Photonic Aggregation of Microwave Signals Based on Phase and Amplitude Control Using a Dual-Polarization Dual-Drive Mach-Zehnder Modulator

Shengkang Zeng
Institute of Photonic Technology
Jinan University
Guangzhou, China
shengkangzeng@stu2020.jnu.edu .cn

Haikun Huang
Institute of Photonic Technology
Jinan University
Guangzhou, China
haikun@stu2022.jnu.edu .cn

Lingzhi Li
Institute of Photonic Technology
Jinan University
Guangzhou, China
lilingzhi@stu2018.jnu.edu.cn

Yu Huang
Institute of Photonic Technology
Jinan University
Guangzhou, China
huangyu@stu2021.jnu.edu.cn

Jiejun Zhang
Institute of Photonic Technology
Jinan University
Guangzhou, China
zhangjiejun@jnu.edu.cn

Jianping Yao
University of Ottawa
Ottawa, ON K1N6N5, Canada
Jinan University, Guangzhou, China
jpyao@uottawa.ca

***Abstract*—Photonic aggregation of microwave signals using a single dual-polarization dual-drive Mach-Zehnder modulator (DP-DDMZM) is proposed and investigated experimentally. Multiple microwave signals are applied to a DP-DDMZM and modulated on a single optical carrier. Four binary phase shift keying (BPSK) microwave signals with an identical carrier frequency of 15 GHz and a symbol rate of 1 GBaud are aggregated to be a single 16 quadrature amplitude modulation (16QAM) optical signal. On the receiver side, the aggregated multiple microwave signals are decoded simultaneously by a single optical coherent receiver. A proof-of-concept experiment is conducted to verify the effectiveness of the proposed technique. The aggregation of four BPSK microwave signals with an error vector magnitude (EVM) of 7.09% is realized.**

Keywords—signal aggregation, microwave photonics, coherent detection, optical communications.

I. INTRODUCTION

Radio-over-fiber (RoF) is a technology that distributes wireless signals over an optical fiber [1]. For example, architectures that support broadband transmission, simultaneous transmission of multiple digitized wireless signals, and full-duplex transmission have been reported [2-4]. However, the evolving wireless communications for high data rate transmission and multiple services have brought new challenges to the RoF technology, as the number of signals to be transmitted increases significantly. A straightforward solution is to separate those signals and modulate them on optical carriers of different wavelengths, a technique called wavelength division multiplexing (WDM) widely used in optical communications systems [5, 6]. However, such systems have very low spectral efficiency.

The capacity and spectral efficiency of an optical link for the transmission of multiple microwave signals can be improved by optical signal aggregation, a method of combing and converting several signals with simple formats into a single optical signal with a complex format [7]. This method can be realized through optical nonlinearities in nonlinear devices, such as a highly nonlinear fiber (HNLF), a semiconductor optical amplifier (SOA), or a periodically poled lithium niobate (PPLN) waveguide [7-13]. There are mainly two approaches to realize optical signal aggregation, nonlinear wave mixing and cross-phase modulation (XPM). In [7-10], the amplitudes and phases of optical signals with different carrier wavelengths were tuned and then sent to a nonlinear optical device for wave mixing. In the generated mixing components, all the optical signals were mapped to the same carrier wavelengths with phase and amplitude control and thus overlapped spectrally. In this way, multiple optical signals are aggregated into a single optical signal with a more complex format. In [11-13], probe signals with the same wavelength and on-off keying (OOK) signals as optical pumps were sent to nonlinear devices. The probe signals were converted to binary phase shift keying (BPSK) signals by optical pumps through XPM. The converted BPSK signals were added coherently with phase and amplitude control and were aggregated into a single optical signal with a more complex format. However, the use of optical nonlinearities for wavelength and format conversion may suffer from low conversion efficiency and the signal-to-noise ratio of the signal may become poorer.

In this paper, a new approach to implement photonic aggregation of microwave signals based on phase and amplitude control using a dual-polarization dual-drive Mach-Zehnder modulator (DP-DDMZM) is proposed and experimentally demonstrated. Microwave BPSK signals with a carrier frequency of 15 GHz at a symbol rate of 1 Gbaud are applied to a DP-DDMZM and modulated on an optical carrier with a single wavelength. The -1st-order optical sidebands generated after electro-optical modulation are overlapped for the multiple microwave signals and are selected by optical bandpass filters. By controlling the phase and amplitude of the -1st-order optical sidebands corresponding to different microwave signals and combining them using a polarizer, an aggregated 16 quadrature amplitude modulation (16QAM) optical signal is generated. The BPSK microwave signals are decoded when demodulating the 16QAM optical signal with the help of an optical coherent receiver. The proposed method is analyzed theoretically and evaluated experimentally. The experimental results show that the aggregation of four BPSK microwave signals with an identical carrier frequency of 15 GHz and a symbol rate of 1 GBaud into a 16QAM optical signal is achieved and the demodulation of the aggregated 16QAM signal with an error vector magnitude (EVM) of 7.09% is demonstrated.

This work was supported by the National Natural Science Foundation of China (61860206002, 61905095) and the Guangdong Province Key Field R&D Program Project (2020B0101110002).

II. Principle

The schematic of the proposed photonic aggregation system is shown in Fig. 1(a). A light wave generated by a laser source is used as an optical carrier, which is sent to an aggregation module to which multiple microwave signals with an identical microwave carrier frequency are applied. The aggregation module consists of a DP-DDMZM, two amplification modules consisting of an erbium-doped fiber amplifier (EDFA) and an optical bandpass filter (OBPF), a polarization controller (PC), and a polarizer.

The DP-DDMZM consists of two sub-DDMZMs, an upper and a lower DDMZMs, with each sub-DDMZM having two phase modulators (PMs) and phase shifters in the two arms, and with their outputs combined at a polarization beam combiner (PBC), as shown in Fig. 1(b). The optical carrier is modulated at the DP-DDMZM by four BPSK microwave signals. In the experiment, a bias voltage is applied to the phase shifters to apply a phase shift of $\pi/2$ between optical signals from the parallel PMs in the upper DDMZM. Two BPSK signals are aggregated into one quadrature phase shift keying (QPSK) optical signal, as shown in Fig. 1(c). And those in the lower DDMZM are aggregated in the same way. Optical signals from the two DDMZMs are combined at the PBC in the DP-DDMZM. At the output of the modulator, the optical carrier and the modulation sidebands are sent to the EDFAs, with the output filtered by the OBPFs to select the -1st-order sidebands while suppressing the amplified spontaneous emission (ASE) noise. Then, the -1st-order sidebands are sent to a polarizer. Since the -1st-order sidebands from the upper and the lower DDMZMs are orthogonally polarized, the sidebands are combined at the polarizer. A PC is incorporated before the polarizer. By tuning the PC, a tunable combination ratio is achieved to realize an amplitude control. The QPSK optical signals with orthogonal polarizations are aggregated into one 16QAM optical signal with a single polarization at the output of the polarizer. The 16QAM optical signal can then be transmitted over an optical link and be demodulated through coherent detection. An optical coherent receiver is utilized to demodulate the aggregated 16QAM optical signal, and the BPSK signals can then be decoded from the 16QAM signal.

The basic principle of the proposed photonic aggregation is to achieve vector summation at the aggregation module. Symbols of modulated signals can be considered as vectors in the constellation diagram, and the aggregation can be regarded as a summation of vectors of different signals [7]. A BPSK microwave signal can be expressed as

$$s_n(t) = a \cdot \sin(\omega t + b_n(t)) \tag{1}$$

where the subscript n denotes the n-th microwave signal, a and ω are the amplitude and angular frequency of the microwave carrier, respectively, and $b_n(t)$ is the BPSK signal encoded on the microwave carrier. By applying the microwave signal to a PM, we have a phase-modulated optical signal in which the -1st-order optical sideband is given by

$$E_{-1,n}(t) = E_{in} J_{-1}(\beta) e^{j[(\omega_c-\omega)t-b_n(t)]} \tag{2}$$

where E_{in} and ω_c are the electric field and angular frequency of the optical carrier, respectively, β is the modulation index, and J_{-1} is the -1st-order Bessel function of the first kind. Eq. (2) shows that an encoded microwave signal can be retrieved from the -1st-order optical sideband through coherent detection. When multiple microwave signals are applied to the PMs, the resulting -1st-order optical sidebands from the PMs are adjusted in phase and in amplitude such that the BPSK microwave signals are aggregated into a 16QAM optical signal. The overlapped sidebands can be expressed as

$$E_{-1}(t) = E_{-1,1}(t) + \alpha E_{-1,2}(t) + \mathrm{j}\cdot\left[E_{-1,3}(t) + \alpha E_{-1,4}(t)\right] \tag{3}$$

where $E_{-1,1/2/3/4}(t)$ is the -1st-order optical sideband generated from the electro-optical modulation of the corresponding microwave signal on the optical carrier, and α is the amplitude ratio between $E_{-1,1/3}(t)$ and $E_{-1,2/4}(t)$, which can be tuned by tuning the PC. As can be seen from Eq. (3), the four BPSK microwave signals are aggregated to be a 16QAM optical signal, which can be demodulated with a single coherent receiver, from which the four BPSK microwave signals can be obtained. Since the four BPSK microwave signals are aggregated to be a 16QAM optical signal on a single optical carrier, the spectral efficiency of the optical link is also improved.

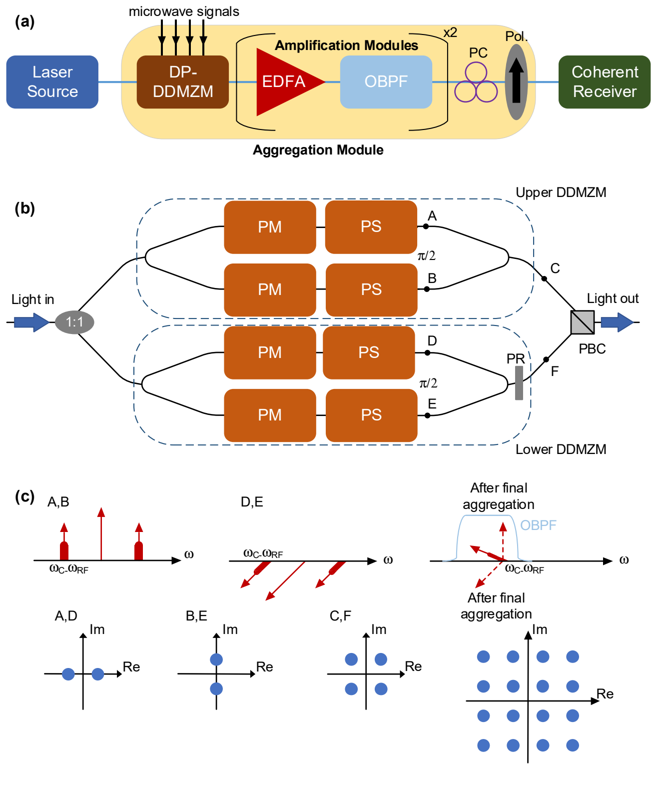

Fig. 1. (a) Schematic of the proposed aggregation system. (b) Schematic of the DP-DDMZM which consists of two sub-DDMZMs, with each sub-DDMZM having two parallel PMs and phase shifters. (c) Optical spectra and constellation diagrams at the indicated locations of the system. DP-DDMZM: dual-polarization dual-drive Mach-Zehnder modulator; EDFA: erbium-doped fiber amplifier; OBPF: optical bandpass filter; Pol.: polarizer; PM: phase modulator; PS: phase shifter; PC: polarization controller; PBC: polarization beam combiner; PR: polarization rotator.

III. Results

A proof-of-concept experiment is conducted according to the architecture in Fig. 1(a). To verify that the signal encoded on the microwave carrier can be retrieved from the -1st-order optical sideband as described by Eq. (2), only one BPSK microwave signal with a carrier frequency of 15 GHz at a symbol rate of 1 GBaud is applied to the DP-DDMZM. The constellation diagram of a recovered BPSK signal is achieved through coherent detection of the -1st-order optical sideband, as shown in Fig. 2, which is consistent with the constellation diagram illustrated in Fig. 1(c). As discussed before, two BPSK signals can be aggregated into one QPSK signal through vector summation when a phase control is conducted by the phase shifters. A constellation diagram of the recovered QPSK signal is achieved when the two BPSK microwave signals are applied to the upper DDMZM, as shown in Fig. 3.

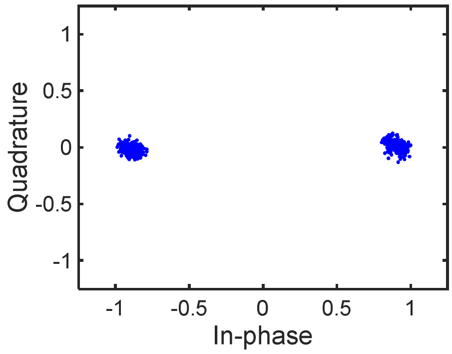

Fig. 2. Constellation diagram of the BPSK optical signal when only one BPSK microwave signal is applied to the DP-DDMZM.

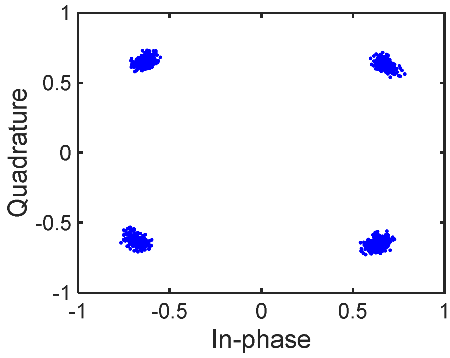

Fig. 3. Constellation diagram of the QPSK optical signal when two BPSK microwave signals are applied to the upper DDMZM.

Two QPSK signals from the upper and lower DDMZMs are aggregated into one 16QAM signal with amplitude controlled by the PC when four BPSK microwave signals are applied. An aggregated 16QAM optical signal is achieved at the output of the aggregation module. Fig. 4 shows the constellation diagram and eye diagram of the demodulated 16QAM optical signal, which demonstrate the successful aggregation of multiple microwave signals and those signals can be decoded simultaneously from the demodulated 16QAM signal. The EVM is 7.09%, which is sufficiently low to achieve error-free transmission.

The optical spectrum at the output of the aggregation module, when four microwave signals are applied, is also shown in Fig. 5. It is clear to see that the -1st-order sidebands are selected, and other optical spectral components are suppressed. Thanks to the use of the OBPFs, the coherent receiver can get rid of interference from other optical components when demodulating the 16QAM signal.

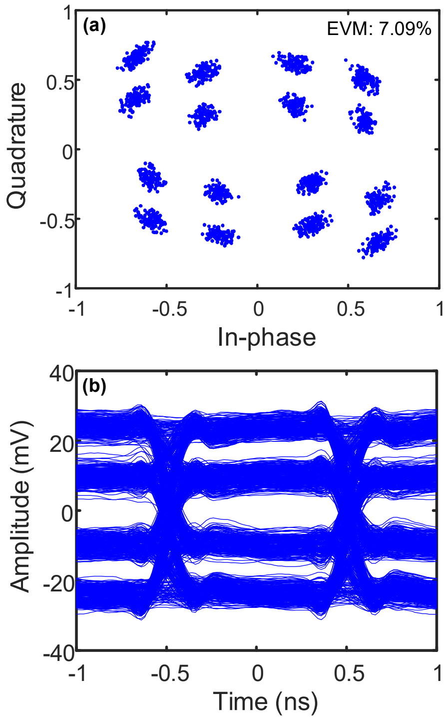

Fig. 4. Constellation diagram and eye diagram of the 16QAM optical signal.

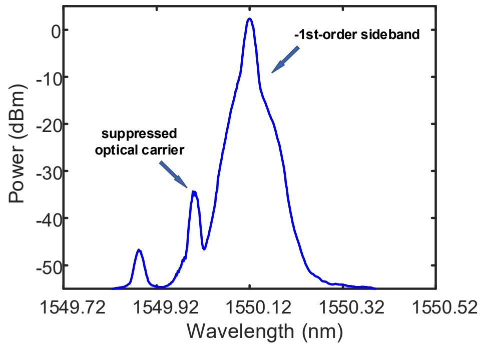

Fig. 5. Optical spectrum at the output of the aggregation module when four BPSK microwave signals are applied to the DP-DDMZM.

IV. Conclusion

Photonic aggregation of multiple microwave signals was proposed and investigated experimentally. By utilizing a DP-DDMZM and applying phase and amplitude control, four BPSK microwave signals with a carrier frequency of 15 GHz at a symbol rate of 1 GBaud were aggregated to one 16QAM optical signal. A coherent receiver was utilized to demodulate the 16QAM signal through coherent detection. The EVM was as low as 7.09% which is low enough to support the error-free transmission with forward error correction (FEC). The proposed method has a high potential for increasing the spectral efficiency and reducing the system complexity of an RoF system.

References

[1] D. Novak, R. Waterhouse, A. Nirmalathas, C. Lim, P. Gamage, T. Clark, et al, "Radio-Over-Fiber Technologies for Emerging Wireless Systems," *IEEE J. Quantum. Elect.*, vol. 52, Art. No. 0600311, January 2016.

[2] M. Zhu, L. Zhang, J. Wang, L. Cheng, C. Liu and G. Chang, "Radio-Over-Fiber Access Architecture for Integrated Broadband Wireless Services," *J. Lightw. Technol.*, vol. 31, pp. 3614-3620, December 2013.

[3] P. Dat, A. Kanno, N. Yamamoto, and T. Kawanishi, “Full-Duplex Transmission of LTE-A Carrier Aggregation Signal Over a Bidirectional Seamless Fiber-Millimeter-Wave System,” *J. Lightw. Technol.*, vol. 34, pp. 691-700, January 2016.

[4] P. Gamage, A. Nirmalathas, C. Lim, D. Novak, and R. Waterhouse, “Simultaneous transmission of digitized multiple wireless services over optical fiber,” in *Proc. OFC/NFOEC*, San Diego, pp. 474-476, March 2009.

[5] Y. Won, H. Kim, Y. Son, S. Han, “Full Colorless WDM-Radio Over Fiber Access Network Supporting Simultaneous Transmission of Millimeter-Wave Band and Baseband Gigabit Signals by Sideband Routing,” *J. Lightw. Technol.*, vol. 28, pp. 2213-2218, August 2010.

[6] P. Dat, A. Kanno, T. Umezawa, N. Yamamoto, and T. Kawanishi, “Millimeter- and Terahertz-wave Radio-over-Fiber for 5G and Beyond,” *2017 IEEE PHOTONICS SOCIETY SUMMER TOPICAL MEETING SERIE*, San Juan, pp. 165-166, July 2017.

[7] A. Fallahpour, F. Alishahi, K. Zou, Y. Cao, A. Almaiman, A. Kordts, et al, “Demonstration of tunable optical aggregation of QPSK to 16-QAM over optically generated nyquist pulse trains using nonlinear wave mixing and a Kerr frequency comb,” *J. Lightw. Technol.*, vol. 38, pp. 359–365, January 2020.

[8] H. Liu, H. Wang, Y. Ji, “Simultaneous all-optical channel aggregation and de-aggregation for 8QAM signal in elastic optical networking,” *IEEE Photon. J.*, vol. 11, pp. 1-8, December 2018.

[9] M. Chitgarha, S. Khaleghi, Z. Bakhtiari, O. Ziyadi, O. Gerstel, L. Paraschis, et al. “Demonstration of reconfigurable optical generation of higher-order modulation formats up to 64 QAM using optical nonlinearity,” *Opt. Lett.*, vol. 38, pp. 3350-3353, August 2013.

[10] Z. Zhong, H. Wang, Y. Ji, “All-optical aggregation and de-aggregation between 3× BPSK and 8QAM in HNLF with wavelength preserved,” *Appl. Optics*, vol. 59, pp. 1092-1098, January 2020.

[11] Y. Wen and K. Feng, “A simple NRZ-OOK to PDM RZ-QPSK optical modulation format conversion by bidirectional XPM,” *IEEE Photonic. Tech. L.*, vol. 27, pp. 935–938, May 2015.

[12] K. Mishina, S. Kitagawa, A. Maruta, “All-optical modulation format conversion from on-off-keying to multiple-level phase-shift-keying based on nonlinearity in optical fiber,” *Opt. Express*, vol. 15, pp. 8444-8453, June 2007.

[13] K. Mishina, S. Nissanka, A. Maruta, S. Mitani, K. Ishida, K. Shimizu, et al. “All-optical modulation format conversion from NRZ-OOK to RZ-QPSK using parallel SOA-MZI OOK/BPSK converters,” *Opt. Express*, vol. 15, pp. 7774-7785, June 2007.