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Direct electron beam writing of electro-optic polymer microring resonators

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Abstract: Electro-optic polymer waveguides in electron beam sensitive polymethyl methacrylate (PMMA) polymer matrix doped with organic nonlinear chromophores could be directly patterned by electron beam exposure with high resolution and smoothness. The polymer in the exposed regions was removed with standard electron beam resist developer and without damaging the chromophore containing polymer waveguides. Feature sizes on the order of 100 nm could be clearly resolved. High quality microring resonators made of YL124/PMMA electro-optic polymer were successfully fabricated with this technique. The measured resonance extinction ratios were more than 16 dB and quality factors were in the range of $10^3$–$10^4$.

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OCIS codes: (130.5460) Polymer waveguides; (160.2100) Electro-optic materials; (230.5750) Resonators; (220.4241) Nanostructure fabrication;

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microring resonators with coupling gap greater than 1 defined by layer thickness [9], not by lithographic and etching process, or laterally coupled used to fabricate vertically coupled microring resonators in which the coupling gap sizes are waveguide layer. Then the pattern is transferred to the waveguide materials with reactive ion pattern as an etch mask. The device pattern is first created in the e-beam resist that covers the resolution is normally achieved through electron beam lithography using the e-beam resist critical to achieve high [12], fabrication of the submicron coupling gap with a precision <100 nm is often found to be main loss mechanism and compromises the between the polymer waveguide core and cladding leads to lower scattering loss, which is the devices. With the same degree of waveguide surface roughness, low refractive index contrast and large cross section (for single mode guiding) of the polymer waveguide provide small device size also requires much less amount of analytes for biochemical sensing [5].

Polymeric materials offer a number of advantages for making micro-ring resonator devices. With the same degree of waveguide surface roughness, low refractive index contrast between the polymer waveguide core and cladding leads to lower scattering loss, which is the main loss mechanism and compromises the Q-factor of microring resonators. Low refractive index and large cross section (for single mode guiding) of the polymer waveguide provide better coupling efficiency to optical fibers and can significantly reduce the device insertion loss. Polymers have the advantage of low cost both of materials and of processing. Different dopants, such as laser dyes [6], rare earth ions [7], quantum dots [8], etc. can be easily incorporated into the polymer matrix to enable microring resonators to perform various functions. Especially, optical polymers doped with second-order nonlinear optic chromophores provide versatile functions of electro-optic (EO) modulation and switching, optical rectification, wavelength conversion and all-optical switching [9-11].

Based on a systematic analysis and simulation of typical polymer microring resonators [12], fabrication of the submicron coupling gap with a precision <100 nm is often found to be critical to achieve high Q-factor, sharp resonance, and large free spectral range. This high resolution is normally achieved through electron beam lithography using the e-beam resist pattern as an etch mask. The device pattern is first created in the e-beam resist that covers the waveguide layer. Then the pattern is transferred to the waveguide materials with reactive ion etching (RIE) or nanoimprinting [13]. Traditional photolithography plus RIE have also been used to fabricate vertically coupled microring resonators in which the coupling gap sizes are defined by layer thickness [9], not by lithographic and etching process, or laterally coupled microring resonators with coupling gap greater than 1 μm [14]. A large coupling gap is not desirable because it normally means longer coupling length and larger ring radius, and therefore small free spectral range. These techniques have multiple fabrication steps, and

1. Introduction

Multi-functionality and compactness of micro-ring resonators make them promising building blocks for high density photonic integration. A wide range of optical signal processing functions, including channel filters, WDM de-multiplexers, switches, dispersion compensators, lasers, polarization rotators, modulators, can be realized with microring resonators [1]. Ultra compact micro-ring resonators of micrometer scale [2,3] have been reported and over 10^5 devices/cm^2 integration densities are possible now. Resonance nature of microring resonators also makes them ideal candidates as optical sensors [4]. High quality factor (Q-factor) and long photon lifetime provide stronger interaction between the light and the waveguide material and thus significantly enhanced response with a small device size. The small device size also requires much less amount of analytes for biochemical sensing [5].

Based on a systematic analysis and simulation of typical polymer microring resonators [12], fabrication of the submicron coupling gap with a precision <100 nm is often found to be critical to achieve high Q-factor, sharp resonance, and large free spectral range. This high resolution is normally achieved through electron beam lithography using the e-beam resist pattern as an etch mask. The device pattern is first created in the e-beam resist that covers the waveguide layer. Then the pattern is transferred to the waveguide materials with reactive ion etching (RIE) or nanoimprinting [13]. Traditional photolithography plus RIE have also been used to fabricate vertically coupled microring resonators in which the coupling gap sizes are defined by layer thickness [9], not by lithographic and etching process, or laterally coupled microring resonators with coupling gap greater than 1 μm [14]. A large coupling gap is not desirable because it normally means longer coupling length and larger ring radius, and therefore small free spectral range. These techniques have multiple fabrication steps, and
many wet chemicals (like resists and resist developers) involved in the processes can damage the chromophore-containing polymers and greatly increase the propagation loss. In the worst case, the chromophore doped polymer waveguides may be totally dissolved and removed by wet chemicals.

In this paper, we report a new technique to make EO polymer microring resonators using direct electron beam writing. After being doped with organic nonlinear chromophores, electron beam sensitive PMMA preserves its imaging capability and can be used as a high resolution electron beam resist. The electron beam resist developer doesn’t damage the unexposed regions and waveguides with smooth surfaces can be formed in the chromophore-containing polymer. Similar technique has been used to fabricate $\chi^{(2)}$ grating and Y-branch with PMMA based nonlinear optical polymers [15]. Without using expensive high resolution photomasks, different designs of microring resonator devices with nanometer scale feature sizes can be generated easily with computer assisted design and control systems. This is especially cost effective for device prototyping and design optimization. This technique simplifies the device fabrication and reduces the sources of error from multiple fabrication steps.

2. Experiments and results

Fabrication of the devices started with preparation of the EO polymers. YL 124 chromophore (Fig. 1) was mixed with PMMA polymers and dissolved in chlorobenzene. The loading density of YL 124 in PMMA was 20 wt% and the total solid content of the solution is about 7.75%. YL124 has strong second-order nonlinear optic effect and has been used for optical rectification and EO modulation [10]. When doped with binary chromophore organic glasses (BCOGs) materials, like DR1-PMMA, an EO coefficient $r_{33}$ of more than 200 pm/V at 100 V/μm electric poling field has been reported. The EO coefficient was measured at a wavelength of 1.55 μm with an ellipsometry method [16]. The PMMA polymer has a molecular weight of 950,000 and PMMA of this molecular weight is routinely used as high resolution electron beam resist. The mixture was thoroughly dissolved using a rotary mixer and filtered with a 0.2 μm filter before using. About 3.6 μm of UV curable polymer UV16 (Master Bond Inc.) was coated onto a Si substrate and cured to serve as a lower cladding. The filtered EO polymer solution was then spin coated at 3000 rpm/min and baked in a vacuum oven at 65 °C for two days so that the solvent was completely removed from the polymer thin film. An EO polymer film of about 2 μm in thickness was formed. Refractive indices of the EO film and UV16 cladding were measured with a Metricon 2010 prism coupler and found to be 1.558 and 1.506, respectively.

![Fig. 1. Chemical structure of YL124 chromophore.](image)

An FEI Sirion scanning electron microscopy (SEM) system with an accelerating voltage of 30 kV was used to expose the EO polymer film. A 5 nA beam current were used to have a shorter writing time. Nanometer Pattern Generation System (NPGS) was used to generate the waveguide designs and to control the writing processes. The EO polymer waveguides have a width of 5 μm. Two strip areas outside the waveguide regions, one strip on each side of the
waveguide, were exposed to electron beam irradiation and the EO polymer in these areas is subsequently removed by electron beam resist developer (methyl isobutyl ketone (MIBK): isopropyl alcohol (IPA) = 1: 3). The developing time is several minutes and the developer didn’t attack the unexposed EO polymer during developing. The two strips provided waveguide confinement in the lateral direction. The total width of the waveguide pattern, including waveguides and the two exposed strips, was 20 μm. EO polymer microring resonators of the basic structure with a single ring resonator coupled to a bus waveguide was fabricated with this waveguide profile. The resonator is race-track shaped with straight sections to couple with the bus waveguide. The radius of the circular sections was 500 μm. Microring resonator designs of different coupling gap sizes and coupling lengths were fabricated. With an electron beam dose of 700 μC/cm², a coupling gap as small as 100 nm could be resolved (Fig. 2).

![Fig. 2. EO polymer microring resonators directly patterned with the electron beam. (a) Microscope image of the device after developing. b) Detailed view of the coupling region with 100 nm coupling gap.](image)

To measure transmission wavelength spectra, individual devices were cleaved from the wafer and the two ports of the bus waveguides were end-coupled to the input and output optical fibers. Output from a tunable laser source (Santec TSL-210) was connected to a Agilent 8169S polarization controller to launch TE or TM mode in a polarization maintaining (PM) fiber. Traverse magnetic(TM) or traverse electric (TE) polarized light was then end-coupled to the input port of the microring resonators through the PM fiber. An optical power meter (Agilent 81623B) was used to measure the optical power coupled from the output port into a standard single mode fiber. Scanning the wavelength of the input light and acquiring the output optical power were controlled by a LabView program.

No higher resonance modes were observed in all the resonance spectra. This confirmed the single mode operation of the ring waveguide. The highest resonance extinction of a microring resonator can be achieved as the critical coupling condition ($\alpha = |t|$, where $\alpha$ is the internal circulation attenuation factor after one round-trip in the ring resonator and $t$ is the phasor field transmission past the coupler region) is met [17]. The coupling was adjusted by changing the size of the coupling gap, coupling length, and the refractive index of the top cladding. For a fixed coupling length of 100 μm, the coupling gaps were varied from 0 to 500 nm in 100 nm steps. The critical coupling condition was achieved at 100 nm coupling gap for both TM and
TE polarizations (Table 1 and Fig. 3). Higher extinction ratio is possible by adjusting the coupling gap in finer steps.

| Coupling gap (nm) | Extinction ratio of TM polarization (dB) | Extinction ratio of TE polarization (dB) |
|-------------------|-----------------------------------------|-----------------------------------------|
| 0                 | 5.7                                     | 6.2                                     |
| 100               | 12.6                                    | 10                                      |
| 200               | 4.1                                     | 5.1                                     |
| 300               | 3.3                                     | 4.6                                     |
| 400               | 1.2                                     | 1.9                                     |
| 500               | 0.6                                     | 1.0                                     |

Fig. 3. The resonance extinction ratios of the EO polymer microring resonators of various coupling gap sizes. The coupling length is fixed at 100 μm. The input light was TM polarized. The traces are vertically offset for clarity.

The coupling can also be adjusted by varying the coupling length while keeping the size of the coupling gap fixed. For the gap of 0 nm, the critical coupling condition was achieved at 50 to 60 μm coupling length for TM polarization and 50 μm for TE polarization (Table 2 and Fig. 4). Comparing these two methods of tuning the coupling, it is found that the method of changing the coupling length is more desirable than the method of changing the coupling gap because the fabrication resolution requirement of the former is two orders lower than that of latter one. However, for ultra high quality microring resonators only the method of changing the coupling gaps could be used, because to achieve ultra high quality factor a circular ring is needed to remove the excess loss of the transition between the straight section and the curved section of a racetrack-shaped ring.
Table 2. Extinction Ratio for Different Coupling Lengths

| Coupling Length (μm) | Extinction ratio of TM polarization (dB) | Extinction ratio of TE polarization (dB) |
|----------------------|-----------------------------------------|-----------------------------------------|
| 40                   | 8.1                                     | 13.5                                    |
| 50                   | 16.2                                    | 15.0                                    |
| 60                   | 16.9                                    | 12.4                                    |
| 70                   | 11.4                                    | 10.4                                    |
| 80                   | 5.3                                     | 8.8                                     |
| 100                  | 5.7                                     | 6.2                                     |

The highest resonance extinction ratio was achieved in a microring resonator with a 100 μm straight coupling length and a zero coupling gap. The resonance spectrum of the TM polarization was fitted to the theoretical transfer function (Fig. 5)

\[ T = \frac{\alpha^2 + |r|^2 - 2\alpha |r| \cos(\theta)}{1 + \alpha^2 |r|^2 - 2\alpha |r| \cos(\theta)}, \]  

where \( \theta = \beta L \) is the total phase shift per ring circumference \( L \) for a ring waveguide propagation constant \( \beta \) [17]. \( \alpha \) and \( |r| \) were determined by the curve fitting and were found to be 0.42 and 0.31, respectively. From these fitting results, \( Q \)-factor was calculated to be 8800, ring waveguide propagation loss 23 dB/cm, and finesse 2.4. The main loss mechanism is thought to be the scattering at the waveguide edges. The pattern generator of the Sirion SEM reduces the arc into polyline of a maximum of 200 vertices and therefore limits the smoothness of the edge. In an earlier comparison study, a similar microring resonator design was fabricated in SU-8 (MicroChem) e-beam resist using the FEI Sirion SEM and also using a Leica VB6 electron beam lithography system. The number of vertices of the arc section was 200 for Sirion and 1000 for Leica VB6. The microring resonators made on Leica had \( Q \) of over 15000 and those made on Sirion had \( Q \) of about 4000. Therefore, by splitting the polygons to finer sections or using a better electron beam writing system, the waveguide loss could be further reduced to achieve higher \( Q \)-factor.
The resonance extinction ratio could be further adjusted by changing the refractive index of the top cladding. By replacing the top cladding of air with a material of higher index of refraction the coupling will be stronger because the waveguide modes will become less confined and more overlapped. Deionized (DI) water was applied to the top of developed EO microring resonators, and the refractive index of the top cladding was changed from 1.0 (air cladding) to 1.33 (DI water cladding). For a microring resonator of 50 μm coupling length and zero coupling gap, the resonance shifted away from the critical coupling condition and the extinction ratio decreased (Fig. 6). Such change indicates that the resonator had been at critical coupling or over-coupled. In contrast for a microring resonator of 0.5 μm coupling gap and 100 μm coupling length, the resonance shifted towards the critical coupling condition and resonance extinction ratio increased (Fig. 7), indicating the resonator had been under-coupled. The coupling condition and resonant wavelengths of fabricated microring resonators can be trimmed by means of photobleaching for better performance [18,19].
3. Conclusion

Doping the electron beam sensitive PMMA polymer with chromophores produces an EO polymer that can be patterned like a typical e-beam resist with an electron-beam. The electron beam resist developer does not damage the unexposed regions and EO polymer waveguides with smooth edges can be obtained. It is a maskless, resistless, and high resolution direct writing process and can be a cost effective way for device prototyping and design optimization. EO polymer microring resonators with feature sizes on the order of 100 nm were successfully fabricated with a SEM-based e-beam lithography system. High extinction ratio of more than 16 dB and quality factor of $10^3$–$10^4$ were achieved. Alignment of the chromophore molecules along the poling electric field at close to the polymer’s glass transition temperature could be conducted either before or after the electron beam writing and developing. Once properly poled, active microring resonator devices with the functions of EO modulation, switching and tunable filtering could be realized. In addition to acrylate-based polymers, this technique is in principle applicable to other e-beam sensitive optical polymers like U-100 polyarylate [15] or polycarbonate [20] resins, with possibly a different optimal e-beam dose and developing condition for each polymer.

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