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Confined Photonic Modes in the Fabry-Pérot Based Photonic Crystal Nanobeam Cavity Structures with Mixed Tapered Air-Holes and Curved-Wall Cavity

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Abstract: - In this paper, confined photonic TE modes in different nanobeam (NB) cavity structures are presented. These structures were the Fabry-Pérot based narrow waveguide system with distributed Bragg reflectors (DBRs) combined with air-holes tapers adjacent to and faraway from the nanocavity (NC). In some parts of simulations the NC side-walls were curved in parabolic form. The tapered air-holes and parabolic narrowed cavity walls provide small modal volume and high quality factor (Q) TE modes. Simulations were done by finite difference frequency method via COMSOL Multiphysics 4.3 software, and results were additionally analyzed by OriginPro 9.0. High Q values $>10^4$ and modal volume as small as $0.7(\lambda/n)^3$ are obtained in the optimized structures.

Keywords: *-Nanobeam Cavity, Confined Modes, Tapered Air-Holes, Curved-Wall Cavity*

I. INTRODUCTION

Light applications of nanometer-scale structures in a half-century ago were unthinkable or hardly possible. Photonic crystals (PhCs) idea was first proposed by Eli Yablonovitch in 1987. The PhC's structures can be designed and created by employing periodic dielectric constant in a variety of lattice, in one, two and three dimensions. The PhCs cavity which is fabricated by introducing a defect in the normal lattice, due to the strong interaction between light and matter has attracted much attention in the recent decades [1]. Photonic crystal nanocavities (NCs) fabricated in the dielectric-semiconductor materials are able to confine light in a volume scale as small as a fraction of cube of the wavelength of light in the medium [2-5]. Very high quality factor (Q) and small modal volume in such nanostructures release new applications in a wide variety of areas such as low-threshold lasers [1, 6-9], the nonlinear Optics phenomena [10-14], realization of cavity quantum electrodynamics experiments in thesolid state materials [15], and quantum information processing and high precision filters [16-17].

In this paper, we investigate the photonic modes in the PhC nanobeam (NB) cavity structures which are the Fabry-Pérot based system with sort of distributed Bragg reflectors accomplished by series of mixed tapered air-holes in combinations with curved-wall cavity. For simulations and analysis of the results we used COMSOL Multiphysics 4.3 and OriginPro 9.0 Commercial softwares.

II. SIMULATION OF NANOBEAM CAVITY MODES USING FINITE DIFFERENCE FREQUENCY DOMAIN (FDFD) METHOD

The photonic crystal nanobeam (PhC-NB) cavity structures, as shown in the Fig. 1-a, consists of a row of air-holes (vertical cylinder shape), along axis of a narrow photonic waveguide (e.g. Silicon) width 500 nm, which is suspended like as a bridge with air in its underneath [18], and the effective refractive index here is considered 3.19. In this paper, TE polarization of the modes has been studied. High quality factor (Q) values obtained in our simulations depend on the correct choices of air-holes parameters, including the hole diameter, holes spacing/period in the mirrors, variation of the lattice size and air-holes' diameters in the taper sections, and the cavity length. Number of air-holes in the taper sections nearby the cavity (N_{TI}) is optimized to N_{TI}=4. Due to

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wave reflection from the walls and cavity arrays of air-holes, coherency of the circulated waves would be modified. So, for compensating the phase shifts, the tapering air-holes' diameters sections have been used nearby and far from NB cavity.

The couple of four holes set in the neighboring cavity (N_{TI}=4), had diameters of 170, 180, 166, and 131 nm respectively, with the hole lattice (center to center distances) of 342, 304, 310, and 290 nm respectively. Whereas couple of four holes set in the farther than cavity place (N_{TO}=4), had contrariwise diameters of 131, 166, 180 and 170 nm respectively, with the hole lattice of 290, 310, 304 and 342 nm respectively [18].

The calculations by finite difference frequency domain (FDFD) method, for a cavity with length 440 nm, resulted quality factor ~2260 for a photonic mode at a wavelength of 1471.8 nm. Typical schematic and computational two and three dimensional energy flux distribution patterns of these modes, via Poynting vector components S_x and S_y are plotted and shown in the Fig. 1. Second-order mode has wider intensity distribution pattern and therefore larger modal volume than first-order / fundamental mode.

By plotting the electric field intensity profile across NB cavity which is resulted from embedded emitters within the cavity, we are able to study properties such as light confinement, and thus allow to estimating of modal volume. The Fabry-Pérot modes formation can also be explored in such structures [19-20]. According to the boundary conditions at the upper and lower surfaces of the NB and estimation of the intensity profile in the vertical direction, height of less than half the wavelength of light in the medium, $<1/2(\lambda/n)$, is adopted. Estimated values along the longitudinal axis and the transversedirection of the waveguide can be calculated from mode intensity profile, using the full width at half maximum (FWHM) of intensity distribution peak. Thus, estimation value of modal volume, as small as $0.7(\lambda/n)^3$ is achieved.

The At one of the stages of calculations, diameters of the four air-holes in the tapers nearby and away from the cavity have been altered simultaneously from initial values which mentioned previously, while the distance between the holes' centers kept fixed and same as initial values. As can be seen in the Fig. 2, the mode wavelength would be reducing by detuning diameters with associated quality factor experiencing fluctuations. The highest maximum Q value is 9850 at the mode wavelength of 1522.79 nm, which corresponds to NB with nearby cavity tapers holes diameters of 140, 150, 136, and 101 nm; While the far away cavity tapers holes diameters were contrariwise taken 101, 136, 150 and 140 nm respectively.

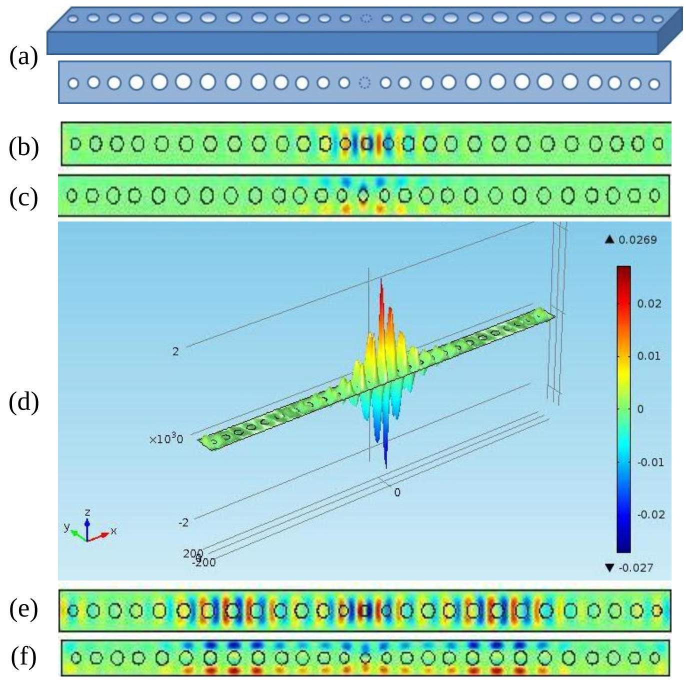

Figure1. a) Schematic diagrams of PhC-NB with couple of four air-holes tapering sets in the neighboring and away from the cavity. The middle dotted circle shows the location of the center of the cavity where quantum dots as light source are put for simulations. b) and c) The 2D energy flux intensity distribution pattern, S_x and S_y of the fundamental mode respectively. d) The 3D distribution profile S_y of the fundamental mode. e) and f) The 2D energy flux intensity distribution pattern, S_x and S_y of the second mode respectively.

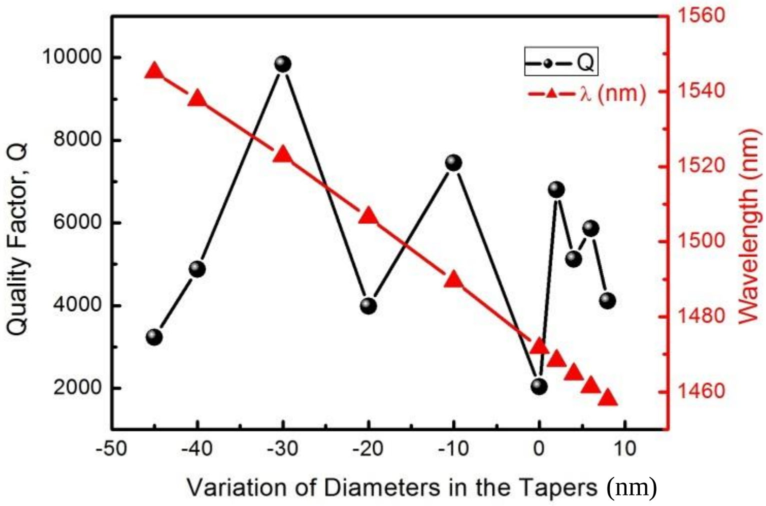

Figure 2: Diagram of wavelength and quality factor of fundamental mode versus detuning of diameters of the four air-holes in the tapers nearby and away from the cavity that are changed simultaneously from initial values which mentioned in the text.

Now, we change lattice period of the four air-holes in the tapers nearby and away from the cavity simultaneously, from their initial values (which mentioned previously), while their diameters kept fixed and same as the initial values. By this means, increasing wavelength can be seen as shown in the Fig. 3, which is due to enlarged cavity volume (unlike of the result explained in the Fig. 2. Albeit, as the wavelength increase, associated quality factor experiencing smaller fluctuations and demonstrate considerably overall increase.

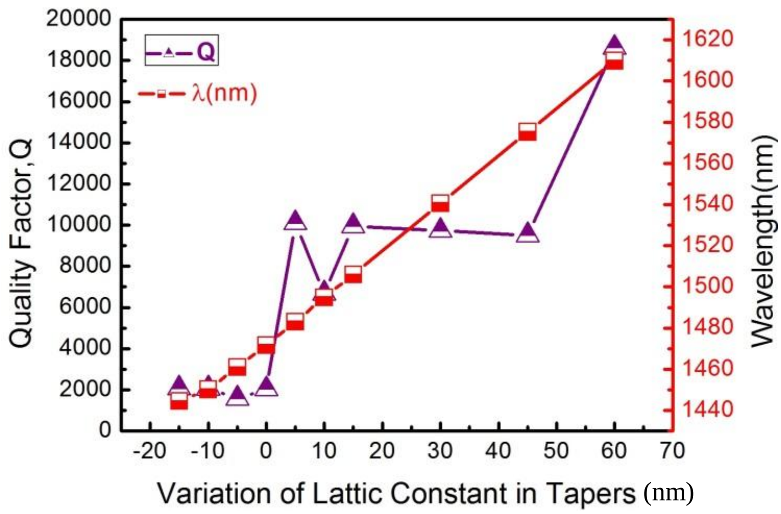

Figure 3: Variation of Q and wavelength of mode in terms of change in the lattice period of the four air-holes in the tapers nearby and away from the cavity simultaneously.

Then, for four air-holes in the far away tapers from cavity N_{TO}=4 and five air-holes as mirrors, N=5, the diameter of the five holes on the sides of the cavity mirrors has been altered. As shown in the Fig. 4, with the increase of the hole diameter up to d=280 nm, a decreasing trend for wavelengths of the fundamental mode is observed. In this situation, quality factors for diameters in the range 200-280 nm show increasing and stabilized values, while there are fluctuations and decreased values out of this range. The maximum Q value of the mode ~20550 happens at wavelength 1459.1 nm and the minimum Q value ~1850 occurs at wavelength 1474.0 nm. One of the most important issues in the light confinement process is the cavity's neighboring tapers as an integral part of the DBRs; the optimized values in theFigure 4 show the role of constructive interference and coherency of light which are reflected from the tapered mirrors.

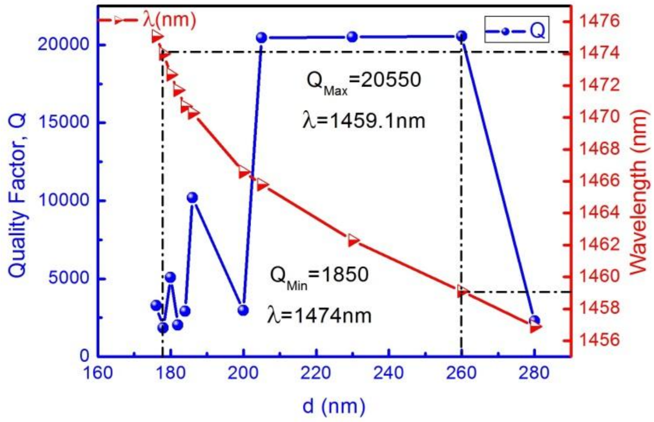

Figure 4: Variation of the resonance wavelength and quality factor of the fundamental mode versus change in the diameter of the air-holes in the mirrors N_{TO}=4 and N=5.

For the second order mode, as shown in the Fig. 5, by increasing the diameter of the holes in the mirrors, wavelength of the mode are decreased, but the quality factor demonstrates increasing up to ten-fold, which highlights aim of our optimization.

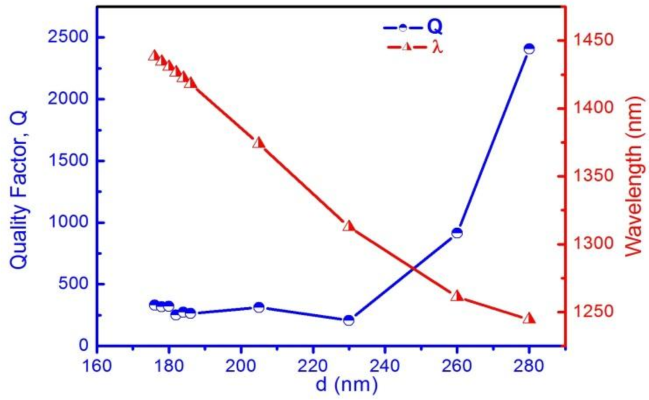

Figure 5: Variation of wavelength and quality factor of the second mode versus change in the diameter of the air-holes in the mirrors N_{TO}=4 and N=5.

Since optimization of the Q factor and cavity modal volume is the concern, thus shrinking the central part of the nanocavity can be one of the tools, achieving with softened curved cavity [7]. In the Fig. 6-a, schematic of a PhC parabolic NB (parabolic-shaped cavity wall) is given accompanied by a typical mesh for simulations (Fig.6-e).

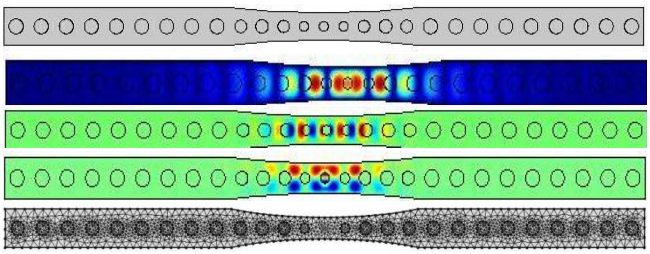

Figure 6: a) Schematic diagram of the PhC-NB parabolic cavity structure, with the minimum central width of W_0=400 nm; number of air-holes in sides mirrors is N=9, with couple of four air-holes tapers adjacent to the cavity. The middle dotted circle shows the center of the cavity. b) Normalized electric field distribution of optical cavity mode. The 2D pattern of c) S_x , d) S_y . e) A typical Mesh for PhC-NB parabolic cavity consisting air-holes tapers, and comprising mirrors with N=7, holes radii=200 nm, period=500 nm, and cavity length=440 nm.

As we can see in the schematic of the Fig.6-a, PhC-NB cavity is created by mixed air-holes tapers and changing the width of central cavity part of NB (width taper), plus controlling lattice constant. In this structure, by changing cavity width, center to center distance and size of the air-holes in the tapers, we could minimize optical loss and therefore increase quality factor. In the schematic and structure shown in the Fig. 6, the mirrors consists of nine air-holes with diameter d=200 nm, and period a=360 nm, and NB width W=500 nm. Diameters of air-holes in the tapers around cavity were chosen 170, 180, 166 and 131 nm, with distance of the holes 342, 304, 310 and 290 nm respectively. Minimum width of the central cavity region was W_0=400 nm. The middle circle shows the center of the cavity. The calculated fundamental mode's frequency and its peak width were f_0=2.0824 THz and FWHM=Δf_0=0.0002 THz respectively.

In the following carrying out computational steps, wavelength and quality factor variation were observed through change in the period constant of the air-holes in the mirrors. The results in the Fig. 7 show that by increasing the distance between the holes, an increase in wavelength would be observed due to the increasing in the real cavity size. On the other hand, although maximum Q value ($>10^4$) obtains at a=360 nm, the graph shows slight reduction for Q in the ranges a=365-382 nm (from 0.7×10^4), and then suffer larger reductions due to more losses through cavity Bragg mirrors (equivalent to more phase mismatch in the reflected lights).

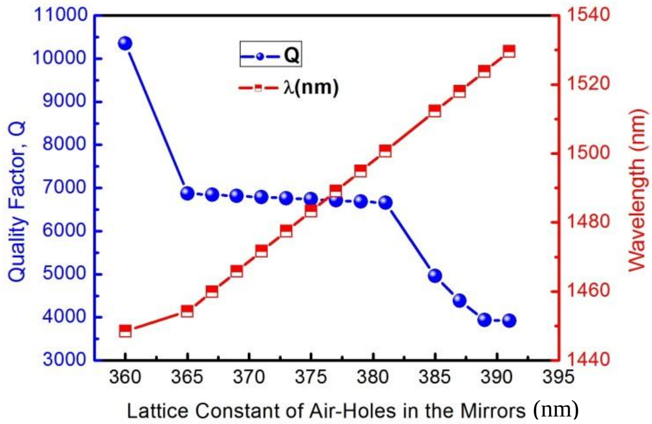

Figure 7: Variation of the quality factor and wavelength of mode in terms of changes in the lattice constant of the air-holes in the mirrors.

In the Fig. 8, quality factor variations for displacement of adjacent 4 air-holes tapers in the NB are shown, where parabolic cavity width is narrowed from 500 nm to 400 nm at the cavity center. In this case, by negative and positive location detuning of couple of adjacent 4 air-holes tapers in the vicinity of cavity NB, the graph likewise shows almost uniformly increasing in wavelength of mode, associated with increasing in cavity size. Moreover, the optimized quality factor was 10,410, which obtained by a decrease of 25 nm in placement of 4 air-holes around the cavity.

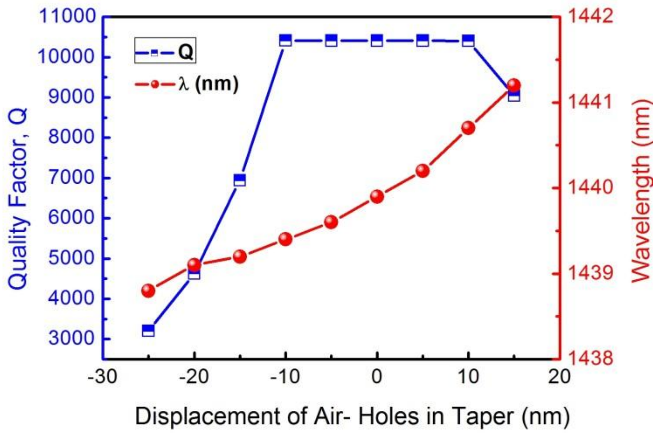

Figure 8: Diagram of the wavelength and related quality factor of cavity mode versus location detuning of adjacent 4 air-holes tapers in the vicinity of cavity NB; the initial values are listed in the text.

III. SUMMARY AND CONCLUSIONS

The Variety of PhC-NB cavity design, in this paper are considered to simulate and investigate the photonic modes in the NC structures which are the Fabry-Pérot based system with distributed Bragg reflectors, included in a narrow semiconductor waveguide. Series of tapered air-holes in combinations with curved-wall cavity are employed to have better confinement. High quality factor TE modes are obtained in our simulations depends on the optimized choices of air-holes parameters, including the holes' diameters, holes spacing/period in the combined tapered mirrors, the cavity length and wall-shape. Coherency of the circulated waves could be altering due to wave reflection from the walls and cavity arrays of air-holes. For compensation of the phase mismatch of the reflected light from different parts of NB system, the tapering air-holes' diameters sections have been used nearby and far from NB cavity. Moreover, cavity modal volume is optimized by using parabolic side-walls. Simulations and analysis of the results by FDFD method for photonic modes of the NC are done using COMSOL Multiphysics 4.3 and OriginPro 9.0 Commercial softwares. By plotting the electric field intensity profile across NB cavity which is resulted from embedded emitters within the cavity, properties such as light confinement were studied, and thus it allowed us to estimate modal volume. In the optimized PhC-NB structure, Q values $>10^4$ for a very confined mode $\sim 0.7(\lambda/n)^3$ are achieved.

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