Microring-based optical pulse-train generator

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Abstract: This paper presents a new photonic integrated circuit, namely optical pulse-train generator, which is developed based on the transfer matrix analysis of microrings and utilizes a time-interleaved architecture. This circuit can generate multiple optical pulses sequentially from a single trigger pulse, with the timing and amplitude of each pulse determined by circuit design. Hence it can be applied in optical arbitrary waveform generation and ultrafast electro-optic modulation. A four-tap prototype pulse-train generator design is demonstrated, and the challenge of distributed optical power combining is discussed. The design techniques presented in this paper will find use in other large scale photonic integrated circuit applications.

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References and links

1. Introduction

Thanks to recent advances in silicon photonics, electronic-photonic integrated circuits (EPICs) can be foreseen in the near future, which seamlessly integrate photonic devices with ultrafast electronics. Microring-based devices such as add-drop filters [1] and modulators [2] exhibit good optical performance with ultracompact device size, especially in high index contrast systems like silicon-on-insulator (SOI) technologies, hence potentially enabling very large scale EPICs [3]. For example, silicon microrings with 1.3 μm radii have been demonstrated [4], and it has been proposed that millions of these devices can be used in an on-chip optical interconnect system [5].

So far most research efforts have been focused on the filtering characteristics of microring circuits in the wavelength domain and their applications in wavelength-division multiplexing (WDM). For example, Little et al. [6] derived the time-dependent transfer functions of a microring resonator with the basic add-drop configuration, treating the ring only as a filter in the wavelength domain. Time-domain properties of microring-based devices and their circuit applications have not been sufficiently explored, which can open up various important applications, e.g., microring-based optical delay lines with large group delays in an extremely small footprint [7]. Therefore, one of the motivations for our work is to further explore the time-domain applications of microrings on the circuit level.

Another motivation for this work is to address the fundamental challenge in EPIC: the large potential bandwidth of photonics vs. the significantly lower speed of electronics. To overcome this mismatch, WDM splits the large optical bandwidth in the wavelength domain. Another approach is to time-share the optical bandwidth by applying time interleaving technique. Time interleaving has been widely used in the high-speed electronic circuits, such as analog-to-digital converters (ADCs), increasing the overall sampling rate by operating two or more data converters in parallel [8]. Recently, time interleaving has also been introduced to EPICs, e.g. the photonic-assisted interleaved ADC [9]. In this paper, we investigate how to utilize time interleaving techniques directly in the optical domain as embodied in the proposed microring-based optical pulse-train generator. Such ultrafast optical pulse-train generator can potentially be applied to optical arbitrary waveform generation, or electro-optic modulation in a time-division multiplexing (TDM) system [10].

The rest of the paper will be organized as following. First, the proposed optical pulse train generator will be presented. Secondly, a design methodology for large-scale microring-based
EPIs based on transfer matrix method will be applied in the analysis of a generic \( M \)-tap, \( N^{th} \) order implementation of this circuit. Then we will show the design of a four-tap, first-order prototype as an example. Finally, potential challenges of this EPI in design and fabrication will be discussed, and their possible solutions will be offered.

2. Optical pulse-train generator

The schematic of the proposed optical pulse-train generator is shown in Fig. 1. All the microrings are coupled to the input trigger waveguide in series. Optical delay lines are inserted between stages to introduce a stage delay of \( \tau \). Each stage consists of a microring add-drop filter, which can be either a single ring or higher-order configuration similar to the multistage structure in [11]. However, different from their filtering function in the WDM application, our time-interleaved circuit uses the ring resonator as a compact switch or coupler. When there is an input pulse, its power is partially coupled into all the \( M \) stages, circulating in the microrings and dropped at the output of each stage. Therefore, one input pulse will always trigger multiple sub-pulses at the output. The amplitudes of these \( M \) sub-pulses can be controlled by properly adjusting the coupling coefficient of each stage. Note that this circuit is very similar to a distributed waveform generator (DWG) in electronics [12].

This circuit may find its application in optical arbitrary waveform generation. Unlike the conventional spatial approach of arbitrary waveform generation, such as chirp filters, frequency-to-space mapping or time-to-space mapping together with spatial modulation [13], the time-domain approach combines multiple narrow basis pulses, which are generated at a specific sampling time, to form a customized output waveform. Therefore, each stage output in our proposed circuit can be viewed as one basis pulse. The final customized output waveform can be generated by modifying the sampling rate and the amplitudes of basis pulses through the control of the stage delay and the coupling coefficient of each stage. Arbitrary waveform generation is widely needed in the high-speed instrumentation or can be applied in the optical communication at ultrahigh data rate. This proposed time-domain approach is more intuitive, easy to control and allows more flexibility in the output waveform.

Furthermore, the proposed circuit can also be used in the ultrafast electro-optic modulation in a TDM system. As shown in the dash line box in Fig. 1, if the microring in each stage is an active device as a modulator, digital data to be transmitted can directly modulate each microring and generate the corresponding modulated output pulse train, enabling ultrafast optical data transmission. The circuit utilizes a TDM system with a time frame the same as the period of input trigger signal. While the \( M \) stages are considered as the \( M \) sub-channels, the timeslots of
each sub-channel is determined by the stage delay $\tau$. The circuit shows an elegant combination of modulation and multiplexing, presenting a simple and cost effective solution compared to the WDM approach.

3. Matrix analysis of the microring network

Transfer matrix analysis combined with full-wave electromagnetic (EM) simulation such as finite-difference time-domain (FDTD) method are used for the system level analysis. While FDTD method is adopted to simulate the accurate numerical coupling coefficients between waveguides and microrings, transfer matrix analysis efficiently gives out the large system behavior based on these parameters. The combination of the two methods gives out an accurate but efficient approach for the large system modeling.

![Diagram](image)

Fig. 2. (a) An $N^{th}$ order add-drop filter; (b) An $M$-tap, $N^{th}$ order microring network for the pulse-train generation.

The proposed $M$-tap microring network for the pulse-train generation is shown in Fig. 2(b). Each stage is utilized by a higher order ($N^{th}$ order) add-drop filter for the general purpose. Poon et al. have done the matrix analysis of an $N^{th}$ order add-drop filter [14]. Using the same notation in [14] as shown in Fig. 2(a), adding a fractional coupler intensity loss $\gamma_0$, which is given by $|b'_n|^2 + |b_{n+1}|^2 = (1 - \gamma_0)(|a_n|^2 + |a_{n+1}|^2)$, the main results are repeated here, but slightly revised.

$$\begin{bmatrix} a_{N+1} \\ b_{N+1} \end{bmatrix} = P_{out}Q(PQ)^{N-1}P_{in} \begin{bmatrix} a_0 \\ b_0 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} a_0 \\ b_0 \end{bmatrix}$$

where

$$P = \frac{1}{\kappa} \begin{bmatrix} -t & \frac{1}{\sqrt{1-\gamma_0}} \\ -\sqrt{1-\gamma_0}t^2 & t^2 \end{bmatrix}, \quad Q = \begin{bmatrix} 0 & e^{-i\beta R\pi} \\ e^{i\beta R\pi} & 0 \end{bmatrix}$$

are respectively the coupling between two internal rings and accumulated phase shift inside one ring. $P_{in}$ and $P_{out}$ are the coupling matrices between the input/output waveguides and rings. $t$ and $\kappa$ are respectively the transmission and coupling coefficients in the coupled region of two adjacent rings, $R$ is the effective ring radius, $\beta = n(\omega)\omega/c - i\alpha$ is the propagation constant, $n(\omega)$ is the effective refractive index and $\alpha$ represents the microring loss [14].
In our application, we only have a single input to the filter, therefore, \( a_{N+1} = 0 \). So the transfer functions at the through port and drop port are given by [14]

\[
\text{Thru}(\omega) = \frac{b_0}{a_0} = -\frac{A}{B} \quad (2a)
\]

\[
\text{Drop}(\omega) = \frac{b_{N+1}}{a_0} = C - \frac{AD}{B} \quad (2b)
\]

We now use Eq. (2) to derive the transfer functions of the \( M \)-tap, \( N^{th} \) order microring network shown in Fig. 2(b). The output direction in Fig. 2(b) is for the case where \( N \) is odd. The direction is opposite when \( N \) is even, but the results are the same. All the \( M \) stages are placed in series, and are apart from each other for a distance \( L \) to introduce a delay at least larger than the pulse width between each stage. This device is essentially a time-interleaved photonic integrated circuit.

The output of each stage is combined by the output combiner instead of one straight output waveguide to avoid the “back-coupling” problem, which occurs when the pulses coming from the latter stages couple back into the former stages. The output combiner can be implemented by Y junctions or a multimode interference (MMI) coupler. However, there will be a \( 10\log_{10} M \cdot dB \) loss due to the “asynchronous” combination of the output pulses. We will discuss this later in detail in Section 5.

As labeled in Fig. 2(b), using the results of Eq. (2), for the \( m^{th} \) stage, we have

\[
b_{0,m} = -\frac{A_m}{B_m} a_{0,m} \quad (3a)
\]

\[
b_{N+1,m} = (C_m - \frac{A_mD_m}{B_m}) a_{0,m} \quad (3b)
\]

where the subscript \( m \) represents the \( m^{th} \) stage. Since the input of the \( m^{th} \) stage comes from the output of the \((m-1)^{th}\) stage

\[
a_{0,m} = b_{0,m-1} e^{-i\beta L} = -\frac{A_{m-1}}{B_{m-1}} e^{-i\beta L} a_{0,m-1} = \ldots = (-1)^{m-1} \frac{A_{m-1}A_{m-2} \cdots A_1}{B_{m-1}B_{m-2} \cdots B_1} e^{-i(m-1)\beta L} a_{0,1} \quad (4)
\]

Therefore, combining Eq. (3a) and (4), the transfer function at the through port of the network can be derived by

\[
\text{THRU}(\omega) = \frac{b_{0,M}}{a_{0,1}} = (-1)^M \frac{A_M A_{M-1} \cdots A_1}{B_M B_{M-1} \cdots B_1} e^{-i(M-1)\beta L} \quad (5)
\]

Assuming symmetric Y junction combination at the output, and the total distance from each stage output to the network output is the same \( d \), the transfer function at the output of the network can be derived from Eq. (3b) and (4)

\[
\text{OUT}(\omega) = \frac{O_{N+1}}{a_{0,1}} = \frac{1}{M} \sum_{m=1}^{M} b_{N+1,m} e^{-i\beta d} = \frac{1}{M} \sum_{m=1}^{M} (-1)^{m-1} \frac{A_mD_m}{B_m} \frac{A_{m-1}A_{m-2} \cdots A_1}{B_{m-1}B_{m-2} \cdots B_1} e^{-i(m-1)\beta L} e^{-i\beta d} \quad (6)
\]
The $1/M$ coefficient in Eq. (6) represents the power loss induced by “asynchronous” combination of the output pulses. The output spectrum is the product between the input pulse spectrum and the transfer function Eq. (6). The corresponding temporal behavior can be obtained by the inverse Fourier transform. Comparison between the FDTD simulation and the transfer matrix method gives out excellent agreement [14].

4. Design of a four-tap, first order prototype

As a demonstration, a four-tap, first order prototype is designed. The schematic is shown in Fig. 3. Very low loss SOI bends with radii of only a few micron has already been demonstrated [15], therefore, delay between each stage is introduced by the meandering waveguides to save chip area. A 4-mm delay line is inserted between each stage to produce a 50-ps time delay. With a bending radius of 5 μm, the total device area is only 0.18 mm$^2$. The output combiner is implemented by a symmetric four-port power splitter/combiner that consists of three Y junctions. There will be a 6 dB power loss because of asynchronous branch input.

Fig. 3. The schematic of a four-tap, first order pulse-train generator.

The silicon waveguides and microrings are all built on a SOI platform with 250-nm top silicon and 3-μm buried oxide. Both waveguides and resonators have a cross section of 450 nm × 250 nm for the single mode operation. As shown in the inset of Fig. 3, racetrack resonator is used instead of ring resonator in order to have a better coupling control. The racetrack is designed to have a radius of 4 μm and a straight coupling length of 3 μm, which corresponds to a ring resonator with effective radius of 5 μm. All the resonators have the same dimensions, thus resonate at the same frequency.

Equal power coupling to all the stages is achieved by adjusting the coupling coefficient of each stage, such as changing the gaps between rings and waveguides. Figure 4(a) shows the normalized drop port transmission of the add-drop filter in each stage, $\text{Drop}_m = b_{N+1,m}/a_{0,m}$, with different coupling coefficients. Due to the waveguide loss of the delay lines and the power drained by the prior stages, microrings in the latter stages are placed closer to the waveguides to increase the coupling coefficient. Assuming the waveguide loss is about 3 dB/cm [15], the designed coupling coefficients in Fig. 4(a) are 0.16, 0.22, 0.31 and 0.70 for 1$^{st}$ to 4$^{th}$ stage respectively. The corresponding gaps between the racetrack and input/output waveguides are 160 nm, 140 nm, 120 nm and 70 nm determined by FDTD simulations. However, coupling coefficients can also be controlled by changing the coupling length in a square-shape ring instead
of changing the gaps between rings and waveguides, maintaining the same perimeter of the resonator by adjusting the length of the perpendicular arms. This approach results in a more accurate wavelength and coupling control since small gaps, such as those less than 100 nm, are not easy to control in fabrication.

Using the transfer matrix analysis developed in Section 3, the normalized transmission at each stage output, \( DOP_m = b_{N+1,m}/a_0,1 \), in a four-tap, first order microring network is shown in Fig. 4(b). We can see the transmission curves of all the stages behind the first one have a notch at the resonant frequency because most of the input power at that frequency is drained at the first stage. As a result, equal power coupling can be intuitively achieved by detuning the center frequency of the input pulse off-resonance [blue dash-dot line in Fig. 4(b)], so that the power transmission of all the stages in the pulse bandwidth are approximately the same. To that purpose, the input pulse should be relatively narrow-band, for example, picosecond mode-locked laser diode can be used as the optical source. In our design, a 10-ps input pulse around 1550 nm wavelength is used.

The center wavelength of the input pulse is fine tuned at 1549.93 nm, which is detuned from the resonance peak of the resonators at 1548.12 nm [Fig. 4(b)]. Inverse fast Fourier transform (IFFT) of the product between the circuit transfer functions and the input pulse spectrum is

![Fig. 4. (a) Normalized drop port transmission of the add-drop filter in each stage, \( Drop_m = b_{N+1,m}/a_{0,m} \); (b) Normalized transmission at each stage output in a microring network, \( DOP_m = b_{N+1,m}/a_{0,1} \).](image)

![Fig. 5. Time domain behavior of the four-tap, first order pulse-train generator. (a) Pulse propagation in the input trigger waveguide (stage input) and each stage output; (b) Pulse waveform at input, output and through port.](image)
applied to get the resulting time-domain waveform as shown in Fig. 5. Figure 5(a) shows the input pulse evolution in the trigger waveguide (black lines) and corresponding stage outputs (red lines). The input pulse propagating in the trigger waveguide becomes smaller and smaller since it couples to the microrings and drops a small portion of the pulse at the output of the stage when passing through them. Since the coupling coefficient of each stage is properly designed, the output pulses are almost identical as shown in the black solid line in Fig. 5(b). The amplitudes of the output pulses are reduced by 6 dB, compared to the stage output, due to the output power combining loss.

Because the center frequency of the input pulse is detuned to off-resonance, the through port transfer function is nonzero in the input bandwidth. Therefore, part of the input energy will pass through the network to the through port [red dash line in Fig. 5(b)], resulting an extra power loss of the whole system. However, this signal might be used as an extra tap in the future.

The output waveform exhibits no distortion since we don’t consider any dispersion in the analysis. Although dispersion can be significant in the high index contrast SOI waveguides, its impact is relatively small due to the short on-chip traveling distance. For example, the material dispersion of silicon is about $-880 \text{ ps/(nm·km)}$ at 1550 nm [16]. Without dispersion compensation, for a 10-ps Gaussian pulse, which corresponds to a spectral width of 0.35 nm, the pulse broadening is only 30 fs after 10-cm on-chip propagation, which is small compared to the original pulse. Furthermore, the anomalous waveguide dispersion can be achieved by tailoring the cross-sectional size of the SOI waveguides, thus compensating the effect of the normal material dispersion and reducing the total dispersion in the waveguides [16].

The overall efficiency of the proposed pulse train generator is mostly affected by the waveguide loss and output combiner. For the designed four-tap prototype, as shown in Fig. 4(b), each stage couples out about 10% of the input pulse energy. Therefore, about 40% input energy is delivered to the four stage outputs. The power loss is caused by the assumed 3 dB/cm waveguide propagation loss. At the system output, as would be discussed in Section 5, another 6-dB loss is introduced by the output combiner compared to the stage outputs. So the overall efficiency of the four-tap prototype is reduced to about 10%, including the through port output. It can be further improved to about 20% if the waveguide loss is reduced to 1 dB/cm.

5. Discussion

There are three issues that need to be addressed in terms of device fabrication and system implementation: (1) the loss of waveguides and microrings, (2) the shift of resonant frequencies due to the process variation, and (3) the inefficient output combiner, which introduces high power loss at large number of stages.

The SOI waveguide loss caused by the sidewall roughness has been studied extensively. Thermal oxidation [17] or even double thermal oxidation [7] can effectively smooth the waveguide sidewalls, and propagation loss as low as 1-2 dB/cm can be achieved, for example, 1.7 dB/cm in [7]. Even lower loss of 0.3 dB/cm has been reported by using etchless process based on selective oxidation [18]. Characterizing and minimizing the waveguide loss is extremely important for our proposed circuit since the coupler design depends on the exact loss number of the delay lines and the overall efficiency of the system is greatly affected by the waveguide loss. Therefore, careful characterization and optimization of fabrication steps are necessary to minimize the loss and obtain the accurate number.

Process variation is unavoidable but critical for successfully implementing the microring-based devices. Figure 6 is a FDTD simulation result showing the change of resonant wavelength as the width of the microring changes. The slope of the curve is relatively high, which means a small change in the microring width will affect the resonant frequency a lot. For example, a width change of ±2 nm at 450 nm will result in the wavelength change of ±1.6 nm at
1557 nm, which is huge since the filter bandwidth is only several nanometers. The process variation would easily cause the random shift of the resonant peaks, even the split of peaks in the output spectrum of our system. Therefore, precise control of the resonant frequency becomes crucial for the success of microring-based systems. Optimization and calibration of the e-beam dose can mitigate the problem, for example, a 5-nm dimensional control has been demonstrated in a SiN microring resonator [19]. In addition, tuning capability of the microring, either thermally or electro-optically, has been introduced to precisely control its resonance frequency [20]. Furthermore, future lithography in production can do better in both accuracy and uniformity.

Fig. 7. (a) Coherent combination of the two-branch inputs; (b) Transmission of a single branch input; (c) Combination of two asynchronously timed pulses.

The output combiner is another issue that limits the circuit performance. For most of the passive on-chip power combiners, such as Y junctions and MMI couplers, people usually focus on their characteristics of coherent power combination. Figure 7(a) gives out such an example in a two-branch symmetric Y junction. When the two input pulses are in phase, the output power is the sum of the two input power, and there should be ideally no power loss. However, if there is only one pulse incident from one arm [Fig. 7(b)], both even and odd modes will be equally excited at the transition region [21]. While the odd mode will convert into the higher-order mode and radiate, the output power is only carried by the even mode, which is half of the input power. Therefore, in our application [Fig. 7(c)], when the two input pulses arrive at the two arms asynchronously, two pulses appear sequentially at the output, but are halved in power. The “asynchronous” power combination results in a $10\log_{10}M$ dB power loss, which fortunately would increase rather slowly as the number of stages, $M$, increases. To address this issue, we plan to investigate new device and circuit solutions, e.g., that avoid unbalanced pulse inputs to a power combiner, hence circumventing the “asynchronous” power combining...
problem.

6. Conclusion

A new microring-based optical pulse-train generator is proposed. The transfer matrix analysis results in the transfer functions of the network, representing an effective approach for system-level analysis of large EPICs. A four-tap prototype pulse-train generator design demonstrates the multiply-by-4 circuit function. Four identical sub-pulses which are 50-ps apart duplicate the input pulse at the output. The issues of the device fabrication and system implementation are discussed.

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