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Investigation on Mode Splitting and Degeneracy in the L3 Photonic Crystal Nanocavity via Unsymmetrical Displacement of Air-Holes

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Abstract

In this paper, the L3 nanocavities have been simulated in a two dimensional (2D) Photonic Crystal (PhC) choosing a hexagonal lattice arrangement of air-holes in a GaAs slab (effective refractive index n_{eff} = 3.09), with lattice constant a=270 nm and constant ratio, r/a = 0.29, where r is radius of air holes. An internal source is embedded in the center of the nanocavity, and excited with pulses to investigate the modes. Using a detector, resonance modes of the cavity (con-fined in the nanostructure), are computationally realized. With unsymmetrical displacement of some air-holes around the nanocavity, mode splitting phenomenon was investigated to the aim of improving quality factor and modes distribution, especially fundamental confined photonic mode. The two degenerate modes under study have the same wavelength (about 1032.7 nm), but by increasing air-holes displacements, wavelength difference between the two modes became more obvious and the degeneracy has been vanished. All the simulations in this article are carried out by BandSOLVE and FullWAVE software of the RSoft Photonics CAD Suite package, and Origin Pro. software as well.

Keywords: *L3 Nanocavity, Unsymmetrical Displacement, Mode Splitting, RSoft's BandSOLVE and FullWAVE.*

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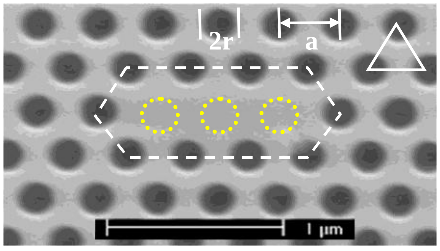
I. INTRODUCTION

The photonic crystals (PhCs) defect nanocavities (DNCs) are the structures which can confine and manipulate light and control light-matter interactions in an optical wave-length size structure[1-4]. Nowadays, the PhC-DNCs are finding vast applications in many areas of Physics and Engineering, including coherent electron-photon interactions[5], ultra-small filters[6,7], low-threshold lasers[8], photonic chips[9], nonlinear optics[10] and quantum information processing[11]. Among the various kinds of PhC-DNCs are the H1, H2 and H3 nanocavities which can be created by omitting 1, 7 and 19 air-holes respectively from etching process of PhCs that are introduced by lithography and chemical etching in hexagonal lattice arrangement into a dielectric/ semiconductor slab. There are different observable mode degeneracies in the mentioned DNCs, due to existence of many symmetries in the geometrical structure, and therefore variety of electromagnetic field patterns of the confined modes would be allowed with equal frequencies ($\omega_1 = \omega_2$), which are not necessarily orthogonal. Usually, there might be one kind of symmetry that is responsible for the phenomena [1].

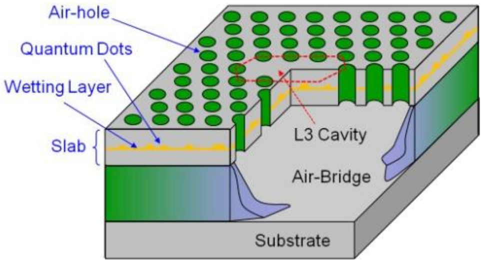
Another kind of PhC-DNCs would be Line defect nanocavity that can be designed by omitting a set of "n" missing air-holes in a row of a PhC slab (Ln). Among them, the L3 nanocavity, three missing air-holes, as shown in the Fig.1, are interested for mode investigation and were under study in this paper. The Fig.1-a shows scanning electron micrograph (SEM) of the L3 nanocavity (3 missing air-holes in a line, which are not etched), grown and fabricated in the "National Centre for III-V Technologies" of the University of Sheffield. Schematic cross sectional diagram of the simulated L3 showing internal source embedded (quantum dots on top of the wetting layer in the dielectric slab) is depicted in the Fig.1-b, and dielectric constant distributions in the L3 PhC-DNCs plotted by the RSoft Photonics CAD software illustrated in the Fig.1-c. These kinds of DNCs are not consisting of much symmetry as the H1, H2 and H3 does. For this reason, degeneracy in the electromagnetic field profile is decreased, although few degeneracy in mode structure yet exists). In this article, the L3 PhC-DNCs with different geometric parameters in the structure have been simulated. With unsymmetrical displacement of some air-holes around the nanocavity, mode splitting phenomenon has been observed for the fundamental mode, and vanishing degeneracy of the modes in the L3 structure will be discussed in the next three sections.

II. SIMULATIONS

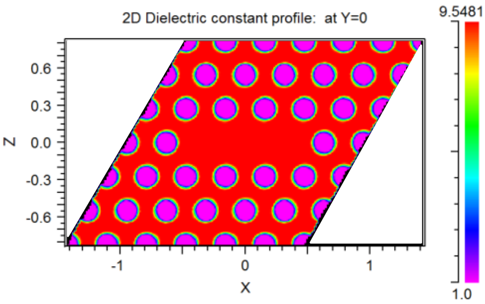
In this paper, the L3 PhC-DNCs are simulated with a hexagonal lattice of air-holes (with refractive index n = 1), in a GaAs slab (with effective refractive index n_{eff} = 3.09), and constant ratio r/a = 0.29 ("r" and "a" are radius and period of the air-holes respectively). The thickness of slab and lattice constant are considered t = 180 and a = 270 nm respectively. The simulated L3 nanocavity is considered in the x-z plane. An internal source has been put at the center of the L3 cavity, x = z = 0. Then, internal source is excited with pulses, and finally with employing a detector, confined resonant cavity modes in the nanostructure are realized computationally. In computations, wavelength and electromagnetic field patterns and profiles of the individual confined modes for different structures of L3 PhC-DNCs have been investigated. A two-fold degeneracy is observed for the fundamental mode of the cavity. To study degeneracy vanishing, the structure's symmetries should be decreased in some degree. For this purpose in this article, some air holes around the nanocavity are asymmetrically displaced outwards, as shown in the Fig. 2.



(a)



(b)



(c)

Figure 1. a) Scanning electron micrograph (SEM) of L3 nanocavity (three missing air-holes in a line, which are not etched), grown and fabricated grown and fabricated in the "National Centre for III-V Technologies" of the University of Sheffield, b) Schematic cross sectional diagram of the simulated L3 showing internal source embedded (quantum dots on top of the wetting layer in the dielectric slab), and c) Illustration of dielectric constant distributions in the L3 PhC-DNCs plotted by the RSoft Photonics CAD software.

III. RESULTS OF COMPUTATIONS

In simulations steps, based on changing air-holes position, the couple of ends air-holes, (demonstrated in the Fig.2-b), are moved outwards in the ±x directions as simultaneously their neighboring air-holes are displaced in the +z direction, to break the symmetry. This procedure of displacements has been carried out with 1 nm increments up to 15 steps. Wavelength variations of the confined modes and the modes splitting values are calculated and reported in the Table 1.

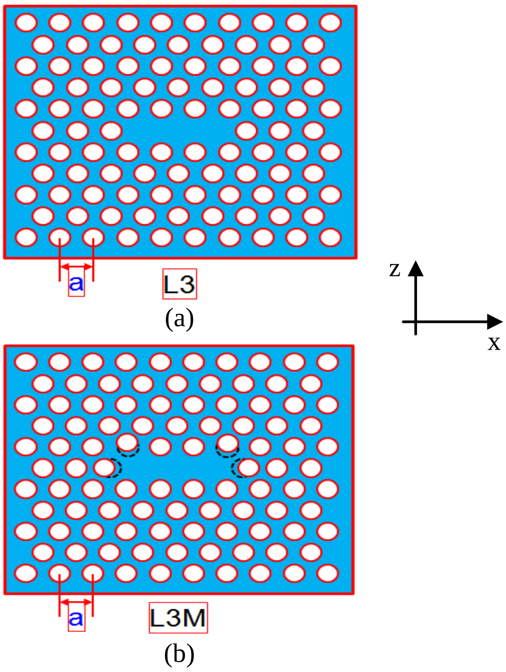


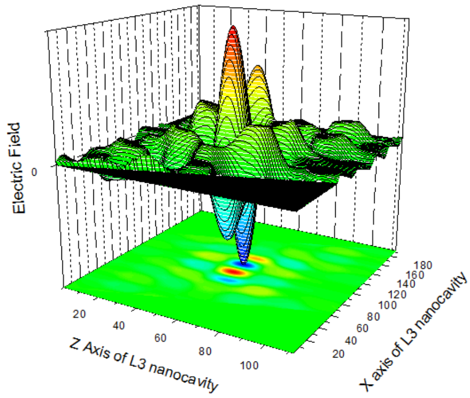
Figure 2. Schematic of top view of a) the normal L3 PhC-DNCs, and b) displaced air-holes and a typical direction of their displacements; L3M is the L3 with modifications.

Table 1. Calculated wavelengths of couple of modes in the L3 nanocavity, with position of air-holes changed from 0 to 15 nm.

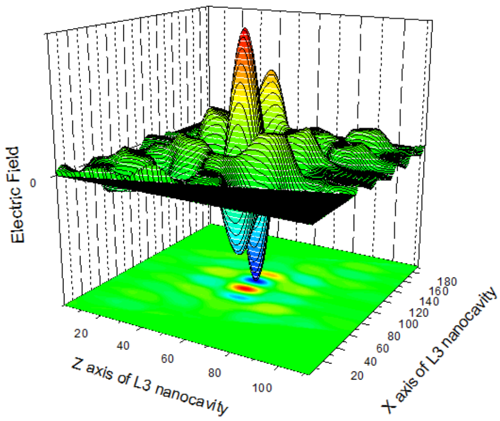
Mode splitting (nm)	Wavelength of second mode (nm)	Wavelength of first mode (nm)	position changes of air-holes (nm)
0.0	1026.0	1026.0	0
0.0	1031.1	1031.1	1
0.0	1031.9	1031.9	2
0.3	1032.7	1033.0	3
1.0	1032.8	1033.8	4
1.8	1033.0	1034.8	5
2.6	1033.1	1035.7	6
3.4	1033.2	1036.6	7
4.3	1033.3	1037.6	8
5.0	1033.4	1038.4	9
5.8	1033.5	1039.3	10
6.5	1033.6	1040.1	11
7.3	1033.7	1041.0	12
8.0	1033.8	1041.8	13
8.8	1033.9	1042.7	14

As it can be found from Table 1, when air-holes are moved as 3 nm from center of the nanocavity, or in other words when position of the ends air-holes are: $x = \pm|2a+3| = \pm 543$ nm, and their nearby displaced air-holes are at: $z = a \sin 30 + 3 = 138$ nm, splitting those two modes is observed. In addition to investigation on the wavelength variations, the electric field distribution profiles were under studies at any stage. At the step of 3 nm displacement of air-holes, the fundamental resonant mode for the L3 and modified L3M nanocavity have been plotted three dimensionally (3D), and shown in the Fig.3. Although there are similarity in the field pattern at this stage and that is difficult to recognize difference in spatial distribution of the modes in the figure, but there has been improvement to change the field peaks towards center of the cavity and consequently the quality factor ($Q=\lambda/\Delta\lambda$) of modes as well. A typical cross-sectional field distribution of this mode along the x axis of nanocavity, for the L3 and L3M cavities are plotted and shown in the Fig.4. The figure shows that the mode distribution is squeezed in a smaller area and would affect decreasing the modal volume (V_{mod}) of the cavity plus improving the Q-value towards increasing Purcell factor (F_p), which is proportional to Q/V_{mod} in the equation:

$$F_p = (3/4\pi^2)(\lambda/n)^3(Q/V_{\mathrm{mod}}) . \tag{1}$$



(a)



(b)

Figure 3. 3D profile of electric field distribution of first resonant mode confined in the L3 nanocavity, a) without any change, and b) with 3 nm displacement of air-holes

Variation of the wavelength of the first and second confined mode and the mode splitting for different positions of the air-holes are computed and plotted in the Fig.5. The graphs confirms that after few steps movement of the ends air-holes it starts to recognize mode splitting, where the modes had wavelength around 1032.7 nm.

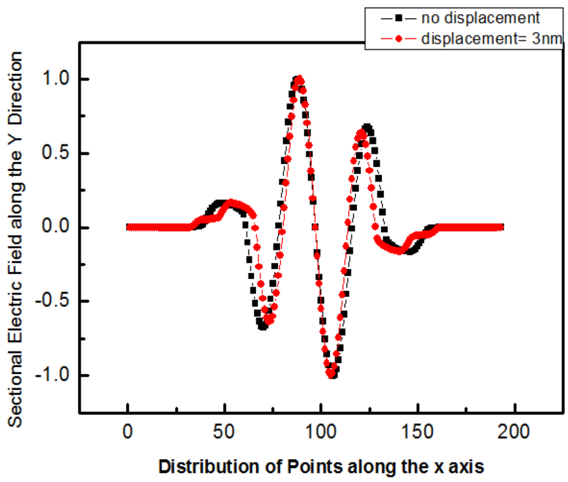
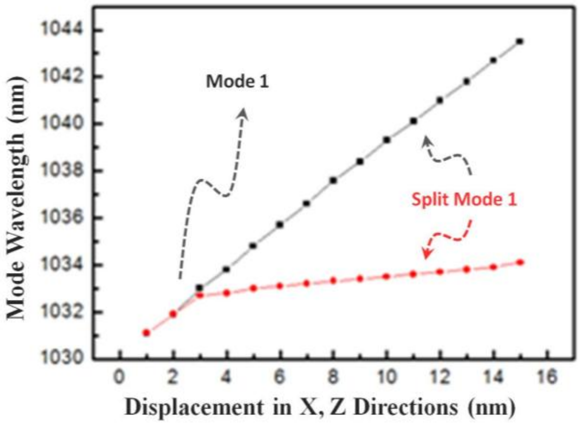
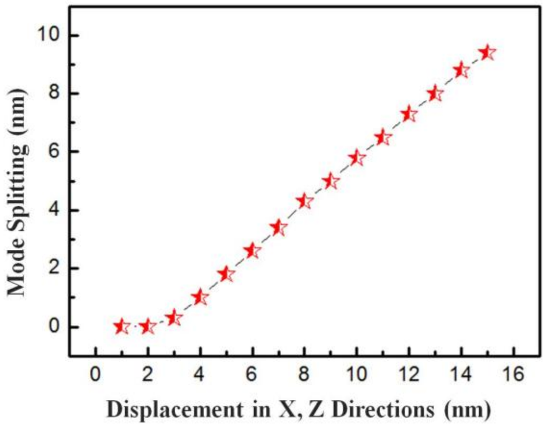


Figure 4. Electric field distribution profile of the modes which shown in the previous figure, across the L3 nanocavity, along the x axis (z=0) for normal L3 and modified L3M with 3 nm air-holes displacements shown in the Fig.2.



(a)



(b)

Figure 5. a) Variations of wavelength belong to the fundamental confined mode which undergoes splitting, and b) splitting values for different air-hole displacements.

IV. CONCLUSIONS

The L3 nanocavities and their modified structures have been simulated in a two dimensional photonic crystal. A hexagonal lattice arrangement of air-holes in a GaAs slab (n_{eff}=3.09), with lattice constant a=270 nm, and constant ratio r/a=0.29 has been chosen for the simulations. The resonance modes of the cavity which were confined in the nanostructure are examined computationally via BandSOLVE and FullWAVE software of the RSoft Photonics CAD Suite package. By means of asymmetrical displacement of some air-holes around the nanocavity, mode splitting features were investigated to improve quality factors and modes profiles (especially fundamental photonic mode), which were analyzed by Origin Pro software. Couple of degenerate modes under study have the same wavelength (≈1032.7 nm), but by increasing air-holes displacements, wavelength difference between the two modes became more obvious and the degeneracy has been vanished. Analyses show that the mode distribution is squeezed in a smaller area and would affect decreasing the modal volume of the cavity plus improving the Q-value towards increasing Purcell factor.

V. ACKNOWLEDGEMENTS

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