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Spectrally Efficient Direct-Detection THz Communication System Enabled by Twin Single-Sideband Modulation and Polarization Division Multiplexing Techniques

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***Abstract*—We propose a spectrally efficient direct-detection THz communication system based on photonics. The direct detection of polarization division multiplexed (PDM) twin single-sideband (twin-SSB) signals without active polarization control can be realized by adding the optical carrier at the optical receiving side. We verify the feasibility of 5.75 GBd 16QAM PDM twin-SSB signals transmission in 300 GHz direct-detection THz communication system by simulation.**

Keywords*—-polarization division multiplexing, single-sideband modulation, THz communication system, envelope detection

I. Introduction

In the recent decade, various advanced techniques such as cloud computing and streaming media have been continuously emerging, and the frequency of radio communication has continuously increased to meet the growing demands of high data transmission capacity. To this end, the terahertz band with near 10 THz spectrum resources are quite favored for future 6G communications [1]. With respect to the terahertz (THz) communication system, the commonly used coherent detection scheme suffers from high power consumption and deployment cost. In contrast, the direct-detection scheme based on the Schottky barrier diode (SBD) is an attractive option due to its simple structure and inexpensive hardware cost [2]. However, the spectral efficiency and transmission capacity of direct-detection system are mainly limited by the characteristics of envelope detection, such as loss the phase information after detection, which cannot support higher-order vector modulation [3]. Thus, for the SBD-based direct-detection THz communication system, how to improve the spectral efficiency and increase the overall capacity becomes an urgent problem to be solved.

As is well known, the polarization division multiplexing (PDM) technique is a universal method for spectral-efficient optical transmission, which can double the transmission capacity of a single optical wavelength [4]. On the other hand, single-sideband (SSB) modulation, especially twin-SSB that carries different information through both left sideband (LSB) and right sideband (RSB) forms, can not only make full use of the bandwidth of system transceiver, but also further improve the spectral efficiency and transmission capacity [5]. Recently, the PDM and SSB techniques are studied intensively in direct-detection optical fiber communication systems [4-7]. Usually, the optical SSB signal also contains one optical carrier in addition to the sideband signal component, which is necessary for direct detection. However, in PDM SSB direct-detection systems, when the optical carrier is generated or added at the optical transmitting side (termed as CAOT scheme), the random polarization state of the optical carrier after fiber transmission exists carrier fading after polarization division, which has been proofed as a critical barrier to signal polarization de-multiplexing [6]. One extreme case is the optical carrier component of one polarization direction at the optical receiving side may occur completely fading. In this case obviously, the polarization de-multiplexing of the two polarization components cannot be achieved by 2×2 MIMO algorithm after direct detection, unless extra active polarization control is considered [4].

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In this paper, we propose a direct-detection THz communication system for the transmission of dual-polarization twin-SSB vector field signals. Compared with traditional single-polarization SSB system, the capacity of this THz system can be increased by almost four times by means of the PDM twin-SSB techniques. Moreover, instead of the CAOT scheme, the carrier is added at the optical receiving side (termed as CAOR scheme), which can support dual polarization de-multiplexing with an arbitrary polarization state of the twin-SSB signals in the direct-detection THz systems, without active polarization control. The feasibility of our proposed solution is verified based on 5.75 GBd PDM twin-SSB 16-quadrature amplitude modulation (16-QAM) signals transmission and envelope detection in 300 GHz band by simulation. The results show that the fundamental barrier to the direct detection of dual- polarization optical field has been overcome in this SBD-based THz envelope detection system.

II. SIMULATION SETUP

Fig. 1 shows the system structure of the PDM twin-SSB direct-direction THz communication system. At the optical transmitter, a 16-QAM electrical twin-SSB signal is generated off-line in the DSP, whose signal process flow is shown in Fig. 1(a). Two sets of 16-QAM symbols mapped from the two different pseudo-random bit sequences (PRBS1 and PRBS2), are pulse shaped via a root-raised cosine (RRC) filter with a roll off of 0.1 after upsampling. The symbol rate is set to 5.75 Gbaud. Then, different frequency shift operations are performed for the obtained two signals, respectively, to produce an electrical twin-SSB signal including both LSB and RSB signals. The electrical dispersion compensation (EDC) and normalization are performed before the digital-to-analog conversion (DAC). Next, the IQ Mach–Zehnder modulator (IQMZM) is used to convert the twin-SSB signal from the electrical domain to the optical domain. The modulator's bias is set at its minimum transmission point for optical carrier suppressing. In order to generate optical PDM twin-SSB vector field signals, two different 16QAM electrical twin-SSB signals are individually modulated by two IQMZMs corresponding to the X and Y polarization states, respectively. One polarization beam splitter (PBS) and one polarization beam combiner (PBC) are used to split and combine the X- and Y- polarization signals, respectively. Noting that the generated PDM twin-SSB signals are not accompanied by an optical carrier, as shown in the inset of Fig. 1, mainly to avoid the above-mentioned carrier fading problem.

The obtained PDM twin-SSB signals are launched into a 60-km standard single-mode fiber (SSMF) after amplified by an erbium-doped fiber amplifier (EDFA). Two variable optical attenuators (VOA) are utilized to adjust the launch and received optical power (ROP) before and after fiber transmission, respectively. After that, the optical twin-SSB signals are divided into the LSB and RSB forms by two optical band-pass filter (OBPF) with different central frequencies.

Before the optical THz conversion, another two external cavity lasers (ECLs), namely the optical carrier and local oscillator (LO), are coupled with the LSB/RSB signal to perform optical heterodyne detection with polarization diversity. The central frequencies of the optical carrier laser is set to 193.1 THz, which is the same as the transmitting laser at the optical transmitter. While the central frequencies of LO is 300 GHz smaller than that of the transmitting laser. Considering that the operations of dual-polarization LSB and RSB signals in the optical THz converter and THz receiver are basically similar, the difference is only the signal spectrum distribution, thus we only take the LSB signal as an example to illustrate the principle of signal demodulation in the following.

The dual-polarization LSB signal as well as the optical carrier and LO are first divided into two branches of X and Y polarization via the PBS, then they are coupled together and

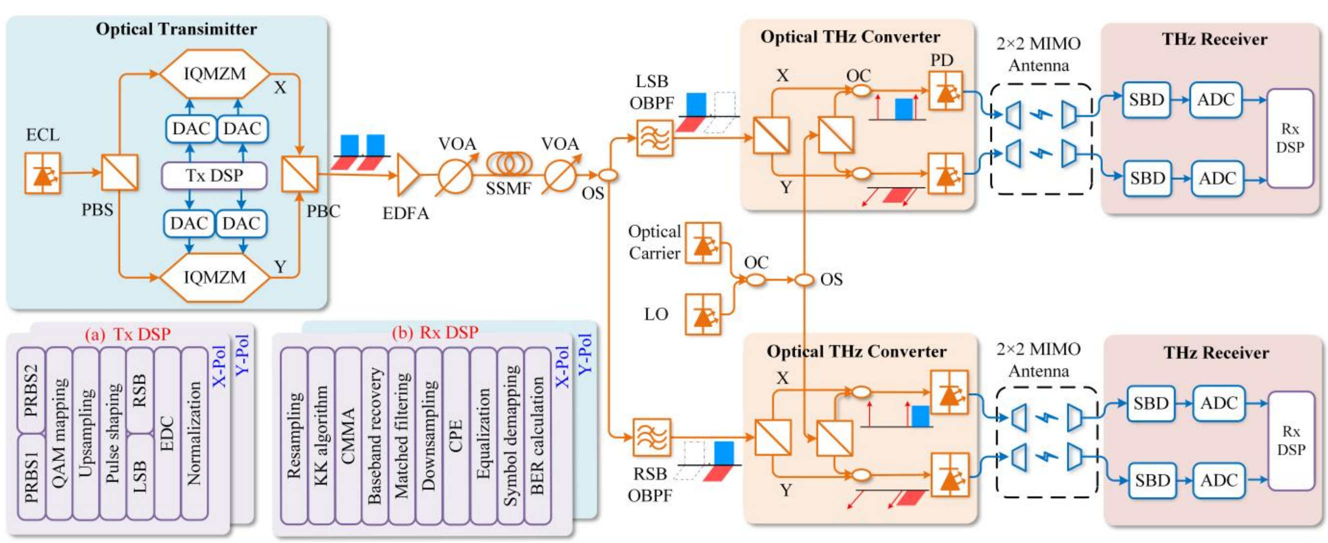

Fig. 1. Schematic architecture of 300 GHz direct-direction THz communication system based on PDM twin-SSB signals transmission. Offline DSP of (a) Tx and (b) Rx.

sent into the photodiode (PD) for photoelectric conversion at each branch. Note, the CAOR scheme can ensure that the carrier powers added to the two orthogonal polarization directions are equal. The PD used in each branch has a responsivity of 0.15 for emulating a uni-travelling carrier photodiode (UTC-PD) to generate THz signals. Based on the optical heterodyne detection, we can obtain the desired 300 GHz THz LSB signals with a carrier. Afterwards, the two THz components from two orthogonal polarization directions are then transmitted by the 2×2 MIMO horn antennas for wireless back to back transmission in the simulation setup. At the THz receiver, two low-cost SBDs are separately used to down-convert the two THz LSB signals to baseband, which then can be sampled by the analog-to-digital converters (ADCs) and demodulated in the receiver DSP. The workflow of the receiver DSP is shown in Fig. 1(b). Firstly, the SSB vector field is recovered from the sampled intensity information via the Kramers–Kronig (KK) algorithm [8, 9], which meanwhile can also eliminate the signal-signal beat interference (SSBI) due to the square-law detection of the SBD [10]. Secondly, according to the recovered SSB field signals, the crosstalk between the X and Y polarizations can be cancelled through the 2×2 MIMO based on the cascaded multi-modulus algorithm (CMMA). Then, after baseband recovery, matched filtering and downsampling, the carrier phase estimation (CPE) based on Viterbi-Viterbi algorithm is used to compensate for the phase noise introduced by two independent free-running lasers. Finally, symbol demapping and bit error ratio (BER) calculation are performed after channel equalization.

III. Result And Discussion

It is noted that in our PDM twin-SSB system above, we adopt the CAOR scheme in which the optical carrier is added at the optical receiving side. Here, we first study the influence of polarization rotation angles on CAOT and CAOR schemes. For simplicity, we only focus on the THz direct detection system with the single RSB signal transmission. For the CAOR scheme, the system structure difference from Fig.1 is that the LSB signal is set to zero, meanwhile a polarization rotator is insert after SSMF to adjust the polarization rotation angle of the transmitted signal. For the CAOT scheme, instead, the optical carrier is generated via the IQMZM modulation (with the bias of above NULL point) at the optical transmitter. Fig. 2 shows the comparison results of the two schemes. It can been seen that the BER of CAOT scheme varies with the polarization rotation angle of transmitted signal. Especially, there is a channel singularity around 50°, mainly because of the complete carrier fading at one polarization direction. Therefore, the active polarization control is necessary for the CAOT scheme. On the contrary, an almost flat BER curve at different rotation angles can be obtained in the case of CAOR scheme. This means the carrier fading has been successfully overcome in our PDM twin-SSB THz direct-detection system, and thus the active polarization control can be avoided which makes the PDM signal transmission much simpler and more practical.

The guard band is an important factor for the SSB transmission system. We evaluate the impact of guard band on BER performance of our PDM twin-SSB THz direct-detection system, as shown in Fig. 3. The normalized gap is characterized by the ratio of frequency gap between the carrier and 5.75 GBd 16QAM signal to the signal bandwidth (BW). Two different receiving schemes with (w/) and without (w/o) KK are studied for comparison. It can be seen that, the BER performance without KK process improves obviously as the guard band increases. This is mainly because the impact of SSBI on the desired signal gradually decreases as the guard band increases. However, after using the KK receiving scheme, a basically stable BER performance can be observed as long as a small frequency gap (not less than 10% of BW) is reserved. It should be noted that when there is no reserved guard band, the BER performance degrades slightly, mainly due to the crosstalk from another sideband during the LSB/RSB filtering operation. According to the above results, the KK scheme can significantly improve system's spectral efficiency. Considering the trade-off between the spectral efficiency and the BER performance, the optimum guard band of the proposed system is set to 0.1 BW.

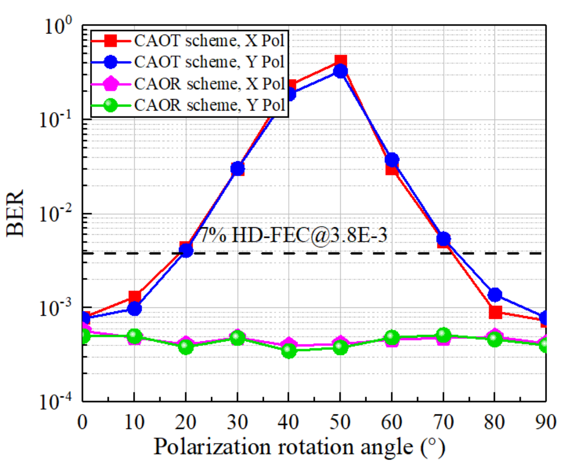

Fig. 2. BER performance comparison for CAOT scheme and CAOR scheme under different polarization rotation angles.

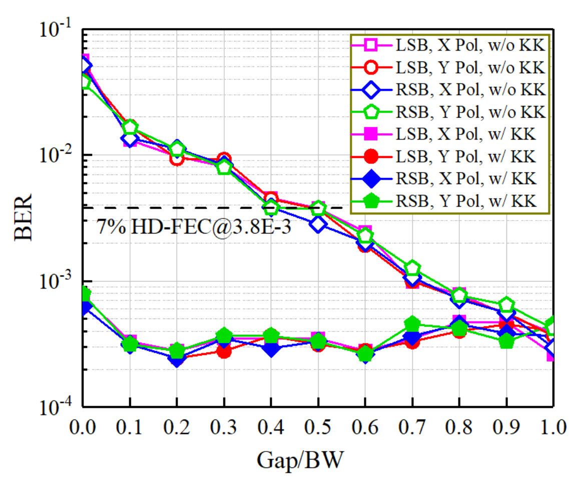

Fig. 3. Impact of different guard bands on BER performance at the cases of with and without KK schemes.

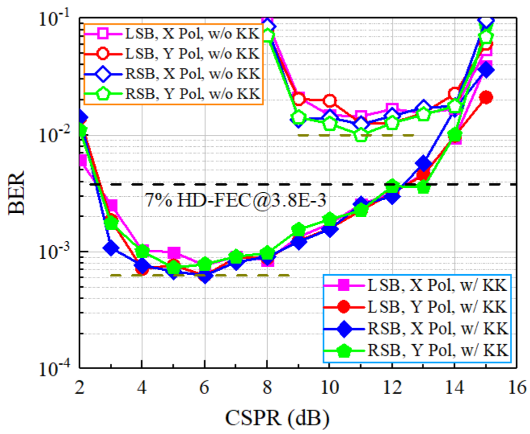

Fig. 4. BER performance under different CSPRs at the cases of with and without KK schemes.

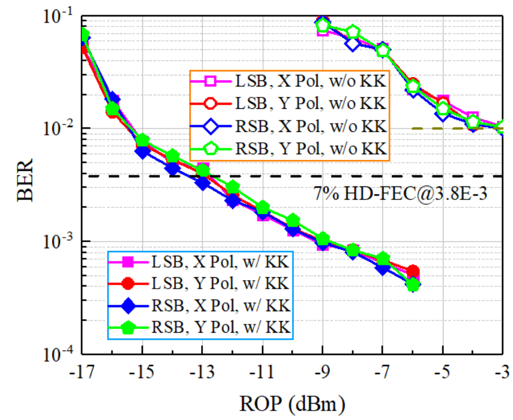

Fig. 5. BER versus ROP curves of 5.75 GBd 16QAM PDM twin-SSB signal with the CSPR of 6 dB.

Under the selected guard band, we further assess the BER performance with different carrier-to-signal power ratios (CSPR). The CSPR value is measured by adjusting the power of optical carrier and sideband signal while keeping their total power constant. As can be seen in Fig. 4, compared with the optimum CSPR without KK scheme, the optimum CSPR with KK scheme can improve by 5 dB. This can further confirm the ability to suppress the SSBI of KK algorithm. Moreover, in the cases of two optimum CSPRs, the BER performance of KK scheme also achieves an improvement of more than an order of magnitude, benefiting from the effective SSBI elimination and accurate field reconstruction capabilities. Since the effect of SSBI on the desired signal decreases with the increase of CSPR, the BER improvement of the KK scheme becomes less pronounced with the increase of CSPR. In particular, at a large CSPR such as 15 dB, the same performance can be achieved whether the KK scheme is used or not.

Finally, we fix the CSPR at 6 dB, and then measure BER performance at different ROPs. As can be seen in Fig. 5, both the two schemes can realize the polarization de-multiplexing of 5.75 GBd 16QAM twin-SSB signals. However, compared with the BER performance without the KK scheme, a BER below the 7% hard-decision forward error correction (HD-FEC) BER threshold (3.8E-3) can be achieved with the KK scheme. With the aid of the KK algorithm, an improvement of more than 10 dB in the required ROP can be achieved at the 7% HD-FEC threshold. Based on the successful demodulation of PDM twin-SSB signals, this direct-detection THz communication system can provide a total capacity of 92 Gbps via the DAC/ADC bandwidth of only about 6 GHz, which exhibits a very high spectral efficiency similar to the costly coherent THz system.

IV. Conclusion

In conclusion, we have proposed and demonstrated a spectrally efficient direct-detection THz communication system based on the PDM twin-SSB signals transmission. After direct detection via the low-cost SBD, the KK algorithm together with CMMA equalization can successfully achieve the demodulation of the dual-polarization twin-SSB vector field signals. Additionally, the optical carrier added at the receiving side can avoid active polarization control, resolving the carrier fading problem encountered in traditional direct detection of the PDM SSB signal. The feasibility of our proposed system is verified through 5.75 GBd PDM twin-SSB 16QAM signal with 60 km optical fiber transmission in 300 GHz direct-detection THz communication system by simulation. The results show that up to 92 Gbps transmission capacity can be achieved with the 6 GHz ADC and DAC bandwidth, corresponding to a very high spectral efficiency.

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