<u>*ARFTAG 2017 SUMMARY*</u>

Rydberg Atom Electric-Field Metrology

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***Abstract* — We present a technique which shows great promise for realizing an atomic standard measurement of RF fields that is intrinsically calibrated, directly linked to the SI and atomic structural constants. This technique relies on the response of Rydberg atoms to radio frequency (RF) electric-field measurements. The rich resonance response of these atoms occurs across a large frequency range from hundreds of MHz and approaching 1 THz. Alkali atoms such as rubidium (Rb) and cesium (Cs) confined in a glass vapor cell are optically excited by two different lasers to high energy Rydberg states. Once in the Rydberg state the atoms exhibit a significant response to RF fields which alters the optical spectrum of the atoms. The RF field strength is then directly obtained from the optical spectrum. We discuss the theory behind this technique. Measurements in the far-field of a standard gain horn antenna as well as a coplanar waveguide mode are made. We also show a recently developed quantum electric-field probe based on this Rydberg atom technique, which is constructed from a fiber optically coupled vapor cell is used for these measurements.**

***Index Terms* — Antenna; Coplanar waveguide; Electromagnetically Induced Transparency (EIT); Far-Field; Electric Field; Radio Frequency; Rydberg Atoms**

I. INTRODUCTION

In the past several years much progress has been made in atom-based sensing of radio- frequency (RF) electric-fields [1-5]. In particular, a relatively new technique for converting an RF field amplitude into an optical frequency response in a gas of atoms has shown much promise. A primary goal is to realize an atomic standard measurement of RF fields that is intrinsically calibrated and directly linked to the SI. Such a measurement consists of a gas of room temperature alkali atoms such as Rubidium (Rb) and Cesium (Cs) contained in a glass vapor cell which are optically excited to a high enough energy such that the atoms become resonant to RF fields. Two lasers can be used to accomplish this. One for initial excitation and a second to increase the atom's energy to where the outer electron orbit is large enough such that the atom behaves much like a hydrogen atom. Such an atom is referred to as a Rydberg atom [6] and can act like a nano-sized antenna which will respond favorably to RF fields.

While in the Rydberg state, the atom exhibits a large response (i.e., a large dipole moment) to RF-fields over the frequency range of about 500 MHz-1 THz. To the lasers, the atomic gas acts like a non-linear optical medium that experiences changes in electrical susceptibility when interacting with an RF field. A consequence of this is that in the absence of the RF field the atomic gas would preferentially transmit a single optical frequency when an RF-field is present two optical frequencies are preferentially transmitted. It can be shown that the difference in the two optical frequencies is linearly proportional to the applied RF-field amplitude [1,4]. In this paper, we discuss the theory behind this phenomenon and how it can be used for performing atom-linked SI-traceable measurements of RF fields. Experimental results are obtained using a recently developed quantum electric field probe based on a fiber optic coupled Rydberg atom micro vapor cell. Results demonstrating the broad frequency range of operation, field strength in the far-field of a standard gain horn antenna, and the near-field mode structure of a coplanar waveguide are presented.

II. ATOM BASED ELECTRIC FIELD METROLOGY

A. Measurement Scenario

A typical measurement scenario is shown in Fig. 1. Rydberg atoms are generated using two different wavelength lasers. For example, in Rb vapor, the probe laser is tuned to excite the D_2 transition $(5S_{1/2} - 5P_{3/2})$ around $\lambda_p \cong 780\ nm$ (red) and the coupling laser is tuned to $\lambda_c \cong 480\ nm$ (blue) in order to excite the final Rydberg states. Fig. 1. shows the specific scenario of exciting the $5P_{3/2} - nD_{5/2}$ transition, where n is the principle quantum number and depends on the exact λ_c chosen. The Rydberg state leads to a strong RF response of the atoms which manifests as the $nD_{5/2} - (n+1)P_{3/2}$ transition. That is, the energy required to cause a Rydberg atom to transition states is matched with that carried by an RF photon. These two lasers are aligned to counter propagate collinearly and are focused at the center of the vapor cell to a nominal $1/e$ beam diameter of around $100\ \mu m$. Beam powers for the probe and coupling laser are nominally 100 nW and 30 mW respectively. A dichroic filter which reflects λ_c and transmits λ_p aids in overlapping the two beams and a band pass filter rejects stray light. The probe laser transmission through the vapor cell is measured with a silicon photodiode detector. It is the *spectrum of the transmitted probe laser* that is of primary interest in determining the strength of the incident RF field.

This is discussed next. For a more detailed discussion of this type of laser system setup the reader is encouraged to see [1].

B. Electric Field Through Rydberg Atom Spectrum

The action of the RF field on the atoms can be connected to the probe laser spectrum by considering the optical susceptibility χ of the Rydberg vapor. As a full derivation of the susceptibility is outside the scope of this paper, we refer the reader to [7] and [8] for an in depth theoretical treatment. Here, we present the thought process and final important results for RF electric-field metrology. The imaginary part of the refractive index can be obtained using the fact that $\sqrt{(1+\chi)} = n + jk$. With n being the real part, thus affecting the phase of the probe beam, and k the imaginary part, which governs the degree of absorption experienced by the probe beam as it traverses the vapor cell. When only the probe laser is present and resonant with the D_2 transition, much of the light will be absorbed by the atoms. However, it can be shown that when both the probe (resonant with D_2 transition) and the coupling (resonant with a Rydberg transition i.e. $5P_{3/2} - nD_{5/2}$) lasers are present, a transparency window occurs for the probe laser beam where absorption of the probe laser is significantly reduced. This phenomenon is well documented and known as Electromagnetically Induced Transparency (EIT) [9].

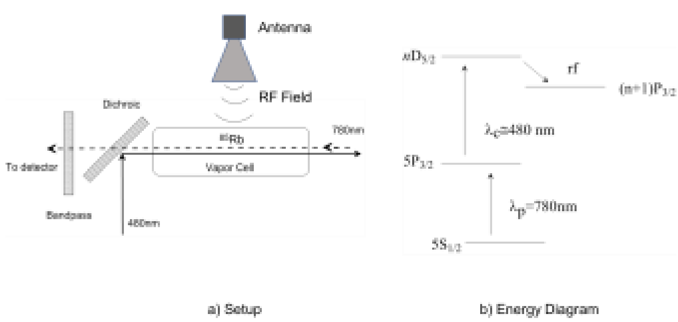

Fig. 1. a) Typical elements in a setup for sensing RF fields using Rydberg atoms in a vapor cell full of ^{85}Rb atoms. (Dotted) The 780 nm probe and 480 nm (Solid) coupling laser would in actuality be overlapping, but are shown here displaced for clarity. b) Energy level diagram for ^{85}Rb.

EIT is observed as a *transmission peak* in the *absorption* spectrum of the probe laser. Furthermore, when in addition to the probe and coupling lasers, an RF field is present and on resonance with a Rydberg transition, the EIT peak splits into two peaks. These two scenarios, one with RF and one without are shown in Fig. 2. The two peaks occur above and below the center frequency of the D_2 transition, $f_{D2} = 384.23\, ...\, THz$. Through the susceptibility χ it is found that the frequency separation of these two peaks Δf_{probe} as measured in the probe laser absorption spectrum is proportional to the RF field strength [10], [11], as,

$$\Delta f_{Probe} = \frac{\lambda_c}{\lambda_p}\frac{\wp_{RF}|E_{RF}|}{2\pi\hbar}\ , \qquad (1)$$

where $\wp_{RF}$ is the atom's dipole moment for the RF transition (analogous to the dipole moment of an antenna), $\hbar$ is Plank's constant, $|E_{RF}|$ is the magnitude of the RF field and λ_c and λ_p are the wavelengths of the coupling and probe lasers respectively. From this expression, a measurement of the RF electric field magnitude has been reduced to an optical frequency measurement. An example spectrum is shown in in Fig 2. The splitting is clearly observed when an RF field at a frequency of 182.15 GHz is incident on a Rb vapor cell. For reference this splitting corresponds to a strength of 0.735 V/m.

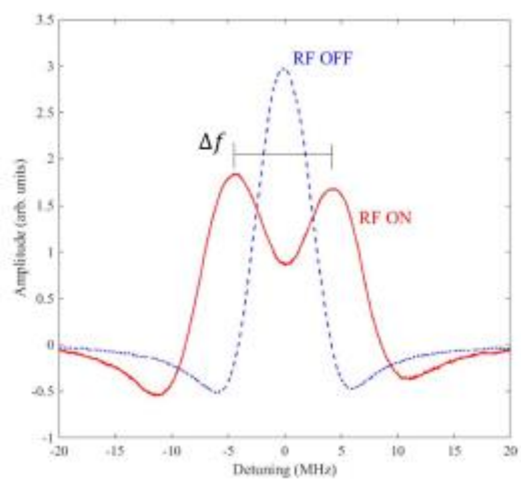

Fig. 2. The optical spectrum for the probe laser. (Dotted) RF field turned off. Only a single EIT peak is observed. (Solid) An applied RF field of 0.735 V/m at 182.15 GHz incident on the vapor cell splits the peak into two peaks separated by an amount Δf.

III. Measurements

A. Field Strength Measurements

For each Rydberg state, there is a corresponding RF transition and associated dipole moment. The RF transition frequency for a given coupling λ_c can be calculated using the total ionization energy of the atom and corresponding quantum defects [11]. Therefore, the coupling laser need only change a few nanometers in order to tune the atom from about 500 MHz up to about 1 THz. As an example, with ^{85}Rb consider cases (a) where the coupling laser is set to $\lambda_c = 479.32\, nm$, and case (b) where $\lambda_c = 483.60\, nm$. In case (a) the corresponding RF frequency occurs at 2.03 GHz whereas in case (b) it occurs at 150.40 GHz. This is depicted in the energy diagram shown in Fig. 3. where by tuning λ_c by about 4 nm the RF resonance frequency is tuned by almost 150 GHz.

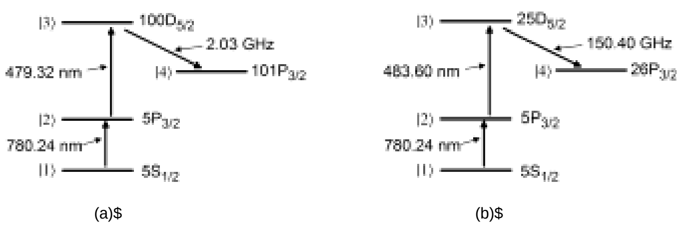

Fig. 3. Energy diagram for [85]Rb showing RF frequency tuning via couple laser wavelength. Tuning the coupling laser by approximately 4 nm achieves almost 150 GHz of RF tuning.

Field measurements across the ULF, L, D, and G bands demonstrating this broadband tuning are shown in Fig. 4. RF frequencies at 723.78 MHz, 1.013 GHz, 132.65 GHz, 171.41 GHz, 182.16 GHz, and 203.32 GHz are shown over various field strengths. As there are no traceable sources above 110 GHz this Rydberg approach may provide a path to a solution. These measurements were obtained in the far field of a standard gain horn antenna operating in-band for the respective frequencies.

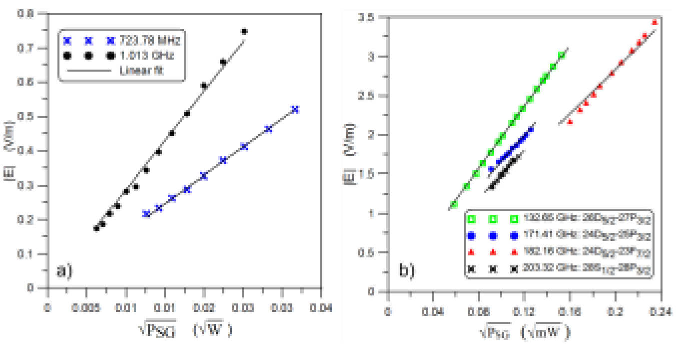

Fig. 4. Demonstration of the broad tuning property of the Rydberg atom approach. Plot a) is within the ULF to L band. Plots b) show measurements within the D and G band.

B. Near-field Coplanar Waveguide Mode

A newly developed quantum E-field probe head [12] was constructed by bonding single mode optical fiber to a cubic micro vapor cell 10 mm on a side. The micro cell was filled with [133]Cs atoms. The quantum E-field probe head is shown in Fig. 5. Traditional use of free-space laser beams confines measurements to an optical table, however, fiber coupling the micro cell overcomes this limitation and allows for the quantum E-field probe to be removed from the optical table. This is a recent advancement which now enables measurements off the optical table. This is demonstrated by measuring the mode symmetry of an unbalanced coplanar waveguide mode [12] as shown in Fig. 6. The symmetrical mode for an ideal CPW was simulated using Ansys HFSS software (mention of this product is not an endorsement but only serves to clarify what was done). However, imperfections in the feed structure and lack of air bridges produce asymmetries in the mode not easily simulated. This is apparent in Fig. 6.

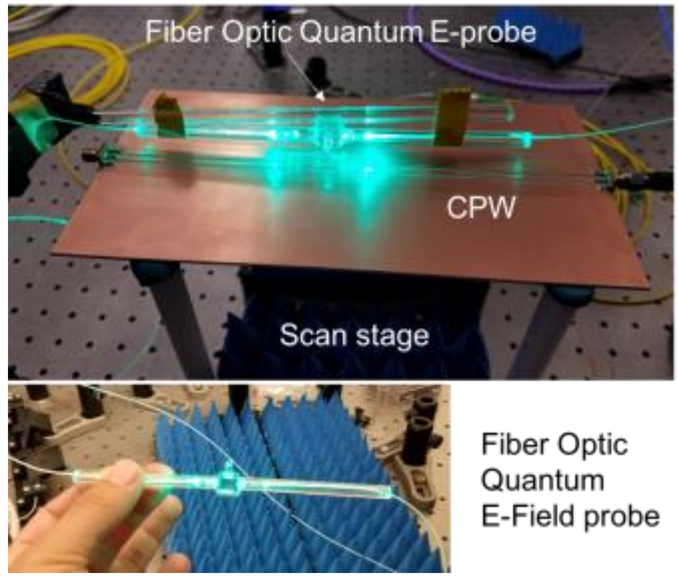

Fig. 5. (Top) CPW and fiber optic quantum electric-field probe. Scan stage moves CPW relative to quantum E-field. (Bottom) Development of this new type of quantum E-field probe allows laser beams, and vapor cell to be taken off of the optics table and held in hand.

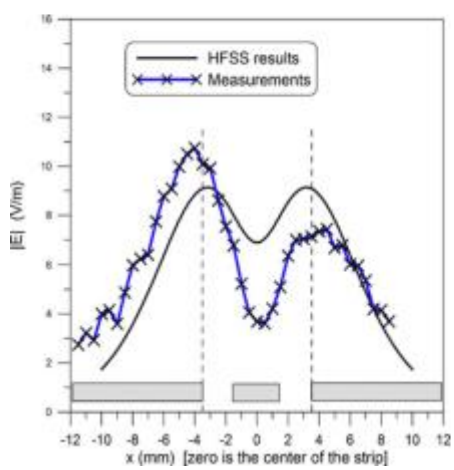

Fig. 6. Coplanar waveguide mode asymmetry determined near-field measurement using the fiber optic quantum E-field probe.

IV. ACKNOWLEDGMENTS

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