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Sub-shot-noise terahertz measurement with electric field amplitude modulation via Rydberg atoms

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ABSTRACT

The terahertz (THz) band (0.1−10 THz) is widely applied in imaging, communications, and spectroscopy. Optics-based terahertz measurement techniques using coherent light as the probe field are limited by the standard quantum shot-noise limit. This study presents an experimental demonstration of quantum-enhanced terahertz electromagnetic field measurement below the shot-noise limit based on a quantum measurement model utilizing squeezed light. By leveraging amplitude-modulation techniques and employing squeezed light as the probe field, we achieve field-strength measurement at 0.14 THz and further conduct terahertz absorption characterization experiments and theoretical simulations for various dielectric samples. The results show that squeezed light improves the signal-to-noise ratio by approximately 1.5 dB. This work validates the feasibility of squeezed light based Rydberg atom optical measurements for high-sensitivity THz detection and establishes a viable technical pathway for quantum THz spectroscopic characterization of diverse dielectric materials.

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Terahertz electromagnetic waves (0.1–10 THz), residing in the transition region between electronics and photonics, exhibit unique properties such as high penetration, strong directionality, and large communication capacity compared to lower-frequency electromagnetic fields.[1] These characteristics have enabled applications in imaging, security screening, and communications. Rydberg atoms, characterized by their large polarizability and substantial transition dipole moments, possess transition frequencies between adjacent energy levels that fall within the microwave and terahertz bands. Through optical manipulation, Rydberg atoms can function as receiving atomic antennas detecting electromagnetic waves spanning from microwave to terahertz frequencies. This approach offers significant potential for advancing terahertz electric field measurement techniques.

High-precision spectroscopy is the core technology of Rydberg atomic antennas. Rydberg atomic spectra based on quantum interference effects enable electromagnetic field detection approaching the quantum shot-noise limit. In 2007, Durham University demonstrated narrow-linewidth electromagnetically induced transparency (EIT) spectroscopy using a room-temperature rubidium atomic vapor cell.[2] In 2012, researchers from the University of Oklahoma realized microwave field measurement based on this scheme, achieving a minimum detectable microwave electric field of 8 μV cm^{-1} and a detection sensitivity of 308 μV cm^{-1} Hz$^{-1/2}$.[3] Benefiting from the large electric dipole moment of Rydberg atoms in the terahertz band, atomic precision detection technology has been successfully extended to terahertz regimes.[4–6] Optimized spectroscopic configurations and schemes such as superheterodyne detection and fluorescence measurement continuously improve sensitivity and imaging speed, supporting the development and practical implementation of high-performance Rydberg atomic terahertz sensing and imaging systems.[7–10]

Terahertz measurement techniques based on optical methods are theoretically limited by the quantum shot-noise limit. In practice, the classical noise in optical measurements often dominates over the

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photon shot noise, restricting the signal-to-noise ratio (SNR) of spectral measurements.[11] In recent years, quantum-enhancement techniques exploiting nonclassical light fields such as entangled and squeezed states have developed rapidly, enabling measurement precision beyond the classical limit[12–16] and finding applications in gravitational-wave detection, magnetometry, and phase measurement.[17–23] However, squeezed states of light within light–atom interaction ensembles remains challenging due to atomic absorption.[24] Shot noise arises from the discrete photon nature of optical fields and defines the fundamental shot-noise limit in optical measurement systems. For vacuum-squeezed states, the quantum fluctuations of the quadrature amplitude and quadrature phase follow the Heisenberg uncertainty principle. By utilizing optical parametric oscillation, the quantum noise of a specific field quadrature can be suppressed below the classical shot-noise limit.[25,26] In this work, we generate squeezed light resonantly matched to the cesium atomic transition through parametric processes and introduce it into a Rydberg-atom sensing system. Assisted by amplitude-modulation (AM) technology, we experimentally realize terahertz electric field measurement with sensitivity beyond the shot-noise limit. Furthermore, we perform terahertz absorption characterization for various dielectric samples and conduct corresponding theoretical simulations to verify the experimental results.

The experimental system consists of squeezed light generation, THz measurement, and balanced homodyne detection shown in Fig. 1. The squeezed light generation system uses a nonlinear crystal in an optical cavity, comprising two cascaded units: the second-harmonic generation (SHG) module that frequency-doubles the 852 nm fundamental light from a Ti:sapphire laser to 426 nm; the optical parametric oscillator (OPO) module that generates an 852 nm vacuum-squeezed state resonant with the cesium D2 line via down-conversion of 426 nm pumping.

The generated squeezed light is split into two paths. One is sent to a spectrum analyzer for squeezing degree characterization, while the other is coupled into the THz measurement system as the probe light. This system is based on the ladder-type three-level structure of cesium atoms ($6S_{1/2} \rightarrow 6P_{3/2} \rightarrow 62D_{3/2}$), which maps the intensity information of the THz field onto the transmittance variation of the probe light via the EIT effect. By applying AM to the THz source, a photodetector extracts the spectral transmission signal to realize THz measurement.

The balanced homodyne detection (HD) system consists of a pair of photodetectors. Their differential signal is split between a spectrum analyzer, which characterizes probe squeezing, and a quantum-noise locking (QNL) unit.[27] The QNL feedback controls the PZT in the local optical path to lock the relative phase between the squeezed field and the local oscillator, maintaining stable squeezing during measurement.

Figure 2 shows the atomic-level structure and corresponding spectra. Counterpropagating and collinear 852 nm probe and 509 nm coupling beams form a ladder-type Rydberg EIT system in a Cs vapor cell with length of 0.05 m and radius of 0.02 m. The two beams jointly excite ground-state Cs atoms to the $62D_{3/2}$ state [Fig. 2(a)], yielding peak EIT transmission at the two-photon resonance [Fig. 2(b)]. The THz field couples the $62D_{3/2}$ state to the $59P_{3/2}$ state, which reduces the EIT transmission. We employ AM for THz field detection and this scheme allows narrowband comparison between coherent and squeezed probes at a fixed analysis frequency and can be implemented directly with our source without requiring an additional THz local oscillator. Figure 2(c) presents the detection performance under the optimized 8 kHz square-wave modulation.

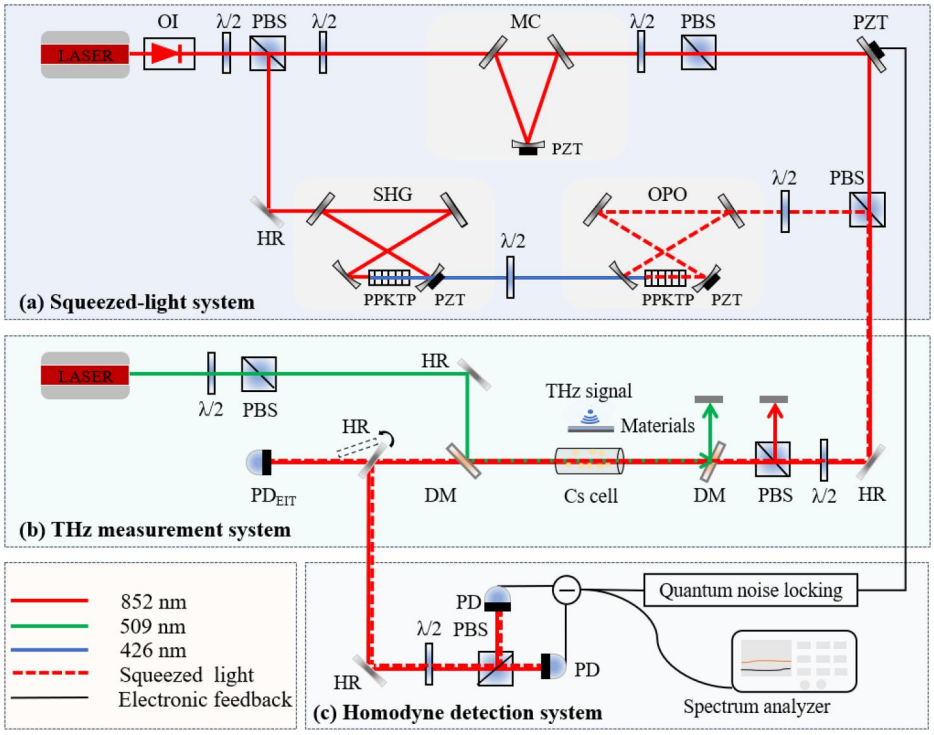


FIG. 1. Schematic diagram of the experimental setup. (a) Squeezed light generation system, which can generate squeezed light resonant with the D2 line of cesium atoms. (b) Terahertz measurement system, which can be used for the measurement and characterization of terahertz signals. (c) Balanced homodyne detection system for noise characterization and quantum-noise locking to stabilize the phase of squeezed light.

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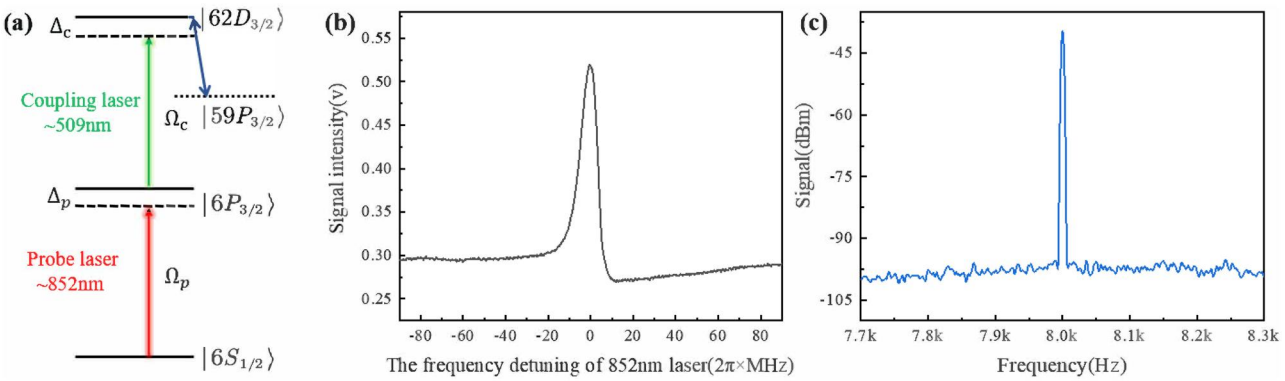


FIG. 2. Schematic diagram of Rydberg atomic energy levels and spectrum. (a) Rydberg atomic energy-level diagram; (b) EIT spectra signal; and (c) THz signal based on AM detection.

The experiment generates 852 nm squeezed light resonant with the cesium D2 transition. The 852 nm output beam from a Ti:sapphire laser is frequency-doubled via an SHG cavity to produce 426 nm pump light, which is injected into an OPO cavity to generate an 852 nm vacuum-squeezed field through parametric downconversion. Scanning the relative phase between the coherent and squeezed fields produces periodic variations in the measured light-field noise distribution, characteristic squeezed and anti-squeezed spectra are observed at specific phases. The vacuum-squeezed field is coherently combined with the coherent field, and quantum-noise locking stabilizes their relative phase to yield a power-tunable squeezed state. Figure 3 shows 5 dB squeezing achieved experimentally at an analysis frequency of 8 kHz under the zero-span mode of the spectrum analyzer. The red line denotes the shot-noise limit (SNL), and the blue line represents the measured noise spectrum of the squeezed light.

The coherent 852 nm probe is replaced by squeezed light as shown in Fig. 4, where black and red curves denote the coherent and squeezed light spectra, respectively, yielding a 1.5 dB SNR improvement. The probe Rabi frequency is $\Omega_p/2\pi = 13.48$ MHz, and its beam diameter is 1.2 mm. Although the independently characterized input squeezing is approximately 5 dB, the cell loss measured at the operating detuning is 41.9%, which includes cell window losses and residual Cs absorption (supplementary material, Fig. S1). In this experiment, optical-path losses, Cs atomic vapor cell losses, and imperfect mode matching introduce vacuum noise and degrade the squeezing degree (supplementary material, Sec. 4). Stronger input squeezing can further improve the SNR, but its benefit is limited by total loss. In the experiment, the single-photon detuning of the probe relative to the $6S_{1/2}(F=4) \rightarrow 6P_{3/2}(F'=5)$ transition is $\Delta_p/2\pi = +300$ MHz, where $\Delta_p = \omega_{probe} - \omega_{atom}$. This working point balances reduced absorption and an effective Rydberg EIT response. We optimized detection using an appropriately detuned, actively locked EIT spectrum and 8 kHz intensity modulation as the analysis frequency for THz characterization. Benefiting from the

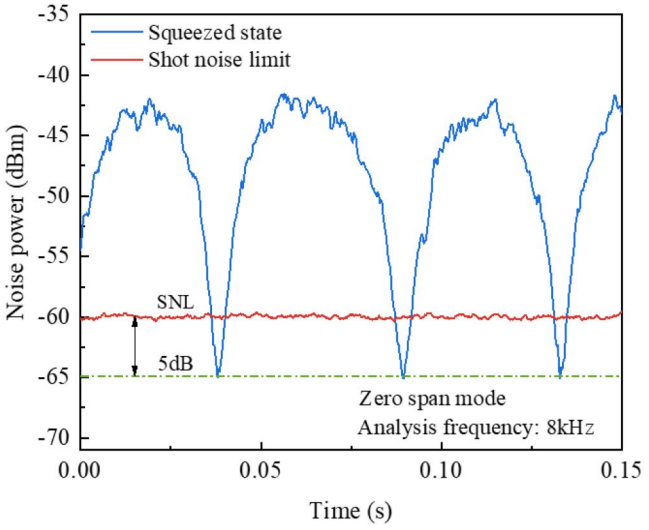


FIG. 3. Squeezed state. The noise curve is obtained by scanning the phase of the local oscillator light.

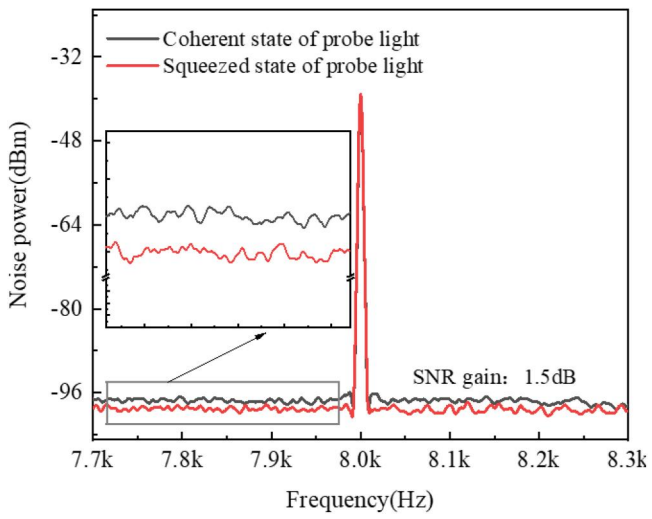


FIG. 4. Comparison of terahertz electric field measurements using a coherent state and a squeezed state probe light.

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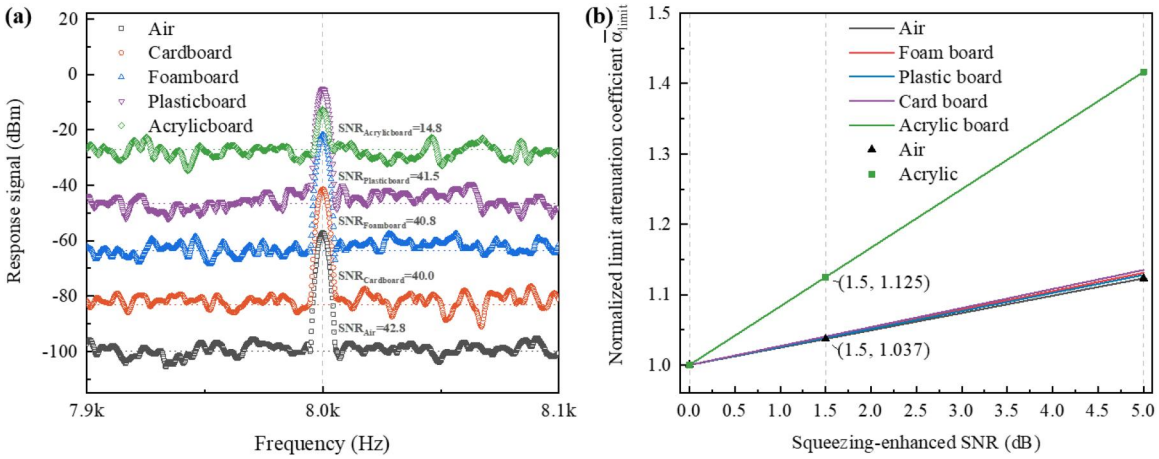


FIG. 5. Terahertz-response experiments and squeezing-enhancement simulation for different media. (a) THz response signals of the Rydberg-atom system for five media (curves offset vertically for clarity). (b) Normalized limit-detectable attenuation coefficient vs squeezing-enhanced SNR, normalized to the no-squeezing case. Dashed lines mark 1.5 dB; triangles and squares denote experimental data for air and acrylic at 1.5 dB, respectively.

low-noise Ti:sapphire laser and low-noise balanced homodyne detectors, the HD system reliably measures photon shot-noise over approximately 50 Hz–200 kHz (supplementary material, Fig. S2). These results confirm that squeezed light enhances the SNR even under residual resonant absorption, validating quantum-enhanced THz detection.

To verify the system's ability to resolve THz absorption differences, we perform EIT-based absorption experiments on five dielectric plates. In the experiment, the THz source is square-wave modulated at 8 kHz with an amplitude of 5 V, and is positioned 0.25 m away from the vapor cell. Media are sequentially replaced for comparative measurements, and the results are shown in Fig. 5(a) (curves are vertically offset to avoid overlap). Foam, plastic, and cardboard exhibit weak THz attenuation, with SNRs maintained around 40 dB, whereas acrylic shows significant THz absorption with an SNR of 14.8 dB, demonstrating that the system can effectively distinguish THz absorption differences among media.

To quantitatively evaluate the detection gain of squeezed light under different loss backgrounds, we establish a limit-detection model based on measured media SNR, distinguishing two types of loss: intrinsic medium attenuation (signal loss background) and weak additional THz attenuation to be detected (minute absorption variation). According to the exponential attenuation law of THz waves, a medium of thickness L and intrinsic attenuation coefficient α introduces a total decibel-domain attenuation of A_{mat}. Defining SNR_0 as the baseline SNR without a medium, the baseline SNR after inserting the medium satisfies $\mathrm{SNR}_{\mathrm{exp,mat}} = \mathrm{SNR}_0 - A_{\mathrm{mat}}$. Let x be the SNR improvement introduced by squeezed light, and $\mathrm{SNR}_{\mathrm{th}}$ be the detection threshold, typically set to 3 dB.

When the system barely resolves the weak additional THz attenuation, the output SNR equals the detection threshold, such that

$$\mathrm{SNR}_{\mathrm{exp,mat}} + x - 4.343\,\alpha_{\mathrm{limit}} L = \mathrm{SNR}_{\mathrm{th}}. \tag{1}$$

Here, the coefficient 4.343 arises from the conversion between the exponential attenuation law and the decibel scale, while α_{limit} is the limit-measurable attenuation coefficient, representing the minimum extra THz absorption signal resolvable by the system against the intrinsic medium loss background. After normalization to eliminate fixed parameters such as sample thickness, the simplified analytical model is given by

$$\bar{\alpha}_{\mathrm{limit}} = 1 + \frac{x}{\mathrm{SNR}_{\mathrm{exp,mat}} - \mathrm{SNR}_{\mathrm{th}}}. \tag{2}$$

The analytical model shows that the normalized limit-detectable additional attenuation coefficient is linearly proportional to the SNR improvement from squeezed light, with the slope $1/(\mathrm{SNR}_{\mathrm{exp,mat}} - \mathrm{SNR}_{\mathrm{th}})$ (supplementary material, Sec. 3). Simulation results as shown in Fig. 5(b). At 1.5 dB squeezing enhancement, low-loss media such as air show only 3.7% detection performance improvement, whereas the high-loss acrylic medium reaches 12.5% relative improvement, confirming that the gain of squeezed light is more prominent in high-loss weak THz detection scenarios.

In this work, we achieve shot-noise-limited weak THz signal measurement using AM modulation and demonstrate quantum-enhanced spectroscopy with low-frequency squeezed light, obtaining a 1.5 dB SNR gain. Multi-medium THz absorption characterization experiments verify the system's resolving capability for nonmetallic materials, and theoretical simulations further show that high-loss samples can achieve more significant relative detection gains. This technique shows potential for applications in THz imaging, biosafety detection, and composite material spectral analysis.[28–31] Future work will suppress atomic resonance absorption loss through Doppler-matched velocity selection and control over the number of effective atoms involved in light-THz interactions, further improving the squeezing degree and advancing practical THz quantum-enhanced spectroscopy.

See the supplementary material for more characterizations and experiment details.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Nan Su: Data curation (equal); Formal analysis (equal); Investigation (equal); Methodology (equal); Validation (equal); Visualization (equal); Writing – original draft (equal); Writing – review & editing (equal). **Yao Liu:** Data curation (equal); Investigation (equal); Methodology (equal); Validation (equal); Visualization (equal). **Tingting Liu:** Data curation (equal); Funding acquisition (equal); Investigation (equal); Validation (equal); Visualization (equal). **Guanhua Zuo:** Data curation (equal); Formal analysis (equal); Investigation (equal); Methodology (equal); Validation (equal); Visualization (equal); Writing – original draft (equal); Writing – review & editing (equal). **Jun He:** Conceptualization (equal); Data curation (equal); Formal analysis (equal); Funding acquisition (equal); Investigation (equal); Methodology (equal); Project administration (equal); Resources (equal); Supervision (equal); Validation (equal); Visualization (equal); Writing – original draft (equal); Writing – review & editing (equal). **Wenting Diao:** Funding acquisition (equal); Project administration (equal); Resources (equal); Writing – review & editing (equal). **Yuchi Zhang:** Formal analysis (equal); Funding acquisition (equal); Project administration (equal); Supervision (equal); Writing – original draft (equal); Writing – review & editing (equal). **Tiancai Zhang:** Conceptualization (equal); Data curation (equal); Formal analysis (equal); Methodology (equal); Project administration (equal); Resources (equal); Supervision (equal); Validation (equal); Writing – original draft (equal); Writing – review & editing (equal). **Junmin Wang:** Conceptualization (equal); Data curation (equal); Formal analysis (equal); Methodology (equal); Project administration (equal); Resources (equal); Supervision (equal); Validation (equal); Writing – original draft (equal); Writing – review & editing (equal).

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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