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Review

Integrated photonics devices on SU8 organic materials

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In this paper, a preview of targeted current research on integrated photonics based on the SU8 material was given. Such an approach takes advantage from a significant know-how regarding optical simulations by various analytical and numerical mathematical methods for the development of optical circuits on polymers. Original organic integrated photonics devoted to optical telecommunications and sensors applications on sundry waveguides structures, Mach-Zehnder interferometer (MZI), 2.5D and 3D Micro-resonators (MR), such as modulators, optical filters, devices for sensing pressure, gas and acid detections, heat flow measurements and future bio-detection schemes have been designed and realized last years. Present-day investigations deal with another main axis: The integration of 2.5D and 3D micro-resonator (MR) elements on photonic chips (optical add-drop filters circuits wavelength division de-multiplexing) which is under study, together with bio-sensors components based on the excitation of whispering gallery modes (WGMs) localized near the edge of the MR with sharp spectral resonance. Such issues and their solving approach highlight the interest to develop in the future specific hybrid processes such as biomolecular film deposition, self-assembled growth and handling, plasma treatments coupled with microtechnologic thin layers processes and micro-fluidic devices.

Key words: Integrated photonics, waveguides structures, Mach-Zehnder interferometers, micro-resonators, organics materials.

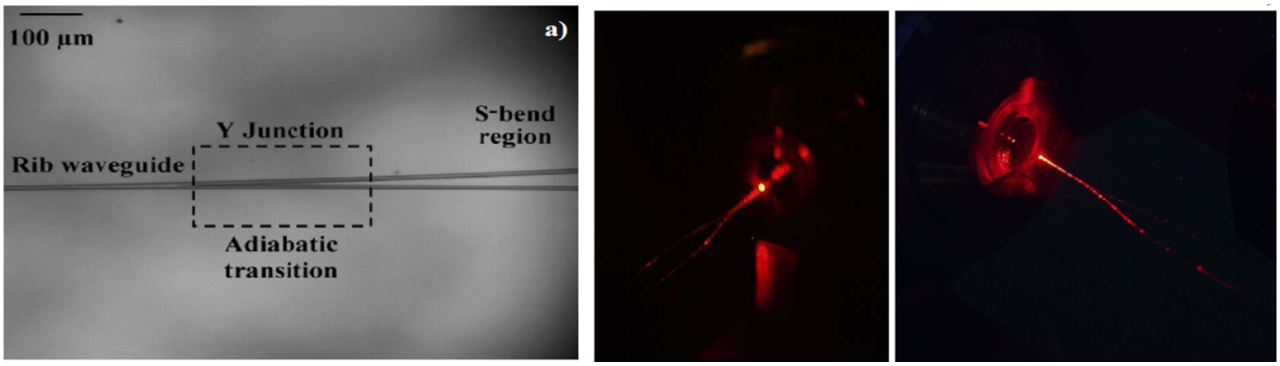
INTRODUCTION

Integrated optics are increasingly being used in sensors and telecommunications applications (Tamir et al., 1990). Moreover, many integrated photonics devices are based on new materials, such as organics and polymers (Labbe et al., 2002; Scheuer et al., 2006). The latter offer numerous advantages as large volume and low-cost for mass production facilities. With the Institute of Physics at Rennes and their collaborations, our current research on micro- and nano-photonics takes advantage from a significant know-how regarding optical simulations by different analytical and numerical mathematical methods (Bêche et al., 2004, 2010; Begou et al., 2008) for the development of optical circuits on polymers. Original organic integrated photonics devoted to optical telecommunications and sensors applications on sundry waveguides structures (Kim et al., 2003; Bêche et al., 2004, 2005; Bosc et al., 2004; Airoudj et al., 2008; Begou et al., 2007; Granier et al., 2009; Duval et al., 2008), Mach-Zehnder Interferometer (MZI) (Bêche et al., 2006), 2.5D and 3D Micro-Resonators (MR) (Zebda et al., 2008; Bêche et al., 2010; Huby et al., 2010), such as modulators, optical filters, devices for sensing pressure (Pelletier et al., 2007), gas and acid detections (Airoudj et al., 2008, 2009), heat flow measurements (Pelletier et al., 2006; Giordani et al., 2007) and original bio-detections have been realized.

Present-day investigations deal with a main axis: The integration of 2.5D and 3D Micro-Resonators (MR) elements on photonic chips (optical add-drop filters circuits wavelength division de-multiplexing) are under study, together with bio-sensors components based on the excitation of Whispering Gallery Modes (WGMs) localized near the edge of the MR with sharp spectral resonance. Then, the development of specific hybrid processes such as biomolecular film deposition, self-assembled growth and handling, plasma treatments coupled with microtechnologic thin layers processes and micro-fluidic devices are presented. This paper exposed as an overview, such integrated photonics devices.

WAVEGUIDES STRUCTURES, MACH-ZEHNDER INTERFEROMETERS, 2.5D AND 3D MICRO-RESONATORS

First, it is necessary to develop powerful and flexible tools



a **b**

Figure 1. a) Photograph of the Y-junction element of a MZI developed with SU8 optical rib waveguide (Pelletier et al., 2007; Bêche et al. 2006). b) Photos of the micro-injection and the TE_{00} optical mode propagation into such MZI for a 670 nm wavelength.

of analysis to simulate, design and optimise versatile polymer structures with sundry geometries such as buried channels, raised strips, ribs, embedded, or ridge waveguides, in order to realise integrated optical devices. Such softwares are pivotal to solve the eigenvalues and eigenvectors in electromagnetism, respectively, to assess effective index values, effective modal propagation constants and the optical spatial field patterns in any integrated optical waveguide. Various mathematical methods (extended Marcatili method, semi-vectorial finite difference method and Galerkin spectral method), have been developed and implemented with a view to simulating optical propagation mechanisms and optimizing the design and the properties of optical waveguides on polymers: Then, they are considered single modes characteristics and best confinement of the optical distributions in the core waveguides for lower optical losses and propagation in S-Bends structures (Bêche et al., 2004; Begou et al. 2008). Then the realization and characterization of relevant elements of integrated optics based on glycidyl ether of bisphenol A (SU8), polymeric silane (PS233) polymers, spin on glass (SOG) materials such as planar rib straight waveguides (Bêche et al., 2004, 2005; Airoudj et al. 2008; Begou et al., 2007; Granier et al., 2009), S-Bends, Y-Junctions and MZ interferometers (Bêche et al., 2006; Pelletier et al., 2007) have been carried out with the aid of the optimization of numerous thin layers processes (Figure 1a and b).

As an example, the linear absorption coefficient of energy for TE–TM rib waveguides have been measured and estimated, near 0.32 and 0.46 cm^{-1}, respectively, for both optical modes TE_{00} and TM_{00} on $Si/SiO_2/SU8$ structures yielding optical losses of 1.36 and 2.01 dB/cm, respectively. Optical losses ascribed to Si/SOG/SU8 microstructures have also been evaluated as 2.33 and 2.95 dB/cm for both polarisations. Moreover, adequate CF_4 cold RF plasma treatments, based on a substitution of H atoms by F atoms, have been allowed to reduce the previous optical losses by 70% at telecommunication wavelength for such SU8 organic waveguides (Bêche et al., 2005; Airoudj et al., 2008) (Figure 2a and b).

Among optical structures, ultra-integrated micro-resonators (MRs) present a broad potential of scientific applications, whose number rises dramatically with integrated photonics applications. Such components rely on a specific resonance spectral property regarding the waveguide-MR coupling that depends on several opto-geometric parameters. Such fundamental concepts and devices hinge upon light control into the tiniest space and the longest photon storage time as possible so as to strongly confine the optical mode excitation called whispering gallery mode (WGM) into micro-volumes with a sharp and accurate resonance described by the cavity Q-factor $\omega_0\tau$ and the modal life-time τ. We have designed and realized three integrated photonic families of micro-resonators (MR) on multilayer organic materials. Such so-called 2.5D-MR and 3D-MR structures show off radius values ranging from 40 to 200 µm. The first family is especially designed on organic multilayer materials and shaped as ring- and disk-MR organics structures arranged on (and coupled with) a pair of SU8-organic waveguides.

Both second and third families are related respectively to 3D-MR structures composed of spherical glass-MR coupled with organic waveguides by a biomolecular lipid film about ten nanometers in thickness (Bêche et al., 2010), and with 3D organic MR with an approach combining microfluidics techniques and thin-film processes (Huby et al., 2010). The second family involves hybrid 3D-MR structures composed of spherical glass-MR arranged on organic pair-SU8-waveguides, an efficient coupling being ensured with a Langmuir–Blodgett Dipalmitoylphosphatidylcholine (DPPC-lipid) film whose thickness range from 12 to 48 nm. We have characterized such add/drop filters as regard intensity

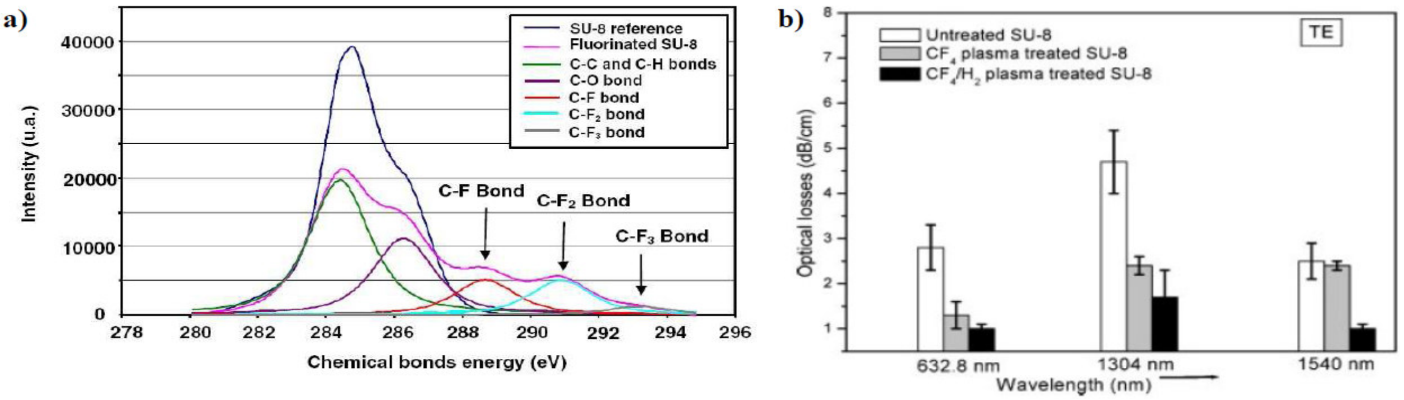


Figure 2. a) XPS measurements of the SU-8 untreated reference and fluorinated SU-8 samples. Deconvolution of the SU-8 fluorinated spectrum clearly shows three peaks due to the fluorine functionalisation for the CF, CF_2 and CF_3 bonds, respectively, at 288.5, 291 and 293 eV (Bêche et al., 2005). b) Optical losses in the waveguides treated by CF_4 plasma and by CF_4/10%H_2 plasma for the TE optical mode at 633, 1304 and 1540 nm (from Airoudj et al., 2008).

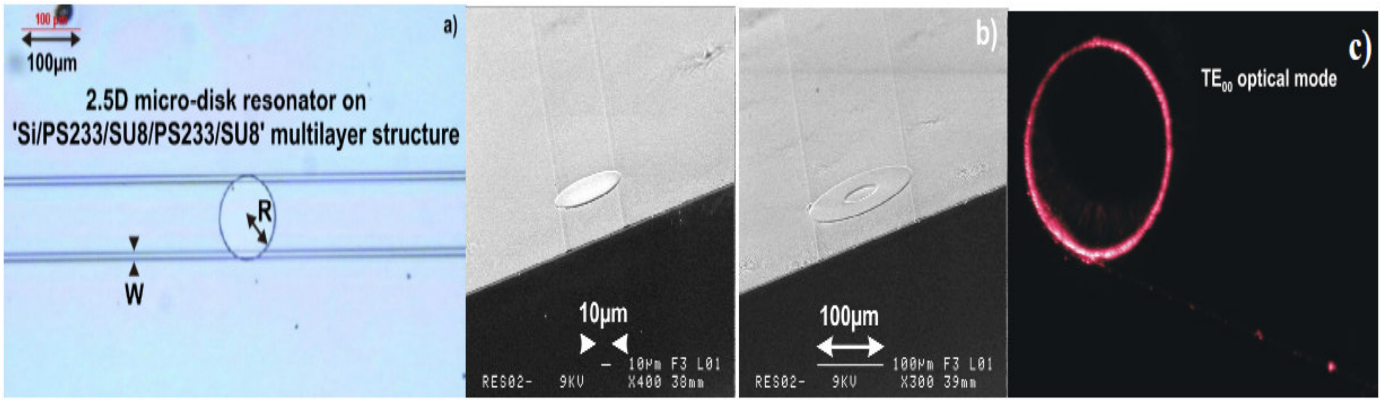


Figure 3. a) Optical microscopy images of 2.5D disk MR structures: MR on Si/PS233/SU8/PS233/SU8 multilayer polymers. Radii (R) of such micro-resonators are respectively, 40 and 70 µm; the width (w) and the height of the rib waveguides are respectively, 6 and 0.8 µm. b) Scanning electron microscopy (SEM) images of 2.5D ring and disk MR structures: MR on Si/SOG/SU8/SOG/SU8 materials. c) Photograph of a TE_{00} WGM excitation into a micro-disk with a single-mode propagation for a 670 nm wavelength (Zebda et al., 2008).

and spectral measurements respectively, and experimentally achieved an evanescent resonant–photonic-coupling between the 3D-MR and the 4-ports structure through the DPPC-gap (Figure 4). The microfluidic framework with flow rates control allows the fabrication of the above mentioned 3D MRs. As first processes, polymer spin coating, surface plasma treatment and selective UV-lithography have been developed to realize 2.5D photonic MRs. Two kinds of 2.5D MR optical microstructures, Si/SOG/SU8/SOG/ SU8 and Si/PS233/SU8/PS233, have been developed. Optical and scanning electronic microscopy (SEM) images of the 2.5D MR make certain the good homogeneity of structures and surfaces shaped by our processes and treatments (Zebda et al., 2008) (Figures 3 a, b and c). Secondly, we have designed and characterized photonic-structures respectively made of 3D-glass-MR arranged on a pair of SU8/lipid waveguides (Figure 4) and 3D-organic MR shaped by a microfluidic approach coupled to photonic devices (Figures 5 a and b). Such an interdisciplinary approach has been judiciously achieved by combining microfluidics techniques and thin-film processes respectively, for the realizations of microfluidic and optical chips. Then such a microfluidic framework with flow rates control allows the fabrication of organic microresonators.

Optical sensors and telecommunications applications

As mentioned earlier, such integrated optics devices (MZI, MR and so on) can be widely used in sensors and telecommunications applications. Specific photonic characterizations have been achieved by way of a

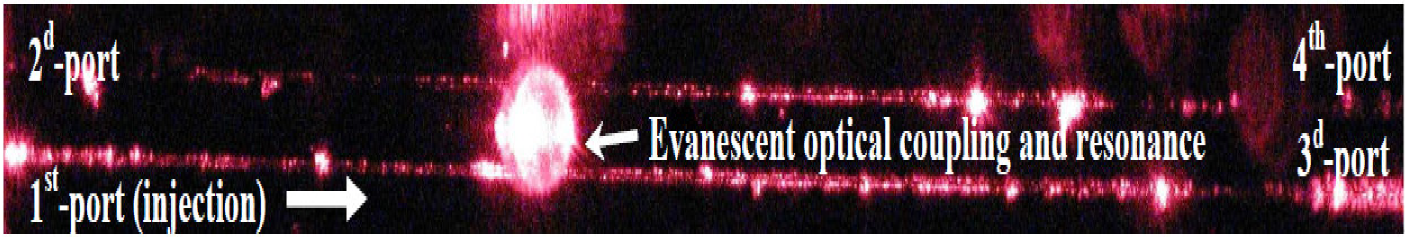


Figure 4. Upper view of the optical injection at 670 nm (1st port SU8/lipid waveguide) and coupling with respectively, the 3D glass-MR and the other ports (2nd to 4tth port) (Bêche et al., 2010).

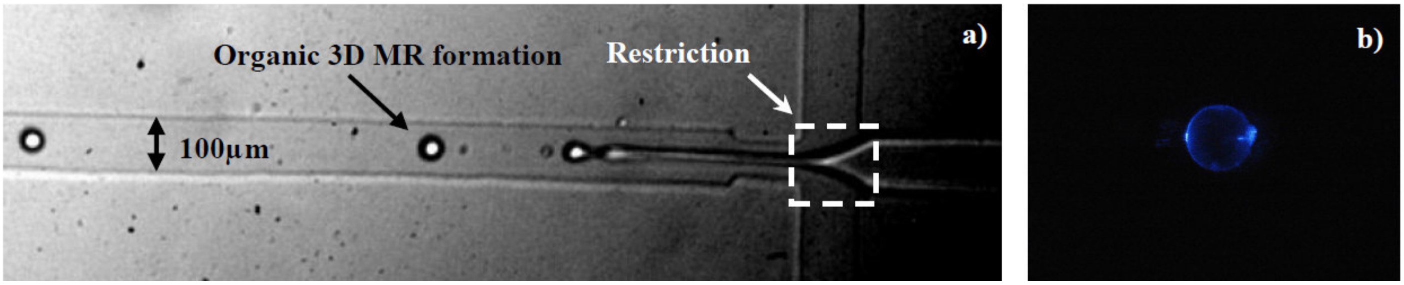


Figure 5. a) Optical picture of the flow-focusing geometry showing the T-junction (white dashed square) and the 80-µm restriction. The formation of droplets (or organic 3D MR) occurs under jetting mechanism onto microfluidic chip (Huby et al., 2010). b) Photograph of a TE_{00} WGM excitation into an organic 3D MR for 470 nm wavelength after integration onto a photonic chip.

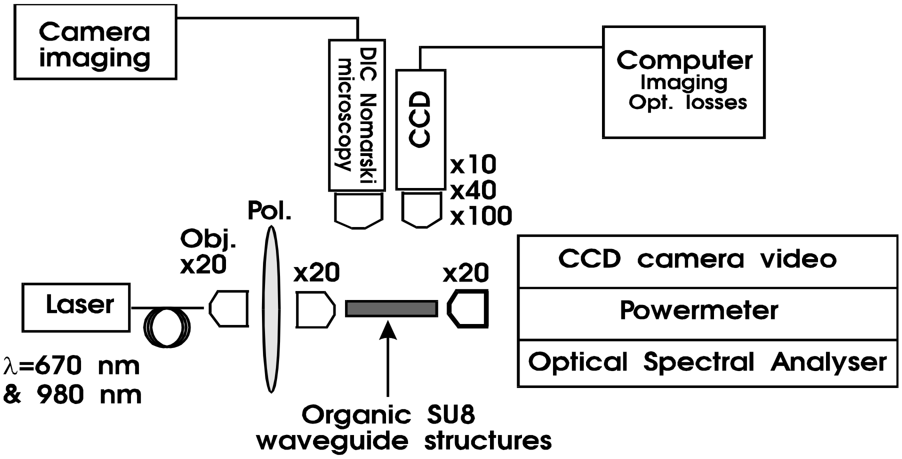


Figure 6. Schematic diagram of the micro-optical bench, detections and imaging devices.

micro-injection process with an optical bench so as to test the performance of the obtained nano-connection design. This micro-optical injection bench consists of a laser source operating at various wavelengths (670 and 980 nm) fitted with an enhanced control in temperature together with associated objectives. Hence, the excitation of any optical mode of the polymeric SU8 waveguide structures together with a relevant optical coupling and propagation are validated. The extremity of the bench is fitted with a camera (Pulnix-PE), together with a video system so as to visualize the output optical signal at the end of both sections of the optical waveguides (Figure 6). As an example, we have designed and developed three families of integrated photonic sensors for ammonia detection (Airoudj et al., 2008; 2009). These photonic sensors are integrated onto single-mode TE_0-TM_0 SU8 polymer planar waveguides and their operating mechanism is based on a polaronic effect with the

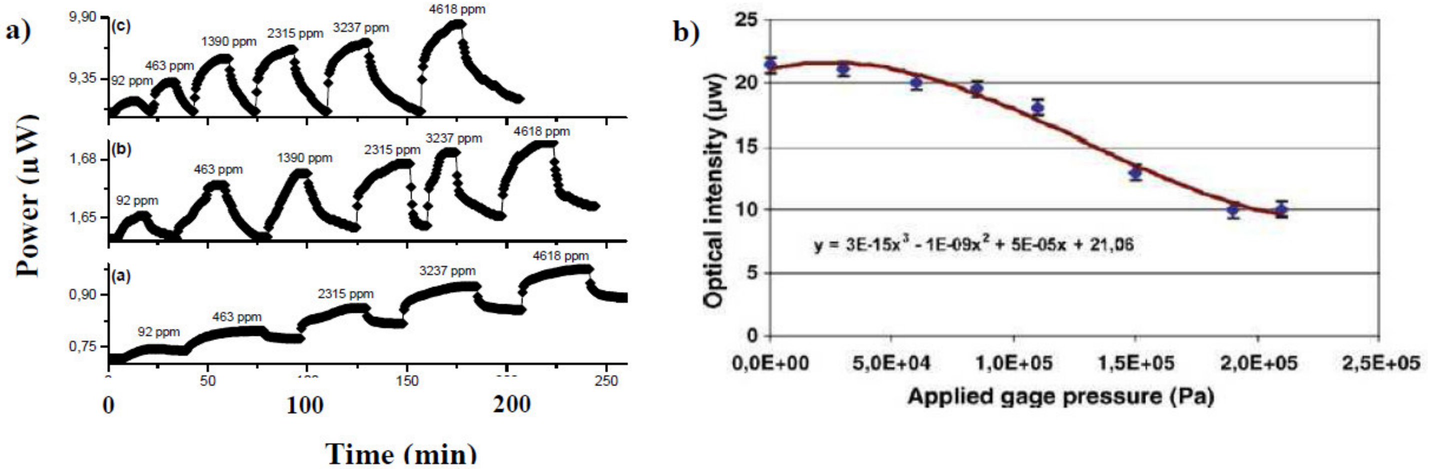


Figure 7. a) Transmitted light power variations for a generic optical sensor exposed to different NH_3 concentrations (Airoudj et al., 2009). b) Optical intensity values observed at the output of the Mach-Zehnder interferometer versus applied gage pressure(Pelletier et al., 2007).

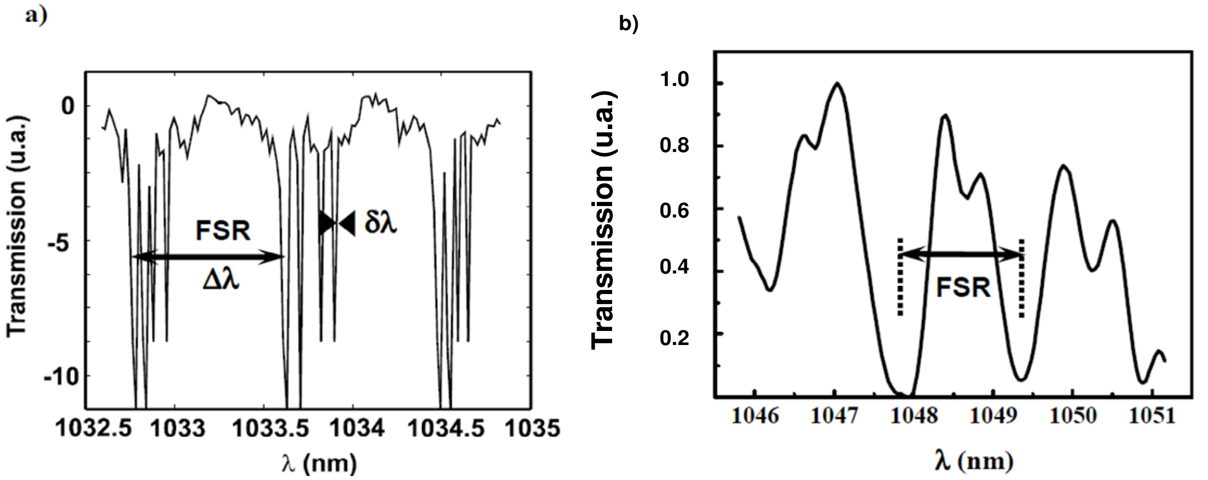


Figure 8. a) Spectral response of the optical MR related to a 4-WGM spectra excitation into the 3D-glass-MR-element. A 0.97 nm value of FSR is measured and yields a quality Q-factor up to 4.10^4 (Bêche et al., 2010). b) Spectral response of the optical organic MR achieved by combining microfluidics techniques and thin-film processes (Huby et al., 2010).

polyaniline (PANI) sensitive polymer material. Figure 7a makes clear, the transmitted light power variations for a prototype of optical sensor exposed to different NH_3 concentrations. Moreover, various pressure sensors relying on MZI devices has been designed with a view to measuring pressure disturbances due to optical path variations (Bêche et al., 2006). Such a system is arranged in order to work in intensity modulation scheme.

The MZI is made up of straight and bent rib optical waveguides composed of SU-8 polymer (Pelletier et al., 2007). The mainstay of the device is based on differential measurements performed by a sensing arm arranged with a micromachined membrane and actuated by a given pressure disturbance, while the second arm of the interferometer is considered as a reference one (Figure 7b). As other examples, Figures 8a and b represent the characteristics of integrated filters based on 3D MR schemes. Spectral analyses with an ASE broadband source (λ_0 = 1030 nm, model BBS 450 from Newport) and an optical spectrum analyzer (MS 9710C from Anritsu) have been carried out for such photonic-devices showing a 4-WGM excitation into the 3D-MR (Figure 8a). As a result, spectral resonances have been observed and characterized with a $\Delta\lambda$ = 0.97 nm free spectral range (FSR), appearing as stemming from a $R = \lambda_0^2/(2\pi n_{eff}.\Delta\lambda)$ = 110 µm radius for the MR structure, associated with a high quality Q-factor $\lambda_0/\delta\lambda$ up to 4.10^4 and a finesse-selectivity $\Delta\lambda/\delta\lambda$ reaching 37. Moreover, since the ratio

FSR/λ_0 comes up as an optical cycle time T to be compared with the round trip time t_{rtt} as seen in a time domain interpretation, then previously described hybrid 3D-MRs are characterized with $t_{rtt}=\lambda_0^2/(c.\Delta\lambda) = 3.7$ ps. Thus, according to the modal-life-time parameter of the system, $\tau = Q/\omega_0 = 21.9$ ps, one can infer from the behavior of the WGM defined as eigenvectors of related electromagnetic description, that t_{rtt} is consistent with an average of six equatorial rounds for light recirculation.

Then we have achieved an evanescent photonic coupling into such a family of micro-resonators photonic structures and excited WGM. Spectral resonances have been characterized, showing off optical resonances most advantageous to realize integrated photonic sensors based on functionalized MR-structures proper for bio-detection (Arnold et al., 2003), as a shift of such resonances can be used. Such experimental results should contribute in designing highly effective photonic devices involving 3D organic optical cavities.

CONCLUSION

Various hybrid thin-film processes have been combined, such as biomolecular film deposition, plasma treatments coupled with microtechnologic processes and micro-fluidic devices, to develop photonic integrated generic structures based on waveguides, MZIs and MRs. These integrated MZI and MR components on polymers and devices are typically devoted to optical telecommunications and can be widely developed for sensors applications too. It is expected that such a MR approach regarding previous filters will be instrumental in many sensing applications in the next future with proper shift optical resonance schemes and various systems detections (intensity detection with or without modulation schemes, phase detection, etc).

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