SU8 polymer materials used in integrated optic microsystems

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The negative epoxy-based polymer photoresist SU8 was used in a lot of applications in the last years because it presents very good properties and is easy to be used in microsystem technology. This paper presents design, simulations and manufacturing of SU8–based optical waveguides photonic integrated circuits, and the possibility to integrate them on the same silicon platform with sensing elements and optoelectronic devices.

1. Introduction

Polymer based materials are of huge interest in microsystems applications as for example, devices for microfluidics, RF, chemical sensing and optics . Polymers are used in integrated optics due to their advantages: adjustable optical and thermo-mechanical properties through a controlled synthesis, mechanical robustness, potentially low cost of preparation and processing (low temperature required), compatible processing with semiconductor technology [1,2]. Additionally, polymeric materials can be deposited directly on any kind of substrate. One of the polymers with a large area of application is the negative, epoxy-based photoresist SU-8 [3]. It has been used both as a photoresist, but mainly as photo-patternable functional material for 3D micromechanical structures with vertical sidewalls and high aspect ratio features in films of only a few microns in thickness or hundreds of microns in thickness for MEMS and packaging parts, due to its excellent mechanical properties, water impermeability, high stability, high uniformity and chemical resistance [1, 3-5]. We have to mention also other attractive properties as: structural integrity over time and biocompatibility.

SU-8 is also very suitable for integrated optics as it shows a noticeable optically quality, a high transparency above 400 nm [3] and long term stability under various environmental conditions. Waveguides and photonic circuits can be easily fabricated using simple techniques suitable for mass fabrication, such as photopatterning [6] and molding [7]. For these reasons, SU-8 based waveguides have been widely applied to flexible optical interconnects, devices for optical communications [7] colour mixing devices for projection display systems, UV-sensors, interferometers for thermal sensing [8].

Moreover, combination of SU-8-based integrated optics with micromechanics allows the development of complex optical MEMS for sensing applications [9].

Due to its biocompatibility and chemical resistance, SU8 is also ideally suited to the fabrication of micro-channels for lab-on- chip applications, bio-MEMS and bio-photonic chips [10].

Although many experimental structures and microsytems have been reported, SU-8 processing is still challenging, every process step influences strongly the results and has to be adapted individually to the desired application.

In this paper we focused on the manufacturing and characterization of SU8 based optical waveguides used in integrated optics - planar lightwave circuits (PLCs) applications: Mach Zehnder interferometers (MZI), multi mode interferometers (MMI) and a microring resonator. The paper presents design, simulations and experimental realization of these components.

2. Design and simulation

SU8 polymer was used as planar optical waveguide for three different types of integrated optic configurations: a Mach-Zehnder interferometer (MZI), design for low losses optical waveguides, a multi mode interference waveguide (MMI) and a microring resonator.

The first circuit consists of a monomode Mach-Zehnder interferometer integrated with a photodiode and a layer sensing (Fig. 1). A Y shape arm, with 1.15° splitting angle, divide the incident electromagnetic radiation in two beams and recombines the interfered beam into another Y shape output waveguide. This structure can be used as sensor (chemo-bio) if we pattern a rectangular window in the upper cladding of the waveguide; chemo-biological species (active cladding) will be in contact with the core of the optical waveguide, determining a change in the effective refractive index. The output signal will measure a change of intensity of the interference signal, due to the

differences of the refractive index of the sensitive and the reference arm of the interferometer. So, the induced change in the refractive index of the chemo-bio cladding layer are monitored by the measurement of the modified properties of the propagation of the optical radiation.

Optical measurements of transduction can offer a high sensitivity, combine with the advantage of a integrated structure on a silicon substrate.
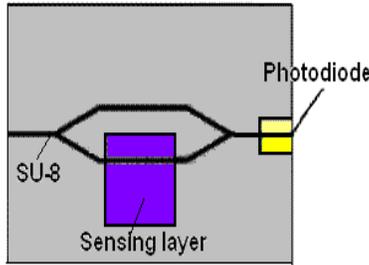
The separation between the sensing and the reference arm was 40 µm.

Fig.1. MZI integrated with photodiode, for sensors.
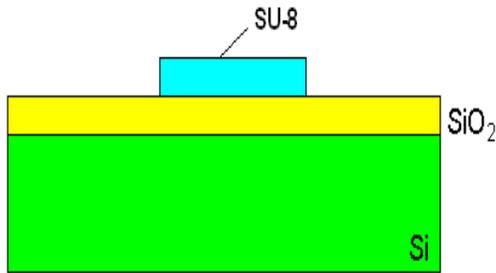
Fig. 2. Optical waveguide configuration (cross section).

The Mach-Zehnder interferometer configuration was optimize for the SU8 rib optical waveguide, presented in Fig. 2 (width: 5 µm, thickness: 1 µm), using analytic methods and OPTI FDTD software, in order to have a monomode propagation for both TE and TM polarization of the electromagnetic radiation (Fig. 3).
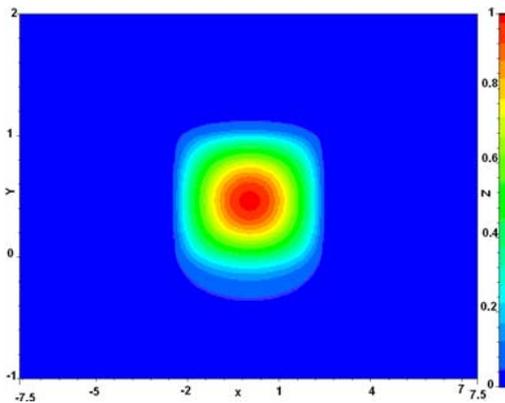

Fig. 3. Electric field distribution for TE fundamental mode (waveguide structure given in Fig. 2).

The simulation were performed for λ= 635 nm, considering for SU8 a refractive index of n = 1.596. In Fig. 4 is presented the simulation of the electromagnetic wave propagation in the Mach Zehnder interferometer, considering a Gaussian profile.

Simulations were also performed to calculate optimum angle between the two arms of the Y junction, in order minimize the propagation losses for TE . We obtained using Opti FDTD software a value of θ = 1.15°, for the SU8 Y- splitter.
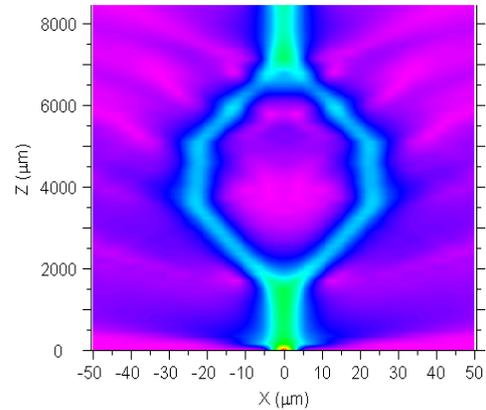

Fig. 4. Simulation of the electromagnetic wave propagation in the Mach Zehnder interferometer (Gaussian profile).

The second configuration (MMI- multi mode interference waveguide) consists of a wide input waveguide, which is the multimodal coupler and the output waveguides, designed for 635 nm wavelength, are easier to be obtained. We designed a multimodal splitter for multimodal waveguides input/output.

The output is a multimodal splitter. The output waveguides have a linear variation of the width (tapered waveguide), being larger in the coupling region, in order to obtain a uniform radiation distribution in all the output waveguides and to minimize the bending losses (see fig. 5). The input waveguide has 5 µm width and 1 mm length. The multimodal interferential coupler has 980 µm in length and 40µm wide. The width of the output waveguides decreases from 10 to 5 µm (layout presented in Fig. 4)
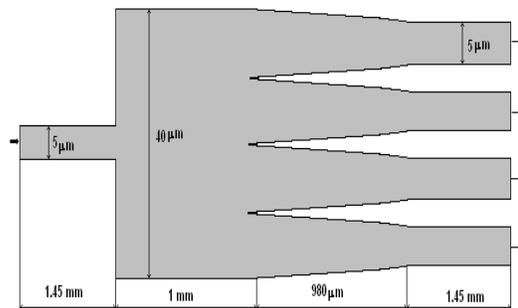

Fig. 5. Layout of the MMI configuration.

Fig. 6 shows the results of the simulations, using Opti FDTD software, for the electromagnetic radiation propagation in the MMI circuit.
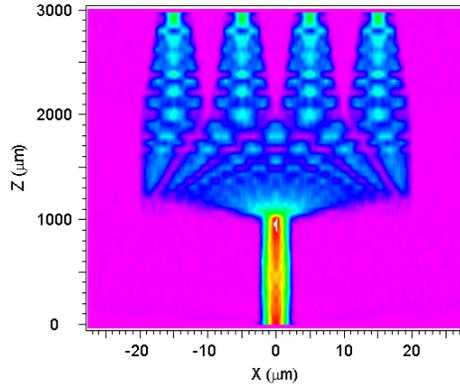

Fig. 6. Propagation in the MMI integrated optic circuit, using Opti FDTD.

The third device is a microring resonator.

The geometrical parameters are: connection waveguides width: 5 μm; coupler region length: 75 μm; coupler region width: 10 μm; ring radius: 50 μm.

In Fig. 7 is presented the the configuration layout.
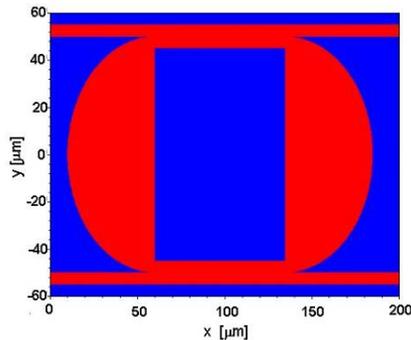
Fig 7. Microring resonator configuration.

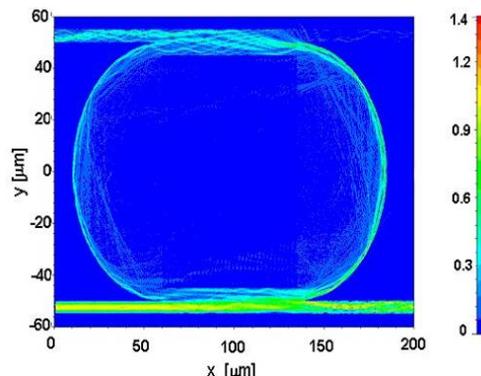The simulation results for the field distribution (using OptiFDTD), are   presented in Fig. 8.

Fig. 8. Field distribution in the microring resonator (OptiFDTD).

We considered a refractive index   n =1.6; the thickness of the waveguide equal with 1000 nm, and a wavelength for the electromagnetic wave λ= 633 nm.

3. Fabrication

Polymeric materials as SU8 are ideal for planar optical circuit processing. Deposition and pattern transfer are achieved with low cost and high precision by spin coating and photolithography.

Polymer-based planar lightwave circuits (PLCs) have advantages over their silica-based counterparts (directly competing technology) in terms of cost, tunability, and polarization dependence. They present also a higher refractive index.

For both photonic integrated circuits and waveguide fabrication, SU8 was coated on a 1-2 μm thick SiO_2, thermally grown on a silicon substrate. SiO_2 is the bottom cladding of the waveguide structure and the polymer is the core, having a good transmission spectrum in the visible wavelength range and a refractive index n = 1,575 (λ=1550 nm), 1.596 (λ=633 nm), 1.67   (λ=365-408 nm).

For manufacturing,   the following procedure was used:

- spin-coating distribution of SU8 (2000 rpm);
- static: the wafer was coated with SU8 – 1 ml
- for every inch in diameter
- spinning (1): ~ 100 r/s, 5 s until 500 r
- spinning (2) : gradual spinning until ~300 r/s, for 30 s
- pre-bake : 65 ^{o}C - 1 min., 95 ^{o}C - 3 min on the hot plate
- exposure
- post - exposure bake: 65 ^{o}C - 1 min. and
- 95 ^{o}C - 1 min on the hot plate
- development; then IPA cleaning and drying
- thermal annealing: 150-200 ^{o}C for 1 hour.

For all configurations presented before (MZI and MMI, microring) we used SU8 polymer   for the fabrication of the optical waveguides. These structures were integrated on the silicon platform with photodiodes, sensing layers or microchannels.

4. Results and caracterizations

The experimental layers and structures were studied using AFM, SEM, and a set-up for light propagation visualization.

Figs. 9 and 10 present experimental results: SEM photo of the Y splitter and of the aria of the MZI to be integrated with a sensing layer.
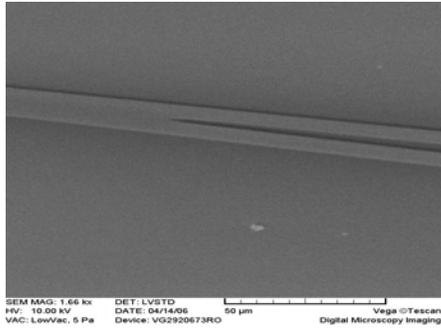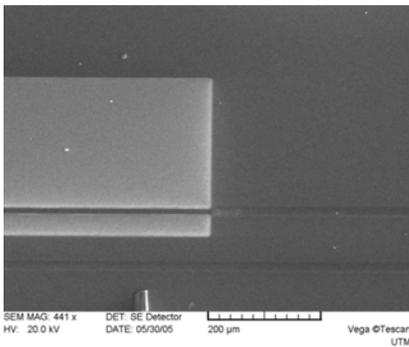
Fig. 9. SEM photo of the SU8 Y junction.

Fig. 10. SEM photo of the sensing area of the MZI, placed on the SU8 optical waveguide.

In Fig. 11 one can see the experimental results regarding the manufacturing of the microring resonator, based on SU8 polymeric optical waveguides (SEM image).
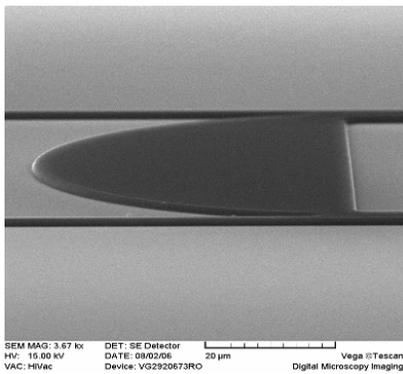

Fig. 11. SEM photo of the SU8 microring resonator.

For the MZI configuration the light is guided along the waveguide and a portion of the field is propagated outside the SU8 core (the evanescent field). In this way electromagnetic radiation is sensitive to the refractive index changes at the surface. Information about a bio or chemo- species can be observed in a modification of the propagation of the optical guided wave.

In Fig. 12 (optical microscope image) are presented two parts of the multi mode interference waveguide (MMI).
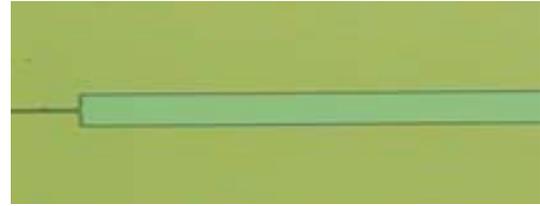
(a)
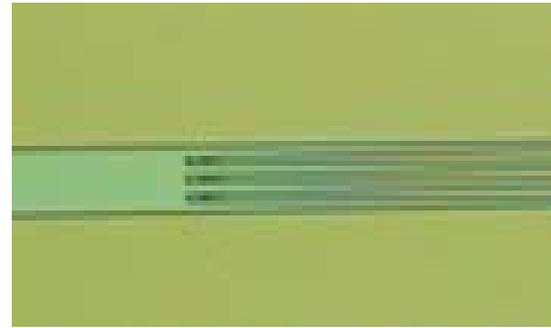
(b)

Fig. 12. SU8- based MMI (a) input, (b) output.

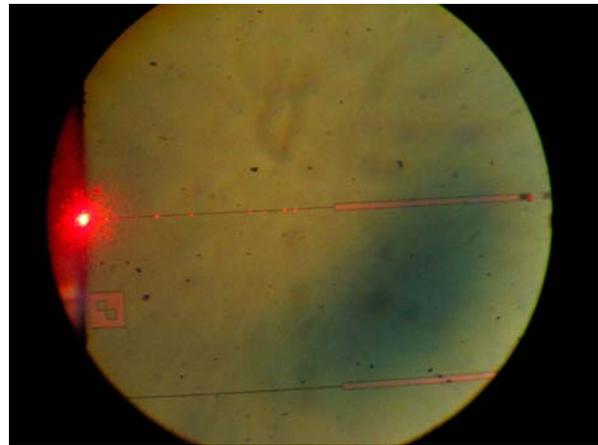Light propagation through this structure is presented in Fig. 13.

Fig. 13. Propagation of electromagnetic radiation in the MMI configuration.

As can be seen in Fig. 14 the propagation losses of the electromagnetic radiation ($\lambda = 635$ nm) are very low.

Also we observed for the splitting angle (1°) of the Mach Zehnder interferometer's arms (Fig. 14) that the losses are negligible and the light is propagated over the entire length, which is 9 mm. We noticed that the light is not coupled for a distance of 2-3 μm between the waveguides. This can be explain considering the attenuation of the vertical mode and the big distance, compared with the wavelength of light (635 nm).
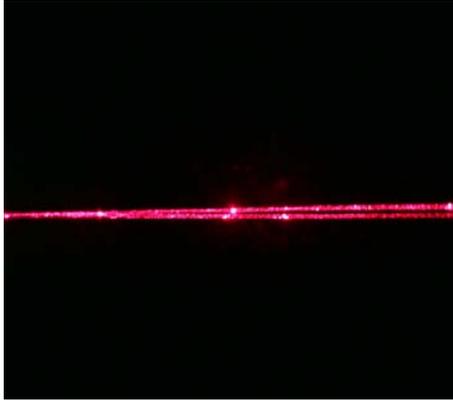
Fig. 14. Image obtaiend at optical microscope showing a detail of the light propagation experimental Mach Zehnder interferometer- detail.

Compared with silica optical waveguides, which can difficult be obtained for larger thickness, and having a relatively low refractive index, SU8 polymer is a versatile material which was obtained with smooth side walls, which was easily coupled with other components (as photodiodes or optical fiber) and allowed single mode or multiple modes to propagate through the guide.
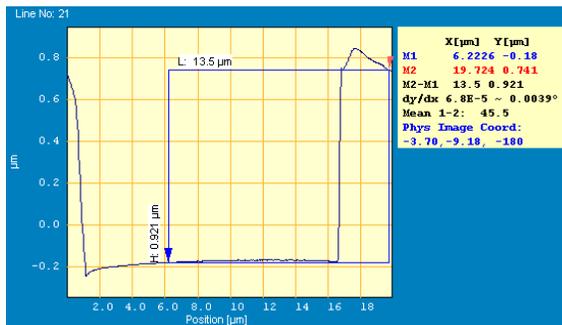
(a)
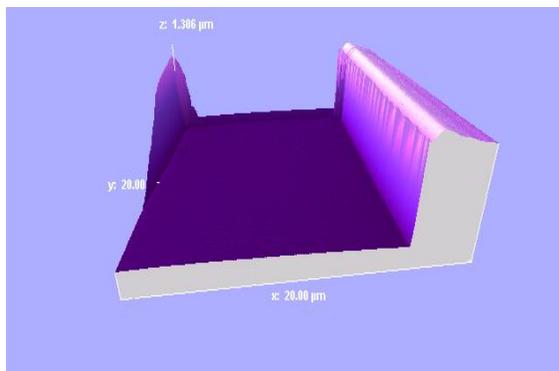
(b)

Fig. 15. 2D(a) and 3D (b) AFM images of the SU-8 optical waveguide.

In the case of the Mach-Zehnder configuration SU8 waveguide thickness was 921 nm (Fig. 15 (a) and (b).

We obtained SU8 polymeric waveguides with high uniformity and low edge beads for a smooth surface.

The pattern quality and transfer reliability was very good.

The results of the referactive index measurements for the SU8 optical waveguide, as a function of the electromagnetic wavelength are presented in the next Fig. (16).
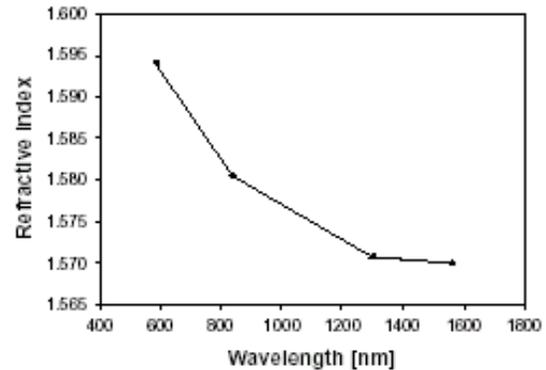

Fig. 16. The referactive index of SU8 core, as a function of the electromagnetic wavelength.

5. Conclusions

The feasibility for integrated SU8 polymeric optical waveguides on silicon platform was demonstrated. Three integrated optic configurations were designed and manufactured: a Mach Zehnder interferometer for sensing applications, a multi mode interference waveguide and a microring resonator, all based on SU8 polymeric photoresist waveguides.

Simulations, carried out using Opti FDTD, helped us to improve the design for low loss propagations.

The experimental results confirm that SU8 can be successfully used in integrated optic circuits.

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