Broadband Rydberg Atom Based Self-Calibrating RF E-Field Probe

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Abstract

We present a significantly new approach for an electric (E) field probe design. The probe is based on the interaction of RF-fields with Rydberg atoms, where alkali atoms are excited optically to Rydberg states and the applied RF-field alters the resonant state of the atoms. For this probe, the Rydberg atoms are excited in a glass vapor cell. The Rydberg atoms act like an RF-to-optical transducer, converting an RF E-field to an optical-frequency response. The 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 the probe laser. This splitting is easily measured and is directly proportional to the applied RF field amplitude. Therefore, by measuring this splitting we get a direct measurement of the RF E-field strength. The significant dipole response of Rydberg atoms over the GHz regime enables this technique to make traceable measurements over a large frequency band including 1-500 GHz. We will show that, with one probe, measurements can be made over a very large frequency range. This is a truly broadband probe/sensor. In this paper, we report on our results in the development of this probe.

1. Introduction

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 extremely large electric dipole response ($\wp > 1000 e a_0$) and can act like a transducer, converting an E-field to an optical-frequency response. The E-field is directly related to a EIT splitting measured in the optical spectrum, the atom's dipole moment, and Plank's constant, giving a direct, traceable measurement of the E-field. This new sensor will have the following benefits: 1) it will allow E-field measurements that are directly linked to SI units (currently not possible), 2) it will be self-calibrating based on calculable atomic resonances, 3) it will not perturb the field during the measurement (no metal is present in the sensor head), 4) it will have significantly improved sensitivity over current E-field sensors (<0.01 mV/m, which is two orders of magnitude improvement over current approaches (i.e., dipole loaded probes), <10 μV/m may be possible), 5) it will have expanded bandwidth versus current technologies, allowing measurements from 1 to 500 GHz and possibly up to 1 THz, and 6) the sensor will be very small and compact (tens of μm to a few mm versus tens of cm). If successful, 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. This sensor is key to developing next-generation radio-frequency (RF) measurement equipment and for characterizing emerging millimeter-wave systems, and in applications where accurate, calibrated, field measurements on a small spatial resolution are desired [1-5].

Accurate measurement of E-field strength at radio to millimeter-wave (mm-wave) frequencies is at the heart of RF system design and evaluation, ranging from commercial to military applications, including wireless, the avoidance of interference between digital devices, the assurance of personal safety near radiating systems, RF-based medical treatments, and calibration of existing sensor and test facilities. From 1 GHz to 50 GHz, current E-field sensors use metallic dipole-loaded probes ranging in size from several mm to a few cm in size, resulting in large spatial averaging, significant perturbation to the field during measurement, and sensitivity no better than 0.1 V/m. These sensors require costly calibration in a reference test-field facility to achieve present uncertainty levels of ± 0.5 dB, or about 5 %, and are at best traceable to the geometry of these test facilities. Uncertainties for thermal power meters used for calibration over the frequency range of 50-110 GHz are at the 2-5 % level, and above 110 GHz there are ***no*** traceable calibration methods to date. Improvement is thus needed in E-field metrology to enable better sensitivity and higher-frequency measurements. The sensor will address limitations of current thermal and non-thermal E-field metrology techniques.

Alkali atoms (in our case, rubidium atoms) are placed in a vapor cells. The RF E-field interacts with alkali atoms that have been optically excited to Rydberg states (n>20). The measure of this interaction is related to the atomic dipole moment ($\wp$) of the atom. At RF frequencies, Rydberg atoms have extremely large electric-dipole response

($\wp > 1000 e a_0$), making them sensitive to E-fields while acting like a transducer used to convert E-field strength to an optical-frequency response. We will exploit a four-level electromagnetically-induced transparency (EIT) scheme, where the EIT quantum inference spectrum will be split by the presence of the E-field we wish to measure (see Figure 1). The RF transition in a four-level atomic system causes an easily identifiable and measurable splitting of the transmission spectrum for the EIT probe laser. This splitting, equal to the Rabi frequency Ω_{rf}, is directly proportional to the applied E-field via the relation, $|E| = \Omega_{rf}\, \hbar / \wp$, where $\hbar$ is Planck's constant [1, 3]. By measuring this splitting we obtain a direct measurement of the E-field. The eventual project goal is to develop a sensor that is fabricated using micro-vapor cell technology and integrated on a chip or placed on the end of a hollow-core optical fiber, or other small-scale MEMS-based technology. In this paper, we present data that illustrate the broadband nature of the E-field probe.

2. Experimental Results

One of the experimental setups used in this study is shown in Figure 2, which includes a vapor cell (filled with rubidium atoms), a horn antenna (and 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. The significant benifit of this probe is that since the atom is a highly tuned resonator, we can use that property to excite the atom to various states (with the blue laser), such that it will respond to a wide range of microwave frequencies.

Figure 3 illustrates the results of measurements performed at 15.59 GHz. This required a blue laser tuned to 479.787 nm. The plot shows splitting of the EIT signal as a function of applied microwave (or RF) field strength. The theory predicts that the splitting should follow a linear relationship versus the E-field strength. Figure 4 shows the measured splitting versus the applied field. We see that the data fit a linear curve very well. By changing the blue laser to 480.125 nm, it is possible to measure a 17.04 GHz source. This data set is shown in Figure 5. Once again the data fit a linear relationship. Finally, changing the blue laser to 482.375 nm, it is possible to measure at 93.7 GHz. With this same setup and same cell we are able to measure an RF source in the millimeter-wave and sub-THz range (see [4] for details). Future analysis will include making direct comparisons of |E| of this approach to exciting approaches.

3. Conclusion

We present a significantly new approach for an electric (E) field probe. The approach is based on the E-field interaction with atoms placed in a glass cell. Since an atom is a highly tuned and stable resonant structure, it can be excited to various atomic states in order to respond to a wide range of microwave frequencies (1 GHz to 500 GHz). This then allows one to accurately measure the E-field strength. In this paper we have demonstrated that with one vapor cell and a tuned blue laser we can measure the E-field for a wide range of frequencies. Since the technique relies on the lasers to excite the atoms to a state where the microwave source can cause a transition, this new measurement technique allows for sub-wavelength imaging on the order on the laser-beam width [5]. The uncertainties in the type of measurements presented here are as of yet unknown. Future work will include a detailed uncertainties analysis.

4. References

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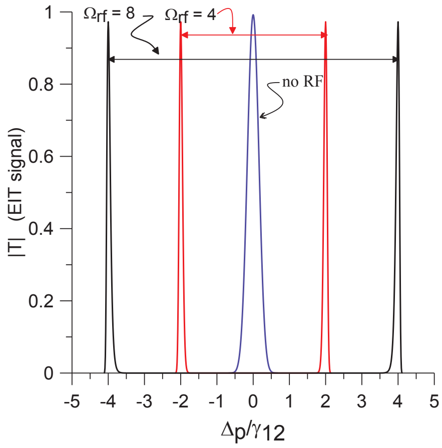

Fig. 1: Illustration of EIT splitting.

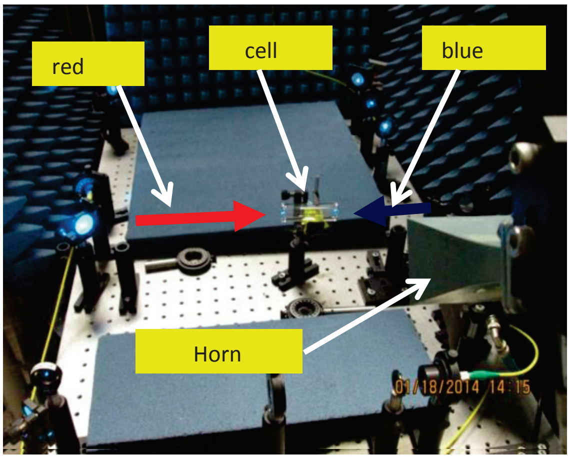

Fig. 2: Illustration of one of the Experimental set-ups.

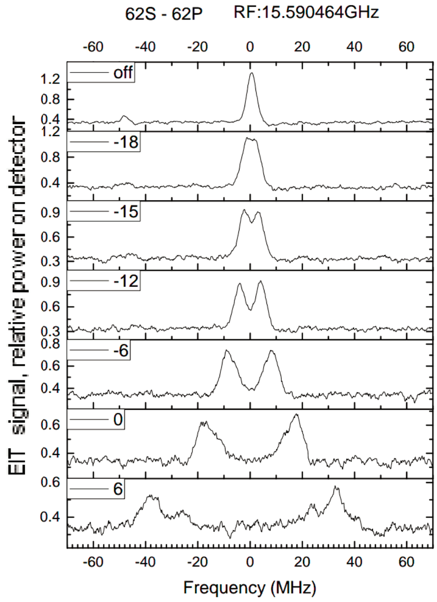

Fig. 3: Measured EIT splitting at 15.59 GHz.

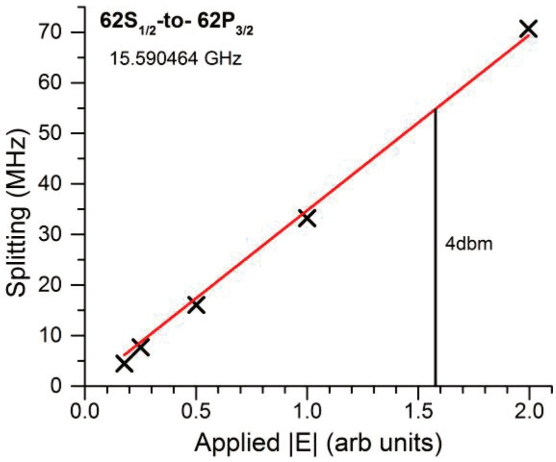

Fig. 4: The linear relationship in Ω_{rf} with |E| at 15.59 GHz.

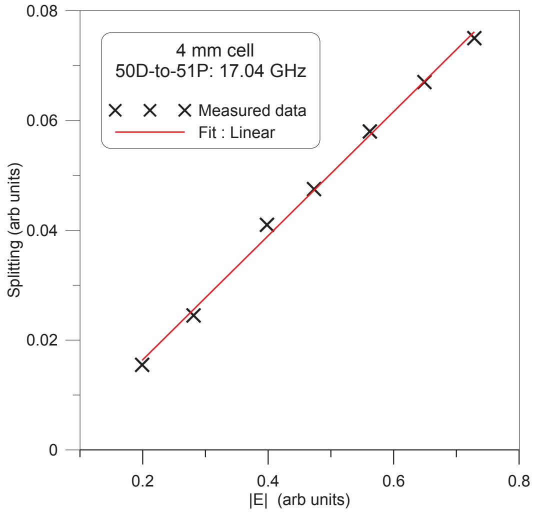

Fig. 5: The linear relationship in Ω_{rf} at 17.04 GHz.

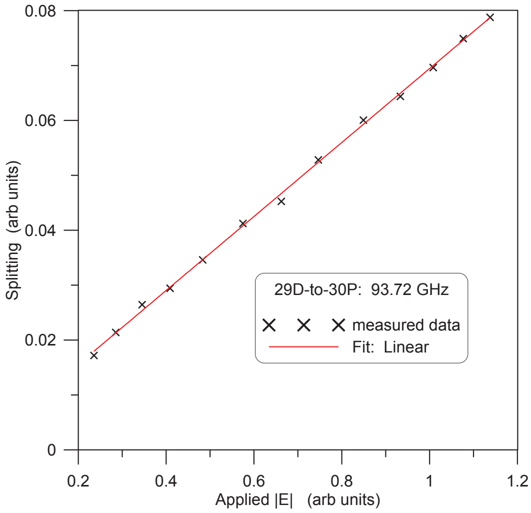

Fig. 6: The linear relationship in Ω_{rf} at 93.72 GHz.