x with the output of the polarimeter.

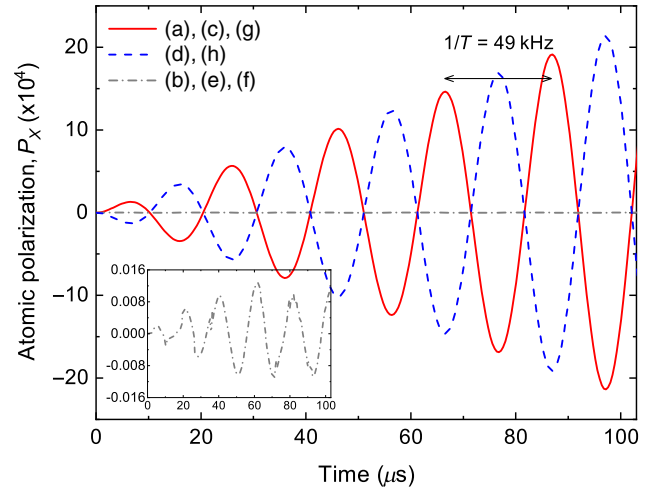


FIG. 4. The time evolution of the atomic polarization P_x for the cases shown in Figs. 3: solid line, cases (a), (c), and (g); dashed line, cases (d) and (h); dashed-dotted line, cases (b), (e), and (f). The insert shows the enlarged vertical scale for cases (b), (e), and (f).

Figure 4 shows the amplitude of the atomic polarization P_x in the x direction as a function of time. The value of P_x oscillates at the Larmor frequency of 49 kHz determined by the bias field $B_0 = 7 \mu\text{T}$. The rf magnetic field is chosen to have a constant magnitude, and a polarization state determined by the variable φ , according to the specific examples depicted in Fig. 3. For certain orientations of the bias field B_0 and the polarization state of the rf field \vec{B}_{rf} , the atomic polarization is negligible [cases (b), (e), and (f)], as expected from arguments discussed in Sec. IV. For cases (a), (c), and (g), the polarization phase is determined by the direction of the counterclockwise direction of the Larmor precession for $B_0 > 0$ and σ^+ pump-light polarization. The calculation predicts a suppression factor of at least 1000 between cases with precessing polarization and those without, as can be seen from the inset of Fig. 4. When the direction of the bias field B_0 is reversed, the phase of the atomic-polarization precession changes by π rad [case (d)] due to the change of direction of the Larmor precession. It also precesses out of phase when $B_0 > 0$, when σ^- circular polarization is used for optical pumping [case (h)].

The dependence of the atomic polarization P_{xy} in the x - y plane on the phase φ controlling the rf magnetic-field polarization is shown in Fig. 5 (upper plot). Results are shown for different bias-field B_0 directions (along or against the quantization-axis direction) as well as for the pump-light polarization (σ^+ or σ^-).

Figure 5 shows that the atomic polarization P_{xy} is close to zero for certain values of the phase φ . These values are $\pi/2$ rad for orientation of B_0 in the positive direction of the z axis and $3\pi/2$ rad for B_0 for B_0 oriented along the negative direction of the z axis. These values correspond to a

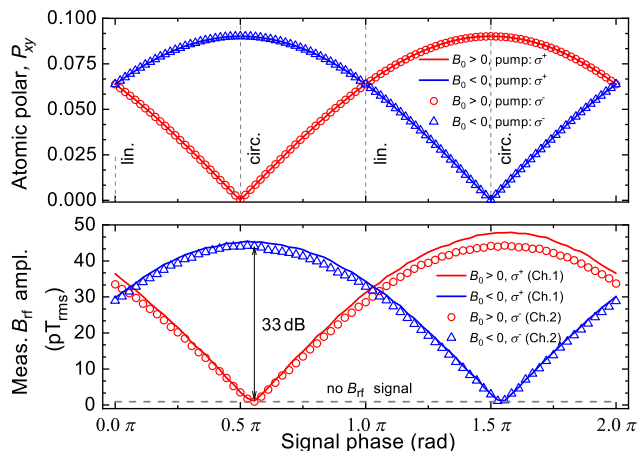


FIG. 5. Upper plot, the atomic polarization P_{xy} as a function of the phase φ between $B_{\text{rf}}^x(t)$ and $B_{\text{rf}}^y(t)$ after a time evolution of $\tau = 100/\nu$: red curve (red circles), $B_0 > 0$, pump-beam polarization σ^+ (σ^-); blue curve (blue circles), $B_0 < 0$, pump-beam polarization σ^+ (σ^-). Lower plot, the measured polarimeter response as a function of the phase φ between $B_{\text{rf}}^x(t)$ and $B_{\text{rf}}^y(t)$ signals at 50 kHz: red curve (red circles), $B_0 > 0$, pump-beam polarization σ^+ (σ^-); blue curve (blue circles), $B_0 < 0$, pump-beam polarization σ^+ (σ^-).

circular rf magnetic-field polarization rotating in the opposite direction to that of the Larmor precession. The results verify the intuitive vector picture described in Sec. IV and shown in Figs. 3(b), 3(e), and 3(f). The change of the pump-light polarization between σ^+ and σ^- does not affect the value of the φ for which the atomic polarization P_{xy} has a minimum, as the Larmor precession does not change direction. On the other hand, changing the orientation of B_0 changes the direction of the Larmor precession and corresponds to a π rad change of the value of φ and a minimum value of P_{xy} .

Without considering the detection-beam direction, the rf magnetometer has azimuthal symmetry, as the bias field B_0 and the optical-pumping beam are parallel to the quantization axis z . The magnetometer is sensitive to rf magnetic fields that have a component in the x - y plane orthogonal to the quantization axis and the direction of the induced atomic polarization is determined by the direction of the magnetic-field vector that rotates in the direction of Larmor precession.

As the detection beam is fixed in space, its direction with respect to the precessing atomic polarization determines the phase of the detected signal. This means that the phase difference between the rf magnetic field and the detected signal depends on the orientation of the magnetic-field vector and the magnetometer detection axis at any given time. This is illustrated in Fig. 6 (upper plot), which shows the instantaneous amplitude of the precessing atomic polarization P_x along the detection axis x as a function of the phase of the linearly polarized rf field. The rf field is applied

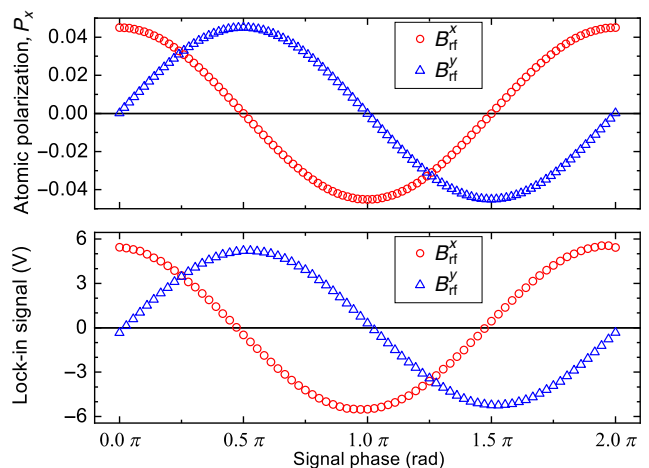


FIG. 6. Upper plot, the instantaneous amplitude of the atomic polarization P_x as a function of the phase of the linearly polarized rf field. Lower plot, the measured in-phase signal of the detected rf field. Red circles, B_{rf}^x ; blue triangles, B_{rf}^y .

either in the x or in the y direction. The $\pi/2$ rad phase difference acquired by P_x when the rf-field polarization is changed from the x to the y axis demonstrates the angular phase dependence of the precessing atomic polarization P_x .

VI. SENSITIVITY TO THE POLARIZATION AND DIRECTION OF THE RF MAGNETIC FIELD—MEASUREMENT

Three sets of measurements are performed according to the intuitive picture and the density-matrix calculations outlined in the previous sections. The first set studies the effect of the pump-light polarization on the magnetometer response. The pump laser beam is collimated to a diameter less than the width of a single magnetometer channel of 1.5 mm. Using a mirror mounted on a precision rotation mount and positioned approximately 60 cm away from the magnetometer, the direction of the pump beam is changed by a small angle. The angle change results in a calibrated spatial displacement along the direction of the probe beam, thus creating spatially varying optical pumping as the pump beam illuminates one magnetometer channel or the other. The magnetometer is tuned to 50 kHz and a 50 kHz signal is applied along the x direction. The 50 kHz signal at the polarimeter output is detected using a lock-in amplifier and a spectrum analyzer, providing phase and amplitude information for the detected 50 kHz signal. The signal amplitude is converted in magnetic-field values by measuring the ac voltage drop across a resistor connected in series with the field coils. The detected rf signal phase and amplitude as a function of the pump-beam displacement are shown in Fig. 7. It is unclear why the in-phase signal component does not reach zero when both channels are simultaneously pumped (around zero pump-beam displacement).

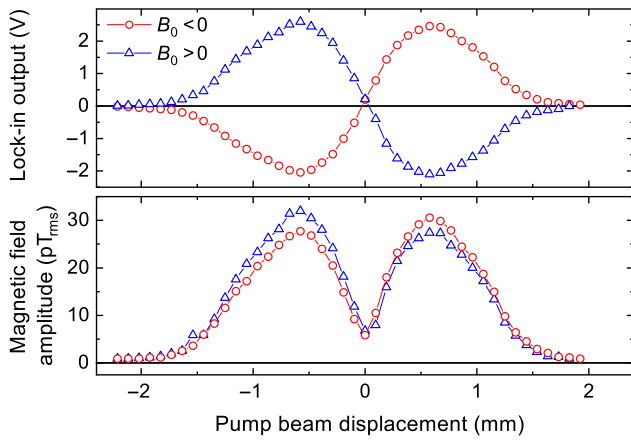


FIG. 7. The measured out-of-phase (upper plot) and in-phase (lower plot) components of the detected rf magnetic signal as a function of the pump-beam displacement along the probe-beam direction (the x axis in Fig. 1). The circles (triangles) correspond to B_0 oriented in the positive (negative) z direction.

The results show that as the pump beam is scanned across each of the magnetometer channels, the maximum amplitude of the detected rf signal is similar for both channels, regardless of the orientation of the bias field B_0 . At the same time, each channel detects opposite signal phase, as expected from cases (g) and (h) (see Fig. 3 as well as Fig. 4). The detected signal amplitude corresponds to the amplitude of the precessing atomic polarization P_{xy} in the magnetometer's x - y plane, while the phase is related to the atomic polarization P_x along the magnetometer's probe-beam direction (the x axis). The small differences in the response of the individual channels to the pump-beam displacement or the magnetic-field orientation are probably due to slight differences in the magnetometer channels, imperfect alignment of the direction and polarization of the bias and rf magnetic fields, as well as the direction and polarization of the pump and probe laser beams.

The measurements show that the precessing atomic polarization P_{xy} has an opposite orientation for opposite circular polarizations of the pump light. This sensitivity can be used to sum the output of two magnetometer channels that would result in a measurement of a linearly polarized rf noise (or signal).

The second set of measurements study the effect of the rf-field polarization on the magnetometer response. The pump laser beam has a diameter of 1.5 mm, less than the width of a single magnetometer channel, and is optically pumping either the first (σ^+) or the second (σ^-) magnetometer channel. Two rf magnetic signals B_{rf}^x and B_{rf}^y of the same frequency are applied simultaneously. The two 50 kHz signals are derived from a two-channel function generator. The phase φ of the B_{rf}^y signal is changed from 0 to 2π rad in 5° (87 mrad) steps. A spectrum analyzer connected to the polarimeter output is used to measure the

amplitude of the polarimeter response at 50 kHz, which is proportional to the magnitude of the precessing atomic polarization P_{xy} in the x - y plane. The measurements are shown in Fig. 5 (lower plot). They show a minimum amplitude of the detected rf signal for values of φ in the vicinity of $\pi/2$ rad and $3\pi/2$ rad. The ratio of the maximum to minimum values close to $\varphi = \pi/2$ rad is 44, corresponding to 33 dB rejection of the corresponding circular rf-field polarization. The minimum value is comparable to the measurement noise floor (without an applied rf signal) and it is expected that the rejection would be even higher. It is also expected that the rejection depends on the difference between the Larmor precession and the magnetic-signal frequencies.

The rotation of the probe-beam polarization is proportional to the atomic polarization along the direction of the probe beam. It is beyond the scope of this work to compare quantitatively the calculation and measurement results shown in Fig. 5; the results nevertheless demonstrate that for certain values of the phase φ corresponding to a circularly polarized rf magnetic field, the rf magnetometer has a minimum or a maximum sensitivity to the rf field depending on the direction of the bias field B_0 . This sensitivity to the polarization of the rf field can be explored to reject rf magnetic noise or signals of linear polarization while keeping the circularly polarized rf signal unaffected by forming the difference between two magnetometer channels with opposite directions of the bias field B_0 .

The measured difference in the sensor's response to a linearly and circularly polarized rf magnetic field is demonstrated in Fig. 8. As a signal B_{rf}^x , we use a phase-modulated (PM) tone at 50 kHz, with a 1 kHz modulation frequency and a deviation of $\pi/2$ rad. As a reference B_{rf}^y , we use a single tone at 50 kHz. With the reference signal turned off, the black curve (a) shows the typical spectrum consisting of a carrier at 50 kHz and sidebands separated by 1 kHz, with the amplitude dependent on the modulation index and the magnetometer's 1.5 kHz frequency bandwidth. When the reference signal B_{rf}^y is turned on, for a certain signal amplitude and its phase with respect to B_{rf}^x , the amplitude of the 50 kHz carrier is increased by approximately 6 dB, as shown by the red curve (b)—the 50 kHz carrier becomes circularly polarized and its polarization rotates in the same direction as the Larmor precession. When the direction of the bias magnetic field B_0 is reversed, the 50 kHz signal has the opposite circular polarization and is suppressed by > 30 dB, as shown by the blue curve (c)—the signal is again circularly polarized but rotates in the opposite direction. The PM sidebands remain linearly polarized in all three cases and are largely unaffected by the bias-field direction switching. The measured difference in the detected signal amplitudes for opposite circularly polarized rf signals is > 36 dB, showing that linearly polarized noise can be suppressed by > 30 dB.

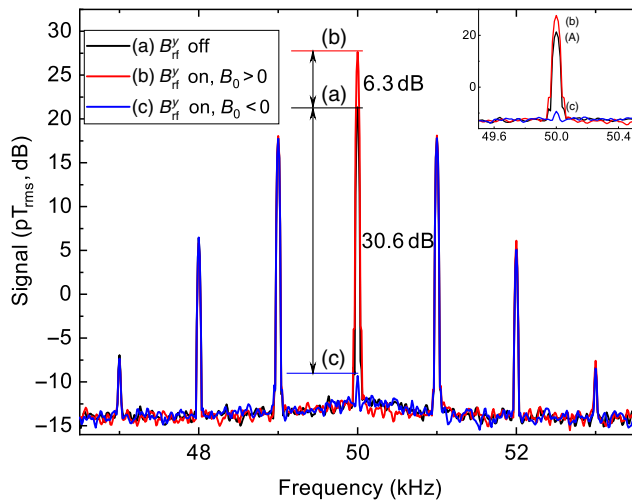


FIG. 8. The measured signal amplitude as a function of the signal frequency for three cases: (a) the PM-modulated B_{rf}^x signal only; (b) the PM-modulated B_{rf}^x signal and a reference signal B_{rf}^y with a $\pi/2$ rad phase offset with respect to the signal B_{rf}^x ; (c) the same PM-modulated B_{rf}^x signal and reference signal B_{rf}^y , with the direction of the bias field B_0 reversed. The insert shows the 50 kHz carrier with a reduced frequency span.

The results from the third set of measurements demonstrate the azimuthal sensitivity of the rf magnetometer. A linearly polarized rf signal at 50 kHz from the function generator is applied either in the x or in the y direction only. The amplitude of the detected signal at the polarimeter output is measured as a function of the phase of the applied signal using a lock-in amplifier referenced by the function generator. The result is shown in Fig. 6 (lower plot). The sinusoidal dependence of the signal amplitude shows the linear relationship between the phases of the applied and detected signals. The $\pi/2$ rad phase difference in the detected signal for an rf field applied along the x or y directions shows the sensitivity of the rf magnetometer to the detection-axis orientation with respect to the polarization direction of the rf-field signal.

VII. DISCUSSION

Based on the results of Secs. IV and VI, the proposed balanced schemes can be used to construct a low-frequency magnetic-field sensor designed to detect circularly polarized signals while suppressing linearly polarized ambient noise. The tunability of the rf magnetometer with the value of the bias magnetic field B_0 can be used to create a sensor operating at a specific frequency in the range of approximately 1 kHz up to 1 MHz and a bandwidth in the range of 1 kHz. The sensor can be used to detect circularly polarized magnetic fields and reject linearly polarized ambient noise either by the use of a channel pair having opposite directions of the bias field B_0 or with σ^+ and σ^- circular polarization of the optical-pumping

light. The necessary difference or sum of the channel-pair outputs can be done electronically, but also optically. The sign reversal can be accomplished by an additional $\pi/2$ rad rotation of a channel's probe-light polarization, after the light-atom interaction but before the light enters the channel's polarimeter using a half-wave plate. In the case of bias-field reversal, the necessary sum of the channel-pair outputs can be done optically by allowing the probe light to propagate consecutively through two spatial vapor-cell regions with opposite directions of B_0 .

The discussed rf magnetometer features depend on the polarization state of the rf signals. In practice, the detected rf signals are typically not circularly polarized. One solution, which might not be practical, would be to use multiple transmitters to create such signals. The requirement for circular signal polarization limits the application of the noise-suppression techniques discussed in this work to the case of artificially created signals, such as ones used in magnetic-field communications [15]. It might be possible to apply the technique to free-induction-decay signals of specific frequency excited by an electromagnetic pulse (such as ultralow-field NMR [25] and nuclear quadrupole resonance [2]). Another possible application is in magnetic-induction imaging, where the presence of conductive objects changes the phase of the detected magnetic signal [17]. Finally, as the optically pumped medium absorbs only one of the two possible circularly polarized rf-field components, we can use this feature to construct an atomic circularly polarized low-frequency antenna of small size.

As shown in this work, the polarization properties of an effective rf signal can be changed by combining a linearly polarized remote signal with a local reference rf signal of the same frequency and with a specific amplitude and phase relation between the remote and reference signals. For example, the signal $B_{\text{rf}}^x(t)$ used in this work can be treated as coming from a remote source and the signal $B_{\text{rf}}^y(t)$ as a reference. If the frequency of the remote signal $B_{\text{rf}}^x(t)$ is known, by adjusting the amplitude and phase of the reference signal $B_{\text{rf}}^y(t)$ we can achieve the desired maximum sensitivity difference shown in Fig. 5. It will be also interesting to investigate the possibility of creating local rf modulation using vector light shifts, avoiding the use of coils [26]. The experimentally demonstrated amplitude rejection factor of 63 (36 dB) of the circularly polarized rf signal rotating against the direction of Larmor precession would allow a factor-of-30 ambient linearly polarized noise suppression. For communications, noise that was an order of magnitude lower would reduce the transmitted rf signal power by a factor of 100, increase the communications range by a factor of 2 (for signals with magnetic-dipole type attenuation), or decrease the averaging time by a factor of 100 [15].

The intrinsic sensitivity of the rf magnetometers to the chirality of the rf field avoids the typical orthogonality

problem when vector sensors are used [27,28]. Metamaterials could be used as small-size polarization rotators [29], or electrically small antennas [30], but their applications are typically restricted to higher frequencies.

The demonstrated azimuthal dependence of the detected signal phase can be used to gain information about the magnetometer's orientation with respect to the source of an rf signal. As has been demonstrated already, the signal phase acquired with an atomic magnetometer can reach the 1 mrad level with averaging [15]. It is expected that a similar level of precision could be achieved with regard to the azimuthal angle using an rf magnetometer.

VIII. CONCLUSIONS

It is shown, both theoretically and experimentally, that an optically pumped rf atomic magnetometer has a minimum or a maximum sensitivity to the direction of a circularly polarized rf signal, depending on the direction of the Larmor precession determined by the magnetometer's bias field. The sensitivity can be tuned by reversing the direction of the magnetometer's bias field. Depending on the direction of the circular polarization of the optically pumping light, the atomic-polarization precession acquires a π rad phase change. These results allow balanced detection schemes to be realized that measure circularly polarized rf signals and suppress linearly polarized noise, or measure the linearly polarized noise and suppress circularly polarized signals. These noise-suppression schemes do not depend on the relative distance between the signal source, the noise source, and the sensor, and can be realized electronically or optically.

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