Microwave electrometry via electromagnetically induced absorption in cold Rydberg atoms

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The atom-based traceable standard for microwave electrometry shows promising advantages by enabling stable and uniform measurement. Here we demonstrate both theoretically and experimentally a traceable and self-calibrated method for measuring the microwave electric field strength with cold Rydberg atoms using electromagnetically induced absorption (EIA). Comparing with the method based on electromagnetically induced transparency, we show that the equivalence relation between microwave Rabi frequency and Autler-Townes splitting keeps more valid and is even more robust against the experimental parameters in the EIA’s linear region. Furthermore, a narrower linewidth of cold Rydberg EIA enables us to realize a traceable and self-calibrated microwave electric field measurement as small as \(\sim 100 \mu \text{V/cm}\) in the linear region.

Introduction.— Atom-based metrologies have been successfully applied for inertial force sensors, magnetometers, length and time standards as well as precision measurements of atomic or molecular properties [1,7]. The reproducibility, accuracy and stability of atom-based metrologies significantly outperform conventional methods due to the stable and uniform of the atomic properties. Recently, Rydberg atoms in vapor cells have been introduced to measure microwave (MW) electric field (E-field) with higher accuracy, sensitivity and stability than that of the traditional antenna-based MW E-field measurement [8–13]. This novel spectroscopic approach has since been exploited extensively for antenna calibration, signal detection, subwavelength imaging and terahertz sensing [14–23].

The Rydberg atom-based MW electrometry utilizes the phenomena of electromagnetically induced transparency (EIT) and Autler-Townes (AT) splitting [24–26]. Under certain conditions, the Rabi frequency (\(\Omega_{\text{MW}} = \mu E/\hbar\), here \(\hbar\) is Planck’s constant and \(\mu\) is the dipole moment) of the MW atomic transition is considered to be equal to the AT splitting (\(2\pi \Delta f\)) in the EIT spectrum:

\[
\Omega_{\text{MW}} = 2\pi \Delta f. \tag{1}
\]

By measuring the AT splitting, we could get a direct International System of Units (SI) traceable, self-calibrated measurement of MW E-field strength. Various aspects of uncertainties of this measurement approach have been investigated [8,27]. Especially, the validity of Eq. (1) is a key aspect of uncertainties of this measurement approach [28]. For hot atoms, though the AT splitting is regularly measured via a double-peak fit, it is a challenge to examine the validity as well as predict the effective parameter regions as a result of the inhomogeneous broadening in the vapor-cell spectrum [16,29]. Furthermore, the range, accuracy, and resolution ratio of direct SI-traceable MW measurements are closely related to the EIT linewidth. To our best knowledge, the full-width half-maxima of Rydberg EIT on record for room temperature atomic vapor is about several MHz owing to the Doppler mismatching in the three-level cascade system with the dual-wavelength lasers [28]. So the low bound of the traceable measurement is limited to around 5 \(\mu \text{V/cm}\).

Motivated by the narrower EIT linewidth and lower dephasing rates of the cold atoms [6,30–31], in this Letter, we demonstrate both theoretically and experimentally a MW electrometry with cold Rydberg atoms. Cold atoms are employed here to obtain the atomic resonances with a subnatural linewidth, and its solvable density matrix allows us to analyze the relationship between the MW Rabi frequency and AT splitting clearly [31]. In the EIT region, we find that the four-level EIT exhibits a transition from double electromagnetically induced transparency (DEIT) to double AT splitting (DATS). And hence besides the MW Rabi frequency, the AT splitting depends on various system parameters (e.g., coupling Rabi frequency, atomic dephasing rates, etc.). Therefore, the equivalence relation given in Eq. (1) breaks down in the EIT condition. In the EIA region, where the excited state is adiabatically eliminated with a large single-photon detuning, the relation in Eq.(1) keeps valid and is robust against the variations of the experimental parameters. Using the narrower EIA signal, we achieve a direct SI-traceable MW electric field measurement as small as 100 \(\mu \text{V/cm}\), about fifty times smaller than the low bound achievable by vapor-cell EIT method. Our results therefore constitute a major step towards the atom-based SI-traceable and self-calibrated standard of MW electrometry.

Experimental setup.—The experimental setup and the MW-driven four-energy-level system are shown in Fig.1 (a) and (b), respectively. A cigar-shaped \(^{87}\)Rb cloud, with longitudinal length \(L = 2.2\) cm, temperature \(T \sim 100\) \(\mu\)K and atomic density \(N \sim 10^{10}\) \(\text{cm}^{-3}\), is prepared in the hyperfine state \(|1\rangle = |5S_{1/2}, F = 2\rangle\) within 4.5 ms. Along the \(z\) direction, the cloud has an optical depth (OD) up to 140 in the \(|1\rangle \rightarrow |2\rangle = |5P_{3/2}, F = 3\rangle\) transition [34]. The counterpropagated vertical-polarized probe and coupling laser beams are focused to the \(1/e^2\) radii of 50 \(\mu\)m and 85 \(\mu\)m, respectively. The frequencies of the probe and coupling lasers are both locked to a high-finesse temperature stabilized Fabry-
Perot cavity through the PDH technique [35]. The stray magnetic field is compensated by three pairs of Helmholtz coils down to 10 mG [35], and the glass cell is shielded with microwave absorbers. The vertical-polarized MW is emitted from a horn antenna, driven by a microwave generator (R&S SMF100A), and propagates perpendicularly to the probe and coupling beams. The MW with a frequency of 36.8961 GHz is resonant with two adjacent Rydberg energy levels [27], [3] = 39D5/2 ↔ [4] = 40P3/2, with a calculated radial transition dipole moment μ = 1926 e·a0. The power of the probe laser (P0 = 1 pW), is kept constant during the experiment, which corresponds to a Rabi frequency of \( \Omega_p/2\pi = 7 \text{ kHz} \). The frequency of the probe laser is scanned around the \([1] \rightarrow [3]\) two-photon resonance from -20 MHz to 20 MHz within 100 μs using an acousto-optic modulator at the beginning of the 0.5 ms experimental window. The transmission spectrum \( P_1 \) of the probe laser, described by \( P_1 = P_0 \exp(-\alpha L) \) with the absorption coefficient \( \alpha \propto N \text{Im}(\gamma_p) \) and \( \gamma_p \) being the atomic polarization (off-diagonal density matrix element) given in Eq. \( \frac{2}{3} \) or \( \frac{3}{3} \), is recorded by a photomultiplier tube (PMT, Hamamatsu, H10720-20).

**Theoretical model.** Our system is schematically shown in Fig. 1(b), which is a four-level atom interacting with the MW field, coupling and probe lasers. Under the weak probe condition, we can obtain the atomic polarization \( \varrho_{21} \) as

\[
\varrho_{21}(\delta) = \frac{\Omega_p}{2} \frac{d_3 d_4 - \Omega_{\text{MW}}^2/4}{d_2 d_3 d_4 - d_2 \Omega_{\text{MW}}^2/4 - d_4 \Omega_{\text{MW}}^2/4}.
\]

where \( \Omega_i \) are the Rabi frequencies of incident fields, and the complex detunings are defined as \( d_2 = \delta - \Delta \), \( d_3 = \delta - \gamma_3 \), and \( d_4 = \delta - \Delta_{\text{MW}} - i\Delta \gamma_4 \) with \( \gamma_i \) being the total dephasing rates of \( |i\rangle \) [29] [38]. Here \( \delta (\Delta_c) \) is the two-photon (single-photon) detuning and \( \Delta_{\text{MW}} \) is the detuning of the MW field. The polarization \( \varrho_{21} \) can be rewritten as \( \varrho_{21}(\delta) = \sum_{i=1}^{3} \varrho_i(\delta - \delta_i) \) (the expressions of the poles \( \delta_i \) and their strengths \( S_i \) for the resonances are presented in the Supplemental Material [38]), which has three poles representing the resonant responses to the probe field. The imaginary part of \( \varrho_{21} \) attributes to the transmission of probe field through the cold ensemble, and thus the probe spectrum can be decomposed into three resonant terms: \( P/\varphi = \prod_{i=1}^{3} R_i(\delta) \), where \( R_i(\delta) = \exp \left[ -\frac{\Omega_{\text{MW}}^2}{2} \text{Im} \left( \frac{S_i}{\delta - \delta_i} \right) \right] \) with \( \Gamma \) being the spontaneous decay rate.

To have a physics understanding of the probing transmission, we discuss our system with the decaying-dressed-state approach under two cases: EIT with \( \Delta = 0 \) and EIA with large detuning \( \Delta_c \). Under the condition \( \Delta_c = 0 \), the resonant responses are shown in Fig. 1(c), which is associated with the transitions from the ground state to corresponding decaying-dressed states with level shifts and dephasing rates given by \( \text{Re}(\delta_i) \) and \( \text{Im}(\delta_i) \), respectively. These level shifts demonstrate that the splitting of the EIT peaks depends on a number of factors, including the Rabi frequencies of coupling and MW fields, as well as the dephasing rates. So it implies that the relation given in Eq. \( 1 \) should be carefully checked.

Under the condition of a large detuning \( \Delta_c \gg \Omega_{\text{MW}}, \Gamma \), excited state \( |2\rangle \) can be eliminated adiabatically and then an effective three-level system is obtained as shown in Fig. 1(d). In this case, strong coupling field induces the probe absorption near two-photon resonance via \([1] \rightarrow [3]\) transition [39]. The EIA polarization has two absorption poles [38], which makes it a superposition of two resonances only associated with the microwave Rabi frequency and Rydberg dephasing. In the effective three-level system, the threshold Rabi frequency of microwave field for the transition between EIT and ATS is \( |\gamma_3 - \gamma_4| > G_{\text{ATS}} \) [25] [26]. As the Rydberg dephasing rates \( \gamma_3 \) and \( \gamma_4 \) are very close, \( \Omega_{\text{MW}} \gg |\gamma_3 - \gamma_4|, \Delta_{\text{AC}} \) (AC Stark shift), the EIA polarization can be written as the sum of two equal-width Lorentzians shifted from the two-photon resonance by \( \pm \Omega_{\text{MW}}/2 \):

\[
\varrho_{31}(\delta) \simeq \frac{\varrho_{\text{eff}}}{4} \left[ \frac{1}{(\delta + \Omega_{\text{MW}}/2) - i(\gamma_3 + \gamma_4)/2} + \frac{1}{(\delta - \Omega_{\text{MW}}/2) - i(\gamma_3 + \gamma_4)/2} \right],
\]

and thereby it is referred as the EIA-ATS region.

**Experimental results for four regions.** In our experiments, we measure the transmission \( P_1 \) as a function of the two-photon detuning \( \delta \), and the results are shown with blue dots.
FIG. 2: Normalized spectra of probe transmission for the indicated MW powers input to horn. (a)-(c) Four-level EIT spectra transition from DEIT to DATS with increase of coupling Rabi frequency: (a) DEIT with \( \Omega_c/2\pi = 2 \) MHz, (b) crossover with \( \Omega_c/2\pi = 6 \) MHz, and (c) DATS with \( \Omega_c/2\pi = 16 \) MHz. (d) EIA-ATS spectra with \( \Delta_c/2\pi = 100 \) MHz, \( \Omega_e/2\pi = 6 \) MHz, and OD = 100. The blue dots are experimental data, averaging over 1000 scans for each trace. Every result is fitted with the four-level susceptibility (red solid curves), and reveals three resonant responses: \( R_1 \), \( R_2 \) and \( R_3 \) (green dotted, yellow dash-dot, and black dash-dot curves respectively). From top to bottom, the MW Rabi frequencies are \( 2\pi \times (0, 1, 5, 10) \) MHz respectively.

FIG. 3: (a) AT splitting \( \Delta f \) as a function of MW power for the four regions: DEIT, crossover, DATS and EIA-ATS. \( \Delta f \) are derived from the double-Lorentzian fits. The square root of power that feeds into the antenna is proportional to the applied MW E-field. The symbols \( \Delta f \) reference line. \( \Delta f \) is retrieved from the analytical fits. The insets display an enlarged view of the corresponding parts.

in Fig. 2. To analyze the data, we use Eq. (2) with OD, \( \Omega_c, \Delta_{MW}, \Delta_{MW}, \gamma_3 \), and \( \gamma_4 \) as adjustable parameters to least-squares fit the spectrum data, while \( \Delta_c \) and \( \gamma_2 \sim \Gamma/2 = 2\pi \times 3 \) MHz are fixed during the analytical fits, and the fitted results are plotted with red solid curves. We can retrieve these free parameters from the fits and then substitute them to the three resonances \( R_1 \), \( R_2 \) and \( R_3 \), and the results are also shown in Fig. 2. These resonances demonstrate four regions in the MW-driven four-level system: DEIT (\( \Delta_c = 0, \Omega_c < \Gamma \), Fig.2(a)), crossover (\( \Delta_c = 0, \Omega_c \approx \Gamma \), Fig.2(b)), DATS (\( \Delta_c = 0, \Omega_c \approx \Gamma \), Fig.2(c)), and EIA-ATS (\( \Delta_c \gg \Omega_c, \Gamma \), Fig.2(d)).

Strong Fano interference occurs with a weak coupling laser (\( \Omega_c < \Gamma \)), and the absorption profile in top subgraph of Fig. 2(a) comprises two Lorentzians centered at the origin: one resonance is broad and positive and the other is narrow and negative. The MW field leads to a third transition pathway, and the destructive interferences among the three resonances induce two narrow transparent windows in other subgraphs of Fig. 2(a), which indicates the presence of DEIT. When the coupling Rabi frequency is close to \( \Gamma \), the interferences among these transition pathways manifest a crossover from DEIT to DATS as shown in Fig. 2(b), and the constructive interferences start to prevail over destructive interferences. In the case of strong coupling strength, the rise of the third resonance \( R_3 \) between \( R_1 \) and \( R_2 \) in Fig. 2(c) demonstrates a transition from ATS to DATS. The resonances are approximate to three Lorentzians with the absence of destructive interference, and the separations between absorption peaks increase as the MW field strength increases. In the EIA-ATS region, as theoretically expected by Eq. (3), the spectra in Fig. 2(d) are almost a double-Lorentzian function, and have a remark feature required for the SI traceable measurement: the separation between the resonances \( R_2 \) and \( R_3 \) is exactly equal to \( \Omega_{MW} \). The full-width half-maxima of the EIA linewidth is about 400 kHz with \( \Delta_c/2\pi = 100 \) MHz.

Relations between the AT splitting and MW Rabi frequency.—We now turn to fit the spectrum data with a double-Lorentzian to determine the AT splitting \( \Delta f \). The spectra in the EIA-ATS region are fitted with Eq. (3), while the transmission peaks of EIT spectra are separately fitted with Lorentzian function. Fig. 3(a) shows the extracted \( \Delta f \) as a function of
MW power input to horn. As shown in Fig. 2(b) and 2(c), the peaks in the crossover and DATS regions are neither symmetric nor Lorentzian in shape, and actually they are gaps between the unequal resonances \( R_3 \) and \( R_1 \) (\( R_2 \)). In Fig. 3(a), the significant departure of the extracted \( \Delta f \) from the theoretical curves in the crossover and DATS regions are due to that the broad and asymmetric peaks are not Lorentzian form.

In contrast, the experimental data in the DEIT and EIA-ATS regions agree with the results of numerical calculations. The dominant sources of statistical errors are the technical noises from laser intensity and detection, while principal systematic error is associated with the uncertainty of MW source amplitude at low MW field [38]. As shown in Fig. 3(a), the nonlinear behavior always happens at the beginning of AT splitting in the EIT scheme, and the \( \Delta f \) threshold between the nonlinear and linear behavior decreases as \( \Omega_c \) decreases. That is because at the nonlinear behavior the coupling terms of \( \Omega_c \) and \( \gamma_2 \) prevail over the MW coupling in the decaying-dressed states. In contrast, the nonlinear behavior almost disappears in the EIA-ATS region as a result of the adiabatic elimination of excited state.

To examine the equivalence relation given in Eq. (1) between the AT splitting and MW Rabi frequency, we retrieve the MW Rabi frequencies \( \Omega_{MW} \) from the fitted spectra (red solid curves in Fig. 2), and then derive the relations between \( 2\pi \Delta f \) and \( \Omega_{MW} \) for the data shown in Fig. 3(a). The results for the four regions are plotted in Fig. 3(b). It shows that the equivalence relation between \( 2\pi \Delta f \) and \( \Omega_{MW} \) breaks down in the EIT condition. In sharp contrast, the data in the EIA-ATS region and the reference line are perfectly coincident with each other, as expected from Eq. (3).

To further quantitatively characterize the deviation, we introduce the mean deviation between the measured splitting \( 2\pi \Delta f \) and \( \Omega_{MW} \) for each region, which is define by

\[
\bar{\Delta} = \frac{1}{n} \sum_{i=1}^{n} \left| (2\pi \Delta f^{(i)} - \Omega_{MW}^{(i)}) / \Omega_{MW}^{(i)} \right|,
\]

where \( n \) is the number of data points. The mean deviation \( \bar{\Delta} \approx 0.5\% \) for EIA-ATS region, while the deviations in DEIT, crossover and DATS regions are 4.6\%, 30.3\% and 45.2\% respectively. Therefore, the MW E-field amplitude would be either underestimated or overestimated in these EIT regions if the relation given in Eq. (1) is used.

\textbf{Performances of the EIA method.–} We further analyze the dependence of the EIA-AT splitting on optical depth, Rabi frequency and detuning of the coupling field. Except for the indicated variables, the EIA measurement is taken under the same conditions as in Fig. 2(d). Figure 4 shows that the linear relations between EIA-AT splitting and applied MW E-field all hold very well for the different control parameters (i.e., \( OD \), \( \Delta_e \) and \( \Omega_c \)). In the figure, we also indicate the relative deviation \( \Delta_E \) between the measured MW E-field strength that is proportional to splitting and the applied MW E-field. As the fitted lines perfectly pass through the original point, \( \Delta_E \) is equal to the difference between the slope coefficients retrieved from linear fits and the slope values calculated with Eq. (1). From the results in Fig. 4(a) and 4(b), \( \Delta_E \) are all below 1\%, and thus the EIA measurements are very robust against the variations of optical depth and \( \Omega_c \). In Fig. 4(c), as long as the excited state |2\rangle is strongly detuned (\( \Delta_e > 10 \Gamma \)), the fitted lines start to converge with each other and these deviations of E-field are below 1\%. Here an AT splitting as small as \( \sim 250 \text{ kHz} \) is observed at \( \Delta_e/2\pi = 200 \text{ MHz} \), corresponding to a minimum SI-traceable MW E-field of 101.4 \( \mu \text{V cm}^{-1} \). At present, the smallest detected EIA-AT splitting is limited by the Rydberg level broadening induced by background electric and magnetic fields and the technical noises from laser intensity noise and detection. While there is a lower limit set by laser linewidth, spontaneous decay, interaction time, etc., lower limit for the traceable MW E-field measurement in the range \( \lesssim 10 \mu \text{V cm}^{-1} \) seems quite feasible, considering that the present dephasing rates \( \gamma_3 \) and \( \gamma_4 \) are ten times greater than the corresponding Rydberg decay rates that are about 18 kHz.
with room temperature blackbody radiation.

To achieve a continuous MW E-field measurement from the EIA linear region to the nonlinear region, we scan the probe laser frequency at low MW field and determine its transmission difference $\Delta T$ relative to the three-level EIA signal. Figure 5 shows the percent difference $\Delta T$ as a function of the MW E-field amplitude. In sub-AT splitting region, the EIA signal smoothly decays as the E-field amplitude increases. The dip of sub-AT splitting is most similar to a single Lorentzian in shape, and its depth is extracted from fitting a Lorentzian function to the spectra. The MW E-field strength is calibrated by measuring a larger MW field in the EIA-ATS region using atom-based sensor and extrapolating the power reading on the MW generator used to drive the horn. The solid curve shows the theoretical calculation with four-level susceptibility and it agrees with the experimental data. The smallest detectable strength in Figure 5 is $21.6 \pm 2.1 \, \mu \text{V/cm}^{-1}$, mainly limited by the intensity stability of the probe laser. Note that the intrinsic transmission change in our MW electrometry is about ten times greater than that of EIT signal in vapor cells [8], which provides several possibilities for extending the lower limit of the smallest detectable MW field.

**Conclusion.**— In summary, we have demonstrated a feasible method for the measurement of microwave E-field based on EIA in cold Rydberg atoms, which shows clear advantages serving as a traceable standard for microwave electrometry. At present, the detection is not shot-noise limited and the apparatus can be improved in many ways [40, 41], including the use of lasers with narrower linewidth and lower amplitude noise, the use of lower noise detectors, the implementation of a homodyne detection or frequency modulation spectroscopy, etc. By further combining with these technologies, much lower SI-traceable and self-calibrated microwave E-field measurement can be achieved with this EIA method.

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