Mode Converter Optical Isolator Based on Dual Negative Refraction Photonic Crystal

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***Abstract*— A new design of an optical isolator based on photonic transitions in the interbands of a honeycomb structure that generates a dual negative refraction in a photonic crystal is presented. The involved photonic transition is associated to the perturbation of the dielectric constant of the medium. The band structure is determined using the plane wave method where the transmission spectra, field profile, and mode amplitudes are obtained by applying the finite difference time domain method. Due to the time-dependent perturbation of the refractive index of the medium that constitutes the dual negative refraction, asymmetric transmission mechanism is achieved for one of the desired modes, demonstrating optical isolation. Using the dual negative refraction effect in photonic crystal structure, the optical isolation is reported for only one of the desired optical modes. It is anticipated that the proposed mode conversion mechanism can be employed for designing ultrahigh-speed optical interconnections. The proposed optical isolator model is expected to have a significant impact on designing ultrahigh-speed integrated optical platforms.**

***Index Terms*— Photonic crystals, metamaterials, nanostmctured materials, photonic integrated circuits, optical computing.**

I. Introduction

OPTICAL computing and signal processing require isolation of light in optical components that can be achieved by a nonreciprocal light propagation. Non-reciprocal light propagation has been studied recently, where isolating optical signals that propagate in the accompanying photonic structures are reported [1]–[8]. Since optical isolators allow light to propagate predominantly in one direction while the signal that propagates in the opposite direction would be blocked or diverted, it prevents the ensued interference from happening [1]. In practice, the isolation of light in an optical component requires time-reversed symmetry breaking. It has been shown earlier that optical isolation can be achieved for instance by applying opto-acoustic effects [9], nonlinear materials and materials containing magneto-optic effects driven by external magnetic fields [10]–[12]. The optical isolators designed in these conventional approaches require large magnetic fields, however for small optical structures it is technically demanding to achieve isolation following these approaches. Hence, currently, several efforts have been geared towards avoiding the application of magneto-optic effects and achieve a complete optical isolation of the light in micro meter scale [13]. Recently, it has been shown that the use of photonic crystals (PCs) opens up to novel ideas and techniques to realize an optical isolator where the light that propagates in the backward direction is blocked or diverted [1]. The obtained optical isolator can be used primarily in optical interconnection which requires a nonreciprocal propagation of the light between different chips.

In this regard, we pursue to demonstrate an active optical isolator based in Dual-Negative Photonic Crystals (DNPC) structure for certain desired optical modes. In practical context, the working principle of DNPC structure is based on the fact that under certain conditions the electromagnetic wave can be dispersed and divided into two negatively refracted waves which lead to the Dual-Negative-Refraction (DNR) phenomena [13]. It is worth noting that in the DNR effect the overlap between two bands is necessary. This entails that the isolation of the light in the DNPC requires controlling of the transition of photons in the inter-sub band. Therefore, in order to realize this idea, the time dependent modulation of the refractive index is used. The DNPC with hexagonal lattices to generate the DNR effect is considered for practical reasons. Based on the geometrical symmetry of this structure, the lowest TM modes (TM_2 and TM_3) can be generated by careful selection of the frequency of the incident modes. The proposed structure supports both propagating modes (TM_2 and TM_3) in the forward direction, however in the opposite direction only the TM_3 mode is propagating. In order to establish the isolation, the dielectric constant of the hexagonal rods is perturbed where the TM_2 mode (desired mode) is blocked in the desired direction. With respect to the definition of the optical isolator introduced by Jalas *et al* [1] and Fan *et al* [2], we add an absorption filter centered at TM_2 mode frequency in the output interface, where the dispersion of the optical modes is calculated by using the plane wave method. For The transmission spectra on the other hand, the field profile and the optical mode amplitudes, in both directions, are determined by employing the Finite Difference

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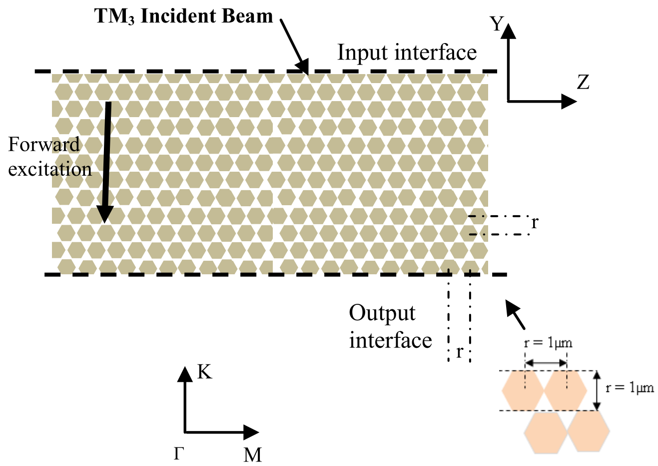

Fig. 1. Schematic representation of the mode converter optical isolator. The normal of the input interface is along ΓM direction. For convenience, the frequency and the wave vector are normalized by the lattice constant of the structure $a = 1\mu$m. The rod dimension is fixed to around center to center distance r $= 0.5\mu$m.

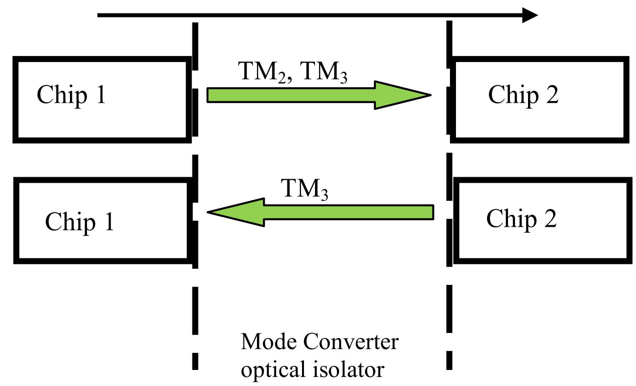

Fig. 2. Schematics of the nonreciprocal optical interconnection when the mode converter optical isolator structure is introduced between Chip1 and Chip 2.

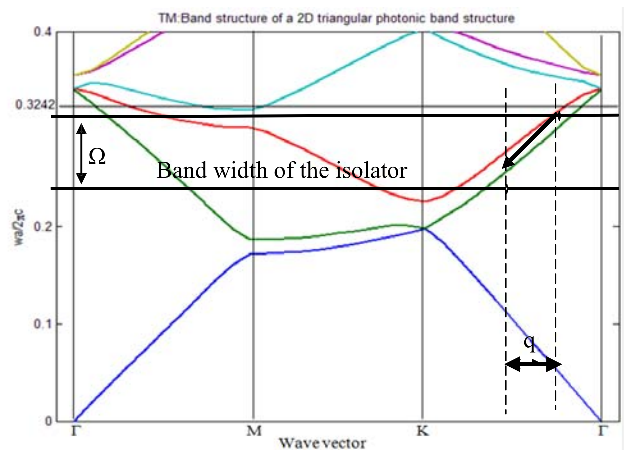

Fig. 3. Plots of the band structure of the unperturbed DNPC crystal. The bold arrow represents the optical transition between TM_2 and TM_3. The bandwidth of the isolator is designated by a maximum of the band overlap between TM_2 (green curve) and TM_3 (red curve) modes.

Time Domain Method (FDTD). The FDTD is a powerful and versatile numerical method that is employed to solve various PCs complex structures [14].

Our simulation results show that the performance of the mode converter optical isolator, proposed in this study, has attained almost 100% at the operating wavelength of 1550nm for the TM_2 mode. In this regard, the proposed idea would have a great impact in transforming the information between various different integrated chips into a single platform or chip-to-chip integrated platforms.

II. Mode Converter Optical Isolator

A proposed mode converter optical isolator structure for a specific mode based on a negative photonic crystal (NPC) is illustrated in Fig. 1. The honeycomb lattice PC is constructed from hexagonal dielectric rods with $\varepsilon_0 = 11.56$, positioned in air with a filling ratio of 82.2%. The rod dimension is fixed around center to center distance r $= 0.5\mu$m. It is envisaged with current advanced available technology that this structure can be realized by using holographic lithography formed by crystalline Si(c-si). We choose to use this material due to its natural abundance and almost an ideal band gap [13].

In the present work, in order to induce mode conversions in the forward direction, we introduced temporal perturbation of the dielectric constant of the rods, whereas the considered modulation is expressed as

$$\varepsilon = \varepsilon_0 + \Delta\varepsilon \quad (1)$$

where $\varepsilon_0 = 11.56$ is the dielectric constant of the non-perturbed structure and $\Delta\varepsilon$ represents the time dependent perturbation. It is worth pointing out that our device is a linear negative photonic crystal for which the Lorentz theorem reciprocity does not hold [1], therefore our proposed device can be used to realize an ideal optical isolator. The time dependence index is used to couple two specific propagation modes (TM_2 and TM_3 modes) only in forward direction. By placing an absorbing filter centered at TM_2 frequency in one direction, this structure can be used to realize a comprehensive optical isolator [2].

Moreover, the proposed system is envisaged to be applicable to create an interconnection between different optical chips. With this idea, Chip-to-chip possible optical interconnection using a proposed mechanism is depicted in Fig. 2, which shows that in the forward direction TM_2 and TM_3 can propagate from chip 1 to chip 2, but in the backward direction only TM_3 is transmitted.

III. Result and Discussion

In order to calculate the photonic band structure, the plane wave method is employed where the electric field of the TM mode parallel to the rod axis is illustrated in Fig. 3.

From Fig. 3, it can be seen that the higher bands are overlapped specially for the second band (TM_2 mode) and third band (TM_3 mode). We notice that in the overlapping band region, the two bands are very close to each other, which is a key factor to design an ideal mode converter. In this regard, we demonstrate that the nonreciprocal light propagation in the NPC can be realized by inducing indirect transition in one direction in the considered photonic structure. In line with this, it has been shown elsewhere that when a photonic structure is subject to a refractive index modulation, the photon states can pass through inter band transitions [2].

In this study, in order to induce mode conversions, we choose to introduce a temporal perturbation of the dielectric constant of the rods, illustrated in Fig. 1. The perturbation can be generated in various ways. One particularly simple method is to exploit the nonlinear properties of one of the materials belonging to the crystal. This modulation allows photons that belong to different bands to go through inter band transitions, where shifts in frequency and momentum of the photon would be observed during the modulation process. On the other hand, an interband transition between two modes can be induced by modulating the rods with an additional dielectric perturbation which is given by

$$\Delta\varepsilon = \delta(r)\cos(\Omega t - qr), \quad (2)$$

where $\delta(r)$ is the modulation amplitude and Ω represents the modulation frequency,

$$\Omega = \omega_1 - \omega_2, \quad (3)$$

where, ω_1 and ω_2 represent normalized frequency of TM_3 and TM_2 modes, respectively. We notice that the phase needed in eq. (2) can be controlled by the modulation frequency Ω. It is important to note, that the wave vector approximately satisfies the phase-matching condition,

$$\Delta K = (K_2 - K_1) - (-q) \approx 0, \quad (4)$$

where K_1 and K_2 represent the wave vector for TM_3 and TM_2 modes, respectively.

It is worth also noting that the mode transition between the TM_3 (ω_1, k_1) mode and the TM_2 (ω_2, k_2) mode occurs only when the phase-matching condition is achieved. In our case, for TM_3 mode this condition is only valid in the forward direction. From Fig. 3, we notice that the mode at (ω_1, $-k_1$) is not phase-matched with any other modes of the NPC. It can also be seen that while the mode at (ω_1, k_1) undergoes a photonic transition its' time-reversed counterpart at (ω_1, $-k_1$) is not affected. In this view the nonreciprocity of propagation of the light is key parameter to design an optical isolator, therefore in order to demonstrate the optical isolation, the frequency of the bandwidth is calculated where the band overlap between the TM_2 and TM_3 modes is at its maximum peak $\Omega = \omega_1 - \omega_2 = 0.0042(a/\lambda)$.

In our simulation, the width of the NPC slab is selected to be 8 periods. To induce transitions between the TM_3 mode at $\omega_1 = 0.3242$ (a/λ) and the TM_2 mode at $\omega_2 = (0.3200$ $a/\lambda)$, the phase matching condition is $q = 0.59k_0 = k_1 - k_2$ at the operating wavelength of 1.55μm (associated with k_0). For the sake of convenience, the modulation amplitude $\delta(r)$ is kept fixed at around 0.251. In order to optimize the length (L) of the slab of the NPC structure, we simulate the modes amplitudes as a function of the propagation axis (z-axis), starting with 3 periods, and proceeding with one step until we reach the 13^{th} period.

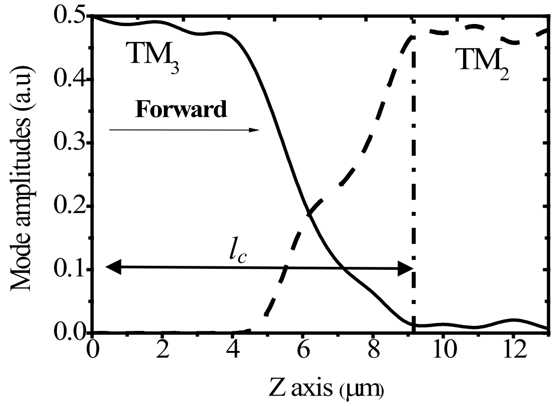

Fig. 4. Plots of the TM_2 and TM_3 mode amplitude in the forward directions against Z axis, when the period is fixed to 1μm, and l_c represent the coherence length.

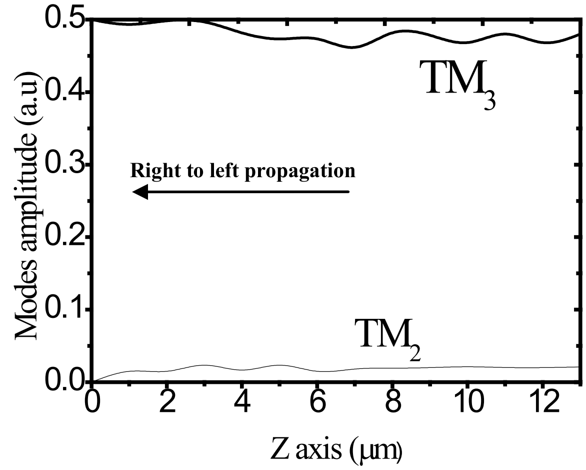

Fig. 5. Plots of the amplitude of the TM_2 and TM_3 modes when the light propagates in the backward direction.

As illustrated in Fig. 4, conversion of the modes is observed for the dielectrics periods from 1 to 4. It can be clearly seen that in this particular region, only the TM_3 mode can propagate through the NPC structure. However, between 4 to 9 periods, one can see that the amplitude of the TM_2 mode increases whereas the amplitude of the TM_3 decreases sharply, indicating that the modes start to be converted. In addition to this, for the regions greater than 9μm (note that the coherence length is defined to be $l_c = 9\mu$m), a complete mode conversion through the NPC slab is achieved. It is worth emphasizing that the coherence length $l_{,c}$ is the propagation distance necessary to observe the complete conversion of the modes.

Next, we realize a mode converter optical isolator for a particular mode (TM_3 mode) when the length (L) is fixed to around 9 periods. Fig. 5 shows the propagation of both modes TM_2 and TM_3 in the backward direction. It is clear from this figure that TM_2 mode amplitude is constant, which is significantly small compared to that of the TM_3. In other words, the amplitude of the TM_3 mode is at a maximum, while the amplitude of the TM_2 mode is nearly zero. The obtained results demonstrate that the photon from the TM_3 mode can be converted to the TM_2 mode, although only in the forward direction, still confirming that the proposed structure exhibits mode conversation optical isolator.

In the forward direction for a length (L) of the slab greater than the coherence length L_c [2], we observe a total mode conversion, where the resulting scattering matrix is calculated by;

$$\begin{bmatrix} TM_3 \\ TM_2 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} TM_3 \\ TM_3 \end{bmatrix} \tag{5}$$

We notice that, this matrix is symmetric. It is worth mentioning that in order to create an optical isolator Fan *et al.* [2] introduced an absorption filter centered at TM_2 mode frequency. This structure can absorb all of the light in one direction and the transmission matrix becomes;

$$\begin{bmatrix} TM_3 \\ TM_2 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} TM_3 \\ TM_3 \end{bmatrix} \tag{6}$$

In this case, the transmission matrix is asymmetric and a complete optical isolation is obtained [15]–[21].

Furthermore, in Fig. 6a, we have illustrated the snapshot of the mode profile when a pulse with a Gaussian of the frequency ω_1 is launched on the left hand side of the mode converter optical isolator structure. Here we use a waveguide source in order to study the propagation of light through the optical isolator [1]. One can see that for an incident angle of $\theta = 30°$, part of the TM_3 mode is converted to ω_2 (TM_2 mode). In this regard, photons are initially located in the mode TM_3 and during propagation, in the NPC structure; they experience a transition process to the TM_2 mode. In order to observe more details on the non-reciprocity of the light that leads to optical isolation, we reverse the source and excite the structure from the right hand side, the snap-shot is illustrated in Fig. 6a. As can be seen from this figure, in this direction only TM_3 mode can propagate through the NPC; non-conversion of the mode is observed.

We notice that when exciting the slab by TM_3 mode, we divert entire light in forward direction and the optical isolator is achieved according to the definition of Yu *et al.* [2] and Jallas *et al.* [1]. However, for convincing reasons we excite the DNPC slab by TM_2 mode in the backward direction, and the obtained results are illustrated in Fig. 6c, indicating that the entire light has been blocked in backward direction.

Our simulations (Fig. 6c) demonstrate that the amplitude power of the propagated TM_2 mode is less than 0.15 (a.u), in contrast the amplitude of the TM_3 propagated mode is around 1, consequently we conclude that this mode cannot propagate in the backward direction and the light is radiated. Fig. 6c shows that the light is blocked and the optical isolation phenomenon is demonstrated. In order to understand in more details the isolation effect, we calculate the transmission matrix, shown in Fig. 7, with TM_2 mode in the backward direction using eq. (7); our calculations show that this matrix is asymmetric.

$$\begin{bmatrix} B_1 \\ B_2 \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} A_1 \\ A_2 \end{bmatrix} \tag{7}$$

In other words, as the TM_3 mode propagates along the +Z direction, it starts to be converted into the TM_2 mode.

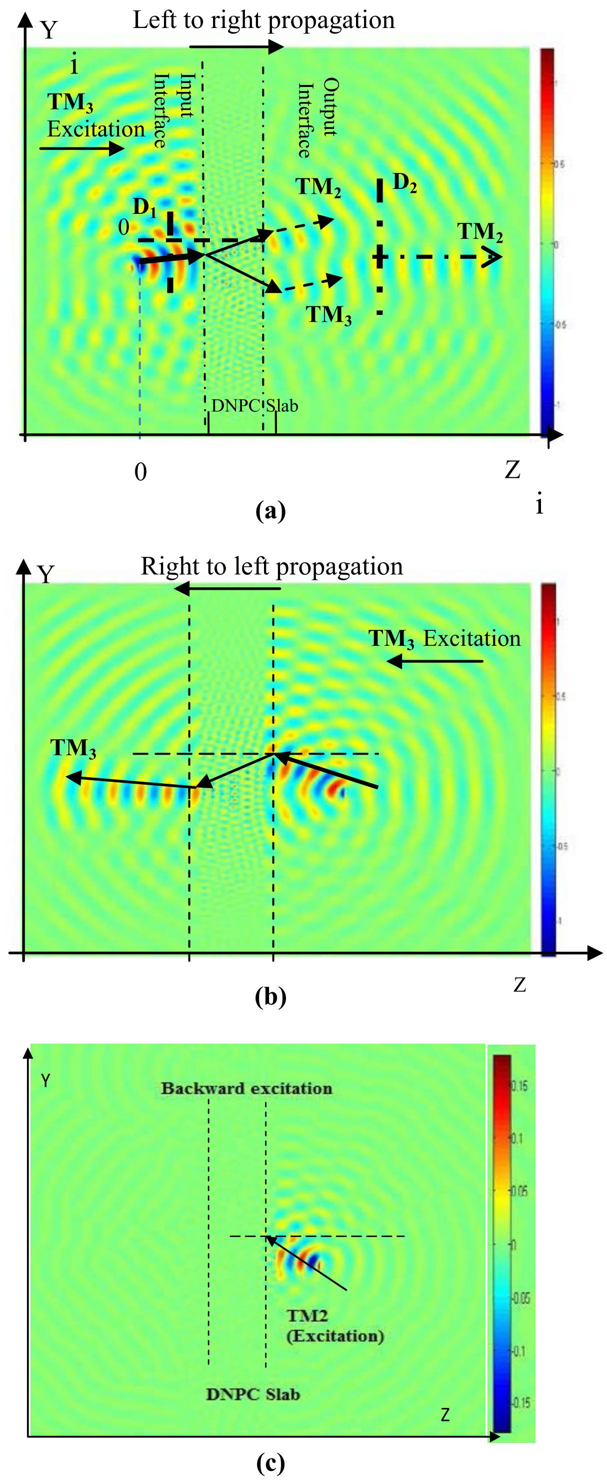

Fig. 6. Snap-shot of the distribution of the magnetic fields in Z direction at 20000 time steps in the forward (a) and backward (b) directions with $\omega a/2\pi c = 0.3242$ (a/λ) for 8 periods of the dielectrics. The DNPC slab is excited with the incident angle $\theta = 30°$. (c) Snap-shot of the magnetic distribution field in Z direction at 20000 time steps in the backward direction for the TM_2 mode for 7 periods of dielectrics. The DNPC slab is excited with incident angle $\theta = 30°$.

Calculation of the power at the source and the detector is also calculated. The incident (P_{inc}) represents the ratio between the power at the detector (D_1) and the power at the source. In a similar way, the transmitted power (P_{trans})

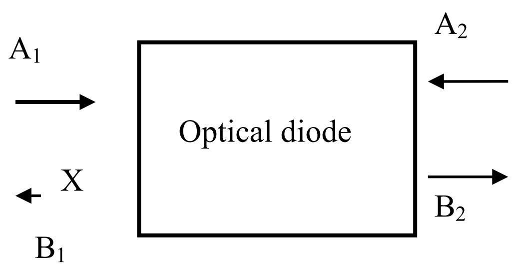

Fig. 7. Transmission matrix of TM_2 mode in backward direction.

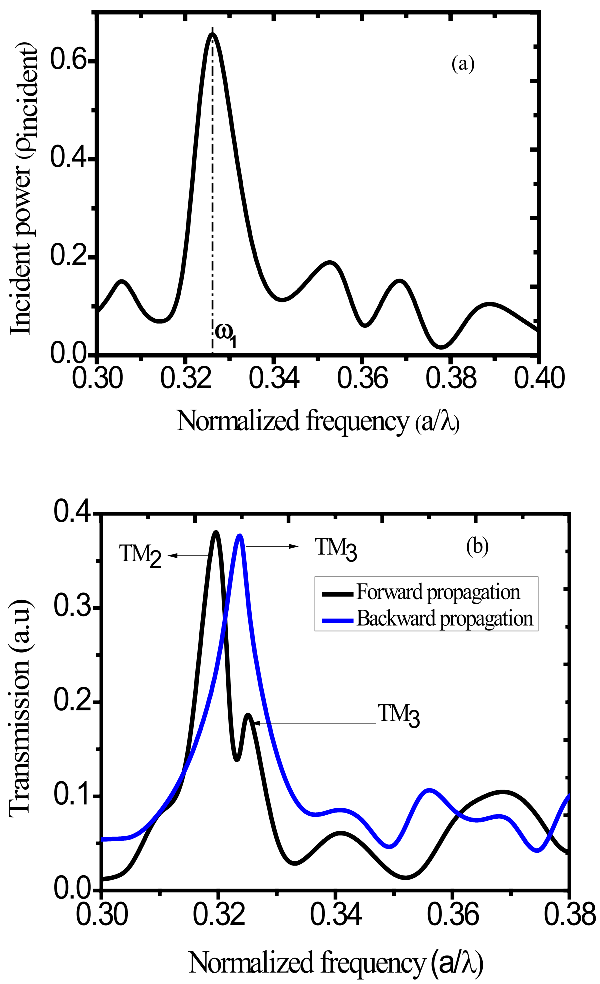

Fig. 8. (a): Plot of the incident power as function of the normalized frequency, when the maximum is fixed at $\omega_1 = 0.3242$ (a/λ), (b): Plot of the transmission power as function of the normalized frequency in the forward and backward propagation, where ω_1 represents the frequency of the TM_3 mode, and ω_2 presents the frequency of the TM_2 mode.

represents the ratio between the power at the detector (D_2) and the power at the source.

In Fig. 8(a) and (b), we illustrated the incident and transmitted powers in the forward direction. It is clear from these figures that in the forward direction the TM_3 mode is converted to TM_2. From Fig. 8(b), it can also be seen that 70% of the incident power is converted, reaching its maximum at 0.32 a/λ. Thus, the incident and transmission powers as a function of the normalized frequency are shown in these figures. As can be seen from Fig. 8(b) the transmission spectra in the backward direction reached its maximum at 0.4 (a.u) where $\omega_1 = 0.32\,(a/\lambda)$. From this spectrum, we calculate the optical loss ratio (S) introduced by the NPC structure. We notice that in this direction, since no conversion of the mode is observed, the total loss in this direction is introduced by the mode converter isolator. By using the following definition

$$S = \frac{\max\left(P_{inciTM_3}\right) - \max\left(P_{transTM3}\right)}{\max\left(P_{incTM3}\right)} \tag{8}$$

where S is around 19% in the backward direction, we notice that most of the power is lost at the input interface of the NPC structure and from the diffusion of the medium. Nonetheless, it should be noted that the optical loss should be the same in both directions for the isolator.

In this design, we excite the TM_3 mode in both directions, as can be seen, in the backward direction non conversion of the light is observed (blue line), nevertheless in the forward direction the entire light is converted to TM_2 mode (black line).

From Fig. 8(b) one can clearly perceive the differences between the forward and backward light transmission behavior magnitudes. It can be observed that the asymmetric transmission is evident from the Fig. 8(b), and that the maximum transmission in the forward direction doesn't concede with that of the transmission in the backward direction which results in a spectra window of the bandwidth equal to 0.0042(a/λ).

IV. Conclusion

We have presented a novel mode converter optical isolator based on dual negative refraction photonic crystal structure where the nonreciprocal isolation is accomplished by temporal refractive index modulations introduced in the direction of the excitation. We have demonstrated the light propagation and optical mode behavior in the forward and backward directions. In the forward direction, we have demonstrated that 70% of the TM_3 mode is converted to the TM_2 mode, however in the backward direction 100% of the TM_3 is transmitted. By using the DNR effect, we have selected and blocked only desired optical modes. It has been demonstrated that the maximum transmission in both directions is located at different frequencies, resulting in an optical isolation region. This study would play an important role in future optical integrating and interconnecting nano-optoelectronic devices which still remain a challenging task that the nanotechnology industry is facing.

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