Highlights:

In the paper, we designed a novel three-stage all-pass filter as a tunable optical delay line to construct an optical time division multiplexer. The proposed design mitigates the deleterious effects of group delay dispersion and provides wide bandwidth and continuously tunable long delays achieved with small variations in the effective refraction index. We also explain the operation principle of our device and demonstrate the simple generation of 40 Gb/s from four 10 Gb/s inputs using chains of tunable three-stage APFs as optical time-division multiplexers. In addition, with the recent demonstration of large bandwidth WDM components (>60 GHz) on a Silicon chip, our OTDM device can be seamlessly integrated into a WDM system.

Tunable optical delay line for optical time-division multiplexer

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Abstract

A novel three-stage all-pass filter (APF) is proposed as a tunable optical delay line to construct an optical time division multiplexer (OTDM), with which, we can get ultrahigh bit rates with several low-speed channels. The proposed design mitigates the deleterious effects of group delay dispersion and provides wide bandwidth with small ripples and continuously tunable long delays achieved with small variations in the effective refraction index, making it suitable for high-speed optical networks on chip.

Keywords: Microring Resonators; All-pass filter (APF); Optical delay line; Optical time division multiplexer (OTDM); Network on chip

1. introduction

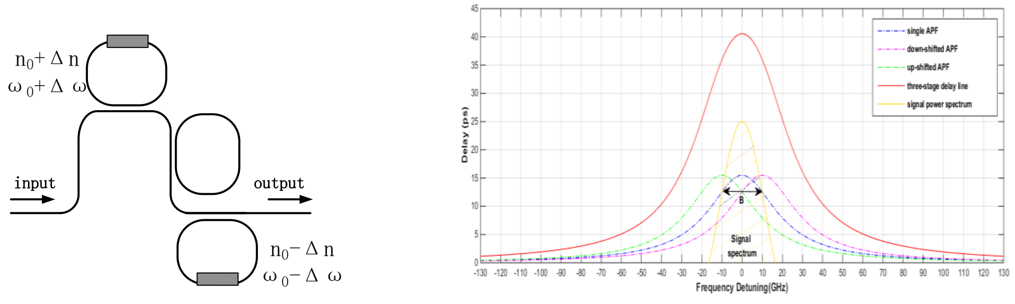
Recently optical time-division multiplexing (OTDM) in the areas of optical communications gets great interests, since OTDM was recommended as an effective way to realize high-speed data rates with several slowly modulated paths[1,2,3]. A typical OTDM starts with a 1: N splitter that splits the input signal into N channels [4,5]. Each of these channels is delayed by τ, and then modulated by low bit-rate data signals. The channels are then recombined into a high bit rate composite channel using an N:1 combiner. For example, if the data source operates at 10Gb/s and eight paths are used, the bit-rate of the photonic link will reach 80Gb/s. From the whole OTDM system [2, 3], we can see that delay lines are the key device and the final bit-rate is only dictated by the relative time-delay between each path.

A number of different approaches to optical delay have been implemented using silica spiral line, atomic vapors, optical fibers amplifiers, and others; however, on-chip all optical delay lines using coupled resonators are potentially most suitable for practical applications owing to their compact size and ability to be integrated with electronic. In the paper, we proposed a tunable optical delay line based on coupled resonators to construct an optical time division multiplexer (OTDM) system on silicon chip. We explain the operation principle of three-stage APFs and how to attain a wide bandwidth, a long tunable delay and a low distortion. Then a simple generation of 40 Gb/s from several 10 Gb/s inputs using our tunable optical delay lines is demonstrated. In addition, with the recent demonstration of large bandwidth WDM components (>60 GHz) on a Silicon chip, our OTDM device can be seamlessly integrated into a WDM system.

2. Three-stage all-pass filters (APFs)

There are mainly two types of delay lines based on coupled resonators [6, 7, 8]: coupled resonator optical waveguides (CROWs) and side-coupled integrated spaced sequence of resonators (SCISSORs). Although CROW delay lines have been implemented and much longer delays can be achieved using more rings, the inevitable spread of resonator parameters in fabricated CROW devices could cause localization and a significant reduction in performance. SCISSOR structures are not so strongly affected by fabrication variations, because these effects can be compensated.

To achieve relative larger group delay and compacter dimension, a novel three-stage APFs based on SCISSOR structures was designed, which is shown in Figure 1(a). Three rings are connected to the bus waveguide in zigzag shape, where heaters are located on the top and bottom rings for tuning the resonance frequency while the middle ring keep working on the centre resonant frequency. Silicon-on-insulator (SOI) sub-micrometre photonic wire waveguides are used, because they can provide strong light confinement at the diffraction limitation, allowing dramatic scaling of device size.



(a) (b)

Fig. 1 (a) Structure of the three-stage APFs; (b) the character of the three-stage delay line;

In general, we may write the delay response of N-stage APFs [9, 10]:

$$T_d(\omega)=\sum_{i=1}^{N} T_i \frac{\sinh \chi_i}{\cosh \chi_i - \cos(\omega T_i + \theta_i)} \qquad (1)$$

Where T is a round trip delay in the cavity of the filter and χ is related to the coupling constant. The peak group delay is at $\omega = m(2\pi / T)$, with m as an integer. Since the free spectral range of all the stages is identical, $T_i = T$, and the delay may be tailored by appropriately "weighting" (by adjusting the coupling constants χ_i) and "phasing" (by adjusting the relative phases θ_i).

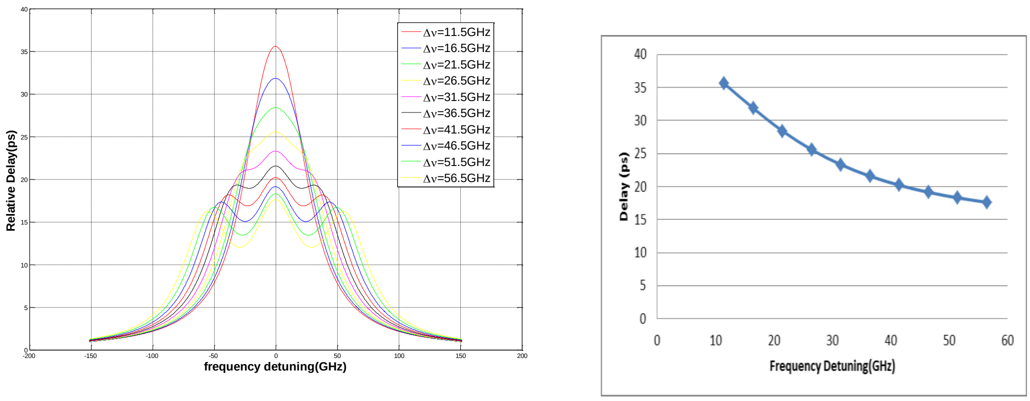
Since the group delay of cascaded APFs in SCISSOR structures is additive, broadband delay can be achieved by adding all-pass stages and phasing them correctly with respect to each other by varying resonant frequencies, just as shown in Fig. 1(b). The spectrum of three-stage APFs group delay (GD) is shown for θ_i ={11.5, 0, -11.5} in equation (1) for the top, middle and bottom rings respectively and the maximum delay T_{delay} is about 41 ps (achieved with 30 μm circumference Si on SiO2 resonators and k=0.25).

Shifting the resonant frequency up or down by the amount $\Delta\omega \approx \left(\Delta n / n\right)\omega$, Δn is the change in the top and bottom rings effective refractive index, which cause a change in the delay time. Considering a signal with 10 GHz bandwidth shown schematically in yellow curve, the delay spectrum of GD in red curve should be larger than the bandwidth of signal spectrum, otherwise there may cause the distortion of signals. Fig. 1(b) depicts the spectrum curves for three-stage APFs and different phase-shifted APFs. In addition to the already mentioned shifted spectra T_d (ω ± Δω) for the "upper" and the "lower" rings drawn by dashed curve, the resulting combined mean delay $T_d=T_d(\omega+\Delta\omega)+T_d(\omega-\Delta\omega)+T_d(\omega)$ is shown by red curve, which is significantly flattened over the bandwidth of the signal B.

3. Tunability

A way to achieve the tunability and at the same time to expand the bandwidth of a SCISSOR structure is now described. This is achieved by taking advantage of the fact that the third- and the fifth order dispersions in Eq. (1) have opposite signs. In the structure shown in Fig. 1, one third of rings have their resonant frequencies shifted up by a small amount, relative to the middle rings working frequency ω_0, while the resonance frequencies of the other one third are shifted down by the same amount, i.e., $\omega_{1,2}=\omega_r\pm\Delta\omega$. In Fig. 1(a), the up- and down-shifted rings are located on opposite sides of the central ring because this is potentially the simplest way to implement the shift using thermal- or carrier induced index change $\pm\Delta n$ on the two sides of the central bus.

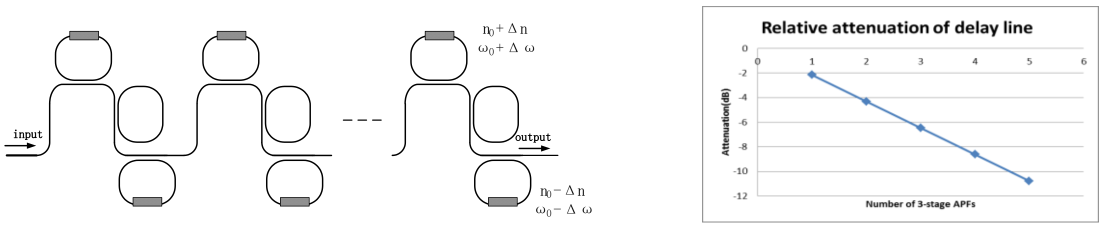
It is obvious by inspection of Fig. 2 that broadband delay may be achieved by increasing the detuning responses. When the detuning frequency is 46.5GHz, the bandwidth of this three-stage APFs can reach 100GHz (shown in Fig. 2(a)), making it suitable for ultra-high speed optical network on chip. However, with the larger bandwidth attained by increasing the detuning frequency, the delay spectrum would be rippled, which might cause distortion for normal digital signals with single lobe spectrum. But for RF photonics, which has a typical double sideband spectrum, such a signal a slight camelback shaped spectrum of the group dispersion (GD) may actually be optimal [11].



(a) (b)

Fig. 2. (a) the delay spectrum for different values of detuning $\Delta\nu$ in the three-stage APF; (b) the delay time with frequency detuning in this three-stage APFs

Also, we can get larger delay by cascading more three-stage APFs, because the delay characteristic in balanced SCISSORs structure is addictive. More APFs are cascaded to construct a chain of 3-stage APFs, as shown in Fig. 3. All the 3-stage APFs are identical and the detuning delay spectrum of such chains of APFs might obtain the needed delay to satisfy different on-chip network applications.



(a) (b)

Fig. 3 (a) Chains of three-stage APFs; (b) Relative attenuation with different numbers of 3-stage APFs

Besides, it is needed to point out, with the number of 3-stage APFs increases, the relative propagation loss turns larger. As is shown in Fig.3(b), the attenuation with numbers of APFs will rise linearly. When five 3-stage APFs is applied, the attenuation comes to about -11 dB, which would be an obstacle to this microring-based optical delay line. Another delay limit of APFs is the value of the maximum GD per ring as a function of the index change. Although small (less than 10^{-3}) index change can accomplish a fairly large fractional change in the delay time, this would cause group delay dispersion (GDD), which is described above. Therefore, it appears that the main restriction on the delay is not the limited ability to change the index but still the GDD.

4. System

The schematic structure of OTDM multiplexer on a chip is proposed in Fig.4. The generation of 40 Gb/s signals using our 10 Gb/s to 40 Gb/s OTDM device. In order to demonstrate continuous generation of 40 Gb/s signals, we constructed an optical time division multiplexing system in OptiSystem. The laser is realized by driving an electro-optic modulator with a pulsed pattern generator operating at 10 GHz and the bit duty circle of RZ pulses is 0.05 bits. Just as shown in Fig. 5, the laser generates pulses of duration about 5 ps that repeat every 100 ps. Then an 1:4 splitter is used to split the pulse sequences to four channels. By adopting different numbers of 3-stage APFs, we can get 25 ps、50ps、75ps delays by shifting the detuning frequency about 30GHz. Finally, the four channel signals are combined at the output and traced by an optical time domain visualizer. The results are seen in Fig. 5, where four clear pulses (P_0, P_1, P_2, and P_3) are produced by our optical delay lines with about 25 ps separation between each of them, corresponding to a 40 Gb/s bit-rate.

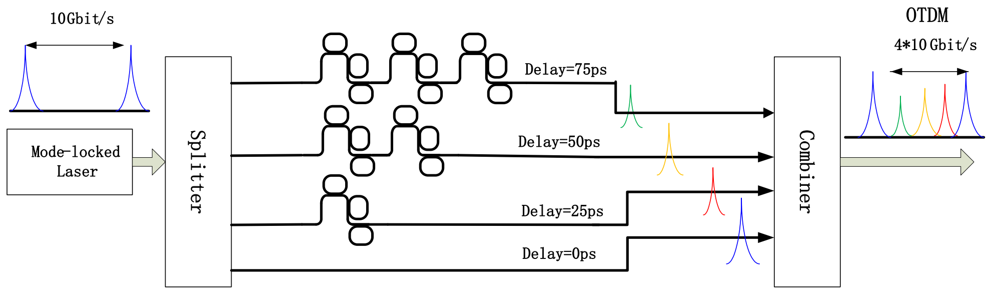


Fig. 4 Schematic of full OTDM multiplexer

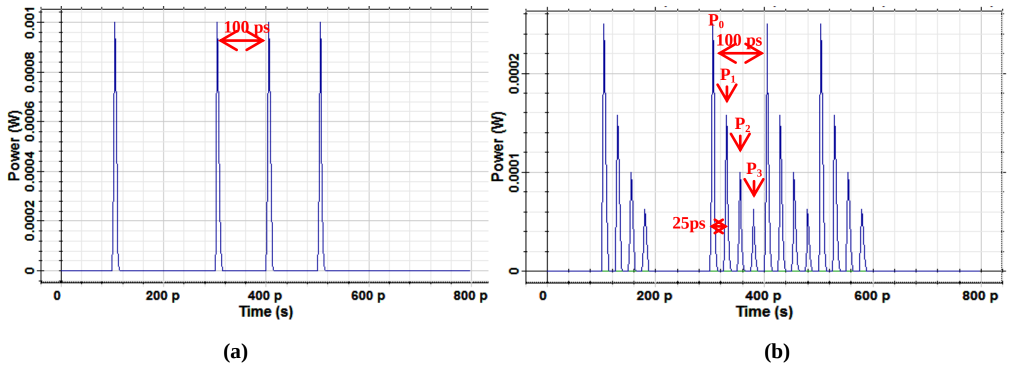


Fig. 5 a) The input stream of pulses at 10 Gb/s from an amplitude modulator. b) 40 Gb/s TDM signal at the output of the device.

We also see that the pulse amplitudes of different paths decrease due to the loss of microring coupling and the decay is exponential and, consequently, attribute it to the inherent propagation loss of the waveguides. Therefore, the amount of cascaded 3-stage APFS should be limited for the decay of signal power with the increase of adopted 3-stage APFs. Further improvements in fabrication techniques and measurement of the pulse train would allow for the generation of ultra-high speed OTDM signals, which will play a key role for high-speed optical networks on chip. In general, this approach has the distinct advantage that inherently slow modulators operating at the same bit-rate as the input pulse train can be used to achieve very high overall bit-rates at a single wavelength. Besides, this is unlike delay lines based on silicon spirals where the footprint would be large and the delay cannot be tunable.

5. Conclusions

In the paper, we designed a novel three-stage all-pass filter as a tunable optical delay line to construct an optical time division multiplexer. The proposed design mitigates the deleterious effects of group delay dispersion and provides wide bandwidth and continuously tunable long delays achieved with small variations in the effective refraction index. We also explain the operation principle of our device and demonstrate the simple generation of 40 Gb/s from four 10 Gb/s inputs using chains of tunable three-stage APFs as optical time-division multiplexers. In addition, with the recent demonstration of large bandwidth WDM components (>60 GHz) on a Silicon chip, our OTDM device can be seamlessly integrated into a WDM system.

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