A hybrid polarization-selective atomic sensor for radio-frequency field detection with a passive resonant-cavity field amplifier

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We present a hybrid atomic sensor that realizes radio-frequency electric field detection with intrinsic field amplification and polarization selectivity for robust high-sensitivity field measurement. The hybrid sensor incorporates a passive resonator element integrated with an atomic vapor cell that provides amplification and polarization selectivity for detection of incident radio-frequency fields. The amplified intra-cavity radio-frequency field is measured by atoms using a quantum-optical readout of AC level shifts of field-sensitive atomic Rydberg states. In our experimental demonstration, we employ a split field-enhancement resonator embedded in a rubidium vapor cell to amplify and detect C-band radio-frequency fields. We observe a field amplification equivalent to a 24 dB gain in intensity sensitivity. The spatial profile of the resonant field mode inside the field-enhancement cavity is characterized. The resonant field modes only couple with a well-defined polarization component of the incident field, allowing us to measure the polarization of the incident field in a robust fashion. Measured field enhancement factors, polarization-selectivity performance, and field distributions for the hybrid sensor are in good agreement with simulations. Applications of hybrid atomic sensors in ultra-weak radio-frequency detection and advanced measurement capabilities are discussed.

I. INTRODUCTION

The emergence of quantum sensor technologies is driving a paradigm shift in modern sensing and measurement instrumentation by enabling fundamentally new detection capabilities and performance metrics that are unmatched by those of traditional sensor technology1–4. Quantum sensing of radio-frequency (RF) electric fields5 using Rydberg electromagnetically-induced transparency (EIT) in atomic vapors6 has made rapid progress towards viable quantum RF measurement technologies7–9. Notable advances include the realization of compact sensing elements capable of broadband RF measurement from MHz10 to millimeter-wave11 and THz electric fields12, detection of weak fields at the ~0.1 mV/m level13, to measurements of high-intensity >1 kV/m fields with continuous RF frequency tuning14. Demonstrated applications of Rydberg sensors have included sub-wavelength near-field and far-field imaging of antenna radiation patterns, mapping of microwave circuitry, characterizations of large RF systems such as gigahertz transverse electromagnetic (GTEM) cells15,16, and measurements of RF noise17.

Several limitations still need to be overcome for the Rydberg-EIT RF field measurement method to be applied in practical quantum RF field sensors. These include improving the achievable sensitivity: the most sensitive measurements demonstrated to date have measured fields down to the ~0.1 mV/m level13, limited primarily by EIT line width and shot noise of the optical readout. Further, this sensitivity level has been achieved by detecting small changes in the EIT peak line shape. Extraction of the RF electric field from a

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detailed analysis of the EIT line shape requires a complex model that depends on exper-
imental parameters such as excitation beam powers, diameters, and vapor pressures. These
dependencies may affect the reliability of operation and the suitability as an absolute field
measurement method.

In the present work we explore passive electric-field amplification as a means to achieve
sensitive field detection with the robustness that is inherent to RF field measurements
based on EIT spectroscopy of field-induced Rydberg energy-level splittings or shifts. We
realize this goal by using a hybrid atomic sensor that combines the advantages of Rydberg-
based quantum RF field measurement with those of integrated RF resonator structures.
The demonstrated resonators are solid metal structures that enable passive, polarization-
selective compression and amplification of incident RF fields in an electric-field mode volume
as small as a few cubic millimeters, for resonant RF wavelengths of several centimeters.
While the resonators mimic the function of traditional radio receiver LC circuits, their
small size allows for integration inside cm- to mm-sized spectroscopic vapor cells. As the
field amplification is based on passive electric-field buildup in a rigid metal resonator, the
hybrid atomic sensor enables robust atom-based RF field sensing by measuring spectroscopic
level shifts and splittings that are comparatively insensitive to experimental parameters.

II. EXPERIMENTAL SETUP

The hybrid atomic sensor and its operating principle for RF electric-field sensing is illus-
trated in Figure 1. Figure 1a shows the sensor consisting of an atomic rubidium (Rb) vapor
cell with an embedded resonator structure comprised of two stainless steel frames separated
by a gap. The impinging electric field resonantly couples into the structure, which com-
presses and amplifies the RF electric field within the 0.46 × 0.50 × 9.0 mm resonator gap
volume (geometry shown in Fig. 1b). In our measurements, the incident field propagates
along the z-axis and has a polarization angle Θ relative to the y-axis. The amplified RF
electric field induces Rydberg-level shifts or splittings within atoms located inside the field-
enhancement gap. These are optically interrogated using Rydberg EIT, with laser beams
directed as illustrated in Fig. 1b and transitions as shown in the level diagram in Figure 1c.
The hybrid sensor in Fig. 1 has a resonator structure designed for RF detection in the
C-band. The cavity geometry is designed to optimally ensure a homogeneous amplification
of the field throughout the entire EIT interrogation region, as the beams probe the atomic
Rydberg energy levels in the vapor cell. The design affords a 1-cm optical path length
through the cell, which is sufficiently long to achieve high absorption and signal-to-noise in
the EIT spectra.

We demonstrate field amplification with the hybrid sensor using the experimental setup
shown in Fig. 1a. The RF field in the cavity is measured using Rydberg EIT as a high-
efficiency non-destructive optical probe for field-induced level shifts of high-lying Rydberg
states of 85Rb atoms within the cavity. The relevant 85Rb Rydberg EIT energy-level dia-
gram for optical readout of the field is shown in the inset of Fig. 1c. Two laser beams with
wavelengths 780 nm (probe) and 480 nm (coupler) are counter-propagated and overlapped
along the resonant channel center, as illustrated in Figs. 1b and c. The 780 nm and 480 nm
beams have respective powers of 8 µW and 40 mW, are both focused to a 70 µm full-width-at-half-maximum (FWHM), and have linear polarizations along y. Rydberg EIT readout
is performed by monitoring the 780 nm transmission through the vapor with the laser fre-
quency stabilized to the 85Rb 5S_{1/2}(F=3) to 5P_{3/2}(F=4) transition, while the 480 nm laser
frequency is scanned linearly across a chosen Rydberg level at a repetition rate of a few
Hz. The 480-nm laser scan is calibrated using a Fabry-Pérot frequency reference cavity.
For improved signal-to-noise in the optical readout we perform modulation spectroscopy
by amplitude modulating the 480 nm beam with a 20 kHz square pulse and demodulating
the detected 780 nm signal using a lock-in amplifier. In our measurements, RF fields are
generated using a signal generator, whose output is amplified by a 20 dB amplifier and
passed into an open-ended WR-229 waveguide, as shown in Fig. 1c. The RF frequency is
FIG. 1. (a) Front-end view of a prototype hybrid sensor with resonator embedded in an atomic vapor cell. (b) Illustration of the resonator’s electric-field channel with dimensions (A, B, C)=(0.45,0.50,9.0) mm along y, z and x, respectively, and geometry of the laser beams used for the optical EIT readout of the RF field. (c) Experimental testing setup for the hybrid sensor, and Rydberg EIT energy-level diagram (inset).

varied from 2.577 to 5.154 GHz. The narrow field-enhancement channel of the resonator is positioned approximately 1 cm away from the front face of the waveguide. In Sec. III the RF field is linearly polarized along the y-axis. In Sec. IV the RF polarization is varied by rotating the waveguide about the z-axis by an angle Θ.

III. FIELD AMPLIFICATION

To determine RF electric fields we measure AC Stark shifts of the 31S_{1/2} level. The probe and coupler Rabi frequencies at the beam centers are, for our laser powers and beam diameters, calculated to be $\Omega_p = 2\pi \times 30$ MHz and $\Omega_c = 2\pi \times 15$ MHz, respectively. Figure 2a shows measured 31S_{1/2} Rydberg-EIT spectra as a function of RF field frequency for a fixed RF power of -10 dBm injected into the amplifier and RF field polarization along y. For the utilized 31S_{1/2} Rydberg level the RF field is far-off-resonant from any dipole-allowed Rydberg transition over the entire tested RF frequency range, and the induced level shift is proportional to the incident RF intensity over a wide RF field range. In Fig. 2a, the 480 nm laser frequency is measured relative to the 31S_{1/2} lline position with an applied 2.5 GHz RF field; at this frequency the Rydberg-EIT resonance did not exhibit a measurable intra-cavity RF shift. For increasing RF field frequency, the 31S_{1/2} level begins to substantially shift, with displacements exceeding the EIT line width at around 3.5 GHz and surpassing 300 MHz at the pronounced cavity-induced resonance at 4.35 GHz. At 4.85 GHz we observe a second, weaker resonance. The presence of multiple resonances is not unexpected due to the complexity of the metal structure employed here.

The RF electric fields, $E$, for the data in Fig. 2a are obtained from the measured AC Stark shifts using the relation $E = (4|\Delta|/\alpha_{AC})^{0.5}$, where $\Delta$ is the measured peak line shift and $\alpha_{AC}$ the calculated AC polarizability for the chosen Rydberg state and RF field frequency. For the Rb 31S_{1/2} state $\alpha_{AC} = 1.7458 \times 10^{-4}$ MHz/(V/m)^2, which varies by less than 0.2% over the 2.5 to 5.2 GHz frequency range of interest here. Figure 2b shows the calculated shift of the 31S_{1/2} Rydberg state as a function of RF $E$-field. Figure 2c shows the RF
FIG. 2. Field amplification in a hybrid atomic RF sensor. (a) Measured $31S_{1/2}$ Rydberg EIT spectra, with 480-nm-laser frequency detuning along the vertical axis, as a function of RF field frequency, at a fixed -10 dBm power injected into the RF amplifier that feeds the microwave transmitter waveguide. (b) Calculated AC Stark shift of the $31S_{1/2}$ Rydberg state versus RF electric field for an applied 4.35 GHz RF field. (c) Intra-cavity RF electric field $E$ extracted from the measurements in (a) and the mapping function in (b).

$E$-field measured inside the cavity as a function of RF field frequency, obtained from the measured spectra in Fig. 2a and the calculation in Fig. 2b. At the 4.35 GHz resonance, we measure a cavity-enhanced field of $E = 2690$ V/m with a relative uncertainty of 50 V/m, set by the ∼0.1 MHz fitting uncertainty of the peak position.

To determine the cavity-induced electric-field enhancement factor in the hybrid cell, we compare the cavity-enhanced field at 4.35 GHz in Fig. 2 with a reference measurement of the RF electric field outside of the cavity. To obtain the latter, the EIT beams are moved from $z = 0$, the center of the cavity, by $\Delta z = -0.9$ mm towards the front of the vapor cell. To obtain a measurable line shift (and field reading) at the reference position outside the cavity, the injected microwave power is increased from -10 to -5 dBm, corresponding to a factor of 3.16 higher incident power and 1.78 higher incident field amplitude, compared to the conditions used in Fig. 2. At the reference position we measure a microwave-field-induced AC-Stark shift of $-3.80$ MHz, or a field amplitude of $E = 295$ V/m. Hence, the field enhancement factor afforded by the cavity is $2690 \times 1.78 / 295 = 16.2$, corresponding to a 24.2 dB gain in RF field intensity. In this estimation we neglect that the EIT beams are moved closer by a minute amount (0.9 mm) to the waveguide aperture (which has a short side of 29.1 mm).

We benchmark the measured gain in the hybrid sensor against simulations of the electric-field mode function of the resonance in the cavity for an incident 4.37 GHz field of amplitude 1 V/m linearly polarized along $y$. Figure 3a shows the simulated RF electric field in the gap of the resonator, which is seen to be resonantly enhanced by a factor of about 18.6, corresponding to a 25.4 dB intensity amplification. This is in excellent agreement with our measured value of 24.2 dB. The fact that the measured gain is slightly lower may be due to the 0.9-mm change in EIT beam position, or differential refraction and reflection effects of the dielectric materials involved. A systematic study of the effect of dielectric cells on RF electric-field measurements with vapor cells is a topic of interest that is beyond the scope of the present work.

In Fig. 2a the EIT line width increases from 21.7 MHz at 2.50 GHz to 84.0 MHz at the 4.35 GHz resonance. We attribute this to the mode function inhomogeneity of the 4.35-GHz resonance within the measurement volume. The mode function, a calculated cut of which is shown in Fig. 3a, describes the field distribution that is specific to the resonant modes, and the measurement volume is given by the geometry of the laser beams that constitute the optical EIT field probe. The inhomogeneity of the resonant field mode is strongest at the cavity edges, which are sampled by the wings of the optical beams. To characterize the field homogeneity in the enhancement region of the hybrid device, we perform a spatial scan of the EIT beams along $z$, relative to the center of the resonator channel at $z = 0$. Figures 3b and c show the $31S_{1/2}$ Rydberg-EIT lines and the averages of the 4.35-GHz microwave field...
derived from the line shifts, respectively, measured as a function of the spatial shift $\Delta z$ for -2 dBm input power. The broadening of the EIT line is mostly given by the variation of the mode field along the $z$-direction. The EIT line width increases away from the center of the cavity channel at $z = 0$, reaching a maximum at $\Delta z \approx \pm 0.3$ mm at the edges of the 0.5 mm-wide channel. The asymmetric decrease in the broadening to either side of the channel is in good qualitative agreement with the calculated field map shown in Fig. 3a. In Figure 3b it is seen that the FWHM of the average-field profile versus $z$ is 0.6 mm, in good agreement with the calculated field profile of the mode.

**FIG. 3.** (a) Finite-element simulation of the resonant electric-field mode function in the hybrid sensor resonator with a $0.46 \times 0.50 \times 9.0$ mm gap for an incident 4.35 GHz microwave field propagating along $z$ with a field of 1 V/m linearly polarized along $y$. The field strength ranges from 1 V/m (blue) to 18.6 V/m (red). (b) $31S_1/2$ EIT spectra versus EIT beam position $\Delta z$ relative to the cavity center for a 4.37-GHz incident microwave field polarized along $y$ at a power of -2 dBm injected into the amplifier. (c) Microwave electric field amplitude versus EIT beam position obtained from the EIT spectroscopic data in (b). Error bars correspond to the fit uncertainties in the peak positions.
IV. POLARIZATION SENSITIVITY

Another feature of hybrid devices is their ability to discriminate between different RF polarizations. For the resonant structure employed here, the cavity acts as a RF-polarization filter in which only RF fields with a linear polarization component along the $y$-axis of the cavity are coupled into the resonator and field-enhanced within the active measurement volume. The orthogonal RF polarizations are rejected.

Figure 4a shows experimental $31S_{1/2}$ Rydberg spectra as a function of RF field frequency at a fixed injected power for different angular alignments $\Theta$ of the RF polarization vector relative to the $y$ axis (see Fig. 1a). This is accomplished by rotating the waveguide in the $xy$-plane counter-clockwise about the $z$-axis from $\Theta = 0^\circ$ (short waveguide axis along $y$) to $90^\circ$ (short axis of waveguide along $x$) in $10^\circ$ increments. At $\Theta = 0^\circ$ the RF polarization is aligned with the polarization of the resonant cavity-mode function, resulting in maximal coupling into the resonator (black curve in Fig. 4a). As $\Theta$ is increased, the field-induced shift of the EIT peak decreases because the projection of the incident RF electric-field vector onto the $y$-axis is reduced. In Fig. 4b we plot of the RF electric field in the cavity, obtained from the measured AC-Stark shifts of the EIT lines shown in Fig. 4a, as a function of $\Theta$. As $\Theta$ is increased, the $y$-component of the field (the component that couples into the resonant field mode of the cavity) decreases as $\cos(\Theta)$. A cosine fit to the data, given by the dashed curve in Fig. 4b, confirms this expectation. It follows that the intensity of a linearly polarized,
resonant electromagnetic wave coupled into the resonator and detected by the atoms within the resonator gap has a $\cos^2(\Theta)$-dependence. If the field is measured via an AC Stark shift, as done in the present work, the EIT line shift is $\propto \cos^2(\Theta)$. It is therefore seen that the cavity resonator emulates the functionality of an integrated microwave polarizer, in a way that mimics Malus’s law.

In Fig. 4 we see that the 4.35 GHz field inside the cavity does not reach exactly zero at $\Theta = 90^\circ$. The residual intra-cavity field at $\Theta = 90^\circ$ may arise from cavity imperfections, such as slight electrode misalignment and surface-quality issues, as well as from slight polarization imperfections of the field emitted by the waveguide. Such effects are not unexpected for components that are traditionally fabricated at machine tolerances.

V. DISCUSSION AND CONCLUSION

A hybrid atomic sensor incorporating a resonant structure for passive radio-frequency field amplification with an atomic vapor cell has been demonstrated. Hybrid detectors with resonator structures either internal or external to the atomic vapor cell and optical readout medium are anticipated to provide improved performance capabilities for Rydberg-atom-based RF field sensors, including high field sensitivity and polarization selectivity for directional field detection.

In the device presented here, the enhancement channel and optical beam geometries were designed to ensure the amplified microwave field remained relatively homogeneous throughout the atomic detection volume, for optical beam sizes that are large enough in diameter so as to avoid interaction-time broadening of the EIT line (given by the average transit time of the thermal atoms through the beams). For measurement applications requiring EIT line widths narrower than realized with the present geometry, the probe and coupler Rabi frequencies can be reduced to lower the homogeneous EIT line width, and the inhomogeneous field broadening can be reduced by using smaller-diameter laser beams or larger resonant structures with more homogeneous field mode functions, or by a combination of such measures. Minimization of the line broadening will be beneficial, for instance, in hybrid sensors for weak-field microwave measurement based on small transmission changes of very narrow EIT line shapes$^{5,13}$.

We further note that the observation of multiple resonances in Fig. 2 as well as the general characteristics of eigenmode problems reinforce that it will be possible to engineer hybrid atomic sensors for passive RF field amplification and sensitive detection at selected, application-specific RF frequencies.

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