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Development of micro-ring resonator-based optical bandpass filter using SU-8 polymer and optical lithography

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ABSTRACT

Laterally-coupled SU-8 ridge waveguide-based micro-ring resonator was designed, fabricated and characterized for optical filtering applications. Fabrication was done by optical lithography using a patterned chrome mask of SU-8 ridge waveguide and micro-ring resonator structures, which was replicated onto a plasma enhanced chemical vapour deposited (PECVD) silicon-dioxide layer on a silicon wafer. Optical characterization showed that the fabricated micro-ring resonator had a free spectral range (FSR) of ~16 nm for a ring radius of 15 μm in TE polarization. A simple semiconductor laser diode and a monochromator were used for the characterization of the device. The measured through port and drop port light output for different wavelengths indicate that the device can be used as an optical filter around 1565 nm centre wavelength, with a 3 dB bandwidth of 5.3 nm and an extinction ratio of ~10.5 dB.

1. Introduction

Optical waveguide device like micro-ring resonator (MRR) is basically a ring waveguide acting as the resonant cavity with one or two bus waveguides acting as input and output ports. The coupling mechanism involved in this device is the evanescent coupling between ring and adjacent bus waveguide [1]. This may be vertically coupled or laterally coupled; both configurations have certain pros and cons. In case of laterally coupled resonator, both the ring and bus waveguides lay on the same horizontal plane, thus requires very accurate lithography and etching processes in order to obtain submicron gap between bus and ring - thereby limiting the flexibility in the device design. On the other hand, ring and bus waveguides in vertical configuration don't lie in the same plane. Ring is placed on top or bottom of the bus waveguides, as a result, the ring and bus may be of different material, and the thickness need not be same and can be controlled accurately during deposition – all these enhances the design freedom. However, this vertical configuration is expensive due to the additional processing step of the ring in contrast to lateral configuration which requires only a single layer. Moreover, fabrication of vertically coupled ring resonators is complex as wafer bonding and regrowth is required to manufacture these devices; also alignment is an issue as there are two processing steps [2,3].

In this work, SU-8 ridge waveguide-based air-cladded micro ring resonator (lateral configuration) is considered which was fabricated by photolithography using chrome mask. The choice of SU-8 polymer was due to its optically transparency both in visible and telecommunication region of 1300–1600 nm wavelength, thus can be used for waveguiding purpose; also it is a low cost material which is easily available [4,5]. In most of the previously reported research articles [6–8], SU-8 waveguide based MRR were fabricated by costly electron beam lithography, and characterized by very narrow bandwidth tunable laser source (TLS) and photodiode (PD) or optical spectrum analyzer (OSA). In Refs. [6,7], researchers fabricated a free-standing flexible MRR to realize a notch filter. They peeled-off the SU-8 structure from silicon surface to make a high-contrast micro-ring. In addition, some researchers [8] used commercially available UV-15 and OG-125 polymers as lower and upper cladding layers to obtain single-mode waveguide structures. P. Girault et al. [9] fabricated MRR by photolithography using chromium mask, where class 100 clean room and dry etching process were used. Their ring radius was ~120 μm, which resulted

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in a low free spectral range (FSR) of 2 nm. In their work, PMATRIFE polymer was used as lower cladding.

Here we made an attempt to develop SU-8 ridge waveguide-based MRR by 365 nm I-line optical lithography; and characterization was performed by using semiconductor laser source, monochromator, and InGaAs detector. We used 15 μm radius of SU-8 micro-ring to obtain ~16 nm FSR; the clean room facility used for our process was class 10,000. Design part of this device was performed by using Effective-Index based Matrix Method (EIMM) [10,11] and Couple Mode Theory (CMT) [12,13]. We had used a silicon dioxide (SiO_2) deposited silicon (Si) wafer as our substrate material. Characterization result of MRR indicates that the device can be useful as a bandpass filter with ~5.36 nm 3-dB bandwidth around 1565 nm transmitting wavelength of light in TE polarization.

2. Design and simulation

Fig. 1 shows the schematic of our designed micro-ring resonator, where '1' is the input port; '2', '3' and '4' are the respective through, drop and add ports; *w* is the width; *R* being the radius of ring; and *g* is the separation between bus waveguide and ring. Effective Index based Matrix Method (EIMM) was used as our computational tool. It is a semi-analytical method which was developed over the years by the authors' group to design different waveguide structures. In EIMM, effective index method was applied in the depth direction of the waveguide; whereas, lateral profile was considered by a transfer matrix method. The technique is useful to design single-mode waveguide, bent waveguide, and directional couplers. In this work, the micro ring device was designed using the following steps: i) waveguide design using effective index based matrix method (EIMM) [10,11]; ii) determination of coupling coefficient between straight and curve waveguide [11]; iii) determination of bending losses of bent SU-8 wire for different radii of curvature by conformal mapping [14] and EIMM [10,11].

Radius of curvature of the ring that we had considered was 15 μm, separation between ring and bus waveguide was 0.5 μm, and waveguide width was 3.5 μm. The tail of the evanescent field of the bus waveguide was ~1.25 μm, which is enough to couple light into the MRR. The computed power coupling coefficient between ring and bus waveguide at the chosen radius was 0.541,607 and propagation power loss coefficient per round trip in the ring was 0.0134,767. This power loss coefficient includes both bending loss and propagation loss. The calculated bending loss at 15 μm radius was 10^{-4} dB/μm while propagation loss value was taken from our own experimental result, which was 0.5 dB/mm [15]. Since air-cladded SU-8 ridge waveguides are high-contrast waveguides, bending loss is low even for 15 μm bending radius. Whereas, as propagation loss is dependent on sidewall roughness for these photonic wires, these are relatively higher. In all our computations we had taken SU-8 refractive index as 1.574 [16], and SiO_2 refractive index as 1.447 [17], around 1550 nm wavelength of light. The computed through port notch of the structure was −87.98 dB at a resonating wavelength of 1550 nm; and the computed free spectral range (*FSR*). Quality factor (*Q*) and extinction ratio (*ER*) of the designed resonator were 16.79 nm, 30,312 and 13.745 dB respectively for transverse electric (TE) mode using the following equations [18]:

$$T_{through} = \frac{(\lambda-\lambda_0)^2 + \left(\frac{FSR}{4\pi}\right)^2 \left(\kappa_p^2\right)^2}{(\lambda-\lambda_0)^2 + \left(\frac{FSR}{4\pi}\right)^2 \left(2\kappa^2+\kappa_p^2\right)^2}; \quad T_{drop} = \frac{4\left(\frac{FSR}{4\pi}\right)^2 (\kappa^4)}{(\lambda-\lambda_0)^2 + \left(\frac{FSR}{4\pi}\right)^2 \left(2\kappa^2+\kappa_p^2\right)^2} \tag{1}$$

$$FSR = \frac{\lambda_0^2}{n_g L}; \quad Q = \frac{\lambda_0}{FWHM}; \quad ER = -10\log_{10}\left[1 - \left\{\left(\frac{\sqrt{1-\kappa^2}-\kappa_p^2}{\sqrt{1-\kappa^2}+\kappa_p^2}\right)\left(\frac{1+\kappa_p^2\sqrt{1-\kappa^2}}{1-\kappa_p^2\sqrt{1-\kappa^2}}\right)\right\}\right]^2 \tag{2}$$

During computation, n_g value was taken as 1.518,672 for TE mode, which was equal to the effective refractive index of the straight SU-8 waveguide, and was approximately same to the group index of the bent waveguide of MRR for 15 μm radius. Similarly, simulations were also done for transverse magnetic (TM) mode

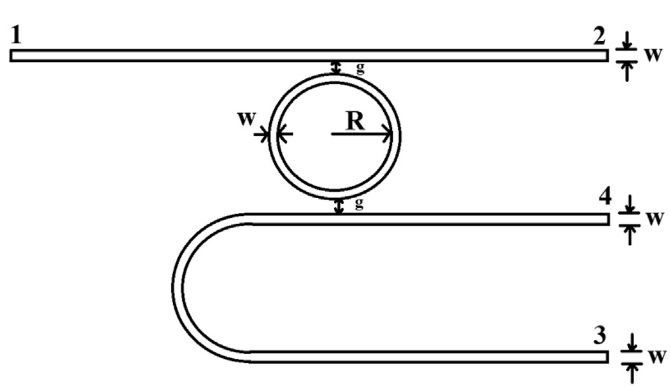

Fig. 1. Schematic of micro-ring resonator.

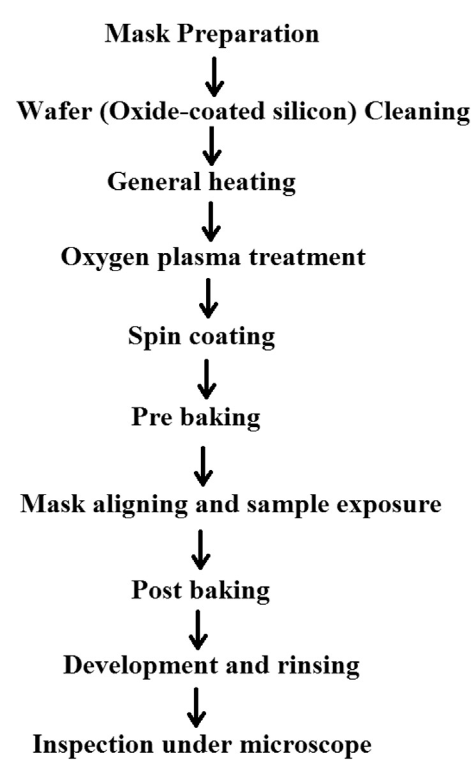

Fig. 2. Fabrication process flow using chrome mask.