Spectrally Efficient PDM-Twin-SSB Direct-Detection THz System Without Active Polarization Control

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***Abstract*— This Letter proposed a spectrally efficient polarization division multiplexed (PDM) twin single-sideband (twin-SSB) transmission scheme for direct-detection THz communication systems. The optical carrier of the twin-SSB is added at the optical THz converter, rather than being generated at the optical transmitter as in traditional SSB scheme. Hence the direct detection of each polarization branch of the PDM-twin-SSB signals at the THz receiver can be achieved, without active polarization control. Moreover, the SSB field recovery enabled by Kramers–Kronig algorithm can effectively eliminate the signal-to-signal beating interferences and contributes to better polarization de-multiplexing. The feasibility of the proposed scheme is verified with 5.75-GBd 16-quadrature amplitude modulation PDM-twin-SSB signals transmission over the 300-GHz direct-detection THz communication system by simulation. This scheme can not only significantly improve the spectral efficiency of direct-detection THz communication systems, but also effectively enhance the system's operability and robustness.**

***Index Terms*— Polarization division multiplexing, twin single-sideband, THz communication, direct detection.**

I. Introduction

WITH the large-scale deployment and promotion of 5G technology, advanced 6G research has been put on the agenda. The THz wireless communication, which is regarded as a promising candidate for 6G technology, has been attracted lots of attentions because of its inherent characteristics, such as high bandwidth, large capacity, low time delay and so on [1]. For the reception of the THz wireless signal, the direct detection scheme is more competitive to the coherent detection scheme, especially in the case of cost and power-consumption sensitive scenarios [2]. This is mainly because the direct-detection receiver just utilizes one simple Schottky barrier diode (SBD), hence it can avoid the complicated THz mixing down-conversion process in coherent detection scheme which requires the expensive RF local oscillator, frequency multiplier chain and THz mixer [3]. However, the direct-detection THz communication system suffers from a limitation on its spectral efficiency and transmission capacity due to the following two main reasons. One is the loss of phase information as well as introducing undesired signal-to-signal beating interference (SSBI) during the SBD-enabled square-law detection, which restricts the system's ability to support higher-order vector modulation [4], [5]. The other is the carrier fading effect encountered in the polarization division multiplexing (PDM) transmission case [6], which hinders the application of PDM technique in direct-detection THz communication systems. As is well known, one carrier is required to accompany with the target signal when using SBD receiver [3]. Taking the PDM single sideband (SSB) modulation as an example, the carrier is always generated or added at the optical transmitter (termed as CAOT scheme). Unfortunately, after optical fiber transmission, the complete carrier fading phenomenon may occur in one polarization direction as shown in Fig. 1(a), due to the random polarization rotation of this optical carrier [7]. It has been proofed as a fatal barrier to the direct detection of PDM-SSB transmission systems [6], [7]. In this case, the manual active polarization control is necessary, whereas the operability and robustness of the system are also greatly reduced.

In this Letter, to overcome the above issues, one novel PDM-twin-SSB scheme without active polarization control is proposed. Different form the commonly used CAOT scheme, one local optical carrier is evenly added to both the X and Y polarization branches at the optical receiving end (termed as CAOR scheme) [8] as shown in Fig. 1(b). Accordingly, the direct detection in each branch via one simple THz SBD is possible, regardless of the received polarization state of the PDM-twin-SSB signals. Hence the system's operability and robustness can be significantly enhanced. Moreover, utilizing the Kramers–Kronig (KK) algorithm [9], the SSB field recovery is achieved with the effective elimination of SSBI, resulting from the direct detection of SBD. At this case,

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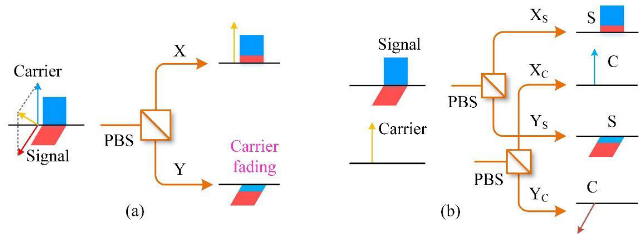

Fig. 1. Spectra of PDM-SSB signals before/after PBS with optical fiber transmission. (a) Traditional CAOT scheme; (b) proposed CAOR scheme.

an improved polarization de-multiplexing performance for the PDM-SSB signals can be obtained. The proposed scheme is demonstrated via 5.75-GBd PDM-twin-SSB 16-quadrature amplitude modulation (16-QAM) signals in 300-GHz direct-detection THz communication system by simulation.

II. Simulation Setup

The PDM-twin-SSB direct-detection THz communication system based on the CAOR scheme is illustrated in Fig. 2. At the optical transmitter, two different 5.75-GBd 16-QAM twin-SSB signals are generated off-line at the transmitting DSP, as shown in Fig. 2(a). Taking the X polarization (X-pol) as an example, two sets of independent pseudo-random bit sequences (PRBS1 and PRBS2) are first mapped into 16-QAM symbols, respectively. After pulse shaped by a root-raised cosine (RRC) filter with a roll off of 0.1, the obtained two 16-QAM signals are performed an opposite frequency shifting to produce the X-pol twin-SSB signal, which includes both one left sideband (LSB) and one right sideband (RSB) 16-QAM signal. Similar to the X-pol, the Y-pol twin-SSB 16-QAM signal is also generated from the other two independent PRBSs. The electrical dispersion compensation (EDC) and normalization are performed before the digital-to-analog conversion (DAC). Afterwards, each twin-SSB signal is converted from the electrical to optical domain using an IQ Mach–Zehnder modulator (IQMZM). Note, the bias of the IQMZM is set at the transmission null point to suppress the optical carrier. The transmitting laser adopts one laser diode (LD) with the central frequency of 193.1 THz. And a pair of polarization beam splitter (PBS) and polarization beam combiner (PBC) are used to split and combine the two polarization components, respectively.

The obtained PDM twin-SSB signals without optical carrier are first amplified by an erbium-doped fiber amplifier (EDFA) and then launched into a 60-km standard single-mode fiber (SSMF). The fiber transmission loss is compensated via another EDFA. And two variable optical attenuators (VOAs) located before and after the SSMF are used to adjust the launch and received optical power (ROP), respectively. After that, two optical PDM-SSB signals (i.e., LSB and RSB), are separated from the combined signals by two optical band-pass filters (OBPFs) with different central frequencies [10].

At the optical THz converter, the other two LDs are coupled together with the LSB/RSB signal, respectively, to perform the polarization diversity optical heterodyne detection. One is the optical carrier laser which has the same central frequency as the transmitter laser to provide the required carrier for the direct detection of SSB signal at the SBD receiver. And the other is used as an optical local oscillator (LO) for THz signal generation. The polarization diversity heterodyne detection structure [11] for LSB/RSB case consists of two PBSs, two optical couplers (OCs) and two uni-traveling carrier photodiodes (UTC-PDs) with the responsivity of 0.15 A/W and operating bandwidth of 260 $\sim$ 400 GHz. By setting the central frequency interval between the two LDs to 300 GHz, thus a 300-GHz THz SSB signal with a carrier can be obtained in each polarization branch after UTC-PD. Noting that in this PDM-twin-SSB direct-detection THz system employing the CAOR scheme, only one extra LD and one optical coupler (OC) are added as compared to traditional CAOT scheme. Therefore, it does not introduce excessive cost and complexity. In addition, both the optical carrier and LO can be evenly added to the two polarization branches in this CAOR scheme. As a result, the SSB signal in each branch can be directly detected via one THz SBD receiver without worrying the carrier fading effect.

After optical THz conversion, the two related THz components originating from the optical PDM-SSB signal are transmitted through one pair of 2×2 MIMO antennas. In this simulation setup, we only consider the back-to-back (BtB) wireless transmission case. At the THz receiver, the received THz SSB signal with the carrier is directly down-converted to IF via one low-cost SBD in each branch, respectively. This IF signal can be sampled by the analog-to-digital converter (ADC) and then demodulated in the receiving DSP, whose workflow is shown in Fig. 2(b). After resampling, using the KK algorithm to recover the SSB vector field from the detected signal intensity by each SBD, and meanwhile eliminates the SSBI resulting from the square-law detection of the SBD [12]. Afterwards, based on the reconstructed two SSB field signals, the cascaded multi-modulus algorithm (CMMA) is used to cancel the crosstalk between the X and Y polarizations. Then each polarization signal undergoes the baseband recovery, matched filtering, and downsampling. Next, the carrier phase estimation (CPE) based on Viterbi-Viterbi algorithm with QPSK partitioning [13] is used to compensate for the laser phase noise introduced by two independent free-running lasers. Finally, after channel equalization and symbol demapping, the bit error ratio (BER) for each polarization branch is calculated.

III. Results and Discussions

Figure 3 shows the influence of polarization state of the transmitted signal on the CAOT and CAOR schemes in optical BtB case. For simplicity, the PDM-twin-SSB structure of CAOR scheme shown in Fig. 2 is simplified to a single PDM-RSB transmission system by setting the PDM-LSB signal to zero. Meanwhile, instead of the fixed fiber transmission link, a polarization rotator is used to arbitrarily adjust the polarization state of the transmitted PDM-RSB signal. Different from the CAOR scheme, the optical carrier of the CAOT scheme is generated via the IQMZM modulation with the bias of above null point at the optical transmitter [14]. It can be found that the BER performance of the CAOT scheme varies dramatically with the polarization rotation angle of the transmitted PDM-RSB signal. In especial, there is a

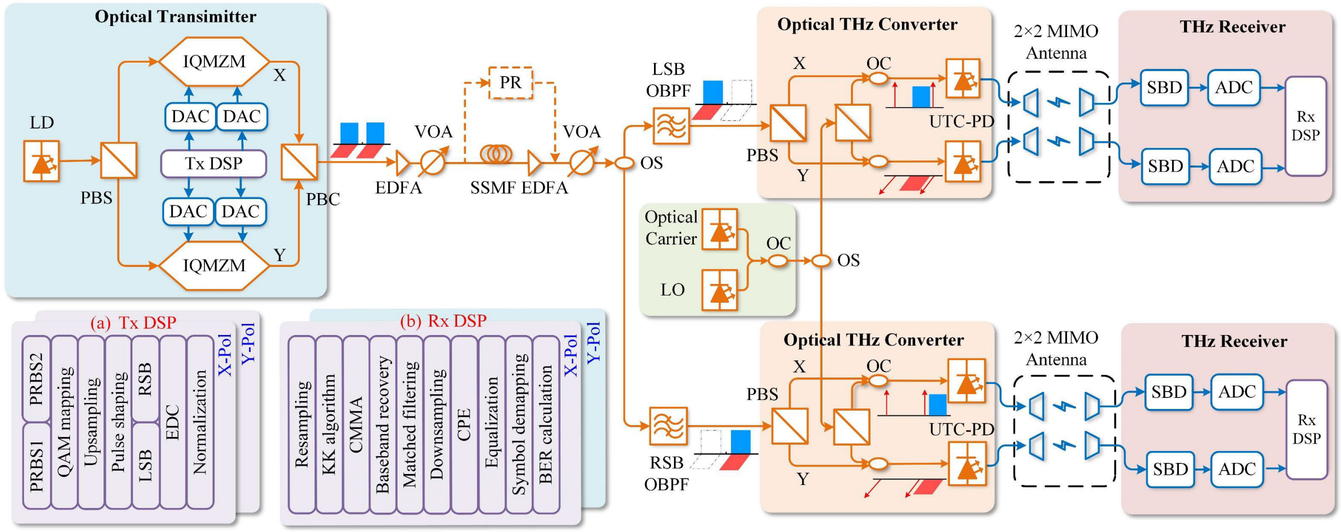

Fig. 2. Schematic architecture of 300-GHz direct-direction THz communication system based on PDM-twin-SSB 16-QAM signals transmission without active polarization control. Offline DSP of (a) Tx and (b) Rx. PR: polarization rotator.

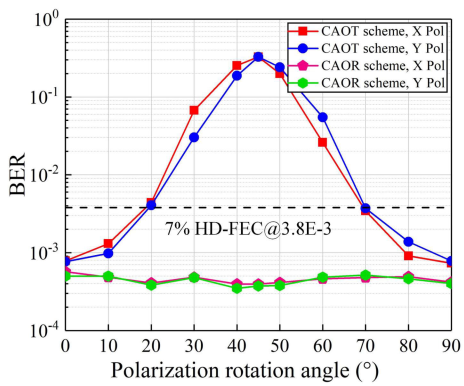

Fig. 3. Influence of polarization state of the transmitted PDM-RSB signal on the CAOT and CAOR schemes.

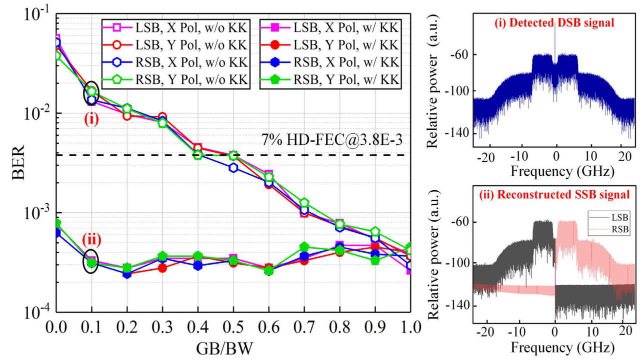

Fig. 4. Impact of different guard bands on BER performance of PDM-twin-SSB signals with and without KK schemes.

TABLE I
PERFORMANCE COMPARISON BETWEEN THE TWO SCHEMES

Scheme	ROP @ 3.8E-3 (dBm)
CAOT	– 9.20
CAOR	– 12.8

serious BER performance degradation around 45°, due to the complete carrier fading at one polarization direction as shown in Fig. 1(a). Therefore, the active polarization control is compulsory for the CAOT scheme. On the contrary, an almost flat BER curve with the arbitrary polarization angle can be obtained in the case of CAOR scheme. In other words, the carrier fading is successfully overcome in our PDM-SSB direct-detection THz system, which makes the system more practical and robust, attributing to without active polarization control. Moreover, the comparison of the required ROP to meet 7% hard-decision forward error correction (HD-FEC) BER threshold (3.8E-3) between the two schemes under a fixed launch optical power of 3 dBm is further given in TABLE I. It can be seen that the proposed CAOR scheme exhibits a 3.6-dB performance advantage over the traditional CAOT scheme. This mainly benefits from the carrier free transmission in the optical fiber.

Based on the proposed CAOR scheme, the BER versus normalized guard band (GB) curves for two different receiving schemes with (w/) and without (w/o) KK in PDM-twin-SSB direct-detection THz system are presented in Fig. 4. It can be seen that the BER performance without KK process improves obviously as the GB increases. Instead, after adopting the KK algorithm, the BER performance can maintain basically stable even with a small GB of 0.1 times of signal bandwidth (BW). This is mainly because the SSBI, which has a negative impact on the desired signal depending on the value of GB, is effectively eliminated by the KK algorithm. Consequently, the KK algorithm can significantly improve the spectral efficiency of the PDM-twin-SSB direct-detection THz systems. The insets (i) and (ii) of Fig. 4 show the spectra of detected DSB signal for without KK scheme and reconstructed SSB signal including LSB and RSB for KK scheme, respectively. In order to facilitate the separation of LSB and RSB signals while maintaining a high spectral efficiency, a GB of 0.1 BW is adopted in this Letter.

The BER performance with different carrier-to-signal power ratios (CSPRs) is further evaluated in Fig. 5 under the selected GB. The CSPR is determined by adjusting the power distribution between the optical carrier and the sideband signal with a fixed total power. It can be seen from Fig. 5 that the optimal

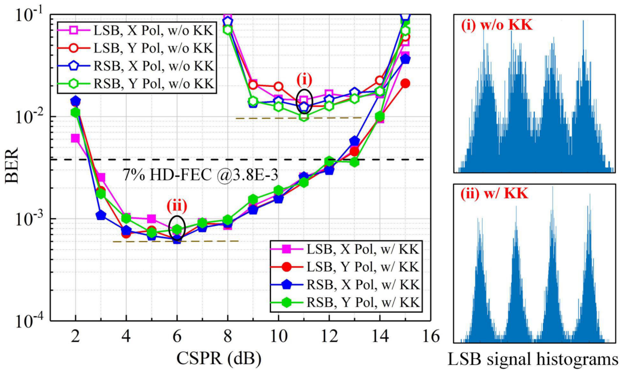

Fig. 5. BER versus CSPR curve with and without KK schemes.

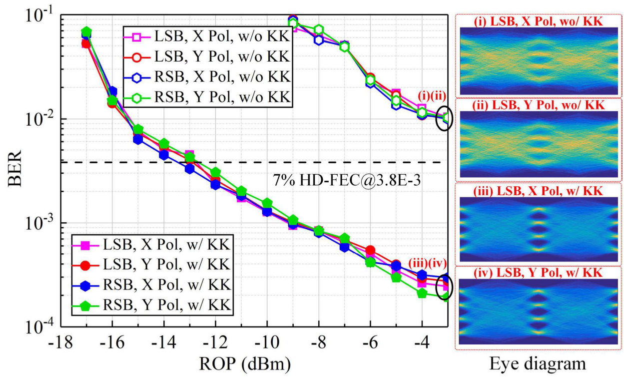

Fig. 6. BER versus ROP curve with the fixed CSPR of 6 dB.

CSPR for the schemes with and without KK are 6 dB and 11 dB, respectively. This means the KK scheme can improve the CSPR by 5 dB for the PDM-twin-SSB direct-detection THz system. Additionally, under the respective optimal CSPR, the KK scheme exhibits more than one order of magnitude improvement in BER performance than the scheme without KK. The performance improvement of KK scheme mainly comes from two aspects. One is the effective elimination of SSBI. The other is a better polarization de-multiplexing performance attributed to the accurate SSB field reconstruction by the KK algorithm. The insets (i) and (ii) of Fig. 5 show the histograms of recovered 16-QAM LSB signal for the scheme without KK (CSPR 11 dB) and with KK (CSPR 6 dB), respectively. A lower noise floor can be observed from the adjacent amplitude levels in the latter scheme.

Finally, we measure the BER performance for 5.75-GBd PDM-twin-SSB 16-QAM signals at different ROPs with the fixed CSPR of 6 dBm. As can be seen in Fig. 6, both the two schemes with and without KK algorithm can realize the polarization de-multiplexing of PDM-twin-SSB signals after 60-km SSMF transmission. However, as compared with the BER performance without the KK scheme, it can be reduced from 1E-2 to about 3E-4 after employing the KK scheme. Additionally, thanks to the KK algorithm for effective SSBI cancellation and accurate field recovery, an improvement of more than 10 dB can be observed in the required ROP to meet the 7% HD-FEC BER threshold. The performance advantage of KK scheme can be also proofed from the eye diagrams given in the insets (i) $\sim$ (iv) of Fig. 6.

IV. Conclusion

In conclusion, a spectrally efficient direct-detection THz communication system is proposed and demonstrated. Since the required carrier is added at the optical THz conversion side, each branch of the PDM-twin-SSB signals can be directly detected through the cost-effective THz SBDs regardless of the received polarization state. As compared with the traditional CAOT scheme which requires active polarization control, the proposed CAOR scheme not only enhances the operability and robustness of the PDM-twin-SSB direct-detection THz system, but also improves the receiving performance by approximate 4 dB. Furthermore, the KK algorithm is used to cancel the SSBI resulting from the SBD, and realize the field recovery of the dual polarization SSB signals. Leveraging on this, an improved polarization de-multiplexing performance more than one order of magnitude in BER and over 10 dB in required ROP to reach 7% HD-FEC BER threshold can be achieved. Based on the 5.75-GBd PDM-twin-SSB 16-QAM signals, a total transmission capacity of up to 92 Gbps with only about 6-GHz DAC/ADC bandwidth has been demonstrated via the THz SBD receiver. In consequence, the proposed scheme can provide benefits for improving the spectral efficiency and overall capacity of the SBD-enabled direct-detection THz communication systems.

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