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ALL-OPTICAL DELAY MODULE USING CASCADED POLYMER ALL-PASS-FILTER RING RESONATORS

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Abstract—An APF (All-Pass Filter) delay module in which eight single-ring resonators are serially cascaded is designed and fabricated. The polymer waveguide used for the realization of the APF delay module is a buried structure whose core width and height are 1.5 μm. The core and cladding index are 1.51 and 1.378, respectively, which corresponds to the relative index difference of 8%. In order to use a thermo-optic effect of polymer materials, electrodes are evaporated above the ring resonator to provide heating currents. The time delay is measured to be about 50 ps when 2 rings are in resonance, and about 105 ps and 150 ps, respectively, when 4 and 6 rings of APF are in resonance, respectively. When all of 8 rings are in resonance, the delay is measured to be about 200 ps.

1. INTRODUCTION

The paradigm of data communication network service has been changing rapidly from simple internet access to high-capacity multimedia service and the traffic of the multimedia contents increases explosively. Thus, networks with transmission rate of a few Tbps have been drastically spreading. In the existing optical communication network routers incoming optical signal is converted to electrical signal, and then the routed packet is transmitted after electronic-optical conversion again. However, the repeated use of optical transceivers brings about high cost in addition to the bottleneck effect in electronic signal processing. To solve this problem through a simplified routing, all-optical packet routing networks are drawing more interest among

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researchers, in which packet routing is performed in the form only of optical signal. In the all-optical packet routing network, optical buffers are essential, which requires "Slow Light" technology [1].

"Slow Light" technology has been one of the major research interests in optics community and various phenomena have been reported to slow light. A electronic resonance effect provides the lowest group velocity while the narrow bandwidth and the low temperature operation make it impractical for the use in large-capacity optical communication system [2–7]. Several GHz bandwidth and 0.3 bit delay have been reported using a phonon transition phenomenon resulting from stimulated Brillouin scattering along a few km long silica optical fiber, but it is still impractical [4, 5]. On the other hand, a few tens bits of a few Gbps optical pulse signal have been variably delayed using a double absorption resonance in hot Cs vapor [6]. Even though this is the best reported performance in terms of bandwidth-delay product, this approach still exhibits several problems in practical employment due to a long cell length of a few centimeters resulting in integration incompatibility with the existing optical communication devices. Variable delay devices are also essential in the realization of phased array antennas [7].

Artificial resonator devices [8, 9] have potentials to solve the inherent problems such as the size, design flexibility, and integration possibility in the slow light modules using the resonating properties of the material itself. In the resonator slow-wave structure, a delay is realized by confining an optical wave in the resonator as far as a quality factor allows. The resonator slow-wave structure can be implemented using Fabry-Perot resonators [10, 11], coupled ring resonators [12–20], or coupled defect mode resonators in photonic crystals [21]. CROW's (Coupled Resonator Optical Waveguides), in which a few tens ring resonators are coupled together, have been implemented in the form of glass waveguides or polymer waveguide [12–20]. In addition, fixed delay modules in the form of CROW and all pass filters composed of a few hundreds micro-ring resonators have been realized in SOI (Silicon on Insulator) photonic wire waveguide. In this photonic waveguide delay device of size 0.09 mm^2, optical delay more than 10 bits at the bit rate of 20 Gbps has been observed [22].

Even though the SOI photonic wire delay modules can be implemented in a very small area, but they do not provide variable delay. Recently, a CROW with eight rings has been fabricated in SiON waveguide structure and variable delay as long as a few hundreds picoseconds has been demonstrated [19].

In this paper, an APF (All-Pass Filter) module which enables variable time delay of optical signal is designed and fabricated. The polymer waveguide APF delay module, in which eight single-ring APF's are cascaded, is fabricated using high-index-contrast polymer materials. The radius of curvature of the curved waveguide in the rings is as small as 250 µm, and the footprint of the delay module is about 20 mm^2. Electrodes are placed on top of the ring resonators to induce the refractive index decrease as the heating current increases.

2. DESIGN

A schematic configuration of the APF delay module is illustrated in Figure 1. Eight micro-ring resonators are serially cascaded without coupling between them. The time delay of the APF increases as the number of rings in resonance [8, 9].

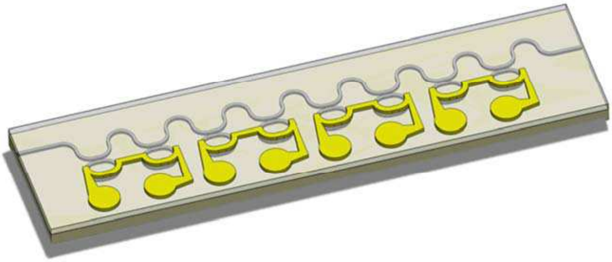

Figure 1. A schematic configuration of APF optical delay module eight single-ring resonators are cascaded serially.

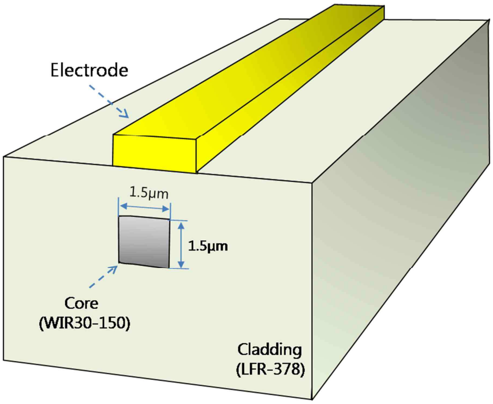

Figure 2. Unit optical waveguide structure for the design and fabrication of the APF delay module. The refractive indices of the core and cladding are 1.51 and 1.378, respectively.

Figure 2 shows a unit waveguide structure for the design of the polymer APF, which is a buried structure whose core width and height are 1.5 μm, respectively. The refractive indices of the core and cladding are 1.51 and 1.378, respectively, which corresponds to the relative index difference of 8%. Due to the high index contrast between core and cladding, optical waveguide has strong confinement, hence the polymer ring device can be made very compact by minimizing bending loss for the small ring radius [12, 13].

In order to use a thermo-optic effect of polymer materials, 4 pairs of electrodes are evaporated above the ring resonator to provide heating currents. When current is injected into the electrodes, the refractive index decreases due to temperature increase, and then resonance wavelength of ring resonator becomes shorter. By adjusting the number of resonant rings through the control of currents in the electrodes, we can control the time delay variably.

Through characteristics are calculated using a transfer matrix method [13–15], and is shown in Figure 3. In the calculation, the number of cascaded ring resonators is eight as shown in Figure 1. The radius of the ring resonator is 250 μm. The effective refractive index of the polymer waveguide shown in Figure 2 is calculated using a mode solver, and is found to be 1.4407 at the wavelength of 1550 nm. The group index of the waveguide is also calculated using several effective index values at a few wavelengths near 1550 nm, which is found to be 1.447. The coupling ratio κ between ring and bus waveguide is assumed to be 0.6. The propagation loss of the polymer waveguide is assumed to be about 1.5 dB/cm. The FSR (Free Spectral Range) is calculated to be 0.84 nm, and the bandwidth about 0.08 nm.

Figure 4 shows the calculated phase shift characteristics. The time

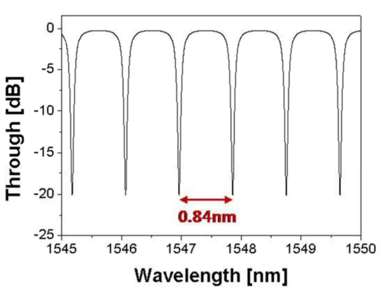

Figure 3. Through transmission of the APF delay module.

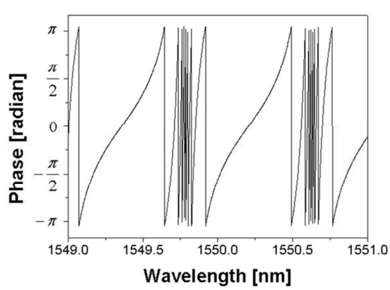

Figure 4. Through phase of the APF delay module.

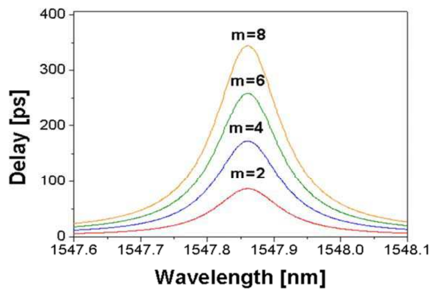

Figure 5. Time delay characteristics of the APF delay module when the number of resonant rings is two, four, six, and eight..

delay characteristics of the APF delay module is calculated using

$$t_d = \left(\frac{1}{2\pi c}\lambda_1^2\right) \cdot \frac{d\phi}{d\lambda}. \tag{1}$$

The time delay at the resonance wavelength of 1547.86 nm is about 85 ps, 172 ps, 257 ps, and 345 ps when two, four, six, and eight rings are in resonance, respectively, as shown in Figure 5. In the calculations, eight ring resonators are assumed to be cascaded as shown in Figure 1, and the effective refractive indices of the resonating rings are tuned so that they resonate at the wavelength of 1547.86 nm.

3. FABRICATION

Figure 6 summarizes the fabrication process of the APF delay module. First, polymer LFR-378 is spin-coated on the silicon substrate as a lower cladding, and then is baked at 200°C for 30 minutes. To form a pattern in this area again, the surface of the wafer is coated with a "photoresist" and then exposed to ultraviolet rays. After that, the prepared mask pattern is projected onto the surface using development process. Next, the cladding region corresponding to the waveguide pattern is dry-etched down 1.5 μm deep for the formation of waveguide core, and then spin-coat the core material WIR30-510 on top of the patterned cladding layer. The whole core polymer layer is etched out so that only 1.5 μm-high core cross-section is formed. Baking and exposing steps are then repeated one more. Then, cladding polymer is spin-coated which is used as the upper cladding, and the baking and full exposure steps are accomplished again. Next, electrodes (10 nm-thick Cr and 100 nm-thick Au) are evaporated and patterned above

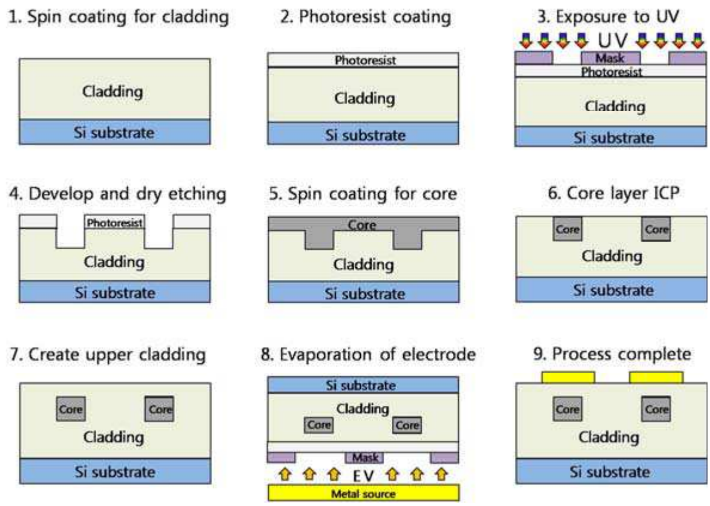

Figure 6. Fabrication process for the APF delay module.

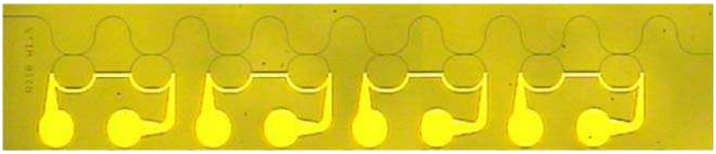

Figure 7. Micro-photograph of the fabricated APF delay module.

the APF delay resonators to introduce thermo-optic effect. Figure 7 shows microscope pictures of the fabricated APF.

4. MEASUREMENT RESULTS

The set-up for measuring the time delay of the APF delay module is shown in Figure 8. The optical wave entering into a $LiNbO_3$ modulator from the tunable laser is modulated by the electrical pulse signal from the PPG (Pulse Pattern Generator) which is applied to the $LiNbO_3$ modulator. The modulated optical signal is controlled by the polarization controller, so that either TE mode or TM mode is excited into the APF delay module. The delayed optical signal through the APF is amplified by EDFA (Er-Doped Fiber Amplifier), and displayed on the DCA (Data Communication Analyzer).

To prevent characteristics from fluctuating due to external

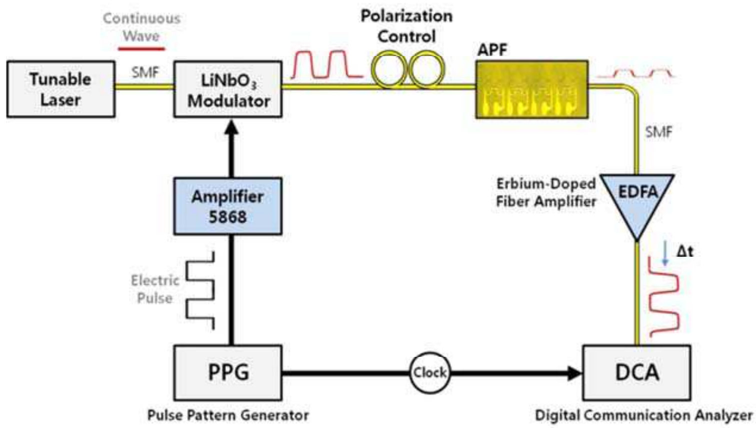

Figure 8. Arrangements for the measurement of the APF delay module.

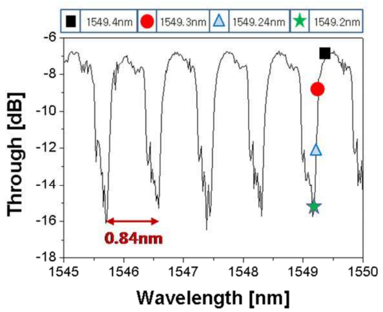

Figure 9. Through transmission characteristics of the fabricated APF delay module.

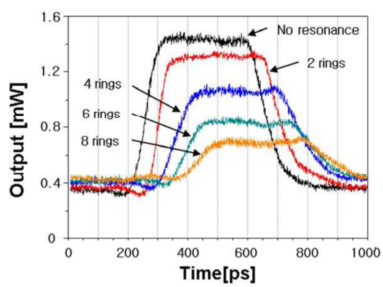

Figure 10. Time delay characteristics of the fabricated APF delay module.

temperature, we maintain surface temperature of device using TEC (Thermo-Electric Cooling). Figure 9 shows measured transmission characteristics of the APF delay module. Measured FSR is observed to be 0.84 nm and almost the same as that obtained from the simulation results shown in Figure 3.

For the measurement of delay characteristics we set the wavelength of the input optical wave to 1545.54 nm corresponding to a non-resonance wavelength. When the current through the electrodes of the first two rings is about 25 mA, the two rings become resonant at 1545.54 nm. No current is applied to the other six rings. In this case, the time delay is measured to be about 50 ps. When four, six, eight rings are tuned to be resonant, the time delay is measured to be about 105 ps, 150 ps, and 200 ps, respectively, as shown in Figure 10. These delay values are about 40% smaller than the maximum theoretical delays (Figure 5) at the center resonant wavelengths. In order to identify the discrepancy, the theoretical calculation is performed assuming the coupling ratio to be 0.77 and the through and the delay characteristics with all eight rings resonant as a function of wavelength are shown in Figure 11 and Figure 12. From the figures, it is seen that the simulation results with the coupling ratio 0.77 are quite close to the measurement results shown in Figures 9 and 10. In other words, the coupling ratio designed for 0.6 became about 0.77 due to certain

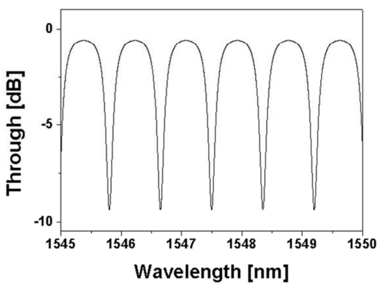

Figure 11. Calculated through transmission characteristics. The bus-ring coupling ratio is assumed to be 0.77.

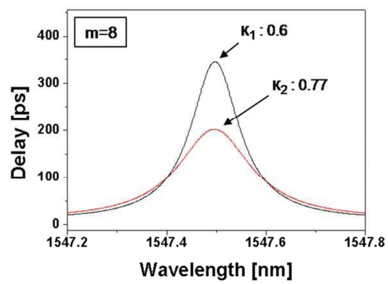

Figure 12. Calculated delay characteristics for two values of coupling ratio.

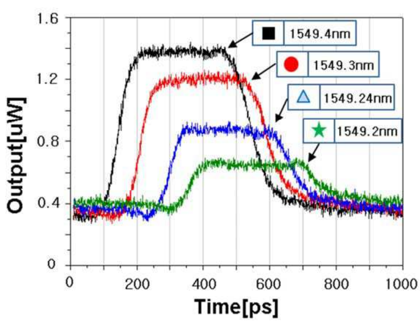

Figure 13. Measured delay characteristics for four operating wavelengths. No tuning currents are applied during the measurements.

fabrication errors.

The optical pulse transmission characteristics are also measured for different wavelengths of 1549.2 nm, 1549.24 nm, 1549.3 nm, and 1549.4 nm with no tuning currents and the results are shown in Figure 13. When the wavelength is set to fully resonant wavelength of 1549.2 nm, the delay compared with the case of the fully non-resonant wavelength of 1549.4 nm is measured to be about 200 ps. As the wavelength shifts from the resonant wavelength to 1549.24 nm, 1549.3 nm, the delay decreases to 150 ps, 50 ps, respectively.

Eye patterns are also measured using the DCA in combination with the 3.2 Gbps PPG. Figures 14(a), (b), (c), (d) show eye patterns of the APF when no, two, four, and eight rings are resonant, respectively. In all these cases, the eyes are well open, which implies that the APF delay module can be used for 3.2 Gbps class optical communications systems.

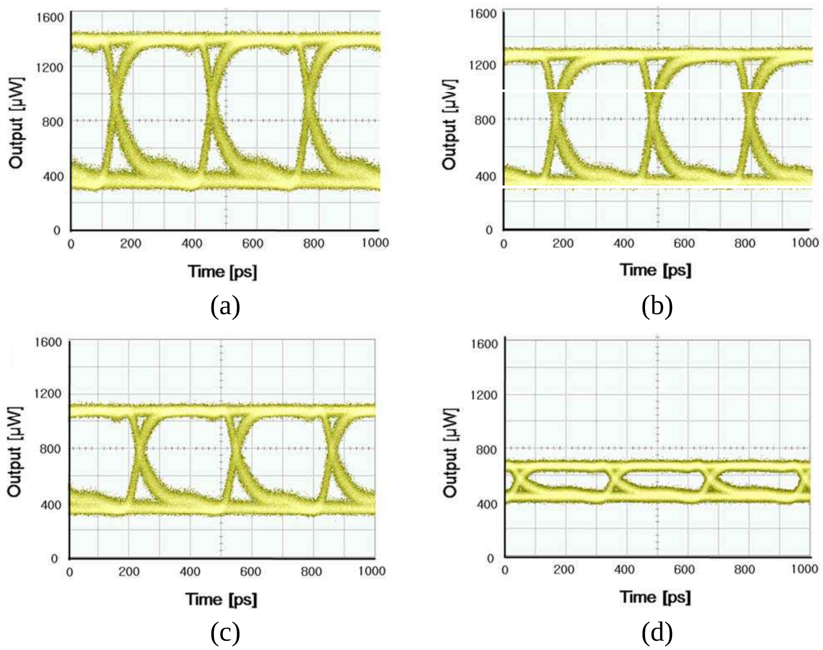

Figure 14. Eye pattern measured from the APF delay module for 3.2 Gbps NRZ digital signal in the case of (a) no resonant rings, (b) 2 rings in resonance, (c) 4 rings in resonance, and (d) all of 8 rings in resonance.

5. CONCLUSIONS

In this paper optical delay modules composed of eight single-ring all-pass-filters which are serially cascaded are designed and fabricated in high-index-contrast polymer materials. Compact ring waveguides with radii of 250 μm can be employed due to the high-index-contrast. The measurement results show that the time delay is measured to be about 50 ps when two rings are in resonance, and about 105 ps and 150 ps, respectively, when four and six rings of the APF are in resonance, respectively. When all of 8 rings are in resonance, the delay is measured to be about 200 ps. The delay values are somewhat smaller than the design values, which is believed to result from the coupling ratio between bus and ring somewhat larger than the design target. The delay characteristics are also measured for several different wavelengths near the resonant wavelength. As the wavelength shift from the fully resonant wavelength to the wavelength 0.1 nm shorter, the optical delay reduces from 200 ps to 50 ps continuously. The eye diagrams for 3.2 Gbps NRZ signals are also characterized in case of zero, two, four, six, and eight rings in resonance. In all of these four cases, clear open eye can be observed.

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