Detuning radio-frequency electrometry using Rydberg atoms in a room-temperature vapor cell

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Abstract
Traceable radio-frequency electric field measurements with high sensitivity have been demonstrated from the centimeter wave to the millimeter wave using room-temperature Rydberg atoms. Here, we investigate the splitting spectra of electromagnetically induced transparency induced by a radio-frequency electric field, which is detuned from the resonant frequency of transitions between two Rydberg states, 47D5/2 ↔ 48P3/2. By varying the detuning of the radio-frequency electric field, we measure the separation between the two peaks, and in particular their relative height. The resulting measured resonant transition frequency between two Rydberg states is found to exhibit a visible change when the power of the radio-frequency electric field is varied, thus causing uncertainty in the traceable radio-frequency electric field measurement. Further, the effect of detuning of the probe light on the radio-frequency electric field measurement is presented.

Keywords: Rydberg atom, radio-frequency electric field measurement, electromagnetically induced transparency

(Some figures may appear in colour only in the online journal)
of approximately $\lambda/650$ [14, 15], where $\lambda$ is the wavelength of the millimeter E-field. The polarization of RF E-fields was also identified; the resolution of polarization reached 0.5° [13]. As a core component of RF E-field electrometry, the effects of the size of the vapor cell on the accuracy of the measurements was investigated [16]. Simons et al demonstrated the improved measurement sensitivity of a weak detuning RF E-field strength compared to an on-resonant RF electric field [17].

In this work, we investigated the EIT-AT spectrum of a ladder four-level system involving Rydberg states in a room-temperature vapor under the condition of the detuning RF E-field and a probe light. The splitting separation and the relative height ratio of two peaks of the AT spectra are presented respectively as a function of the frequency detuning and the power of the RF E-field. It is shown that the power of the RF E-field will cause the frequency shift of the 47D$_{5/2}$-48P$_{3/2}$ Rydberg transition. The model of a four-level system theory is used and provides a good qualitative explanation for the experimental observation. Moreover, the effect of the EIT-AT splitting on the detuning of the probe light is demonstrated.

2. Experimental approach

Figure 1(a) is the four-level atomic energy level scheme in our experiments. In a typical three-level EIT system, a ‘dark state’ is created by a probe field ($\Omega_p$) and a coupling field ($\Omega_c$), which prevent the resonant absorption of the probe laser. An applied RF field that is resonant with the two adjacent Rydberg states breaks down the three-level system and causes the probe photons to be absorbed again. The EIT spectrum will split into two peaks: this is called AT splitting. The AT splitting ($\Delta f$) is proportional to the RF E-field strength $E$ and is described as

$$E = \Omega_M = \frac{2\pi \hbar}{\varphi_{MW}} \Delta f$$  \hspace{1cm} (1)

where $\varphi_{MW}$ is the transition dipole moment of the adjacent Rydberg states and $\hbar$ is Planck’s constant, and $\Omega_M$ is the Rabi frequency of the Rydberg state transition induced by the RF E-field [18].

Figure 1(b) shows the experimental setup. We use a cylindrical vapor cell with 50mm length and 20mm diameter containing cesium (133Cs) atom vapor. The probe laser drives the 6S$_{1/2}(F = 4) \rightarrow$ 6P$_{3/2}(F' = 5)$ transition and is generated with an external cavity diode laser. To observe an EIT signal, we apply a counter-propagating coupling laser (~510nm) with a scanning frequency near the transition between 6P$_{3/2}$ and 47D$_{5/2}$. The coupling laser (Toptica TA-SHG110) is supplied by a frequency doubled diode laser at 1020nm. The Rabi frequency of the probe (coupling) laser is $\Omega_p = 8.08$ MHz $\times 2\pi$ ($\Omega_c = 2.05$ MHz $\times 2\pi$). Both lasers have the same linear polarization and are locked to a high-finesse Fabry–Pérot cavity made by the ultra-low-expansion glasses. Each laser has a spectral bandwidth less than 1 kHz according to the cavity transmission linewidth. It is necessary to shift the laser frequency to the resonance transition by the double-passed acoustic-optical modulator (AOM). The RF E-field at about 6.946 GHz, which couples resonantly to the transition of 47D$_{5/2}$ $\leftrightarrow$ 48P$_{3/2}$, is led into the vapor cell by a horn antenna. The frequency of the coupling laser is scanned by an AOM so that the precise frequency of the splitting interval can be obtained. Meanwhile, the laser power is stabilized by a proportion-integral-differential feedback loop system by controlling the AOM diffraction efficiency to reduce the intensity noise.

3. Experimental results and discussion

The EIT signal and AT splitting spectrum of the probe transmission induced by an RF E-field are shown in figure 2(a). Figure 2(b) shows the signals under the detuning of the RF E-field. The splitting peaks in the upper figure show almost equal heights for the near-resonance RF E-field. The other signals in the lower part of figure 2(b) show the asymmetric height of the splitting peaks under the detuning frequency $\pm 5$ MHz. Taking into account the relation between the splitting and Rabi frequency of the RF transition in equation (1), the splitting separation can be given by

$$\Delta f = \sqrt{(\Delta f_0)^2 + (\Delta f_0)^2},$$  \hspace{1cm} (2)

where $\Delta f = f - f_0$ is the frequency detuning of the RF E-field, $f$ is the measured E-field frequency, $f_0$ is the resonance frequency of the 47D$_{5/2}$ $\leftrightarrow$ 48P$_{3/2}$ transition. Here, $\Delta f_0$ is the splitting interval induced by the resonant RF E-field and is equal to the Rabi frequency of the RF resonance transition in our experimental configuration. The RF E-field with the resonance frequency has the minimum AT splitting. Figure 3(a) shows the dependence of the splitting interval $\Delta f$ on the absolute radio frequency $f$. The simulation curves using equation (2) are shown with the solid lines. The Rabi frequency on the Rydberg resonance transition equal to $2\pi \times (5.187 \pm 0.4$ MHz), $2\pi \times (6.732 \pm 0.21$ MHz), $2\pi \times (8.356 \pm 0.1$ MHz), $2\pi \times (10.386 \pm 0.06$ MHz) and $2\pi \times (12.952 \pm 0.05$ MHz) corresponds to the different output power of the RF generator: $-21$ dbm, $-19$ dbm, $-17$ dbm, $-15$ dbm and $-13$ dbm, respectively. The RF E-field strength can be calculated by the splitting $\Delta f_0$ using equation (1): for example, the RF E-field strength equals 19.86 $\pm$ 1.53 mV cm$^{-1}$ for the on-resonant AT splitting of $2\pi \times (5.187 \pm 0.4$ MHz). The detuning RF E-field would cause larger splitting and improve the measurement sensitivity than that of the resonance frequency [17]. Moreover, the splitting measurement can offer a method to obtain the resonance frequency of the Rydberg transition through equation (2).

However, the simulation results of the resonance frequency for the different RF E-field strength in figure 3(a) is shown in figure 3(b). It is noted that the resonance frequency shifts with the variation in RF E-field strength, which is similar to the effect of the molecule photo-association [19]. The RF E-field induced the frequency shift of the resonance transition between Rydberg states. Here, the induced frequency shift is smaller than 0.3 MHz according to the mean values in figure 3(b). Considering the error of the fitting results, the maximum frequency shift is about 1.2 MHz.

To investigate the frequency shift with the power of detuning RF E-fields in detail, we illustrate the relation of the height
The ratio of two AT splitting peaks to the detuning of the E-field frequency. The radio frequency is varied in a small range from 6.9455 GHz to 6.9485 GHz. In figure 4(a), we show the height ratio of right peak $H_2$ to left peak $H_1$ of AT splitting curves for the different radio frequencies with the selected output power: $-13$ dbm, $-15$ dbm, $-17$ dbm, $-19$ dbm and $-21$ dbm. Figure 4(a) shows the slope of the height ratio is dependent on the applied RF E-field power. The smaller RF power produces the bigger slope. The curves corresponding to the variation in RF power intersect at a resonant frequency when the height ratio of the AT splitting peaks is equal to 1. It is noted that the frequency shift is about 1.1MHz under the different RF E-field power. Figure 4(b) shows the theoretical simulation curves for the four-level ladder system, which is similar to [20]. Here, the frequency shift induced by the RF E-field is not considered. The Hamiltonian matrix of the four-level ladder system is given:

$$H = \frac{\hbar}{2} \begin{pmatrix} 2\Delta_p & \Omega_p & 0 & 0 \\ \Omega_p & \Omega_c & 2\Delta_c & \Omega_M e^{-i\phi} \\ 0 & \Omega_c & 2\Delta_c & \Omega_M e^{-i\phi} \\ 0 & 0 & \Omega_M e^{i\phi} & 2\Delta_M \end{pmatrix} ,$$

where $\Omega_p$, $\Omega_c$, and $\Omega_M$ are the Rabi frequency corresponding to the probe laser, coupling laser and the RF E-field, respectively, $\phi$ is the initial phase of the RF E-field. Here, $\Delta_p$, $\Delta_c$, and $\Delta_M$ are the detuning associated with the transition of states, respectively.

The master equations are given as

$$\dot{\rho}_{ij} = -\frac{i}{\hbar} \sum_k (H_k \rho_{kj} - \rho_{ik} H_k) - \frac{1}{2} \sum_k (\Gamma_{ik} \rho_{kj} + \rho_{ik} \Gamma_{kj}),$$

where $\Gamma_{ik} = \delta_{ik} \gamma_i$, the subscripts $i$, $j$, $k$ correspond to the states, $\Gamma_{ik}$ indicates the spontaneous radiation attenuation.
from $i_l$ to $k$, and the parameter $\gamma_j$ is the decay rate for the various states. Here, $\rho_{kj}$ is the coherence between states $k$ and $j$. Solving the probability density equations can obtain $\rho_{21}$, to obtain the dispersion and absorption spectra of Rydberg EIT including the RF E-field. The imaginary part of the $\rho_{21}$ can be calculated as

$$\text{Im}(\rho_{21}) = \Omega_P \frac{2(\gamma_{14}(\Delta_p + \Delta_c) + \gamma_{13}\delta) a_2 + \left(\frac{1}{4}\Omega_P^2 - (\Delta_p + \Delta_c)\delta + \gamma_{13}\gamma_{14}\right)a_1}{a_1^2 + 4a_2^2},$$

where

$$a_1 = \frac{1}{2}\Omega_P^2\gamma_{12} - 2\delta(\gamma_{13}\Delta_p + \gamma_{12}(\Delta_p + \Delta_c)) + 2\gamma_{14}\left(\frac{\Omega_p^2}{4} - \Delta_p(\Delta_p + \Delta_c) + \gamma_{12}\gamma_{13}\right).$$
\[ a_2 = \frac{1}{4} \Omega_{\Delta_p}^2 \Delta_p + \delta \left( \frac{\Omega_{\Delta_r}^2}{4} - \Delta_p (\Delta_r + \Delta_c) + \gamma_{12}\gamma_{13} \right) \\
+ \gamma_{14} (\gamma_{13} \Delta_p + \gamma_{12} (\Delta_p + \Delta_c)) , \]
\[
\delta = \Delta_p + \Delta_c + \Delta_M \quad \text{and} \quad \gamma_{ij} = (\Gamma_i(i - 1)) / 2 (i, j = 2, 3, 4).
\]

We select reasonable experimental parameters to fit the height ratio of the splitting peaks by using equation (5). Here, we set \( \Delta_p = 0, \ \gamma_{12} = 2\pi \times (5.2 \ \text{MHz}), \ \gamma_{13} = 2\pi \times (0.1 \ \text{MHz}), \ \gamma_{14} = 2\pi \times (0.1 \ \text{MHz}), \ \Omega_p = 2\pi \times (1.4 \ \text{MHz}) \) and \( \Omega_c = 2\pi \times (1.4 \ \text{MHz}) \). \( \gamma_{12} \) is the decay rate of \( 6P_{3/2} \); and \( \gamma_{13} \) and \( \gamma_{14} \) are the decay rates of Rydberg states accounting for the large collision cross-section of Rydberg atoms [1]. Here, \( \Omega_M \) are the variation values from the splitting for different detuning in figure 3. In figure 4(b), all curves cross at the resonance frequency (\( \Delta_M = 0 \)) in which the relative height ratio equals 1. It is reasonable to conclude that the RF E-field causes the resonant frequency shift and the height ratio of AT splitting can offer the reference to calibrate the resonance frequency for different RF E-field strengths. For the frequency shift introduced by the splitting fitting in figure 3 and height ratio in figure 4, the introduced error of the E-field strength using equation (2) is smaller than 1% for the weak field measurement.

Furthermore, we investigate the effect of the detuning of the probe field on the RF E-field measurement. The RF E-field...
RF E-field metrology. Red detuning of the probe laser will produce the asymmetric measurement deviation in the detuning of the probe laser is tuned on the blue side, the measurement deviation shows the asymmetric characteristic for the red detuning and blue detuning of the probe laser. While the splitting interval is smaller than 6.3% in our experiments.

When the RF field is off-resonant with the Rydberg states, the splitting interval shows the asymmetric characteristic for the red detuning and blue detuning of the probe laser. The probe laser is tuned on the blue side, the measurement deviation for the blue detuning RF E-field. The asymmetric characteristic is attributed to the asymmetric shift of hyperfine levels under the stray magnetic field around the vapor cell [21, 22].

In conclusion, we investigated the effect of the detuning frequency of adjacent Rydberg state transitions on the RF E-field metrology in a cascade four-level system in a room-temperature vapor cell. We demonstrated the dependence of both the splitting intervals and the height ratio of two splitting peaks on the RF E-field frequency. The frequency shifts of Rydberg transition induced by the RF E-field are investigated. Furthermore, we showed the effect of probe detuning on the RF E-field measurement. Red detuning of the probe laser will produce the asymmetric measurement deviation in the detuning RF E-field metrology.

**Figure 5.** The AT splitting of EIT for the probe detuning and RF frequency. $\Gamma$ is the natural linewidth of $6P_{3/2}$.

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