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Atom-Based RF Field Probe: From Self-Calibrated Measurements to Sub-Wavelength Imaging

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***Abstract* — In this presentation, we discuss a fundamentally new approach for an electric (E) field probe design. This new approach is significantly different than currently used field probes in that it is based on the interaction of RF-fields with Rydberg atoms (alkali atoms placed in a glass vapor cell are excited optically to Rydberg states). The applied RF-field alters the resonant state of the atoms. The Rydberg atoms act like an RF-to-optical transducer, converting an RF E-field to an optical-frequency response. The RF probe utilizes the concept of Electromagnetically Induced Transparency (EIT). The RF transition in the four-level atomic system causes a split of the EIT transmission spectrum for a probe laser. This splitting is easily measured and is directly proportional to the applied RF field amplitude. The significant dipole response of Rydberg atoms enables this technique to make self-calibrating measurements over a large frequency band including 1-500 GHz. In this paper, we report on our results in the development of this probe. We also discuss two key applications: that is, self-calibrated measurements and sub-wavelength imaging and field mapping.**

Keywords— atom-base metrology; Autler-Townes effects; electric field measurements; EIT; sub-wavelength imaging; Rydberg atoms

I. INTRODUCTION

There is a pressing need to have small size probes that are not only self-calibrating but can also perform measurements on a small spatial scale (i.e., sub-wavelength). Existing field probes require some type of calibration and the calibration process is somewhat of a chicken-and-egg dilemma. To calibrate a probe, we must have a "known" field. But to have a "known" field, we must have a calibrated probe. In recent work, we (and others) have demonstrated a fundamentally new approach for E-field measurements [1]-[6] that can lead to a self-calibrated measurement and has the capability to perform measurements on a fine spatial resolution.

This probe is a quantum-based, compact, self-calibrating, SI-traceable electric (E) field sensor based on excitation of Rydberg atoms. Alkali atoms are optically excited to Rydberg states and the applied E-field alters the resonant state of the atoms. Over 1 GHz to 500 GHz, Rydberg atoms have an extremely large electric dipole response ($\wp > 1000 e a_0$, where e is the electric charge and a_0 is the Bohr raduis) and can act like a transducer, converting an E-field to an optical-frequency response. The new approach has several benefits over existing techniques, including, 1) a direct, SI units linked *E*-field measurement, 2) a self-calibrating measurement due to atomic resonances, 3) expanded bandwidth versus current technologies, allowing measurements from 1 to 500 GHz and possibly up to 1 THz, 4) a technique that is independent of current approaches, 5) a very small spatial resolution (optical fiber and chip-scale), and 6) a technique with vastly improved sensitivity and dynamic range over current E-field methods. This sensor will have far-reaching applications, including transferrable E-field standards, new biomedical metrology, traceable calibrations above 110 GHz (currently not available), and sub-wavelength imaging.

The approach utilizes the concept of electromagnetically induced transparency (EIT) [1, 2]. In this approach, one laser is used to probe the response of the atoms (called a "probe" laser) and a second laser is used to excite the atoms to a high energy state (called a "coupling" laser). In the presence of the coupling laser, the atoms become transparent for the probe laser transmission (this is the concept of EIT). The coupling laser wavelength is chosen such that the atom is at a high enough state such that an RF field can cause an atomic transition of the atom. The RF transition in this four-level atomic system causes a splitting of the transmission spectrum (the EIT signal) for a probe laser. This splitting of the probe laser spectrum is easily measured and is directly proportional to the applied RF E-field amplitude (through Planck's constant and the dipole moment of the atom), see [1] for detail of the theory behind the technique. By measuring this splitting (Δf) we get a direct measurement of the RF E-field strength from the following [1, 2]:

$$|E| = 2\pi \frac{\hbar}{\wp} \Delta f \quad , \qquad (1)$$

where $\hbar$ is Planck's constant and $\wp$ is the atomic dipole moment of the RF atomic transition (see [1] for discussion on determining $\wp$). We consider this type of measurement of the E-field strength a direct SI-traceable self-calibrated measurement in that it is related to Planck's constant and only requires a frequency measurement (Δf, which can be measured very accurately).

II. Experimental Results

One of the experimental setups used in this study is shown in Figure 1, which includes a vapor cell (filled with rubidium atoms), a horn antenna (a waveguide antenna for the high-frequency measurements), a lock-in amplifier, a photo diode, a red laser (780 nm) and a blue laser (approximately 480 nm). The blue is tuned to different wavelengths in order to measure the field strength at different microwave frequencies. The precise wavelength of the blue laser governs which atomic states can be used to measure this microwave field strength, and the energy difference between these states determines the frequency of the microwave field whose strength is measured, see [1] for details.

Figure 2 shows the observed splitting of the probe laser transmission spectrum (the EIT signal) for different values of applied RF field. Note that the separation of the two peaks (the splitting) increase with increasing applied field strength, as predicted by (1). In order to validate this technique, we have compared the estimated E-field obtained for this atom-based approach to far-field calculations. Figure 3 shows one set of compared data for a 17.04 GHz field. The good comparison between these results illustrate the validity of the atom-based method.

Because of the nature of these atom-based measurements, the probe is well suited to perform measurements and images on a very small spatial scale. We can illustrate this by mapping the E-fields inside a glass cell. When an incident field encounters a glass cell (see Figure 4) a standing wave will develop inside the cell due to internal reflections from the cell walls. We used the atom-based approach to map and image the field distribution inside a 25-mm x 75-mm cylinder vapor cell. The cell is translated across the probe and coupling lasers in discrete steps. At each step position, we measured the splitting of the EIT signal and converted it an electric field. Figure 5 shows the field amplitude inside the cell for two different step sizes (corresponding to one-11th and one-29th of a wavelength resolution at 104.77 GHz). These two sets of measurements lie on top of one another, showing that the measurement is repeatable. To validate these results we use a numerical simulation for the field inside a cylinder cell. These numerical results are also shown in Figure 5. Good qualitative agreement between the numerical results and the measured data is observed. The uncertainties associated with this measurement technique are discussed in [1] and [7].

The spatial resolution of the method is, in principle, limited by the optical diffraction limit. This is a significant improvement over the measurement resolution achievable by conventional probes. There are many possible applications of this technique. For example, the sensing volume could be scanned over a printed-circuit-board (PCB) or nano-structure in order to map their fields, as well as other applications where E-field measurements on a small spatial resolution are desired. We will investigate these applications in future work.

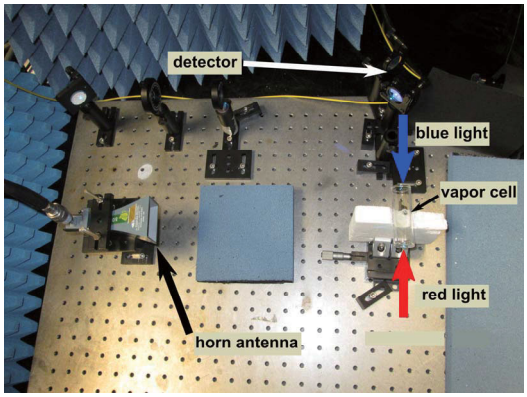

Fig. 1. Illustration of one of the Experimental set-ups.

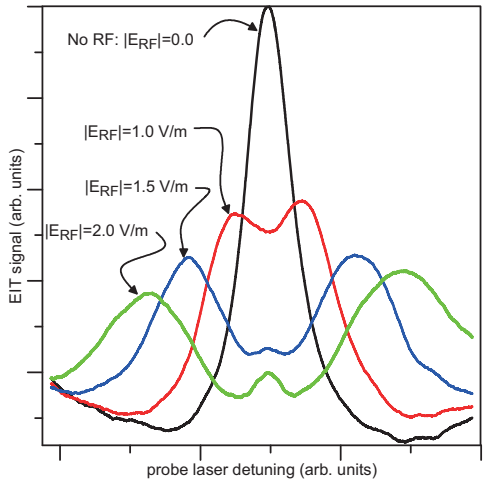

Fig. 2. Illustration of the EIT signal (i.e., probe laser transmission through the cell) as a function of probe laser detuning Δp. This dataset is for a 15.095 GHz and corresponds to this following 4-level atomic system: $5S_{1/2}$-$5p_{3/2}$-$52D_{5/2}$-$53P_{3/2}$.

III. SUMMARY

We have discussed a fundamentally new method for measuring E-fields. This new approach has numerous advantages, as discussed above. Most notably are the self-calibrating and sub-wavelength measurement aspects. This technique allows the development of an E-field probe that does not require a calibration, since calibration is an inherent property of the Rydberg atom itself. This technique can also be used to perform sub-wavelength imaging and field mapping over a large range of frequencies. The applications of such small spatial imaging capability are numerous, including nanostructure and biological imaging.

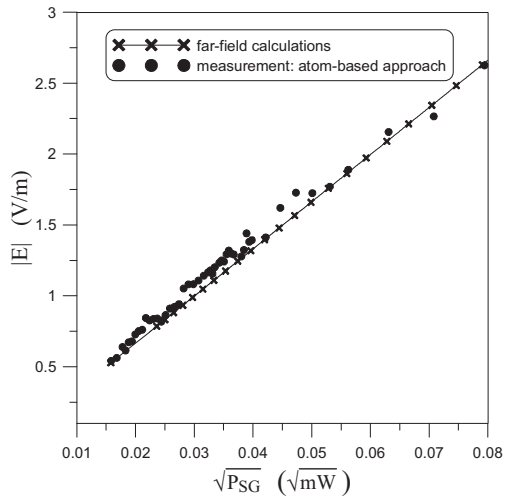

Fig. 3. These data compare the measured $|E|$ to values obtained from far-field calculations. This dataset is for a 17.04 GHz field and P_{SG} corresponding to the power setting on the RF source.

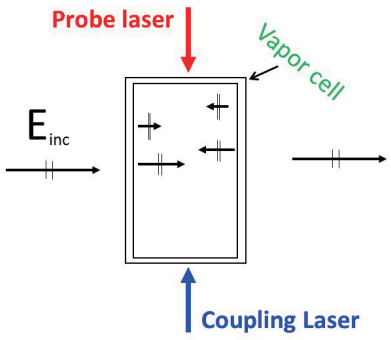

Fig. 4. Illustrate of multi-internal wall reflections that cause standing waves inside a glass cell.

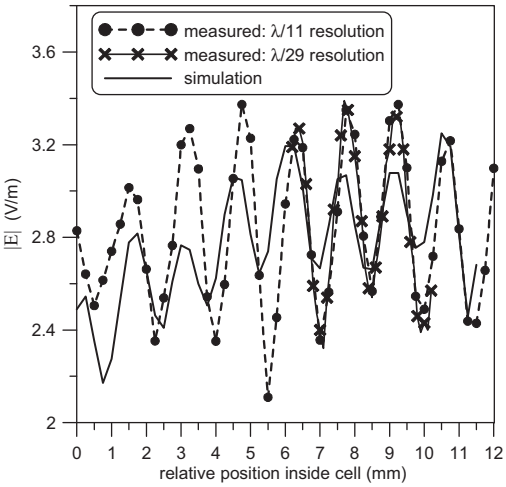

Fig. 5. Illustration of field mapping and sub-wavelength imaging of the field distribution in a glass vapor cell. This dataset if for 104.77 GHz.

Acknowledgment

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REFERENCES

[1] C.L. Holloway, J.A. Gordon, A. Schwarzkopf, D. A. Anderson, S. A. Miller, N. Thaicharoen, and G. Raithel, "Broadband Rydberg atom-based electric-field probe for SI-traceable, self-calibrated measurements," *IEEE Trans. on Antenna and Propagation*, **62**, no. 12, 6169-6182, 2014.

[2] J.A. Sedlacek, A. Schwettmann, H. Kübler, R. Low, T. Pfau and J. P. Shaffer, "Microwave electrometry with Rydberg atoms in a vapor cell using bright atomic resonances", *Nature Phys.*, **8**, 819, 2012.

[3] C.L. Holloway, J.A. Gordon, A. Schwarzkopf, D. A. Anderson, S. A. Miller, N. Thaicharoen, and G. Raithel, "Sub-wavelength imaging and field mapping via electromagnetically induced transparency and Autler-Townes splitting in Rydberg atoms," *Applied Phys. Lett.*, 105, 244102, 2014.

[4] J.A. Gordon, C.L. Holloway, A. Schwarzkopf, D.A. Anderson, S.A. Miller, N. Thaicharoen, and G. Raithel, "Millimeter-wave detection via Autler-Townes splitting in rubidium Rydberg atoms", *Applied Phys. Lett.*, **105**, 024104, 2014.

[5] J.A. Sedlacek, A. Schwettmann, H. Kübler, and J.P. Shaffer, "Atom-based vector microwave electrometry using rubidium Rydberg atoms in a vapor cell," *Phys. Rev. Lett.*, **111** 063001, 2013.

[6] H. Q. Fan, S. Kumar, R. Daschner, H. Kübler, and J. P. Shaffer , "Sub-wavelength microwave electric-field imaging using Rydberg atoms inside atomic vapor cells," *Optics Lett.*, **39**, no. 10, 3030-3033, 2014.

[7] C.L. Holloway, J.A. Gordon, M. Simons, H. Fan, S. Kumar, J.P. Shaffer, D.A. Anderson, A. Schwarzkopf, S. A. Millier, N. Thaicharoen, and G. Raithel, "Atom-based RF electric field measurements: an initial investigation of the measurement uncertainties," Joint IEEE Intern. Symp. on EM and EMC Europe, Dresden, Germany, Aug. 2015.