

Special Topic: Terahertz Communications for 6G and Beyond: How Far Are We?

Exploiting polarization isolation for high diversity gain in a THz MIMO system

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Photon-assisted terahertz (THz) technology can give full play to the large bandwidth and high-frequency response characteristics of optical devices, effectively breaking through the capacity limitations of electronic methods to realize 6G communication [1]. Nevertheless, strong atmospheric attenuation leads to high path loss. Therefore, multiple-input multiple-output (MIMO) technology is introduced. By deploying antenna arrays at both the transmitter and receiver, it can enhance link quality. Examples include the 4600-meter millimeter wave (MMW) single-input multiple-output (SIMO) system proposed by Li et al. [2]. The author team of this paper has previously innovatively realized 2-meter wireless transmission of 93.7 GHz W-band signals based on a 2×2 single-polarization MIMO architecture, achieving a signal-to-noise ratio (SNR) gain of 7.1 dB compared with single-channel transmission [3].

In the previous experiments, it was found that differences in the relative distances between transmitting and receiving antennas can cause phase changes in signals of the same frequency and polarization, which in turn leads to coherent destructive interference, resulting in ultimate data loss. To solve this problem, this paper proposes a polarization division multiplexing (PDM) MIMO architecture. That is, both the transmitter and receiver use 2-pol antennas, and the electromagnetic waves in the two polarization directions are perpendicular to each other, which can significantly reduce inter-channel interference. On this basis, if the antennas in the two polarization directions carry the same signal and transmit synchronously, the receiving end can obtain SNR gain through the offline maximum ratio combining (MRC) algorithm, which assigns weights to the signals of all receiving paths according to the differences in signal quality of different paths and performs weighted summation [3]. If the two channels carry different signals, the data rate can be increased, reflecting the high flexibility of the system.

In addition, in the photon-assisted THz PDM-MIMO system, the generated dual-polarization THz signals need to

have high stability to ensure minimal crosstalk between the two signals during wireless transmission. The traditional method generates THz signals through the beating of two light beams, and then uses dual-polarization antennas to obtain 2-pol signals [4]. However, because light waves undergo polarization rotation during transmission in optical fibers, it is difficult to ensure that the polarization directions of the baseband signal and the local oscillator light are consistent during beating in the photodiode, which is known as the “polarization sensitivity” problem. Therefore, this paper proposes a polarization multiplexing module at the optical transmitter to directly generate a single optical signal that contains two polarization directions. This makes it possible to transmit two signals with different polarization states through the same antenna. Even if the light waves rotate during their transmission in the optical fiber, these two polarization directions will still remain perpendicular.

In a 2×2 PDM-MIMO system, since the polarization directions of the two transmitted signals are perpendicular, there is no interference between the two signals in theory. We assume that two independent channels with different polarization directions are h_1 and h_2 , according to the MRC algorithm. Compared with the SISO system, the receiving SNR gain of the 2×2 PDM-MIMO system is $g = \frac{\sum_{i=1}^{N_r} h_i^2}{h_1^2} = 2$, and the theoretical SNR gain is 3 dB only when $h_1 = h_2$. The experimental settings of the photon-assisted THz PDM-MIMO system are illustrated in Figure 1(a). We first utilized an ECL1 with a wavelength of 1549.32 nm as an optical carrier to carry a baseband electrical signal. Where the electrical signal is generated by a 92 GSa/s arbitrary waveform generator (AWG), amplified by an electrical amplifier (EA), and then modulated by an I/Q modulator. The modulated signal is sent to a polarization multiplexer after passing through a polarization-maintaining erbium-doped fiber amplifier (PM-EDFA) to generate two independent H-polarization and V-polarization signals. The polarization multiplexer consists

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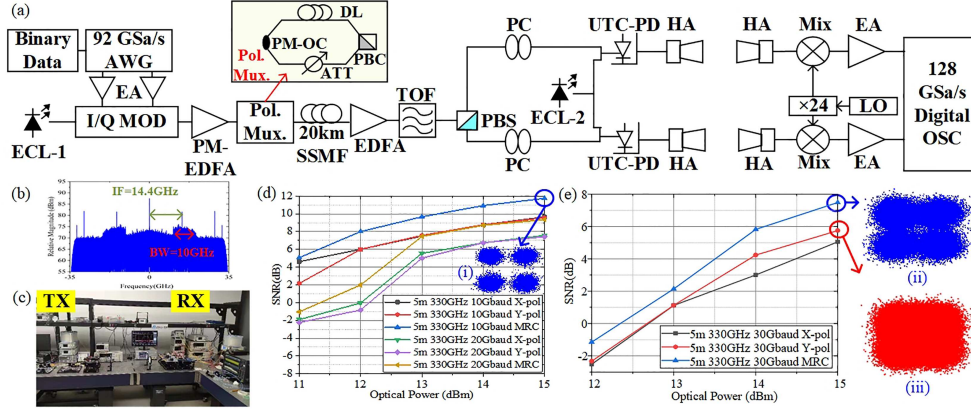


Figure 1 (Color online) (a) Experimental setup of the proposed PDM-MIMO system. (b) The spectrum of the IF signal when transmitting 11 dBm 10 Gbaud QPSK signals. (c) Experimental photo of a 1 m PDM-MIMO system. The received signal SNR of (d) 10 Gbaud, 20 Gbaud, and (e) 30 Gbaud 330 GHz signals at different optical powers after 5 m wireless transmission. The constellations are the received QPSK signals of (i) 10 Gbaud w/ MRC, 30 Gbaud (ii) w/ MRC, and (iii) w/o MRC when the input optical power is 15 dBm.

of a polarization-maintaining optical coupler (PM-OC), an optical delay line (DL), an attenuator (ATT), and a polarization beam combiner (PBC). The light wave is first split by PM-OC, and after the data decorrelation and two-arm power control, we use PBC to generate the dual-polarization signals. Then the PDM-QPSK signal is transmitted over a 20 km SSMF link. Link loss is compensated by inserting an EDFA. After that, we use a tunable optical filter (TOF) with a bandwidth of 0.5 nm to filter out-of-band noise caused by the amplified spontaneous emission (ASE) of the EDFA, and then connect it to the local oscillator (LO) light emitted by another 1551.97 nm ECL-2 through a PM-OC. Before the two beams are connected, we use two polarization controllers (PCs) to adjust the polarization states of the baseband signal light and the local oscillator light respectively to keep them in a stable incoherent state. Finally, the 330.4 GHz wireless signal is separated by a polarization beam splitter (PBS), detected by two 280–380 GHz THz UTC-PD, and then transmitted through antennas. The 2×2 PDM-MIMO THz wireless transmission link has two 25 dBi gain surface corner cone horn antennas in the transmitter and receiver. We also utilize two poly tetra fluorine ethylene (PTFE) lenses with a diameter of 10 cm to increase the wireless transmission distance due to their low dielectric constant. The gain of the PTFE lens is 12 dBi. For the THz wireless signals received by the two parallel PTFE antennas and HAs as transmitter, we performed a signal down-conversion which consists of two $24 \times$ -multipliers and two mixers. The radio frequency (RF) source is 13.167 GHz. The intermediate-frequency (IF) signal, which operates at a frequency of 14.4 GHz, is acquired using a 128 GSa/s oscilloscope (OSC) with a bandwidth of 59 GHz. Spectrum of the IF signal is shown in Figure 1(b). This signal is then utilized for offline DSP with T/2 MIMO constant modulus algorithm (MIMO-CMA), fast Fourier transform-based frequency offset estimation (FFT-FOE), Viterbi-Viterbi carrier phase estimation (VV-CPE), decision-directed least mean square (DD-LMS) algorithm, and MRC.

A typical experimental setting is shown in Figure 1(c), and the transmission distance can be extended to over 5 m. We experimentally compared the SNR of the 2×2 PDM-MIMO system over the 1×1 single-path after the 10–30 Gbaud 330 GHz signal was transmitted over 5 m. Figure 1(d) shows the received signal SNR values of 10 and

20 Gbaud 330 GHz signals at different optical powers. The 10 Gbaud signal can achieve up to 2.2 dB SNR gain in the PDM-MIMO system compared with a single channel, and the 20 Gbaud signal can achieve up to 2 dB SNR gain in the PDM-MIMO system. Figure 1(e) shows the received signal SNR of 30 Gbaud 330 GHz signals at different optical powers and the constellation diagram when the optical power is 15 dBm. The 30 Gbaud signal can achieve up to 1.8 dB SNR gain and the data rate can reach 60 Gbit/s without wasting spectrum resources.

This work demonstrates a 330 GHz photon-assisted 2×2 PDM-MIMO system to solve the coherence destruction issue. Addressing polarization sensitivity in traditional 2-pol signal generation, polarization multiplexing modules are introduced to generate highly stable 330 GHz dual-polarized signals. Integrating 2-pol signals with MIMO-MRC and adopting fully blind digital signal processing, the system achieves 60 Gbit/s over 20 km standard single-mode fiber (SSMF) and 5 m wireless transmission, with a maximum 2.2 dB SNR gain over single-channel transmission. Additionally, operating in the 330 GHz atmospheric attenuation window (superior to 320/340 GHz bands) makes these results more challenging and significant [5].

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