The Effect of Electric Field Inhomogeneity in Rydberg Atom-Based Electric Field Sensing

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ABSTRACT

The use of Rydberg atoms for radio frequency electric field sensing has emerged as a promising alternative to traditional antenna-based designs that enables all-optical readout. However, the need for atomic vapor cells comprised of dielectric materials can adversely affect the electric field distribution at the probing volume. Here we describe the effects of electric field inhomogeneity on measured optical electromagnetically induced transparency (EIT) spectra. This is accomplished using custom-designed waveguide-embedded atomic vapor cells with stub tuners that allow control of the degree of electric field inhomogeneity within the cell. We describe the resulting broadening of the measured EIT feature and the associated reduction in magnitude, which results in an overall reduced sensitivity of the resulting measurement.

Keywords: Rydberg Atom, Electrometry, Electromagnetically Induced Transparency

Rydberg atom-based electric field sensing can provide significant advantages over traditional antenna-based detection. In this approach, the effect of an incident radio frequency (RF) electric field on high-lying Rydberg states of an atomic species is measured using laser spectroscopy via an electromagnetically-induced transparency (EIT).[1] Unlike resonant antennas, the size scaling of atomic vapor cells is wavelength-independent,[2,3] and the optical readout provides a new sensing paradigm.[4]

The use of an atomic vapor provides new challenges in addition to opportunities. For one, the long lifetimes of Ryberg states limit the achievable bandwidth, although recent results have suggested that tens of MHz of bit rate are possible.[5] The need for an atomic vapor – typically highly reactive alkali metals – requires the use of high purity and low pressure dielectric cells. These cells can have undesired effects on incident RF fields that can modify the field strength at the position of the lasers and introduce significant spatial inhomogeneity.[6] Here we will examine the effect of field inhomogeneity on EIT spectra and amplitudes under applied RF fields.

In a typical measurement a Rydberg state of an alkali metal vapor is prepared using two spatially overlapped counterpropagating lasers.[4] These two lasers – probe and coupling lasers (ω_P and ω_C, respectively) – probe the Rydberg state via the electromagnetically induced transparency (EIT) of the probe laser, with the cesium states used in this work illustrated in Fig. 1(A). When an external RF field is incident on the atomic vapor it will affect the probed Rydberg state via induced Autler-Townes (AT) splitting under resonant conditions[7] or the AC Stark effect in the off-resonant case.[8] An incident RF field can thus be measured by monitoring the transmission of the probe laser through the vapor cell via its effect on the lineshape or spectral shift of the EIT feature. As a consequence, the overall measurement sensitivity is determined by the spectral lineshape of the EIT feature measured, which can adversely be affected by effects such as contaminants in the vapor cell or variations in the RF electric field across the probing volume. EIT spectra are measured by sweeping the coupler laser frequency relative to the EIT resonant frequency with detuning Δ_C.

To better understand the effect of electric field inhomogeneity within traditional vapor cells, we use specially designed cesium vapor cells embedded into RF waveguides[9] that allow control of the field inhomogeneity within the cell as shown in Fig. 1(B). These cells utilize directional couplers at the waveguide ends to combine the RF fields in the waveguide with the optical fields that pass unobstructed. Control of RF field variations is achieved using stub tuners that can be used to adjust the amount of back-reflection (impedance matching) of propagating waveguide-confined fields that can establish standing waves within the vapor cell. Under optimized conditions the time-averaged electric field magnitude within the cell is constant, giving an EIT feature with optimal Doppler-limited linewidth. Conversely, with an internal back-reflection the standing field pattern establishes an electric field inhomogeneity along the longitudinal axis of the atomic vapor cell.

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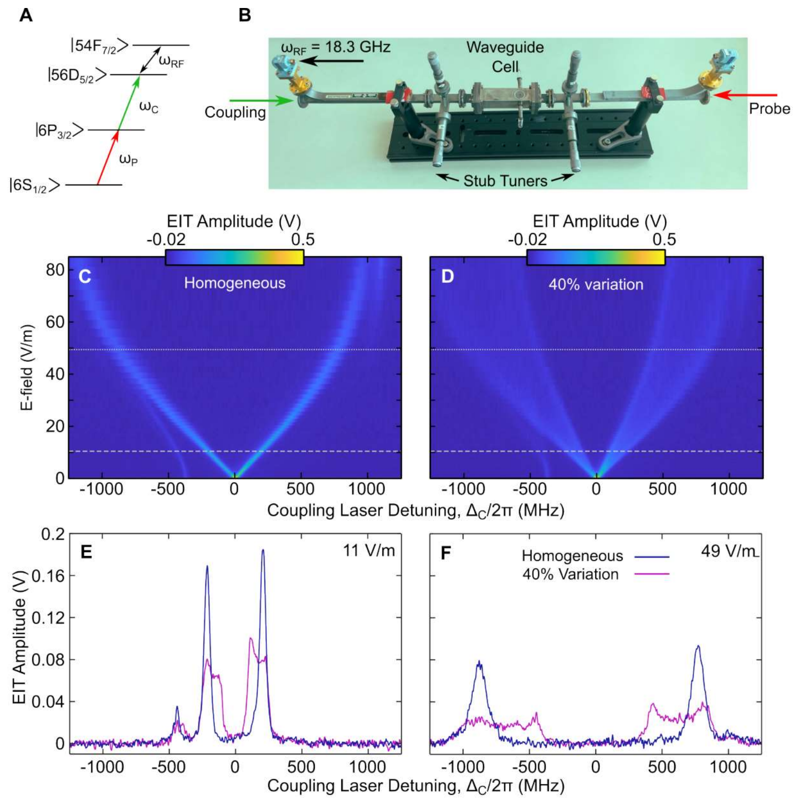

Figure 1. Schematic of the atomic states with the probe (ω_P) and coupling (ω_C) lasers used to prepare the Rydberg state in cesium (A). Labeled photograph of the waveguide setup used with directional couplers to facilitate insertion of the RF signals for copropagation with coupling and probe lasers (B). Evolution of the EIT signal with applied RF field as a function of field strength with homogeneous (C) and inhomogeneous (D) field conditions. Line cuts taken at 11 V/m (E) (dashed line in C and D) and 49 V/m (F) (dotted lines in C and D).

Shown in Fig. 1(C) is the evolution of the EIT feature from the cesium $56D_{5/2}$ state that undergoes AT splitting as an RF field resonant with the 56D-54F transition at 18.3 GHz is applied. The electric field has been optimized to be homogeneous using the peak width and thus gives rise to a sharp AT doublet that remains clearly discernible even as nonlinear effects and the influence of nearby states become visible at electric field strengths of $>$ 60 V/m. Also seen at Δ_C = -396 MHz is the $56D_{3/2}$ peak. The corresponding measurement where we have deliberately induced a 40% variation in the electric field along the length of the cell is shown in Fig. 1(D). Here it can be seen that the AT doublet is broadened with a peak width directly proportional to the amount of AT splitting induced. Line cuts taken along the dashed and dotted lines in Fig. 1(C) and (D) are shown in (E) and (F), respectively. These line cuts clearly reveal the broadening and diminished amplitude of the EIT peak that results from variations in the electric field.

These results clearly reveal the effect of electric field variations within the probing volume on the EIT spectra that underlie Rydberg atom-based electric field sensing. The resulting spectral broadening and overall reduction in EIT magnitude will have a direct effect on measurement sensitivity. This can occur either via a diminished signal-to-noise ratio due to the reduced signal as well as the reduced EIT slope, although we note that the relative change in the slope is less than the overall peak height. These results caution that the electric field distribution in vapor cell-based measurements must be accounted for in order to achieve optimum sensor performance.

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