The Room-Temperature Rydberg-Atom Receiver For Terahertz Wireless Communications

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Terahertz wireless communications promises to satisfy the future high-capacity demand. However, practical system for terahertz communications faces many challenges. Among them, the communications distance is a crucial problem due to serious propagation loss. Here we demonstrate a 338.7 GHz wireless link based on the cesium Rydberg atoms in a room-temperature vapor cell. The minimum detectable electric field of 132 ± 13 μV/cm (9.72 s detection) is realized in our system. With this atomic receiver, the phase-sensitive conversion of amplitude-modulated or frequency-modulated terahertz waves into optical signals is performed to realize the wireless communications with 8-state phase-shift-keying. The experimental results show that the atomic receiver has many advantages due to its quantum properties. Especially, the communications distance has the potential to be over 18 km. Furthermore, the atomic receiver can be used in the terahertz wireless-fiber link to directly convert the wireless signals into optical signals. Our work provide the new path to future terahertz wireless communications.

Since the data traffic requirement in wireless communication networks is increasing exponentially, the spectral band resources will inevitably be extended to terahertz (THz). And integration of THz links into fibre-optic infrastructures seamlessly is crucial important1–3. Significant progress has been made to construct the high performance THz wireless communication systems which mainly consist of transmitters and receivers4–12. By combining the photonic transmitter and electronic receiver, the high data rate system transmitting data over 20 m at 237.5 GHz was realized13. With all electronic devices, the 21 km wireless communication at 140 GHz was demonstrated14. Besides, the graphene-based devices15,16, plasma-based transistors17,18 and topological photonics are also promising technologies for THz communication19.

However, the practical applications of THz wireless communication systems still face great challenges. The free space path loss (FSPL) and atmospheric attenuation make the long distance THz wireless communication difficult20,21. Moreover, because the THz transmitter power and receiver sensitivity tend to be lower at higher frequency, it’s hard to improve the performance of THz wireless communication systems. Another side, the THz-over-fibre architecture using receiver which can directly convert received wireless signals into optical signals is of great importance but technically difficult22,23.

Recently, the Rydberg atoms have been demonstrated as electromagnetic field sensors with ultrahigh sensitivity and capability of self-calibration24–29: the Rydberg-atom sensors have been proved to be excellent quantum receivers for the microwave communications30–32. In the THz frequency range, the Rydberg atoms still have large dipole moment making them ideal candidates for THz quantum sensors33–36. The ultimate performance of Rydberg-atom receiver is restricted by the quantum limits. This enables the Rydberg-atom receiver to have potential improving the overall performance of THz wireless system. Furthermore, the atomic receiver can be used in the THz wireless-to-optical link because it’s able to directly convert the wireless signals into the optical ones37.

In this paper, we demonstrate that the Rydberg atoms in a room-temperature cesium (Cs) vapor cell can be an excellent receiver for THz wireless communication. Firstly, we use the electromagnetically induced transparency (EIT) and Autler-Townes splitting (ATS) technique to calibrate the THz electric field strength produced by a 32-times frequency multiplier source. Then we implement the atomic receiver for THz wireless communication. The phase-sensitive conversion of amplitude-modulated or frequency-modulated THz wave into optical signals is used to perform a canonical digital communication with 8-state phase-shift-keying (PSK). Our work demonstrates that the Rydberg-atom receiver has advantages due to its quantum properties for THz wireless communication. Especially, the communication distance has the potential

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to be over 18 km.

The schematic of the standard four-level EIT-based Rydberg electrometry is illustrated in Fig. 1. The probe and coupling laser beams counter-propagate through a room-temperature Cs vapor cell. The 852 nm probe laser is 100 μW with 1/e^2 radius 120 μm and the coupling laser is 14.5 mW with 1/e^2 radius 70 μm. To avoid interfering the probe transmission, both lasers are locked using separated cells by frequency modulation methods. The probe beam is locked to the 6S_{1/2}(F = 4) → 6P_{3/2}(F' = 5) transition using the modulation transfer spectroscopy. While the 515 nm coupling laser is locked to the 6P_{3/2} → 2S_{1/2} transition using the Zeeman modulation scheme. An amplified balanced photodetector (PDB) is served to measure the transmitted probe power subtracting the noisy background to observe EIT. A microwave source (R&S SMF100A) and a 32-times frequency multiplier chain (9.72 s detection).

The transmission of the probe laser is measured when the coupling laser is scanned. With the THz field on resonance, the EIT peak splits due to the ATS as shown in Fig. 2(a). The AT peak splitting is proportional to the Rabi frequency $\Omega_{THz}$ of the THz electric field. With the calculated transition dipole moment $\mu_{THz} = 242 e \alpha_0$, the electric field strength $E_{THz} = h\Omega_{THz}/\mu_{THz}$. This relation (linear region) is valid until the splitting is smaller than the linewidth of the EIT peak which is 7.69 MHz in our experiment. To calibrate the minimum detectable THz field, the technique similar to the recently published paper is applied. In the linear region, the measurement of THz electric field is traceable and self-calibrated. The minimal detectable THz electric field in the linear region is $25.37 \pm 0.77 \text{ mV/cm}$. The electric field strength of THz wave at the atoms is firstly measured in the linear region shown in Fig. 2(b). Then the relationship between THz electric field and fundamental microwave power in the linear region is calibrated shown in Fig. 2(c). Our result shows that the output power of the THz source (32-times frequency multiplier chain) has a nonlinear relationship with the microwave power. To generate the weak THz electric field, the -57.31 dB attenuator is used. After attenuation, the splitting is hard to be distinguished (nonlinear region). The THz detuning is swept to observe the peak of probe transmission (Fig. 2(d)) whose value is positive correlation with THz field strength. From the precisely measured curve of THz electric field versus microwave power, the attenuated field strength can be determined accurately shown in Fig. 2(e). In Fig. 2(f), the variation of THz electric field with microwave power is measured in the nonlinear region. When the signal to noise ratios (SNR) equals 1, the minimum detectable THz electric field is $132 \pm 13 \mu \text{V/cm}$.

To demonstrate the wireless THz communication using the atomic receiver, the protocol that imposes the modulated THz signal into transmission of probe beam when the frequencies of laser beams are locked is performed. The digital signal of communication information is encoded in 8 states of modulation phase $\phi_{THz}$ generated by the digital synthesis signal generator (DDS) in Fig. 1. For frequency modulation, this digital signal is directly sent to the microwave source.
Meanwhile, an external microwave switch controlled by the digital signal is needed to implement the amplitude modulation. Through a 32-times frequency multiplier chain, the modulated THz wave is produced from the microwave. When the THz wave acts on the atoms, the transmission of probe beam is modulated via the EIT process. Thus an amplified balanced photodetector (PDB) is used to monitor the intensity of probe beam after the Cs vapor cell. The communication signal from PDB is analyzed and quadrature demodulated by a lock-in amplifier with reference signal from DDS. After that, the modulated probe transmission by the THz field is demodulated into an In-Phase voltage and a Quadrature-Phase voltage with the phase \( \phi_{\mu} = \arctan(V_Q/V_I) \). The demodulated phase \( \phi_{\mu} \) is corresponding to the modulation phase \( \phi_{THz} \) of THz field.

First, the amplitude modulation protocol is tried in the THz wireless communication demonstration. The THz wave is turned on and off by the external microwave switch controlled by the phase modulated signal from DDS. In the linear region, the THz electric field is \( E_{THz} = 85.18mV/cm \) and the demodulated 8PSK constellation diagrams is shown in Fig. 3(a). In the nonlinear region, the THz electric field is \( E_{THz} = 4.05mV/cm \) and the demodulated 8PSK constellation diagrams is shown in Fig. 3(b). The 8 phase states are encoded from \( \phi_{\mu} = 0^\circ \) to \( \phi_{\mu} = 315^\circ \) with interval 45°. And the modulation frequency 500 kHz and 1 MHz is employed which is limited by the bandwidth of our PDB and lock-in amplifier. Both in the linear region and nonlinear region, the 8 phase states can be clearly discriminated. But the phase noise becomes lager in the nonlinear region since the THz field is weaker.

It’s well known that frequency modulation can avoid the influence of amplitude interference in the propagation progress that can significantly improve the communication quality. Therefore, the frequency-modulated methods are also tried in our THz wireless communication scheme. In the frequency modulated communication, the fundamental microwave frequency hopping is controlled by the phase modulated signal from DDS. After 32-times frequency multiplication, detuning of THz wave hops from resonance to a large detuning 156.8 MHz. Relatively, transmission of probe beam varies from maximum peak to small value or even zero when the THz detuning jumps from resonance to 156.8 MHz. So the periodic frequency hopping can be converted into the intensity oscillation of probe beam passing through the Cs vapor cell. Then the collected signal of probe beam intensity by the PDB is sent to the lock-in amplifier. After quadrature demodulation, the 8PSK constellation diagrams illustrated in Fig. 3(c)(d) can be acquired. From Fig. 3, the atomic receiver has the same performance compared with amplitude modulation.

The THz transmission distance is one of the biggest challenges for wireless communication as the serious propagation attenuation. For distance below 1 km, the free space path loss (FSPL) is dominated. The FSPL can be given in terms of the frequency as

\[
\text{FSPL} = (4\pi df/c)^2. \tag{1}
\]

In our system, the frequency \( f = 338.7 \text{ GHz} \). Considering the distance \( d = 1 \text{ km} \) and vacuum speed of light \( c \), the FSPL is 143 dB. For distance larger than 1 km, the atmospheric attenuation must be taken into account especially for THz wireless links with large carrier frequency. For example, the atmospheric attenuation is 5 dB/km at 338.7 GHz. One way

\[
\text{FSPL}(\text{atmospheric}) = \text{FSPL}(\text{free space}) + 5 \text{ dB/km}.
\]
to extend the communication distance is to raise the power of THz source. However, this is very difficult for both photonic and electronic based THz source. Another way is to use the THz receiver with higher sensitivity, that’s why we tried the Rydberg-atom receiver. In our THz wireless link, the output power of THz source corresponding to the minimum detectable THz electric field in the nonlinear region is 159-169 dBm. The full power of the commercial source we used can be 12 dBm, so there is link budget 68 dB for propagation loss. The maximum transmission distance 3.5 m can be achieved. Unlike the electronic receivers, the ultimate sensitivity of the atomic receiver is restricted by the standard quantum limit (SQL). The sensitivity for SQL is described as\(^{42}\),

\[
\frac{E_{\text{min}}}{\sqrt{Hz}} = \frac{2\pi \hbar}{\mu_{THz} \sqrt{NT_2}}
\]  

(2)

In our experiment, the atom number participating in the EIT progress is \(N = 1 \times 10^5\). Considering dephasing time \(T_2 = 21 \mu s\), the SQL sensitivity is about 2.3 nV cm\(^{-1}\)Hz\(^{-1/2}\). For room-temperature atoms, the effectiveness of EIT probing is reduced by 30-40 dB\(^{43}\). This means the total budget relative to the SQL for wireless transmission is 159-169 dB. Then corresponding distance is about 5 km. Recently, some excellent work has been carried out on embedding the Rydberg-atom sensor into antennas or waveguides\(^{44,45}\). If use a 50 dB\(i\) transmitter antenna and embedding the Rydberg-atom sensor into a 50 dB\(i\) receiver antenna, this distance will be over 18 km. In addition, the Rydberg transitions have large dipole moments in a wide frequency range from 100 GHz to nearly 3 THz, so the atomic receiver can keep this performance in a very wide band\(^{3,36}\). Unlike the bandwidth of electronic receiver which is limited by the antennas and waveguides, atomic receiver bandwidth depends on the Rydberg transitions and lasers.

For any type of communication receiver, the maximum channel capacity \(C\) is important and described by the Shannon-Hartley Theorem\(^{30,46}\),

\[
C = f_m \log_2(1 + \text{SNR})
\]  

(3)

Here the \(f_m\) is the symbol frequency and the SNR is signal-to-noise ratio. The modulation frequency is limited by the time needed for the EIT/AT to develop\(^{30,32,46}\). Considering maximum 10 MHz modulation frequency, the channel capacity is 10 Mbits/s at the minimum detectable THz field.

Finally, the atomic receiver can be used in the THz wireless-to-optical link because it’s able to directly convert the wireless signals into the optical ones\(^{37}\). Usually the wireless-to-optical receiver systems rely on electronic devices. The signal of electromagnetic wave is received and mixed down to lower frequency. Then an electro-optic modulator can be used to convert this signal into optical domain\(^{22,23}\). In the demonstration of our THz wireless communication system, the amplitude-modulated or frequency-modulated information is directly converted into laser signal at 852 nm by the Rydberg-atom receiver. Comparing with electronic ones, the wireless-to-optical atomic receiver is simpler and lower in cost without frequency down-mixing and extra modulator.

To summarize, the room temperature cesium Rydberg atoms are demonstrated to be sensitive THz electric field sensors. The minimal detectable THz electric fields 132 ± 13\(\mu\)V/cm (9.72 s detection) are calibrated. Furthermore, the phase-sensitive conversion of amplitude-modulated and
frequency-modulated THz wave into optical signals is conducted to realize the communication with 8-state phase-shift-keying. The atomic receiver has potential to realize 18 km terahertz wireless communication at 338.7 GHz. Furthermore, the atomic receiver can be used in the terahertz wireless-fiber link to directly convert the wireless signals into optical signals. Our work provide the new path to future THz wireless communication.

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