Optics Communications 401 (2017) 1–5

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Photonic digital-to-analog conversion based on wavelength multiplexing

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ARTICLE INFO

Keywords:
Photonic digital-to-analog conversion
Wavelength multiplexing
Effective number of bit

ABSTRACT

A novel photonic digital-to-analog conversion (PDAC) scheme, which is based on optical intensity weighting and multiplexing/summing of different wavelengths, is proposed. The employment of wavelength multiplexing in the system, which conducts the function of modulated light intensity summation, greatly simplifies the system complexity and improves the conversion speed/accuracy limited by large-area photo-detectors and associated electronics. A 4-bit PDAC with a conversion speed of 10 GS/s demonstrates the feasibility of the proposed scheme. In addition, the performance degradation induced by the limited extinction ratios of the applied electro-optic modulators, the synchronization errors among different wavelength channels, and the bit resolutions of the built system is also discussed.

1. Introduction

High-speed digital-to-analog conversion (DAC) technique plays an important role in wideband radars, arbitrary waveform generation, instrumentation, communication and many other civil and military applications. However, due to the limited conversion rate, the current electronic DAC becomes the major bottleneck of many systems with wideband requirements [1,2]. As the development of photonic technology, DAC with photonic processing has shown promising capability to increase the operating speed. Compared to the conventional electronic DACs, photonic DAC has the potential virtues such as high speed clocking and sampling, large bandwidth capability, small time jitter, lightweight components, resistance to electromagnetic interference, and so on [2–4,6]. In addition, photonic DAC is compatible with the optical fiber communication and sensor networks; therefore it can be applied in label processor in all optical switching networks [5].

Recently, photonic DAC has attracted lots of research efforts [2,6–13]. Based on the input method of being-converted digital streams, the existing photonic DAC can be categorized into parallel approach [6,7,9–12] and serial approach [13]. The proposed parallel approaches include the photonic DAC implementations utilizing array EOMs [2,6,12], optical loop mirrors [9,10] and pulse pattern recognition [11]. The basic idea for all these techniques is to weight the intensities of multiple optical carriers and then to sum them at the end of optical link according to the input electrical digital signals. The major technical difficulty comes from the intensity summation of the modulated optical carriers. In order to obtain the incoherent summation of optical intensities, the general way is to use large-area PDs (photo-detectors) and associated electronics, which highly limit the conversion speed, accuracy and system complexity of overall PDAC structure [2,7]. In order to solve such problems, a serial PDAC scheme based on summing of weighted multi-wavelength pulses has been proposed [13]. The major improvement lies in the introduction of a multi-wavelength pulse source, and accordingly, the being-converted digital signals are modulated into different wavelengths (i.e. optical carriers), thus the optical interference beat noise from the optical intensity summation is significantly reduced. However, this scheme builds PDAC structure in serial way, and thus the respective conversion speed is comparably low (i.e. for an N-bit system, the conversion speed of parallel PDAC is N times of that of serial photonic DAC). Therefore, how to achieve the incoherent intensities summation while avoiding the high system complexity is the major work in the present paper.

In this paper, we propose a novel photonic DAC scheme which combines the parallel input of digital signals with the intensity summation of multiple wavelengths. One major feature of this scheme lies in the employment of wavelength multiplexer, which realizes the incoherent summation of weighted light intensity from different wavelengths. It also eliminates potential high-speed conversion bottleneck inherent in large-area PDs and associated electronics. We demonstrate a 4-bit PDAC with a conversion speed of 10 GS/s which shows the feasibility of the proposed scheme. We also analyze the performance degradation induced by the limited extinction ratios of the applied electro-optic modulators, the synchronization errors among different wavelength channels.

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http://dx.doi.org/10.1016/j.optcom.2017.04.063
Received 20 February 2017; Received in revised form 30 March 2017; Accepted 25 April 2017

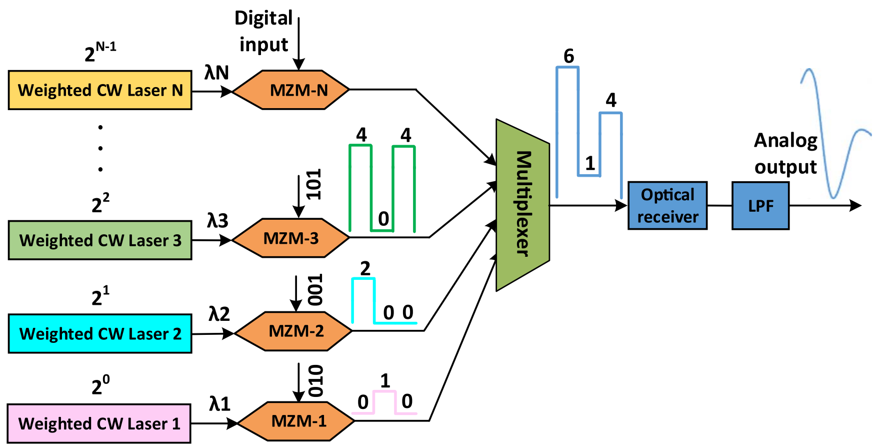

Fig. 1. Schematic diagram of an N-bit PDAC based on wavelength multiplexing.

2. Operation principle and results

Fig. 1 shows the schematic diagram of the proposed DAC scheme, which converts the parallel digital streams into an analog output signal. In this scheme, N separate weighted continuous wave (i.e. CW) lasers are used to realize the different intensity weighting factors to optical carriers corresponding to each bit of the digital input signals, where N is the resolution of PDAC. It is noticeable that the N channels have N different wavelengths with identical wavelength interval and the light intensity of each channel is weighted by the factors of 2^0, 2^1, 2^2, ..., 2^{N-1}, respectively. Then, the optical carrier is fed into MZM (i.e. Mach-Zehnder modulator) to realize the optical intensity modulation. Each MZM is driven by one bit of the digital data: the most-significant bit (MSB) drives the MZM in the path with the most optical power (2^{N-1}), and the least-significant bit (LSB) drives the MZM in the path with the least optical power (2^0). The electrical digital input for each MZM is either 0 or 1, depending on the desired bit. The weighted light would pass when the digital signal is “1” and blocked when “0”. After that, the intensity modulated optical signals from MZMs would be combined incoherently by wavelength multiplexer owing to its multiplexing characteristics. The output optical signal from multiplexer is sent to an optical receiver to perform optical-to-electrical conversion and the final analog signal is achieved by low pass filter (i.e. LPF). Note that if the intensity modulations at the MZMs have sufficient extinction ratios, the output optical power from the modulators would be determined by the bit values of input digital signal streams, and the output light power from multiplexer is proportional to the weighted summation of the input digital streams. Fig. 1 also presents an example of a 3-bit DAC implementation using three CW light channels connected to the modulators (MZM-1 to MZM-3) with the digital inputs, the corresponding discrete values and the desired output analog signal are also given in Fig. 1.

In order to evaluate the performance of the proposed DA conversion scheme, a 4-bit proof-of-principle simulation model is built. Four weighted CW lasers with different center frequencies (i.e. 193.1 THz, 193.2 THz, 193.3 THz, 193.4 THz) are used to generate weighted CW light for each channel, and the respective optical power is 0 dB, 3.01 dB, 6.02 dB, and 9.03 dB. Each of CW lasers' output is fed into an MZM, which works as an optical switch. Since the extinction ratio of MZM is one major performance factor for PDAC, for all simulations we set it as 20 dB, which is feasible fabricated. We employ NRZ (non-return-to-zero) pulse generators to generate each bit of digital signals with pulse width of 0.1 ns. The respective bit rate is 10 Gbit/s. After the modulators, the outputs of MZMs are combined by a 4x1 wavelength multiplexer with bandwidth of 10 GHz. The 3-order Butterworth filter is applied to obtain the final analog signal. The respective passband and stopband cuttoff frequencies are 400 MHz and 2 GHz, and the maximum attenuation of passband and stopband are 0.1 dB and 60 dB, respectively.

To demonstrate the 4-bit PDAC operation, two sets of simulations were conducted: one is to illustrate the analog saw-tooth waveform generation and the other is to present the triangle waveform generation with the digital inputs. By programming the input digital sequence, the optical power combined by the wavelength multiplexer is shown in Fig. 2(a), which is detected by optical receiver. Fig. 2(b) gives the comparison between the waveforms after being filtered (blue solid line) and the corresponding ideal waveforms (red dashed line). Since the optical power from four different weighted CW lasers is 0 dB, 3.01 dB, 6.02 dB, 9.03 dB, the output light intensity from four MZM with digital value as “1” is very close to 1 mW, 2 mW, 4 mW, and 8 mW respectively. From Fig. 2(a) we observe that the amplitude of the obtained analog signal is exactly the weighted summation of the four input digital streams, which validates that the digital to analog conversion is successfully achieved by our proposed DAC scheme. Moreover, Fig. 2(b) reveals that the filtered minimum value of both saw-tooth and triangle waveforms is a little larger than the corresponding ideal value (the ideal value is equal to 0), which mainly results from the background power induced by the limited extinction ratio of MZMs. Since the extinction ratio of MZMs is fixed as 20 dB, which leads to the minimum signal power is larger than 0, the measured minimum signal power is larger than ideal case. Note that the attenuation of passband and stopband of the employed Butterworth filter is 0.1 dB and 60 dB, and the cuttoff frequency of filter is fixed for all cases.

3. Discussion

Compared with the existing approaches of PDAC, our proposed DAC scheme removes the performance bottleneck limited by the large-area PDs and associated electronics. Accordingly, the respective conversion speed is improved and the system complexity is simplified. Meanwhile, the employment of multi-wavelength optical carriers significantly reduces the optical interference beat noise at the detection port. However, our implementation has three critical aspects which heavily affect the performance of the whole converter system. One is the timing synchronization of multiple parallel digital input streams; another is the extinction ratio of the employed MZMs; the third is the nominal bit resolution of the built system. All of those factors will be discussed in this section. Effective number of bits (i.e. ENOB), which is a key performance indicator to compare the performance of an actual PDAC with that of the expected ideal PDAC system, will also be discussed in this section.

3.1. ENOB measurement

In order to obtain ENOB, we have to find the SINAD (i.e. signal-to-noise and distortion ratio), which denotes the ratio of output sine-wave