

# Effect of the Nonlinearity on Optical Properties of One-Dimensional Photonic Crystal

Oumayma Habli\*, Jihene Zaghdoudi, and Mounir Kanzari

**Abstract**—Nonlinear effect on optical properties of one-dimensional photonic crystal (1D-PC) of the type  $(HL)^n(LH)^m(LLHH)^k$  was investigated. It is an asymmetric hybrid Fabry-Perot resonator type of 1DPC structure which is composed of linear (H layers) and nonlinear (L layers) materials. The linear and nonlinear transmission spectra are graphically illustrated using a numerical approach based on the Transfer Matrix Method (TMM). Results show the appearance of a Perfect Transmission Peak (PTP) in the photonic band gap which makes the structure constitute a monochromatic filter. By analyzing this PTP it is shown that the Full-Width at Half-Maximum (FWHM) depends not only on the number of symmetry layers of the studied 1D-PC but also on the refractive index of the nonlinear layers. The change of the refractive index (Kerr effect) causes a dynamically shift in the band gap including the resonance peak. As a result, such a structure has the potential to be used for designing optical filters and nonlinear optical devices.

## 1. INTRODUCTION

In recent years, the possibility of designing and controlling the optical properties of materials has shown their capacity for more valuable applications in optoelectronic devices. An alteration within the optical properties of the material will cause contrasts within the reactions of the electromagnetic waves and can be seen within the optical transmission or reflection spectra.

Photonic crystals (PCs) are artificial dielectric structures in which the refractive index can be modulated in one (1D), two (2D), or three dimensions (3D) on a scale comparable to the wavelength of operation. The most important characteristic of a PC structure is the Photonic Bandgap (PBG) which consists on a range of frequencies where the photon can be controlled and manipulated effectively [1, 2]. The simplest geometry of a PC is the one-dimensional photonic crystal (1DPC). It is known by the name of Bragg mirror where the periodicity exists only in one dimension. It consists of a stack of alternating layers having low and high refractive indices whose thicknesses satisfy the quarter-wave condition [3, 4].

1D linear PC has potential applications in various fields such as nanolaser [5], high-quality filter [6], and tunable mirror [7]. Recently, it is used in sensing applications like gas sensing [8] and bacterial contaminants sensing [9].

Lately, employing nonlinear elements in PCs opens up lots of new design opportunities. In comparison to ordinary linear PC structures, many interesting phenomena have been demonstrated using optically nonlinear components in PCs such as third-harmonic generation [10], four-wave mixing [11], and optical bistability [12]. When non-linearity is incorporated into a photonic crystal, the light propagation can be controlled dynamically [13], due to the intensity dependency of the refractive index (Kerr effect). Kerr nonlinearity modifying the refractive index holds great importance due to its suitability in ultra-fast devices.

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In this regard, one-dimensional nonlinear photonic crystals (1D-NLPCs) which consist of Kerr-nonlinear materials (semiconductors, glasses, and polymers) [14], have been of specific interest to researchers. They are used in promising applications in integrated optical devices such as low-threshold optical limiting [15], short pulse compressors [16], all-optical switching [17], and all-optical diodes [18].

The aim of this work is the application of a numerical approach based on the Transfer Matrix Method (TMM) to simulate the propagation of light through an asymmetric hybrid Fabry-Perot resonator structure of the 1D-PC type. This structure includes both linear and nonlinear optical layers. Then study the effect of the non-linearity (the Kerr effect) on the optical properties of this structure. The application of this model for designing optical filters and nonlinear optical devices as optical limiting, all-optical switching, and all-optical diode seems promising.

## 2. MODEL AND THEORY

The method that we introduce here for calculating the optical response of asymmetric quasiperiodic 1D-PC is the Transfer Matrix Method (TMM). Referring to Abeles method, we obtain the amplitude of the electric fields of the incident wave  $E_0^+$  and the reflected wave  $E_0^-$  as a function of both the transmitted and reflected electric field amplitudes within the  $m$ th layer [19–22]:

$$\begin{pmatrix} E_0^+ \\ E_0^- \end{pmatrix} = C_1 C_2 C_3 \dots C_m \begin{pmatrix} E_{m+1}^+ \\ E_{m-1}^- \end{pmatrix} \quad (1)$$

Here  $C_m$  is the transfer matrix defined as [23, 24]:

$$C_m = \begin{pmatrix} \frac{e^{-i\varphi_m}}{t_m} & \frac{r_m e^{i\varphi_m}}{t_m} \\ \frac{r_m e^{-i\varphi_m}}{t_m} & \frac{e^{i\varphi_m}}{t_m} \end{pmatrix} \quad (2)$$

The phase shift  $\varphi_m$  between the layers ( $m$ ) and ( $m+1$ ) is expressed by [25]:

$$\varphi_0 = 0; \quad \varphi_m = \frac{2\pi}{\lambda} n_m d_m \cos(\theta_m) \quad (3)$$

where  $\lambda$  defines the wavelength of the incident light in the vacuum, and  $n_m$ ,  $d_m$  and  $\theta_m$  are respectively the refractive index, thickness, and refractive angle of the  $m$ th layer.

The Fresnel transmission and reflection coefficients are given by [26]. The total reflection and transmission coefficients, which correspond to the amplitude reflectance  $r$  and transmittance  $t$  are given by:

$$r = \frac{E_0^-}{E_0^+} = \frac{T_{21}}{T_{11}}, \quad (4)$$

$$t = \frac{E_{m+1}^+}{E_0^+} = \frac{t_1 t_2 \dots t_{m+1}}{T_{11}} \quad (5)$$

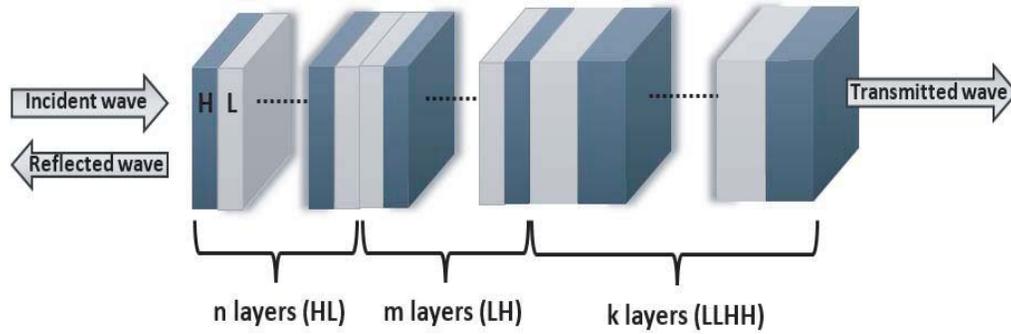
The quantities  $T_{11}$  and  $T_{21}$  are the matrix elements of the all product matrix  $C_m$  [26].

$$\prod_1^{m+1} C_m = \begin{pmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{pmatrix} \quad (6)$$

All the results in this work are given in normal incidence, so the transmittance  $T$  for both polarizations TM and TE is the same.

## 3. RESULTS AND DISCUSSIONS

In the following numerical investigation, we choose to study a 1D asymmetric photonic crystal built according to the structure  $(HL)^n(LH)^m(LLHH)^k$  (Fig. 1). The materials and their parameters for the



**Figure 1.** Schematic of 1D-PC structure with the asymmetric arrangement  $(HL)^n(LH)^m(LLHH)^k$ .

H and L layers were chosen by Zhukovsky and Smirnov [27], where  $TiO_2$  was used for the H layers and polydiacetylene 9-BCMU for the L layers. Their linear refractive indexes are respectively  $n_H = 2.3$  and  $n_L = 1.55$ . It should be noted that the nonlinear refractive index of the layer L depends on the electric field intensity and is given by  $n_L^{NL} = n_L \cdot (1 + \chi^{(3)}|E|^2/2)$  with  $\chi^{(3)}$  being the susceptibility or the Kerr coefficient [28].

The optical thicknesses of H and L layers were restricted by the quarter wavelength condition, i.e.,  $n_H d_H = n_L d_L = \lambda_0/4$ , in which  $\lambda_0$  is the reference wavelength and is taken to be  $\lambda_0 = 572$  nm in numerical calculations. The well-known simple and powerful Transfer Matrix Method is employed to obtain the transmittance spectrum through the proposed structures.

### 3.1. Linear Properties of the Structure

In this part, we investigate the linear properties of the 1D-PC structure  $(HL)^n(LH)^m(LLHH)^k$ . It should be noted that all the layers are linear. We start by studying the influence of the iteration numbers  $n$ ,  $m$ , and  $k$  on the transmission spectrum to optimize them. In Fig. 2, we plot the transmission spectrum as a function of the normalized frequency  $(\omega/\omega_0)$  and  $n$  for some values of  $m$  and for  $k = 2$  in order to find the optimal numbers of iterations which give a perfect transmission peak.

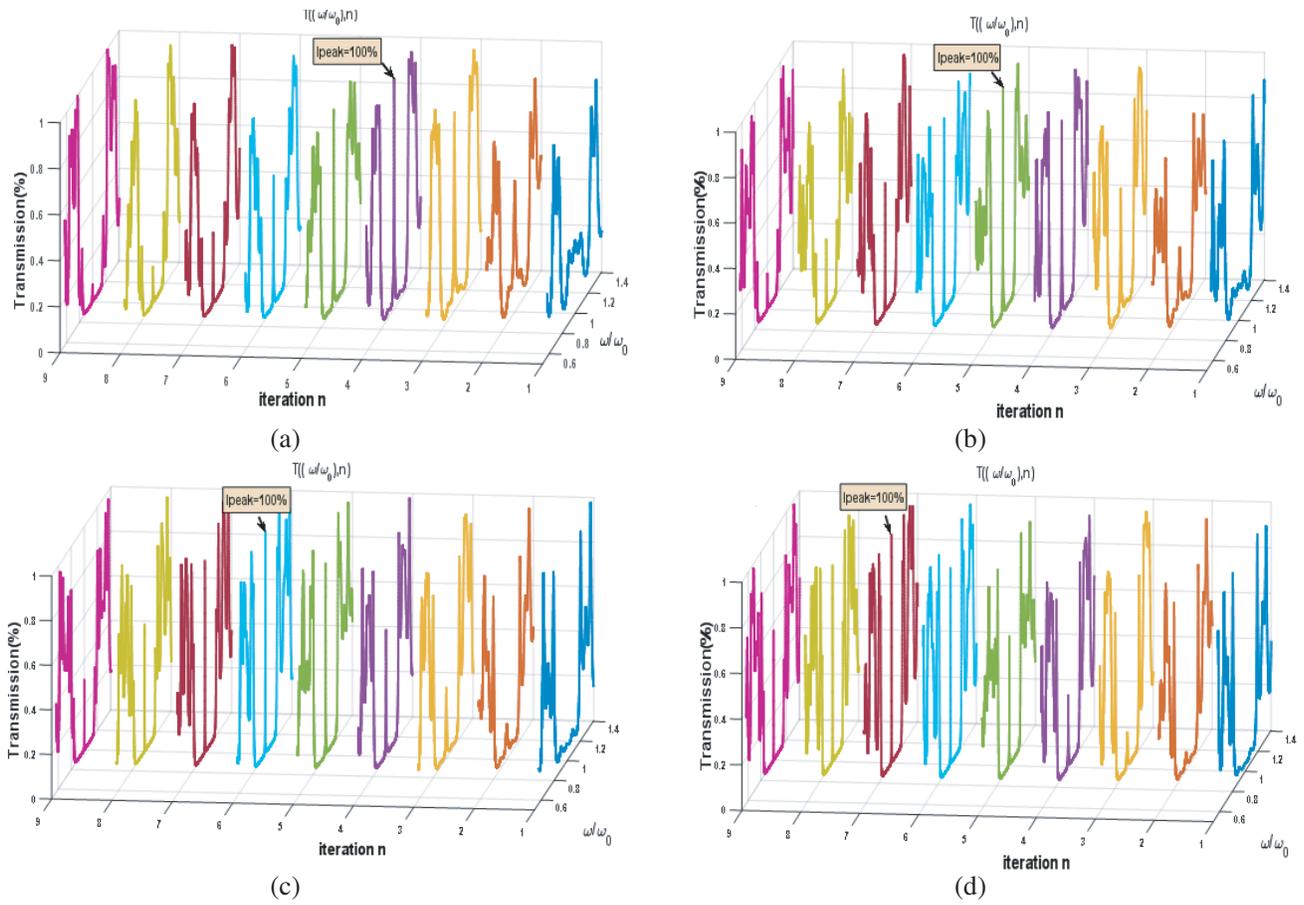
From Fig. 2, we can see the appearance of a resonance peak in the middle of the Photonic Band Gap (PBG). The intensity of the transmitted frequency takes different values for each  $m$  and  $n$ , and the maximum intensity of the peak is obtained when  $n$  and  $m$  are equal. These results are demonstrated in Fig. 3.

Assuming  $n = m = j$ , the transmitted peak keeps the same position exactly at  $\omega = \omega_0$  for different iterations  $j$  (see Fig. 4). This structure can constitute a monochromatic filter: the appearance of this single Perfect Transmission Peak (PTP) is due to the symmetric part of the structure  $(HL)^j(LH)^j$ . Further studies revealed this result [29–31].

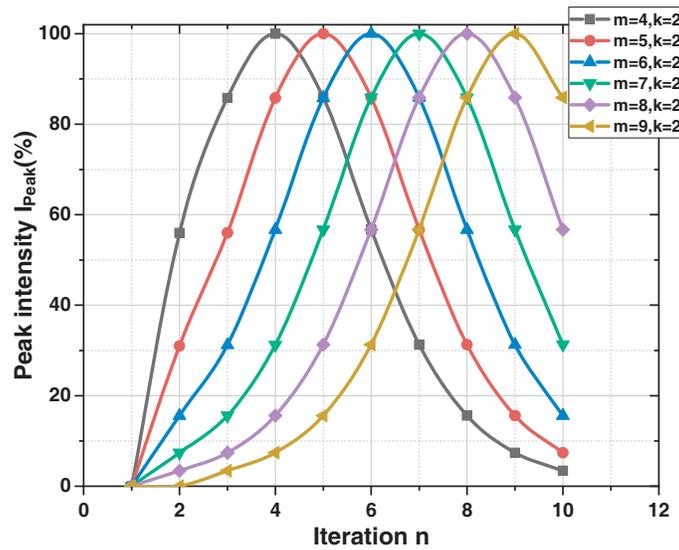
The results obtained in Fig. 5(a) show the effect of the increase in the number of iterations  $j$  on the Full-Width at Half-Maximum (FWHM) of the resonance peak for the structure  $(HL)^j(LH)^j(LLHH)^k$ . We note that when the repeated number  $j$  increases, the FWHM decreases, and the quality factor  $Q$  increases (see Fig. 5(b)).

As it is known, the quality factor  $Q$  depends on the FWHM of the transmission peak. In addition, it makes it possible to quantify the “quality of a filter”: indeed, when  $Q$  is high, the peak becomes finer which makes it more significant in terms of its reliability. Moreover, the filter becomes selective. In our case,  $Q$  is maximum for  $j = 9$  (44 layers). Indeed, for this iteration value we have an important quality factor  $Q = 5882.35$  and a narrow FWHM,  $\Delta(\omega/\omega_0) = 0.00017$ . According to these optical properties of the resonance peak, our structure can be used as an optical filter.

Furthermore, the existence of these PTPs in asymmetric structures is promising in designing nonreciprocal optical devices such as nonlinear all-optical diodes. This result is revealed by many works [32–35]. Indeed, a spatially asymmetric light localization associated at resonance induces a nonreciprocal nonlinear optical response, while perfect transmission ensures that reflection losses remain small.



**Figure 2.** Transmitted spectrum versus  $\omega/\omega_0$  and  $n$ , for  $k = 2$  and for (a)  $m = 4$ , (b)  $m = 5$ , (c)  $m = 6$  and (d)  $m = 7$ .



**Figure 3.** Transmitted peak's intensity  $I_{peak}$  versus number of iterations  $n$ , for  $m \in [4, 9]$  and  $k = 2$ .

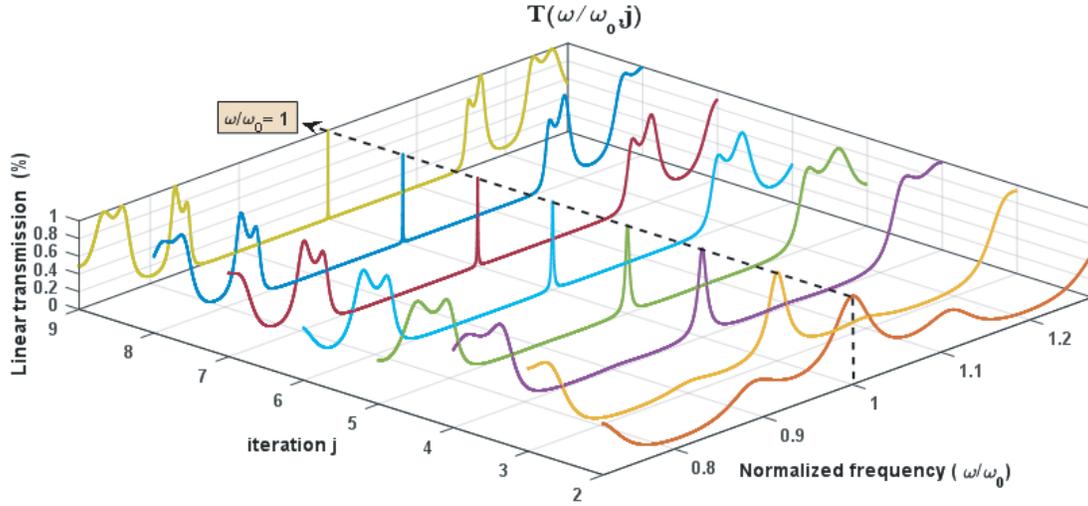


Figure 4. Linear transmission (LT) spectrum as a function of  $\omega/\omega_0$  and  $j$ , for  $k = 2$ .

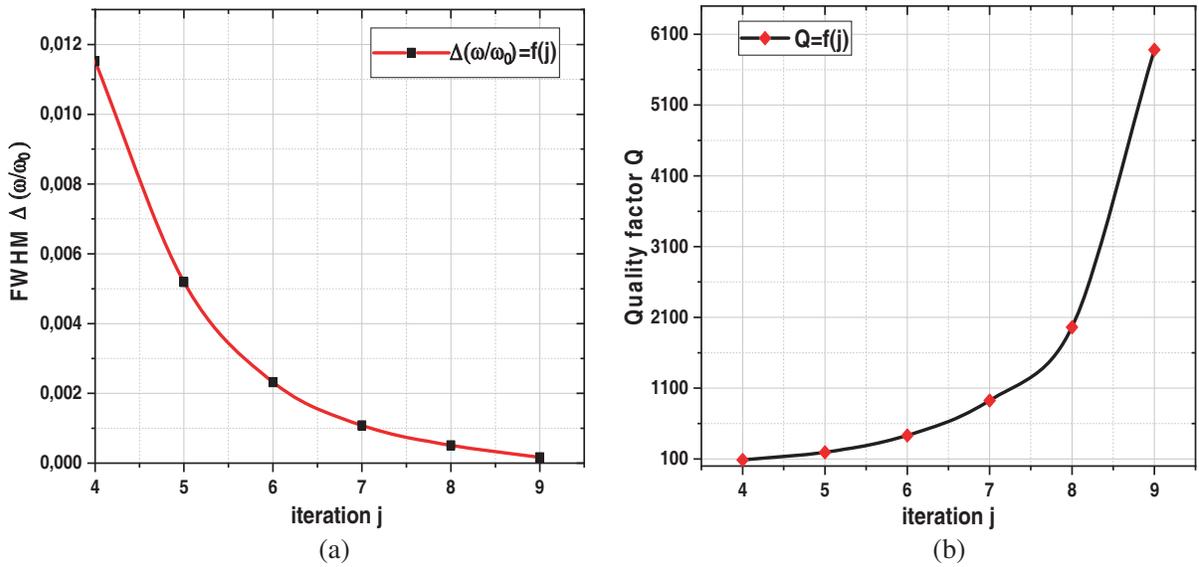


Figure 5. Variation of (a) FWHM and (b) the quality factor  $Q$  for different repeated number  $j$ .

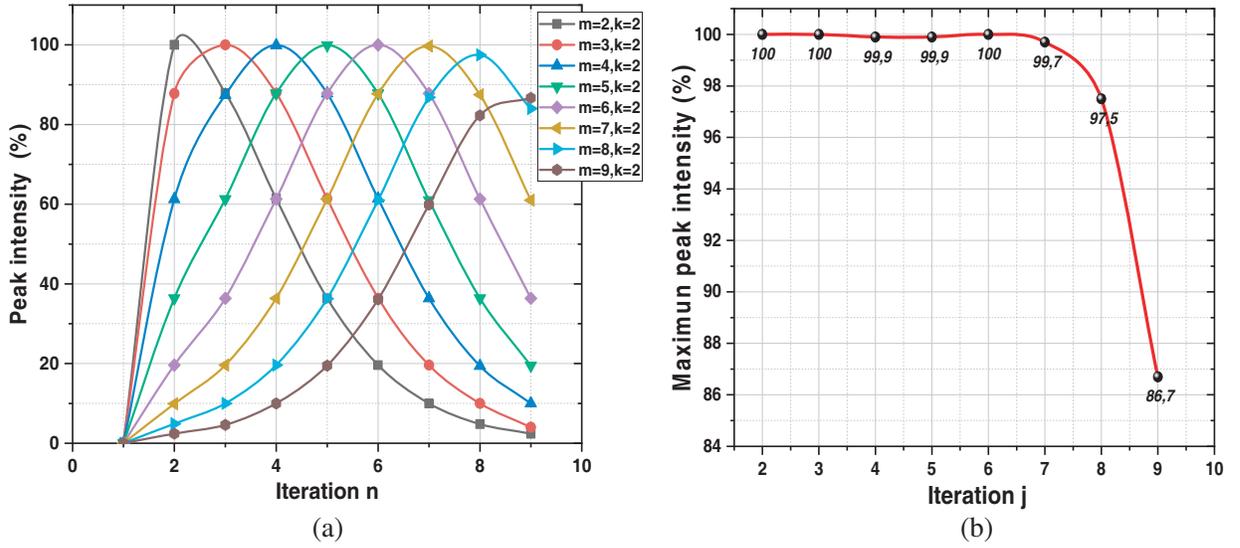
### 3.2. Nonlinear One-Dimensional Structure

After studying the linear properties of the 1D structure  $(HL)^n(LH)^m(LLHH)^k$  and showing that it presents a monochromatic filter of good quality, we investigate, in this part, the effect of nonlinear optical properties, precisely the impact of third-order optical non-linearity on the resonance peak and the PBG. We assume that a Kerr nonlinearity with  $\chi^{(3)} = 2.5 \times 10^{-5} \text{ cm}^2/\text{MW}$  is present in all low refractive index layers.

#### 3.2.1. Non-Linearity Effect of Layers L

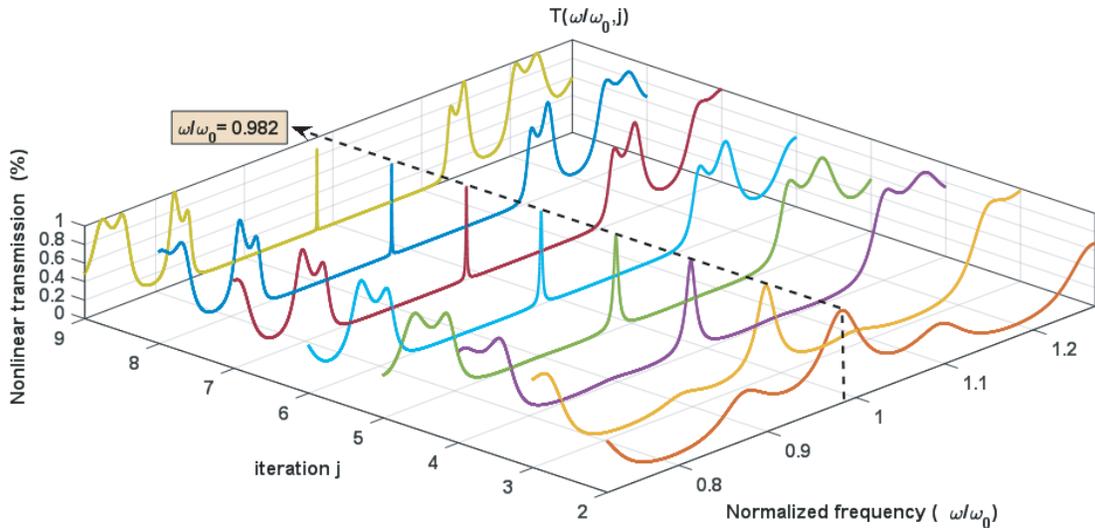
Firstly, the field intensity and iteration number  $k$  are fixed respectively at  $I = 50 \text{ MW/cm}^2$  and  $k = 2$ .

In Fig. 6(a), we represent the intensities of the peak for different values of  $m$  and  $n$ . The results show that the intensity of the peak becomes maximum when  $j$  is less than or equal to 6 assuming  $n = m = j$ . These results are demonstrated in Fig. 6(b).



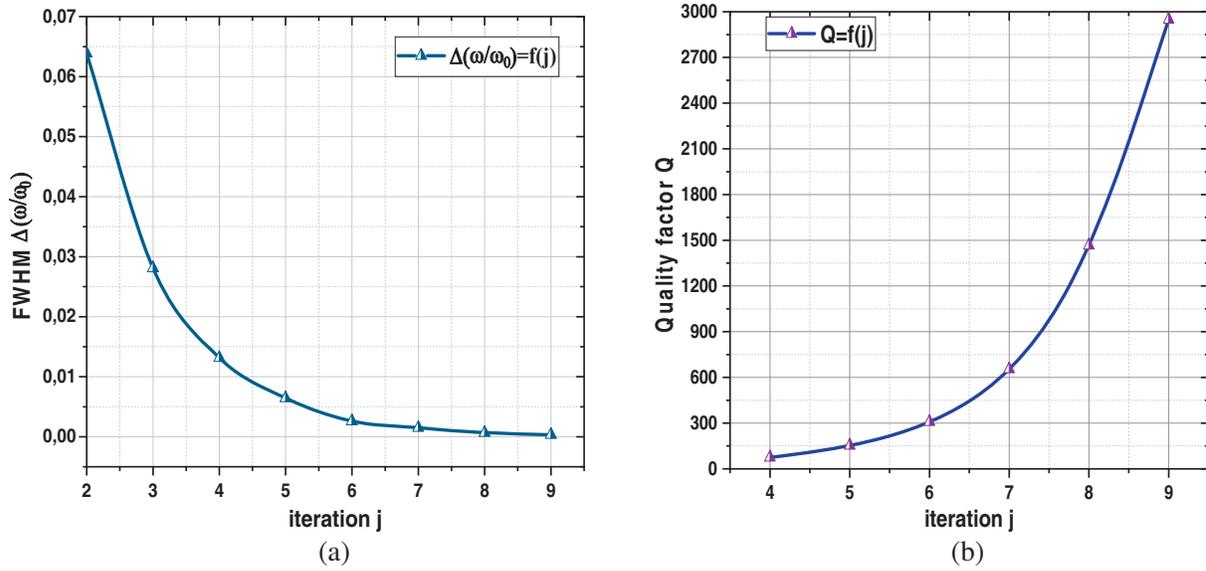
**Figure 6.** (a) Transmitted peak's intensity versus  $n$ , for  $m \in [2, 9]$ ,  $k = 2$ , and input intensity  $I = 50 \text{ MW/cm}^2$ . (b) Maximum peak intensity as function of  $j$ .

For the selected value of input intensity, the PBG and peak position are slightly shifted towards  $\omega/\omega_0 = 0.982$  and remain constant for the different values of  $j$  (see Fig. 7). This shift is in good agreement with the works of Maksymov et al. [36], Bhargava and Suthar [37], and Meng et al. [38].



**Figure 7.** Nonlinear transmission (NLT) spectrum according  $\omega/\omega_0$  and  $j$  for  $k = 2$ .

For the 1D NLPC, the shift of the band structure can be explained using Scalora et al.'s approach [39]. Indeed when Kerr nonlinearity is introduced in the PCs, the value of the refractive index changes which results in a dynamic shift of the forbidden band and the resonance peak. This process is the basis for intensity-driven optical limiting and all-optical switching. In these devices, the refractive index is changed by a high-intensity incident beam to dynamically control the transmission of light. Under this condition, the optical limiting is achieved by modifying the incident intensity while the all-optical switching requires an additional strong pump beam to control the switching of a weak probe signal tuned to the band gap region [36, 37].



**Figure 8.** Variation of (a) FWHM and (b) the quality factor  $Q$  according to  $j$  for the 1D NLPC structure.

In Fig. 8, we represent the effect of the increase in the number of iterations  $j$  on the FWHM  $\Delta(\omega/\omega_0)$  of the resonance peak and the quality factor  $Q$ . In comparison with the linear case, we find that the FWHM also decreases as a function of  $j$ , but it takes larger values (it is still narrow) than the linear case which gives a lower quality factor; for example for  $j = 6$ , we have  $Q = 307$ , and in the linear case we have  $Q = 431$ .

Considering  $j = 6$ , we have a perfect resonance peak with narrow FWHM  $\Delta(\omega/\omega_0) = 0,00319$ , and the structure has low number of layers (32 layers). Therefore, we can define the optimal numbers of iterations  $j = 6$  and  $k = 2$ . In the rest of this work, the studied structure becomes  $(HL)^6(LH)^6(LLHH)^2$ .

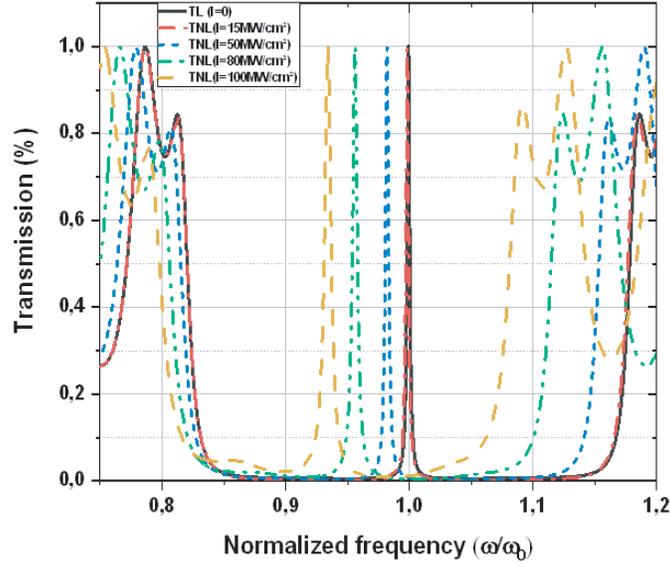
### 3.2.2. Effect of the Field Intensity

In this part, we will study the effect of the field intensity on the optical properties of the chosen structure. For this we represent in Fig. 9 the transmission spectrum of the chosen 1D photonic crystal in the linear regime (LT) (solid curve) and in the nonlinear regime (NLT) (dashed curve). In the nonlinear case, the results are presented for different values of input intensity  $I$ .

Increasing the electric field intensity  $I$  inside the layers having a low refractive index with nonlinear response changes their refractive index. According to Table 1 and Fig. 9, we notice that the bandgap width ( $\Delta_{PBG}$ ) is decreased by increasing  $I$ , while the FWHM of the resonance peak is increased. So the FWHM depends not only on the number of symmetry layers of 1D-PC but also on the refractive index of the nonlinear layers.

**Table 1.** The effect of the field intensity on the resonance peak and the bandgap width.

| Field intensity $I$ (MW/cm <sup>2</sup> ) | FWHM | $\Delta_{PBG}$ | Peak position | Bandgap position |
|---|------|----------------|---------------|------------------|
| 0   | 237  | 0.359          | 1             | 0.821 to 1.180   |
| 50  | 341  | 0.338          | 0.943         | 0.814 to 1.152   |
| 80  | 493  | 0.308          | 0.939         | 0.805 to 1.115   |
| 100                                       | 609  | 0.283          | 0.913         | 0.797 to 1.081   |



**Figure 9.** Linear (solid curve) and nonlinear transmission spectra (dashed curves) for  $(HL)^6(LH)^6(LLHH)^2$  structure with different input intensities.

It can also be noted that if  $I$  is low ( $I = 15 \text{ MW/cm}^2$ ), the NLT peak is very close to the linear regime (LT). However, if  $I$  is high, the bandgap including the resonance peak alters and shifts dynamically towards lower normalized frequencies. This shifting is in good agreement with the results of Kumar et al. [40].

The dynamic shifting of the PBG or the resonance peak can produce optical bistability phenomena as proved in the references [12, 41, 42].

According to the above statements, the intensity of the incident light is one of the important parameters that can affect the nonlinear transmittance through the structure.

So given all the above, our model can be used as an optical filter due to the PTP, also in nonlinear optical devices like all-optical diodes, optical limiting, and all-optical switching. In addition, because of the spatially asymmetric configuration of the structure and the PTP, it just requires an anisotropic field intensity distribution inside the layers, and it will act as all-optical diode. Optical limiting and all-optical switching can be achieved by the dynamic shift of the PBG or the resonance peak.

#### 4. CONCLUSION

In conclusion, we have studied the linear and nonlinear optical properties of the asymmetric one dimensional structure  $(HL)^n(LH)^m(LLHH)^k$ . We have shown that for  $n = m = j$  the linear transmission spectra of the structure contain a Perfect Transmission Peak in the middle of the forbidden bandgap. This PTP is due to the symmetric part of the structure  $(HL)^j(LH)^j$  which constitutes a monochromatic filter. In the nonlinear case, we have noted a dynamically shift in the position of the PBG and the resonance peak towards lower frequencies. This shifting is due to the Kerr effect which is a promising nonlinearity as it means the change of the refractive index of material in response to the applied electric field. Then we have fixed  $j = 6$  and  $k = 2$  which gives a minimum number of layers (32 layers). We have demonstrated that the optical properties of the PBG and the resonance peak depend on the input field intensity  $I$ .

Our asymmetric 1D system exhibits both a perfect transmission peak in the linear regime and a bandgap shift in the nonlinear regime. In this study as valuable results, we find that our model is suitable for different applications as optical filters, all-optical diode, optical limiting and all-optical switching.

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