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Rydberg Atoms for One-Step Traceability for Sensing Electric Fields

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Summary:

Absolute electric field measurements present a “chicken-and-egg” situation where calibration of field probes relies on accurate knowledge of the field while precise determination of the field involves measurements with a calibrated probe. Metrology institutes overcome this dilemma by employing careful geometric measurements, Maxwell’s equations, and a long chain of calibrations to determine absolute field strength with order of 5% uncertainty. We describe an alternative approach using Rydberg atoms that ties radio frequency electric field strength to Planck’s constant through calculable quantum properties of the atoms for improved accuracy and simplicity. In addition to improved calibrations, Rydberg atom probes can be used as sensors and receivers for a wide swath of applications that we describe.

Keywords: Rydberg atoms, electrometry, revised SI, radio frequency, sensing, communications

Introduction

Rydberg atoms are highly excited atoms with high sensitivity to electric fields making them attractive for measurements and sensing. By selecting alkali atoms, like rubidium (Rb) or cesium (Cs), which have a single valance electron, we can accurately calculate the quantum mechanical response of these atoms to incident radio frequency (RF) electric fields. We employ a spectroscopy technique known as electromagnetic induced transparency (EIT) and a resonant effect known as Autler-Townes (AT) splitting to precisely determine RF field strengths radiated onto the atoms [1]. These techniques and some use cases are described in this paper.

One-Step Traceability with EIT/AT

We begin with a vapor cell filled with room temperature alkali atom vapor. A probe laser, resonant with the transition between the ground state $|1\rangle$ and first excited state $|2\rangle$ of the atoms is strongly absorbed as it propagates through the vapor cell before being measured by a photodetector as depicted in Fig. 1. Due to the motion of the room temperature atoms state, the resonant absorption line is broad, on the order of 100s of MHz as depicted in Fig 2. However, a narrow <10 MHz transmission window can be induced by applying a second (coupling) laser that is resonant with state $|2\rangle$ and a Rydberg state $|3\rangle$ and produces EIT.

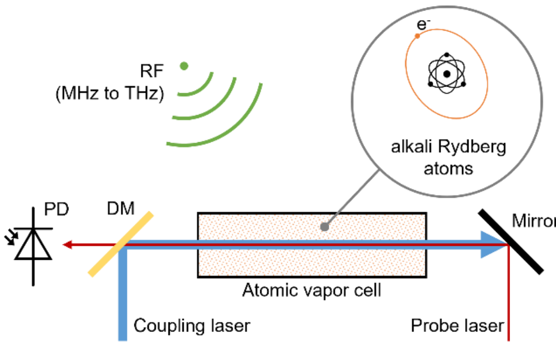

Fig. 1. Diagram of the electric field measurement setup. PD-photodetector, DM-dichroic mirror.

By using the coupling laser to excite the atoms to a Rydberg state, an RF field can be applied that is resonant with state $|3\rangle$ and a second Rydberg state $|4\rangle$ causing the EIT spectral line in Fig. 2 to split, an effect known as AT splitting. The frequency separation Δf between the split AT lines is directly proportional to the amplitude of the incident RF electric field $|E|$ with $\wp$, the atomic dipole moment of the RF transition, and h, Planck’s constant, as proportionality constants: $|E| = (h/\wp)\,\Delta f$.

This splitting is valid for a wide range of RF frequencies, from MHz to THz, and the resulting field measurement can be completed with 1% uncertainty [2]. Very strong RF fields (>10 V/m) cause an additional Stark shifting effect that goes as $|E|^2$ and require a more complicated Floquet analysis [5]. Very weak fields

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(<10 mV/m), on the other hand, induce splitting that is not resolvable, but a linear response can still be achieved by applying a second RF field as a local oscillator (LO) detuned from the test field by an intermediate frequency (IF) on the order of kHz. When the frequency of probe and coupling lasers is locked, the photodetector signal turns into a sine wave at the IF with an amplitude and phase that is proportional to the test RF field [6]. Using this technique, Rydberg atom sensors have been shown to achieve sensitivities down to 5 $\mu Vm^{-1}Hz^{-1/2}$ [7] and as receivers of amplitude, frequency, and/or phase modulated signals [9,10].

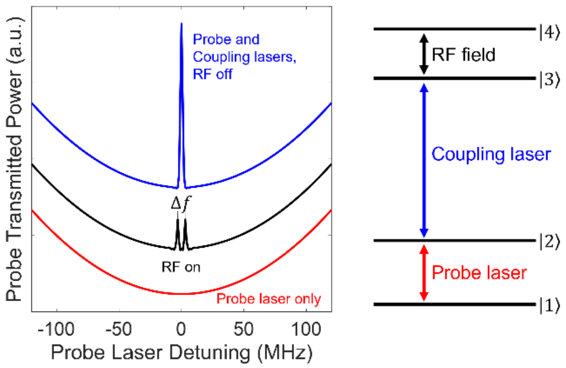

Fig. 2. EIT signal with Doppler background as probe laser frequency is detuned. Frequency separation between the two peaks generated when the RF field is on provides a traceable measurement of the RF electric field strength.

Rydberg atoms for sensing and receiving

In the AT splitting regime, the Rydberg atom-based technique provides a direct traceability path for RF electric field strength to the fundamental units of the SI, namely Planck's constant, through the calculable response of the atoms, the dipole moment $\wp$, dictated by quantum mechanics. Not only is this an excellent tool for field strength metrology, but the Rydberg atoms also turn out to be useful in sensing, communications, and RF power metrology.

At NIST, we have demonstrated the use of Rydberg atoms for in situ, traceable measurements of power in waveguide [11], voltage reference measurements [12], and determination of the angle of arrival of an over the air test signal [13]. We have studied a scheme that extends the sensitivity of the Rydberg atoms to lower, few MHz, RF frequencies by applying an additional GHz field to engineer the desired Rydberg atom response [14]. Dressing the atoms with other RF fields also allows us to stretch the resonant AT behavior over a continuous range of RF frequencies [15]. Most recently, we have demonstrated an interferometric technique that enables detection of RF phase without the need for an RF LO [16]. Rydberg atom-based receivers operate over an extremely wide band of RF frequencies (MHz to THz). They also can be electrically small, and the dielectric sensor head minimizes scattering of the incident field. These features of Rydberg atoms are unlike classical antennas.

Conclusion

We define the benefits of using Rydberg atoms for one-step traceability for sensing RF electric fields. In addition, we review many other applications that are under investigation at NIST using these atoms, highlighting the unique features of this measurement system as compared to classical antennas.

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