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Telecommunication filter based on the symmetrical photonic crystal $Bg_5/Cu_1/Bg_5$

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Thanks to the transfer matrix method, we perform a theoretical investigation of the optical properties of the symmetrical photonic crystal designed as $Bg_5/Cu_1/Bg_5$, where Cu_1 is the first generation of the copper mean sequence and Bg_5 is the fifth generation of the Bragg sequence. We design a developed polychromatic filter which allows the transmission of all the telecommunication wavelengths 0.85, 1.3, and 1.55 μm at oblique incidence for both of TE and TM polarization with a high transmission rate and high quality factor. This photonic crystal can be employed in the fabrication of telecommunication devices.

Keywords: symmetry, telecommunication, photonic crystals.

1. Introduction

The 1D photonic crystals are composite structures with a specific arrangements of the materials with two different refractive indices [1]. Due to the repartition of materials inside the multilayers and the multiple Bragg scattering, we can obtain a certain range of frequencies which are prohibited from propagating through the structure well known as a photonic band gap. The incident light can be perfectly reflected within the photonic band gap. The photonic band gap represents the principal attractive feature of photonic crystals devices [2]. As well the photonic crystal can allow the transmission of the electromagnetic waves only in certain direction and confine them within a specified volume named cavity for the enhancement of the optical communication [3]. The photonic components provide an array of advantages over conventional electronic devices. They can provide enhanced speed of operation and reduced size. Also the quasicrystal which has five-fold symmetries increased the interest in the studies of quasiperiodic structures. The propagation of photon in quasiperiodic multilayers is different from that in periodic and disordered one [2]. The transmission spectrum of the photonic crystal multilayer constructed according to a quasiperiodic sequence is extensively studied.

On the other side, the 1D symmetrical photonic crystals have aroused interest due to possible optical applications such as highly emitting diodes and particularly the optical filters because of their high quality factor. The optical filter has the property of adding or dropping desired wavelength channels from the multiwavelength network [4, 5, 6]. It is of interest to investigate the optical properties of the hybrid photonic multilayers constructed by introducing a quasiperiodic photonic structure between two periodic photonic ones which can be a good candidate for the design of the photonic filter in the infrared region [4]. In the present paper, we will design a symmetrical filter based on the combination of copper mean photonic crystal (Cu_1) and Bragg photonic structure in order to study its optical response for both polarisations (TM and TE) covering the telecommunication wavelength (0.85, 1.3, and 1.55 μm).

In next section we present a brief description of the simulation method, Section 3 is devoted to the discussion of the numerical in details. The conclusions are summarized in Section 4.

2. Simulation method

The transfer matrix method (TMM) is the most suitable technique for the prediction of the optical properties of 1D staked layers. This theoretical method is extensively used in the analysis of 1D photonic crystals independently of the nature of the used materials and the involved number of layers. Thanks to this method, we can connect the amplitude of the incident electric field E_0^+ and the amplitude of the reflected electric field E_0^-, with the amplitude of the transmitted electric field E_{m+1}^+ after the passage of m layer using the following equation [7, 8]:

$$\begin{bmatrix} E_0^+ \\ E_0^- \end{bmatrix} = C_1 C_2 C_3 C_m \begin{bmatrix} E_{m+1}^+ \\ E_{m+1}^- \end{bmatrix}$$

Here C_m is the transfer matrix defined as

$$C_m = \begin{bmatrix} \exp(-i\varphi_m)/t_m & r_m \exp(i\varphi_m)/t_m \\ r_m \exp(-i\varphi_m)/t_m & \exp(i\varphi_m)/t_m \end{bmatrix}$$

where φ_m is the phase variation between the layers m and $(m+1)$, and t_m, r_m are the reflection and the transmission coefficient of Fresnel, respectively.

The detail of this method is extensively used in our last work [7]. We will use the same steps of calculation to obtain the transmission response for the both polarization (TM and TE) of the hybrid symmetrical structure $Bg_5/Cu_1/Bg_5$, where Cu_1 is a copper mean structure and Bg_5 is a Bragg one.

3. Results and discussions

For the sake of the numerical simulation, we select Si and SiO_2 as two elementary dielectric materials which represent respectively the layer H with the refractive index

$n_H = 3.7$ and the layer L corresponds to the low refractive index material with $n_L = 1.45$. The spectral range contains the near infrared region [0.8 μm, 2.3 μm] in order to cover the telecommunication wavelengths. The optical thicknesses of the layers H and L are symbolized respectively by d_H and d_L and verify the Bragg condition

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

where λ_0 is the reference wavelength.

The copper mean sequence $(Cu)_j$ is arranged according to the recursive relation [9–11]

$$G_{j+1} = G_{j-1}^2 G_j, \qquad j \geq 2$$

where j designs the number of iterations for each structure; $G_0 = L$, $G_1 = H$, and $G_2 = LLH$.

To obtain the symmetrical form of any sequence S_n, we use the following formula [7]:

$$S_n = \{G_n, \overline{G}_n\}$$

where S_n is the symmetrical sequence, and $\overline{G}_n$ is the reversed sequence of G_n. The Bragg sequence (Bg_n) is arranged as $L(HL)^n$ with $n \geq 1$.

Figure 1 represents the symmetrical photonic crystal $Bg_5/Cu_1/Bg_5$. After many investigations we have chosen the hybrid photonic structure constructed as $Bg_5/Cu_1/Bg_5$ that can allow us to obtain significant results in this case.

To further investigate the behavior of the system at oblique incidence, the incident electromagnetic wave is chosen as a transverse magnetic (TM) wave at the first time and the transverse electric (TE) wave in the second time. To be in the chosen spectral range, we fix λ_0 at 1.04 μm.

According to Fig. 2, the 3D spectra of transmittance as a function of λ and φ_0 show that our system allows the transmission of three wavelengths for the two polarisations – TE and TM.

The symmetrical system achieves a polychromatic filter which transmits the subsequent wavelengths $\lambda_1 = 0.8565$ μm, $\lambda_2 = 1.04$ μm, and $\lambda_3 = 1.324$ μm at normal incidence.

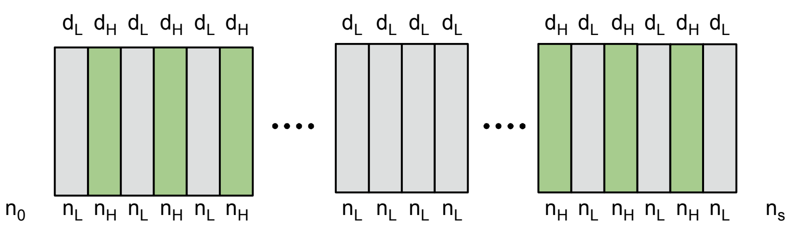

Fig. 1. The symmetrical photonic crystal; the refractive index of the incident medium is $n_0 = 1$ and the refractive index of the substrate is $n_s = 1.5$.

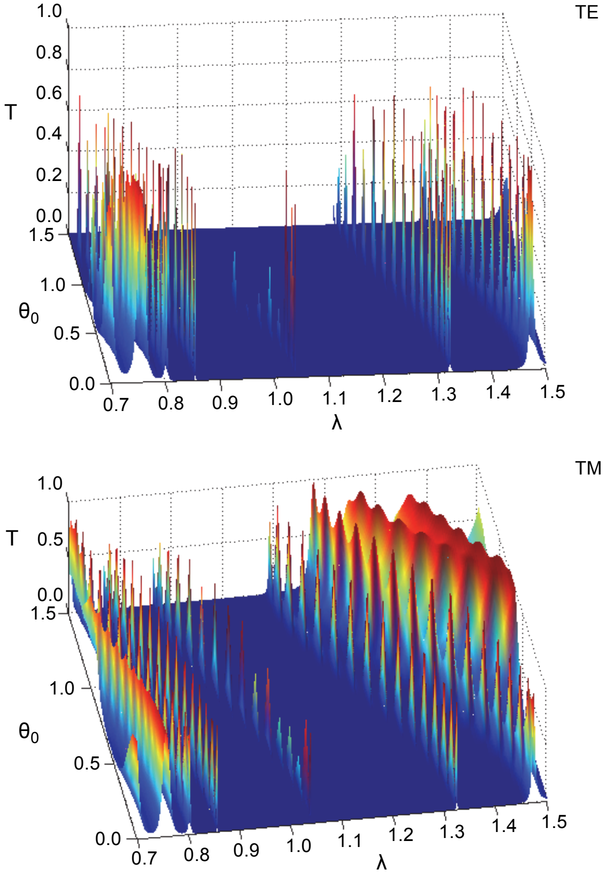

Fig. 2. The 3D transmission spectra for the TE and TM polarizations when λ_0 = 1.04 μm.

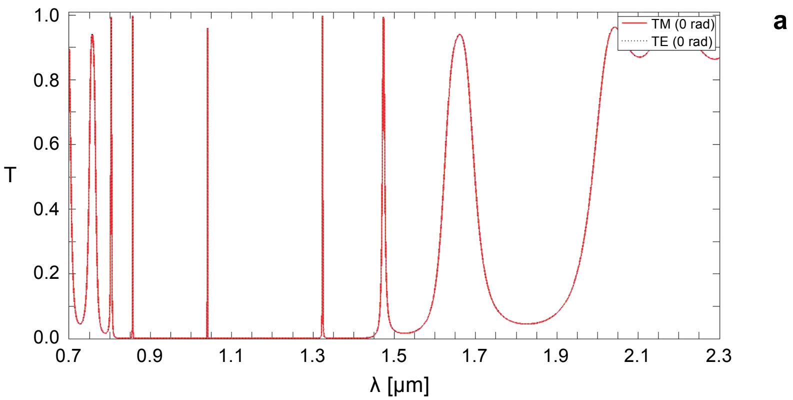

Fig. 3. To be continued on the next page.

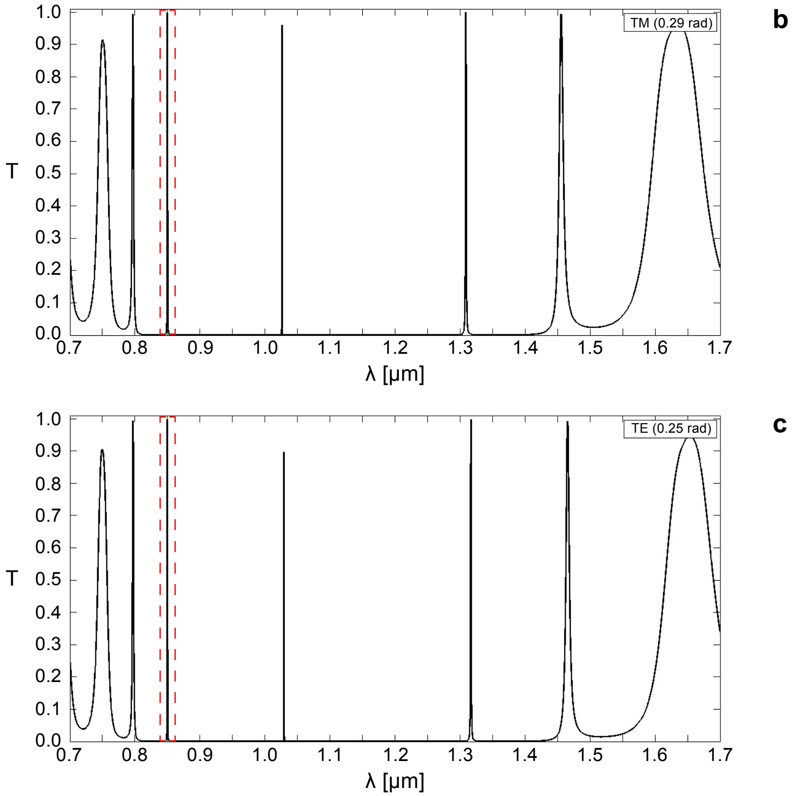

Fig. 3. The transmission spectra of the system $Bg_5/Cu_1/Bg_5$: θ_0 = 0 rad (**a**), θ_0 = 0.29 rad for TM polarization (**b**), and θ_0 = 0.25 rad for TE polarization (**c**).

Taking into account the 2D transmission spectra as represented in Fig. 3, we observe that the first wavelength λ = 0.85 μm is filtered under two different oblique incidences such that θ_0 = 0.25 rad for the TE polarization and θ_0 = 0.29 rad for the TM polarization.

Table 1 gives more detailed information about the wavelengths of the defect mode.

Besides, the first telecommunication window 0.85 μm is transmitted with a high transmission rate which touches T = 0.99% for the two polarizations. The resonant defect peak is characterized by a high quality factor which attains Q_{TE} = 3863.63 and Q_{TM} = 1044.82 in each state of polarization.

T a b l e 1. The wavelengths of the defect modes for the TE and TM polarizations.

	Wavelengths [μm]		
	λ_1	λ_2	λ_3
TM mode	0.85	1.026	1.309
TE mode	0.85	1.029	1.317

The thickness of the defect layers is one of the most important parameters that can affect the defect mode inside the band gap [3].

According to the Bragg condition any change of the reference wavelength λ_0 affects the geometrical thickness of the layers and therefore the positions of optical windows move to reach the telecommunication wavelengths 1.3 and 1.55 μm. Thus the reference wavelength becomes $\lambda_0 = 1.6$ μm.

By following the same approach, we show that the symmetrical photonic crystal allows the transmission of the wavelength 1.3 and 1.55 μm.

According to Fig. 4 which represents the 3D transmission spectra, firstly we should observe the superposition of the transmission spectrum for the TE and TM polarizations at normal incidence. Secondly, as it is seen, the hybrid photonic crystal realizes a wide photonic band gap that contains 3 transmission peaks described as follows $\lambda_1 = 1.318$ μm, $\lambda_2 = 1.6$ μm, and $\lambda_3 = 2.036$ μm. The photonic band gap covers a very high range of wavelengths and attains the value $\Delta\lambda = 0.956$ μm.

Now we turn our attention to investigate the effect of the oblique incidence as shown in Fig. 5. It is clear that the defect modes and the bang gap shifted to short wavelengths and this shift is also called blue shift [12].

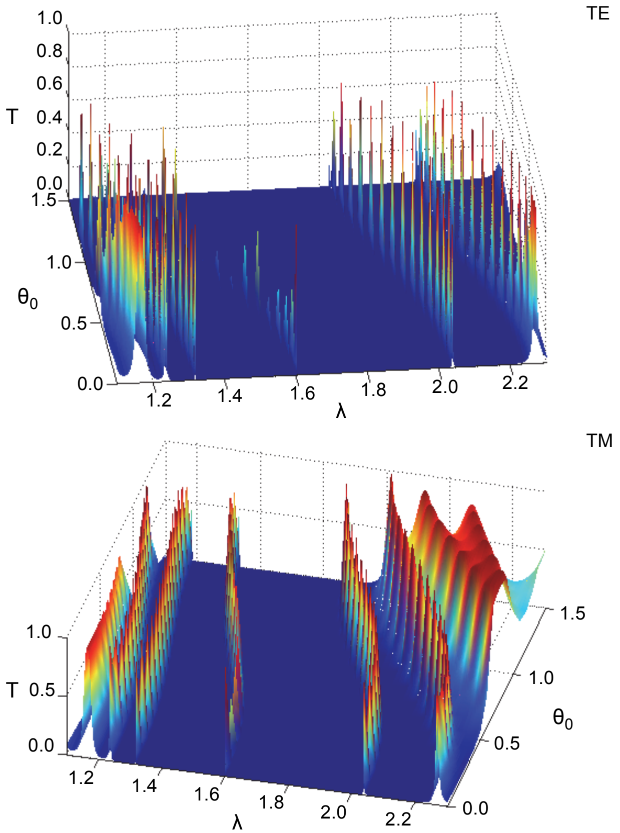

Fig. 4. The 3D transmission spectra for the TE and TM polarizations when $\lambda_0 = 1.6$ μm.

When the angle of incidence θ_0 reaches 0.39 rad (for TM polarization) and 0.33 rad (for TE polarization), our system allows the transmission of the second telecommunication window λ = 1.3 μm as depicted in Fig. 5.

We observe the superposition of the position of sharp transmission peak 1.3 μm and the presence of 3 optical windows inside the band gap. Table 2 gives further information about the defect modes and the correspondent wavelengths.

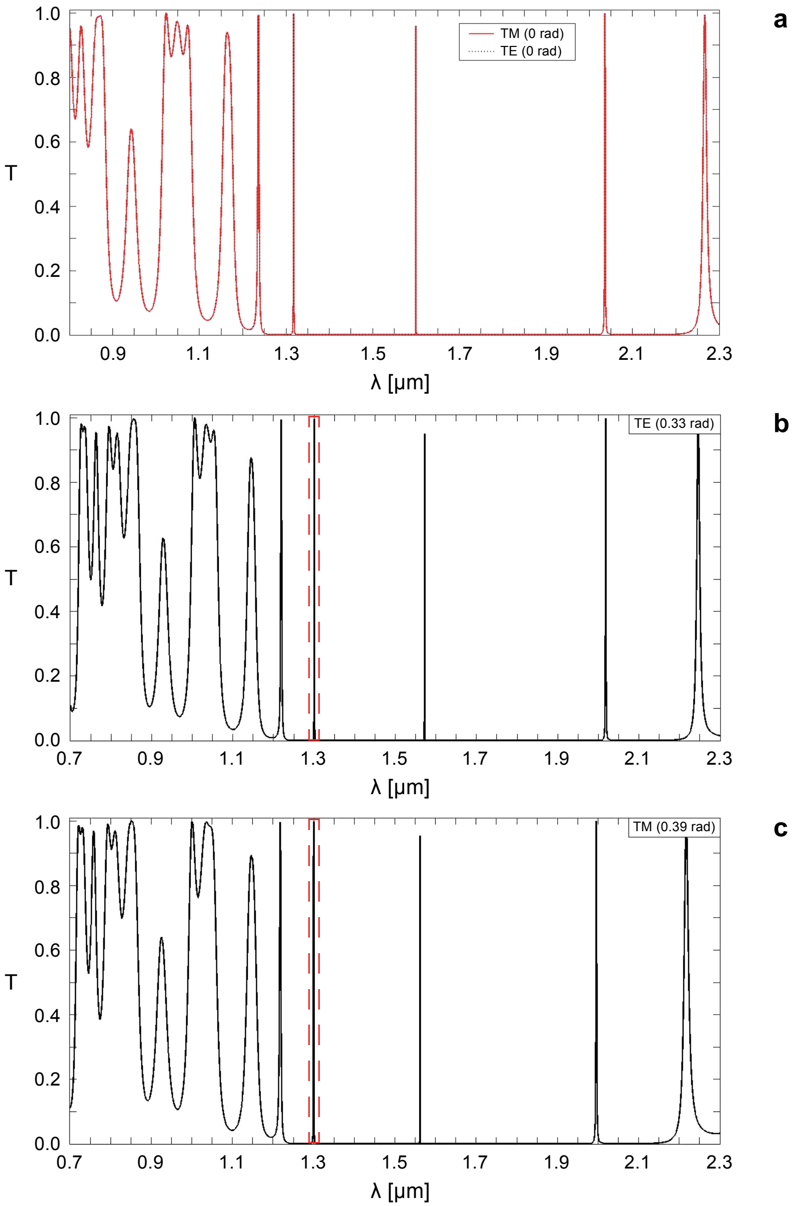

Fig. 5. To be continued on the next page.

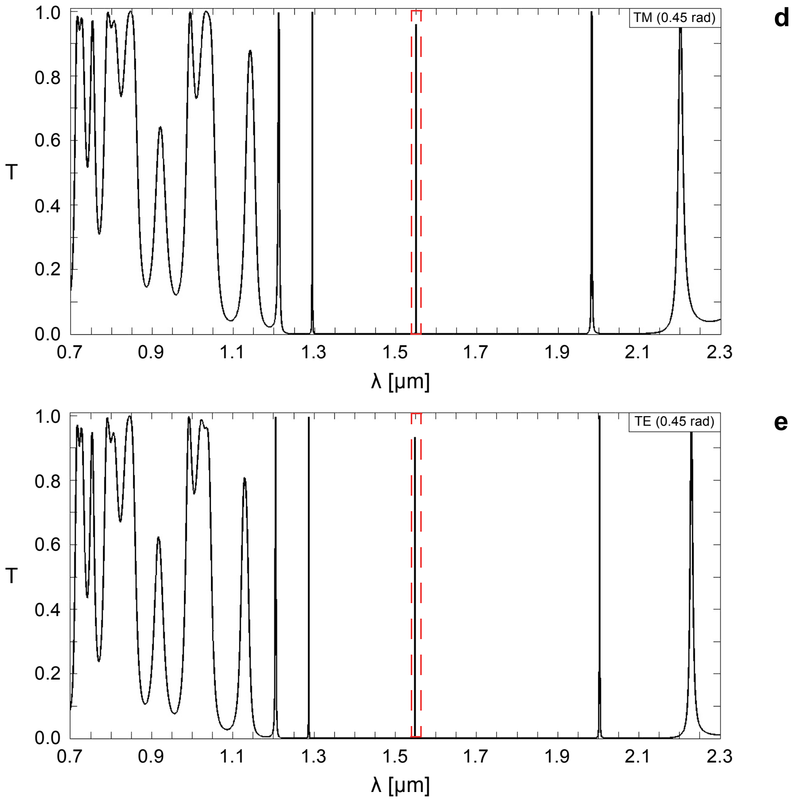

Fig. 5. The transmission spectra of the system $Bg_5/Cu_1/Bg_5$ for TM and TE polarizations: θ_0 = 0 rad (**a**), θ_0 = 0.33 rad (**b**), θ_0 = 0.39 rad (**c**), θ_0 = 0.45 rad (**d**), and θ_0 = 0.45 rad (**e**).

T a b l e 2. The wavelengths of the defect modes for the TE and TM polarizations.

	Wavelengths [μm]		
	λ_1	λ_2	λ_3
TM mode	1.562	1.3	1.996
TE mode	1.572	1.3	2.018

Also, the second telecommunication window (1.3 μm) is filtered with a high transmission rate equal to T = 0.99% and with a high quality factor Q_{TE} = 3715.878 and Q_{TM} = 2416.22 for the TE and TM polarizations, respectively.

The increase of the angle of incidence assures the decrease of the optical path and the displacement of the band gap towards the short wavelengths.

This behavior proves that the defect modes and the band gap are strongly dependent on the angle of incidence and the polarization.

So for the TE polarization and when θ_0 = 0.45 rad, the full width at half maximum (FWHM) of photonic band gap rises and reaches $\Delta\lambda_{TE}$ = 0.944 μm. While for the TM polarization, the FHWM of the band gap decreases and becomes $\Delta\lambda_{TM}$ = 0.864 μm.

T a b l e 3. Position of the transmission peak for the TE and TM polarizations.

	Wavelengths [μm]		
	λ_1	λ_2	λ_3
TE mode	1.287	1.55	2.003
TM mode	1.294	1.55	1.983

For both TE and TM polarizations, the system is characterized by a large photonic band gap. The high contrast index $n_H/n_L = 2.55$ is the reason why the photonic band gap is very wide. Table 3 describes the positions of the optical windows within the band gap.

The defect layers behave as a cavity which allows the presence of the tunneling mode in the photonic band gap and causes the appearance of the sharp peaks in the transmission spectrum [13].

The defect layers can be considered as the Fabry–Pérot cavity. Thus, multiple reflections will take place inside the cavity when the optical path difference between the neighboring transmission light Δ is an integer multiples of the wavelength λ for the incident light which means that

$$\Delta = 2nd = m\lambda, \quad m = 1, 2, 3$$

where n and d are the refractive index and the thickness of the defect layer, respectively [14].

It is very important to note the existence of the well-known telecommunication wavelength 1.55 μm which represents the most suitable optical spectrum for communication purpose and the present filter is designed especially for this aim [15]. The superposition of the positions of this peak for both of polarizations (TE and TM) is a very interesting feature of this filter. We can run away simultaneously from the normal incidence and the constraint of the polarization to facilitate the experimental use of the developed filter.

Thanks to the symmetry, we can achieve a developed 1D photonic crystal filter with high transmission rate and high quality factor.

The symmetrical distribution of the layers decreases the phase shift between the waves reflected at each interface and ensures a more constructive interference which allows the broadening of the photonic band gap [16].

The transmission of the telecommunication wavelength 1.55 μm is realized with a high transmission rate which reaches $T = 0.94\%$ for the TE polarization and the quality factor of this optical channel attains $Q_{TE} = 34675.61$ and $Q_{TM} = 17278.47$ for the TE polarization and TM polarization, respectively. Also we should understand why the factor of quality is more important for the TM polarization than for TE polarization.

For a given angle of incidence, the localization of the TE polarized waves in the cavities is stronger in comparison with the TM waves, which makes the existence of the energy more important inside the cavities [17]. This reason explains the fact that the quality factor is more important in the TE case.

Finally, this configuration allows the transmission of the 0.85, 1.3, and 1.55 μm telecommunication wavelengths by tuning the optical path of the light.

The theoretical analysis of the optical response of the system $Bg_5/Cu_1/Bg_5$ gives helpful information for the designing and the manufacturing of a narrow telecommunication filter [12].

4. Conclusion

In summary, we use the dependence of the defect modes on the state of polarization and also on the intensity of the peak and the position of the sharp transmission peak to design a developed telecommunication filter. The symmetry is exploited in order to improve the performance of the filters too.

An engineered symmetrical combination of periodic photonic crystal and copper mean photonic crystal is carried out. This configuration allows the transmission of all the telecommunication wavelengths 0.85, 1.33, and 1.55 μm. This device is easy to fabricate thanks to the limited number of layers and to its wide range of telecommunication applications.

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