Unidirectional Light Transmission 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 inversion [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 (ι=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 numerically to maximize 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 PCR TM band for rL/a=0.352, Fig. 1(b). The stop bands in PCR and the variations of TM stop-bands along the rL/a ratio (b). The dashed line in (b) denotes the rL/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 PCR TM band for rL/a=0.460.

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

Rotation of the surface normal and the construction line by π/4 at the PCr-PCR junction makes coupling into a mode of PCr possible, Fig. 2(b). Refracted waves across the junction at ιa/2πc = 0.32 (0.37) experience almost self-collimated propagation in PCR, 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 ιa/2πc = 0.32 indicates a secondary excited mode in PCR.

Finite-Difference Time-Domain (FDTD) simulations are carried out with grid sizes dx=dy=0.02a and a 0.5a-thick Perfectly-Matched Layer boundary [8]. Time step c.dt/dx2=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. 1- Design of the PC diode (a) and the variations of TM stop-bands along the ΓX direction with the rL/a ratio (b). The dashed line in (b) denotes the rL/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 PCR TM band for rL/a=0.460.](Image 323x171 to 553x242)

![Fig. 2- EFCs at ιa/2πc=0.32 and 0.37 of PCr (a) and PCR (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.](Image 345x546 to 530x638)
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 PCL and PCR 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-PCR interface, where the penetration is more significant in the lower stop band so that the deflected waves at the air-PCR interface can reach PCL 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 (TR) and left (TL) 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 TL in vacuum. Transmission spectra in Fig. 4 show that TR fluctuates around 50% for 0.32<ωa/2πc<0.42, while TL remains below 20% over stop bands. The peak TR value (26%) is attained at the lower end of the upper stop band.

Although TR is comparable among the stop bands, TL is significantly smaller in the lower one, where it reaches 9% at the upper-limit of it. This is related to smaller 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 CLR=(TR-TL)/(TR+TL) [2], remains closer to 1.0 within the lower stop band, making this range more appropriate for rectification.

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.

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REFERENCES