Ultrasensitive magnetometer using a single atom

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Precision sensing [1], and in particular high precision magnetometry [2–4], is a central goal of research into quantum technologies. For magnetometers often trade-offs exist between sensitivity, spatial resolution, and frequency range. The precision, and thus the sensitivity of magnetometry scales as 1/√T2 [5] with the phase coherence time, T2, of the sensing system playing the role of a key determinant. Adapting a dynamical decoupling scheme that allows for extending T2 by orders of magnitude [6] and merging it with a magnetic sensing protocol, we achieve a measurement sensitivity even for high frequency fields close to the standard quantum limit. Using a single atomic ion as a sensor, we experimentally attain a sensitivity of 4 pT Hz−1/2 for an alternating-current (AC) magnetic field near 14 MHz. Based on the principle demonstrated here, this unprecedented sensitivity combined with spatial resolution in the nanometer range and tuneability from direct-current to the gigahertz range could be used for magnetic imaging in as of yet inaccessible parameter regimes.

Introduction – Before introducing a novel magnetometer scheme and describing the experimental procedure, we briefly outline state-of-the-art magnetometry by means of a few examples. Often, detecting magnetic fields with highest sensitivity and spatial resolution is mutually exclusive [7]. Magnetic field sensitivities in the range of femto- or even sub-femtotesla Hz−1/2 have been reached using superconducting quantum interference devices [8] or atomic magnetometers [9]. Optical atomic magnetometers [10, 11] are alternative sensors based on the magneto-optical properties of atomic samples in vapour cells reaching a sensitivity in the fT Hz−1/2 range [12]. A persistent current quantum bit held at 43 mK was used to obtain a sensitivity of 3.3 pT Hz−1/2 measuring an AC magnetic field near 10 MHz [13].

A high spatial resolution in the nanometer range with relatively low sensitivity is possible using sensors based on magnetic force microscopy [14], or with Hall sensors [15]. Using Nitrogen vacancy centres in diamond, nT Hz−1/2 field sensitivity can be combined with (sub-)nanometer spatial resolution [2, 4, 16]. Surface imaging with Bose-Einstein condensates reaches sensitivities of ~10 pT Hz−1/2 and 50 μm spatial resolution [17].

State-of-the-art magnetometry often relies on dynamical decoupling where fast pulses or continuous fields drive a quantum mechanical two level system. The role of these fields is to decouple the system from the environment, and thus to enhance the T2 time, while at the same time retaining the ability to sense a signal that is on resonance with the pulse rate or the Rabi frequency of the decoupling field. Random ambient magnetic field fluctuations, which are not featureless white noise but tend to have a limited bandwidth, are the dominant noise source in many cases and limit T2. Pulsed dynamical decoupling (DD) was proposed and demonstrated for prolonging coherence times by subjecting a two-level system to a rapid succession of pulses leading to decoupling from the environment. This technique, often termed Bang-Bang control, originates in nuclear magnetic resonance experiments and can be applied in diverse systems [18–22].

Throughout a dynamical decoupling pulse sequence the quantum probe is decoupled from ambient magnetic noise while increasing its sensitivity to alternating magnetic signals at specific frequencies. Thus, DD can be used to extract information about the magnetic noise spectrum [21, 22], and to improve the signal-to-noise ratio (SNR) in magnetic sensing by several orders of magnitude. Measuring high frequency components with high sensitivity requires a high pulse rate and in turn shorter pulses with increased peak amplitude [2, 16, 22]. Using such a technique, a magnetometer sensitivity of 15 pT Hz−1/2 for magnetic field frequencies up to 312.5 Hz was achieved using a single trapped ion as a probe [18] while with about 103 NV centers in diamond frequencies up to 220 kHz were measured with a sensitivity of order 10 nT Hz−1/2 [16].

Dynamical decoupling can also be achieved, in the so-called spin locking regime, via a simple continuous drive dressing atomic energy levels [23, 24]. This usually requires stabilization methods to decrease the effect of amplitude noise in the dressing field on the sensitivity [25]. However, it has been recently demonstrated using trapped ions [6, 26] that by using additional atomic levels, the effect of control noise can be dramatically reduced. This method is applicable to a variety of other systems, including hybrid atomic and nanophysics technologies [(27, 28) and references therein].

Here, we adapt a decoupling scheme, introduced in [6], such that it is robust against amplitude noise by making use of the multilevel structure of atomic systems and demonstrate that it can be merged with a magnetic sensing protocol to achieve a measurement sensitivity close to the standard quantum limit. Unlike other state-of-the-art magnetometry schemes that either sense signal fields resonant with the pulse rate (pulsed DD, e.g., [18]) or the Rabi frequency (continuous DD, e.g., [29]) of the decoupling field, the novel magnetometry protocol introduced here relies on the signal to be resonant with the frequency of the decoupling field. Today, RF frequencies can easily be stabilized to high precision (e.g., compact commercial atomic clocks provide a relative frequency stability ∆ν/ν ≈ 10−15) while RF amplitude stability at this level would be challenging to attain. This is in particular true for large Rabi frequencies required for high frequency sens-
ing using continuous or pulsed DD, thus limiting state-of-the-art magnetometry to relatively low frequencies. The sensing scheme introduced here could be tuned to a desired frequency from DC to the GHz range by variation of a static bias magnetic field.

The method — The protocol proposed and implemented here is based on the level structure shown in fig.1. In this scheme the frequency of the signal to be sensed is determined by the frequency difference between two microwave fields. This frequency difference is set to be of the order of the Zeeman splitting between the atomic states $|0\rangle$, $|+1\rangle$, and $|-1\rangle$.

The level structure shown in Fig. 1 is implemented here using hyperfine states of the electronic ground state of a single trapped $^{171}$Yb$^+$ ion.

The two microwave fields (fig.1) cancel the effect of ambient magnetic field fluctuations (dynamical decoupling) by creating the dressed state $|B\rangle \equiv (|+1\rangle + |-1\rangle)/\sqrt{2}$. By adjusting the relative phase of two resonant microwave fields, we populate state $|B\rangle$. The other two dressed states — superposition states of $|D\rangle \equiv (|+1\rangle - |-1\rangle)/\sqrt{2}$ and $|0\rangle$ — are separated from $|B\rangle$ by an energy gap $\Omega/\sqrt{2}$. Therefore, dephasing of $|B\rangle$ by ambient fields can occur only if the ambient field supplies energy at a frequency matching this energy gap. Thus, if the noise field lacks this frequency component, then the coherence time of $|B\rangle$ is enhanced by orders of magnitude as compared to the bare atomic states $|0\rangle$. Nevertheless, the $|B\rangle \leftrightarrow |0\rangle$ transition is sensitive to an AC magnetic field (the signal to be measured) at the frequency of the $|0\rangle \leftrightarrow |-1\rangle$ transition or of the $|0\rangle \leftrightarrow |+1\rangle$ transition. These two resonances are not degenerate due to the second order Zeeman shift. This unique opportunity for precise magnetometry is detailed in the following calculation treating a signal on the $|0\rangle \leftrightarrow |+1\rangle$ transition. The Hamiltonian of the system is

$$H_{\text{sig}} = \omega_0 |0\rangle\langle 0| + \lambda_+ (|+1\rangle\langle -1| - |-1\rangle\langle +1|) + \Omega \left[ |\pm 1\rangle \langle \pm 1| e^{i\omega_0 t} + e^{i\Omega t} |0\rangle\langle 0| e^{i\omega_{+1} t} + h.c. \right] + \Omega_2 \cos(\lambda_+ t + \phi) (|+1\rangle\langle 0'| + h.c.),$$

(1)

where $\omega_0$ is the zero field hyperfine splitting, $\lambda_+$ and $\lambda_-$ is the Zeeman splitting, $\Omega_2$ is the signal field, $\phi$ is the initial phase difference between the two microwave sources at frequencies $\omega_{+1}$, $\omega_{-1}$ and $\phi$ is the initial phase difference between the first microwave source and the signal field.

In the rotating wave approximation and in the interaction picture with respect to the time independent part after setting $\theta = \pi$ and $\phi = 0$, we get:

$$H = \sqrt{2}\Omega (|D\rangle\langle 0| + h.c.) + \sqrt{2}\Omega_2 (|B\rangle\langle 0'| + h.c.)$$

$$= \frac{\Omega}{\sqrt{2}} |u\rangle\langle u| - \frac{\Omega}{\sqrt{2}} |d\rangle\langle d| + \frac{\sqrt{2}\Omega_2}{\sqrt{2}} (|B\rangle\langle 0'| + h.c.),$$

(2)

where $|u\rangle$ and $|d\rangle$ are superpositions of states $|0\rangle$ and $|D\rangle$. The first two terms shift states $|u\rangle$ and $|d\rangle$ (that both contain $|D\rangle$) away from state $|B\rangle$, and the second part is the magnetic signal. The interactions created by the two microwave fields with Rabi frequency $\Omega$ decouple the $|B\rangle$ state from magnetic noise.

Unlike usual dynamical decoupling, in which the signal field to be measured induces oscillations at the frequency of the pulse sequences or at the Rabi frequency of the continuous field, here oscillations are induced at the frequency difference between a clock transition (that is insensitive to magnetic fields to first order, $\omega_0$ in Fig. 1) and half of the relative detuning of the two microwave frequencies ($\omega_{+1}, \omega_{-1}$). This frequency splitting is close to the Zeeman splitting induced by a DC bias magnetic field. Thus, the frequency of the signal to which the magnetometer is susceptible can be tuned by variation of this bias field to sense a broad range of frequencies. In particular, DC as well as high frequency fields (in the experiments reported here 14.076 MHz) can be sensed with a sensitivity close to the standard quantum limit. It should be stressed, that the sensitivity of the magnetometer is not influenced by possible fluctuations of the static bias magnetic field as these are being suppressed by a factor proportional to the ratio between the magnetic field fluctuations and the microwave Rabi frequency.

![Figure 1. Level scheme for magnetometry. a) Hyperfine levels for magnetic sensing (not to scale). The signal field to be measured creates rotations between the states $|0\rangle$ and $|B\rangle \equiv (|+1\rangle + |-1\rangle)/\sqrt{2}$. b) Partial $^{171}$Yb$^+$ level structure: the optical transition used for Doppler cooling and readout (not to scale).](image-url)
Ramsey oscillations and magnetometry sensitivity. — The coherence time of the bare atomic states and of the dressed state qubit \(|B\rangle\) and \(|0\rangle\), respectively, is tested by a Ramsey-type experiment. After creating a superposition of the two magnetically sensitive \(m_F = \pm 1\) bare states, their coherence is rapidly lost due to fluctuating ambient magnetic fields. The bare states are characterized in this experiment by a coherence time of 5.3 ms whereas the experimental result in Fig. 2 shows that coherence can be preserved for more than 2000 ms when using the dressed state qubit. Thus, the coherence is preserved for a time almost three orders of magnitude longer than the dephasing time of the atomic states \(|-1\rangle\) and \(|+1\rangle\).

In order to measure the sensitivity of the magnetometer, we apply an RF field set to resonance with the \(|0\rangle\leftrightarrow|+1\rangle\) transition to induce Rabi oscillations (Fig. 3) with frequency \(\Omega_g\) between the dressed state \(|B\rangle\) and state \(|0\rangle\) [26]. The population \(P(T)\) of state \(|-1\rangle\) after application of the RF pulse is mapped onto state \(|0\rangle\). Rabi oscillations are sustained for 1000 ms without loss of contrast demonstrating the long-lived coherence of the dressed states this time driven by RF radiation.

The shot-noise-limit sensitivity for the measurement of \(\Omega_g\) is given by

\[
\delta \Omega_g = \frac{\Delta P(T)}{\partial P(T)/\partial \Omega_g} \sqrt{T_{\text{tot}}}
\]  

where \(\Delta P\) is the standard deviation (which gives the error bar in Fig.4 associated with the population measurement after time \(T\)). Here we use \(T_{\text{tot}} = n(T + T_{\text{add}})\) which is the total time needed for \(n\) repetitions of the measurement at time \(T\).

Figure 2. Coherence time of dressed and bare states. A coherent superposition of \(|B\rangle\) and \(|0\rangle\) is prepared and probed after time \(T_R\) (red data points and black fit). For comparison, the result of a Ramsey-type experiment between the bare states \(|-1\rangle\leftrightarrow|0\rangle\) (blue data points and green fit) is shown. For the dressed states an RF field implements two \(\pi/2\)-pulses separated by time \(T_R\) of free evolution. The RF frequency is slightly detuned from resonance yielding Ramsey oscillations with a period of \(1/(0.52 \text{ Hz})\) between 0.1 ms and 2000 ms. Each of the 11 measurement points consists of 10 repetitions. In case of the bare states the 51 measurement points between 0.1 ms and 10 ms are repeated 50 times. The error bars indicate one standard deviation.

Figure 3. Qubit rotation between coherence protected states \(|B\rangle\) and \(|0\rangle\). Rabi oscillations take place between 0.1 ms and 1000 ms with a Rabi frequency \(f_{\Omega_g} = \Omega_g/2\pi = 11.3 \text{ Hz}\). Each of the 21 measurement points consists of 20 repetitions. The solid line is a fit to the data yielding \(f_{\Omega_g}\). The error bars indicate one standard deviation.

The factor \(\partial P(T)/\partial \Omega_g\) in equation 3 is obtained by taking the slope of the blue fitted function (Fig. 4 (a)) at \(\Omega_g\) of a specific data point at experimental time \(T\). The above quantity \(\delta \Omega_g\) (in units of Hz/\(\sqrt{\text{Hz}}\)) characterizes the minimum change in \(\Omega_g\) that can be discriminated within a total experimental time of one second. We thus obtain an estimate for the sensitivity derived from the error bar in Fig.4 (a). It can be seen from Fig.4 (b) that, if the pulse duration \(T\) becomes longer, the sensitivity approaches the standard quantum limit (the blue curve gives the corresponding standard quantum limit). For short \(T\), the sensitivity is limited due to the overhead in the experiment time \(T_{\text{add}}\) for system preparation, state readout and cooling. Exemplary, the sensitivity of three data points is emphasized with different color coding and marker symbols. For an experimental time \(T = 500 \text{ ms}\) a sensitivity of \(\delta \Omega_g = (0.2147 \pm 0.0033) \text{ Hz/\(\sqrt{\text{Hz}}\)}\) is achieved (cyan).

For the red data point at experimental time \(T = 850.015 \text{ ms}\) a sensitivity of \(\delta \Omega_g = (0.1999 \pm 0.0031) \text{ Hz/\(\sqrt{\text{Hz}}\)}\) is estimated. For the longest pulse duration time \(T = 1500 \text{ ms}\) (green symbol) in our experiment, we achieve the best sensitivity \(\delta \Omega_g = (0.1151 \pm 0.0018) \text{ Hz/\(\sqrt{\text{Hz}}\)}\) corresponding to a sensitivity of 4 pT Hz\(^{-1/2}\) at a signal frequency near 14 MHz.

Summary and outlook.— A novel method for magnetometry is presented that is robust against amplitude fluctuations of the decoupling fields. We have demonstrated this method using a single atomic ion confined to a spatial region of order (20 nm)\(^3\) and showed a record sensitivity for magnetic fields near 14 MHz. This method could be applied to operate in a
Supplementary Information

Dressed states preparation using $^{171}$Yb$^+$ — The experiments are carried out using a single Doppler cooled $^{171}$Yb$^+$ ion confined in a 2-mm-sized Paul trap. The ion is localized in a spatial region of about (20 nm)$^3$. The electronic ground state $S_{1/2}$ splits up into hyperfine states with total angular momentum quantum number $F = 0$ ($|0⟩$) and $F = 1$ ($|−1⟩, |0⟩′$ and $|+1⟩$), where the magnetic quantum number $m_F$ is used as a label (Fig. 1). The degeneracy of the Zeeman levels is lifted by a static bias magnetic field. The second order Zeeman effect shifts states $|−1⟩$ and $|+1⟩$ by different absolute values. The ion is initialized in state $|0⟩$ by optical pumping on the $S_{1/2} F = 1 ↔ P_{1/2} F = 1$ resonance (Fig. 1b)). State selective detection at the end of a measurement sequence is achieved by applying laser light to drive the $S_{1/2} F = 1 ↔ P_{1/2} F = 0$ resonance and detecting scattered resonance fluorescence. After initializing the ion, the preparation of a desired dressed state is done via an incomplete stimulated raman adiabatic passage (STIRAP) sequence [30] with microwave fields.

For that purpose, two microwave fields are used with Gaussian amplitude envelopes shifted in time relative to each other driving the $|−1⟩ ↔ |0⟩$ and the $|+1⟩ ↔ |0⟩$ transitions, respectively. Microwave fields are generated using two phase locked RF sources adjustable in frequency, amplitude, and phase. Depending on the initial state, on the relative phase between the two microwave fields, and on the order of the pulse sequence, the incomplete STIRAP sequence prepares different dressed states, and ends after completion of the sequence in different final atomic states. In order to prepare the dressed state $|B⟩$ starting from the initial atomic state $|+1⟩$, the first pulse of the STIRAP sequence drives the $|−1⟩ ↔ |0⟩$ resonance and the second microwave field the $|+1⟩ ↔ |0⟩$ resonance. A relative phase of $\pi$ between the two microwave dressing fields leads to a transfer of atomic population to the dressed state $|B⟩$. Before probing the final state, a $\pi$-pulse swaps the population of $|−1⟩$ and $|0⟩$. Now it is possible to distinguish the population of states $|B⟩$ and $|0⟩′$ when detecting scattered resonance fluorescence on the $S_{1/2} F = 1 ↔ P_{1/2} F = 0$ resonance.

For inducing Rabi oscillations, an RF pulse is applied during the hold in evolution of the STIRAP pulse sequence (the microwave dressing fields are held at constant amplitude) once the dressed state $|B⟩$ is populated. After the RF Rabi pulse, the STIRAP sequence is completed and the population of state $|0⟩$ is probed. When the RF Rabi pulse populates state $|0⟩′$, the second part of the STIRAP sequence has no effect and population will remain in $|0⟩′$ resulting in a bright signal during detection. Results of the experiment are shown in Fig. 3. Taking into account a possible decay of the contrast due to dephasing, the signal takes the form of $P(T) = \frac{1}{2}[1 + f(T)\cos(\Omega g T)]$. For typical data as shown in

Figure 4. Sensitivity of the dressed state magnetometer. (a) Rabi signal measured for various pulse durations $T$ and different values of $\Omega_g$ plotted versus $\Omega_g T$. The derivative of the blue fitted curve gives the slope $\frac{dP(T)}{d\Omega_g}$ for a fixed time $T$. (b) Sensitivity for changes in $\Omega_g$ as a function of the pulse duration $T$. The sensitivity derived for three exemplary data points in a) is shown with different color coding and marker symbol. For an experimental time $T = 500$ ms a sensitivity of $\delta\Omega_g = (0.2134 \pm 0.0033) \text{Hz/}\sqrt{\text{Hz}}$ is achieved (cyan). For the red data point at experimental time $T = 850.015$ ms a sensitivity of $\delta\Omega_g = (0.2062 \pm 0.0032) \text{Hz/}\sqrt{\text{Hz}}$ is derived. The best sensitivity $\delta\Omega_g = (0.1145 \pm 0.0018) \text{Hz/}\sqrt{\text{Hz}}$ is reached for an experimental time $T = 1500$ ms (green). The blue curve indicates the standard quantum limit.
figure 4, $f(T) \approx$ constant.

The experimental parameters for the data shown in Fig. 3 are as follows: The parameters of the STIRAP pulses are: pulse separation of $5/f_\Omega = 135 \mu s$, pulse width of $8.35/f_\Omega = 224 \mu s$ and discrete time-increments $\Delta t = \frac{1}{f_\Omega} = 2.68 \mu s$, with $f_\Omega = \Omega/(2\pi) = 37.27$ kHz. Each of the 21 measurement points consists of 20 repetitions. The microwave frequency on the $|+1\rangle \leftrightarrow |0\rangle$ resonance is set to 12.6531 GHz and on the $|-1\rangle \leftrightarrow |0\rangle$ resonance it is 12.6325 GHz. In case of the Ramsey measurement with the bare states, two $\pi/2$-pulses on the $|-1\rangle \leftrightarrow |0\rangle$ resonance are applied. The microwave field is slightly detuned from the resonance at 12.6328 GHz. 51 measurement points between 0.1 ms and 10 ms are repeated 50 times.

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