Terahertz electrometry via infrared spectroscopy of atomic vapor

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Abstract—Here a system of electrometry in which a THz signal can be characterized is demonstrated using laser spectroscopy of highly excited (Rydberg) atomic states. The proof-of-principle measurements here reveal a minimum detectable THz electric field amplitude of $0.07 \pm 0.06$ V/m at 1.06 THz with 3 ms detection time, corresponding to a THz power at the atomic cell of approximately 3.4 nW. This method is applicable across the THz and millimeter-wave range. The relative simplicity and cryogen-free nature of this system makes it potential to provide a route to a SI traceable THz calibration technique and provide an alternative to calorimetric methods.

I. INTRODUCTION

The terahertz (THz) band, ranging from 0.1 THz to 3 THz and often referred to as the 'terahertz gap', is the electromagnetic wave range falling between the microwave band and the infrared band. Nowadays, the characterization of the terahertz (THz) gap has become a significant issue due to the increasing implementations of THz systems in applications such as chemical analysis, non-destructive testing, security screening, telecommunications, and medical diagnostics [1]. THz detection technologies have advanced dramatically, yet traceable calibration of THz radiation remains challenging [2].

In recent years, Rydberg atoms with one or more electrons excited to a very high principal quantum number $n$ have emerged as a key contender in a variety of quantum technologies, especially sensing due to large dipole moments. Such atomic systems with well-known and calculable properties are suitable for SI-traceable measurements of electric fields. There is particular interest in metrology using Rydberg spectroscopy for SI-traceable standards across the microwave and millimeter wave region [3]. Yet not much THz range has been reported.

In this paper, we demonstrate sensitive electrometry in the THz frequency range using Rydberg atoms in a thermal vapor. Compact, cryogen-free measurements in this apparatus are allowed, as well as rapid optical readout and being robust to environmental conditions variation. Furthermore, the measurements can be traced to SI units through the well-known properties of the atomic states.

II. METHOD

Fig.1 shows the experimental setup in (a) and energy levels in the used atomic species $^{85}$Rb in (b). In order to achieve an atomic density of Rb in the cell of the order of $10^{17}$ m$^{-3}$ the $^{85}$Rb atomic vapor in the quartz cell are heated to 45°C with ceramic resistor. A small remaining magnetic field B of around 100 mG is added onto the atoms from shim coils around the vapor cell to cancel the stray magnetic field from the environment and to provide a defined quantization axis for the atoms. Three lasers (probe laser-780 nm, dressing laser-1367 nm, Rydberg laser-752 nm) are used to excite the atoms from the ground state to the first Rydberg state $r_1$: $5S_{1/2} \rightarrow 5P_{1/2} \rightarrow 6S_{1/2} \rightarrow 23P_{1/2}$ ($r_1$). The three beams are counter propagated and focused in the cell with $1/e^2$ radius of 80 µm, 190 µm, and 85 µm respectively. The three lasers are all linearly polarized.

The narrow-band continuous-wave THz field (1.06 THz) is generated from an amplifier-multiplier chain (Virginia Diodes Inc.), with a microwave source seed. Then the free space travelling THz is focused into the cell center with gold coated parabolic mirror. The $1/e^2$ radius of the focused THz beam is estimated to be 1.2 mm at the cell center, thus much larger than the laser beams. A calorimetric power meter (Virginia Diodes’ PM5) was used for power comparison with the atomic measurements.

The probe laser and dressing laser are stabilized using polarization spectrum. When scanning the detuning of the Rydberg laser, a 3-photon electromagnetically induced transparency (EIT) signal is observed by measuring the probe transmission using the photodiode detector, shown as the green spectrum in the inset figure of Fig.2. When the atoms are irradiated by the THz field, the Autler–Townes (AT) effect causes splitting of both the peak frequency $f_t$ and dip frequency $f_d$, shown as the red spectrum in the inset figure of Fig.2. Both of the splitting are proportional to the THz field amplitude $E_{THz}$. According to equation [4]:

$$2n\hbar f_d = \hbar \Delta_{THz} = \mu E_{THz},$$

with the frequency splitting $f_d$, and the well calculated dipole moment $\mu$, the THz electric field amplitude $E_{THz}$ can be derived.

III. RESULTS

The inset plot of Fig. 2 is typical EIT spectra used to extract...
the THz field intensity information. Specifically, the AT splitting of the absorptive spectral feature $f_\Delta$, the splitting of the transmission features $f_a$ and $f_b$, and the resonant transmission change $\Delta T$ are extracted to indicate different THz amplitudes. For our analysis, we demarcate two regimes of incident THz power: the low power regime, and the high power regime, from the point where the frequency splitting is twice the linewidth of the bare EIT feature [6]. When THz power is higher than this, the relationship between splitting and incident THz power is linear related through Eq. (1). When THz power is lower than this, the relationship between splitting and incident THz power is nonlinear. Thus, we use the resonant transmission change $\Delta T$ to indicate the THz amplitude.

**A. High THz Power Regime**

Figure 2 shows the evolution of $f_\Delta$ (purple dots) and $f_a$ (orange dots) with the square root of the incident THz power $\sqrt{P_{THz}}$. A gray vertical line at $P_0 = 11.6$ uW is used to separate the data into the low and high power THz regimes following the definition above. On the right-hand side of the gray line, i.e. the high power regime, the cyan solid and dashed lines are least-squares straight line fits to the corresponding datasets. The fitted gradients of $f_a$ and $f_b$ match within the uncertainty of measurement. These linear fits are also projected into the low power regime for illustrate the deviation from linearity in this region. The lower panel shows the residuals between the data and fitting lines, which demonstrate good linearity in the high power region.

The AT splitting $f_\Delta$ can be used to calculate the THz electric field directly using Eq. (1) with the dipole moment of the THz transition $\mu_{THz} = 31.17$ ea. This relation is also used to calculate the electric field on the x axis in Fig. 3 used for the low power regime calibration.

**B. Low THz Power Regime**

When $\sqrt{P_{THz}} < P_0$ in Fig. 2, the relationship between the splittings and $\sqrt{P_{THz}}$ is not linear, due to a quantum interference effect when the THz Rabi frequency is comparable to the Rabi frequencies of the IR lasers. In this regime, we can instead use the resonant transmission change $\Delta T$ to indicate the amplitude $E_{THz}$, shown in Fig. 4. Here the very low THz amplitude is achieved by attenuating the THz beam using PTFE blocks with a total thickness of 5.7 cm, which are calibrated from the linear trend of the AT splitting [7].

In Fig. 4, the purple dots are experimental data of resonant transmission of THz on minus THz off ($\Delta T$) from five repetitions. The blue line shows the theory modelling results based on numerically solving 5-level Lindblad equations [7]. There is a high level of agreement between the theory predictions and the experimental data. The minimum detectable THz field amplitude is chosen where the error bars of $\Delta T$ data intersect with zero $\Delta T$, indicated by the gray line in Fig. 3. The data shows that this occurs at approximately $(1.07 \pm 0.06)$ V/m, which equals to a minimum detectable THz power of around 3.4 nW inside the cell.

**IV. SUMMARY**

In this paper, we have demonstrated an SI-traceable THz detection system using three IR lasers spectroscopy in room temperature atoms at Rydberg state. The stronger THz amplitude calibration to SI units is shown to be possible using the frequency splitting caused by the AT effect. For weaker THz fields, the calibration is achieved in our sensor by using the resonant transmission change induced in the EIT signal, which is also traceable to SI units. The minimum detectable power achieved here is $(1.07 \pm 0.06)$ V/m at the demonstrated frequency 1.06 THz with 3 ms of total integration time, which corresponds to a THz power of approximately 3.4 nW inside the cell. But the method is applicable across the THz and millimeter-wave range. Benefit from the relative simplicity and low-cost nature of the room temperature working device, the system is potential to provide a route to a SI traceable THz calibration in industrial applications.

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