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Simplified 2-bit photonic digital-to-analog conversion unit based on polarization multiplexing

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Abstract. A 2-bit photonic digital-to-analog conversion unit is proposed and demonstrated based on polarization multiplexing. The proposed 2-bit digital-to-analog converter (DAC) unit is realized by optical intensity weighting and summing, and its complexity is greatly reduced compared with the traditional 2-bit photonic DACs. Performance of the proposed 2-bit DAC unit is experimentally investigated. The established 2-bit DAC unit achieves a good linear transfer function, and the effective number of bits is calculated to be 1.3. Based on the proposed 2-bit DAC unit, two DAC structures with higher (>2) bit resolutions are proposed and discussed, and the system complexity is expected to be reduced by half by using the proposed technique. [DOI: 10.1117/1.OE.55.3.031115]

Keywords: digital-to-analog conversion; polarization multiplexing; microwave photonics.

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1 Introduction

Digital-to-analog conversion is the key technology to generate arbitrary waveforms in communication, radar, and measurement systems. Particularly, high-speed and high-precision digital-to-analog converters (DACs) are required to generate signals with high frequency and large bandwidth, e.g., a DAC with a sampling rate of more than 40 GSa/s is required to generate multilevel quadrature amplitude modulation signals in the 400 Gb/s or 1 Tb/s coherent optical communication systems.[1] However, the bandwidth of traditional electrical DACs is usually limited to around 10 GHz.[2] Although the sampling rate can be increased through temporal interleaving, it is still difficult to get a high-resolution DAC due to the large clock jitter and the severe electromagnetic interference in electrical systems. In addition, it is hard to further improve the performance of electrical DACs due to the electric bottleneck. In order to deal with these problems, a photonic DAC (PDAC) is proposed to realize digital-to-analog conversions by photonic technologies.[3–9] Compared with the traditional electrical DACs, PDAC has the advantages such as large bandwidth, small time jitter, resistance to electromagnetic interferences, and so on.[6] In addition, PDAC is compatible with the optical fiber communication and sensor networks, thus the application of DACs can be enlarged such as a label processor in all optical switching networks.[5] A popular method to realize a PDAC is weighting and summing the intensities of several optical carriers according to the input electrical digital signals.[3] The main problem with such PDACs is that, to realize an n-bit PDAC, n channels should usually be constructed, and in each channel, an optical source, an electro-optical modulator, and a photodetector (PD) are required. As a result, the system would be very complicated and the cost is very high for a PDAC with a high-bit resolution.

To reduce the complexity and cost of the traditional PDACs, we propose a 2-bit photonic DAC unit based on polarization multiplexing in this paper. The proposed 2-bit DAC unit realized by optical intensity weighting and summing can greatly reduce the system complexity compared with a traditional 2-bit PDAC, i.e., only one laser source, one integrated modulator, and one PD are required to realize 2-bit digital-to-analog conversion. Thanks to the use of a single integrated modulator, the system stability can be enhanced. The performance of the proposed 2-bit DAC unit is experimentally investigated, and based on the proposed 2-bit DAC unit, two DAC structures with higher (>2) bit resolutions are proposed, and the system complexity is discussed and compared with that of the traditional PDACs.

2 2-Bit Digital-to-Analog Converter Unit by Polarization Multiplexing

2.1 *Operation Principle*

Figure 1 shows the schematic diagram of the proposed 2-bit DAC unit, which can convert two parallel digital streams into an analog output signal. A continuous wave (CW) light generated by a laser diode (LD) is sent to a dual-polarization modulator via a polarization controller (PC). The dual-polarization modulator is an integrated device that includes a polarization beam splitter (PBS), polarization beam combiner (PBC), and two Mach–Zenhder modulators (MZMs) in parallel, as shown in Fig. 1. After passing through the PBS, the input CW light is split into two orthogonal polarization states (X- and Y-polarizations). By adjusting the PC to let the polarization state of the CW light have an angle of ∼26.57 deg with the X principal axis of the PBS, the output power from the PBS in X-polarization can be twice of that in Y-polarization, indicating a power weighting of 2∶1 is realized. Then, the optical carrier in each polarization is modulated by an MZM to realize optical intensity modulation,

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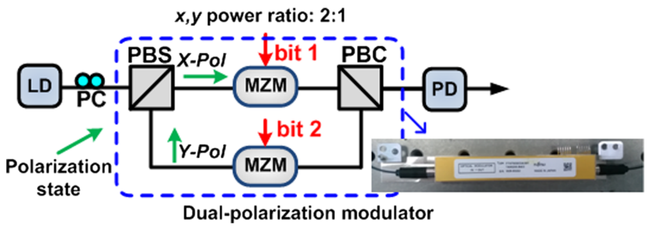

Fig. 1 Schematic diagram of the proposed 2-bit digital-to-analog converter (DAC) unit. LD: laser diode; PC polarization controller; MZM: Mach–Zehnder modulator; PBS: polarization beam splitter; PBC: polarization beam comber; PD: photodetector.

respectively. In the X-polarization branch, the MZM is driven by the most significant bit (MSB) stream, and the MZM in the Y-polarization branch is driven by the least significant bit (LSB) stream. After that, the intensity modulated optical signals in the two branches are multiplexed at the PBC, and the output signal is sent to a PD to perform optical-to-electrical conversion. If the intensity modulations at the two MZMs have sufficient extinction ratios and assuming bit "1" in X- and Y-polarizations have a power of $2P$ and P, respectively, the output optical power from the dual-polarization modulator would be determined by the bit patterns of input digital signal streams, as shown in Table 1. As can be seen, the output optical power is proportional to the weighted sum of the input digital streams. Digital-to-analog conversion can be achieved after optical-to-electrical conversion at the PD. The proposed DAC unit based on polarization multiplexing uses only one laser source, one modulator, and one PD to realize 2-bit digital-to-analog conversion. Thus, the system complexity is reduced compared with the conventional PDAC schemes, and a simplified structure and reduced cost can be achieved. In addition, the use of an integrated modulator instead of two discrete MZMs can enhance the stability of the system.

2.2 *Experimental Demonstration*

An experiment is carried out to investigate the performance of the proposed 2-bit DAC unit. An LD is applied to generate a CW light at 1550 nm with an output power of 15 dBm. The integrated modulator is a dual-polarization binary-phase-shift-keying $LiNbO_3$ modulator (Fujitsu FTM7980EDA) which has a bandwidth of ∼10 GHz and a half-wave voltage of ∼3.5 V for each MZM. After the modulator, a 10-GHz PD and an electrical amplifier are followed. The two parallel-input digital bit streams are generated by a pulse pattern generator with a bit rate of 10 Gb/s. By using another PC and another PBS following the dual-polarization modulator, the intensity modulated optical signal in X- or Y-polarization

Table 1 Output optical power versus different input patterns.

Input pattern	X-Pol power	Y-Pol power	Output power
00	0	0	0
01	0	P	P
10	$2P$	0	$2P$
11	$2P$	P	$3P$

can be measured and analyzed. A 40-GHz optical sampling oscilloscope (Agilent 86100A) is used to measure the temporal waveform the optical signals.

To test the feasibility of the proposed 2-bit DAC, the MSB stream is set as "01010110010" and the LSB stream is "00101011001." Figures 2(a) and 2(b) show the waveform of the intensity modulated optical signal in X- and Y-polarizations, respectively. As can be seen, the amplitude of bit "1" in the MSB signal is nearly twice of that of bit "1" in the LSB signal, indicating the intensity weighting of 2:1 is achieved. It should be noted in Fig. 2(a), the amplitude of bit "1" becomes slightly higher when two successive bits of "1" appear. This pattern effect is mainly due to the limited bandwidth of the modulator and the PD compared with the bit rate of the input digital signals, and this problem can be solved by using devices with sufficient bandwidth. When the two optical signals are combined at the output of the dual-polarization modulator, the measured waveform measured is shown in Fig. 2(c). As can be seen, the amplitude of the obtained analog signal is exactly the weighted sum of the two input digital streams, i.e., "02121231021," confirming the digital-to-analog conversion is successfully achieved.

Then, the transfer function of the established 2-bit DAC unit is investigated. By setting the MSB and the LSB streams to be "00110011" and "01010101," respectively, a stair-step waveform is generated. Figures 3(a) and 3(b) show the measured waveform of the MSB and LSB signals, respectively. The waveform of the generated stair-step signal with a sequence of "01230123" is shown in Fig. 3(c). According to the result in Fig. 3(c), the transfer function of the established 2-bit DAC unit is obtained. The result is shown in Fig. 4, where a linear fit is implemented according to the measured amplitudes for different input patterns. The deviations of the four measured amplitudes from the linear fitted curve are 2.19, −3.68, 0.793, and 0.699 mV for input patterns of "00," "01," "10," and "11," respectively, which is controlled to be no more than 6.87% of the amplitude step (53.53 mV) between two adjacent codes in the linearly fitted curve. Through the results in Fig. 4, the relative error for each input pattern is calculated to be 39.7%, 5.31%,

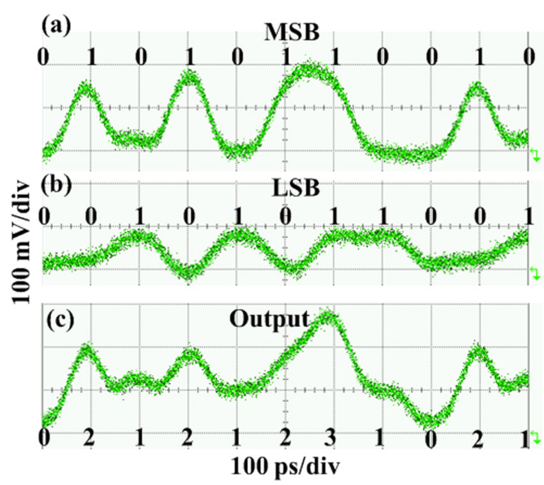

Fig. 2 (a) Waveform of the intensity modulated optical signal in X-polarization with a pattern of "01010110010," (b) waveform of the intensity modulated optical signal in Y-polarization with a pattern of "00101011001," and (c) waveform of the DAC output signal.

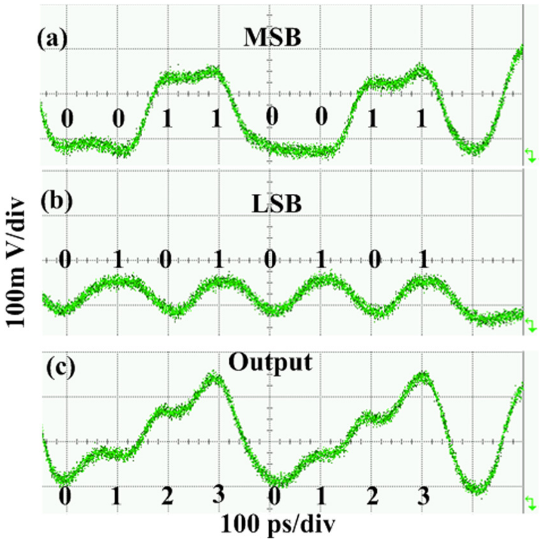

Fig. 3 (a) Waveform of the most significant bit (MSB) signal with a pattern of "00110011," (b) waveform of the least significant bit (LSB) signal with a pattern of "01010101," and (c) waveform of the generated stair-step signal.

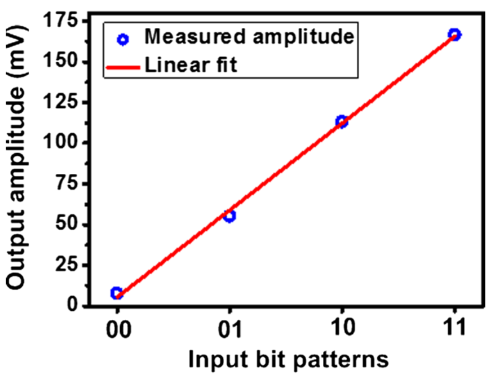

Fig. 4 Measured transfer function of the established 2-bit DAC unit.

0.7%, and 0.42%, respectively. It should be noted that the relative error for pattern "00" is large because the fitted curve has a very small value for pattern "00."

Finally, the effective number of bits (ENOB) of the two-bit DAC unit is investigated. To realize this goal, a sine wave is generated by producing a sequence of "012321012321" at the DAC output. Figure 5 shows the waveform of the generated sine wave, where an ideal sine waveform is also included. The generated sine wave is sampled and the signal-to-noise and distortion ratio (SINAD) is calculated according to the method in Ref. 10. Then, the ENOB is calculated by (SINAD-1.76)/6.02,[11] which is 1.3 for the established two-bit DAC unit. In this experiment, the limiting

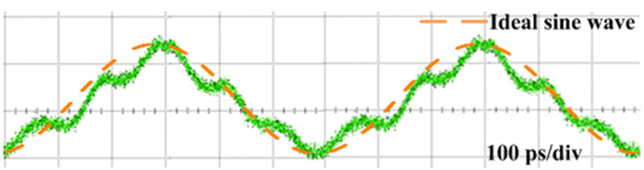

Fig. 5 The sine waveform generated by the 2-bit DAC and the waveform of an ideal sine waveform.

factor of the ENOB is mainly the noises from the PD and the electrical amplifier. By using devices with better performance, the ENOB can be further improved.

3 Digital-to-Analog Converter with Higher Bit Resolution

Based on the proposed 2-bit DAC unit, a DAC system with higher (>2) bit resolution can be constructed. By applying a single laser source and multiple laser sources, respectively, two basic structures are proposed to realize a $2n$-bit DAC (n is a positive integer larger than 1).

Figure 6 shows the proposed structure of the $2n$-bit DAC using a single laser source. The CW light from the LD is split into n branches by an optical power splitter. By tuning the optical power adjuster in each branch, the power ratio between two adjacent branches can be adjusted to be 4:1. Then, the optical carrier in each branch is sent to a dual-polarization modulator that is driven by two adjacent bit streams of the input digital signal, as shown in Fig. 6. After each modulator, a PD is followed to perform optical-to-electrical conversion. Here, the use of multiple PDs is to avoid optical interference between different branches. The obtained electrical signals are combined at an electrical combiner. Finally, the combined electrical signal passes through a low-pass filter (LPF) with a proper bandwidth, and the output is the converted analog signal.

Figure 7 shows the proposed structure of the $2n$-bit DAC using multiple laser sources. The system applies n laser sources with different wavelengths. In this case, the power ratio between adjacent light sources should be controlled to 4:1. Then, each light source passes through a dual-polarization modulator and the input $2n$ parallel digital bit streams are applied to drive the modulators, as shown in Fig. 7. The output optical signals are combined by a wavelength division multiplexer (WDM) and then sent to a PD followed by an LPF. In this system, the wavelength spacing between adjacent laser sources should be large enough such that the frequency components generated by beating between adjacent branches can be easily separated from the output analog signal.

The proposed DACs in Figs. 6 and 7 both apply n branches to realize $2n$-bit digital-to-analog conversions, while in a traditional $2n$-bit PDAC, $2n$ branches should be constructed. Therefore, the complexity of DAC system can be reduced by the proposed technique. Specifically, a traditional $2n$-bit PDAC applying a single laser source requires $2n$ modulators and $2n$ PDs, while the proposed DAC needs n modulators and n PDs. In a traditional $2n$-bit PDAC

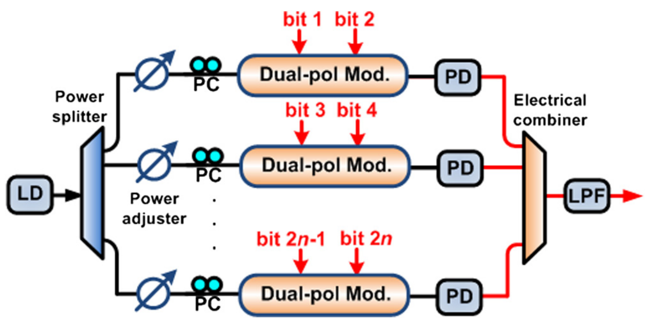

Fig. 6 The proposed $2n$-bit DAC architecture using a single laser source.

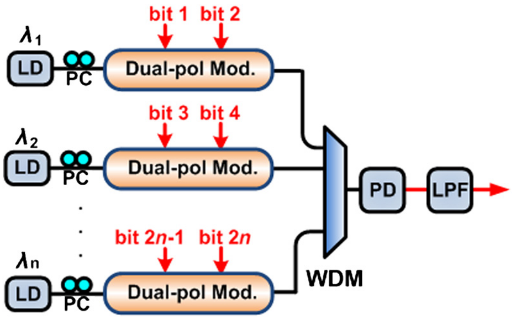

Fig. 7 The proposed $2n$-bit DAC architecture using n laser sources.

using multiple laser sources, $2n$ laser sources and $2n$ modulators are needed, while the proposed DAC requires n laser sources and n modulators. For a large value of n, it can be regarded that the required devices are reduced by half by using the proposed DAC structures. In addition, the requirements for multichannel power splitter, combiner, and WDM are all alleviated in the proposed DAC structures.

4 Conclusions

A 2-bit photonic DAC unit based on polarization multiplexing has been proposed and demonstrated, of which the system complexity is reduced compared to a conventional 2-bit PDAC. Performance of the proposed 2-bit DAC unit is experimentally investigated and the established 2-bit DAC unit achieves a good linear transfer function with an ENOB of 1.3. The proposed 2-bit DAC unit has good potentials in constructing DAC structures with higher bit resolutions. Two DAC structures with higher bit resolutions are proposed based on the proposed DAC unit and the system complexity could be reduced by half compared with traditional PDACs.

Acknowledgments

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Biographies for the authors are not available.