

Micro-photonic polymer devices

Payam Rabiei,¹ William H. Steier,¹ Cheng Zhang,² Larry Dalton²

¹Department of Electrical Engineering, ²Department of Chemistry,
University of Southern California, Los Angeles, CA, 90089
E-mail: rabiei@usc.edu

In this article, the authors review their work with micro-ring resonators using polymers, whose rings are integrated with vertically coupled input and output waveguides. Filters with a finesse of 141 and bandwidth of 8GHz are discussed, along with micro-ring modulators using polymer electro-optic materials with a FWHM bandwidth of 16GHz and a modulation FWHM voltage of 12V

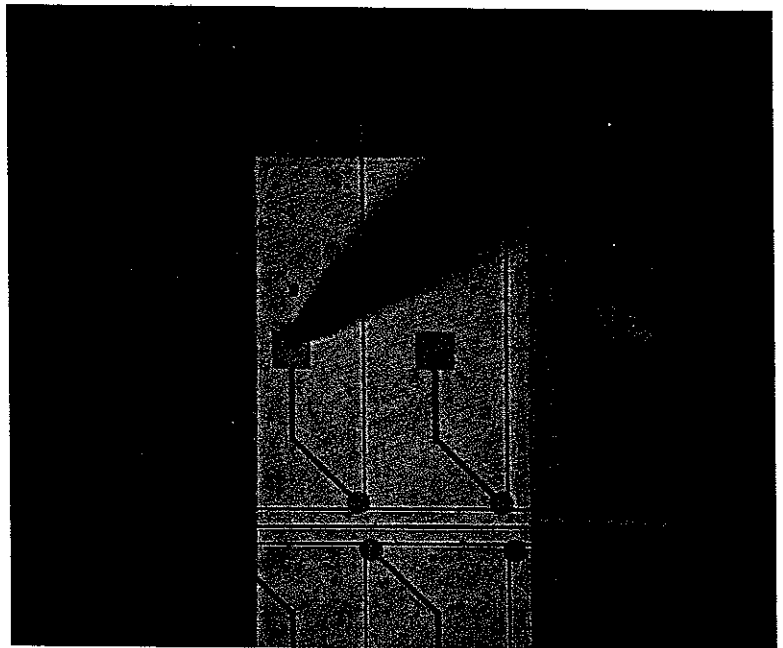
Micro-ring modulator using electro-optic polymers. The picture shows several devices under the microscope. The waveguides and the electrode can be seen with three fibres coupled to different ports of the device. Also there is an electrical contact to one of the devices

Micro-resonators can be considered as the main building blocks of future opto-electronic circuits. Micro-resonators with a free spectral range (FSR) more than 1THz and a bandwidth of a few GHz have recently been demonstrated using planar integrated optics technology.^{1,2}

Polymer integrated optics has been under research in the past two decades and recently polymer electro-optic materials with large electro-optic coefficients have been demonstrated.^{3,4} Highly functional devices can be obtained by using the electro-optic material in a micro-resonator. In this paper we review our recent work on the fabrication of polymer micro-resonators incorporating electro-optic polymers. Firstly we describe the fabrication and experimental results for passive devices. Secondly the electro-optic polymer devices are covered. Finally some potential applications using these devices are discussed.

PASSIVE MICRO-RESONATORS

Figure 1 shows the structure of a polymer micro-resonator that is vertically coupled to two waveguides. Based on the range of refractive indices available in polymers (1.3 to 1.8), micro-resonators as small as 10µm in diameter



USING POLYMERS, IT IS POSSIBLE TO DEFINE STRUCTURES OPTICALLY. THE QUALITY OF THE WAVEGUIDE IS LIMITED BY THE OPTICAL MASK QUALITY USED TO DEFINE THE MICRO-RESONATOR

with a FSR of 6THz can be fabricated. Smaller devices are not possible due to large bending loss. Most micro-resonators are fabricated using ion etching and the Q is limited by the scattering loss of the rough surface between

the core and cladding. It can be shown that with an index difference of 0.3 between the core and cladding of the waveguide and assuming 20nm roughness in the walls of the waveguide, the scattering loss is as large as 10dB/cm.

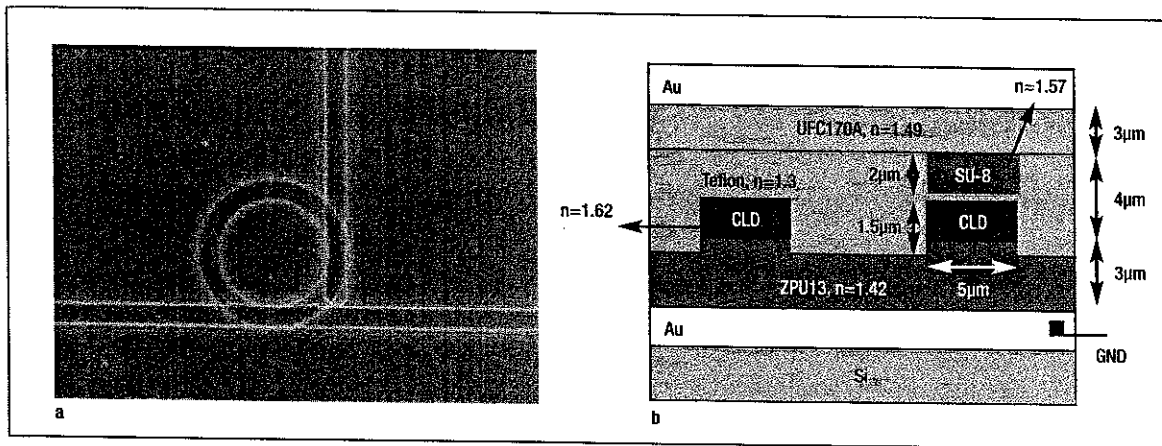


Figure 1a. Photograph of the micro-resonator device (without electrodes). Input and output waveguides can be observed in the figure. Figure 1b. The cross-section of an active device

Using polymers, it is possible to define structures optically – no ion etching is required. The quality of the waveguide is then basically limited by the quality of the optical mask used to define the micro-resonator. The fabrication of the micro-resonator starts with spin-coating the lower cladding on a silicon substrate. The second layer is spin-coated and patterned to form the micro-ring structure. The middle cladding layer planarises the sample. In the next step, a trench is etched into the middle cladding layer, patterning the waveguides. The dimensions and material of the coupling waveguides are chosen to match their effective index to the effective index of the micro-ring structure. The waveguide material is spin-coated on the substrate and fills the trenches to form an inverted ridge waveguide structure. The slab part of the waveguide is removed by reactive ion etching. Finally an upper cladding is spin-coated on the device.

We have used SU-8 as the material for the micro-ring structure for the fabrication of passive devices. SU-8³ is a photo-resist, which can be patterned optically. For the cladding, Teflon AF⁵ is used. This material has a very low refractive index and a large index difference is achieved and thus a relative large FSR is obtained. Devices with a finesse of 141 and 6GHz bandwidth at 1,300nm and a finesse of 117 and 8GHz bandwidth at 1,550nm have been demonstrated. Using smaller index difference (and hence smaller

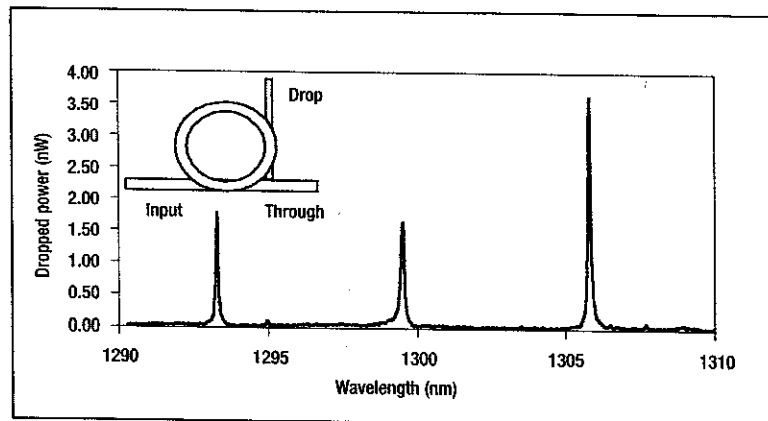


Figure 2. The drop port power of the active 50µm diameter device as a function of the input laser wavelength

wall roughness scattering loss), devices with a bandwidth as small as 1.7GHz and a finesse of 80 at 1300nm have been demonstrated.

ACTIVE MICRO-RESONATORS

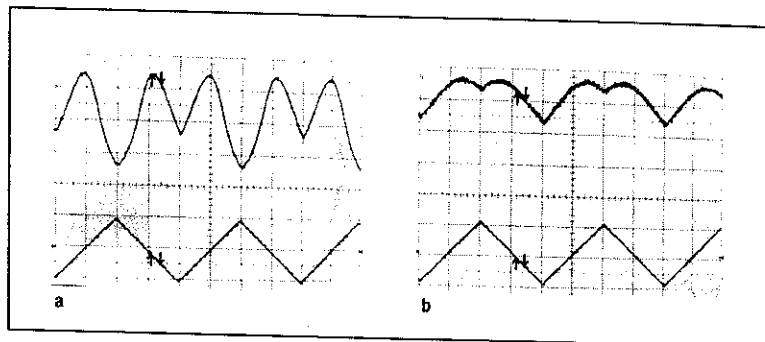
If an electro-optic polymer is used in the ring resonator and the quality factor of the resonator is high, a low-voltage electro-optic modulator is obtained. A small change in the refractive index of the micro-ring can cause a large change in the output of the device by changing the resonance frequency. If the change in the refractive index is caused by the electro-optic effect (and hence, is very fast) a modulator is obtained. Based on the available electro-optic polymers, the resonance frequency can be shifted as much as 3GHz/V. Assuming the bandwidth of the modulator is defined as the optical bandwidth of the resonator, a 6GHz bandwidth modulator will require 2V.

The fabrication of the active device is similar to the passive device except for the upper and lower electrodes that are used to apply signal to the device. Also electric field poling is required to align the molecules so that a large electro-optic co-efficient is obtained. The fabrication starts with a gold-coated substrate. A lower cladding is spin-coated on the device. The electro-optic polymer (CDL1/APC³) is spin-coated next and is then poled using corona poling. The poled layer is patterned using optical lithography and the ring waveguide is etched using RIE. A middle cladding layer is then spin-coated, the trenches are formed, and the waveguide layer is spin-coated. Finally the upper cladding layer is made and the upper electrodes are formed.

Figure 1 shows the cross-section and an optical microscope picture of a fabricated electro-optic device. Figure 2 shows the transmitted power to the drop port as a function of input

IF AN ELECTRO-OPTIC POLYMER IS USED IN THE RING RESONATOR AND THE QUALITY FACTOR OF THE RESONATOR IS HIGH, A LOW-VOLTAGE ELECTRO-OPTIC MODULATOR IS OBTAINED

Figure 3. The modulation of the drop port power as a function of the applied voltage to the electrodes of the device, (a) 150 μm , (b) 50 μm devices. The upper trace is the drop port power and the lower is the 20Vp-p 1kHz saw-tooth drive voltage



wavelength with no voltage applied for a 50 μm diameter ring. The variation of the power output between the modes is due to the changing power output of the tunable source. The FSR of the device is more than 1THz, the bandwidth is 16GHz, and the finesse is 67. It is clear that single-mode operation is obtained. The larger bandwidth of the active device is due to the higher scattering loss created by the RIE. To show the modulation properties of the device, the input laser wavelength is adjusted close to one of the resonance peaks and a 20Vp-p saw-tooth voltage at 1 kHz is applied to the electrodes. Figure 3 shows the modulated light intensity at the drop port of the device for two devices with different diameters (50 μm and 150 μm). The larger device shows a larger change in output for a given voltage change because of its larger Q and better confinement of the light in the device core. The resonance frequency shift varies from 0.5GHz/V to 1.2GHz/V from smaller devices to larger devices. The bandwidth of the device varies between 12GHz to 16GHz. Hence the FWHM voltage changes from 10V to 32V. For a larger device with a FSR of 100GHz and FWHM bandwidth of 3.5GHz, a FWHM modulation voltage of 4V has been demonstrated.⁶ The r_{33} achieved

in these early demonstrations is not optimal and higher r_{33} and hence lower voltages are expected with an optimised process.

APPLICATION OF ACTIVE MICRO-RESONATORS

Several different applications can be considered for electro-optic micro-resonators. One interesting application is a multi-wavelength modulator in which several different wavelengths are modulated in a compact chip. The resonant wavelength of each modulator is adjusted to one of the input wavelengths and therefore each modulator will modulate only one wavelength.⁷ If critical coupling is achieved, the through port is modulated with a large extinction ratio. Based on the available polymers, one could achieve a 10Gb/s NRZ modulation rate with 3dB insertion loss with 1.5V drive. By using 40 wavelengths, an aggregate total rate of 400Gb/s modulation could be possible. Since the modulators can also be used as passive filters, if detectors are integrated in additional drop ports of the modulators, a transmit/receive module is possible.

Other interesting applications include tunable lasers using the electro-optic effect as proposed by Liu.⁸ By using two ring structures

and the Vernier effect, it might be possible to make a fast, voltage-tunable light source for optical frequency shift keying and eventually optical CDMA systems. ●

REFERENCES

1. B.E. Little, S.T. Chu, H.A. Haus, J. Foresi, and J.-P. Laine, 'Microring resonator channel dropping filters', *J. Lightwave Technol.*, vol. 15, pp. 998-1005, June 1997.
2. D. Rafizadeh, J.P. Zhang, S.C. Hagness, A. Taflov, K.A. Stair, S.T. Ho, and R.C. Tiberio, 'Waveguide-coupled AlGaAs/GaAs microcavity ring and disk resonators with high finesse and 21.6-nm free spectral range', *Opt. Lett.*, vol. 22, pp. 1244-1226, Aug 1997.
3. Yongqiang Shi, Cheng Zhang, Hua Zhang, Bechtel, J.H., Dalton, L.R., Robinson, B.H., Steier, W.H., 'Low (sub-1-volt) halfwave voltage polymeric electro-optic modulators achieved by controlling chromophore shape', *Science*, vol. 288, pp.119-122, 2000.
4. Min-Cheol Oh, Hua Zhang, Cheng Zhang, H. Erlig, Yian Chang, B. Tsap, D. Chang, A. Szep, W.H. Steier, H.R. Fetterman, L.R. Dalton, 'Recent advances in electrooptic polymer modulators incorporating highly nonlinear chromophore', *IEEE Journal on Selected Topics in Quantum Electronics*, vol. 7 issue 5, pp. 826-835, Sept/Oct 2001.
5. Teflon AF 1600 is supplied by Dupont, SU-8 is supplied by MicroChem Co., ZPU13 is supplied by Zen photonics, Korea.
6. P. Rabiei, W.H. Steier, C. Zhang, L. Dalton, 'Integrated WDM polymer modulator', *Optical Fiber Communications Conference, Technical Digest*, pp. 31-33, 2002.
7. P. Rabiei, W.H. Steier, et al., 'Polymer micro-ring modulator with 1THz FSR', CLEO post deadline session, 2002, Paper CPDB8.
8. Bin Liu, A. Shakouri, J.E. Bowers, 'Wide tunable double ring resonator coupled lasers', *IEEE Photonics Technology Letters* 14, no. 5, pp. 600-2, May 2002.