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Design and Modeling of the ENR Polymer Microring Resonators Add/Drop Filter for Wavelength Division Multiplexing

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Abstract:
We report about design, modeling, fabrication and properties of the polymer optical microring resonator. First step was to design single mode optical polymer ridge waveguides by using BeamPROP^{TM} software and then optical polymer microring resonator was designed by using FullWAVE^{TM} software. The design of the single mode waveguides was done for the operating wavelengths 650 nm and 1550 nm. The design of the microring resonators was done for operating wavelength 1550 nm and for elimination wavelength 1490 nm. The resonator was designed on the bases of optical polymer waveguides Epoxy Novolak Resin deposited onto silica-on-silicon substrate. We used Polymethylmethacrylate as cover layers, or eventually, no cover layer was applied. Deposition tests of the designed structures were done by using standard photolithography process and electron lithography process. Surface qualities of the fabricated samples were checked using optical microscope (Olympus DX60) and waveguiding properties were examined by Metricon 2010 prism-coupler system.

INTRODUCTION

Optical Microring Resonators (OMR) have been intensively investigated in recent years because such structures can be used for many photonics and optical communications applications (for example optical signal processing such as add-drop filters, delay elements, switches, wavelength division multiplexing, lasers, modulators, sensors and etc.) [1], [2], [3]. Integrated OMRs structures on Si-SiO_2, Ta_2O_5-SiO_2, SiN, SiON and also III/V and etc., have been already demonstrated [4], [5]. For our design of the OMRs we choose polymer materials as the polymers have been playing an important role in photonic structures thanks to their interesting properties such as suitable refractive index, low optical losses, reasonable time, temperature stability, easy fabrication process and low cost [6], [7], [8].

In this paper we suggest the OMR for operating wavelength 1550 nm and for elimination wavelength 1490 nm. These wavelengths were chosen because as suitable for development of Passive Optical Network (PON), which will be used for providing internet access service.

DESIGN OF THE OPTICAL POLYMER RIDGE WAVEGUIDES

First step for OMR suggestion was to design single mode polymer optical ridge waveguides. For the design we used Epoxy Novolak Resin (ENR) polymer as core waveguide layer because of its excellent optical properties (optical losses 0.15 dB/cm at 1310 nm, 0.46 dB/cm at 1550 nm) [9], [10]. Prior to the actual proposal in order to achieve the most accurate design the refractive indices of the particular layers were measured by ellipsometry in spectral range from 500 nm to 1600 nm (see Fig. 1).

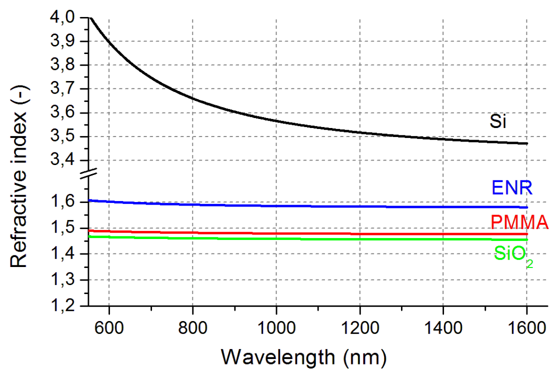

Fig. 1: Refractive indices of the layers used for the design of the optical waveguides and OMRs obtained by ellipsometry measurement.

We designed single mode waveguides by using 3D Beam Propagation Method using BeamPROP^{TM} software. To make the integration process easy we designed our structure on silicon substrate and as buffer layer we applied silica (SiO_2) layer. Polymethylmethacrylate (PMMA) was utilized as cover protection layer due to its easy fabrication process and suitable properties; or eventually, no cover layer was applied. The designed polymer ridge waveguide structures are shown in Fig. 2. The thickness (h_f) and width (w) of the ridge optical waveguide layer were set to be single mode-guiding for applied operating wavelengths and thickness of the buffer layer and PMMA cover protection layer were set according to the calculated ones, which ensures that the out-coupled energy of the evanescent wave would be less than 1 %.

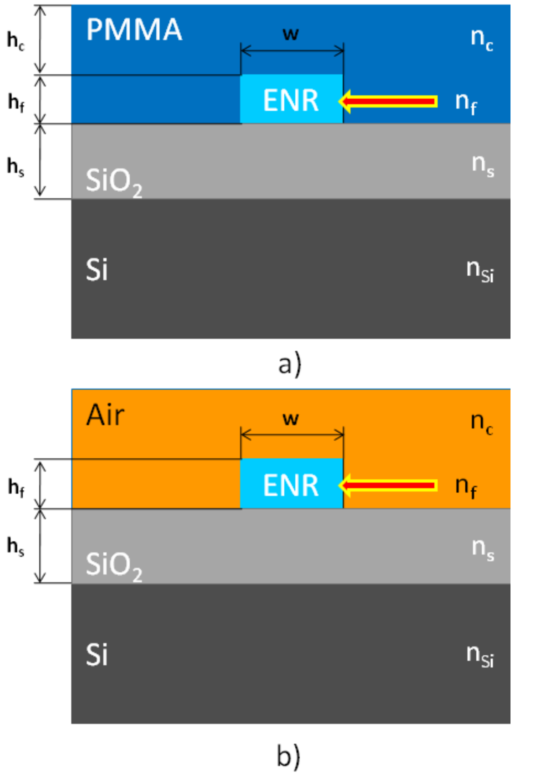

Fig. 2: Schema of the ENR optical polymer ridge waveguide on silica on silicon substrate a) PMMA cover layer, b) without protection cover layer.

The dimension of the waveguide (without PMMA cover layer) is around 0.63 µm (width) and around 1.68 µm (height) for the wavelength 1550 nm. The calculated effective refractive indices for fundamental mode of a single mode rib waveguide for operating at 650 nm is approximately 1.5520 and 1.4948 at 1550 nm. The simulations show that thicknesses of the silica layer have to be bigger than 3.8 µm.

DESIGN OF THE OPTICAL POLYMER MICRORING RESONATORS

The fundamental building blocks of the OM devices are one input bus waveguide, ring or disk resonator and one output bus waveguide. The principle of the design of four ports OMR is shown in Fig. 3.

The signal passes through the input bus waveguide and is coupled to the output bus through the resonator due to evanescent field.

There are principally two configurations for the coupling between the ring or disk resonator and the bus waveguides, namely, a vertical coupling configuration, where the bus waveguides are either on the top or beneath the ring or disk resonator and the lateral coupling configuration, where the bus waveguides and the ring or disk resonator are in the same plane [11]. The vertical coupling method allows the precise control of the coupling coefficient. In this configuration it is also possible to construct the ring and the bus waveguides out of separate materials, which opens a possibility of creating active ring or disk structures when using an appropriate material. However, this realization of the disk resonator increases the fabrication complexity and therefore we decided to design a laterally coupled resonator.

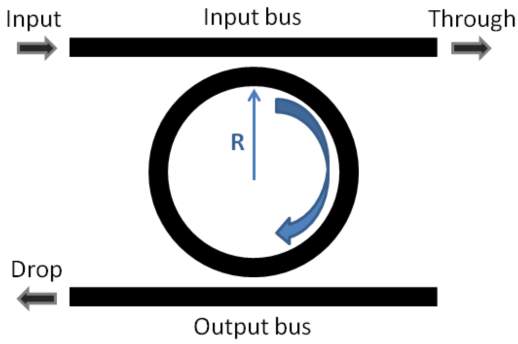

Fig. 3: Schematic view of a four port OMR.

We designed the OMR as an add/drop filter for Wavelength Division Multiplexing (WDM) by Finite-Difference Time Domain (FDTD) method using 2D FullWAVE^{TM} software. For operating wavelength 1550 nm and filtered out wavelength 1490 nm we started with designing OMR with use of single mode waveguides shown in Fig. 2a for wavelength of 1550 nm. The detailed drawing of the designed OM structures is shown in Fig. 4a and calculated transfer characteristic is shown in Fig. 4b.

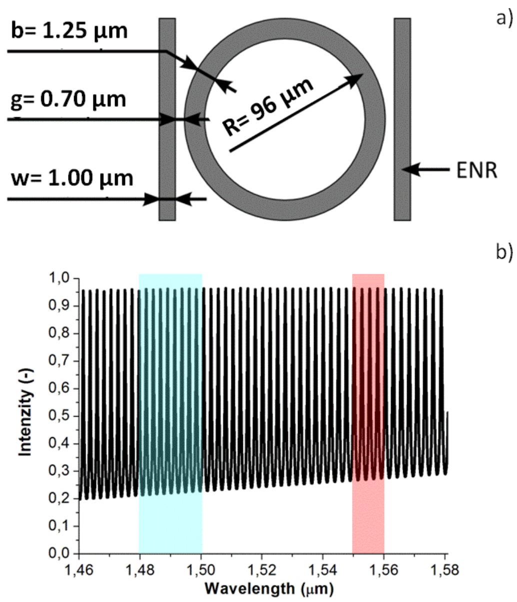

Fig. 4: a) Schematic view of the OMR design, b) transfer characteristic of the OMR design.

Simulation shows that the value of the Free Spectral Range (FSR) is 2.5 nm and that of the Full Width at Half Maximum (FWHM) is 0.8 nm. It is clear that this OMR is not suitable as optical filter for 1550 nm due to unsatisfactory spectral range of the transmitted wavelength band of 1550 nm and a lack of filtering of wavelength 1490 nm.

Next we designed the OMR using single mode waveguides shown in Fig. 2b for 1550 nm. The detailed drawing of the designed OM structures is given in Fig. 5a and calculated transfer characteristic is shown in Fig. 5b.

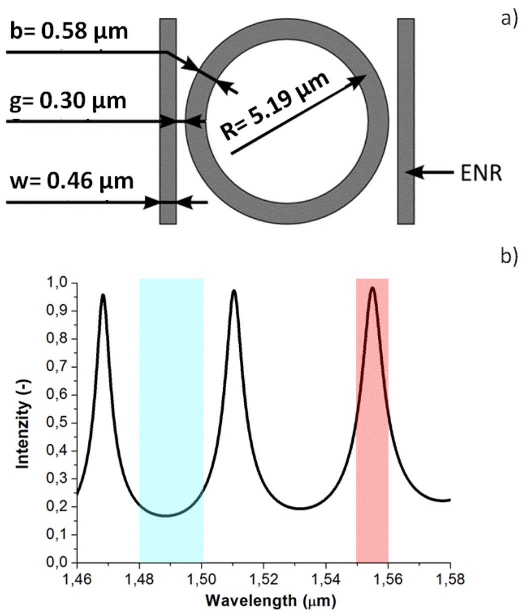

Fig. 5: a) Schematic view of the OMR design, b) transfer characteristic of the OMR design.

In this case simulation shows that the signal at 1490 nm is not adequately filtered out and the resonance curve at 1550 nm signal is not wide enough. The value of the FSR is 44 nm and that for FWHM is 10 nm.

The above mentioned simulations showed that it is not possible to implement ENR polymer by using single microring resonator structures for operating wavelength 1550 nm and for elimination wavelength 1490 nm. Therefore, to improve the transmission characteristics, it is necessary to design a coupled polymer OMR.

Next we studied a possibility of implementation of this structure by serially coupled double OMR. In the beginning we optimized the design of the single OMR with special respect to the best value of the gap (*g*) between ring and input waveguide and the value of the ring radius (*R*). Next we simulated and optimized the parameters for serially coupled double OMR. The simulation shows that the value of the FSR is 44 nm and that of the FWHM is 10 nm. This solution significantly improved the shape of the transmission characteristics. Losses at 1550 nm are lower and signal at 1490 nm is better filtered out.

Finally, for improving the transfer characteristic, we proposed serially coupled triple OMR. The detailed drawing of the designed serially coupled triple OMR structure is shown in Fig. 6a and the calculated transfer characteristic is given in Fig. 6b.

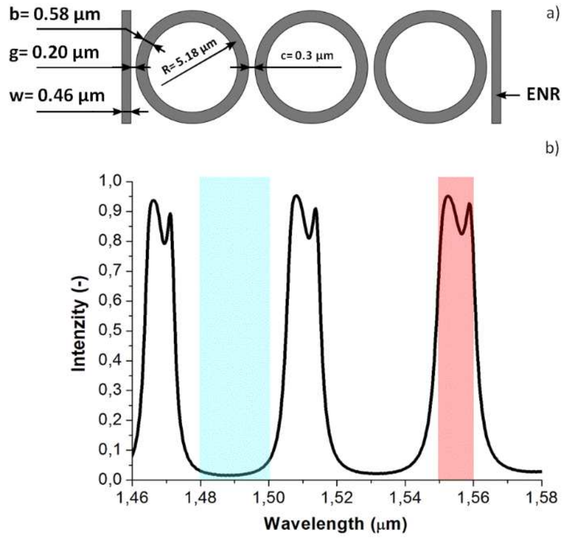

Fig. 6: a) Schematic view of the designed serially coupled triple OMR structure, b) transfer characteristic of the triple OMR.

Calculated transfer characteristic for serially coupled triple OMR shows that the value of the FSR is 44 nm, FWHM is 12 nm, F is 3.7 and Q is 130. This proposed serially coupled triple OMR have suitable properties for operating wavelength 1550 nm and filtered out the signal at 1490 nm.

DEPOSITION TESTS OF THE MICRORING RESONATOR FABRICATION

The designed OMR structures were deposited by standard photolithography process (Perkin-Elmer 300 HT Micralign) and by using electron beam lithography (Raith eLiNE lihtograph).

Realization of the ENR waveguides by using photolithography process was described in more details in [12]. First, SiO_2 layers were deposited on Si substrate by using thermal oxidations and then ENR core waveguide layer was deposited by spin coating. Next the samples were let to harden by UV light over the photolithography mask and MR-DEV 600 developer was used for the etching of the undeveloped ENR layer.

Fabrication process of ENR polymer OMR structure by using electron beam lithography is step by step shown in Fig. 7. First, silicon substrate was cleaned by standard cleaning procedures (Fig. 7a). Next silica layer on silicon substrate was deposited by using thermal oxidations (Fig. 7b). Then primer layer HMDS:Xylen was deposited by spin-coating in order to improve adhesion between silica on silicon substrate and ENR waveguiding layer (Fig. 7c). After that ENR core waveguide layer was deposited by spin coating (Fig. 7d). Then the samples were let to harden by electron beam lithography (Fig. 7e). After that the samples were dipped for 15 seconds into MR-DEV 600 developer (Fig. 7f).

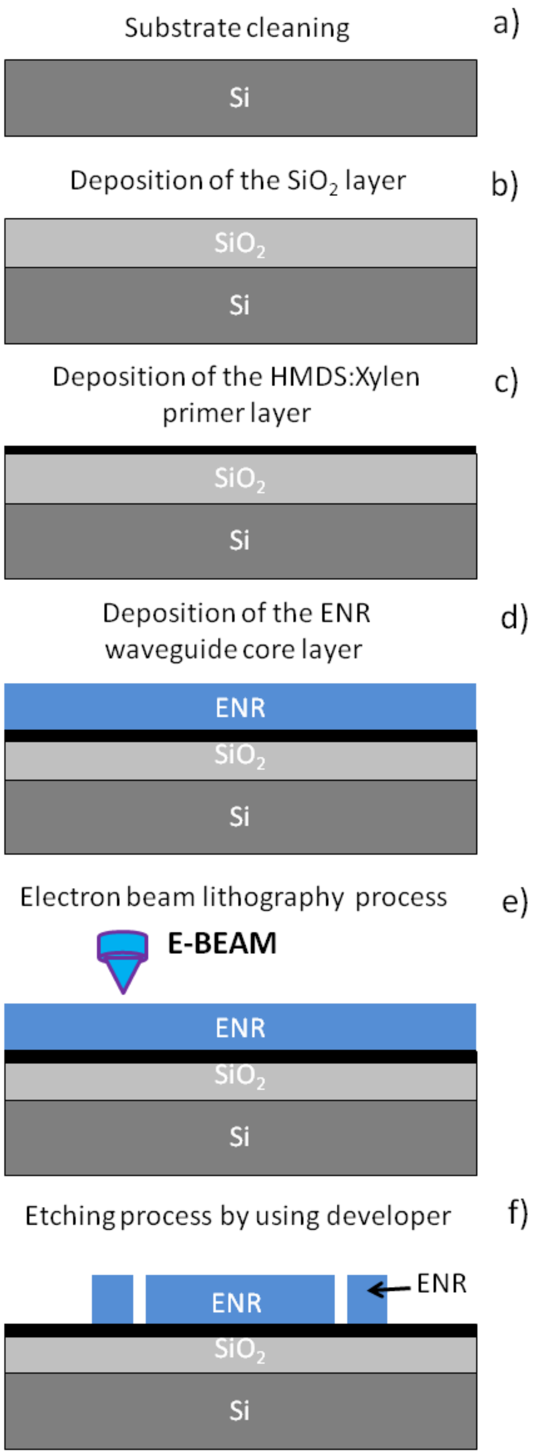

Fig. 7: Fabrication process of the OMR structure a) substrate cleaning, b) deposition of the silica layer, c) deposition of the primer layer, d) deposition of the ENR optical waveguides, e) electron beam lithography process, f) ENR resist etching.

PROPERTIES OF THE SAMPLES

Quality of the surfaces of the fabricated structures was checked by using optical microscope (Olympus DX60). Fabricated OMR structures are shown in Fig. 8., while the OMR fabricated by standard photolithographic process is shown in Fig 8a and OMR fabricated by electron beam lithography is shown in Fig. 8b.

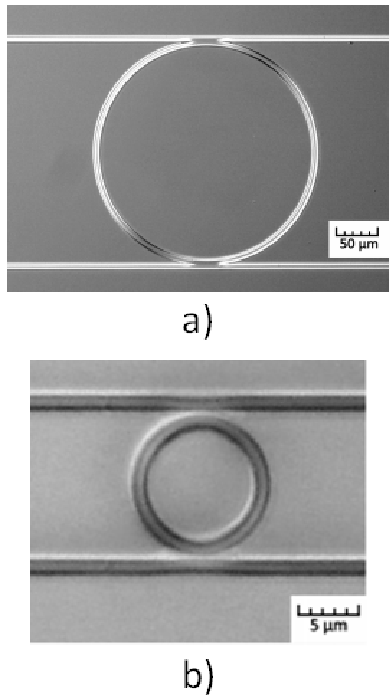

Fig. 8: Optical microscopy images of the OMR fabricated by a) optical lithography process, b) electron beam lithography process.

Figs. 8 reveal that the structures had very good optical quality without any defects but the design of the ENR single mode waveguides showed that thickness and width of the waveguides have to be around 0.5-2 µm depending on the used cover layer and operating wavelength. However, deposition test showed that OMR structures fabricated by optical lithography process are much bigger than it is necessary for single mode ridge waveguides (around 5 µm). Therefore OMR structures cannot be fabricated using our photolithography process, and therefore we have to use electron lithography.

Waveguiding properties of our ENR planar waveguides were examined by Metricon 2010 prism-coupler system. This apparatus works on the principle of the dark mode spectroscopy and obtained date are shown in Fig. 9. This figure shows small decrease of the refractive index values with the increasing wavelengths and confirmed a good quality of the waveguides.

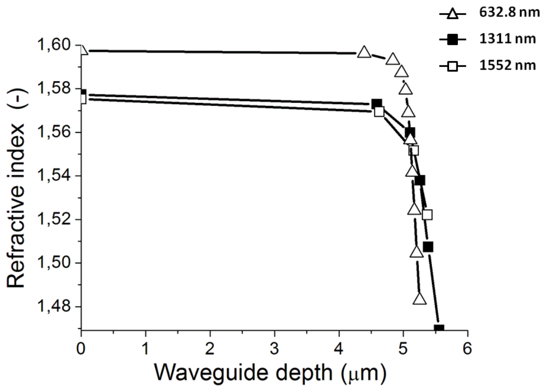

Fig. 9: Evaluation of the refractive index depth profile of ENR polymer waveguide fabricated on Si/SiO_2 substrate (TM modes).

CONCLUSIONS

We report about design and modeling of the polymer microring resonators as an add/drop filter for wavelength division multiplexing. First we designed single mode Epoxy Novolak Resin polymer optical rib waveguides on silica-on-silicon substrate by using BeamPROP^{TM} software. The ENR polymer as waveguide materials was chosen because of its excellent optical properties and easy fabrication process.

After that optical microring resonators were made by Finite Difference Time Domain Method that uses FullWave^{TM} software. The design of the OMR was done for operating wavelength 1550 nm and for filtered out signal at 1490 nm. There are two configurations for the coupling between the ring or disk resonator and the bus waveguides: a vertical coupling and lateral coupling configuration. The vertical coupling OMR allows the precise control of the coupling coefficient, but this realization of the disk resonator increases the fabrication complexity. Therefore we designed laterally coupled OMRs.

The simulations showed that it is not possible to implement ENR polymer by using single microring resonator structures for operating wavelength 1550 nm and for elimination wavelength 1490 nm. Therefore, to improve the transmission characteristics, we designed a coupled polymer OMR. The pertinent simulations showed that serially coupled triple OMR have suitable properties for transmitting signal at 1550 nm and filtered out signal at 1490 nm. The designed OMRs were realized by photolithography and electron beam lithography process. The fabricated samples had good surface quality, however OMRs samples fabricated by optical photolithography had no single mode dimension of the waveguides.

Optical waveguiding properties of our ENR polymer planar waveguides samples were confirmed by using Metricon 2010 prism-coupler systems and the measurement showed a good quality of the waveguides.

ACKNOWLEDGMENTS

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