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Rydberg atom-based sensors for radio-frequency electric field metrology, sensing, and communications☆

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ABSTRACT

The recent redefinition of the SI bolsters the push towards quantum-based sensors. Rydberg atoms provide a natural link between atomic quantities and electromagnetic fields, where direct absolute measurements can be challenging. We review recent demonstrations of SI-traceable electric field metrology for both high frequency and static fields, communications reception, and angle-of-arrival detection using Rydberg atom spectroscopy.

1. Background

Rydberg atoms are very sensitive to external fields [1], making them a promising platform for field sensors and detectors [2]. The development of high-power, tuneable, single-frequency diode lasers in the visible spectrum enabled multi-photon excitation and spectroscopy of room-temperature Rydberg states of alkali atoms. Since 2010, there has been a growing use of Rydberg atoms for the measurement and detection of radio-frequency (RF) fields (from MHz – THz) [3–8]. Initial applications of this technique focussed around the direct measurement of RF field strength, but the high sensitivity and extremely large frequency range of this technique extended their application to more general quantum sensors. In this work, we review some recent developments and present new results of Rydberg atom-based quantum electric field sensors to demonstrate the breadth of applications that are possible with Rydberg atoms.

2. Rydberg atom sensors for fundamental metrology

The technique at the heart of Rydberg atom-based RF sensing in a room-temperature atomic vapor is electromagnetically induced transparency (EIT). This spectroscopic technique allows direct optical probing of high energy Rydberg states, such that the effect of an RF field can be read out on a photodetector. EIT occurs when both a probe laser, tuned to a ground state transition, and a coupling laser, tuned to a Rydberg transition, are incident on an evacuated glass cell filled with a single atomic species, typically rubidium (Rb) or caesium (Cs). EIT creates a narrow transmission peak of the probe laser within the larger Doppler absorption region. The Rydberg states are highly sensitive to external electric fields, which perturb the EIT in predictable ways. Fields that are not resonant with a Rydberg transition cause Stark shifts, while resonant fields cause a splitting of the EIT peak. These effects can be used to determine the strength of the external field or receive a signal sent by modulating the field.

2.1. RF field strength metrology

When an RF field that is resonant with a nearby Rydberg transition is also incident on the atoms, this EIT peak splits into two with a separation Δf, in the effect known as Autler-Townes splitting [9]. The separation Δf in optical frequency is directly related to the strength of the applied field E via

$$\Delta f = \frac{\wp}{h}|E| \tag{1}$$

The measured splitting only depends on the field strength, Planck's constant, and the dipole moment of the Rydberg transition, which can be reliably calculated [10]. This equation is valid for a large range of energy levels, which spans a large range of RF frequencies, from MHz – THz. Fig. 1 shows the field strength measured by the atoms vs. RF input power to a horn antenna [6]. This demonstrates atom-based measurements from 10 GHz–200 GHz.

2.2. DC/AC voltage metrology

Low-frequency and DC electric field strengths can be determined by measuring the Stark-shift of the EIT peak. The frequency shift of the EIT peak Δ_{EIT} is related to the electric field amplitude E by

$$\Delta_f = -\frac{\alpha}{2}|E|^2 \tag{2}$$

where Δ_f is the Stark shift of the EIT peak and α is the polarizability of the atom [11]. We create the electric field using parallel-plate electrodes embedded in a Rb vapor cell. This configuration generates an electric field of V/d between the plates, where V is the voltage and d is the separation between the plates. The voltage can then be determined by measuring the Stark shift via

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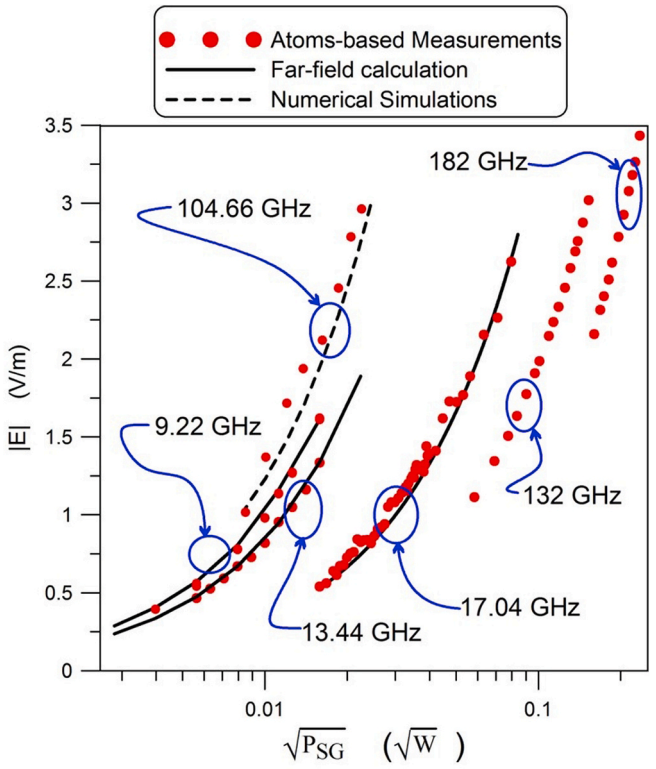

Fig. 1. Measured and calculated RF field strengths vs. input RF power over a large range of frequencies. All measurements use the same vapor cell, and $\sqrt{P_{SG}}$ is the square root of the power out of the signal generator [6].

$$V = d\sqrt{\frac{2\Delta_f}{\alpha}} \tag{3}$$

Fig. 2 shows an example of the EIT shift of a Cs 40 $S_{1/2}$ state with various applied voltages from 0 to 1.6 V. The polarizability increases with energy level n, so higher energy Rydberg states can be used for lower voltages. This Rydberg atom-based voltage measurement technique is being investigated as an accurate, stable and portable voltage reference [12–14].

2.3. RF power metrology

The Rydberg atom field measurements can also be used to determine RF power. Inside an RF rectangular waveguide, the relation between the peak electric field and power is well-defined by the relation

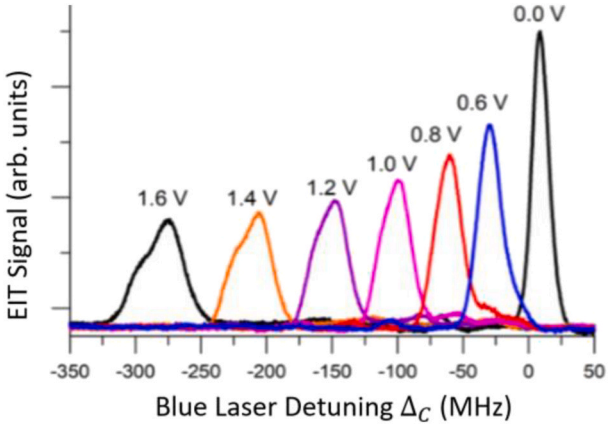

Fig. 2. EIT shifts in frequency in direct relation to the applied electric fie ld magnitude, from Ref. [14]. Δ_c is the coupling laser detuning.

$$P = E_0^2 \frac{ab}{4}\sqrt{\frac{\varepsilon_0}{\mu_0}}\sqrt{1-\left(\frac{c}{2af}\right)^2} \tag{4}$$

where E_0 is the amplitude of the electric field at the center of the waveguide, a and b are the width and height of the waveguide cross-section, respectively (a being the larger dimension), f is the RF frequency, ε_0 and μ_0 are the permittivity and permeability of free space, respectively, and c is the speed of light in vacuum [15]. With this relation and the known waveguide geometries, an SI-traceable measurement of power can be achieved by placing the atomic vapor in a waveguide and measuring the field strength at the center of the waveguide. Traceable power measurements using the Autler-Townes splitting technique have been demonstrated at discrete microwave frequencies in a WR-42 waveguide [16].

3. Communications & sensing applications

Recent developments have enabled the use of Rydberg atoms for RF phase detection, by using the atoms as a nonlinear mixing medium [17,18]. This has direct implications for communications reception and spectrum analysis. This has also opened up other types of sensing, including near-field antenna pattern measurements [19] and direction of arrival of an RF field [20].

3.1. Communications applications

The high sensitivity of Rydberg atoms to fields over a very large range of frequencies (from DC to THz) makes them attractive for communications reception. Over the last few years, Rydberg atoms have been used to receive amplitude modulation [21–23], frequency modulation [24,25], phase modulation [20,26], and various quadrature and amplitude modulation (QAM) schemes. For instance, in Ref. [26] reception of modulation up to 64 QAM was demonstrated in a Cs vapor cell with a 1 MHz modulation bandwidth. Another notable feature is the direct conversion of the RF modulation to an optical modulation of the probe beam, allowing for a radio-over-fiber link [27].

Phase sensitive detection is possible through the use of a local oscillator (LO) field, in an atom mixer or super-heterodyne configuration [17,18]. When the LO is slightly detuned from the signal field, the low-frequency difference between the two fields is generated in the probe field by the atomic response, whose phase is directly related to the phase difference between the two fields. When the LO and signal frequencies are equal, as in a homodyne atom mixer configuration, the field strength seen by the atoms is related to phase difference. By scanning the LO frequency, various signal frequencies can be detected and received selectively, creating an atom-based spectrum analyzer. In Fig. 3, we show new results of scans of the LO for various signal frequencies using a resonant LO. This frequency range can be extended using an off-resonant LO with the AC Stark effect [28], such that the atoms can detect frequencies continuously from 0 to 20 GHz.

Phase-sensitive detection in a heterodyne configuration (with a slightly detuned LO) has been used to improve sensitivity. A sensitivity down to 55 nV/cm $\sqrt{\text{Hz}^{-1}}$ and a minimum electric field of 780 pV/cm have been demonstrated with this method [18].

3.2. Angle-of-arrival

Due to the subwavelength nature of the atomic detection, phase detection with the Rydberg atoms can be used to determine the direction of arrival of an RF field [20]. Fig. 4 shows an example configuration where two optical probes within a single vapor cell are used to measure the spatial phase variation given a signal RF field propagating along the black arrow. The blue line defines the axis of the two optical probes and the angle of arrival of the RF field is given by

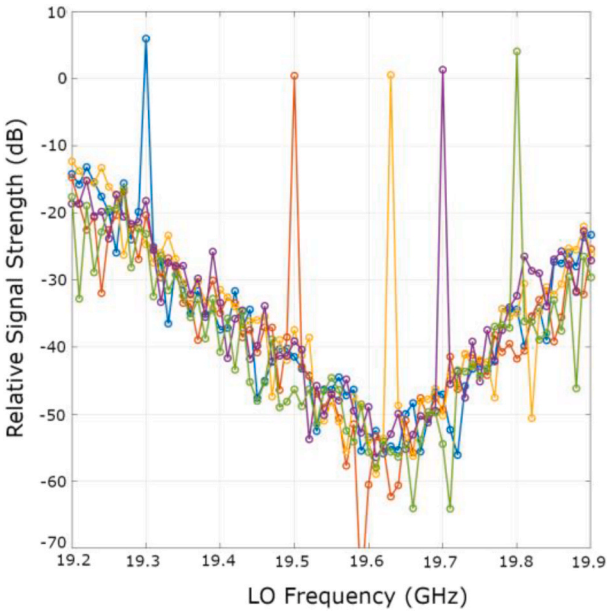

Fig. 3. Several scans of the LO frequency, each with a different signal frequency, with a signal strength relative to a resonant signal field (at 19.6 GHz) in dB. The signal strength was normalized, because the sensitivity drops away from resonance.

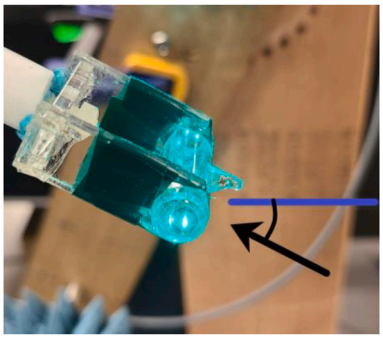

Fig. 4. Rydberg sensor used for angle-of-arrival measurements [20]. Two probe paths propagate through the cell to make phase measurement.

$$\theta = \sin^{-1}\left(\frac{\varphi_2 - \varphi_1}{kd}\right) \quad (5)$$

where φ_1 and φ_2 are the measured phase at each optical probe location, d is the distance between the two optical probe locations, and $k = 2\pi/\lambda$, and λ is the wavelength of the RF signal.

In a recent development, we extend these angle-of-arrival measurements to two-dimensions and use them in the context of channel sounding measurements. In this case, a fiber-coupled Rydberg atom probe is placed inside an anechoic chamber. By scanning the probe across a two-dimensional plane, phase measurements are captured (Fig. 5) and used to locate a series of scatterers (a corrugated plate) within the chamber. Fig. 6 shows the angular distribution of scatterers predicted by the phase measurements. The radial axis is the elevation, and the angular axis is the azimuthal direction. These results correspond closely to the scattering from the corrugated plate oriented with the azimuth.

This 2D measurement might also be made by an array of vapor cells instead of scanning a single probe, creating an RF camera. This would allow rapid measurements of phase and amplitude, which could be used to determine the characteristics of the RF channel environment, improving communications metrology for next generation wireless infrastructure.

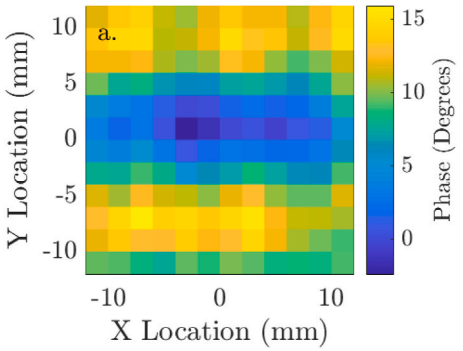

Fig. 5. 2D measured phase differences with an RF scatterer placed at in the YZ plane at X = 25 cm.

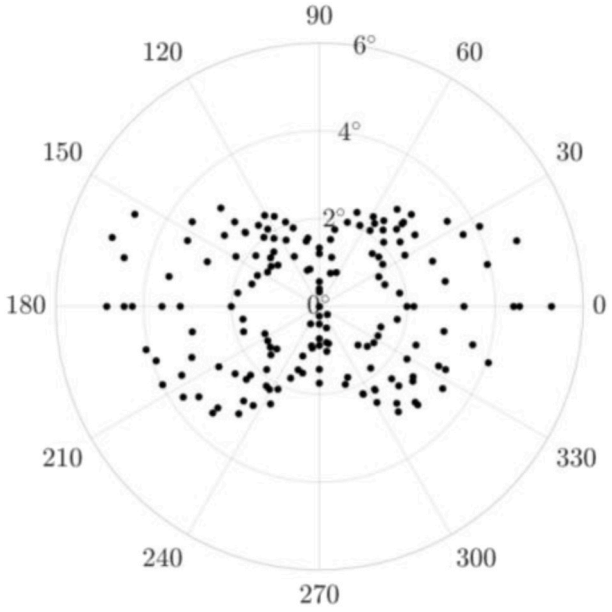

Fig. 6. Measured angle of arrival distribution where the phase angle in the plot shows the elevation angle (in spherical coordinates) of the measured RF field from the scatterer and the radial position in the plot gives the azimuthal angle (in spherical coordinates).

4. Conclusions

Rydberg atoms have proven to be a flexible platform for quantum-based electric field sensing. Starting from fundamental RF field metrology, this technique has been used to perform various types of sensing including low-frequency and DC voltage measurements, broadband spectrum analysis, in-situ RF power measurements, and angle-of-arrival detection. Recently, an array of atom-based measurements has been shown to have application to next-generation channel sounding measurements. This is only a sample of the recent results in Rydberg atom-based RF field sensing.

Acknowledgments

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