Experimental demonstration of microring-based optical pulse train generator

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Abstract: Recently, we proposed the concept of a microring-based optical pulse train generator, which uses a series of microrings coupled to a waveguide and time-interleaves a trigger pulse propagating on this waveguide to generate an optical pulse train. When each ring is electrically modulated, this electronic-photonic integrated circuit (EPIC) can be used for optical arbitrary waveform generation (OAWG) and ultrafast electro-optic (EO) modulation. This paper presents the proof-of-concept experimental demonstration of this technique with two four-stage chip prototypes fabricated on silicon-on-insulator (SOI) substrate. Device fabrication and testing of the chip prototypes are presented. The measurement results show that from a 20-ps-wide input trigger pulse, two circuits generate four sequential pulses at the output with a constant stage delay of 55 ps and 30 ps respectively, which translate into pulse repetition rates of 18 GHz and 33 GHz.

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OCIS codes: (130.3120) Integrated optics devices; (230.5750) Resonators; (250.5300) Photonic integrated circuits; (320.7080) Ultrafast devices.

References and links
1. Introduction

Microrings have been extensively studied in recent years as one of the most promising devices in silicon photonics, e.g., as optical add-drop filters [1, 2] or as EO modulators [3, 4]. Thanks to their versatile functionalities and ultracompact size, microring devices potentially enable large-scale EPICs, e.g., for on-chip optical interconnects [1, 4] or analog-to-digital converters [2]. These earlier research efforts focus on utilizing the frequency-domain properties of microrings, and the related EPICs typically rely on wavelength-division multiplexing (WDM) to achieve the large potential bandwidth of photonics beyond the capabilities of CMOS electronics. In our work, we are exploring new EPIC concepts based on the time-domain properties of microrings, and intend to develop technologies based on time-division multiplexing (TDM).

Recently, we proposed a new microring-based optical pulse train generator (M-OPTG) [5], which utilizes the time-interleaving circuit technique and uses multiple microrings as couplers to divide the input pulse into multiple output pulses. The generated optical pulses can be as short as picoseconds, with the timing and amplitude of each pulse determined by design. When the input trigger is a low repetition-rate pulse train, this circuit effectively multiplies the pulse repetition rate, which can be as high as hundreds of GHz.

Sander et al. have demonstrated an OPTG with a 10 GHz repetition rate using waveguide delay lines as time interleavers and waveguide couplers as power splitters/combiners [6]. In comparison, our M-OPTG has the advantage on the device size due to the ultracompact size of microrings. Moreover, our M-OPTG can be directly developed into an OAWG by tuning the microring resonant frequency to adjust the output pulse amplitude at each stage individually. When the tuning inputs are implemented as digital bits, this circuit becomes an ultrafast optical digital-to-analog converter (DAC). On the other hand, other recent OAWG work is based on frequency comb technology [7], i.e., by individually modulating each comb frequency in both amplitude and phase and hence equivalently control the waveform in the time domain [8]. Compared to these frequency-domain methods, our approach directly controls multiple basis pulses in the time domain to generate the output waveform. Since it only manipulates the amplitude of the generated optical pulse while maintaining the phase coherence, our time-domain approach is simpler, more compact and more suitable for monolithic integration.

OPTGs with high repetition rates are also attractive in high-speed optical communications [9]. An M-OPTG can be easily expanded into an ultrafast EO modulator in a TDM system by actively modulating the resonant wavelengths of microrings. Such a modulator can potentially enable future optical communication systems with terabit-per-second data rates, and will find use in large scale EPIC applications such as optical interconnects.

In this paper, we experimentally demonstrate the proposed M-OPTG concept. The rest of the paper will be organized as following. First, the circuit design of the two M-OPTG prototypes with different stage delays will be presented and the device fabrication process will be described. Then we will show the time-domain measurement results of both chip prototypes, one with separate outputs and the other with Y-junction combined outputs. Finally, spectral measurement results will be discussed to better understand the time-domain behavior of the circuit.
2. Circuit Design and Fabrication

Based on our previous paper [5], a four-stage, first-order M-OPTG, which has four stages and each stage is composed of a first-order microring resonator, is designed on SOI substrate. The circuit schematic is shown in Fig. 1(a), where the input trigger waveguide is implemented as a meandering line to produce large stage delay $\tau$, e.g., a 2-$\mu$m-long waveguide generates a stage delay of $\sim 25$ ps. All the microrings are coupled to this meandering line in series, and are used as compact couplers to partially couple the input pulse energy to the stage output. By combining the sequential stage outputs, an optical pulse train is formed in the output waveguide, with the pulse amplitude controlled by the stage coupling coefficient and the pulse repetition rate controlled by the stage delay.

Since it is difficult to control the fabrication accuracy of different gaps under 100 nm, all the gaps are fixed at 120 nm in the design to reduce the fabrication variation between stages, and the stage coupling coefficient is adjusted by changing the coupling length instead of gaps between the waveguides and microrings. As a result, we use rectangular ring resonators, as shown in the inset of Fig. 1(a), to modify the stage coupling by the coupling lengths $l_1$ and the perimeter of the microrings by the perpendicular straight length $l_2$. To compensate the waveguide loss as well as the power loss drained by the prior stages, latter stages need larger coupling coefficients thus longer $l_1$ [5]. All the rings have the same corner radius $r = 4 \mu m$ and the same perimeter of $\sim 37.6 \mu m$, which corresponds to an effective ring radius of $\sim 6 \mu m$ and a free spectral range (FSR) of $\sim 15-16$ nm. Two M-OPTG prototypes with two different stage delays of 30 ps and 50 ps are fabricated. Besides, test circuits of these two prototypes without output combiners are also fabricated to individually test each stage output.

Fig. 1. (a) The schematic of a four-stage, first order M-OPTG. (b)-(d) SEM images of the circuit after etching: (b) Overall view; (c) Close-up of the first stage; (d) Vertical sidewall.

To fabricate the circuits, we start with the Unibond® SOI wafer from SOITEC with 250-$nm$-thick top silicon and 3-$\mu$m-thick buried oxide. Since all the waveguides and microrings have a sub-micron cross section of 450 nm $\times$ 250 nm for the single mode operation, we use e-beam lithography to pattern all the structures on a negative e-beam resist. The circuit patterns are then transferred to the top silicon layer by reactive-ion-etching (RIE) in chlorine chemistry. Figures 1(b)–1(d) show the scanning electron microscopy (SEM) images of the circuit pattern on Si after etching. As expected, we can see the significant shape change of the ring resonators in different stages in Fig. 1(b). All the top silicon is etched away with vertically smooth side-walls as shown in Fig. 1(d). Although the edge roughness of the resist is transferred to the waveguide during the chlorination etching, resulting in sidewall roughness in the lateral direction,
it can be smoothed by thermal oxidation. Oxide cladding is also important in reducing the scattering loss, which scales proportionally to the cubic of the core-cladding index difference of the waveguide \( (\Delta n)^3 \) [10]. Therefore, thermal oxidation is applied after Si etching, followed by a 1.5-\( \mu \)m-thick oxide cladding layer deposition. The chip is then diced and polished for the measurement.

3. Measurement Results

Figure 2 shows the experimental setup for the time domain measurement. The fiber laser generates 300-fs pulses at 1551.5 nm at a low repetition rate of 55 MHz. The femtosecond pulses are then broadened to \( \sim 20 \) ps by an FBG as assumed in the design. The center frequency of the trigger pulses needs to be detuned off-resonance of the microring resonators to achieve equal input power allocation for all the stages [5]. For this batch, input wavelength around 1556 nm is best for this purpose, as will be shown shortly in section 4, so we choose an FBG with a center wavelength of 1555.8 nm. The broadened pulses are then amplified by the EDFA and tuned to be TE polarized before coupled into the input of the M-OPTG circuit as trigger pulses.

![Fig. 2. Experimental setup for the time domain test. FBG: fiber Bragg grating; EDFA: erbium-doped fiber amplifier; PC: polarization controller; PD: photodetector.](image)

The polished M-OPTG chip is mounted on a platform and the light is coupled into/out of the chip by the input/output lens fibers, which have an optical field size about 2 \( \mu \)m in diameter at the fiber tip. We use on-chip inverse nanotapers [11] to enlarge the optical field size at the end of the waveguide and match with that of the lens fiber at the coupling interface. The optical module of our oscilloscope is used for the waveform detection, which has an optical bandwidth about 20 GHz. The fiber-to-chip coupling is maximized by tapping out 5% of the chip output as a monitor signal when adjusting the alignment. The monitor output of the fiber laser is used as the trigger signal for our sampling oscilloscope.

The time-domain behavior of the test circuits with separate stage outputs are first measured. Here, we report the measurement results of the prototype with the 30-ps stage delay, as shown in Fig. 3(a). The pulse input to the M-OPTG circuit is measured through a short on-chip waveguide to deembed the fiber-to-chip coupling loss. The power loss due to propagation loss of this short waveguide, which is characterized to be 3.8 dB/cm for this batch, is considered and compensated. Although the measured pulse width is broadened from \( \sim 20 \) ps to \( \sim 40 \) ps due to the limited optical bandwidth of our oscilloscope, the timing of each stage output pulse is correct, and a constant stage delay is measured to be 30 ps as designed (inset of Fig. 3(a)). The output pulses from the latter stages are smaller than the prior ones, especially for the fourth stage, which has a relatively large output power drop compared to the other stages. This is partially caused by the waveguide propagation loss. The other reason will be discussed in section 4 from the spectral perspective of the circuit. The through port of the circuit also has a pulse output. By designing its delay to the last stage the same as the prior stage delay, it can be used as an extra bit of the M-OPTG circuit (shown as the 5\(^{th}\) stage in the inset).
Figure 3(b) shows the measurement results of the M-OPTG circuit with Y-junction combined output with a stage delay designed to be 50 ps. Since the pulse width is broadened to 40 ps, and each pulse has a tail inherited from the input pulse, it is difficult to get distinguished output pulses as they superimpose on each other. However, the timing of the four major peaks indicates them as the four stage outputs with an average stage delay measured to be 55 ps, as shown in the inset of Fig. 3(b). Relatively large beating of the tails ($t > 250$ ps) is observed in the combined output waveform, which is caused by the phase mismatch introduced by the delay lines between the stages. Therefore, the signal quality can be improved by adding thermal heaters to the waveguides to tune the stage outputs to be phase-matching with each other.

Comparing the two plots in Fig. 3, more power loss is observed in the circuit with combined output than that with the separate outputs, which is caused by the asynchronous output power combining as we discussed before [5]. The overall efficiency is about 27.5% in the test circuit with the separate outputs, corresponding to a power loss of about 5.6 dB. This power loss is mostly caused by the waveguide propagation loss as well as the resonance frequency shifts. Therefore, the efficiency of our M-OPTG circuit can be improved by further optimizing the fabrication parameters and adopting thermal tuning to the microrings.

4. Discussion

To further understand the time-domain behavior of the circuit, spectral response at each stage output of the test circuit with 30-ps stage delay is measured by sweeping the wavelength of a tunable continuous wave (CW) laser and recording the output PD current at each wavelength in LabView, as shown in Fig. 4. Measured data points are plotted in dots with different colors representing different stages. The data discontinuity around the resonant peak of the fourth stage (green dots) is the instrumental measurement error caused by the multimeter when it’s auto-changing the measurement ranges. By curve-fitting the measured data, the loaded $Q$-factors of the microring resonators $Q_{\text{load}} = \frac{\lambda_0}{\delta \lambda_d}$ are extracted, where $\lambda_0$ is the resonant wavelength and $\delta \lambda_d$ is the 3-dB bandwidth at drop-port of the microring resonator. The extracted $Q_{\text{load}} \approx 3300, 2500, 1750$ and 550 for the 1$^{\text{st}}$ to 4$^{\text{th}}$ stage respectively, matching with our design. Despite of low $Q_{\text{load}}$, the extracted intrinsic $Q$-factors $Q_{\text{int}}$ are approximately 15,000 for all the four stages, indicating small losses inside the microrings.

All the four stages are designed to resonate at the same frequency with different $Q$-factors as
Transmission at each stage output; The resonance peaks around 1556 nm is enlarged.

Fig. 4. Transmission at each stage output; The resonance peaks around 1556 nm is enlarged.

described in section 2. However, as evident in Fig. 4, resonant frequency shift is quite large for the fabricated microrings. Only the third stage has the same resonant frequency as the second stage, which appears as a sharp dip at the expected resonant peak of the third stage transmission curve, indicating the input power is completely drained by the second stage at that resonant frequency [5]. The frequency shift is caused by both fabrication variations and coupling-induced resonance frequency shifts [12], especially for the fourth stage that has the largest coupling coefficient (green dots/line in Fig. 4). The large drop loss in the latter stages is caused by waveguide loss of the long delay lines inserted between stages.

The resonance peaks around 1556 nm is enlarged and shown in Fig. 4, which also shows the input laser pulse spectrum (blue dash line in Fig. 4). The 20-ps input pulse corresponds to a FWHM bandwidth about 0.16 nm at 1556 nm, which is very narrow compared to the bandwidth of the ring resonators. As mentioned before, the center wavelength of the input pulse is detuned off-resonance of the microring resonators so that the transmission of each stage in the input bandwidth is almost flat and relatively constant for the first three stages. Unfortunately, without the tuning capability of the microrings, the resonant frequency shift of the fourth stage is so large that its transmission within the input pulse bandwidth is very small. This explains the relatively large output pulses at the first three stages while the small output at the fourth stage. Therefore, post-fabrication thermo-optic (TO) and/or EO tuning capabilities are needed to improve the circuit performance.

5. Conclusion

The first proof-of-concept chip prototypes of a four-stage, first order M-OPTG is demonstrated. Both prototypes, with combined and uncombined outputs, show correct timings of the four output pulses, with 55 ps and 30 ps delay per stage respectively. It is expected that the pulse repetition rates can be further improved, paving the way for DACs and EO modulators operating at hundreds of GHz. TO and/or EO tuning capabilities are needed for the output pulse amplitude adjustment to further improve the circuit performance.

Acknowledgment

The authors appreciate the help in fabrication and measurement from Professor Philippe M. Fauchet’s group and Professor John R. Marcian, both of University of Rochester.
We acknowledge Cornell NanoScale Science and Technology Facility for the support in device fabrication. This work is partially supported by NSF Grants 0829915 and 0901701.