Demonstration of a 3-bit optical digital-to-analog converter based on silicon microring resonators

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Received August 7, 2014; accepted August 30, 2014; posted September 2, 2014 (Doc. ID: 220611); published September 30, 2014

We propose an N-bit optical digital-to-analog converter based on silicon microring resonators (MRRs), which can transform an N-bit electrical digital signal to an optical analog signal. A 3-bit optical digital-to-analog converter is fabricated as proof of concept through a CMOS-compatible process on a silicon-on-insulator platform. The silicon MRRs are modulated through the electric-field-induced carrier injection in forward biased PN junctions embedded in the ring waveguides. The electro-optical 3-dB bandwidths of the silicon MRRs are approximately 800 MHz. The device works well at a speed of 500 MSample/s under driving voltage swings of 0.75 V. © 2014 Optical Society of America

OCIS codes: (130.3120) Integrated optics devices; (250.5300) Photonic integrated circuits; (250.4555) Coupled resonators.
http://dx.doi.org/10.1364/OL.39.005736

Unlike analog signals, digital signals can be transmitted, manipulated, and stored without degradation, albeit with the use of more complex equipment. Analog-to-digital converters (ADCs) and digital-to-analog converters (DACs) [12] are part of enabling technologies that have contributed greatly to the digital revolution. As electrical circuits become increasingly faster, the bottleneck of sampling accuracy and aperture jitter becomes more serious. Optical implementations of ADC and DAC are considered potential solutions to this problem [3–13]. Recently, many optical DACs based on pattern recognition and nonlinear optical loop mirrors have been proposed and demonstrated; however, they are complex in structure and bulky in volume [5–13]. Silicon photonics [14] has the advantage of integrating optical devices and electrical circuits in the same platform, and are considered candidates for mitigating the problems faced by future high-speed ADC/DAC. Silicon microring resonators (MRRs) are widely employed for their compactness and low power consumption [15–22]. In this Letter, we propose an N-bit optical DAC based on silicon MRRs. A 3-bit optical DAC that adopts three MRRs is fabricated as proof of concept. PN junctions are embedded in these MRRs and work in a forward injection mode. The device works well at a speed of 500 MSample/s under low driving voltage swings of 0.75 V.

The proposed architecture schematically shown in Fig. 1 consists of N electrically modulated MRRs with N initial resonance wavelengths (\(\nu_0, \nu_1, \nu_2, \ldots, \nu_{N-1}\)). All the electrically modulated MRRs have a common bus waveguide that directs the off-resonance light to the output port of the circuit. N binary electrical signals are used to modulate N MRRs, which are related to N bits of the N-bit electrical input digital signal. When there is a bit of “1” in the electrical input digital signal (e.g., at the \(i\)th bit), MRR, is off-resonance at wavelength \(\nu_i\), and light at wavelength \(\nu_i\) bypasses MRR, and appears at the output port of the circuit. When there is a bit of “0” in the electrical digital input (e.g., at the \(i\)th bit), MRR, is on-resonance at wavelength \(\nu_i\), and light at wavelength \(\nu_i\) is coupled into MRR, and does not appear at the output port of the circuit. A continuous light that includes all initial resonance wavelengths of \(N \) MRRs is coupled into the input port of the optical DAC. The power of the \(i\)th monochromatic light is set to \(P_i/2^i\), where \(P\) is a constant value. The optical powers of the input light with different wavelengths are set as the reference weight for different digital bits, which is similar to that in the electrical DAC. Thus, the optical power at the output port is the converted optical analog value of the input digital value, and it can be expressed as \(\sum_{i=0}^{n-1} a_i (P/2^i)\), where \(a_i\) is the \(i\)th bit of the electrical input digital signal. The status and results of the proposed optical DAC are summarized in Table 1.

A 3-bit optical DAC based on three electrically modulated MRRs is fabricated as proof of concept on an 8-in. (20 cm) silicon-on-insulator (SOI) wafer with a 220-nm top silicon layer and a 2-μm buried silicon dioxide layer. Figure 2 is a microscope image of the fabricated device. The width of the straight ridge waveguide is 400 nm, with a height of 220 nm and slab thickness of 70 nm. The radii of the three MRRs are designed to be 10, 10.03, and 10.06 μm, which cause the MRRs to have different initial resonance wavelengths. The gaps between the ring waveguides and the straight waveguides are 280 nm. The PN junction is located in the middle of the ring waveguide. The concentrations of the p-doped region and the n-doped region are \(1 \times 10^{18}/\text{cm}^3\) and \(8 \times 10^{17}/\text{cm}^3\), respectively. The heavily doped regions are located 400 nm from the sidewalls of the ring waveguides. Titanium nitride (TiN) microheaters that are 150-nm thick and 1-μm wide are fabricated to tune the resonance wavelengths of the MRRs slightly through a thermo-optic effect in case the initial resonance wavelengths of the three MRRs are not same. In order to determine the working wavelengths of the three MRRs, the static response spectra of the device (as shown in Fig. 3) are measured with an amplified spontaneous emission (ASE) source and an optical spectrum analyzer (OSA).

Figure 3 shows the static response spectra of the device under different forward voltages. The insertion loss
of the device is 6.5 dB, which includes 6 dB coupling loss from two facets and 0.5 dB on-chip propagation loss. The resonance wavelengths of the three MRRs are almost equally separated without thermal tuning. The MRRs have maximum extinction ratios under biases of 1 V, which means that the MRRs without applied forward voltages are on the excess coupling statuses. When the voltages applied on the MRRs increase, PN junctions are opened and more carriers are injected into the ring waveguides, which increase the propagation loss of the ring waveguides. When the voltages applied on the MRRs are 1 V, the coupling coefficients equal the losses of the ring waveguides, and the MRRs are on critical coupling statuses. When the working wavelengths are set to be the initial resonance wavelengths of the MRRs and the applied forward voltages are 1.4 V, the resonance wavelengths of the MRRs shift sufficiently large to make the absolute inversion between the status “0” and the status “1.”

The experiment setup shown in Fig. 4 is used to characterize the dynamic performance of each MRR and of the optical DAC. Three continuous lights with working wavelengths from three tunable lasers are combined into one fiber and coupled into the device. Three pseudo-random-bit-sequence (PRBS) electrical signals are generated by a multi-channel pulse generator (PPG) and applied on the MRRs by radio-frequency multi-contact probe. Time delays between different signals are controlled by the built-in function of the multi-channel PPG and phase-matched electrical cables to guarantee synchronization at the electrical input port of the device. Erbium-doped fiber amplifier (EDFA) is adopted to amplify the optical signal after the device, and an optical filter is used to reduce the spontaneous noise induced by the EDFA. Note that only the corresponding tunable laser and PPG are powered when characterizing a specific MRR. A vector network analyzer is used to characterize the electro-optical S parameter of each MRR. An Agilent digital communication analyzer is used to characterize the eye diagram of each MRR. A Tektronix real-time oscilloscope is used to characterize the waveforms of the 3-bit optical DCA. When characterizing the 3-bit optical DAC, three lasers are powered, and their output powers are set to be the weight of the different bits.

Figure 5 shows the electro-optical responses of the MRRs. The electro-optical 3-dB bandwidths are 760, 820, and 860 MHz for MRR0, MRR1, and MRR2, respectively, which indicates that MRRs with forward biased PN junctions can work well at a speed of approximately 1 Gbps. Figure 6 shows the eye diagrams of the MRRs at 200 and 500 MHz. For each MRR, the voltage swing is 0.75 V and the forward bias is 0.45 V. All eye diagrams have the power of an absolute status “1,” which means that there is no additional dynamic optical loss. This loss performance is better than the previous work at such low driving on-off keying (OOK) signal [17, 18]. The dynamic extinction ratios at 200 MHz are 16.90, 16.96, and 17.00 dB for MRR0, MRR1, and MRR2, respectively, which are only slightly less than the corresponding static extinction ratios (approximately 20 dB). The dynamic extinction ratios at 500 MHz show insignificant drop and are 15.55, 15.67, and 15.77 dB for MRR0, MRR1, and MRR2, respectively. The high extinction ratio, low driving voltage, and low optical propagation loss make the device very suitable for moderate-speed applications.

Figure 7 shows the waveforms of the 3-bit optical DAC based on the silicon MRRs with forward biased PN junctions at sampling rates of (a) 200 MSample/s and (b) 500 MSample/s. All driving voltages are 0.75 Vpp with forward biases of 0.45 V. Because the device has high extinction ratios at different speeds (as shown in Fig. 6), it has a very good status of data “0,” and the gaps between

| Table 1. Digital to Analog Conversion from an N-Bit Electrical Signal to an Analog Optical Signal |
|-----------------|-----------------|-----------------|-----------------|-----------------|
|                  | \( P/2 \)        | \( P/A \)       | \( P/2^{N-1} \) |
| \( a_0 \)       | 0                | 0               | 0               |
| \( a_1 \)       | 0                | 0               | 1               |
| \( a_2 \)       | 0                | 1               | 0               |
| \( \ldots \)    | \( \ldots \)    | \( \ldots \)   | \( \ldots \)   |
| \( a_{N-2} \)   | 1                | 1               | \( (2^{N-2} - 2) \cdot P/2^{N-1} \) |
| \( a_{N-1} \)   | 1                | 1               | \( (2^{N-1} - 1) \cdot P/2^{N-1} \) |

Fig. 2. Microscope image of the fabricated 3-bit optical DAC based on silicon MRRs.
different adjacent steps in all eight steps are uniform. If the extinction ratios are not sufficiently high, the different statuses of data “0” from the three MRRs have non-negligible amplitudes, and the eight steps cannot have a uniform shape; there are even more that eight steps for a 3-bit optical DAC. From Fig. 7, we can conclude that the device can work well at a speed of 500 Msample/s.

For the proposed optical DAC, the bit number is determined by the number of cascaded MRRs along one waveguide, which is further determined by the free spectral range (FSR) of the MRR and the channel spacing that each MRR occupies. Reducing the radius of the MRR can be used to increase the FSR, and thus increase the number of cascaded MRRs. It has been reported that an MRR with a radius of 1.5 \mu m has an FSR of 62.5 nm [21]. In addition, reducing channel spacing for a given FSR can be used to increase the number of cascaded MRRs. However, a trade-off should be made between channel spacing and adjacent channel crosstalk. Each MRR has two statuses “0” and “1.” Therefore, each MRR occupies two wavelength channels. Suppose that the MRR with a radius of 1.5 \mu m has the same modulation speed as the reported 25 Gb/s micro ring modulator [22]; then, reasonable channel spacing is 100 GHz, and the bit number is approximately 78. In this case, the required extinction ratio of the MRR with the largest weight is a maximum of 240 dB, which is hardly achievable for state-of-the-art. Thus, the main challenge for the proposed optical DAC is to realize high-speed silicon MRR with a high extinction ratio. In the future, a 10-bit optical DAC at approximately 10 Gbaud/s can be expected. Because of the intrinsic advantages of low jitter and lower crosstalk for parallel optical signals, this structure has some advantages over the current single-chip electrical DAC.

In conclusion, we propose an N-bit optical DAC based on N silicon MRRs. A 3-bit optical DAC based on three MRRs is fabricated as proof of concept. The silicon MRRs with forward biased PN junctions work by injecting free carriers into the ring waveguide and have very high extinction ratios at speeds of 200 and 500 Mb/s under a low driving voltage of 0.75 Vpp. The 3-bit optical DAC works well at a speed of 500 Msample/s.
Fig. 7. Waveforms of the 3-bit optical DAC at the sampling rates of (a) 200 MSample/s and (b) 500 MSample/s.

The authors thank IME for the device fabrication. This work has been supported by the National Natural Science Foundation of China under grants 61204061, 61235001, and 61377067, by the National High Technology Research and Development Program of China under grants 2012AA012202 and 2013AA014203, and by the Scientific and Technological Innovation Cross Team of the Chinese Academy of Sciences.

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