Photonic Crystal (PC) Waveguide Based Optical Filters for Dense Integration of High Sensitivity PC Biosensors

Hai Yan[1], Yi Zou[1], Chun-Ju Yang[1], Zheng Wang[1], Naimei Tang[2], Swapnajit Chakravarty[2], Ray T. Chen[1, 2]
[1]Dept. Electrical and Computer Engineering, The University of Texas at Austin, Austin, TX 78758, USA
[2]Omega Optics Inc., Austin, TX, 78759, USA
e-mail address: hai.yan@utexas.edu, swapnajit.chakravarty@omegaoptics.com, raychen@uts.cc.utexas.edu

Abstract: A photonic crystal (PC) waveguide based optical filter that enables dense integration of high sensitivity L55 PC microcavities for biosensor microarrays is demonstrated.
OCIS codes: (280.0280) Remote sensing and sensors; (050.5298) Photonic crystals; (130.0130) Integrated Optics

Photonic crystal (PC) cavities side-coupled to photonic crystal waveguide (PCW) have been demonstrated as a competitive candidate for high-sensitivity biosensors [1-5]. In ref. [5], a detection limit of 50 femto-molar was reported using a PC cavity consist of 55 missing air holes. The PC cavity of such length is able to provide higher quality factor and more surface area for the interaction between optical mode and the biomolecules to be detected. Optical diagnostics also require that specific and control binding reactions be performed, preferably at the same instant of time, simultaneously on the same chip with the same sample. Microarrays of this type of biosensor were also demonstrated with multiplexed structures [3] for the specific detection of lung cancer cell line lysates [2]. This structure uses a 1×4 multimode interference (MMI) coupler to connect four PC cavity biosensors in parallel and thus allow the sensing of different type of biomolecules simultaneously.

In the design of photonic chips for multiplexed biosensing, one must also take into account the external optical interface that couples light into the silicon optical chips. In a benchtop diagnostic system, light is coupled into and out of the photonic waveguides via grating couplers. The system configuration merely requires a single laser and a single photodetector, coupled through free space or optical fibers, while the chip or the external system is raster scanned during measurements. Therefore, when designing a portable diagnostic device, with limited space for off-chip optical components, one needs to maximize the number of sensors that can be simultaneously interrogated with a single input and output, since an optical fiber array scales prohibitively from an economic perspective with increasing array size. In a conventional L3 PC microcavity side coupled to a W1-type PC waveguide in a silicon-on-insulator (SOI) chip, a single resonance couples to the PCW (as shown in Fig. 1(a). Hence, it is possible to couple several L3 PC microcavities in series between a single grating coupler input and a single grating coupler output as we have demonstrated in Fig. 1(b). However, higher sensitivity PC microcavities, such as the L55 type, have several resonances that couple to the W1 PCW which precludes series connection of the L55 type PC microcavities (Fig. 1(c)). Under the circumstances, one must integrate new components with L55 PC microcavities to acquire the spectra of all channels from the 1×4 MMI..

In the paper, we propose a scheme that integrates a PCW bandpass filters on each channel of the multiplexed system. PCW filters are designed to select a narrow band in the range of wavelengths in the C-and L-bands that filter a specific resonance or resonances of a L55 PC microcavity designed in the same bands. Devices are fabricated by etching features in a 250 nm silicon device layer of a SOI wafer, combining electron beam lithography with reactive ion etching. Devices are cleaned using standard Piranha process before measurement. Fig. 2(a)-(b) show the PCW transmission spectra in water for a PCW (without the coupled L55 PC microcavity), and a polymer SU8 coated PCW filter respectively. Fig. 2(c) shows the predicted composite transmission spectra when the structures in Figs. 2(a) and 2(b) are connected in series. As observed in Fig. 2(c), the SU8 coated PCW only allows a narrow 25 nm range of wavelengths to be transmitted from the broad range of wavelengths otherwise transmitted by the PCW in Fig. 2(a). When connecting the PCW filter with the PC cavity sensor in series, a group index taper is introduced in each PCW to efficiently couple light into the slow light region from regular channel waveguide and eliminate Fabry-Perot fringes between the two PCW structures [6].

Fig. 3(a) shows schematic of our proposed PC biosensor microarray. Fig. 3(b) shows the corresponding predicted spectrum acquired from the single output waveguide. On each arm, PC biosensor is cascaded with another PCW filter. The lattice constants of the two PCW are engineered so that a passband is created whose rising edge comes from the PCW filter while the falling edge from the bandedge of the PC sensor. Within the passband, there will be resonance peaks of the PC cavities. The pass bands are carefully designed with selected lattice constants, to avoid any overlap with each other. For the L55 biosensor mentioned above, as observed from Fig. 1(c), a bandwidth of 5 nm to 10 nm is enough to include a resonance suitable for biosensing. In this way, resonances from all four L55 PC microcavities can be interrogated simultaneously with a single input and a single output optical fiber.

While a 1×4 MMI device as shown in Fig. 3(a) will be demonstrated in the future, we demonstrated initial proof-of-concept band pass filtering on one arm of the MMI. A W1 line defect PCW side coupled with L55 microcavity biosensor and then cascaded in series with a W1 line defect PCW (as a filter) is fabricated on one arm. In the second arm, a single L55 PC microcavity is fabricated with a smaller lattice constant than the L55 PC microcavity in the other arm. Hexagonal structure with a uniform lattice constant of 405nm and 390nm is adopted for PC biosensor and PCW filter respectively, to ensure a pass band in the spectrum. Silicon slab thickness is 250nm, while the air hole diameters for PC biosensor and PCW filter are 216nm and 170nm, respectively. During the test, the PC microcavity is in water (n=1.33) ambient as required in biosensing.

Fig. 4 shows spectra of three different devices: a single PC biosensor (L55 PC microcavity coupled to W1 PCW, black line), a single PCW filter (blue line) and serially connected PC biosensor and PCW filter (red line). The PCW filter shows a rectangular-shape passband from 1575 nm to 1610 nm. Within this range, the L55 PC biosensor shows several resonance peaks suitable for biosensing. When connecting them together, the resonances within filter passband almost remain unchanged with low additional loss (2-3 dB), while other resonances outside the pass band are filtered out. The measurement result demonstrates our idea of filtering certain resonances of PC microcavity biosensors. In following measurements, the pass band width will be tuned and the multiplexed sensor in Fig. 3(a) and in ref. [2] will be demonstrated with a single optical fiber input and a single optical fiber output. The use of integrated optical filters would thus increase device integration density in high sensitivity PC sensor architectures.

The work is supported by the National Cancer Institute (NCI) under SBIR contract # HHSN261201200043C.

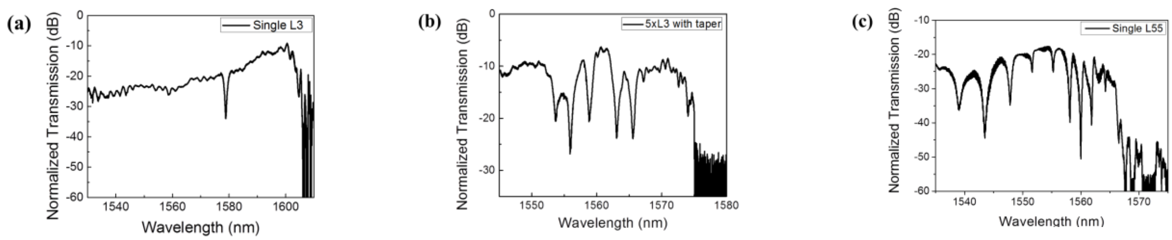

Fig. 1. Transmission spectrum in water for a W1 PCW coupled to (a) a single L3 PC microcavity, (b) series connected five L3 PC microcavities in cascaded PCWs and (c) a single L55 PC microcavity. Spectra are taken in water from biosensing perspective.

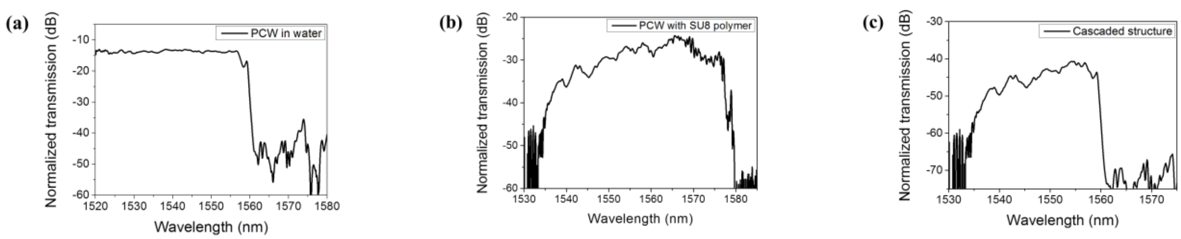

Fig. 2. Waveguide transmission spectra of (a) PCW in water (b) PCW with SU8 polymer, in water and (c) predicted series connected devices in (a) and (b).

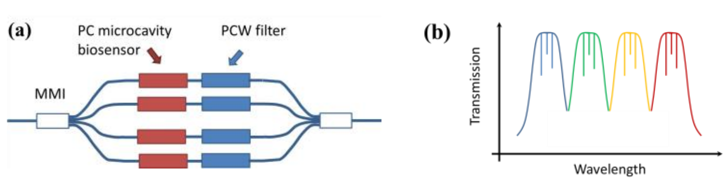

Fig. 3. (a) Schematic of multiplexed biosensor microarray with single output port. (b) Predicted transmission spectrum of the device in (a), with different colors corresponding to different PC microcavity biosensors.

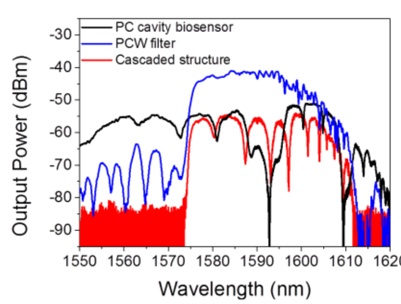

Fig. 4. Measured spectra for single PC cavity (black), single PCW filter (blue), and cascaded structure of these 2 devices (red).

References

[1] W. C. Lai, S. Chakravarty, Y. Zou, Y. Guo, and R. T. Chen, Appl. Phys. Let., 2013, **102**, 41111.
[2] S. Chakravarty, W.-C. Lai, Y. Zou, H. A. Drabkin, R. M. Gemmill, G. R. Simon, et al., Biosens. Bioelectron., 2013, **43**, 50.
[3] Y. Zou, S. Chakravarty, W.-C. Lai, C.-Y. Lin, and R. T. Chen, Lab Chip, 2012, **12**, 2309.
[4] S. Pal, A. R. Yadav, M. A. Lifson, J. E. Baker, P. M. Fauchet, and B. L. Miller, Biosens. Bioelectron., 2013, **44**, 229.
[5] Y. Zou, S. Chakravarty, D. N. Kwong, W. C. Lai, X. Xu, X. Lin, et al., IEEE J. Sel. Top. Quant. Electron., 2014, **20**, 6900710.
[6] C.-Y. Lin, X. Wang, S. Chakravarty, B. S. Lee, W.-C. Lai, and R. T. Chen, Appl. Phys. Lett., 2010, **97**, 183302.