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Optical Resonance in a Low-Symmetry Photonic Crystal Cavity

Ozgur Onder Karakilinc

Department of Electrical-Electronics Engineering

Pamukkale University, Denizli, Turkiye

okarakilinc@pau.edu.tr

ABSTRACT

Photonic crystals (PCs) are periodic dielectric structures that exhibit photonic band gaps that strongly depend on the geometry of the lattice elements and material properties [1,2]. Since the design parameters of the photonic crystal structure are amenable to modification and adjustments, light can be manipulated and easily controlled, guided, and trapped in these structures [3]. Conventional photonic crystals have high-symmetry unit cells. Low-rotational-symmetry structures are formed by breaking the high symmetry in the photonic crystal unit cell. Low-symmetry structures are more sensitive to light manipulation and provide more control and flexibility over light with geometric and structural diversity [4]. In this study, the resonance effect in the cavity structure of a square-lattice photonic crystal composed of C2-type low-symmetry dielectric rods is investigated. The dispersion diagram and transmission spectra of the low-rotational-symmetry photonic crystal are obtained with Lumerical, MPB, and MEEP software to examine the resonance properties[5,6]. Besides, it is shown that the splitting or merging of the resonant mode can be achieved by using the symmetry property of the low-symmetry PC structure. Analyzing optical properties through symmetry manipulation and resonance refraction will contribute to understanding light collimation and confinement.

INTRODUCTION

Microcavity structures: Light is temporally and spatially confined at the resonant frequency in cavity structures called optical resonators. The optical resonator is the basic functional block in integrated optical circuit systems. Photonic microcavity is characterized by cavity resonant wavelength and quality factor (Q factor). Optical resonators are usually used with waveguides and their interaction is determined by coupling mode theory (CMT). Optical resonators are divided into two groups, which are associated with standing wave (SW) and traveling wave (TW) resonators. Distributed feedback resonator and ring resonator can be given as an example for SW and TW resonator, respectively [3,7]. Optical communication devices such as filters, and add/subtract multiplexers are realized by SW or TW types of resonators placed between two optical waveguides in photonic crystal as shown in Fig. 1.

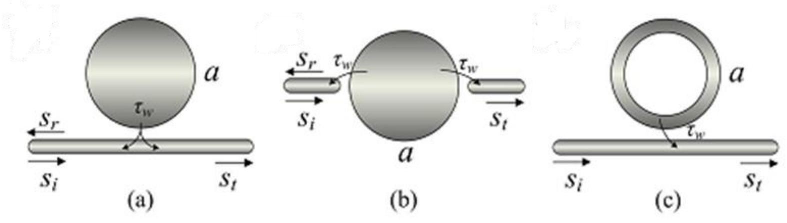

Fig 1. (a)-(b) Standing wave (SW) resonator, (c) Travelling wave (TW) resonator [7]

Mode Splitting: A designer can change the bandwidth or frequency response shape by adjusting the coupling coefficients between the resonances in the system. In dual-mode resonators, the process relies on the coupling between two modes that initially degenerate through a geometric distortion of the symmetry of the structure. When the designer controls the severity of the distortion, the splitting between the two resonant mode frequencies changes accordingly. Essential components of photonic crystal circuits, such as channel subtraction filters and coupled cavity waveguides, exploit the coupling of defect modes. Degeneracy arises from the symmetry properties of the modes in the photonic crystal, where the modes see the same lattice when rotated [3]. Mode splitting allows for more frequency bands in the resonant structure, thus increasing signal processing capabilities.

METHOD

To obtain a low symmetry photonic crystal structure (LSPC), two more rods with different radii were added next to the rod in the center of the lattice of the photonic crystal arranged in a square lattice in air and the high symmetry in the unit cell was broken. Then, a standing wave shoulder coupling type cavity was created in the LDWG. The splitting and merging of the cavity modes were investigated by changing the position and radius of the rods forming the low symmetry. Mode analysis of the cavity was performed at different radii and rod positions of the low symmetry rods given in Table 1, and transmission graphs were obtained.

Table 1. Structural parameters of LSPC

Lattice constant	a=1μm
Base structure	air
Dielectric constant of base	1
Rod type	cylindrical
Dielectric constant of rods	12
Rods Radius (r)	0.2a
Low symmetry rods Radius (rs)	0.1a

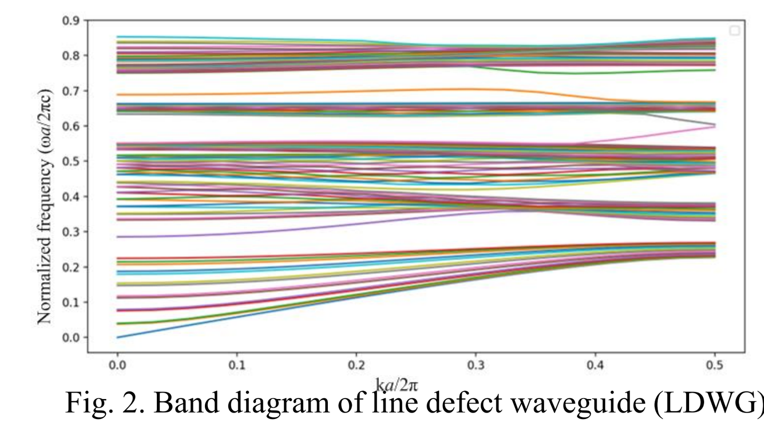

Fig. 2. Band diagram of line defect waveguide (LDWG)

Table 2. Variation of the low symmetry parameters

Case no	r	$rs1$	$rs2$	angle (Θ)	Result
1	0.2	0.1	0.1	0	single frequency
2	fixed	fixed	fixed	only $rs1$	split
3	fixed	fixed	fixed	Θ1=75°	split
4	fixed	fixed	fixed	Θ2=105°	merged
5	fixed	fixed	decreased to 0.1a	fixed	single frequency
6	fixed	decreased to 0.1a	decreased to 0.1a	fixed	split

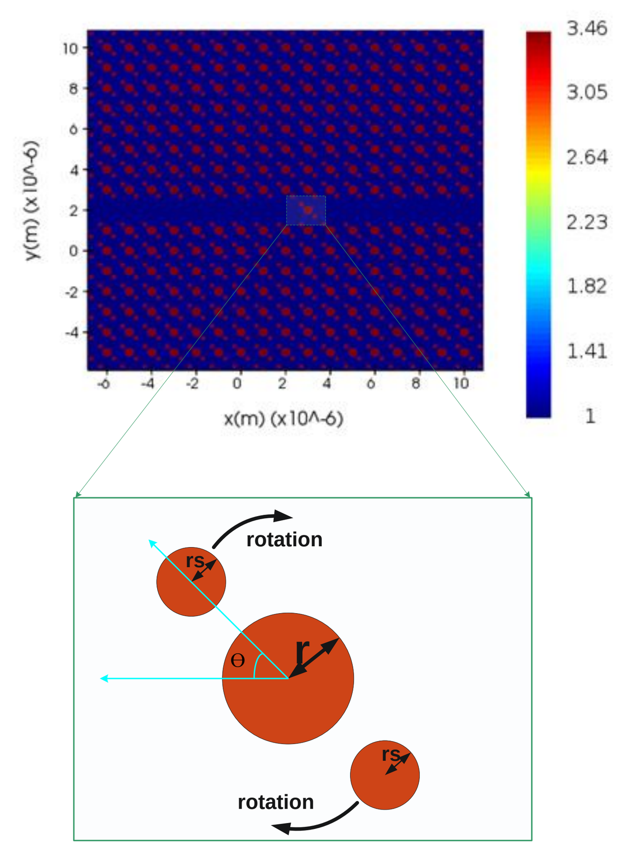

Fig. 3. Image of dielectric constant of the LSPC structure and schematic of the cavity in LDWG

RESULTS & DISCUSSION

When the results were examined, it was shown that the splitting or merging of the degenerate cavity modes could be adjusted by changing the position and/or radius of the rods forming the low symmetry without the need for an additional perturbation. For example, when the angle between the low symmetry rod and the x-axis is increased, the mode is seen to split, and when the angle is increased a little more, it merges.

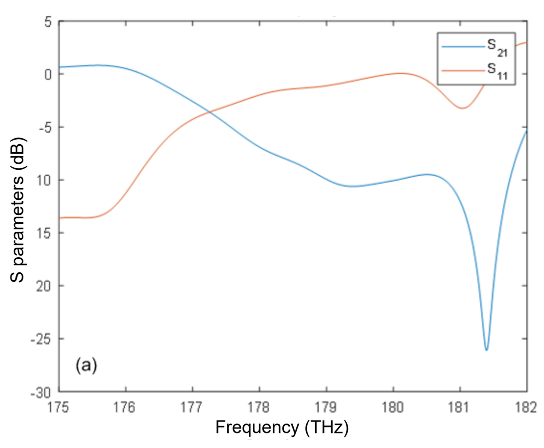

Fig. 4. S parameters for $r = 0$ $rs = 0$

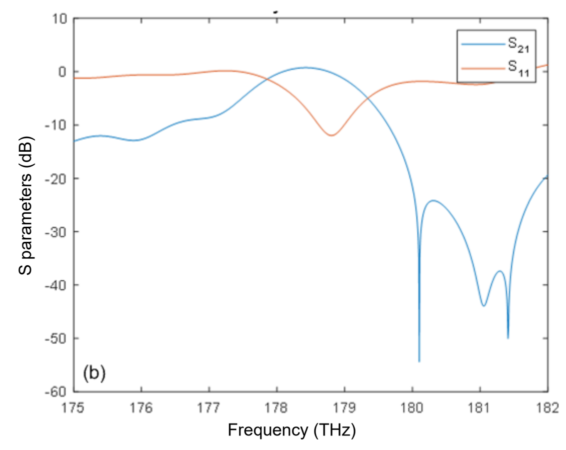

Fig. 5. S parameters for $r = 0.2a$ $rs = 0.01a$

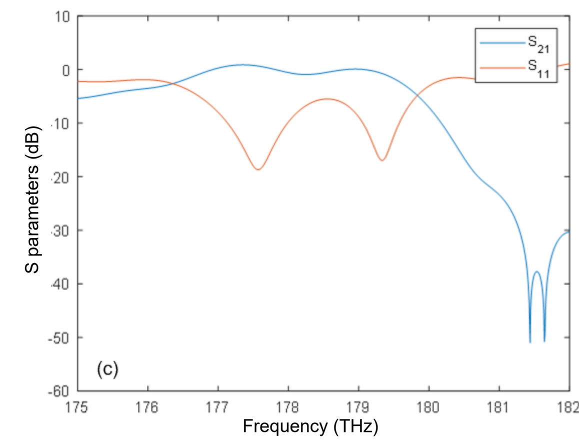

Fig. 6. S parameters for $r = 0.2a$ $rs = 0.1a$ with Θ1=75°

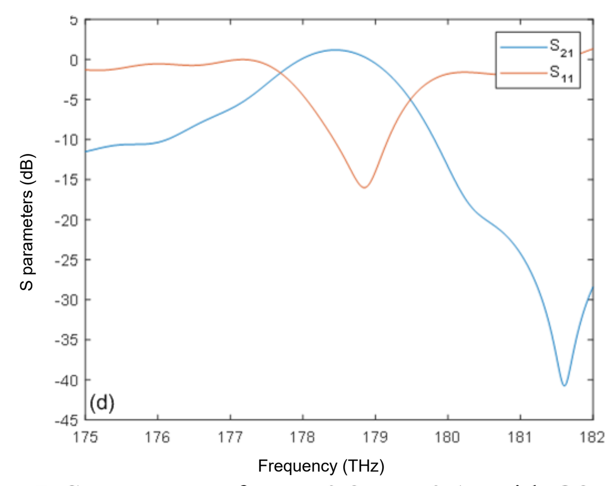

Fig. 7. S parameters for $r = 0.2a$ rs=0.1a with Θ2=105°

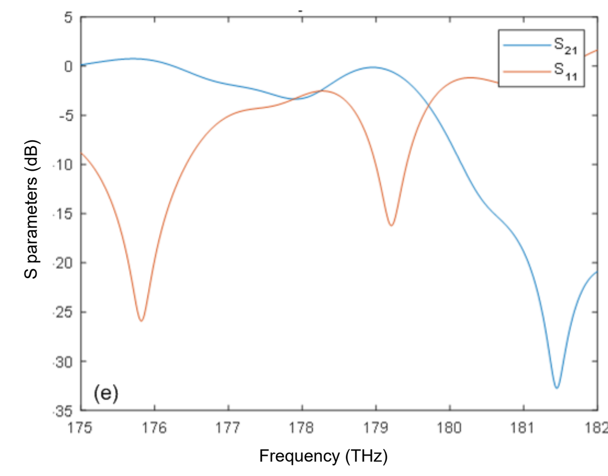

Fig. 8. S parameters for $rs = 0.05a$

Finally, I also tried the experimental procedure in order to support the simulation results. A single rod constructed from the 3D printer was used as a cavity in the square lattice photonic crystal consisting of alumina rods as seen in Fig. 9. For each of the simulation and experiment, the dimensions were taken in the microwave region using the scalability feature of photonic crystals. For example, if I take the lattice constant as a = 1 μm and a = 15.8 mm, the normalized frequency of 0.4 corresponds to the real frequencies of 120 THz and 7.5 GHz, respectively. The value of the lattice constant a in the structure was selected as 15.8 mm. The Alumina rods with a radius of 3.16 mm (0.2a) were used in the measurement. As shown in Fig. 7., a cavity was created with zero-degree LSPC within a photonic crystal structure consisting of Alumina rods arranged in a square lattice. A source with the frequency range of 5.38 GHz-8.17 GHz was applied to the input horn antenna connected to the vector network analyzer and measurements were taken from the output horn antenna. Although the transmission spectra of the shoulder coupling structure with several low symmetry angles and rod radius were obtained, the simulation and the experimental results of only the shoulder coupling structure with one rod are given in Fig. 3 and 9., respectively, as representative. It can be told from these figures that, some deviations between the results of the two methods due to different conditions between the experimental setup and simulation region, and the physical defects of the materials. In the simulation, the source was located within the structure, whereas this was not feasible in the microwave measurement setup. A point dipole source can be used as an alternative, but the wave does not propagate directionally, and all frequencies cannot be excited, in this case. Another difference is that a plane wave or broadband Gaussian-type signal is used as a source in the simulation, while only the broadband signal is employed in the experimental setup. The structure was perfectly isolated from the external environment and surrounded by an anti-reflective matching layer in the simulation box, which was not feasible in the experimental setup. Moreover, the diameters of the supplied dielectric rods are not manufactured uniformly. The dielectric constant of the rods also depends on their impurity and operating frequency. Therefore, the S21 coefficient could be measured by using a network analyzer in the experimental condition of the study whereas the S11 measurement was less reliable and is not presented in Fig. 9b.

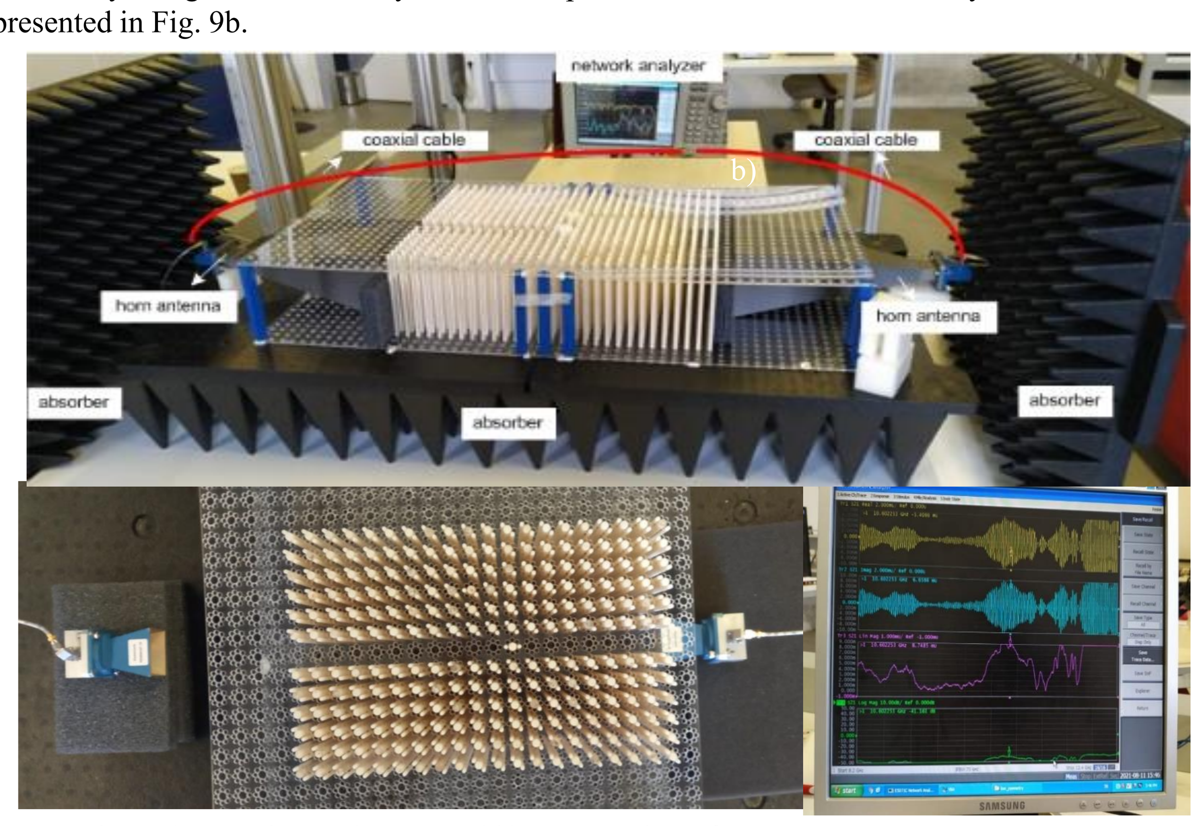

Fig.9. a) Experimental setup and b) a screenshot of S parameters measurement

CONCLUSION

In this study, the dependence of the degenerate resonance mode on the low-symmetry parameters was investigated, and unlike other studies, the intrinsic symmetry property of the low-symmetry PC structure was used for mode splitting. Since degeneracy is caused by the symmetry properties of the modes in the photonic crystal, it was possible to split the resonance by breaking the internal symmetry of the structure in the low-symmetry PC structure. Although the experimental verification stage was tried to be done in the microwave region, the desired result could not be obtained due to the differences between the experimental and simulation environments. In future studies, the experimental setup will be modified, and the simulation results will be verified.

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