Unidirectional Light Transmisson through Refractions across Photonic-Crystal Junctions

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***Abstract*- A photonic crystal system composed of air holes in a dielectric host to form two square photonic crystals, with the same orientation and lattice constant but different scatterer radii, making an interface along their body diagonals is numerically demonstrated to facilitate unidirectional light transmission.**

I. Introduction

Unidirectional wave propagation in the electromagnetic (EM) spectrum has been achieved through many techniques based on breaking either the time-reversal [1], parity-time [2] or spatial invertion [3] symmetries. Recently, refractions and band structure concepts are put into practice to obtain a sonic crystal diode that breaks spatial inversion symmetry [4]. This approach could also be utilized in photonic crystal (PC) systems since the refraction of an EM wave across an interface of a PC depends on the material and geometrical parameters of the contact medium.

In this work, unidirectional transmission of light through a PC junction system constructed by two PCs possessing different scatterer radii is numerically investigated.

II. Computational Methods and Diode Design

PC system in Fig. 1(a) is constructed from two PCs, in which air holes in an AlGaAs host (ε_r=11.162) are arranged in square lattices with different scatterer radii. The PCs on the left (PCL) and right (PCR) have a common lattice constant, a=1.00 μm, and are cut along the ΓM direction. They are then brought together along the ΓX direction. PCR is offset by d, whose optimal value is determined as 0.2a, normal to the interface to minimize reflection losses. The PCR has scatterer radii rR/a=0.352, while PCL has r_L/a=0.460.

Plane Wave Expansion (PWE) [5] computations with 216 plane waves reveal that stop bands along the GX direction exist for an r range in case of TM (electric field normal to the plane) polarization, Fig. 1(b). Attention is, thus, confined on the two stop bands along the GX direction whose total bandwidth is maximized at r/a=0.352. For this r/a, the lower stop band lies between the top of the second and the third bands for $0.311<\omega a/2\pi c<0.331$, while the upper rests between the bottom of the fourth and the fifth bands in the $0.346<\omega a/2\pi c<0.368$ range at r/a=0.352, Fig. 1(b). The stop bands disappear for r/a>0.45, Fig. 1(b). Thus, optimized transmission to the right is attained at r_L=0.460a, for which the second TM band ($0.287<\omega a/2\pi c<0.407$) covers both stop bands of PC_R.

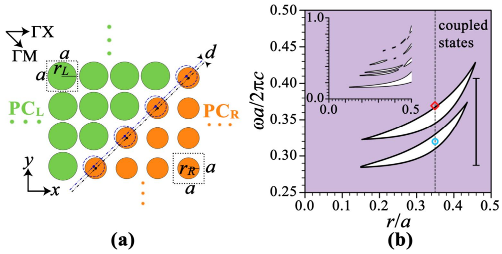

Fig. 1- Design of the PC diode **(a)** and the variations of TM stop-bands along the ΓX direction with the r/a ratio **(b)**. The dashed line in (b) denotes the r/a value maximizing the total stop band width, while the symbols denote the two working frequencies. Inset in (b) presents all observed stop bands, where the vertical line indicates the 2nd PC_L TM band for r/a=0.460.

Diode action is investigated at two frequencies $\omega a/2\pi c$ = 0.32 and 0.37, marked in Fig. 1(b), at which EFCs of PC_R are M-centered and fall into the 3rd and 4th bands, respectively, Fig. 2(b). Directional band gaps at both frequencies prohibit transmission by PC_R, while a recent heterojunction system diverts reverse waves sideways [6].

Rotation of the surface normal and the construction line by $\pi/4$ at the PC_R-PC_L junction makes coupling into a mode of PC_R possible, Fig. 2(b). Refracted waves across the junction at $\omega a/2\pi c$ =0.32 (0.37) experience almost self-collimated propagation in PC_R, as both EFCs have small curvatures in the vicinity of the construction lines, Fig. 2(b). The construction line intersects the EFCs at multiple points, leading to reflected components, represented by pale arrows directed upward and to the left in Fig. 2(b). The downward-directed arrow at $\omega a/2\pi c$ =0.32 indicates a secondary excited mode in PC_R. These components reduce overall efficiency of the PC diode.

Finite-Difference Time-Domain (FDTD) simulations are [7] carried out with grid sizes dx=dy=0.02a, and a 0.5a-thick Perfectly-Matched Layer boundary [8]. Time step $c.dt$=dx/2=0.001a satisfies the Courant-Friedrichs-Lewy condition [9]. The Gaussian-enveloped plane wave source is 4a wide, while transmission spectra are calculated over normalized frequencies between 0.25 and 0.50.

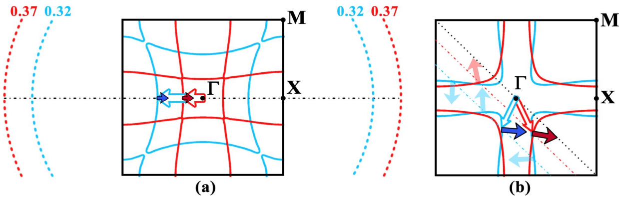

Fig. 2- EFCs at $\omega a/2\pi c$=0.32 and 0.37 of PC_L **(a)** and PC_R **(b)** for the TM polarization. The dashed arcs in (a) represent the corresponding EFCs in the host, while the hollow and solid arrows denote the wave vectors and the propagation directions, respectively. The dash-dotted lines are construction lines.

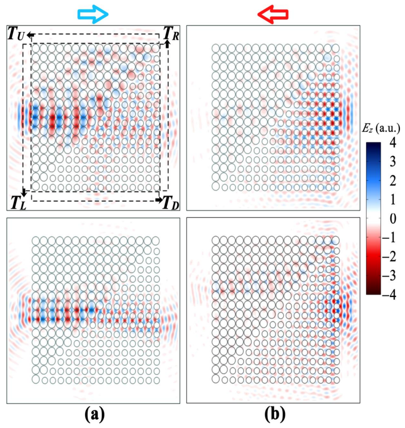

Fig. 3- FDTD simulations of waves traveling to the right **(a)** and left **(b)** for $\omega a/2\pi c$ =0.32 (top) and 0.37 (bottom), denoted by arrows. The dashed rectangles represent the areas where the transmission data are calculated.

Light propagation across the PC diode is demonstrated in Fig. 3, where transmission only to the right, Fig. 3(a), is allowed. Waves are self-collimated in both PC_L and PC_R at the normalized frequency of 0.37, while more remarkable reflection losses at the interface are incurred at 0.32.

In the reverse direction, Fig. 3(b), waves are reflected at the air-PC_R interface, where the penetration is more significant in the lower stop band so that the deflected waves at the air-PC_R interface can reach PC_L and the output port. Leakage in the reverse direction stems from the finite source size of the source and the fact that EFCs are close to the ΓX line. The latter can be compensated by enlarging stop bands through use of annular PCs [10].

Frequency-dependent efficiency of the PC diode is investigated by calculating the transmission to the right (T_R) and left (T_L) across the rectangular regions in Fig. 3(a) by integrating the total EM energy density at each frequency. The results are normalized to the integral over T_L in vacuum. Transmission spectra in Fig. 4 show that T_R fluctuates around 50 % for $0.32<\omega a/2\pi c<0.42$, while T_L remains below 20 % over stop bands. The peak T_L value (26 %) is attained at the lower end of the upper stop band.

Although T_R is comparable among the stop bands, T_L is significantly smaller in the lower one, where it reaches 9 % at the upper-limit of it. This is related to samller EFC curvature at 0.37, as in Fig. 2(b), leading to a more efficient collimated guidance in both directions.

The transmission contrast ratio defined as $C_{LR}=(T_R-T_L)/(T_R+T_L)$ [2], remains closer to 1.0 within the lower stop band,maing this range more appropriate for rectification.

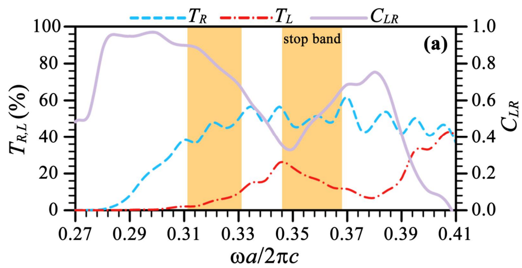

Fig. 4- Variation of transmission to the right and left (left axis) accompanied by the contrast ratio (right axis)

IV. Conclusion

A system of two square photonic crystals with different scatterer radii, brought together along body diagonals, is demonstrated to facilitate unidirectional light transmission over two stop bands. The lower stop band offers larger contrast ratio, while the upper facilitates better self-collimation. Lateral losses are small for forward waves.

Acknowledgment

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