Curved fishbone nanosticks to control the higher order 1-D photonic crystal cavity resonances

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***Abstract*—Uncontrolled higher order resonance competition in traditional 1-D photonic crystal high-Q cavities (nanosticks) can lead to mode-hopping when used in hybrid laser applications. Playing with evanescent phase matching coupling techniques to take out a single mode lack specificity due to the closeness of allowed resonances. Curving the structure is observed to be ideal for targeting higher order resonances.**

Keywords—Photonic crystal, nanostick, Q factor, SMSR

I. INTRODUCTION

Lasers which heterogenously combine III-V active materials with passive materials (Silicon or Silicon Nitride) called as the hybrid lasers[1][2][3] are popularly known for its wide range of applications in spectroscopic sensors, dense wavelength division multiplexing (dWDM) in data centres and biological nanoscale sensors [4]. Photonic crystals (PhCs) and micro ring resonators (MRR) are often used to give feedback reflections in the hybrid laser. 1-D PhCs have become popular in this role due to their ease of design and fabrication compared to 2-D PhCs. People have used both Bragg gratings and grating based cavities for the role. 1-D PhC high-Q cavities called nanosticks becomes a perfect fit due to their high-Q factors and low 2 dimensional footprint. The output of a hybrid laser heavily depends on the allowed solutions inside the nanostick [5]. The main figure of merits (FOMs) of a nanostick are its Q factor, photonic crystal (PhC) amplitude side mode suppression ratio (SMSR) and extinction ratio (ER) of the fundamental resonance. These parameters evolve by opposing each others effect. A cavity designed for a high Q can naturally make resonances compete and leads to mode hopping when used as a resonant mirror in a hybrid laser. The nanostick is often excited by a waveguide evanescently phase matched and playing with its coupling parameters can target resonances. However, the resonances are close enough and get affected the same way. There is also an additional constraint that the natural design of the nanostick (perodicity and stick dimensions) cannot be changed as it is optimized for the highest Q. One good way to target higher order resonances by balancing the three FOMs along with the constraints is curving the structure. The paper compares the curving and coupling scheme effects on resonances for the two different devices geometries.

II. STRAIGHT NANOSTICKS

A. Theory and design

A nanostick is a usual Bragg grating with one of its reflective properties modulated along its length (periodicity, duty cycle, height or thickness). The main resonance wavelength is chosen to be at the band-edge so that it travels extremely slow through the structure (nearly zero group velocity). In our case, we taper the stick heights to achieve the modulation and the quadratic tapering is observed to give the maximum Q factor owing to its ability to create more Gaussian like solutions in the cavity [6]. The quadratic tapering law is as follows :

$$W_y(i) = W_y(0) + i^2 \left((W_y(i_{max}) - W_y(0)) / (N/2) \right) \qquad (1)$$

Where $W_y(i)$ is the height of the i^{th} stick, $W_y(0)$ is the middle stick height, $W_y(i_{max})$ is the final stick height and N is the total number of sticks. The number of resonances trapped in the nanostick is determined by a parameter $\Delta\lambda_{BE}$ which is the difference between dielectric band-edge of the first and the final stick of the Bragg grating. We design our structure on 300nm thick silicon nitride platform in an asymmetric configuration (with bottom silicon dioxide). The main physical parameters of a nanostick are its periodicity (P), middle stick height ($W_y(0)$), final stick height ($W_y(i_{max})$) and number of sticks (N). Periodicity and middle stick height are chosen by plotting dispersion diagrams such that the required wavelength is exactly at the band-edge to make use of the slow light effect. $W_y(i_{max})$ and N are then determined using sweeps from 3D FDTD simulations.

B. Main FOMs and their mutually opposing effects

The three main FOMs of a nanostick are its Q factor, PhC side-mode-suppression ratio (SMSR) and main resonance ER. Increasing the Q factor requires reduction of out-of-plane losses inside the nanostick which is done by increasing the middle stick-final stick height gradient and increasing the number of sticks N. The first process gives maximum reflection to the resonant wavelength to make it well confined in the cavity and second process allows the height modulation to be more gradual. Both of these leads to increase in $\Delta\lambda_{BE}$ and hence increase the number of allowed cavity modes. PhC-SMSR and ER could be managed by adjusting the coupling properties but as the resonances are very close to each other, all of them get affected equally and reduce the Q factor. If we have to balance all the FOMs without changing the basic properties of a nanostick, the best technique is to curve the structure.

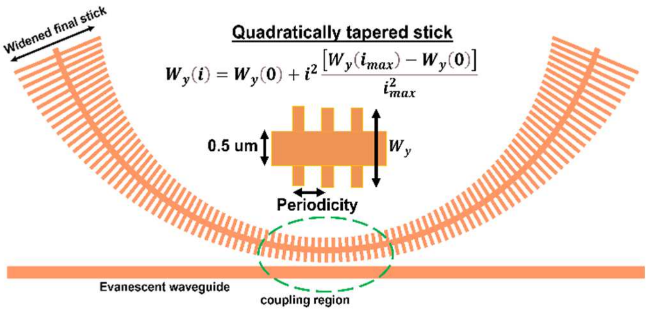

Fig. 1. Geometry of curved nanostick on 300 nm thick silicon nitride platform evanescently coupled to a feeding waveguide

Curving can be used to selectively target higher order modes owing to their different electric field distribution inside the nanostick as evident from the simulation results below.

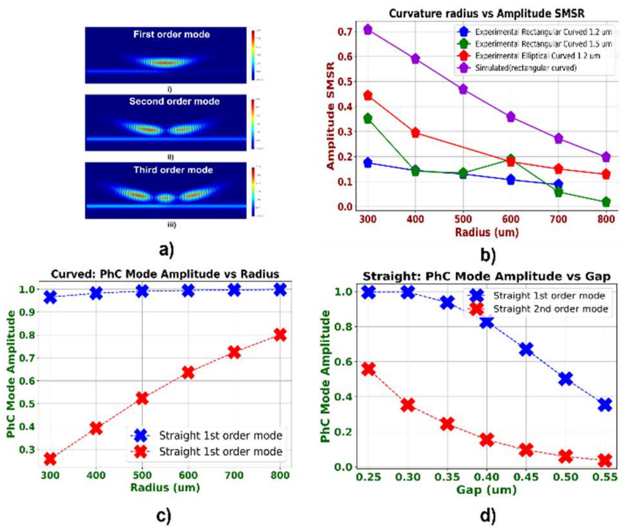

Fig. 2. a) shows the filed profiles of first three main resonances inside the curved nanostick. b) Shows the comparison between simulation and experiments for amplitude dependance of PhC-SMSR. c) and d) shows how the perturbation parameters (radius fro curved designs and coupling gap for straight designs) affect 1st and 2nd resonance amplitudes.

The devices were fabricated using electron beam lithography and dry-etching techniques and measure using an end-fire setup to record the transmission.

III. Results and analysis

Fig. 2 a) shows the magnitude of electric field intensities simulated using varFDTD. It is evident that only the fundamental resonance has its maximum electromagnetic energy confined close to the centre where the curvature is minimum. The higher order modes are affected by the curvature as their energy centre is away from cavity centre.

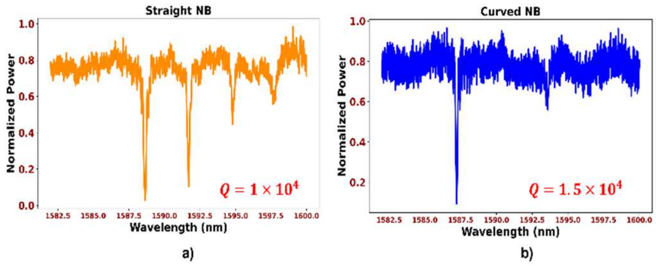

Fig. 3. Comparison between curved and straight device experimental transmission spectra and their respective loaded Q factors

This is confirmed by the experimental data in Fig. 2 b) showing the increase in main resonance amplitude domination with decrease of radius(increase of curvature). Fig. 2 c) and Fig. 2 d) shows the varFDTD comparative study of curvature and coupling gap adjustment. Coupling gap is shown to affect both fundamental and second order mode equally but curvature induce only minimal effect on the first order amplitude.

IV. Conclusion

Higher order resonance competition in straight 1-D high-Q cavities cause mode-hopping when used in hybrid lasers and needs to be effectively managed. Curving the structure are shown to be more advantageous than modifying evanescent coupling schemes owing to its higher order specific targeting ability. To use in hybrid laser, the active III-V gain medium can be integrated with the nanostick using butt coupling, transfer printing or using flip-chip integration in the future.

V. Acknowledgement

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References

[1] A. P. Bakoz, A. A. Liles, A. A. Gonzalez-Fernandez, T. Habruseva, C. Hu, E. A. Viktorov, S. P. Hegarty, and L. O'Faolain, "Wavelength stability in a hybrid photonic crystal laser through controlled nonlinear absorptive heating in the reflector," Light: Science and Applications **7**, 39 (2018).

[2] A. J. Zilkie, P. Seddighian, B. J. Bijlani, W. Qian, D. C. Lee, S. Fathololoumi, J. Fong, R. Shafiiha, D. Feng, B. J. Luff, X. Zheng, J. E. Cunningham, A. V. Krishnamoorthy, and M. Asghari, "Power-efficient III-V/Silicon external cavity DBR lasers," Optics Express **20**(21), 23456–23462 (2012).

[3] K.-J. Boller, A. van Rees, Y. Fan, J. Mak, R. E. M. Lammerink, C. A. A. Franken, P. J. M. van der Slot, D. A. I. Marpaung, C. Fallnich, J. P. Epping, R. M. Oldenbeuving, D. Geskus, R. Dekker, I. Visscher, R. Grootjans, C. G. H. Roeloffzen, M. Hoekman, E. J. Klein, A. Leinse, and R. G. Heideman, "Hybrid Integrated Semiconductor Lasers with Silicon Nitride Feedback Circuits," Photonics **7**(1), 4 (2020).

[4] D.-Q. Yang, B. Duan, X. Liu, A.-Q. Wang, X.-G. Li, and Y.-F. Ji, "Photonic Crystal Nanobeam Cavities for Nanoscale Optical Sensing: A Review," *Micromachines*, vol. 11, pp. 1–20, Jan. 2020.

[5] Parag B. Deotare, M. W. McCutcheon, I. W. Frank, M. Khan, and M. Lončar, "High quality factor photonic crystal nanobeam cavities," *Applied Physics Letters*, vol. 94, pp. 121106, March 2009.

[6] S. Iadanza, J. H. Mendoza-Castro, T. Oliveira, S. M. Butler, A. Tedesco, G. Giannino, B. Lendl, M. Grande, and L. O'Faolain, "High-Q asymmetrically cladded silicon nitride 1D photonic crystal cavities and hybrid external cavity lasers for sensing in air and liquids," *Nanophotonics*, vol. 11, no. 18, pp. 4183-4196, August 2022.