High-Finesse Laterally Coupled Organic–Inorganic Hybrid Polymer Microring Resonators for VLSI Photonics

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***Abstract*—We produced laterally coupled optical microring resonators having high finesse ($\mathcal{F} \simeq 17$ at 1.5-μm wavelength) using a two-step patterning technique based on optical photolithography. The technique used allows us to separately control the height of both ring and port waveguides and structure submicrometer gaps. The resonance spectrum of microrings with radii of 50 μm made of an organic–inorganic hybrid polymer have an extinction ratio of about 12 dB and a filter bandwidth $\delta\lambda \simeq 0.28$ nm (full-width at half-maximum) at a wavelength $\lambda = 1547.78$ nm. We show that the resonances can be thermooptically tuned by 0.2 nm/°C, thus allowing us to modulate the transmission of the through port signal.**

***Index Terms*—Integrated optics, lateral coupling, microring resonator, organic–inorganic hybrid polymers, Ormocer.**

I. Introduction

POLYMERIC optical microring resonators lately gained a considerable interest due to their suitability in photonic integrated circuits for filtering or modulation applications in the telecom environment [1]–[3], and more recently also in sensing technology [4], [5]. Today, integrated optical elements have to compete with bulk devices but the increasing demand on end user access network bandwidth will require low-cost mass production technologies and materials. Here polymers can play an important role. Besides the advantage to potentially reach any specification just by designing the appropriate functionality, e.g., using nonlinear or electrooptic active chromophores, polymers are relatively easily patterned and generally do not require any expensive technological feature. For the case of ring-like waveguides, however, the material's low refractive index limits the miniaturization of the radii due to a reduced confinement of the electromagnetic mode fields if compared to semiconductors [6]. Most recent publications in this domain point out a presumed difficulty in patterning laterally coupled waveguides with optical fabrication technologies owing to a restriction in establishing submicrometer gaps of the asymmetric directional couplers, preferring, therefore, a vertically stacked arrangement [7], [8].

In this letter, we propose a simple and fast two-step patterning technique that allows us to clear the submicrometer gap between rings and port waveguides in lateral couplers, as well as independently adjust the height of the different waveguides. The presented novel technique exploits the characteristics of the direct photopatternable hybrid polymer Ormocer, from Micro Resist Tech but originally developed by the Fraunhofer Gesellschaft. It enables us to produce higher finesse microrings with a radius of 50 μm, while polymeric ring resonators with comparable properties commonly have radii in the order of tenths of millimeters [1]–[4], [9], [10].

Finally, we demonstrate the tuning of the resonance spectrum via the thermooptic effect.

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II. Material Characteristics and Fabrication Process

The material used for the waveguides is Ormocore, from the family of Ormocer, a commercially available inorganic-organic hybrid polymer that behaves as a negative photoresist, with refractive index 1.536 and typical losses of 0.6 dB/cm at 1.55-μm wavelength, and glass transition temperature above 270 °C [11]. A Silicon wafer, covered with a 2-μm-thick thermally produced oxide as refractive index barrier ($n_{\mathrm{SiO_2}} = 1.445$), was used as substrate.

After a careful cleaning and dehumidification of the substrate, and correct dilution of the Ormocore resin in propyl acetate, the first production step was to spin coat a droplet of the lacquer to get a wet 4-μm-thick film. This was followed by the ultraviolet (UV) exposure in oxygen poor atmosphere through a negative chrome mask to pattern the port waveguides. The mask aligner we used is a standard Karl Süss MJB3 UV300 equipped for contact illumination only. Since a *proximity mode exposure* was required and the apparatus could not guarantee good parallelism and precisely controlled distance from the wafer to the mask, 25-μm overall separation was achieved by using a Kapton HN spacer from Goodfellow, which was placed around the coated surface of the sample. The exposed sample was then developed in methylpentanone. Directly after that we proceeded with the second production step. We spin coated a second film of about 5-μm thickness from the same solution, which despite the already present waveguides appeared flat. After aligning the 50-μm radius ring on the mask 0.5 μm close to the waveguides produced before, we exposed and developed the second lacquer film. Final hard baking at 150 °C in inert atmosphere was performed. The whole procedure lasts less than three hours.

The resulting Ormocore waveguides had cross sections of 2.7-μm width and 3.6-μm height for the ports, and 3.8×4.5 μm^2 for the ring, respectively (Fig. 1). The gaps between

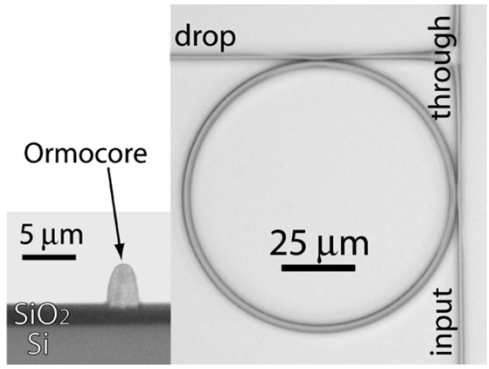

Fig. 1. Left: Microscopic front view of a cleaved sample showing the Si substrate, the SiO_2 barrier, and the cross section of a port waveguide. The structures are by about 10% thinner than the films before development since the oxygen at the surface reduces the polymerization during the exposure. Right: Microscopic top view of a laterally coupled ring resonator of Ormocore. The external radius of the ring is 50 μm with a cross section of 3.8-μm width and 4.5-μm height; the port waveguides are 2.7 μm wide and 3.6 μm high. The gaps at the couplers are 0.3 μm wide.

the ports and the ring were 0.30 ± 0.02 μm wide as measured by scanning electron microscopy. Among 25 samples produced in the same way, all dimensions were reproducible within an uncertainty of 0.1 μm, which could be reduced by using, e.g., a Süss MA8 mask aligner with a more precise alignment tool. Despite the proximity mode exposure, inducing a strong diffraction of the UV light at the pattern apertures on the mask, the straight waveguides became only 0.2 μm wider than designed. The rings, on the contrary, have increased their width by 1.8 μm toward the center, where the photon density due to diffraction is higher. In fact, the competition between oxygen diffusing into the wet film and the UV light causing the polymerization reduces the effect of the diffraction: where the diffracted light intensity is too small to link the molecules to each other, they react with oxygen and patterning does not take place [12]. We need to point out here that the different dimensions of bent and straight waveguides are decisive to guarantee acceptable losses for the former and single-mode character for the latter. As estimated by calculations using the commercially available two-dimensional mode solver Selene, from C2V, the chosen ring dimensions avoid introducing additional bend losses to the first mode while keeping a high loss for the second mode, and cut off all higher modes.

There are several advantages of having pure SiO_2 as common buffer material: besides a better confinement of the bend mode compared to other configurations with usual polymeric buffer layers, glass avoids planarization problems and physicochemical incompatibilities of the different compounds, enhancing, therefore, the adhesion of the structures compared to similar vertically stacked rings [1], [4], [8], [13]. This increases the design freedom and reduces the number of crucial production steps to pattern critical features.

III. Experimental Results

Measurements were performed using a tunable diode laser Santec TSL-210 as light source and a photodiode as detector. The recorded resonance spectra for both "through" and "drop"

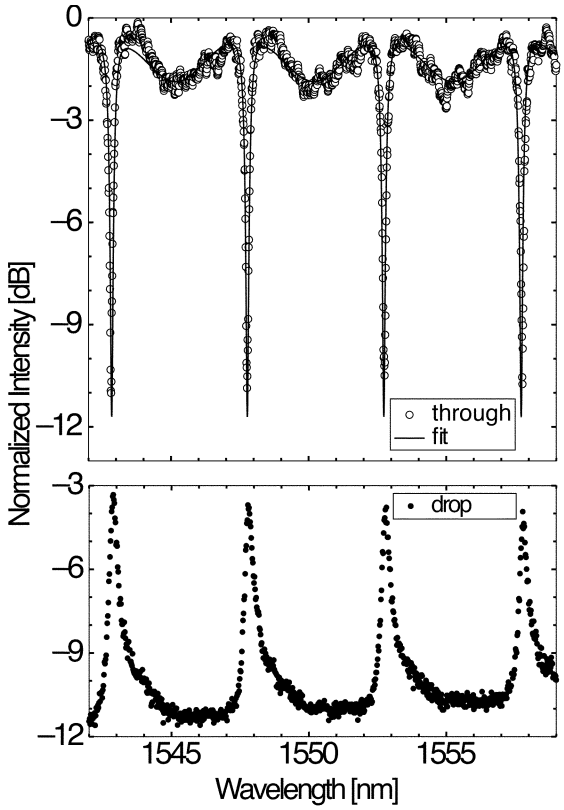

Fig. 2. Top: Measured TE resonance spectrum of an Ormocore microring of 50-μm radius at the "through" port (open circles) at room temperature together with a corresponding sum of two Fabry–Pérot resonance functions (solid line). Two modes can be distinguished. The finesses are $\mathcal{F} \simeq 17$ and $\mathcal{F} \simeq 0.5$ for the two modes, respectively. The small modulation overlapping the data series is due to the end facets of the port waveguide acting as mirrors. Bottom: The same resonance spectrum as shown above but measured at the "drop" port. Due to fabrication imperfections at the coupling regions the weaker mode is extinguished in this second case.

ports are presented in Fig. 2. The produced rings were shown to support two modes. Very deep resonances (more than -11 dB) were observed for the first mode while the less confined second mode exhibited only a weak modulation (2-dB peak-to-peak amplitude). The resonances are characterized by a *finesse* $\mathcal{F} = 17.1 \pm 0.5$ for the first and $\mathcal{F} \simeq 0.5$ for the second mode. The bandwidth of the sharp resonance is $\delta\lambda = 0.28 \pm 0.01$ nm (full-width at half-maximum) at a wavelength of 1547.78 nm leading to a *quality factor* $Q = 5500 \pm 200$. The finesse reached is 1.5 to 3 times higher than commonly reported for polymeric devices [1]–[4] due to the larger free spectral range (FSR $\sim$ 5 nm). Higher finesses are typically achieved in high refractive index compounds like semiconductors [6], where beside the strong confinement of the bent modes, the nature of the materials and the applied technologies allow to reduce the scattering losses and, therefore, increase also the quality factor.

The absence of the second mode in the "drop" port spectrum is most likely due to a small difference in aligning the two port waveguides to the ring (5% difference between the gap widths). As the coupling regions at the input and drop port are not equal, a lack of symmetry extinguished the portion of the weak second mode coupled out of the ring. Any attempt to reduce the dimensions of the cross section of the ring in order to suppress the higher mode also at the "through" port resulted in

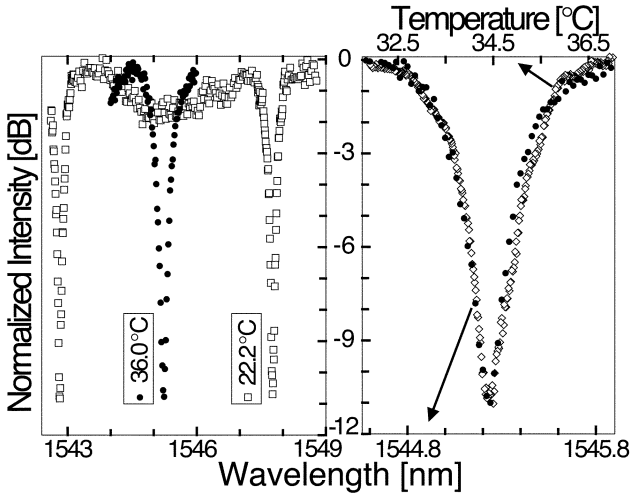

Fig. 3. Left: Resonance spectrum detail at room temperature, 22.2 °C (open squares) showing a shift toward shorter wavelengths by 2.52 nm if measured at 36.0 °C. We can notice a small widening of the resonance in the measurement at higher temperature due to the reduction of the material refractive index and, therefore, the confinement of the bent mode. Right: Same detail as on the left for a resonance peak at 36.0 °C reproduced by variation of the sample temperature at a fixed wavelength of 1545.6 nm (open rhombi).

a deterioration of the confinement of the first mode and consequently in a drastic decrease of the related finesse. This argument is supported by mode calculations and by the fact that just by repeating the measurement at 36.0 °C, the finesse drops from about 17 at room temperature down to 11 due to the small but notable decrease in the Ormocore refractive index (see the following and Fig. 3). Depending on the final application, one can choose to either produce a single-mode ring with wide but weak resonances or a multimode microring with at least one pronounced sharp resonance per period.

THERMALLY DRIVEN RESONANCES: In the presented device, a shift of the resonance was possible through the *thermooptic* effect.

The temperature has been very precisely driven by a Lakeshore 330 controller through a heating resistor of 37 Ω and a Pt100. The sample was placed onto the resistance that played also the role of sample holder.

A temperature change from 22.2 °C to 36.0 °C allowed us to move the resonance spectrum toward smaller wavelengths by 2.52 nm, which is more than half of the FSR in the considered spectral region [Fig. 3(left)]. The observed shift of the resonance peaks by about -0.2 nm/°C corresponds to a mode group index change of -1.8×10^{-4}/°C. The index change is of the same order of magnitude as for most of the polymers [14]. Furthermore, changing the device temperature by 5 °C at the fixed wavelength of 1545.6 nm, we were able to reproduce the same resonance as in the case of a wavelength scan at fixed temperature [Fig. 3(right)].

IV. CONCLUSION

We have demonstrated the structuring of submicrometer gaps in polymeric asymmetric lateral couplers without any special configuration of the patterning equipment. Furthermore, we demonstrated that even using polymer compounds with notably lower refractive index than semiconductors, it is possible to produce high performance microring resonators with a finesse as high as $\mathcal{F} \simeq 17$ and a bend radius as small as 50 μm only by independently choosing the dimensions of the different waveguides. Moreover, an easy way to control the separation between sample and mask in proximity mode exposure processes was proposed for aligners that do not have this feature. Finally, a possibility to tune the resonances of the Ormocore microrings via thermooptic effect was presented.

The proposed patterning technique allows for widening the spectrum of possible applications of ring-like resonators and is of fundamental importance for the further miniaturization of the structures toward VLSI photonics.

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