Optics Communications ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Optics Communications

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

Tunable optical delay line for optical time-division multiplexer

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ARTICLE INFO

Article history:
Received 30 October 2015
Received in revised form
27 June 2016
Accepted 1 July 2016

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

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.

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 [1–3]. 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 10 Gb/s and eight paths are used, the bit-rate of the photonic link will reach 80 Gb/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 [6–8]: 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 Fig. 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 center resonant frequency. Silicon-on-insulator (SOI) sub-micrometer photonic wire waveguides are used, because they can provide strong light confinement at the diffraction limitation, allowing dramatic scaling of device size.

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

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http://dx.doi.org/10.1016/j.optcom.2016.07.002
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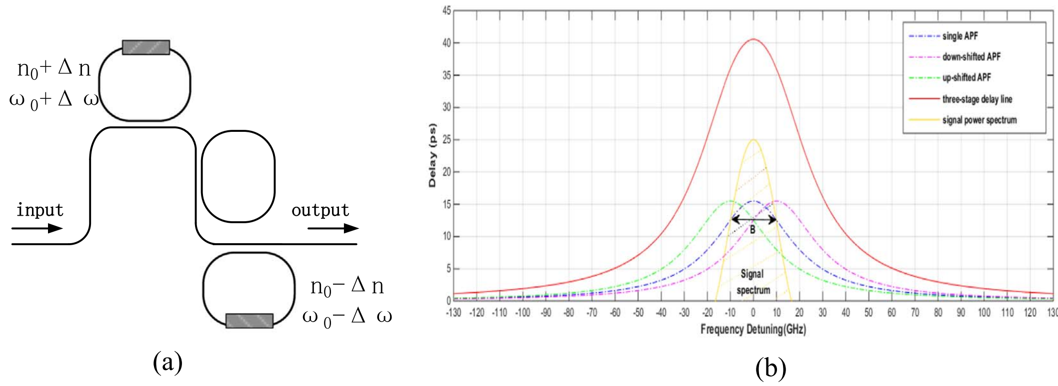

Fig. 1. (a) Structure of the three-stage APFs; (b) the character of the three-stage delay line.

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

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 Eq. (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 SiO_2 resonators and k=0.25).

Shifting the resonant frequency up or down by the amount $\Delta\omega \sim (\Delta n/n)\omega$, 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 $T_d\,(\omega \pm \Delta\omega)$ 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 responsesb [12-14]. When the detuning frequency is 46.5 GHz, the bandwidth of this three-stage APFs can reach 100 GHz (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

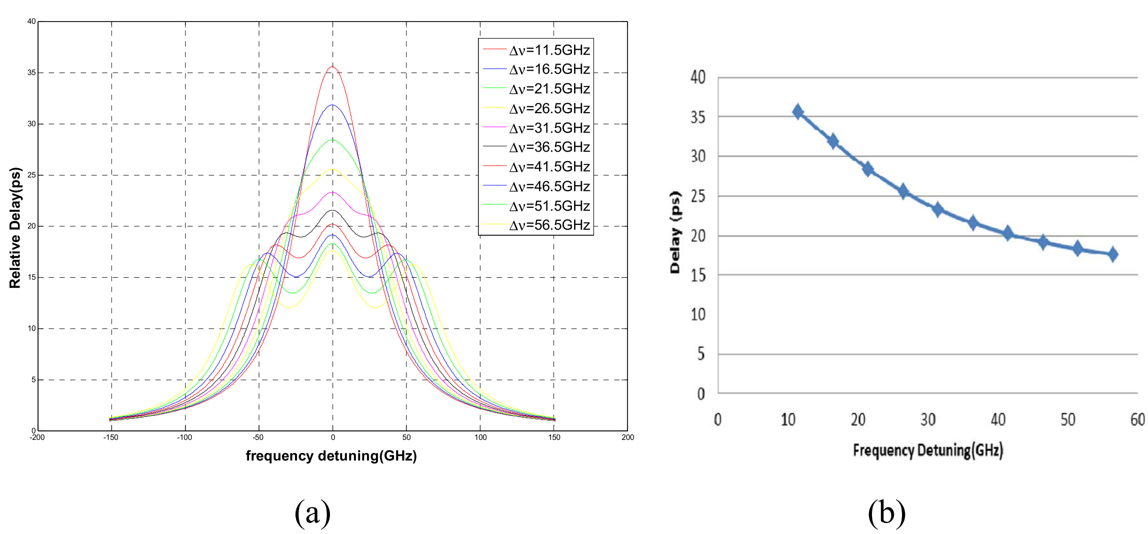

Fig. 2. (a) the delay spectrum for different values of detuning ΔV in the three-stage APF; (b) the delay time with frequency detuning in this three-stage APFs.

Please cite this article as: Z. Yu, et al., (2016), http://dx.doi.org/10.1016/j.optcom.2016.07.002