Ring resonator-based Tunable Optical Delay Line in LPCVD Waveguide Technology

C.G.H. Roeloffzen[1], L. Zhuang[1], R.G. Heideman[2], A. Borreman[2], and W. van Etten[1]

[1]: Telecommunication Engineering Group, CTIT Research Institute, University of Twente, P.O. Box 217, 7500 AE Enschede, The Netherlands, phone +31 53 4892804, fax +31 53 489 5640, e-mail: C.G.H.Roeloffzen@ewi.utwente.nl

[2]: LioniX BV, P.O. Box 456, 7500 AH, Enschede, the Netherlands

Optical circuits providing a time delay to signals modulated on optical carriers are considered important for optical communication systems and phased array antennas. A continuously tunable optical delay line is demonstrated in low-cost CMOS compatible LPCVD planar waveguide technology. The device consists of three cascaded ring-resonator all-pass filters with fixed circumference of 2 cm (delay of 0.12 ns and FSR of 8.4 GHz). The measured group delay ranges from 0 ns up to 1.2 ns with a bandwidth of 500 MHz and delay ripple smaller than 1 ps, which is in accordance with the calculations.

Introduction

Optical beam forming networks have several well-known advantages over their electrical counterparts, their broadband nature, reduced weight and size, and immunity to EMI. Recently integrated photonic devices that can provide a broadband tunable RF phase shift have been introduced. Many implementations make use of fixed delay paths with incremental length interconnected by switches. With this implementation the delay is not continuously tunable, and its resolution is defined by the minimum path length [1]. One promising option is to use optical ring-resonator all-pass filters to implement variable delays, as depicted in Figure 1. The ideal (optical) ring-resonator filter is an all-pass filter, which has a characteristic of a large group delay (the modulated signal is delayed by the group delay) at resonance and a unity magnitude response. This delay can be tuned by the amount of power coupling to the ring. All this makes the optical ring resonator filter more and more popular nowadays for the design of optical delays [2, 3]. This paper introduces a ring resonator-based tunable optical delay line that can continuously change its delay.

Device structure and design

Figure 1a shows the layout of the three-ring resonator delay filter. The rings are connected to the waveguide by Mach-Zehnder interferometer (MZI) based variable couplers. Heaters are located on the ring for tuning the resonance frequency, and on one of the branches of the channels of the MZI ring coupler for adjusting the power coupling to the ring. Using 3 mm long heaters, a 2π phase shift could be easily obtained. The group delay T of one roundtrip in the ring is

$$T = \frac{1}{f_{FSR}} = \frac{Ln_g}{c} \qquad (1)$$

where L is the circumference of the ring, n_g is the group index of the waveguide, and c is the speed of light in vacuum. The circumference of the rings are 1.96 cm resulting in a 8.4 GHz FSR and a roundtrip delay of 0.12 ns. It can be shown that the normalized group delay τ_n which is the sum of the individual normalized group delays τ_{ni} for a lossless waveguide is given by

$$\tau_n(\Omega) = \sum_{i=1}^{3} \tau_{ni}(\Omega) = -\sum_{i=1}^{3} \frac{\mathrm{d}\Phi_i(\Omega)}{\mathrm{d}\Omega} = \sum_{i=1}^{3} \frac{1-c_i^2}{1+c_i^2 - 2c_i \cos(\Omega + \phi_i)} \qquad (2)$$

where $\Omega=\omega T$ is the normalized angular frequency; $\Phi_i(\Omega)$ is the phase response of each individual filter; $c_i = \sqrt{1-\kappa_i}$ is the bar port transfer of the waveguide to ring coupler, κ_i is its power coupling coefficient, and ϕ_i is an additional phase of the ring that can be set by the ring heater. The normalized group delay has to be multiplied by T to obtain the absolute delay. By appropriately adjusting the coupling coefficient κ_i and the extra phase shift ϕ_i of each single stage, a broadband group delay response can be achieved (staggered tuning). An example is shown in Figure 1b. The delay curve of a ring resonator always has a constant surface independent of the coupling coefficient κ_i. As a consequence there is a trade-off between the maximum delay and bandwidth for a certain bandwidth ripple. Calculations show a maximum delay of 1.2 ns for bandwidth of 500 MHz and a ripple ($\Delta\tau$) of 1 ps.

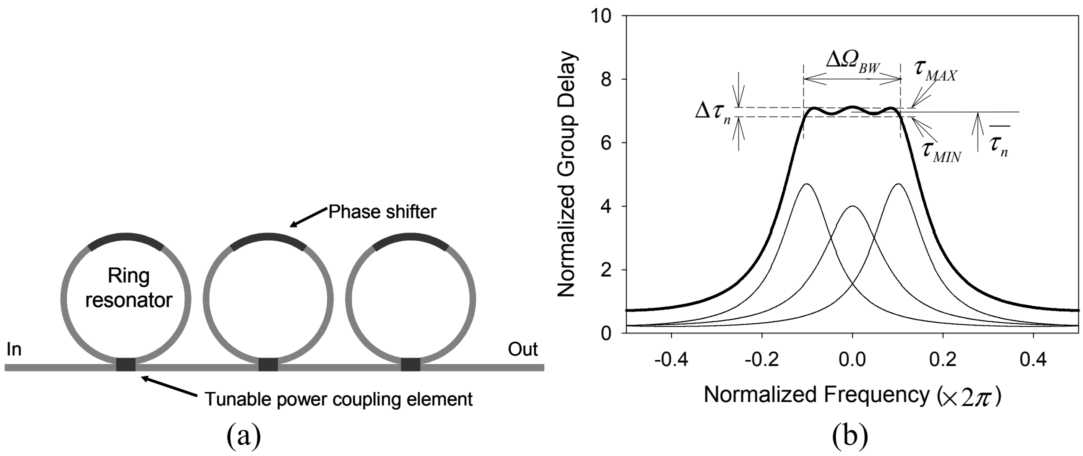

Figure 1: ***(a)*** *Schematic layout of the 3-stage ring resonator filter, and* ***(b)*** *calculated normalized group delay response of a 3-stage ring-resonator filter, where the coupling coefficients and the extra phase shifts of each single stage have been adjusted to yield a broadband group delay. The bold line represents the sum (3-stage response) of the thin lines (single-stage responses).*

The device has been fabricated at Lionix using a new class of integrated optical waveguide structures, based on low cost CMOS compatible LPCVD processing [4].

Device characterization

The setup shown in Figure 2 has been used to measure the delay of the filter. The measurement is known as the phase shift method. Monochromatic light from a tunable laser (Santec TSL-210, λ=1500-1600 nm) is intensity modulated with a sinusoidal signal (fixed frequency, 100 MHz) by an external modulator. Next the light is split by a fiber splitter. One part goes to a photo detector. The other part is coupled into the device under test (DUT) after it has been re-polarized. Since the intensity was too low to be detected an EDFA (Firmstein Technology) was used for amplification. The light was detected by a second detector. Central in this setup is the Lightwave Component

Analyzer (Hewlett-Packard, HP8702B), which drives the modulator and receives the signals from the two detectors. It measures the amplitude and phase of the two signals. The group delay is expressed in terms of the phase as follows:

$$\tau_g(\lambda) = \frac{\varphi_A - \varphi_B}{\omega_m} \qquad (3)$$

where φ_A and φ_B are the measured phases of the two signals and ω_m is the modulation angular frequency. The phase is measured at multiple points over one FSR of the device. It is not possible to measure the absolute group delay, because the total group delay is the sum of the delays of the extra fiber length in the device branch of the measurement setup, total length of the channel waveguides and the filter, but we are only interested in the variation of the delay, which originates from the filter.

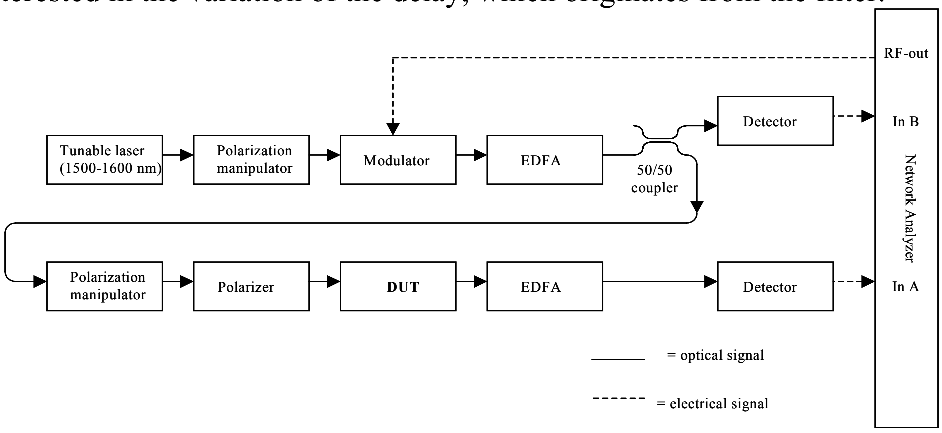

Figure 2: *Group delay measurement setup.*

The measured delay transfer spectra of the filter are shown in Figure 3a. The measurement was performed with TE polarized light. When all six heaters are properly tuned a flat delay response is clearly observed and it could be tuned from 0 to 1.3 ns with a minimum bandwidth of 500 MHz. In the measurement result shown in Figure 3b the average delay is kept constant and the bandwidth is varied. It clearly shows delay ripple for a larger bandwidth, which confirms the trade-off between bandwidth and delay.

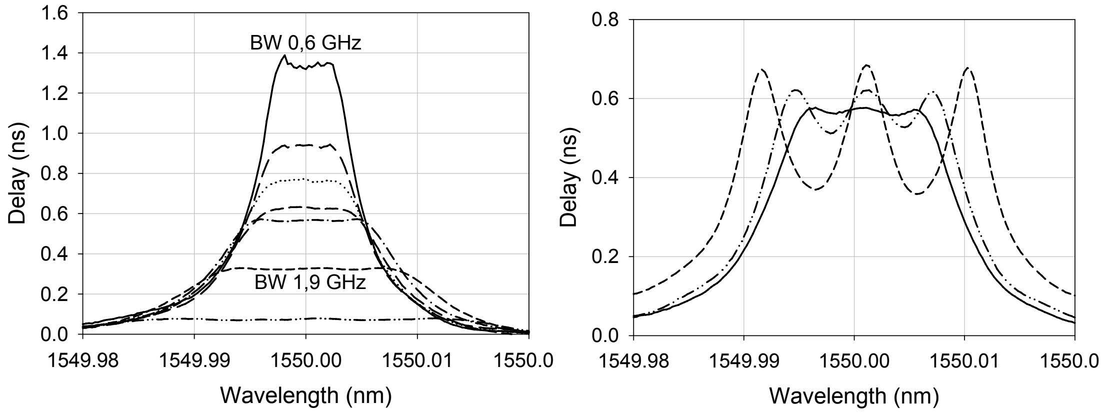

Figure 3: *Delay spectra of a 3-stage ring resonator filter (a) where the coupling to the ring and resonance frequencies of each stage have been adjusted to yield a broadband delay; (b) where the coupling to the ring and resonance frequencies of each stage have been adjusted to yield a constant average delay and varying bandwidth.*

A measured power and delay spectrum of the filter is shown in Figure 4. The device is tuned so that, although a ripple is visible, the maximum delay is 0.6 ns (equal to 5 roundtrips and in total 10 cm delay). As can be seen both graphs look similar which is easily understood since a delay is created by roundtrips in the ring resonators. The measured average propagation loss in the ring resonator is 0.8 dB/cm, which is relatively large, but it will be reduced with recently improved waveguide fabrication technology [4].

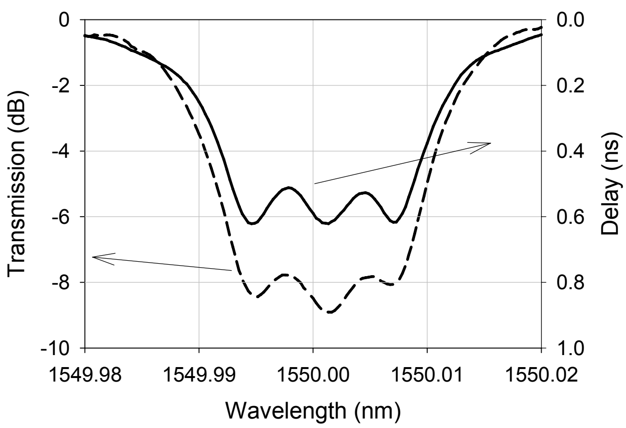

Figure 4: *Measured power (dashed line) and delay (solid line) spectrum of a 3-stage ring resonator filter.*

Conclusions

A cascade of optical ring resonator can be used as a tunable delay line. A three-stage tunable delay line filter has been fabricated and characterized and a flattened delay, tuned from 0 to 1.2 ns with a minimum bandwidth of 500 MHz, has been measured. Simulations show a delay ripple of 1 ps. The measured waveguide loss was 0.8 dB/cm.

Acknowledgements

This work was supported by the Netherlands Agency for Aerospace Programmes (NIVR), under 61424.

References

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