Photonics-Aided THz-Wireless Transmission over 4.6 km Free Space by Plano-Convex Lenses

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Abstract: *We demonstrate a photonics-aided THz-wireless transmission over 4.6 km free space by plano-convex lenses. The use of plano-convex lenses greatly extends the wireless transmission distance. Advanced digital signal processing (DSP) algorithms improve the spectral efficiency of the system. ©2022 The Authors*

Introduction

At present, both 5G and 6G are facing three major technical challenges of coverage, power consumption, and cost [1]. The dielectric lens is low in cost, does not require current to drive, and has a wider working frequency band [2,3]. It can greatly simplify the Radio frequency Remote unit, antenna feeder system, heat dissipation system of the base station. Therefore, it meets the requirements of wide coverage, low cost, and low power consumption in the large-scale deployment of B5G and 6G, and has high engineering usability and broad application scenarios. In addition, photonics technology can overcome the bandwidth bottleneck of electronic devices, combine the mobility of wireless communication and the large-capacity advantage of optical fiber communication, and realize the seamless integration of optical fiber communication and wireless communication [4]. In recent years, many research teams have achieved long distance transmission in the THz-band. For example, Kallfass et.al achieved 240 GHz wireless transmission over 850 meters free space [5], Harter et al. achieved a wireless transmission at 300GHz, which can transmit 110 meters away [6]. Castro et.al achieved 300GHz wireless transmission over 500/1000 meters free space based on pure electric equipments [7], However, the wireless distance was too short to be further improved, or the spectral efficiency was too low in the experimental results they showed.

In this article, we demonstrate a photonics-aided THz-wireless transmission over 4.6 km free space by plano-convex lenses. The use of plano-convex lenses greatly extends the wireless transmission distance. Advanced digital signal processing (DSP) algorithms improve the spectral efficiency of the system. In the experiment, we achieved a wireless net rate of 19.64 Gbit/s at a record transmission distance of 4600 meters with the spectral efficiency of 3.27 bit/s/Hz. As far as we know, this is the maximum product of spectral efficiency and wireless distance at the THz band, i.e., 3.27 bit/s/Hz × 4.6 km = 15.04 bit/s/Hz •km.

Principle and Experimental setup

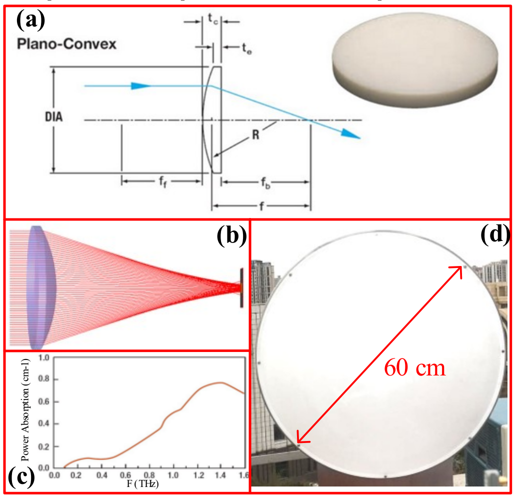

Fig. 1: (a) The structure of a standard plano-convex lens; (b) the schematic diagram of the optical simulation; (c) the Power Absorption of Poly tetra fluoroethylene; (d) the photo of plano-convex lens our designed

In the THz-band, the propagation mode of electromagnetic waves in space is beam propagation, so quasi-optical technology is used to transmit electromagnetic signals, which has the advantages of low loss, high transmission power, and multi-beam and multi-polarization work. In the collimation system, a lens can be used to achieve the collimation and focusing of the electromagnetic beam. Fig.1(a) shows the structure of a standard plano-convex lens. An ideal lens is like a phase shifter, which changes the radius of curvature of the isophase surface of the beam by introducing a phase shift to achieve the effect of beam focusing. It is well known that the transformation formula of Gaussian beam passing through lens is [8]:

$$\frac{1}{f}=\frac{1}{R_1}-\frac{1}{R_2}$$

Where f is the focal length of the required standard lens; R_1 is the radius of curvature of the Gaussian beam at the incident plane; R_2 is the radius of curvature of the Gaussian beam at the exit plane.

In the traditional design theory of a hyperbolic plano-convex lens, it is approximately considered that the Gaussian beam has the same beam radius on the incident surface and the exit surface of the lens. This will result in a certain error between the focusing performance of the designed standard lens and the expected value, and the thicker the lens, the greater the error. In order to solve this problem, a reasonable ray tracing model is established to simulate the focusing of the lens on the Gaussian beam, and then the genetic algorithm is combined to achieve the optimal design of lens shaping to improve the focusing effect [9]. The designed lenses are made by Poly tetra fluoroethylene (PTFE), which has a low dielectric constant of approximately 1.96 at 520 GHz and an index of refraction of approximately 1.4. This will ensure that the insertion loss is reasonably low, and the typical operation frequency can be extended to a wider range from 0.07 to 1.6 THz with small performance degradation at the edges of the band. Meanwhile, they demonstrate a good focusing function over a broad frequency range. Plano-Convex lenses have a positive focal length and approach best form for infinite and finite conjugate applications. Fig.1(b-d) shows the schematic diagram of the optical simulation, the Power Absorption of PTFE, and the photo of our designed plano-convex lens respectively.

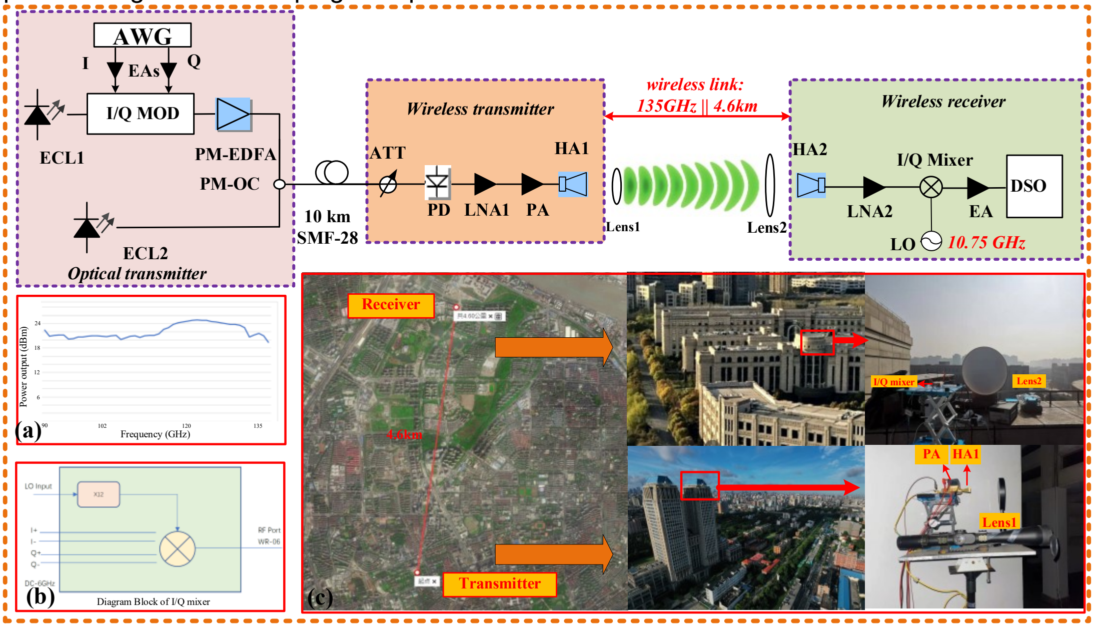

Fig. 2: The experimental setup of photonics-aided THz-wireless transmission over 4.6 km free space by plano-convex lenses; (a) the output power curve of power amplifier; (b) the diagram block of I/Q mixer; (c) the map of wireless link and the photos of the transmitter, receiver.

Fig.2 shows the experimental setup of photonics-aided THz-wireless transmission over 4.6 km free space by plano-convex lenses. At the optical transmitter, two free-running lasers ECL1 and ECL2 are used to generate continuous light waves, which work at 193.0THz and 193.135 THz respectively, and their line widths are less than 100kHz. The laser generated by ECL1 is used to drive an I/Q modulator with a 3dB bandwidth of 30GHz. The electrical OFDM signal is generated offline by Matlab software. Then we convert the digital signal to the analog signal through an arbitrary waveform generator (AWG). The electrical signal output from the AWG is amplified by a pair of parallel electric amplifiers (EAs), and then modulated by the I/Q modulator. The modulated optical signal is amplified by a polarization-maintaining Erbium-doped fiber amplifier (PM-EDFA) to compensate for the insertion loss of the modulator, and then coupled with the laser generated by ECL2 through a polarization-maintaining optical coupler (PM-OC). The optical signal then enters into a tunable optical attenuator (ATT) after being transmitted over 10 km SMF-28. Note that part of the experimental setup prior to SMF-28 is located indoors. In addition, a tunable optical attenuator (ATT) is used to adjust the input optical power into the PD. Finally, we obtain THz-band signal at 135 GHz after PD. The THz-band signal is boosted by a low noise amplifier (LNA1, gain 20dB) and THz-band power amplifier (PA, the output power curve is shown in fig.2(a)) successively, and then it is transmitted by a horn antenna (HA1) working at 110-170 GHz. A communication link with a wireless distance of 4.6 km (between the two campuses of Fudan University) is set. HA1 and HA2 are placed at the focal points of Lens 1 and Lens 2, respectively. The diameter of lens1 is 10 cm, and the focal length is about 20 cm. It can be used to collimate light from a point source. In addition, the diameter of lens2 is 60 cm, and the focal length is about 100 cm. It can be used to focus a collimated beam to the back focus. The combined gain of HA1 and Lens1 is about 34dBi. The combined gain of HA2 and Lens2 is about 56dBi. In the wireless receiver, the THz-band signal is first boosted by LNA2 which has 30dB gain, and then down-converted to a 6 GHz IF signal by an I/Q mixer, which is driven by the RF signal whose frequency is 10.75 GHz. The diagram block of I/Q mixer is shown in fig.2(b). We use an EA with a gain of 26dB to enhance the IF signal, and finally use a digital storage oscilloscope (DSO, 40GSa/s, Agilent DSO81304B) to capture it. The DSP process at the receiving end include down-conversion, resampling, synchronize and so on. We use the I/Q MIMO structure Volterra equalizer (VNE) with 33 taps at the 1st-order and 183 taps at the 2nd-order to compensate for the linear and non-linear damage in the system transmission, use the Intra-symbol frequency-domain averaging (ISFA) for channel estimation, and finally cascade the LMS and DD-LMS algorithm structures as a hybrid time-frequency domain equalizer to obtain a better demodulation signal. Fig.2(c) shows the photos of the transmitter, receiver, and experimental scene. The transmitter is located on the roof of Guanghua Building on Handan Campus, with a height of 142 m. The receiver is located on the roof of the Physical Building of Jiangwan campus, with a height of 24 m. Our experiment was carried out on a cloudy day with a temperature of 15°C and a humidity of 33%.

Results and Discussion

We firstly transmit 6 Gbaud OFDM-QPSK, OFDM-16QAM, respectively. As shown in Fig.3, we plot the BER versus the input optical power of PD. As the input power increases from 5 to 9 dBm, the value of BER gradually decreases due to the improvement of the optical signal-to-noise ratio. When the input power continues to increase to 9 dBm, we have achieved the minimum BER value of 1.2×10^{-3} for 6 Gbaud OFDM-QPSK, 8.6×10^{-3} for OFDM-16QAM, which is below the SD-FEC threshold of 1×10^{-2}. In addition, during a continuous operation period of 12 hours on a cloudy day in early December 2021, we observed an atmospheric loss variation of 0.2 dB due to the changes in atmospheric turbulence, temperature, humidity, and other factors, which do not cause many effects on the performance of BER. Next, we adjust the baud rate of signal from 2 to 6 Gbaud when the input optical power of PD is 9 dBm, as shown in Fig.3(b). Due to the decrease of the signal baud rate, the requirement for system bandwidth decreases, which leads to the optimization of BER performance. Finally, we can achieve the minimum BER value of 9.1×10^{-4} for 2 Gbaud OFDM-16QAM and zero error for 2 Gbaud OFDM-QPSK signal.

The overhead of our OFDM structure is 5.88%. So the maximum rate for OFDM-16QAM signal in our system is: 6×4×(1-5.88%)=22.59 Gb/s. After removing the 15% SD-FEC overhead corresponding to the BER threshold of 1×10^{-2}, we can calculate the maximum net rate as 6×4×(1-5.88%)×1/1.15=19.64 Gb/s. Therefore, the spectral efficiency of the system is 19.64/6=3.27 bit/s/Hz.

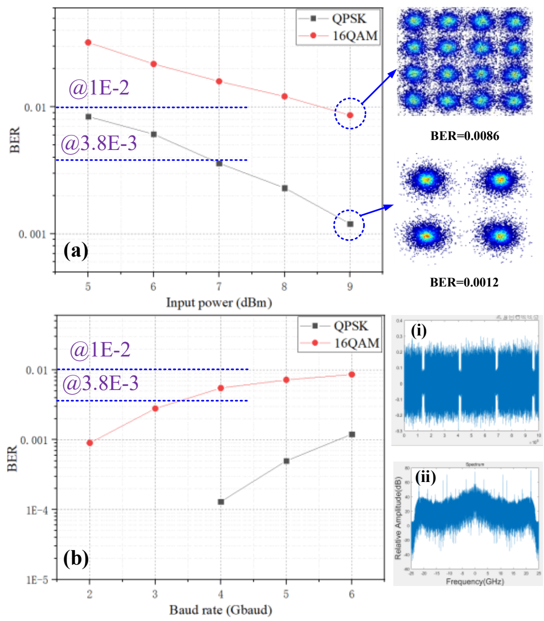

Fig. 3: (a) BER of 6 Gbaud QPSK and 16QAM signal vs. the input optical power of PD; (b) BER of QPSK and 16QAM signal vs. the Baud rate (i) time domain waveform; (ii) electrical spectrum of sampled 6Gbaud signal

Conclusions

We have experimentally demonstrated a photonics-aided THz-wireless transmission over 4.6 km free space by plano-convex lenses. In the experiment, we have achieved the minimum BER value of 1.2×10-3 for 6 Gbaud OFDM-QPSK, 8.6×10-3 for OFDM-16QAM. Totally, we achieved a wireless net rate of 19.64 Gbit/s at a record transmission distance of 4600 meters with the spectral efficiency of 3.56 bit/s/Hz.

Acknowledgements

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