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Photonic devices prepared by embossing in PDMS

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ABSTRACT

In this paper, we present useful technique for fabrication of novel photonic devices created in the polydimethylsiloxane (PDMS). We use combination of direct laser writing in thin photoresist layer with embossing process of liquid PDMS. We prepared ring resonator and Mach-Zehnder interferometer in PDMS. The shape of prepared PDMS photonic devices was analyzed by confocal laser microscope and atomic force microscope. Optical characterization of these devices reveals extinction ratios of up to 20 dB.

1. Introduction

Polydimethylsiloxane (PDMS) material has recently become very attractive for lab on a chip (LOC) technology. This technology integrates multiple elements on a single chip in order to prepare devices with reduced dimensions and very short interconnects. PDMS material is characterized by good transparency in visible and near-infrared region with unique elastic properties what predetermines PDMS as an excellent candidate for LOC technologies [1]. Also, PDMS has found application in field of nanostructure fabrication [2], microfluidics [3,4], biomedicine [5], soft lithography [3] and sensing area [6]. In silicon photonics, various optical devices as Y-branch waveguide splitters [7], ring resonators [8], Mach-Zehnder interferometers [8], and arrayed waveguide gratings [9] were presented. Integration of optical devices on a chip was used for various applications as a key components for optical signal processing, routing [10], coupling [11] filtering [12] and sensing [13]. Preparation of photonic devices with tunable properties was a challenge for polymer materials. To date, various PDMS optical devices were presented, for example, optical fibers [14], optical couplers [14], optical waveguides [15,16], Y-branch splitters [17].

PDMS material is interesting for development of new photonic devices, especially different waveguide structures and tunable devices. Its flexibility, as an excellent property allows preparation of tunable devices with unique optical properties. Well sensitivity of PDMS to the temperature or gas was also presented in some works [18,19].

In many photonic devices with sensing properties the dimensions tunability plays an important role. Silicon-based photonic devices do not allow much to change the spectrum using dimensions elongation because of low elasticity. To achieve flexible photonic devices with possibility of tuning the spectral characteristic we try to prepare new photonic devices based on polymer PDMS. With the change of structure dimensions the optical spectrum shift can be achieved.

For a planar optical waveguide formation, appropriate refractive index contrast has to be achieved between the higher refractive index material as a core and the lower refractive index material as a cladding. In LOC devices based on PDMS material, techniques as UV curable resist [17], proton beam writing [20] and soft lithography [21] were presented to achieve appropriate refractive index contrast. In our experiments we used two PDMS materials with different refractive indices for core and cladding formation. Direct laser writing (DLW) is used as a very effective maskless technique for photoresist channel patterning followed by channel filling.

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In this paper, we present DLW in combination with PDMS embossing as a useful technique for fabrication of photonic devices in the PDMS surface. We focused on fabrication of important photonic devices as ring resonator and Mach-Zehnder interferometer prepared in PDMS.

2. Experimental

Homebuilt direct laser writing (DLW) lithography system was used for the photoresist patterning as a master in combination with embossing technique of liquid PDMS. Preparation of photonic devices in PDMS surface consists of several steps. First, thin photoresist layer with the thickness of 3 μm was deposited on Si substrate using SPIN 150 spin coater at 4000 rpm and cured at temperature of 115 °C for 60 s. This positive photoresist Microposit S1828 G2 was used as a master for the next PDMS embossing process.

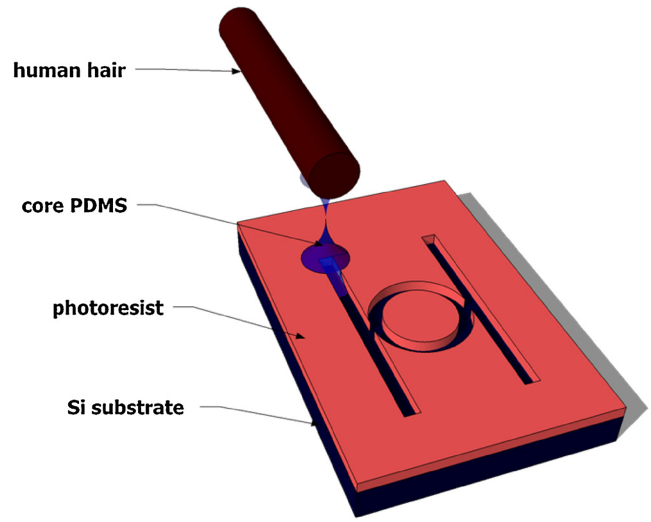
For the photoresist exposure, we used DLW lithography system in arrangement with high resolution dual-axis galvanometer scanning mirror system CT 6215 [22]. The master sample was prepared by patterning of thin photoresist layer by 2D scanning of the focused laser beam over the sample surface. In our experiment we used configuration with 473 nm laser and 40 × objective for photoresist exposure with exposure time of 800 ms and with intensity 1.3 mW/cm^2. After exposure, the sample was developed in AZ 400 K developer for 10 s, rinsed in deionized water and dried with nitrogen.

The refractive index difference between the core and the cladding is typically achieved using different mix ratio of two parts of the polymer [21]. In our work we used combination of different siloxanes – Sylgard 184 and LS-6943 for cladding and core. Both polymers were prepared from combination of liquid elastomer and curing agent at ratio 10:1. The refractive indices of Sylgard 184 and LS-6943 at wavelength of 1310 nm and room temperature were 1.403 and 1.417, respectively [23,24]. For a polymer device formation in patterned photoresist channel, we first precisely dropped small amount of LS-6943 directly on the photoresist surface near the patterning waveguide (Fig. 1a). The patterned area was filled by capillary effect with liquid PDMS after 5 min and the sample was cured for 45 min at 75 °C. Next, Sylgard 184 as a cladding layer with the thickness of 200 μm was deposited on the sample surface and cured. Using PDMS embossing technique [25], the cladding layer with embossed PDMS core was mechanically separated from the photoresist layer (Fig. 1b). Finally, for the measurement purposes the end-faces of the waveguides were cut perpendicularly using razor blade.

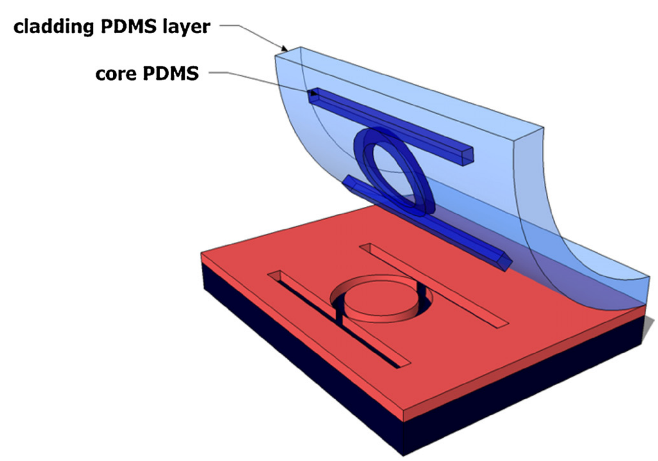
In the next experimental investigations we characterized the shape and dimensions of prepared structure and also the spectral properties of prepared devices. The morphology of prepared devices was analyzed using confocal laser scanning microscope (CLSM), atomic force microscope (AFM) and the spectral characteristics were measured using Optical Spectrum Analyzer (OSA). We used simple experimental setup for spectral measurements as is shown in Fig. 2. LED with central emission wavelength at 1310 nm was coupled into one PDMS waveguide channel of PDMS ring resonator using single-mode optical fiber (SMF). We detected the transmitted light from the same channel using exactly positioned SMF and OSA Anritsu MS9710B.

3. Results and discussion

Morphological properties of prepared PDMS devices were analyzed using CLSM. Due to the excellent embossing properties of liquid PDMS, the sample very well reflects the shape of the patterned photoresist channel. CLSM image of PDMS ring resonator with 23 μm ring radius and waveguide length of about 700 μm is shown in Fig. 3. The detailed inspection of morphology and interface of coupling region was studied by AFM (Fig. 4a). AFM line profile documents the waveguide depth of 3 μm and 50° slope of the sidewalls (Fig. 4b). In PDMS ring resonator, 2 μm coupling height between the ring and the waveguide was attained. This parameter is crucial on coupling properties and quality of ring resonator.



(a)



(b)

Fig. 1. a) Illustration of channel filling with PDMS for the ring resonator structure preparation and b) illustration of mechanical separation of cured PDMS ring resonator.

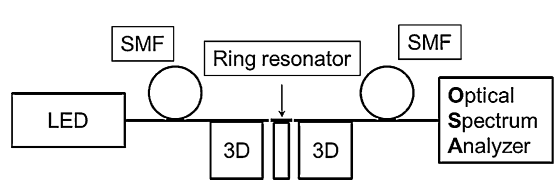


Fig. 2. Experimental stage for the spectral characterization of PDMS waveguide structures, LED – light emitting diode, SMF – single-mode optical fiber, 3D – nanopositioning mechanical stage.