120Gb/s Wireless Terahertz-Wave Signal Delivery by 375GHz-500GHz Multi-Carrier in a 2×2 MIMO System

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(Top-Scoring Paper)

***Abstract*—We propose and experimentally demonstrate a photonics-aided 2×2 multiple-input multiple-output (MIMO) wireless Terahertz-wave (THz-wave) signal transmission system, which realizes 6×20-Gb/s six-channel polarization division multiplexing quadrature-phase-shift-keying (PDM-QPSK) THz-wave signal delivery over 10-km wireline single-mode fiber-28 (SMF-28) link and 142-cm wireless 2×2 MIMO link with a bit-error ratio (BER) under the hard-decision forward-error-correction (HD-FEC) threshold of 3.8×10^{-3}. Our employed multi-carrier frequencies are located within the range from 375GHz to 500GHz. To the best of our knowledge, this is the first experimental demonstration of 2×2 MIMO wireless transmission of multi-channel THz-wave signal. Here, it is worth noting that our wireless 2×2 MIMO link, which offers point-to-point straight transmission and brings neither interference nor gain, is different from the traditional MIMO link defined in the field of wireless communications.**

***Index Terms*—Terahertz-band, integrated photonics technology, multiple-input multiple-output, optical multi-carrier modulation, optical polarization multiplexing.**

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I. Introduction

THE Terahertz-band (THz-band, 0.3-10THz) can provide multi-gigabit mobile data capacity, with a very simple modulation format and system architecture, due to its huge available bandwidth [1-4]. Moreover, the THz-band antenna can be monolithically integrated with other front-end circuits, because of its small and compact size [5]. Considering the high atmospheric attenuation of the THz-band, the research community is paying more attention to the application of the THz-band to indoor short-range wireless personal area networks (WPANs) and wireless local area networks (WLANs) [6-11]. Integrated photonics technology is more practical than bandwidth-limiting all-electric technology to realize the generation, modulation, and detection of the Terahertz-wave (THz-wave) [3, 4]. The reported photonics-aided THz-wave signal systems typically employ a single-input single-output (SISO) wireless transmission link, and moreover, no fiber transmission is considered [8-11]. It is well demonstrated that wireless multiple-input multiple-output (MIMO), combined with optical polarization multiplexing, can effectively double the wireless transmission capacity [12-18]. Optical multi-carrier modulation can be further introduced into the wireless MIMO systems to decrease the signal transmission baud rate and increase the wireless transmission capacity [19-21]. Therefore, it is important to investigate the photonics-aided 2×2 MIMO wireless THz-wave signal transmission system with optical multi-carrier modulation.

In this paper, we experimentally demonstrate a photonics-aided multi-channel 2×2 MIMO wireless transmission system at THz-band [22]. Our demonstrated system can deliver 6×20-Gb/s six-channel polarization division multiplexing quadrature-phase-shift-keying (PDM-QPSK) THz-wave signal over 10-km wireline single-mode fiber-28 (SMF-28) link and 142-cm wireless 2×2 MIMO link, with a bit-error ratio (BER) under the hard-decision forward-error-correction (HD-FEC) threshold of 3.8×10^{-3}. To the best of our knowledge, this is the first time to realize multi-channel wireless THz-wave signal delivery in a 2×2 MIMO system. Here, it is worth noting that our wireless 2×2 MIMO link, which offers point-to-point straight transmission and brings neither interference nor gain, is different from the traditional MIMO link defined in the field of wireless communications.

The remainder of this paper is organized as follows. Section II gives the principle of our proposed technique of wireless MIMO combined with optical multi-carrier modulation. Section III introduces the experimental setup of our demonstrated photonics-aided multi-channel 2×2 MIMO wireless transmission system at THz-band. Section IV gives the measured BER performance of our demonstrated system. Section V concludes our work.

II. Principle of Wireless MIMO Combined with Optical Multi-Carrier Modulation

Fig. 1 gives the principle of our proposed technique of wireless MIMO combined with optical multi-carrier modulation. Here, we take the generation and 2×2 MIMO wireless transmission of a multi-channel THz-wave signal as an example. At the optical transmitter end, multiple optical carriers with a certain frequency spacing from an optical multi-carrier source (OMS) are modulated by the transmitter data and then polarization multiplexed to generate the multi-channel polarization-multiplexing optical baseband signal. The transmitter data can employ advanced vector signal modulation, such as QPSK, 8-ary quadrature amplitude modulation (8QAM), 16QAM, and so on. The OMS can be multiple free-running lasers or a multi-carrier optical comb. In our following experiment, the scheme of multiple free-running lasers is employed because it has two obvious advantages. The first one is that it is relatively easy to generate the THz-wave at any carrier frequency based on multiple free-running lasers. The second one is that the outputs of free-running lasers have a relatively high signal-to-noise ratio (SNR) than those of a multi-carrier comb. However, the employment of multiple free-running lasers has a drawback that digital signal processing (DSP) is needed at the receiver to compensate for the frequency drift. Insets (a) and (b) show the schematic optical spectra before and after polarization multiplexing, respectively. After single-mode fiber (SMF) transmission, the multi-channel polarization-multiplexing optical baseband signal is received by the wireless transmitter end.

At the wireless transmitter end, a free-running laser functions as an optical local oscillator (LO) source. Then we use an integrated polarization-diversity phase-diversity 90° optical hybrid to implement the optical polarization diversity of the received multi-channel polarization-multiplexing optical baseband signal and the optical LO. The integrated optical hybrid, with two input ports and eight output ports, integrates two polarization beam splitters (PBSs) and two 90° optical hybrids. As shown in Fig. 1, we simply use two output ports of the integrated optical hybrid, and the output of these two output ports can be considered as a multi-channel polarization-multiplexing optical THz-wave signal. Considering its small and compact size, the THz-band antenna is typically integrated with the THz-band photomixer in the commercially available products. Therefore, we use two parallel antenna-integrated photomixer modules (AIPMs) to up-convert the multi-channel polarization-multiplexing optical THz-wave signal to an electrical one and radiate the up-converted electrical THz-wave signal into free space. Note that, the X- or Y-polarization component after PBS1 contains both data encoded onto X- and Y-polarization at the optical transmitter end, due to polarization rotation caused by fiber transmission. Therefore, the selected two outputs of the integrated optical hybrid as well as the two different signal components of the generated electrical THz-wave signal all contain X- and Y-polarization transmitter data. The X- and Y-polarization marked in Fig. 1 and appearing in the following text are only used for simplification. Inset (c) in Fig. 1 shows the schematic electrical spectrum of the radiated X- or Y-polarization multi-channel electrical THz-wave signal. Then, the X- and Y-polarization multi-channel electrical THz-wave signals are simultaneously delivered by the parallel X- and Y-polarization wireless transmission links, that is, the 2×2 MIMO wireless THz-wave transmission link.

At the wireless receiver end, two THz-band horn antennas (HAs) are used to simultaneously receive the X- and Y-polarization multi-channel electrical THz-wave signals. Then, the analog down conversion is implemented to down-convert the X- and Y-polarization multi-channel electrical THz-wave signals from THz-band carrier frequencies to microwave/millimeter-band carrier frequencies. The two parallel radio-frequency (RF) low-noise amplifiers (LNAs) can

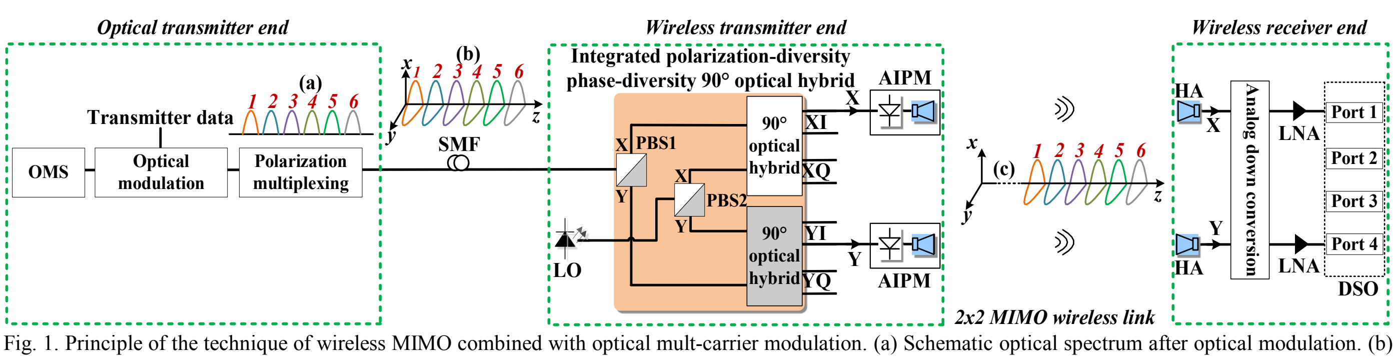

Fig. 1. Principle of the technique of wireless MIMO combined with optical mult-carrier modulation. (a) Schematic optical spectrum after optical modulation. (b) Schematic optical spectrum after polarization multiplexing. (c) Schematic electrical spectrum after AIPM. OMS: optical multi-carrier source, SMF: single-mode fiber, PBS: polarization beam splitter, AIPM: antenna-integrated photomixer module, HA: horn antenna, LNA: low-noise amplifier, DSO: digital storage oscilloscope.

not only boost the down-converted electrical signals, but also function as two parallel band-pass filters to select the desired channel. Then, the selected channel is captured by a digital storage oscilloscope (DSO) for subsequent offline DSP.

III. EXPERIMENTAL SETUP

Fig. 2 gives the experimental setup of our demonstrated 6×20-Gb/s photonics-aided multi-channel wireless THz-wave signal delivery in a 2×2 MIMO system over 142-cm wireless distance. In our demonstrated system, we utilize photonic remote heterodyning to generate a six-channel PDM-QPSK modulated wireless THz-wave signal, located within the frequency range from 375GHz to 500GHz, and with 25-GHz channel spacing. Six external cavity lasers (ECLs), i.e., ECL1-ECL6, with 25-GHz frequency spacing, are used to generate a six-channel optical signal, while ECL7 is used as an optical LO. ECL1-ECL7, manufactured by AInair-Labs Corporation with the type number of TLG-300M, are all free-running with <100-kHz linewidth.

At the optical transmitter end, the three continuous-wavelength (CW) lightwaves generated from ECL1-ECL3 are combined by a polarization-maintaining optical coupler (denoted by PM-OC1) and then modulated by a 5-Gbaud electrical QPSK signal via an in-phase/quadrature modulator (denoted by I/Q MOD1). While the three CW lightwaves generated from ECL4-ECL6 are combined by PM-OC2 and then modulated by another 5-Gbaud electrical QPSK signal via I/Q MOD2. Each 5-Gbaud electrical QPSK signal, with a pseudo-random binary sequence (PRBS) of 2^{15}, is generated by an arbitrary waveform generator (AWG) and boosted by two parallel electrical amplifiers (EAs). Each I/Q MOD has 2.3-V half-wave voltage at 1GHz and 32-GHz 3-dB optical bandwidth. The two parallel Mach-Zehnder modulators (MZMs) in each I/Q MOD are both biased at the null point and driven at the full swing, while the phase difference between the upper and lower branches of each I/Q MOD is fixed at $\pi/2$. The output of two I/Q MODs are combined by PM-OC3, and then boosted by a polarization-maintaining Erbium-doped fiber amplifier (PM-EDFA) and polarization multiplexed by a polarization multiplexer (PM), to generate a six-channel (ch1-ch6) PDM-QPSK modulated optical baseband signal. Fig. 3(a) gives the measured optical spectrum (0.1-nm resolution) after the PM. The PM comprises a PM-OC to split the signal into two branches, an optical delay line (DL) in one arm to provide a 150-symbol delay, an optical attenuator in the other arm to balance the power of two branches, and a polarization beam combiner (PBC) to recombine the signals. Then, we deliver the generated six-channel optical signal over 10-km SMF-28, with 17-ps/km/nm chromatic dispersion (CD) at 1550nm, from the optical transmitter end to the wireless transmitter end.

At the wireless transmitter end, the received six-channel optical signal has 3.4-dBm optical power, while the CW lightwave generated from ECL7 is boosted by EDFA1 to 14.4dBm. A polarization controller (PC) is added before EDFA1 to manually adjust the polarization direction of the optical LO. The integrated optical hybrid is manufactured by Optoplex Corporation with the type number of HB-C0GFCS002. Fig. 3(b) gives the measured optical spectra (0.1-nm resolution) after ECL7. Fig. 3(c) gives the measured optical spectrum (0.1-nm resolution) of one output port of the integrated optical hybrid. The parallel EDFA2 and EDFA3 are used to boost the six-channel optical THz-wave signal. We employ two NTT Electronics AIPMs (IOD-PMAN-13001) for the optical-to-electrical conversion of the six-channel optical THz-wave signal. Each AIPM, with a typical output power of -28dBm and an operating frequency range from 300GHz to 2500GHz, integrates a uni-traveling-carrier photodiode (UTC-PD) and a bow-tie or log-periodic antenna.

Here, note that an ideal photomixer used to detect the optical polarization-multiplexing signal should be polarization insensitive since the optical polarization-multiplexing signal contains two signal components at orthogonal polarization (X- and Y-polarization). However, the photomixer used in our experiment is polarization sensitive to the input optical signal and will therefore degrade the performance, which leads to the need of more input optical power. In our experiment, we add a PC before each photomixer to adjust the polarization direction into each photomixer, in order to get the maximal output from each photomixer.

Then, we deliver the six-channel electrical THz-wave signal over a 142-cm 2×2 MIMO wireless THz-wave transmission link from the wireless transmitter end to the wireless receiver end. Here, three pairs of lens are employed. The center of lens 1, 3 and 5 is aligned with the X-polarization wireless transmission link, while that of lens 2, 4, and 6 is aligned with the Y-polarization wireless transmission link. For X-polarization (Y-polarization) wireless transmission link, the separation

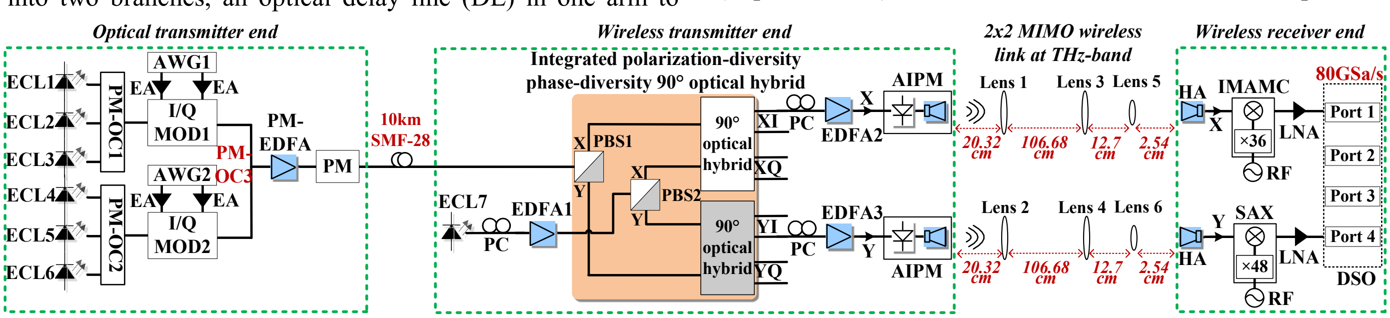

Fig. 2. Experimental setup for our demonstrated 6×20-Gb/s photonics-aided multi-channel wireless THz-wave signal delivery in a 2×2 MIMO system over 142-cm wireless distance. ECL: external cavity laser, PM-OC: polarization-maintaining optical coupler, I/Q MOD: I/Q modulator, AWG: arbitrary waveform generator, EA: electrical amplifier, PM-EDFA: polarization-maintaining Erbium-doped fiber amplifier, PM: polarization multiplexer, SMF-28: single-mode fiber-28, PC: polarization controller, PBS: polarization beam splitter, AIPM: antenna-integrated photomixer module, HA: horn antenna, IMAMC: integrated mixer/amplifier/multiplier chain, SAX: spectrum analyzer extender, RF: radio-frequency, LNA: low-noise amplifier, DSO: digital storage oscilloscope.

between the AIPM and lens 1 (lens 2), lens 1(lens 2) and lens 3 (lens 4), lens 3 (lens 4) and lens 5 (lens 6), as well as lens 5 (lens 6) and the receiver HA are 20.32cm, 106.68cm, 12.7cm, and 2.54cm, respectively. Lens 1-4 are identical, and each of them has 10-cm diameter and 20-cm focal length. Lens 5 and 6 are identical, and each of them has 5-cm diameter and 10-cm focal length. The two pairs of larger lens, i.e., lens 1-4, are used to focus the wireless THz-wave signal to maximize the received wireless power by the wireless receiver end. While the pair of smaller lens, i.e., lens 5 and 6, are used to do the fine adjustment of the position of the converged optical beam since the receiver THz-band antenna has a very small size.

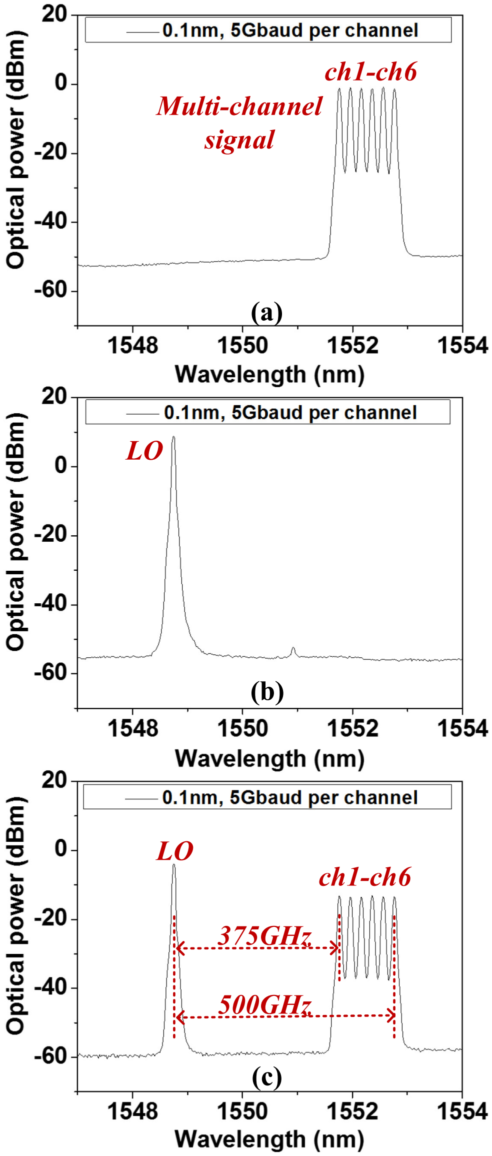

Fig. 3. Optical spectra are measured at 0.1-nm resolution after: (a) PM, (b) ECL7, and (c) polarization diversity.

At the wireless receiver end, we receive the six-channel wireless THz-wave signal with two parallel 26-dBi HAs, each operating within a THz-wave frequency range from 330GHz to 500GHz. For X-polarization signal, we utilize a VDI integrated mixer/amplifier/multiplier chain (IMAMC), driven by a 13.720-GHz sinusoidal LO source, to implement analog down conversion. The IMAMC, integrating a mixer, an amplifier, and a ×36 frequency multiplier, has an operating frequency range from 330GHz to 500GHz. Here, the LO frequency used to drive the mixer is therefore 36×13.720=493.92GHz. Then, the down-converted X-polarization intermediate-frequency (IF) signal is boosted by a LNA with 40-dB gain, 14-dBm saturation output power, and 4~18-GHz operating frequency range.

For Y-polarization signal, we utilize a VDI spectrum analyzer extender (SAX, WR2.2SAX), driven by a 10.290-GHz sinusoidal LO source, to implement analog down conversion. The SAX, integrating a mixer and a ×48 frequency multiplier, has an operating frequency range from 330GHz to 500GHz and an about 16-dB intrinsic mixer single-sideband (SSB) conversion loss. Here, the LO frequency used to drive the mixer is thus 48×10.290=493.92GHz, which is equal to the LO frequency used to drive the mixer at X-polarization. Then, the down-converted Y-polarization IF signal is boosted by a LNA with 50-dB gain, 15-dBm saturation output power, and 7~16-GHz operating frequency range.

Both LNAs at X- and Y-polarization paths also function as a band-pass filter to select the down-converted 6-GHz IF signals corresponding to ch6 at 500GHz, while suppress the down-converted IF signals corresponding to other five channels. Here, note that, due to the lack of available components, we use different analog down-converters and LNAs for X- and Y-polarization signals.

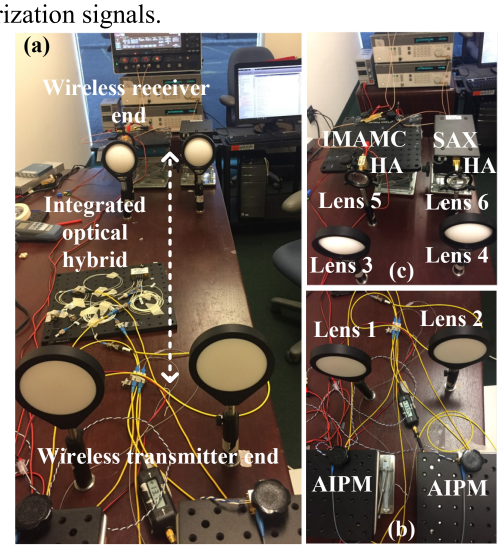

Fig. 4. Photos of: (a) 142-cm wireless transmission link, (b) wireless transmitter end and (c) wireless receiver end.

Then, we use two 80-GSa/s analog-to-digital convertor (ADC) channels of a DSO to simultaneously capture the X- and Y-polarization IF signals. Each 80-GSa/s ADC channel has 30-GHz electrical bandwidth. The subsequent offline DSP includes channel de-multiplexing, down conversion to baseband, 87-tap constant-modulus-algorithm (CMA) equalization, carrier recovery, and BER calculation [23]. Here, 87-tap CMA equalization is realized by four 87-tap complex-valued T/2-spaced butterfly-configured adaptive digital finite-impulse-response (FIR) filters based on the classic CMA. Figs. 4(a)-4(c) give the photos of the 142-cm 2×2 MIMO wireless THz-wave transmission link, the wireless transmitter end, and the wireless receiver end, respectively.

IV. Experimental Results

Fig. 5 gives the measured BER versus the input power into each AIPM for all six channels after 142-cm wireless MIMO delivery. Each channel carries 5-Gbaud PDM-QPSK signal. A tunable optical attenuator (TOA) is added before each AIPM to adjust the input power into each AIPM for BER measurement. 87-tap CMA equalization is employed. The BER of all six channels can be below the HD-FEC threshold of 3.8×10^{-3} when the input power into each AIPM is ≥15dBm. Ch1-ch3 have the similar BER performance, while ch6 has the best BER performance of all.

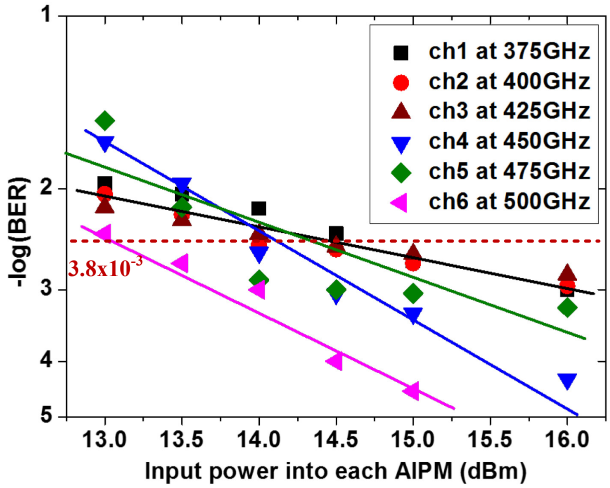

Fig. 5. BER versus input power for all six channels.

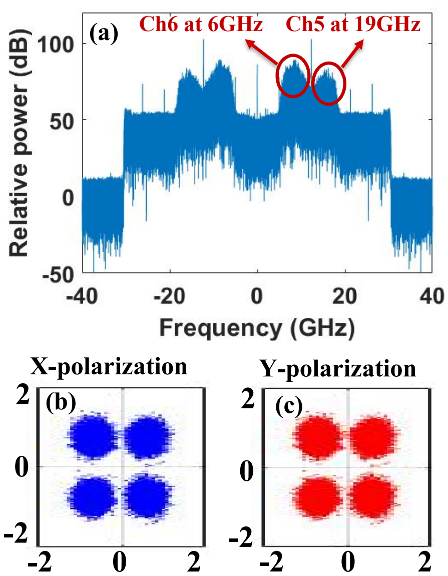

Fig. 6. (a) Captured IF signal spectrum by the DSO corresponding to ch6. Recovered (b) X-polarization and (c) Y-polarization QPSK constellations.

Figs. 6(a)-6(c) give the captured IF signal spectrum by the DSO as well as the recovered X- and Y-polarization QPSK constellations, corresponding to ch6 at 500GHz, with 15-dBm input power and a BER of 3.1×10^{-5}. We can see from Fig. 6(a) that, in the captured IF signal spectrum, in addition to our desired 6-GHz IF signal component with a relatively large power corresponding to ch6 at 500GHz, there also exists our undesired 19-GHz IF signal component with a relatively small power corresponding to ch5 at 475GHz. This is because of the mismatch and imperfect band-pass filtering characteristic of the two LNAs employed at the wireless receiver end. All the other IF signal components corresponding to ch1-ch4 are completely suppressed. We can also see from Fig. 6(a) that, there exist several line peaks in the captured IF signal spectrum, which is caused by the imperfect characteristic of our employed DSO. The signal performance will be degraded when these line peaks are located within the desired signal channel. However, ch6 can completely avoid these line peaks and therefore has the best BER performance of all the six channels, just as shown in Fig. 5.

Fig. 7 gives the measured BER versus the number of CMA taps, corresponding to ch6 at 500GHz after 142-cm wireless MIMO delivery. The input power into each AIPM is fixed at 15dBm. The optimum BER performance is attained when 87 CMA taps are employed. Here, larger CMA taps are required to compensate for the fiber delay caused by the distance difference between X- and Y-polarization transmission paths (The fiber length between EDFA2 and EDFA3 is different).

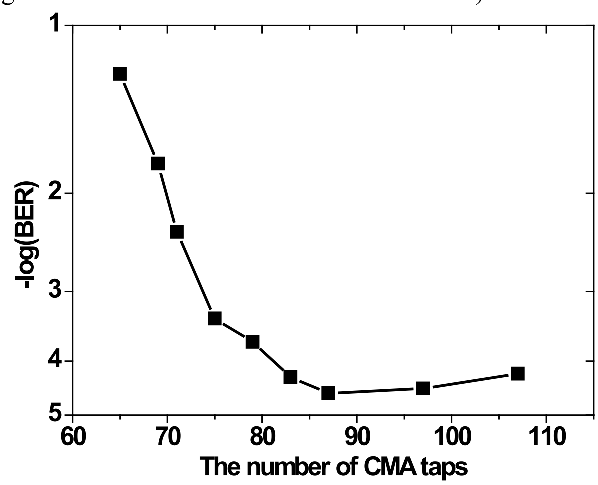

Fig. 7. BER versus the number of CMA taps.

V. Conclusion

We experimentally demonstrate a photonics-aided 2×2 MIMO wireless THz-wave signal transmission system, which, for the first time, realizes 2×2 MIMO wireless transmission of multi-channel THz-wave signal by multi-carrier frequencies of 375GHz-500GHz. In our demonstrated system, 6×20-Gb/s six-channel PDM-QPSK THz-wave signal can be delivered over 10-km wireline SMF-28 link and 142-cm wireless 2×2 MIMO link. We believe the transmission baud rate can be further increased if high-performance components and polarization-insensitive photomixers are employed.

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