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Slow Light in Double-Period One-Dimensional Quasi-Periodic Photonic Structure

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Abstract

Slow light in Double-period one-dimensional quasi-periodic photonic structure formed by stacking alternative silicon and silica Si/SiO2 layers is investigated in near infrared range through a theoretical model based on the transfer matrix method. The effects of generations number, layers number, incidence angle, wavelength reference of exciting light and index contrast materials are presented and discussed. The maximal slowing down factor obtained in the proposed structure is compared to those found in the Bragg periodic multilayers, in the Thue-Morse quasi-periodic structure and in the cantor structure for same number of layers.

We show that our proposed structure giving the possibility to control and manipulate light for bending, switching, reflecting in photonic systems used for diverse optoelectronic devices

Keywords: Slow Light; Photonic Crystals; Quasiperiodic

Introduction

Since the first works reported in 1987 by Yablonovitch [1] and John [2], the concept of photonic crystals (PCs) became the subjet of intensive research because their attractive properties for guidation and manupilation of light which occurs many applications in photonic devices, optoelectronic and telecommunication, such waveguides, cavities, efficient lasers , reflectors, optical sensors,couplers, detectors and optical filters… [4,5]. PCs are artificial structures with periodic arrays of two dielectric materials having different refractive indexes. This periodicity induces the appearance of frequency ranges in which the propagation of light is forbidden called photonic band gap (PBG) which are compared to electronic band gaps in semiconductor crystals. PCs can be fabricated in: one- (1D),two- (2D) and three-dimensional (3D) PCs . 1D PCs are more attractives since its production relatively easy to achieve through many depositiontechniques when compared to 2D and 3D PCs, and its modeling by simple analytical and numerical calculations [3]. Recently quasi-periodic structures of photonic crystals have become significant systems [5] which can be generated by substitution rules based on two building blocks H and L, with High nH and Low nL refractive indexes respectively. These rules obey to a periodic mathematical sequences as Fibonacci [6], Thue-Morse [7], Cantor [8] and period doubling [9]. Compared to periodic photonic crystals [10], quasi-periodic structures have not translation symmetry [11].

These quasi-periodic systems are promising candidates for a new path of fundamental and applied research in the field of non-linear and quantum optics such as controlling, guiding and slowing down of light, they permit also to decrease or increase the group velocity of exiting optical pulse. In this work , we interest of so called slow light that is obtained with a group velocity much smaller than the velocity of light in the vacuum. The slow wave effect in photonic crystalsis based on their unique dispersive properties and thus entirely dielectric in nature. In this work we demonstrate an interesting opportunity to decrease drastically the group velocity of light in one-dimensional photonic crystals constructed form materials with large dielectric constant without dispersion). We use numerical analysis based on the Transfer Matrix Method to study the photonic properties of Double period quasiperiodic one dimensional photonic crystal realized to engineer slow light effects. Various geometries of the photonic pattern have been characterized and their photonic band-gap structure analyzed. Indeed, one dimensional Bragg periodic photonic multilayer structure and quasi periodic photonic multilayer structure based on Thue-Morse, and Cantor sequences were studied. Quasiperiodic structures have a rich and highly fragmented reflectivity spectrum with many sharp resonant peaks that could be exploited in a microcavity system. A comparison of group velocity through periodic and quasiperiodic photonic crystals was discussed in the context of slow light propagation. The velocity control of pulses in materials is one of the promising applications of photonic crystals. The material systems used for the numerical analysis are SiO_2/ Si which have a refractive index contrast of approximately 1.5a nd 3.4 respectively.

Slow light is a physical phenomenon where the light is propagated in a medium with low group velocity (vg), it produces a hight interaction between light and matter , which offering additional control over of the spectral bandwidth of this interaction and allows to delay temporarily the storage of light in all-optical memories. Anather consequence is enhancement of the linear effects as termo-optic and electro optic gain . As the interactions between photons and transparent matter are not strong, the high power laser is then required for breaking this limitation and inducing non-linear responses. Slow light [20] in photonic crystal means slow the transmission of information by reducing her propagation in transparent medium that is very important in many optical signals processing applications as telecommunication and photovoltaic cells. Today, the majority of these applications is based on data transmission with less loss, as well as control of the speed of propagation of such data, such as slowing down or complete blocking of transmitted information using photonic systems in many applications as examples: optical fibers [21], waveguides[22, 23], gas sensors[20, 23].

The slowing of the light can increase the light-matter interaction times, due to the multiple reflection of the light inside the multilayer system. Indeed, the return of the light on the interfaces of each layer produces a sudden variation of the transmission phase at the resonance, which decreases the speed of propagation of light inside the multilayer system [24].

Periodic and quasi-periodic structures

Periodic one dimensional photonic crystal

One dimensional PC is an alternating arrangement of layers with different refractive index n_H and n_L and different thickness d_L and d_H. We model this crystal by placing periodically a finite number of layers as illustrated in Figure 1.

Cantor sequence

The Cantor [13, 14, 15] sequence presented in Figure 2 is a deterministic fractal geometry obtained by stacking two different basic materials H and L representing respectively, the high and the low refractive indexes using a simple substitution rule:

H→HLH and L→LLL

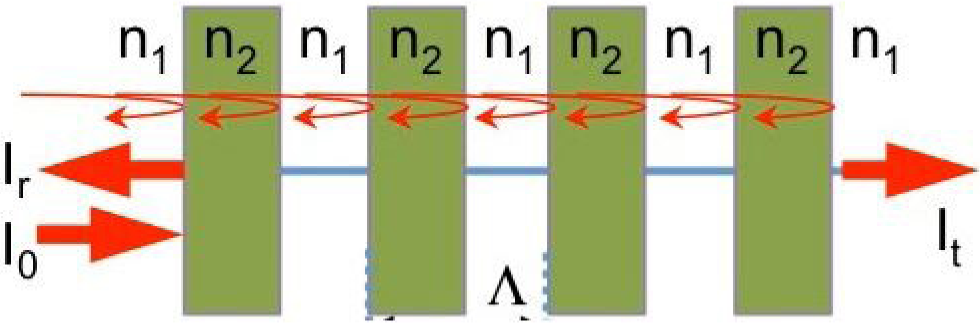

Figure 1: Example of multilayer periodic structure of alternated H/L layers, with refractive indexes n_H and n_L, and thicknesses d_H and d_L, respectively

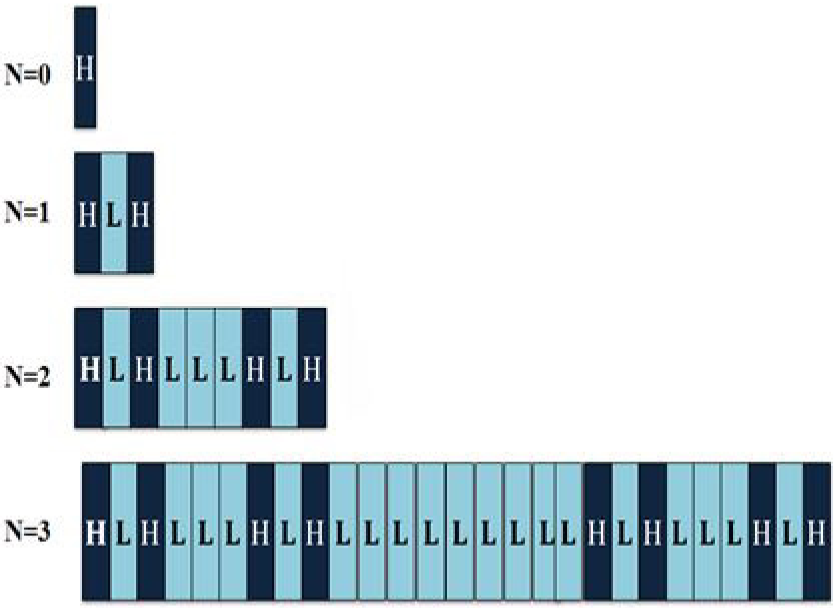

Figure 2: Example of multilayer Cantor quasi-periodic structure of alternated H/L layers, with refractive indexes n_H and n_L, and thicknesses d_H and d_L, respectively

Thue-Morse sequence

The Thue-Morse [11, 12, 17] structure presented in Figure 3 is one of the well-known one-dimensional photonic quasi-crystals and extensively studied in mathematical literature. It is constructed by two building blocks of H and L, which are arranged according a substitution rule:

H→HL and L→LH

Double-period sequence

The Double period illustrated in Figure 5 [16, 17] is one of the recent quasi-periodic one-dimensional photonic sequences. It can simply be obtained by repeating the substitution rule:

H→HL and L→HH.

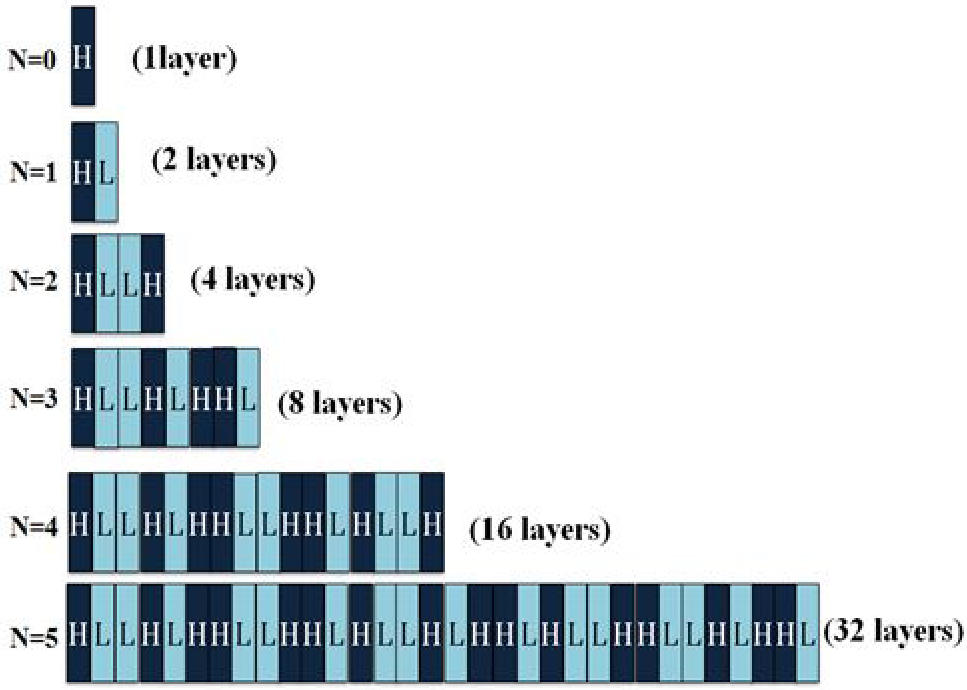

Figure 3: Example of multilayer Thue- Morse quasi-periodic structure of alternated H/L layers, with refractive indexes n_H and n_L, and thicknesses d_H and d_L, respectively

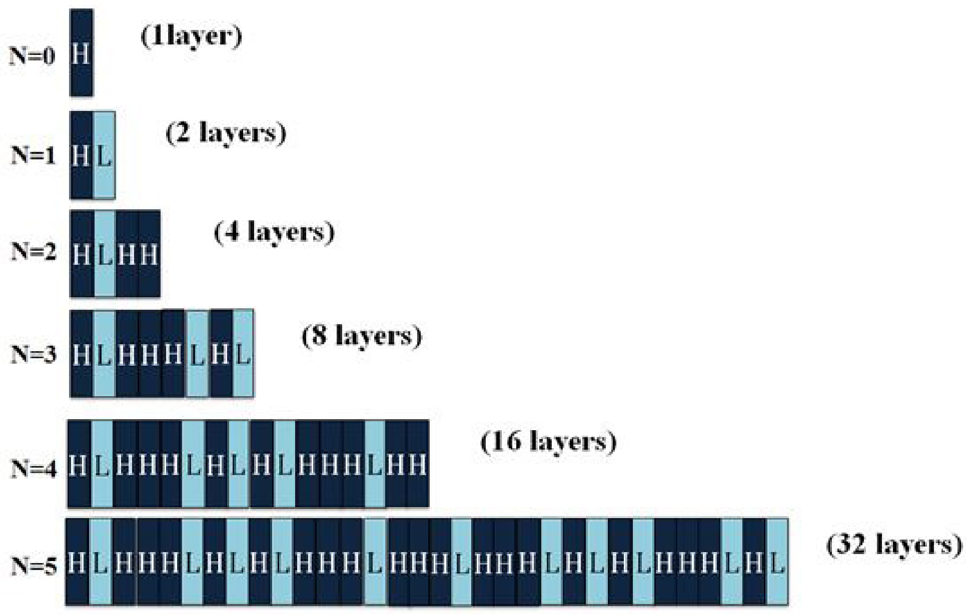

Figure 4: Example of multilayer Double Period quasi-periodic structure of alternated H/L layers, with refractive indexes n_H and n_L, and thicknesses d_H and d_L, respectively

Theoritical method

Theoritical model is based on the transfert matrix model which is used succefully in periodic PC structure, to provide transmission and reflexion spectra and then photonic band gap by determining the relation between the amplitudes of incident $E_i(x_0^+)$ reflected $E_r(x_0^-)$ and transmitted $E_t(x_{N-1}^+)$ of electric fields after crossing N material layers(as presented in Figure 1) . In this work to use this method to determinate the group velocity and the slowing down factor at wavelengths near the transmission resonances at the edges of the photonic band gap in periodic and quasiperiodic structure.

The amplitudes of incident $E_i(x_0^+)$ reflected $E_r(x_0^-)$ and transmitted $E_t(x_{N-1}^+)$ of electric fields can be related with the following relation:

$$\begin{pmatrix} E_i(x_0^+) \\ E_r(x_0^-) \end{pmatrix} = T_{0N} \begin{pmatrix} E_t(x_{N-1}^+) \\ E_r(x_{N-1}^+) \end{pmatrix}$$

With $T_{0N} = \prod_{j=1}^{N} T_j T_{j,j+1} = T_{01} T_1 T_{12} \ldots T_{N-1} T_{N-1,N}$

T_{0N} The global Transfer Matrix of the multilayer structure

The Transfer matrix of the j[th] sequence can be written:

$$T_j \,.\, T_{j,j+1} = \begin{pmatrix} \frac{1}{t_{j,j+1}} \exp(i\varphi_j) & \frac{r_{j,j+1}}{t_{j,j+1}} \exp(i\varphi_j) \\ \frac{r_{j,j+1}}{t_{j,j+1}} \exp(-i\varphi_j) & \frac{1}{t_{j,j+1}} \exp(-i\varphi_j) \end{pmatrix}$$

Where T_j, $T_{j,j+1}$ are respectively the propagation matrix and the interface matrix

$$T_{j,j+1} = \frac{1}{t_{j,j+1}} \begin{pmatrix} 1 & r_{j,j+1} \\ r_{j,j+1} & 1 \end{pmatrix} \quad T_j = \begin{pmatrix} \exp(i\varphi_j) & 0 \\ 0 & \exp(-i\varphi_j) \end{pmatrix}$$

φ_j indicates the phase shift of the wave between $j, j+1$ layers can be obtained by taking

$$\varphi_j = \frac{2\pi}{\lambda_0} \hat{n}_j \, d_j \cos\theta_j$$

$\varphi_0 = 0$

With λ_0 is the reference of the wavelength of the structure, d_j is the thickness of the j[th] layer, $\hat{n}_j = n_j + k_j$ the complex refractive index , θ_j the complex refractive angle and t_j and r_j are the Fresnel coefficients between $j, j+1$ layers.

$$R_{TE} = |r_{jTE}|^2 \qquad R_{TM} = |r_{jTM}|^2$$

The transmittance T is defined by:

$$T_{TE} = \mathrm{Re}\left(\frac{\hat{n}_{M+1} \cos\theta_{M+1}}{\hat{n}_0 \cos\theta_0}\right) |t_{jTE}|^2 \quad ;$$

$$T_{TM} = \mathrm{Re}\left(\frac{\hat{n}_{M+1} \cos\theta_{M+1}}{\hat{n}_0 \cos\theta_0}\right) |t_{jTM}|^2$$

For this numerical investigation all materials are assumed to be homogeneous and non- absorbing ($k_j = 0$) and then $\hat{n}_j = n_j$.

In this paper, we considered only waves with normal incidence, so, the reflectance and the transmittance are the same for both polarizations (i.e. TM-polarization and TE-polarization).

The slowing down of the light necessarily depends on the relationship between the group velocity and the refractive index. More the dispersion of the refractive index is high, more the group velocity is low.

In this work, waves with normal incidence are considered. Consequently, the transmittance *T* for both polarizations is the same.

The Fresnel transmission coefficient *t* of the overall system constructed with *N* layers is complex and expressed as:

$$t = x + iy$$

where x et y are respectively the real part and the imaginary part of the transmission coefficient.

From the analytical expression of the transmission, we can deduce the expression of the total phase which expressed as:

$$\varphi = \arctan\left(\frac{\mathrm{Im}(t)}{\mathrm{Re}(t)}\right) \Rightarrow \arctan\left(\frac{y}{x}\right)$$

The group velocity [21] describes the velocity at which an envelope of a modulated optical signal is travelling. The modal group velocity can be calculated from the dispersion curve of an optical mode for a long lattice using the following relation:

$$V_g = \frac{d\omega}{dk} = L.\frac{\partial \omega}{\partial \varphi}$$

Where L represents the physical length of the multilayer system.

The group velocity of a propagating mode in the multilayer system can therefore be determined by Using the expression of the phase previously found can be determined as follow

$$V_g = L.\frac{\partial \omega}{\partial \varphi} = L(\frac{x^2 + y^2}{y'.x - x'.y}) = L.\frac{T}{(y'.x - x'.y)}$$

With $x' = \frac{\partial x}{\partial \omega}$ and $y' = \frac{\partial y}{\partial \omega}$

We determined also the phase time τ^T that allows us to study the slowing down of the light. The phase time represents the time taken by an impulse to cross the multilayer system. This time, noted, is defined as follows:

$$\tau^T = \frac{\partial \varphi}{\partial \omega}$$

At the resonance τ^T becomes: $\tau_R^T = \left.\frac{\partial \varphi}{\partial \omega}\right|_{\omega=\omega_R}$

We can calculate its slowing factor defined by:

$$S_f = \frac{V_m}{Vg}$$

is the average group velocity which defined by:,

$$V_m = \frac{1}{2}(\frac{c}{n_L} + \frac{c}{n_H})$$

With n_H and n_L are the high and the low refractive indexes respectively, V_g is the group velocity and c the speed of the light in vacuum.

We can calculate also the group index [22] which defined by:

$$n_g = \frac{c}{v_g}$$

As example, we present in Figure 1 the variation of the transmittance, the group velocity and the slowing down factor as function of the angular frequency for a periodic structure containing 18 layers. The variation of the group velocity indicate that it is maximal in the photonic band gap and minimal at its resonance edges. In the other hand, we observe that the slowing down factor is maximal at its resonance edges. Therefore, we can deduce that the slow light is due to the reductio of the group velocity, which corresponds to the superluminal tunneling velocity of a wave packet through a photonic band gap structure. Figure 5 present the variation of the transmittance, the group velocity and the slowing down factor as function of angular frequency for a periodic structure containing 18 layers.

Slow light in quasi-periodic structure

Slow effect in double periodic structure *Si/SiO$_2$*

Slowing down factor as function of the angular frequency in double period one-dimensional photonic structure is determined by using the transfer method matrix at normal incidence in the near infrared region [800 nm , 2500 nm] corresponding to the angular frequency [2.35 10^{15} rad, 7.55 10^{15} rad] and by varying many parameters of the photonic system as the number of layers , the reference wavelength, the index contrast and the incidence angle…).

We have performed our calculation in the double period structure based on Si/SiO_2 which is constructed by arrangement of two elementary materials silicon H and silica L with a high refractive index n_H = 3 .4 and low refractive index n_L = 1.45 respectively. Thicknesses $d_{H=}$85nm and d_L=205nm of Si layer (H) and SiO_2 layer (L) correspond to the quarter-wavelength stack

$$n_H d_H = n_L d_L = \frac{\lambda_0}{4}$$

Where λ_0= 1550 nm is the reference wavelength corresponding to the optical communication. Layers are deposited on glass substrate with refractive index n_S = 1.5.

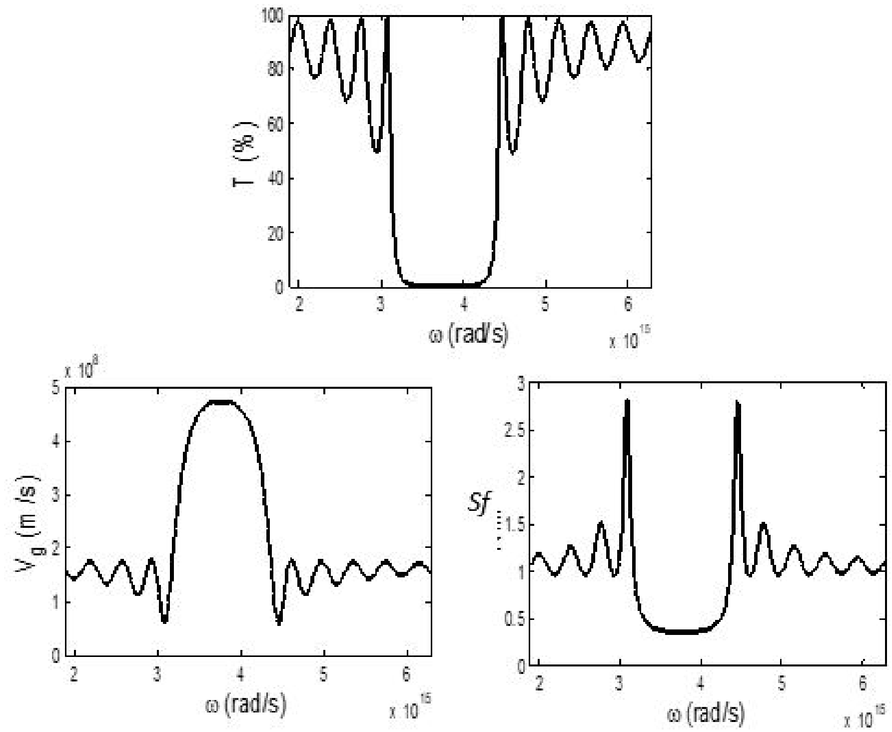

Figure 5: Variation of the transmittance, the group velocity and the slowing down factor as function of angular frequency for a periodic structure containing 18 layers

Effect of the number of generation

We have presented in Figure 6 the slowing down factor as a function of the angular frequency of the Double period one-dimensional structure for different generations number (N=2, 3, 4, 5 and 6) corresponding respectively to layers number p (p=4, 16, 32, 64 and 128). We observe that the slowing factor increases with increasing of the generation number. Figure 3 shows also the presence of different peaks corresponding to several slow frequencies which indicated that the double period structure offers the possibility to obtain a broad slow frequencies band.

We note that by increasing the number of layers to 128, the slowing down factor increase and takes the value 2845. This value is an interesting result for many applications of slow light in photonic crystals. However, the experimental fabrication of a multilayer structure containing 128 layers is not easy due to the difficulty to deposit such great number of layers. Therefore, in the following investigation, we fixed the number of layers at 32 for the possibility of deposition of this number. A double period structure with 32 layers as realized experimentally in our previous work [17].

Effect of the reference wavelength

We present in Figure 7 the variation of the slowing down factor as function of angular frequency for different wavelength reference (λ_0=1μm, λ_0=1.2 μm, λ_0=1.33 μm and λ_0=1.55μm). It can be noticed that the value of this remains almost constant. It is clear that the reference wavelength has no effect on the group velocity in the structure proposed. However, It is noted that when the reference wavelength varies, the peaks of slow frequencies moves and their number increases, we obtain only two peaks for (λ_0=1μm, λ_0=1.2 μm) on the other hand we obtain four peaks for, λ_0=1.33 μm and λ_0=1.55μm). Consequently, we can control the position and the number of slow frequencies. Therefore, the Choice of the reference wavelength (e.g. modifying the layers thicknesses) allows a better control of the selection of slow frequencies by this structure. This allows a better choice of the adequate application of this structure which, therefore, enlarges the field of use of Double period photonic crystal in slow light in many domains as examples: optical fibers [20], waveguides[21, 22], gas sensors[19, 22].

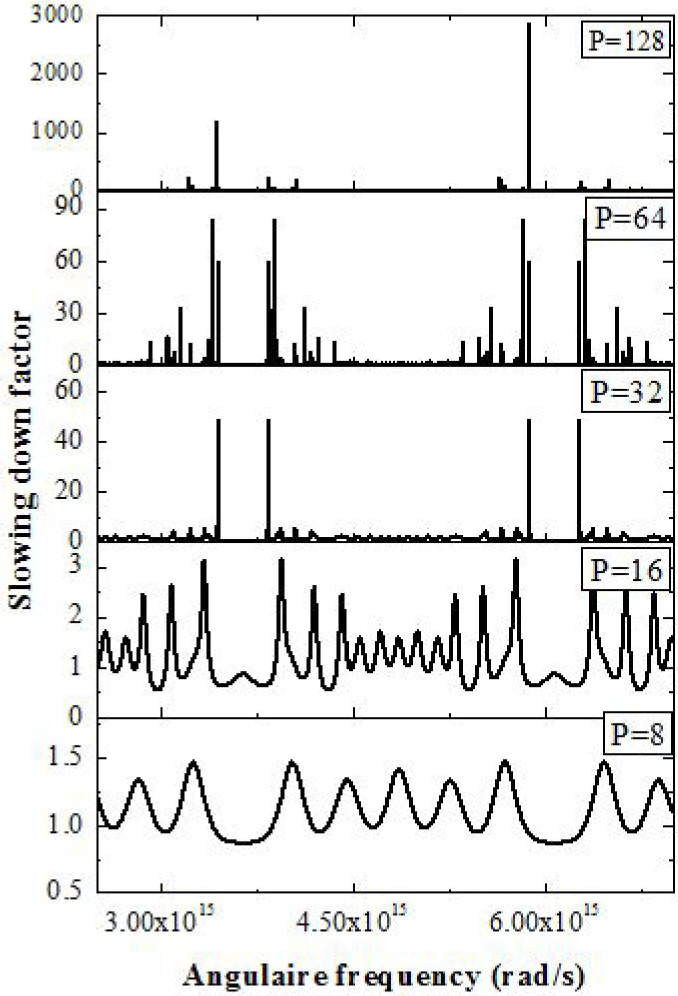

Figure 6: Variation of slowing down factor as a function of the angular frequency of the Double period one-dimensional structure for different generations number (N=2, 3, 4, 5 and 6) corresponding respectively to number of layers p (p=4, 16, 32, 64 and 128)

Effect of the contrast index

The variation of the slowing down factor as function of angular frequency is studied for two different materials H and L (e.g. for different contrast indexes) for a Double period structure containing 32 layers such as:

$$\Delta n = n_H - n_L$$

The results obtained in Figure 8 show that the slowing down factor increases when the contrast index increases. We found that the maximal slowing down factor reaches a value of 157 for $\Delta n = 3$ in the other hand it equal to 5 when $\Delta n = 0.85$. It is clearly the importance of the choice of materials for its effect on the slowing down factor (e.g. the group velocity).

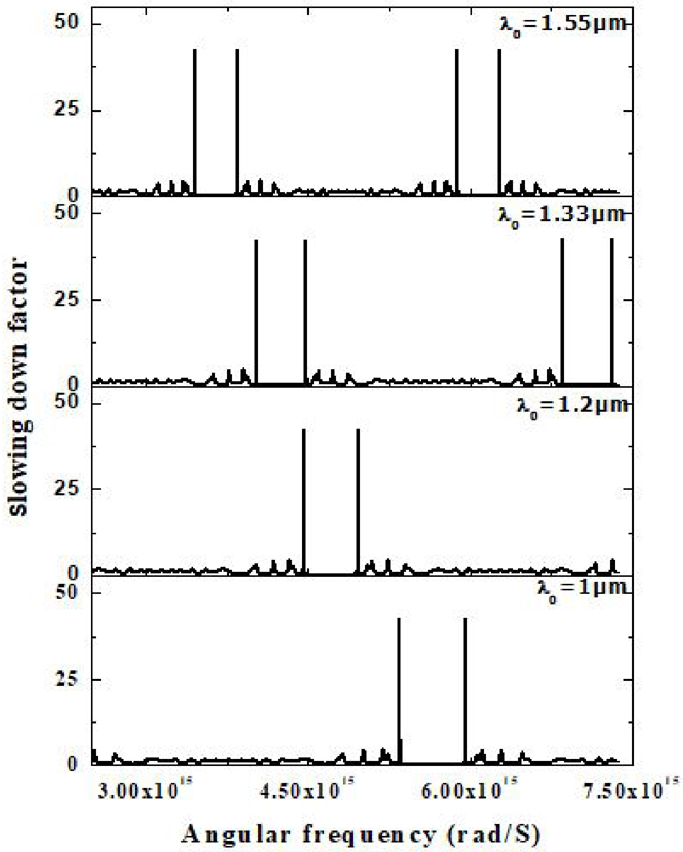

Figure 7: Variation of the slowing down factor as function of angular frequency of the Double period one-dimensional structure containing 32 layers for different wavelength reference (λ_0=1μm, λ_0=1.2 μm, λ_0=1.33 μm and λ_0=1.55μm)

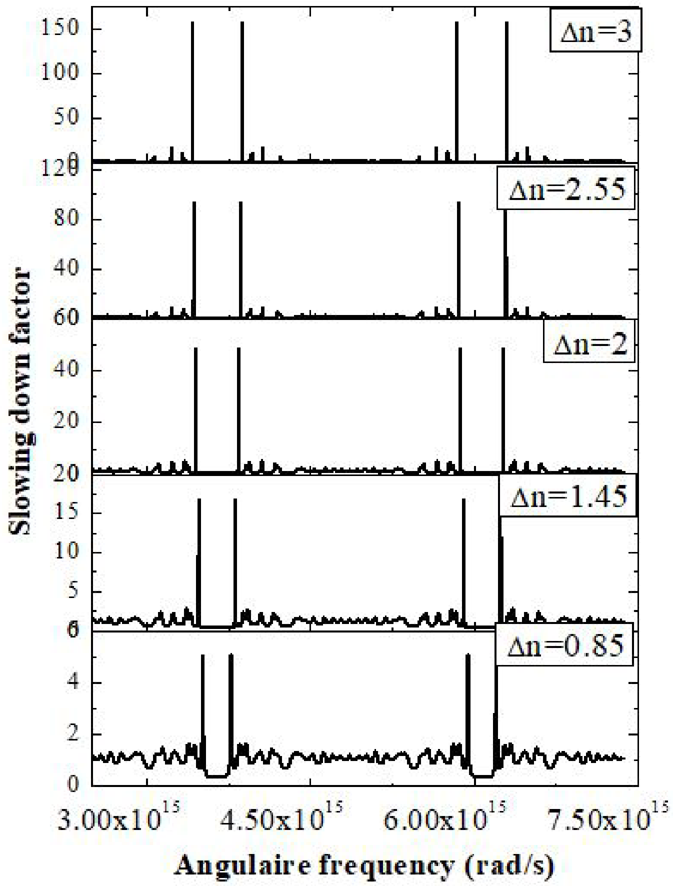

Figure 8: Variation of the slowing down factor as function of angular frequency of a Double period structure containing 32 for two different materials H and L (e.g. for different contrast indexes $\Delta n = 0.85$, $\Delta n = 1.45$, $\Delta n = 2$, $\Delta n = 2.55$ and $\Delta n = 3$)

Effect of the incidence angle

We report in Figure 9 the slowing down factor as function of angular frequency for different incidence angle Θ are obtained. From these results, it can be noticed that the increase of incidence angle leads to increase the slowing down factor. We show that the maximal of slowing down factor increases from 42.5 for Θ =0rad to 610 for Θ =1.5 rad. We note a very important variation of slowing down factor is in evidence. We note a very important variation of slowing down factor are given by a double period structure which containing only 32 layers. The value of slowing down factor 610 is very interesting for many application above all we can get it by a double period structure formed by a few number of layers (32layers) which we can deposit experimentally [17].

Then we will compare the results obtained with the slowing down factor of other photonic periodic and quasi-periodic crystals in the same conditions.

Comparison of Slowing down factor in photonic structures

In order to compare the maximal slowing down factor in one-dimensional photonic structures which are constructed by arrangement of two elementary materials silicon H and silica L with a high refractive index $n_H = 3.4$ and low refractive index $n_L = 1.45$ respectively . We choose for this comparison the incidence angle Θ=1.5 rad and the reference wavelength λ_0=1.55μm.

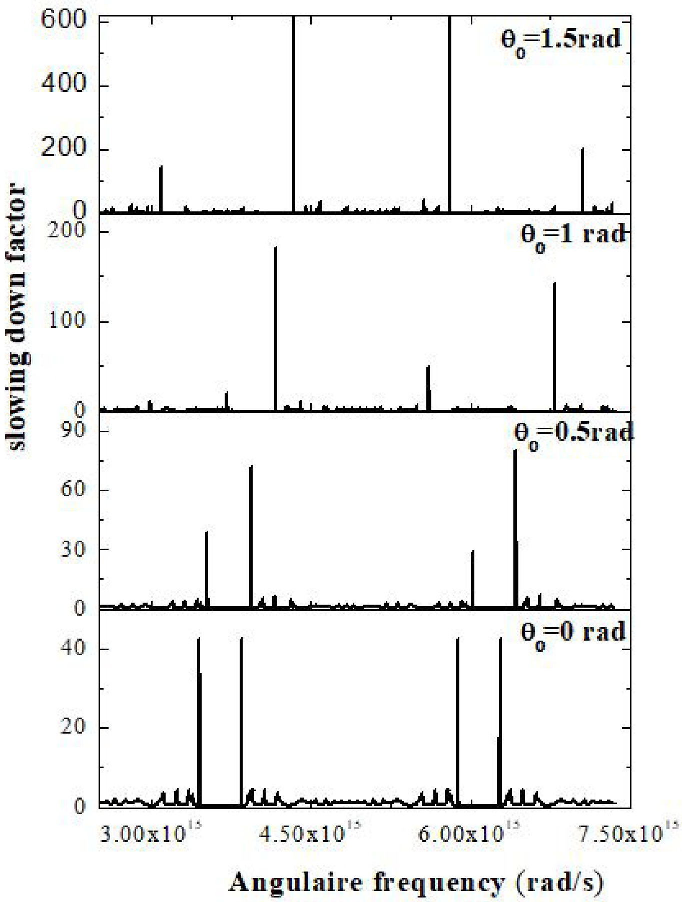

Figure 9: Variation of the slowing down factor as function of angular frequency of the Double period one-dimensional structure containing 32 for different incidence angle (Θ= 0rad, Θ=0.5 rad, Θ=1.5 rad, and Θ= 2rad)

Comparison between Double period structure and Bragg structure

In order to compare the maximal slowing down factor took by the Double period quasi-periodic proposed structure and the periodic structure based on Si and SiO_2 dielectric materials for the same number of layers equal 32 , we have plot on Figure10 the slowing down factor as function as function of frequency angular of these structures.

The corresponding values for the maximal slowing down factor deduced from Figure 10 are equal to 52 (e;g vg=2.8310^{6} ms^{-1}) for the the Bragg periodic structure and to 610 (e.g vg=2.4110^{5}ms^{-1}) for the quasi-periodic Double period one. These resuls clearly ndicate that the slowing down factor of Bragg structure is very weak in front of the value obtained by the Double period one.

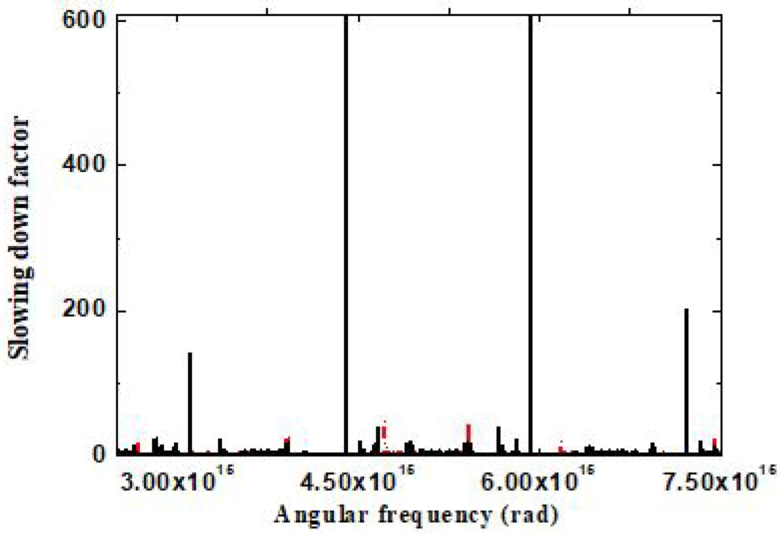

Figure 10: Variation of the slowing down factor as function of angular frequency of the Double period structure (solid line) and the periodic structure (dashed line) obtained for the same number of layers equal to 32

Comparison between Double period structure and Thue-Morse structure

Now, the number of layers of Double period and Thue-Morse structures is fixed at 32 layers to compare the maximal slowing down factor obtained by the two quasi-periodic structures.

From the slowing down factor as function of frequency angular presented in Figure 11, we determine the maximal slowing down factor given by the Double structure is 610, on the other hand, that of the Thue-Morse is 140 (vg=1.0410^{6} ms^{-1})). These results show that the slowing down factor of The Double period structure is greater than the Thue- Morse one (Figure 12).

Comparison between Double period structure and Cantor structure

We determine the values of the maximal slowing down factor of Double period and Cantor structures for a comparable number of layers.

The Figure 9 clearly indicates that for the Double period structure, the slowing down factor reaches the maximum value of 610 for a structure containing 32 layers, which is higher than that obtained for the Cantor structure which equal to 160 (e.g vg=0.92 10^{6} ms^{-1})) giving by structure composed of 27 layers.

We summarize in the table 1 the results obtained by the comparison of the maximal slowing down factor of one-dimensional photonic structures:

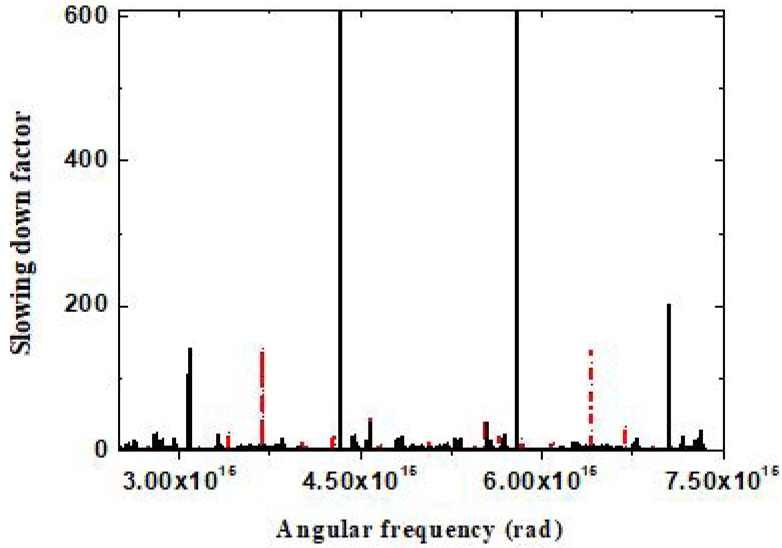

Figure 11: Variation of the slowing down factor as function of angular frequency of the Double period structure (solid line) and the Thue Morse structure (dashed line) obtained for the same number of layers equal to 32

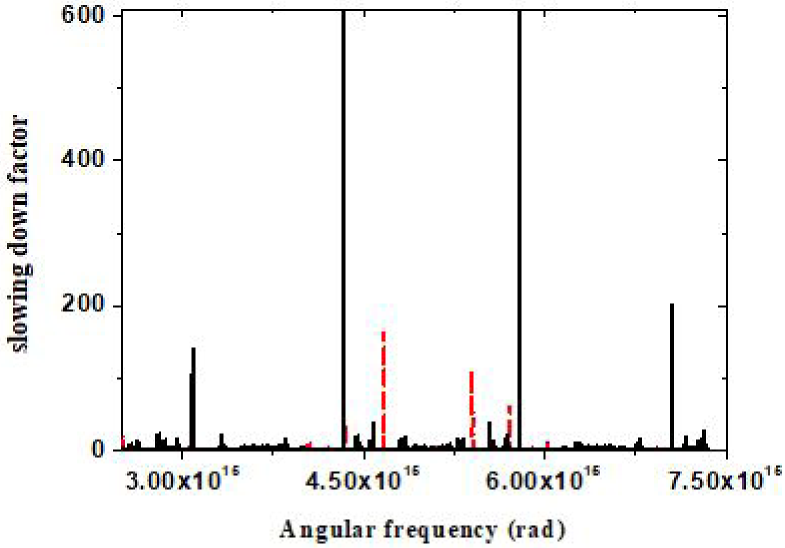

Figure 12: Variation of the slowing down factor as function of angular frequency of the Double period structure (solid line) obtained for 32 layers and the Cantor structure (dashed line) obtained for 27 layers

Table 1: Summary of the structural and the optical parameters, obtained for the Double- period Thue-Morse, the Cantor and the periodic structures

	Bragg	**Thue-Morse**	**Cantor**	**Double period**
Layer number	32	32	27	32
Maximal slowing down factor	52	140	160	610
Group index	106	288,5	326	1245
Group velocity (ms^{-1})	0.0094 c	0.0035 c	0.003 c	0.0008 c

Conclusion

In this work, the slow light in double period one-dimensional photonic structure was investigated. It has been shown that the slowing down factor depends extensively of the distribution and the number of layers, the number of generations, the angle of incidence, and the contrast index of materials in the photonic crystal. We note also that the variation of the reference wavelength of the exciting light doesn't vary the slowing down factor value, however it vary the positions of slow frequency peaks and their number which allows a better control of the selection of slow frequencies, This result allows a better choice of the adequate application of this structure.

By using the Double period one dimensional photonic based on Si/SiO2 containing 32 layers, we obtain a high slowing down factor, equal to 610 corresponding to low group velocity equal to 0.0008 c. It has also shown that the slowing down factor given by the Double-period structure is more important than those obtained by periodic structure and non-periodic structures according to the cantor and Thue-Morse sets.

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