Photonic Generation of 3-D UWB Signal Using a Dual-Drive Mach–Zehnder Modulator

Pan Cao, Xiaofeng Hu, Jiayang Wu, Liang Zhang, Xinhong Jiang, and Yikai Su, *Senior Member, IEEE*

***Abstract*— We propose and experimentally demonstrate a new method to generate a 3-D ultrawideband (UWB) signal by utilizing a dual-drive Mach–Zehnder modulator (DDMZM). Three degrees of freedom of the generated 3-D UWB signal are pulse position, pulse phase, and pulse amplitude. In this scheme, each radio frequency (RF) port of the DDMZM is modulated by a combination of two encoded signals with different amplitudes. By properly adjusting the amplitudes of the encoded signals and the bias voltages of the two RF ports, a 5-Gb/s 3-D UWB signal with a central frequency of 3.5 GHz and a 10-dB fractional bandwidth of 163% is successfully generated by using only a single DDMZM.**

***Index Terms*— Ultra wideband (UWB), pulse modulation, three-dimensional (3-D).**

I. Introduction

Ultra wideband (UWB) impulse signal is promising for short-range wireless communication due to its advantages of low power spectral density (PSD), high bandwidth, low cost, and compatibility with other wireless systems [1]–[3]. UWB-over-fiber (UWBoF) technology has been proposed to increase its coverage range [4], [5]. Meanwhile, photonic generation of UWB signals has been demonstrated to reduce the complexity of radio frequency (RF) components and overcome the speed bottleneck of electronic devices [6]. Various techniques of all-optical UWB generation have been studied in recent years, such as phase modulation to intensity modulation conversion [7], [8], cross-gain modulation (XGM) or cross-phase modulation (XPM) in semiconductor optical amplifiers (SOAs) [9]–[12], etc. For practical applications of UWBoF technology, it is desirable that the UWB signals can be simultaneously generated and modulated in optical domain. In previous reports [13]–[15], generations of UWB signals with different modulation formats have been demonstrated, including pulse position modulation (PPM), pulse phase modulation, pulse amplitude modulation (PAM), and pulse shape modulation (PSM). Most of the proposed techniques can generate one modulation format. In Ref. [16]–[18], different modulation formats can be obtained by adjusting certain parameters. However, those schemes can only generate one-dimensional modulation formats.

In this letter, we propose and experimentally demonstrate a method for photonic generation of high-speed three-dimensional (3-D) UWB signal employing a dual-drive Mach–Zehnder modulator (DDMZM). In the proposed scheme, each RF port of the DDMZM is driven by a combination of two signals with different amplitudes, where each signal possesses different pre-coded position information. By properly setting the signal amplitudes and the bias voltages of the DDMZM, a 3-D UWB signal, containing pulse position, pulse phase, and pulse amplitude modulations, can be successfully achieved. A proof-of-concept experiment is performed to verify the feasibility of our proposal. A 5-Gb/s UWB signal is obtained, where the bit-rate is significantly increased by using the 3-D modulation. The central frequency and 10-dB fractional bandwidth of the generated UWB signal are 3.5 GHz and 163%, respectively.

II. Operation Principle

The schematic diagram of the proposed 3-D UWB signal generation is shown in Fig. 1(a). In the proposed scheme, a continuous wave (CW) light is sent into a DDMZM which consists of two phase modulators (PMs). As depicted in Figs. 1(b-i) and (b-ii), two combined electrical signals are fed to the two RF ports of the DDMZM, respectively. By adjusting the amplitudes of the pre-coded data, maximum phase shift of $\pi/2$ can be obtained for the two combined signals as indicated in Figs. 1(b-iii) and (b-iv). Meanwhile, the two PMs achieve $\pi/2$ relative phase shift by properly setting the bias voltages. Fig. 1(b-v) illustrates the generation of 3-D UWB signal at the interference output of the DDMZM, where the data can be transmitted through pulse position, pulse phase, and pulse amplitude modulations. Fig. 1(c) presents the UWB waveforms, corresponding transmitted bits, and the data patterns of the four data, respectively. In this work, each symbol has 8 time slots and each UWB impulse occupies 2 time slots. To avoid overlap between the UWB pulses of adjacent symbols, four possible positions in a symbol are allocated for a UWB impulse, including ‘01100000’, ‘00110000’, ‘00011000’, and ‘00001100’, where ‘11’ represents a UWB impulse. Thus, 2-bit information can be transmitted via PPM. Meanwhile, pulse polarity and amplitude can respectively carry 1-bit information through phase and amplitude modulations [18]. Therefore, the proposed method can transmit 4-bit information in each symbol, meaning that the bit-rate of the

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The authors are with the State Key Laboratory of Advanced Optical Communication Systems and Networks, Department of Electronic Engineering, Shanghai Jiao Tong University, Shanghai 200240, China (e-mail: caopan@sjtu.edu.cn; huxf@sjtu.edu.cn; jiayangwu@sjtu.edu.cn; zhangliang1986422@sjtu.edu.cn; jiangxinhong@sjtu.edu.cn; yikaisu@sjtu.edu.cn).

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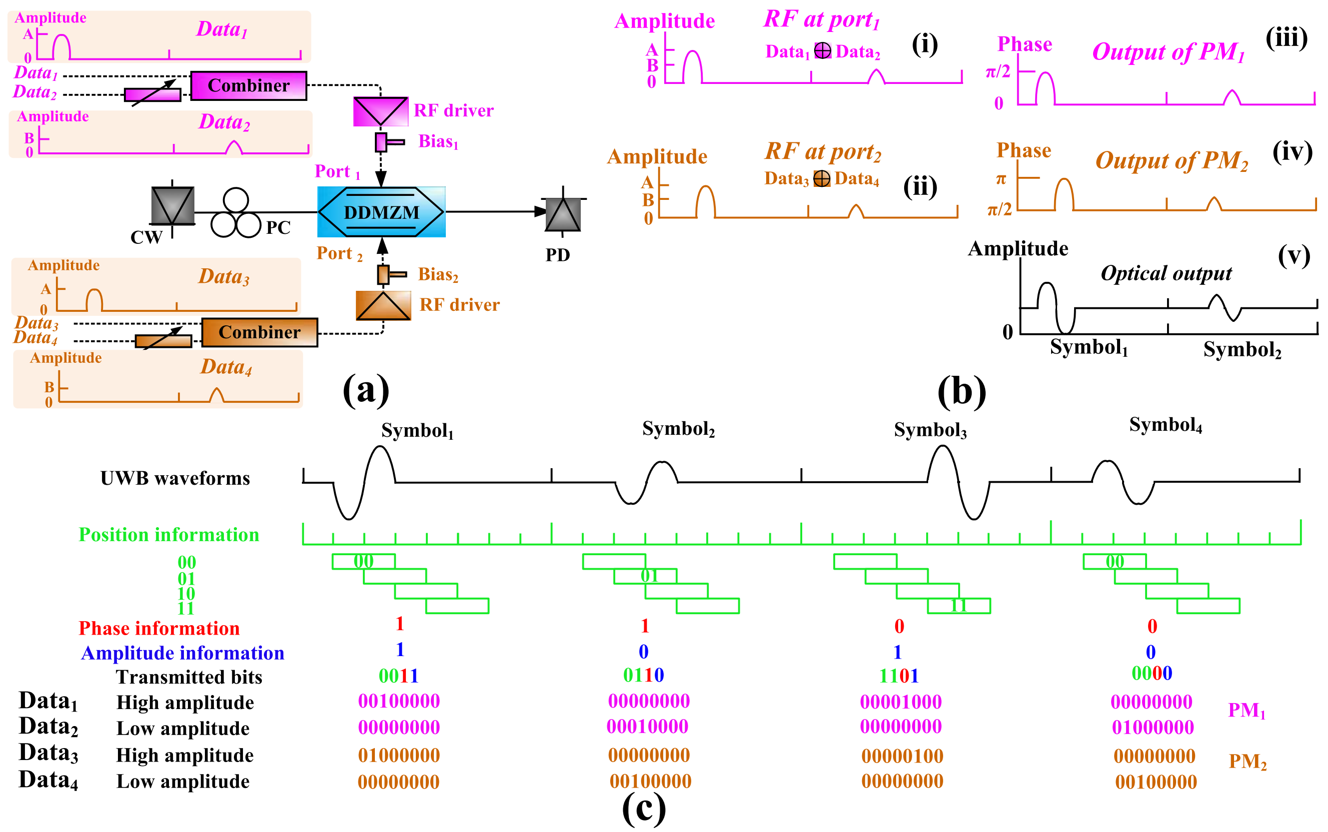

Fig. 1. (a) Schematic diagram of the proposed 3-D UWB generation. (b) Principle of 3-D UWB signal generation. (c) 3-D UWB waveforms, transmitted bits, and data patterns of the four data.

TABLE I
POSITION OF BIT '1' IN THE 8-BIT SYMBOL UNDER DIFFERENT TRANSMITTED BITS

Transmitted bits		00 00	00 01	00 10	00 11	01 00	01 01	01 10	01 11	10 00	10 01	10 10	10 11	11 00	11 01	11 10	11 11
Position of bit '1'	$Data_1$		2		3		3		4		4		5		5		6
	$Data_2$	2		3		3		4		4		5		5		6	
	$Data_3$		3		2		4		3		5		4		6		5
	$Data_4$	3		2		4		3		5		4		6		5	

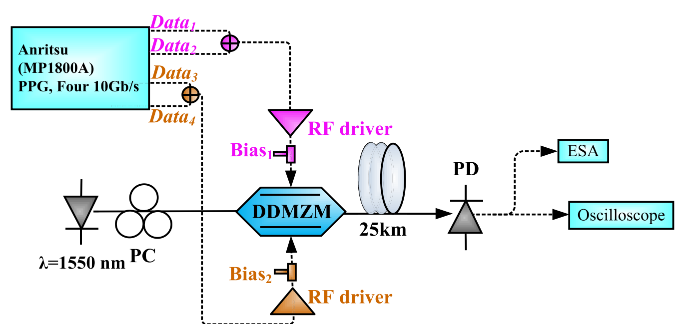

Fig. 2. Experimental setup of the proposed 3-D UWB generation.

UWB signal can be increased by using the multi-dimensional modulation technology.

As each symbol transmits 4-bit information, there are 16 different transmitted bits, resulting in different data patterns for the four data. Table I depicts the four data patterns under different transmitted bits, where the number indicates the position of bit '1' in the 8-bit symbol. For instance, when the transmitted bits are '0000', the data patterns of $Data_1$, $Data_2$, $Data_3$, and $Data_4$ are '00000000', '01000000', '00000000', and '00100000', respectively. Moreover, $Data_{1\&3}$ and $Data_{2\&4}$ have high and low amplitudes, respectively.

III. EXPERIMENTAL SETUP AND RESULTS

We perform a proof-of-concept experiment to verify the feasibility of 3-D UWB signal generation using a single DDMZM. As shown in Fig. 2, a pulse pattern generator (PPG, Anritsu MP1800A) operating at 10 Gb/s is used to generate electrical Gaussian pulses [19]. Here, the pattern length of the four data is 64. Since each symbol has 8 bits, the symbol rate of the UWB signal is 1.25 GHz. A CW light from a tunable laser (Southern photonic TLS150D) at 1550.00nm with 5-dBm output power is fed into a 10-GHz DDMZM (Fujitsu FTM7921ER), and a polarization controller (PC) is employed to guarantee transverse electrical (TE) mode input. $Data_1$ and $Data_2$ with different amplitudes are combined together and then amplified by a RF amplifier. The amplified signal is input through a bias-T to RF $port_1$ of the DDMZM. In the meantime, $Data_3$ and $Data_4$ are input to RF $port_2$ by the same method. Fig. 3 presents the waveforms of the two combined signals.

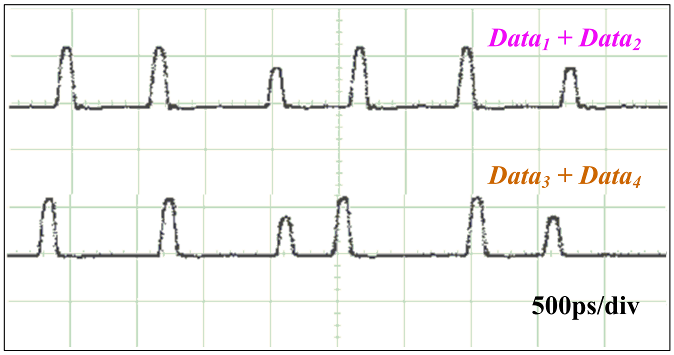

Fig. 3. Waveforms of the two combined signals.

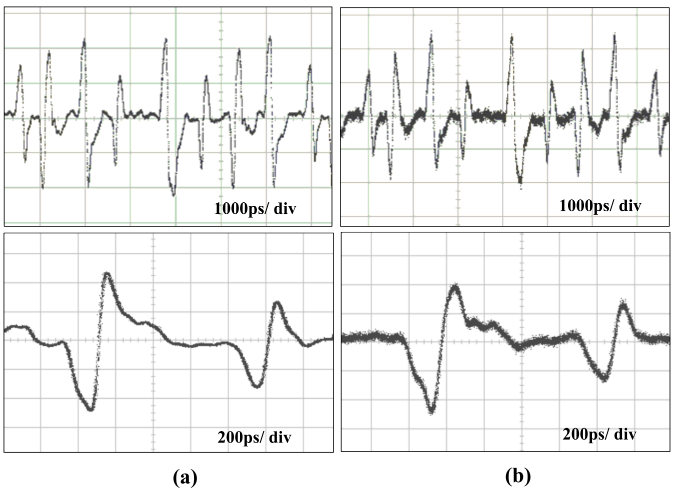

Fig. 4. Waveforms of the generated 3-D UWB signal recorded (a) in BTB configuration and (b) after 25-km SSMF transmission under different time scales.

By carefully adjusting the amplitude of each pre-coded data and the bias voltage of each RF port, the 3-D UWB signal can be generated by utilizing the aforementioned method. After transmission over a 25-km standard single-mode fiber (SSMF), a high-speed photo detector (PD) is used to convert the optical UWB signal to electrical domain. Fig. 4 shows the waveforms of the generated 3-D UWB signal in the back-to-back (BTB) configuration and after 25-km transmission, respectively. The time scales are 1000ps/div and 200ps/div, respectively. As observed in Fig. 5, the low-frequency region of the 3-D UWB signal is more than 10-dB lower power than that of the central frequency. Therefore, wireless transmission is not expected to severely degrade the UWB signal. Furthermore, certain technique such as pre-distortion or post-compensation can be applied. Meanwhile, thanks to low central frequency and narrow optical bandwidth of the 3-D UWB signal [20], [21], the fiber dispersion has a small effect on the pulse shape of the 3-D UWB signal. The UWB impulses are slightly broadened after fiber transmission.

The electrical spectrum of the 3-D UWB signal before transmission is measured by an electrical spectrum analyzer (ESA, Rohde & Schwarz FSUP50) as depicted in Fig. 5. For the generated 5-Gb/s 3-D UWB signal, the central frequency is 3.5 GHz and the 10-dB bandwidth is 5.7 GHz (from 1.2 GHz to 6.9 GHz), corresponding to a fractional bandwidth of 163%.

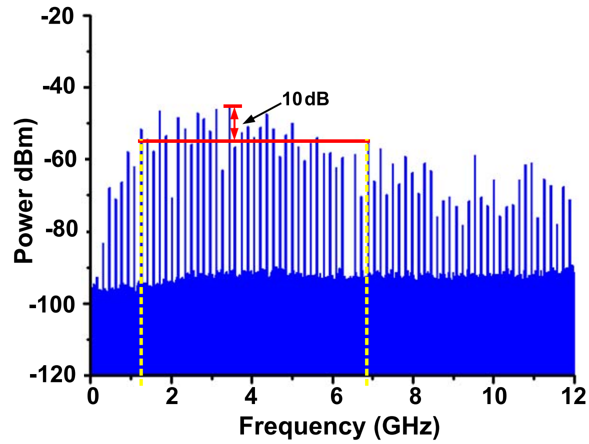

Fig. 5. Electrical spectrum of the generated 3-D UWB signal.

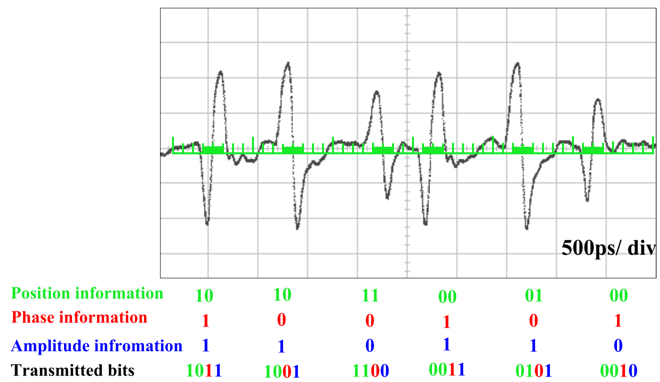

Fig. 6. 3-D UWB waveforms and the corresponding bit information.

Fig. 6 shows the UWB waveforms and the transmitted bit information of the generated 3-D UWB signal. The data transmitted by pulse position modulation can be recovered by the position of the UWB pulse in each symbol, which are ‘10’, ‘10’, ‘11’, ‘00’, ‘01’, and ‘00’. Meanwhile, the phase and amplitude information can be easily obtained, as ‘11’, ‘01’, ‘00’, ‘11’, ‘01’, and ‘10’. Then the transmitted bits in each symbol are ‘1011’, ‘1001’, ‘1100’, ‘0011’, ‘0101’, and ‘0010’, respectively. Since the symbol rate of the UWB signal is 1.25 GHz and each symbol carries 4-bit information, 5-Gb/s 3-D UWB signal is successfully generated by using a single DDMZM.

To evaluate the transmission performance, the alternate current (AC) term of the 3-D UWB signal is detected by a PD, and then the output signal is sampled by a real-time oscilloscope (LeCory, 806Zi-A) with 40-GS/s sampling rate. After offline processing, the recovered eye diagrams before and after fiber transmission are shown in Figs. 7(a) and 7(b), respectively.

Firstly, to obtain the position information, one can calculate the total power of the four positions in each symbol, and the position information is determined by the two adjacent time slots with the maximum power. Secondly, in each symbol, the phase information can be obtained by comparing the average amplitudes of the two time slots occupied by the UWB signal. Here, the phase information is ‘1’ if the average

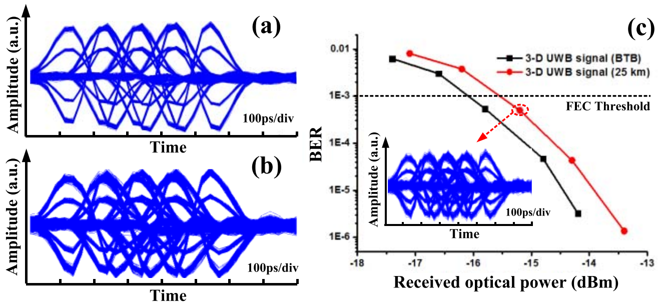

Fig. 7. Eye diagrams of the 3-D UWB signal (a) in B-to-B configuration, and (b) after 25-km SSMF transmission, respectively; (c) BER performances of the 3-D UWB signal.

amplitude in the first time slot is smaller than that in the second time slot. Finally, to obtain the amplitude information of each symbol, one can calculate the total power of different symbols and then obtain the optimum decision threshold. The amplitude information is ‘1’ if the symbol has higher total power than the optimum decision threshold. Therefore, one can recover the 4-bit information, and the bit error rate (BER) performance of the 3-D UWB signal can be obtained. Fig. 7(c) depicts the BER performances of the 3-D UWB signal, where the power penalty is about 0.5 dB after 25-km fiber transmission. At the forward error correction (FEC) threshold of 1×10^{-3}, the receiver sensitivity of the 3-D UWB signal is about -15.6 dBm after fiber transmission. For practical applications, the 3-D UWB signal after photodetection can be captured by an analogue-to-digital (ADC) chip, and then the 3-D information can be successfully recovered by field programmable gate array (FPGA)-based digital signal processing (DSP) [22], [23].

IV. Conclusion

We have proposed and experimentally demonstrated a 3-D UWB signal generation utilizing a single DDMZM. In the proposed scheme, two RF ports of the DDMZM are modulated by two different combined signals, respectively. 3-D UWB signal, containing pulse position, pulse phase, and pulse amplitude modulations, can be obtained by carefully adjusting the corresponding parameters. The bit-rate of the UWB signal is greatly increased employing the multi-dimensional modulation method. 5-Gb/s 3-D UWB signal with a central frequency of 3.5 GHz and a 10-dB fractional bandwidth of 163% is successfully generated. Experimental results demonstrate that the proposed method could be a promising solution to generate multi-dimensional high-speed UWB signal.

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