Electric Field Measurement Method Based on Rydberg Atom

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***Abstract*—With the increasing demand for electric field measurement accuracy, the traditional electric field measurement method has reached its measurement accuracy bottleneck. Therefore, this paper mainly analyses the (Electromagnetically Induced Transparency-Aulter Town, EIT-AT) effect caused by a single electric field incident on the Rydberg atomic gas cell. Based on this approach, the amplitude of the incident electric field can be obtained indirectly through the spectral splitting spacing due to the EIT-AT effect. In addition, when the incident electric field is amplitude-modulated. Therefore, the amplitude and frequency of the base electric field can be obtained through the EIT-AT effect, and thus, a relatively novel measurement method is obtained. The proposed approach can be applied to millimetre-wave and terahertz applications.**

Keywords—electric field measurement, Rydberg atom, Electromagnetic induced transparency, Liouville equation

I. INTRODUCTION

The rapid evolution of electromagnetic fields underscores the pressing need for heightened sensitivity in measuring electric field parameters. Across various research domains, accurate assessment of parameters such as amplitude, frequency, and phase is essential for elucidating complex phenomena and advancing scientific understanding.

Two primary strategies have emerged to enhance measurement sensitivity: refining sensor design and processes and implementing reverse reproduction techniques to capture elusive electric field nuances [1]. The accurate determination of the electric field intensity vector hinges upon the foundational principles of Maxwell's equations, where physical quantities play pivotal roles as key measurement parameters. Achieving precise values for these parameters ensures accurate measurement of the electric field vector [2] and unlocks deeper insights into the underlying dynamics of electromagnetic interactions. Moreover, in specialised fields such as materials science and telecommunications, precise measurement of the polarisation direction of the electric field holds paramount importance, influencing the design and optimisation of various systems and devices [3].

Traditional electric field measurement methods often struggle with inherent limitations, impeding their adaptation to modern applications. Among these, Rydberg atomic electric field measurement has emerged as a groundbreaking method, leveraging the unique properties of Rydberg atoms to offer unparalleled accuracy and precision. This method represents a paradigm shift in measurement technology by converting electric field parameters—such as amplitude, phase, and frequency—into probe light transmission intensity assessments. Its metal-free sensor design mitigates interference and enhances reliability, particularly in complex electromagnetic environments where traditional methods falter. Paired with advanced spectrum measurement techniques, Rydberg atom-based electric field measurement promises to mitigate errors, offering robust solutions to challenges posed by scattered noise and environmental variability. This heralds a new era in electromagnetic sensing. Rydberg atom-based techniques are poised to transform scientific inquiry and technological innovation across various applications, from fundamental research to telecommunications and remote sensing [4].

II. THEORY

A. *The Liouville equation with decoherence*

The measurement of the Rydberg atomic electric field requires theoretical analysis using the semi-classical theory of light-matter interaction. In general, due to the relatively small impact of atomic collisions on the calculation results, it is not necessary to consider the phase loss caused by atomic collisions. Furthermore, the number of arrangements between energy levels changes due to spontaneous emission in excited state energy levels. Therefore, it can be described by subjectively adding parameters such as the spontaneous emission rate of each energy level.

$$\frac{\boldsymbol{d}}{\boldsymbol{dt}}\boldsymbol{\rho} = -\frac{\mathrm{i}}{\hbar}[\boldsymbol{H},\boldsymbol{\rho}] - \frac{1}{2}\{\Gamma,\boldsymbol{\rho}\} \tag{1}$$

B. *Analysis of electric field characteristics*

In order to calculate the Hamiltonian of the interaction between the electric field and the Rydberg atom. The following form is adopted to express a single electric field.

$$E_s(t) = \frac{E_s}{2}(e^{\mathrm{i}\omega_s t} + e^{-\mathrm{i}\omega_s t}) \tag{2}$$

In order to understand and analyse the interaction mechanism between the modulated electric field and Rydberg atoms, the electric field is assumed to be an amplitude-modulated electric field, and its specific formula is as follows.

$$E_m(t) = E_{ca}\left[1 + m\cos(\omega_b t)\right]\cos(\omega_{ca} t) \tag{3}$$

C. Interaction between electric field and Rydberg atom

When a single electric field interacts with the Rydberg atom, the whole system can be described and calculated by the Hamiltonian, and the following Hamiltonian between the four-level system and the single electric field can be obtained

$$\hat{H} = \frac{\hbar}{2}\begin{bmatrix} 2\omega_1 & \Omega_p e^{i\omega_p t} & 0 & 0 \\ \Omega_p e^{-i\omega_p t} & 2\omega_2 & \Omega_c e^{i\omega_c t} & 0 \\ 0 & \Omega_c e^{-i\omega_c t} & 2\omega_3 & \Omega_s e^{-i\omega_s t} \\ 0 & 0 & \Omega_s e^{i\omega_s t} & 2\omega_4 \end{bmatrix} \tag{4}$$

The above formula is called the Hamiltonian between a single electric field and Rydberg atom in the Schrodinger representation.

III. Numerical Results

A. Variation of the probe transmission intensity

In order to analyse the influence of the coherent term between energy levels on the incident electric field when the four-level model is in a steady state, the steady-state solution of the equation (1) and (4) can be obtained.

$$\rho_{21} = \frac{i\Omega_p A\left(4\gamma_2\Delta_c^2 - \gamma_2\Omega_s^2 - 2i\Delta_c\Omega_c^2\right)}{\gamma_2^2 A^2 + 4\Delta_c^2 C + 2\Omega_s^2\Omega_p^2(\Omega_p^2 + \Omega_c^2 + \Omega_s^2) + 32\Omega_p^2\Delta_c^4}$$
$$A = \Omega_s^2 - 4\Delta_c^2 \tag{5}$$
$$C = 2\Omega_p^2(\Omega_c^2 - 2\Omega_s^2) + 2\Omega_p^4 + \Omega_c^4$$

Thus, the following schematic diagram of the variation of the probe light transmission intensity with the couple light frequency detuning can be drawn.

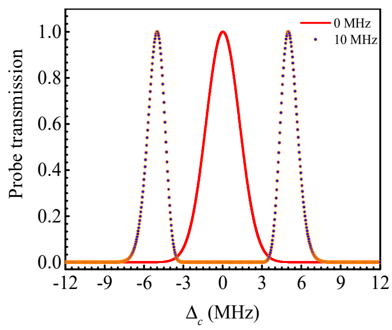

Fig. 1. the variation of the probe light transmission intensity with the couple light frequency detuning

Fig. 1 shows that with the gradual increase of the electric field strength to be measured, the spectrum of the probe light will split, which is EIT-AT.

B. Analysis of amplitude-modulated electric field based on Rydberg atom

The above section is for the case when the electric field is a single frequency, but in general, it is difficult to measure only the single-frequency electric field signal in real life. In this case, this section will analyse and calculate the results of the Rydberg atom interacting with it when the electric field is an amplitude-modulated electric field.

As shown in the previous section, the total Hamiltonian of the amplitude-modulated electric field under the interaction representation can be obtained as follows.

$$H_I = \frac{\hbar}{2}\begin{bmatrix} 0 & \Omega_p & 0 & 0 \\ \Omega_p & -2\Delta_p & \Omega_c & 0 \\ 0 & \Omega_c & -2(\Delta_p + \Delta_c) & \frac{\Omega_m}{2}[m\cos(\omega_b t) + 1] \\ 0 & 0 & \frac{\Omega_m}{2}[m\cos(\omega_b t) + 1] & -2(\Delta_p + \Delta_c - \Delta_m) \end{bmatrix} \tag{6}$$

In order to analyse the influence of the coherent term between the energy levels on the amplitude-modulated electric field when the four-level model is in a steady state, the steady-state solution of the equation (1) and (6) can be obtained.

$$\rho_{21} = \frac{-i\gamma_2\Omega_p\Omega_m^2 A^2}{2\Omega_p^2\left(4\Omega_p^2 + 4\Omega_c^2 + \Omega_m^2 A^2\right) + \gamma_2^2\Omega_m^2 A^2} \tag{7}$$
$$A = m\cos\left(\omega_b t\right) + 1$$

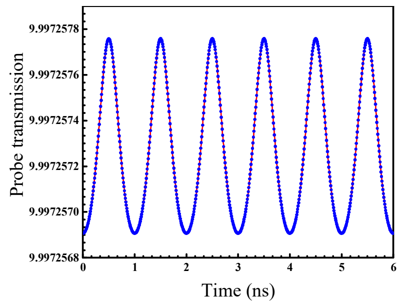

Fig. 2. Variation of transmission intensity of probe light with time

It can be seen from Fig. 2 that its oscillation frequency is basically the frequency of the baseband electric field.

IV. Conclusion

Rydberg atomic electric field measurement represents a revolutionary leap in electromagnetic sensing, particularly in contrast to traditional methods. Traditional electric field measurement technologies often struggle in complex electromagnetic environments. However, the structure of Rydberg atomic electric field measurement technology, devoid of metal components, renders it superior and more durable, particularly in the face of external interference. Additionally, its inherent accuracy and simplicity surpass those of traditional methods. By leveraging these advantages, Rydberg atom-based techniques promise to reshape the landscape of electromagnetic sensing, offering unparalleled precision and reliability across various applications.

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