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The role of group index engineering in series-connected photonic crystal microcavities for high density sensor microarrays

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We experimentally demonstrate an efficient and robust method for series connection of photonic crystal microcavities that are coupled to photonic crystal waveguides in the slow light transmission regime. We demonstrate that group index taper engineering provides excellent optical impedance matching between the input and output strip waveguides and the photonic crystal waveguide, a nearly flat transmission over the entire guided mode spectrum and clear multi-resonance peaks corresponding to individual microcavities that are connected in series. Series connected photonic crystal microcavities are further multiplexed in parallel using cascaded multimode interference power splitters to generate a high density silicon nanophotonic microarray comprising 64 photonic crystal microcavity sensors, all of which are interrogated simultaneously at the same instant of time. © 2014 AIP Publishing LLC. [http://dx.doi.org/10.1063/1.4871012]

Integrated optical devices based on photonic crystals (PCs) show a unique slow light phenomenon that significantly enhances light-matter interaction. Several applications have been proposed and demonstrated, such as tunable delay lines, ultracompact optical switches, and highly efficient modulators. In recent years, PC microcavities have attracted a lot of interests in biological and chemical sensing due to their compact sizes (of the order of a few square microns in surface area) and high sensitivity. PC microcavities side coupled to a photonic crystal waveguide (PCW) take advantage of strong slow light effect, high quality factor resonances, and a larger optical mode overlap with the analyte within a compact optical mode volume to provide superior performance compared to other chip based photonic technologies. The miniaturized geometries enable multiple sensor microcavities on chip to be integrated simultaneously, thus advancing the platform towards high density biosensing microarrays.

Dense integration of PC sensors on chip requires that PC microcavities be laid out in series and parallel in the optical circuit. In the past, we have demonstrated that multimode interference (MMI) power splitters can be employed to connect several PC microcavity sensors in parallel. Multiplexing of two and five H1 (one missing or modified hole) PC microcavities in series were demonstrated previously in 2D (Ref. 17) and 1D (Ref. 18) PCs, respectively. While the 1D PC couples to a strip waveguide at group index of n_g ~ 3.7, the 2D H1 PC microcavity couples to the 2D PCW at n_g ~ 4.2. 2D PC microcavities of the L3, L13, or L55 types (where Ln denotes that the PC microcavity is formed by removing n holes along the Γ–K lattice direction in a hexagonal lattice), have demonstrated experimentally higher sensitivities than devices in Refs. 17 and 18. In Ln type PC microcavities, the resonances couple to the PCWs at n_g > 12 (Ref. 19); hence group index engineering is necessary from coupling strip waveguides to the input and output of the PCWs to overcome Fresnel reflection losses at the resonance frequency of the PC microcavity. In this paper, we experimentally demonstrate that group index taper engineering is necessary to efficiently multiplex L3-type PC microcavities in series. We demonstrate five L3 PC microcavities in series. We also demonstrate a dense microarray of 64 microcavity-based sensor nodes with series and parallel connected PC microcavity sensors, all sensors being simultaneously interrogated at the same instant of time, from a single optical source.

The engineered PC structure, as shown in Fig. 1(a), has a L3 PC microcavity side coupled to a W1 line defect PCW, where L3 denotes 3 missing air holes and W1 denotes that the width of the PCW is 3a, where a is the lattice constant. Silicon slab thickness and air hole diameter are h = 250 nm and d = 0.55a, respectively. For transverse electric (TE) polarization, the PCW only supports a single propagation mode inside the band gap as shown in the dispersion diagram in Fig. 1(b). The band diagram of the W1 PCW is obtained by three-dimensional plane wave expansion (PWE) simulations, considering water (refractive index n = 1.33) as the ambient.

Four such structures of Fig. 1(a) are connected in series to result in 4 PC microcavities in series. In contrast to the previous designs, where the two PC microcavities are coupled to the same PCW, the isolated PC microcavity design ensures negligible cross-talk between individual sensors. Each PC structure in series is designed with a different lattice constant a of 392.5, 393.5, 394, and 396 nm, respectively, to stagger the transmission band edge in each PC section. Since the L3 PC microcavity resonance is offset by a fixed wavelength (~20 nm) from the transmission band edge of the corresponding PCW, the staggering of lattice constants thus ensures that the individual PC microcavity resonances do not overlap in the final output transmission spectrum. In each PC pattern, the group index taper is engineered by...
gradual widening of the PCW from W1 to W1.08 near the coupling strip waveguide as depicted in Fig. 1(a). W1.08 indicates that the width of the PCW in that section is $1.08 \times \sqrt{3}a$. Fig. 1(b) is the dispersion diagram of the W1 PCW with the smallest lattice constant $a = 392.5$ nm. The dispersion profile for the W1.08 PCW, also at $a = 392.5$ nm, is shown by the dashed black line. The corresponding group indices are also indicated in the figure.

The devices were fabricated on a silicon on insulator (SOI) wafer with 250 nm silicon layer and 3 $\mu$m buried oxide (BOX) layer. Fabrication details can be found in Ref. 15. All components including PCWs, PC microcavities, group index tapers, and strip waveguides are patterned on SOI chip simultaneously. PCW devices with and without PC tapers were fabricated on the same chip. Scanning electron microscope (SEM) images of the fabricated structure and individual sections are shown in Fig. 2.

Light is coupled into and out of the devices using subwavelength grating couplers via polarization maintaining single mode fiber on the input side and standard single mode fiber on the output side, respectively. Optical spectrum analyzer (OSA) is used to analyze the transmitted light. All the transmission spectra of PC devices with and without PC tapers were normalized to the spectrum from a reference waveguide comprising two grating couplers and one single strip waveguide. In the L3 PC microcavity coupled to W1 PCW in water, a single resonance is dropped in the output transmission spectrum of the PCW. Fig. 3 plots the output transmission spectra from 2, 3, and 4 cascaded L3 PC microcavities in series, with and without index taper. All spectra are measured in water with the objective to implement biosensing.

With group index tapers, as shown in Figs. 3(a)–3(c), 2, 3, and 4 resonant peaks, respectively, are clearly seen. In Fig. 3(c), when four PC microcavities are connected in series as shown in Fig. 2(b), the resonances of the L3 PC microcavities in the respective sections are dropped from the transmission spectrum of the series connected W1 PCWs. The four resonances are indicated as A, B, C, and D, respectively, arising from resonances in largest to smallest lattice constant PC sections. The resonances are easily distinguished, and the band edges are also sharp with 20 dB extinction ratio between the transmission band and the band gap. In contrast,
in Figs. 3(d)–3(f), without PC group index tapers, the resonant peaks are probably buried in noise fringes resulting from group index mismatch between the strip waveguide and PCW.

The normalized resonance frequencies of 4 cascaded L3 PC microcavities are calculated from the experimental transmission spectra as indicated by lines with different colors A, B, C, and D in Fig. 1(b). In demarcating the position of the resonance wavelength in the dispersion diagram, based on previous results,19,21 we estimate that the group index at the experimentally observed transmission band edge is \( n_g \approx 35 \). Mode D represents the microcavity resonance for the L3 PC microcavity in the PC pattern with smallest lattice constant \( a = 392.5 \text{ nm} \). The resonance wavelength that is dropped by this PC microcavity is coupled to the PCW at the strip waveguide-PCW interface at \( n_g \approx 6 \) instead of \( n_g \approx 13 \) which is in the absence of a group index taper.

Since the wavelengths C, B, and A that are dropped in succeeding PC stages must first propagate through the PC stage with \( a = 392.5 \text{ nm} \), Fig. 1(b) shows that in the absence of a group index taper, these wavelengths would be coupled into the first PC stage at increasing group indices, reaching \( n_g \approx 34 \) at the resonance wavelength A. Such a large group index mismatch with the single mode strip waveguide makes the coupling efficiency very low. It also results in huge Fresnel reflections and Fabry-Perot resonance fringes in the output transmission spectra as observed in Figs. 3(d)–3(f).

We also note the higher propagation loss with increasing series cascading of PC sections. The higher loss and decrease in extinction ratio are also evidenced by Fig. 3, where a band edge is vaguely discernible in Fig. 3(d), by comparing with Fig. 3(a); however, no sharp band edges can be seen in Figs. 3(e) and 3(f).

When a group index taper is employed, resonance wavelength A instead couples to the first PC pattern and succeeding PC patterns at a low group index \( n_g \approx 7.5 \) which significantly lowers the reflection losses and Fabry-Perot fringes. Noise ripples arising from such reflection is thus suppressed below 2 dB. The transmission band edge is clearly observable in each case. The dispersion engineering is done in each stage, so that the resonance wavelength A dropped in the PC microcavity in the last (fourth) stage with \( a = 396 \text{ nm} \) has significantly reduced reflection losses in preceding stages. The same argument holds for resonances C and B dropped by the L3 microcavities in the second and third PC stages in series.

In Fig. 4, we show the output transmission spectrum from 5 series-connected L3 PC microcavities, with group index engineering in each stage. 5 distinct resonant peaks are observed. In biosensing, resonance wavelength shifts in the range of 1–2 nm have been observed at the highest detected concentration of 1 \( \mu \text{M} \). Hence, we strive to maintain 2 nm spacing between individual resonances, so that resonances from individual PC microcavities do not overlap with others in the microarray when a shift in the corresponding PC microcavity is caused by probe-target biomolecule conjugation induced refractive index changes. From Fig. 4, the five resonance peaks are separated by roughly 2 nm from each other. We note that the extinction ratios of peaks marked by solid arrows are around 12 dB. A Lorentz curve fitting of the two resonance peaks indicated by dashed arrows indicates that the extinction ratios are roughly 8 dB and 15 dB, respectively, for the peaks at 1554 nm and 1556 nm. The variation of extinction ratio is within the range typically observed due to fabrication differences. Fabrication differences from
designed etched hole diameters within the same chip results in the two resonances shown by dashed arrows being closer to each other than designed. Since the L3 PC microcavity resonance is offset approximately 20 nm from the W1 PCW transmission band edge, by appropriate choice of lattice constants, and better control of fabrication, we estimate that up to 8 PC microcavities can be easily connected in series using the method demonstrated here.

The series cascaded PC microcavities are next combined with two-stage cascaded 1 × 4 MMIs to build a high density microarray with 1 input arm and 16 output arms. 4 PC microcavities are connected in series on each arm. Thus, in total, 64 (4 × 4 × 4) PC microcavities are integrated in one device. The output transmission spectrum in all 16 arms (4 × 4) is shown in Fig. 5. All 16 arms have similar spectra; 4 distinct resonant peaks and sharp band edges can be seen from each spectrum. The Q-factor in all microcavities in water varies between 2000 and 4000, which is a typical range of Q’s that have been observed in our oxide clad single L3 PC microcavities in silicon. The location of the resonant peaks and band edges are very similar. Small differences in absolute wavelength are observed due to fabrication imperfections. In biosensing, or chemical sensing, such small differences in the absolute wavelength do not matter since the relative resonance wavelength shift is the parameter of interest.

The multiplexed design presented here is similar to multi-channel drop filters in air ambient demonstrated previously,14-24 with 4 L3 PC microcavities coupled to the same PCW in free-standing silicon membranes. The transmission spectrum of the PCW after the resonance drops was extremely noisy.25 From the measurement system perspective, individually monitoring the dropped resonances out-of-plane from the individual PC microcavities is significantly more complicated than measuring all the dropped resonance wavelength shifts simultaneously in the in-plane output transmission spectrum of the coupled PCW.

Efforts to access the dropped resonances in-plane in Ref. 23 resulted in low quality factor (Q) ~ 1000 in air at the output of the coupled PCW compared to Q ~ 35 000 observed by the authors out-of-plane in Ref. 24. Our sensing experiments in water ambient also indicate that series multiplexing beyond two PC microcavities coupled to a single PCW is difficult due to poor spectral quality in the in-plane output transmission spectrum from the PCW. Group index engineered PC designs help to overcome the limitation and allow several PC microcavities to be multiplexed in series, as demonstrated here.

In summary, we demonstrated that group index tapers engineered in PCW architectures is critical to enable series connection of PC sensors. We demonstrated a method for simultaneous interrogation of 64 PC microcavities from a single optical source. While important in dense integration of sensors in biosensing microarrays, similar designs may also be incorporated in the future into compact add-drop filter designs for optical communications on-chip.

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