Static- and oscillating-field optical magnetometer.
Same setup, two sensitivities.

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ABSTRACT

In the following article we present an analysis of performance of optical magnetometers detecting static (DC) and oscillating (AC) magnetic fields. To facilitate the comparison, the analysis is performed in the same experimental arrangement under very similar experimental conditions, where only specific parameters, like static-field strength and oscillating-field frequency are interchangeably controlled. In particular, we investigate the sensitivity of the devices versus such parameters as laser light intensity and AC-field amplitude, which not only enables determination of a dependence of the sensitivity on the parameters, but also its optimal values. With this, we demonstrate that the sensitivity of the AC magnetometers is more than ten times better than that of the DC magnetometer. We conclude that the difference originates from different response of an atomic medium to these two types of field, i.e., a resonant response of the atoms to the oscillating magnetic field and non-resonant response to the static field. Bandwidth of the magnetometers is also analyzed. Additionally, an analysis of the magnetometers’ bandwidth demonstrates a significant difference in light-power behavior, showing that AC-magnetometer bandwidth can be significantly increased without significantly impacting its sensitivity. These results provide means for broadband ultra-sensitive measurements of the AC field, with reduced influence of static-field instabilities.

Introduction

Over the past 15 years, research on magneto-optical phenomena led to the development of various types of optical magnetometers¹, significantly enhancing the capabilities of all magnetic-field sensors. For example, the most sensitive magnetometer ever constructed is the so-called spin-exchange relaxation-free (optical) magnetometer, which reached a near-DC sensitivity of 1.6 pG/√Hz². Other advantages of optical magnetometers are: low price and maintenance, low power consumption and relative ease of miniaturization. These qualities are attractive for applications ranging from fundamental science (searches for 5th force, dark matter and dark energy, electric dipole moment, Lorentz and CPT violation)³–⁷, through semi-practical or emerging applications (zero- and ultra-low-field nuclear magnetic resonance and magnetic resonance imaging, archeology, palomagnetism)⁸–¹¹, to purely utilitarian applications (medical diagnostics, prospecting for natural resources, military surveys)¹²,¹³.

Modern optical magnetometers can be used for detection of (quasi-) static (DC) and oscillating (AC) magnetic fields (in a narrow tunable frequency range). Somewhat surprisingly, the sensitivity of DC and AC magnetometers can vary significantly despite the fact the fields are measured in similar or even identical experimental arrangements¹⁴–¹⁶. One may naively associated this difference with 1/f noise, which should affect DC measurements more acutely, but its real origin is more fundamental and is related to a resonant response of the medium to an AC magnetic field. Under the resonance condition, when the frequency of the perturbing oscillating field coincides with the spin precession frequency (the Larmor frequency), an effect of even a small perturbation can accumulate, leading to significant modifications of properties of a whole medium.

In this article, we analyze the performance of DC and AC optical magnetometers. The measurements are carried out in the same experimental arrangement. This goal is achieved by application of radio-frequency nonlinear magneto-optical rotation (NMOR)¹⁷,¹⁸, i.e., rotation of the polarization plane of linearly polarized, resonant probe light, propagating through a medium subject to static and oscillating magnetic fields¹⁹. In such an arrangement, the strongest polarization rotation is observed when the frequency of the oscillating field is tuned to the frequency splitting of adjacent Zeeman sublevels (the Larmor frequency). Thus, controlling the static-field magnitude or the oscillating-field frequency allows for the detection of either AC or DC magnetic field. Particularly, in the case of static-field measurements, determination of the resonance frequency corresponding to maximum rotation of the polarization, provides information about the static-field strength. Alternatively, by tuning the static field in resonance with the AC field and analyzing the amplitude of the rotation signal we are able to measure the strength of the oscillating field. We also investigate such parameters of the magnetometers as their sensitivity and bandwidth, analyzing them as functions of light intensity and AC-field amplitude. This allows us to determine optimal conditions for their performance.
Materials and Methods

Experimental arrangement

![Diagram of the experimental apparatus used for magnetic-field detection.](image)

Figure 1. Diagram of the experimental apparatus used for magnetic-field detection. $\lambda/2$ is a half-wave plate, $\lambda/4$ is a quarter-wave plate, PBS is a polarizing beamsplitter, FC is a fiber-optic coupler, $\lambda M$ is a wavelength meter, Rb is a rubidium cell, D is a diaphragm, P is a polarizer, M is a mirror, A is an inlet of hot air used for cell heating, WP is a Wollaston prism, DPD is a differential photodiode, PC is a computer, DAVLL is a dichroic atomic vapor laser lock system, $B_{AC}$ is an oscillating field and $B_0$ is a static field used for magnetometric purposes. Directions of magnetic fields are marked by bright blue arrows.

Figure 1 presents an experimental setup used in our measurements. A diode laser (Toptica DL100) generates light detuned by about -480 MHz from the $F = 2 \rightarrow F' = 1$ transition of rubidium $D_1$ line (795 nm). Right after the laser the light is split off and its fraction is sent to a side arm for wavelength monitoring with a wavemeter (HighFinesse/Angstrom Wavelength meter WS-U) and stabilization with a dichroic atomic vapor laser lock system. The main beam, 4 mm in diameter, is used to illuminate a spherical (4 cm in diameter) atomic vapor cell, whose walls are paraffin coated. A narrow capillary, attached to the side of the cell, contains a metallic droplet of isotopically enriched $^{87}$Rb. The cell is placed inside a cylindrical magnetic shield, consisting of four mu-metal layers (Twinleaf MS-1). While the shield significantly reduces external, uncontrollable magnetic fields (a shielding factor on the order of $10^6$), a set of magnetic-field coils mounted inside is used to compensate for residual fields (including first-order gradients) and to generate a static field along $x$ (typically on the order of 10 mG). The coils are powered with a precision current source (Keithley 6220). An additional oscillating field is generated along $y$ and its amplitude and frequency is controlled with a generator built in a lock-in amplifier. The rubidium-vapor cell is heated with hot air to about $50^\circ$C (resulting in concentration of $3 \times 10^{11}$ atoms/cm$^3$). The probe light is $x$-polarized and controlled in a range from 0 to 1000 µW with a half-wave plate and a high-quality crystal polarizer. After passing through the cell, the light is reflected and leaves the shield throughout the same optical port at a small angle with respect to the incident beam. This increases interaction length and hence improvement of an NMOR signal amplitude. The polarization rotation of the light is measured with a balanced polarimeter, consisting of a Wollaston prism and a balanced photodetector (Thorlabs PDB450A). The photodetector difference signal is demodulated with a lock-in amplifier (Zurich Instruments HF2LI) at the first harmonic of the AC-field frequency. The whole system is controlled with a computer, which also provides data storage.

Methods

The maximum rotation of polarization in NMOR with oscillating magnetic field is observed when the AC-field frequency $\omega_{AC}$ coincides with the Larmor frequency $\omega_L$ ($\omega_L = g \mu_B B_0 / \hbar$, where $B_0$ is the field strength, $g$ is the Landé factor, $\mu_B$ is the Bohr magneton, and $\hbar$ is the reduced Planck constant) (for simplicity only the linear Zeeman effect is considered). The rotation-signal dependence on AC field frequency has a resonant shape, where rotation is nonzero in a finite frequency range around $\omega_L$, determined by an atomic ground-state relaxation rate. Thereby, the $B_0$-field change manifests as modification of the observed signal, which, if calibrated, may be used to determine the static-field change. In such measurements, it is convenient to detect the rotation component phased with the oscillating field (an in-phase component of the signal), which is dispersively shaped and hence provides a way to determine the direction of the field change. An example of such signals, for two different static fields $B_0$, are shown in Fig. 2(a). It is worth noting that the amplitudes and widths of the resonances are the same.
Changes of the rotation signal is also observed when the amplitude of the oscillating field varies, while other parameters, including the static field \( B_0 \), are fixed. In this case, however, the resonance position remains the same but its amplitude increases. An example of NMOR signals recorded for two different AC-field amplitudes but same other parameters are shown Fig. 2(c). The dependence of the NMOR-signal amplitude and in-phase component on the static-field strength \( B_0 \) and the AC-field amplitude enables detection of the fields. For example, in the so-called passive mode, where no feedback between the NMOR signal and magnetometers’ input parameters is present, one can determined the field change by observing the rotation change when \( \omega_{AC} \approx \omega_L \). In such a way, the field change results in modification of the signal, which, if calibrated, provides information about the DC- and AC-field variations.

To compare the DC- and AC-field measurements, we analyze the NMOR signals versus the light power and the AC-field amplitude. By measuring the amplitude and width of these signals, we are able to determine a slope of the in-phase component at resonance or to study the response to AC-field amplitude change. This is turn, after normalization by the magnetometer noise, yields us the sensitivity of the magnetometer. We also determine the bandwidth of the DC magnetometer by modulating the static field. Finally, we investigate the bandwidth of the AC magnetometer by applying a square-wave pulse of the oscillating field and observing the rising edge and amplitude of the rotation signal.

Results and Discussion

System response to the DC and AC field stepwise change

To analyze the response of the DC and AC magnetometers to the field changes, we measure both the in-phase component and amplitude of the signals. As discussed above, the change of static magnetic field leads to the shift of the observed resonance. For the DC measurements, the static field \( B_0 = 7.5 \text{ mG} \) is changed by \( 15 \mu \text{G} \) which manifests in a shift of the resonance position by about 10 Hz, as seen in Fig. 2(a). Similarly, Fig. 2(c) presents the NMOR signal observed for two different AC-field amplitudes. While the initial resonance is recorded under identical condition as its static counterpart, the new resonance is observed when the \( 1 \mu \text{G} \text{rms} \) AC field is changed by \( 15 \mu \text{G} \). While the field changes in both scenarios are the same, the modification of the signal induced in the AC case is much larger than in the DC magnetometer.

Figure 2. Examples of the DC an AC magnetic-field measurements using NMOR. (a) In-phase component of the NMOR signal measured versus the AC-field frequency near the Larmor frequency \( (\omega_L \approx 5.25 \text{ kHz}) \) for two different static-field values. Notice the shift in the resonance position after the field change by 15 µG (vertical arrow marks a difference in in-phase signal corresponding to the resonance position shift). (b) Change in the in-phase component of the signal for the fixed frequency (initially \( \omega_{AC} = \omega_L \)) when the static field is modified at \( t = t_0 \). (c) Amplitude of the NMOR signal measured for two different AC-field amplitudes and fixed static field. Notice the change in the resonance amplitude as the AC-field amplitude is modified by 15 µG (vertical arrow indicates difference in signal amplitudes). (d) Rotation signal measured in resonance when the AC-field amplitude is changed.
The difference between the DC- and AC-magnetometer response manifests more strongly when the time traces of the signals recorded for identical resonance conditions are analyzed [Figs. 2(b) & (d)]. Initially, both magnetometers operate under the resonance conditions ($\omega_{\text{AC}} = \omega_L$) and maximum rotation is observed. At time $t_0$, the static [Fig. 2(b)] or oscillating [Fig. 2(d)] magnetic field is abruptly changed. The changes result in modification of the NMOR signals, which, after some transient time determined by the magnetometers’ bandwidths, settle at new values (It is noteworthy that under special conditions, a transient signals unlimited by the resonance bandwidth may be observed). While these signals may be used for fast changes detection, their magnetometric application ranges beyond the scope of the paper.). The two plots clearly show that even the same change in the field leads to very different magnetometer responses. Below we analyze the NMOR signals versus light power and AC-field amplitude to gain more insight into the difference between sensitivity and bandwidth of the DC and AC magnetometers.

**Magnetometer sensitivity**

In the DC magnetometer, the response of the device to the field change is determined by a slope of the in-phase component of the NMOR resonance [Fig. 2(a)]. The strongest response to the field change is achieved by maximizing the NMOR resonance amplitude and minimizing the resonance width. Since the resonance amplitude and width depend on the light power and AC-field amplitude, optimization of the response is a complex multidimensional procedure.

To measure the slope of the resonance the AC-field frequency is scanned across the NMOR resonance ($\omega_L \approx 5.25 \text{kHz}$) and the in-phase and quadrature components of the rotation are recorded. A complex Lorentzian function, where the in-phase component determines the real and the quadrature component the imaginary part of the function, is fitted to the data and the amplitude and width of the resonance are retrieved. The measurement is repeated for different light powers and AC-field amplitudes, which allows us to construct a map of the DC response of the magnetometer [Fig. 3(a)].

Data presented in Fig. 3(a) shows that the response of the magnetometer to the DC-field change monotonically increases with the AC-field amplitude. The increase is nearly linear to about 15 µG$_{\text{rms}}$, but for larger light powers the increase diminishes, however, within the accessible range of parameters it never levels out. The dependence of the magnetic response to the field change versus the light power is more complicated. Initially, it increases with the power reaching its maximum at about 50 µW. Further increase of the light power results in deterioration of the resonance. This effect stems from optical repumping and destruction of the anisotropy initially created with light. At higher light powers, the repumping may become the dominant source of relaxation, leading to large power broadenings of the resonances. For example, for strong light (800 µW) the resonance broadens nearly 5 times and its amplitude is correspondingly reduced. This results in the decrease of the response of the magnetometer to the field change by about two orders of magnitude. The analysis of the data presented in Fig. 3(a) reveals that a maximum response of the rotation to the magnetic-field change of about 0.8 mrad/µG is observed for light power of about 50 µW and AC-field amplitude of nearly 25 µG$_{\text{rms}}$.

Maximum response of the magnetometer to the field change does not automatically translate into the best sensitivity of the device, this is because another factor determining the sensitivity is noise. At the most fundamental level, shot noise of light, spin-projection noise of atoms, and the back action between light and atoms limit the sensitivity of optical magnetometer (see, for example, Ref. and references therein). On the top of this, there are various other contributions, e.g., those associated with electronics, vibrations, temperature fluctuations, which burden the signal with auxiliary noise, often characterized by the $1/f$
frequency dependence. Finally, there is the environmental magnetic-field noise (uncontrollable magnetic-field fluctuation), which is not inherent to the magnetometer but also affects its practical sensitivity (Despite not being an intrinsic magnetometer noise, the environmental noise can be orders of magnitude larger than all other contributions and hence can severely affect magnetometer performance.). To estimate the sensitivity of the DC magnetometer, the raw photodiode signal is recorded bypassing the lock-in amplifier for different light powers. In such a way, we not only account for light-intensity independent noise contributions but also include contributions such as photon shot noise. The fast Fourier transform of the polarimeter signal is performed in 1-Hz wide bins in the absence of the AC magnetic field to determine the noise floor. With these measurements, we determine that close to the nominal resonance frequency, the noise is flat. We are also able to obtain the DC-field sensitivity, i.e., by dividing the noise spectral density by the magnetometer response [Fig. 3(b)].

The analysis of the data shown in Fig. 3(b) reveals that an optimum DC sensitivity of $75 \text{pG}/\sqrt{\text{Hz}}$ is achieved for a light power of about 100 $\mu$W and an AC-field amplitude of 30 $\mu$G, parameters different from those corresponding to optimum magnetometer response. Moreover, the DC sensitivity does not deteriorate with the light intensity as quickly as the DC response, shown in Fig. 3(a). This is a consequence of the fact that the signal-to-noise ratio improves with increasing light intensity, which compensates the rotation-signal deterioration.

To determine a response of the NMOR signal to a change of the AC field, the NMOR-resonance amplitude is recorded versus the amplitude of the AC field. By taking the difference between NMOR-resonance amplitudes for two successive AC-field values, the response of atoms to the field change is determined. The measurement is then repeated for different light powers and a map, similar to that produced for the DC magnetometer [Fig. 3(a)], is constructed [Fig. 4(a)].

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure4.png}
\caption{(a) Response of the AC magnetometer to the change of the AC-field amplitude and (b) AC-magnetometer sensitivity versus light intensity and AC-field amplitude.}
\end{figure}

Data presented in Fig. 4(a) shows that the response of the AC magnetometer to the oscillating-field change is different than that of the DC magnetometer. For instance, the same change in magnitude of the measured field leads to a response of the AC magnetometer that is larger by a factor of 8 than in the DC case. Yet, the two magnetometers reveal a similar behavior with respect to the AC-field amplitude; with weak AC fields (up to about 2 $\mu$G$_{\text{rms}}$) the response does not depend on the field amplitude. However, for stronger fields the sensitivity deteriorates, which is result of saturation with the oscillating field. Some similarities between the AC and DC responses may be also observed in the light-power dependence. While for lower light powers, the AC response increases with the parameter, it eventually reaches its maximum at about 180 $\mu$W and deteriorates for even stronger fields. However, even though the shape of the behavior is similar, its amplitude is very different; in the DC configuration the response of the magnetometer spans 3 orders of magnitude, in the AC case, the whole change is smaller than a factor of 10 for a corresponding change in light power.

The map shown in Fig. 4(b) reveals that the sensitivity of the AC magnetometer is roughly and order of magnitude better than in its DC counterpart. Moreover, its dependence on light power is much weaker, which has important implications (see bandwidth discussion below). The data also shows that the magnetometer reaches an optimum sensitivity of $6 \text{pG}/\sqrt{\text{Hz}}$ for a light power of 240 $\mu$W and an AC-field amplitude of 1.1 $\mu$G. This is over than 10 times better result than that obtained with the DC magnetometer.

\section*{Bandwidth considerations}
Apart from the sensitivity, the bandwidth is another crucial parameter determining magnetometer performance. Since a passive DC magnetometer can be considered an RLC circuit\textsuperscript{25}, its bandwidth is determined by the width of the observed resonance, given the ground-state relaxation rate. This immediately reveals an opposite dependence of the sensitivity and bandwidth on the
resonance width. Therefore to optimize the magnetometer means finding a compromise between how small magnetic field can be detected versus how fast such a measurement can be performed (It should be noted that in magnetometers with an active tracking of the resonance position in the feedback loop, it is not a resonance width but signal-to-noise ratio of the observed signals and bandwidth of the electronics used for the process that limit the response of the device to the magnetic-field change.).

To determine the bandwidth of the DC magnetometer, the double demodulation technique is implemented. In this case, a small, sinusoidal, low-frequency (< 200 Hz) modulation of 100 nG_{rms} is applied to a strong static magnetic field (7.5 mG). The amplitude of the modulation is chosen to be large enough to detect signal with a good signal-to-noise ratio, yet small enough to still lay within the dynamic range of the DC passive magnetometer (within the width of the resonance). For the measurements, the photodiode difference signal is first demodulated at \( \omega_{AC} \) (\( \omega_{AC} \approx 5.25 \text{ kHz} \)) (An integration constant in the locking is chosen such that it guarantees that demodulation do not affect the shape of the pulse.), then the in-phase component of the signal is demodulated at the static-field modulation frequency. This frequency is then varied and the amplitude of the magnetometer response to the fixed amplitude oscillations is determined. This allows us to obtain a 3-dB point and hence determine the bandwidth of the magnetometer. After completing a given set of measurements, the measurements are repeated for different light power and AC-field amplitude. This is continued until the whole parameter space is covered and a bandwidth map is produced.

Figure 5 shows the bandwidth of the DC magnetometer versus light power and AC-field amplitude. As the light power increases, power broadening increases the ground-state relaxation rate. This shortens the response time of the device, increasing the magnetometer bandwidth. At the same time, a change of the AC-field amplitude has almost no impact on the bandwidth. This confirms the linear regime of the AC-field interaction and nonlinear regime of the optical interaction.

![Figure 5. DC magnetometer bandwidth extracted from the 3-dB point using different modulation frequencies. The measurements are performed for different light intensities and AC-field amplitudes.](image)

To investigate the bandwidth of the AC magnetometer, we applied a 50 ms, 2 \( \mu \text{G}_{rms} \) square pulse of a resonant oscillating magnetic field oriented in the y direction. Figure 6(a) shows a signal measured with the balanced photodiode (without demodulation). An initially flat magnetometer signal starts to oscillate when the pulse is applied at \( t = 0 \). For low light powers, the response of the device is small and slow, which results in very small and strongly flattened pulse of oscillations. The situation changes with increasing light power, when the signal amplitude rises and its square shape is more closely reproduced. Since the bandwidth scales nearly linearly with the laser power [Fig. 6(b)], the response time is inversely proportional the power, reaching 1-ms rising time (1/e) for large light powers (\( P \approx 700 \mu \text{W} \)) [Fig. 6(c)]. The data shows that the bandwidth of the magnetometer increases with the light power [Fig. 6(b)], reaching hundreds of hertz for the strongest light power. Increasing light power also increases the amplitude of the oscillations. The increase, however, is accompanied by a rise of intensity-dependent noise (not visible in the plots), which in turn leads to some deterioration of the sensitivity for more intense light [Fig. 4(b)].
Operation at higher light power provides several advantages for AC magnetometry. Particularly, more intense light increases the bandwidth of the AC magnetometer, i.e., rise and fall times of the pulses are significantly reduced. This is beneficial for measuring rapidly decaying magnetic fields (e.g. optical detection of the NMR signal\textsuperscript{24}, magnetic particles imaging\textsuperscript{25}). At the same time, the strong light decreases the response of the magnetometer to static-field fluctuations (a flattened DC-field dependence), reducing influences of uncontrollable static fields. Eventually, it may lead to AC-field detection in partially or even completely unshielded environment\textsuperscript{26}.

**Conclusions**

In conclusion, we demonstrated and analyzed the difference in operation of the DC and AC optical magnetometers. Particular attention was paid to the sensitivity of the magnetometers based on nonlinear magneto-optical rotation, where measurements of static and oscillating magnetic fields may be performed in the same experimental arrangement under very similar experimental conditions. In such a system, we have shown that the resonant response of the atoms to the oscillating field is significantly stronger (eightfold) compared to one induced by the equivalent DC-field change. Determination of the noise of the system allowed us to analyze sensitivity of both types of magnetometers versus such parameters as light power and AC-field amplitude. We demonstrated initial increase, saturation, and successive deterioration of the sensitivity on the light power and much weaker dependence of the sensitivity on the AC-field amplitude. This analysis allowed us to determined optimum sensitivity of the two magnetometers, which were $75\text{ pG}/\sqrt{\text{Hz}}$ for the DC measurements and $6\text{ pG}/\sqrt{\text{Hz}}$ for the AC measurements. This difference
is a result of variation in the response of two magnetometers, but also in a signal-to-noise for the optimal light power for AC and DC measurement \((8\sqrt{240\mu W/100\mu W} \approx 12.5)\). The DC and AC magnetometer bandwidth was investigated, revealing roughly linear relation between the bandwidth and light power. This dependence is clearly visible in the AC-pulse detection, when the magnetometer response was slow at low light power, leading to the spreading of the short, square pulse. We showed that increasing the power not only improves the bandwidth of the AC magnetometer without significant deterioration of its sensitivity, but also makes the device more immune to the fluctuations of the static fields.

The presented results not only contribute to the better understanding of the performance of the DC and AC magnetometers but also suggest approaches toward application of the optical magnetometers. Particularly, detection of electromagnetic fields in a frequency range reaching 1 MHz is interesting in this context. The reduced role of the static-field fluctuations on the performance of the AC magnetometer, opens avenues toward unshielded detection of oscillating fields. This may be particularly interesting in detection of magnetic particles, nuclear magnetic resonance, magnetic resonance imaging in ultra-low fields, nuclear quadrupole resonance, and inductive detection of metals.

Data Availability

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

References


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**Author contributions statement**

K.P. and P.P. conducted the experiment(s), P.P. and S.P. analyzed the results. All authors contributed to writing and reviewing the manuscript.

**Additional information**

**Competing financial interests**

The author(s) declare no competing interests.