Bandpass Biomedical Color Filter Based on 1-D Photonic Crystal Structure

H. Alipour-Banaei [a] and N. Khorrammaslack [b]

[a]Department of Electronics, Tabriz Branch, Islamic Azad University, Tabriz, Iran
[b]Department of Electrical Engineering, Ahar Branch, Islamic Azad University, Ahar, Iran
*** Corresponding author email: alipour@iaut.ac.ir**

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ABSTRACT— We propose a flexible design for tunable bandpass biomedical color filter based on one-dimensional photonic crystals with introducing defect layers into one dimensional periodic structure which permits localized modes to exist with frequency inside photonic band gap (PBG). In the proposed structure we can tune localized modes for manifesting different colors by selecting a specific wavelength in the visible light spectrum and also we tuned localized modes in PBG for RGB wavelengths applicable in biomedical systems. With changing the defect layer refractive index, the tuning of the frequency has been done and therefore this structure is suitable for optical biomedical bandpass filter.

KEYWORDS: Photonic Crystal, Color Filter, Photonic Band Gap, RGB Colors, Biomedical Systems.

I. INTRODUCTION

Human eyes are sensitive to light which lies in a very small region of the electromagnetic spectrum corresponds to a wavelength rang of 400-700 (nm) labeled “visible light”. Red, green, and blue are the primary provocative for human color sensation and are the primary additive colors [1]-[4]. As we know in television and computer or any other medium RGB is the basic color model that projects the color and also it is used for Web graphics [5]-[6]. As far as we know by mixing spectral light in different combinations we can produce Additive colors for example television screens and computer monitors produce colored pixels by shooting red, green, and blue electron guns at phosphors on the television or monitor screen. We can produce white light with combining equal amounts of Red Green and Blue light. By subtracting one of the primary additive colors (red, green, and blue) from white light we can produce primary subtractive colors (cyan, yellow, and magenta). Subtractive colors are the temperament of color print production and CMY, as used in four-color printing, are considered to be subtractive primaries. A color filter manifests different colors by selecting a specific wavelength in the visible light spectrum [7]. Color filters are used as core elements in different applications [8]-[12].

One way to solute, the problem of optical control and manipulation is photonic crystal, a periodic dielectric medium which have been an interesting field of intense research during the past years. In particular, we can design and construct photonic crystal with photonic band gap in desire frequency rang which prevent light from propagating in certain direction. And also a photonic crystal can allow propagation in different and useful procedure [10], [13]-[14].

In this paper we introduce defect layer into one dimensional photonic crystal which permit localized modes to exist with frequency inside photonic band gap in this method we embodies different colors by selecting a specific wavelength in visible light spectrum and also we tuned localized modes in PBG for RGB wavelength with changing the defect layer refractive indices at the same manner we can tune localized modes with changing defect layer width .as we know by mixing equal amounts of Red , Green and Blue light we can produce White light and also by subtracting one of the primary additive colors from white light we can produce primary subtractive colors which used in color printing production .as illustrated in figures 3,4 we can tune localized modes between pairs of RGB colors which can used for producing subtractive colors. And also in this paper we studied effect of defect layer refractive indices commutation and defect layer width increasing on localized modes wavelength and its number. We simulate reflection and transmission spectra from Transfer Matrix Method. This one-dimensional filter is very simple and easy to accomplish and simply we can tune the localized modes wavelength in visible light region with changing the defect layer refractive indices.

II. PERIODIC STRUCTURE DESIGN

A one-dimensional photonic crystal is an artificial structure in which the refractive indices vary periodically in one direction, which causes PBG. PBG prevent light from propagation in certain direction with specified frequencies. We can recognize band above and below the PBG by where the energy of their modes is concentrated: in the high $-\varepsilon$ region or in the low $-\varepsilon$ region. Modes with high frequency have larger fraction of their energy in the low- ε regions and Modes with low frequency concentrate their energy in the high - ε region [10]-[11].

For one periodic structure shown in Fig.1 with refractive indices n_a and n_b and thicknesses d_b and d_b respectively and lattice constant a; PBG is maximized when:

$$n_a d_a = n_b d_b \qquad (1)$$

In this specific case, midgap frequency ω_m is:

$$\omega_m = \frac{n_a + n_b}{4 n_a n_b} \cdot \frac{2\pi c}{a} \qquad (1)$$

and corresponding vacuum wavelength $\lambda_m = \frac{2\pi c}{\omega_m}$ should satisfy:

$$n_a d_a = n_b d_b = \frac{\lambda_m}{4} \qquad (3)$$

Visible light electromagnetic spectrum is corresponded to a wavelength rang of 400-700 (nm) which result:

$$\lambda_m = \frac{\lambda_a + \lambda_b}{2} = 550(\text{nm}) \qquad (2)$$

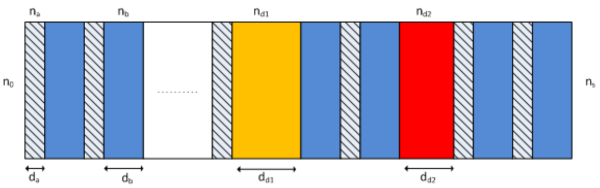


Fig. 1. schematic diagram of 1-D photonic crystal stacks

A one-dimensional periodic photonic crystal structure is shown in Fig. 1.
From above equations and trial and error to find the most appropriate band gap we choose periodic structure characteristic as $n_a = 3$, $d_a = 43(nm)$, $n_b = 1.25 d_b = 99(nm)$ and the number of the periods is 10 and corresponding band diagram is illustrated in fig. 2.

III. BAND STRUCTURE CALCULATION

To design RGB tunable Band Pass Filter we use one-dimensional crystal photonic and also we calculate the reflection and transmission of electromagnetic radiation through a multilayer with the TMM method [14]. our One dimensional structure are made of two layers, with refractive indices n_a and n_b and thicknesses d_a and d_b respectively, and lattice constant $n_b = 1.25 d_b = 99(nm)$ and also we introduced two defect layers between layers 13 and 14 and layers 16 and 17 with $d_{d1} = 250\ (nm)$, $d_{d1} = 250\ (nm)$, $d_{d2} = 200\ (nm)$ and n_{d1} respectively and also

Total thickness of filter is $1.87(\mu m)$. The structure is coupled to a homogeneous medium characterized by $n_0 = 1$ (initial medium) and $n_s = 1$ (final medium) corresponded to air.Fig.1 shows this structure.

$$n(x) = \begin{cases} n_0 & x < x_0 \\ n_a & x_0 < x < x_0 + d_a \\ n_b & x_0 + d_a < x < x_0 + a \\ . & \\ . & \\ n_{d1} & 6a + d_a < x < 6a + d_a + d_{d1} \\ n_b & 6a + d_a + d_{d1} < x < 7a + d_{d1} \\ n_a & 7a + d_{d1} < x < 7a + d_b + d_{d1} \\ n_b & 7a + d_b + d_{d1} < x < 8a + d_{d1} \\ n_{d2} & 8a + d_{d1} < x < 8a + d_{d1} + d_{d2} \\ n_a & 8a + d_{d1} + d_{d2} < x < 9a + + d_{d1} + d_{d2} \\ . & \\ . & \\ n_b & 9a + d_{d1} + d_{d2} + d_a < x < 10a + d_{d1} + d_{d2} \\ n_s & x > 10a + d_{d1} + d_{d2} \end{cases} \quad (5)$$

Dynamical matrix D_m is given by:

$$D_m = \begin{cases} \begin{bmatrix} 1 & 1 \\ n_m \cos\theta_m & -n_m \cos\theta_m \end{bmatrix} & \textit{for TE wave} \\ \begin{bmatrix} \cos\theta_m & -\cos\theta_m \\ n_m & -n_m \end{bmatrix} & \textit{for TM wave} \end{cases} \quad (6)$$

Where m= a, b, d, 0, s and θ_m is the ray angle in each layer.

Propagation matrix P_m is given by:

$$P_m = \begin{bmatrix} \exp(ilk_m h_m) & 0 \\ 0 & \exp(-ilk_m h_m) \end{bmatrix} \quad (7)$$

Transfer matrix of one period is given by:

$$M_a = D_a P_a D_a^{-1} D_b P_b D_b^{-1} \quad (8)$$

Transfer matrix of defect layer is given by:

$$M_{d1} = D_{d1} P_{d1} D_{d1}^{-1} \quad (9)$$

$$\Delta\omega = -\frac{\int \omega d^3 r \Delta\varepsilon(r) |E(r)|^2}{2\int d^3 r \varepsilon(r) |E(r)|^2} \quad (10)$$

Total transfer matrix for our one dimensional structure is given by:

$$M = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix} = D_0^{-1}[(\prod_1^6 M_a) D_a P_a D_a^{-1} M_{d1} D_b P_b D_b^{-1} M_a M_{d2} M_a^{2}] D_s \quad (11)$$

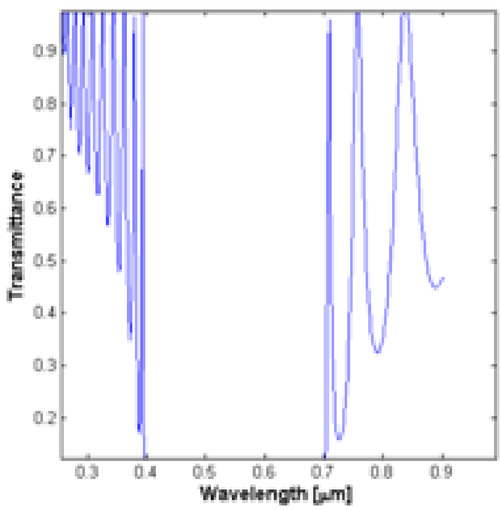
The transmittance in the structure:

$$T = \left| \frac{1}{M_{11}} \right|^2 \quad (12)$$

and the reflectance:

$$R = \left| \frac{M_{21}}{M_{11}} \right|^2 \quad (13)$$

As we illustrate in Fig.2 without defect layer our structure PBG is corresponded to 400-700 nanometers. This region of the electromagnetic spectrum corresponds to visible light. This means without defect layer our structure filters visible light.



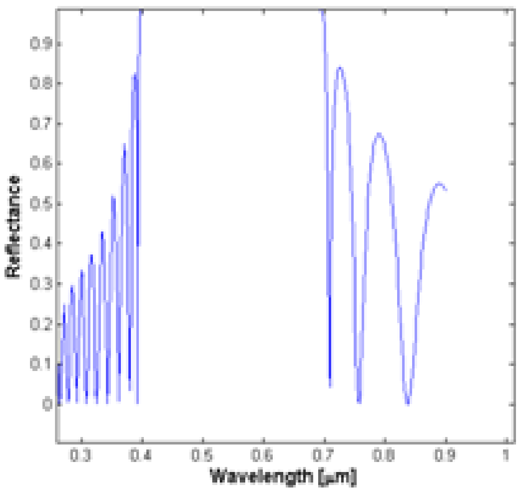


Fig. 2 reflectance and transmittance spectra of proposed periodic structure without defect.

IV. TUNING THEORY

Introducing defect layer into perfectly periodic structure broke translation symmetry of system, in fact defect layer cause a small perturbation $\Delta\varepsilon$ of the dielectric function of perfectly periodic structure. Now we use a simple equation for frequency shift $\Delta\omega$ that result from a small perturbation $\Delta\varepsilon$ of the dielectric function:

$$\Delta\omega = -\frac{\int \omega d^3 r \Delta\varepsilon(r) |E(r)|^2}{2\int d^3 r \varepsilon(r) |E(r)|^2} \quad (14)$$

From above equation we can understand that a small change in refractive indices causes a small change in frequency and also minus sign appear because an increase in the refractive indices lowers the mode frequency [10].

White light is composed of all visible wavelengths, which can be divided into three primary-color bands, red, green and blue. A filter that reflect one wavelength band has the transmit color of the other two; it is the complement of the color it subtracts from white light. If we choose defect layers reflective indices $n_{d1} = 3$ and $d_{d1} = 250(nm)$ and $n_{d2} = 2.9$ and $d_{d2} = 200(nm)$ respectively, our structure transmit blue and green colors spectra and reflects red color spectra as illustrated in Fig.3. in this method we made a band pas filter which transmit blue and green colors spectra and reflects red color spectra. This kind of filter can be used for producing subtractive colors and any Filters which reflect red color spectra and transmit green and blue colors can be used for producing Cyan.

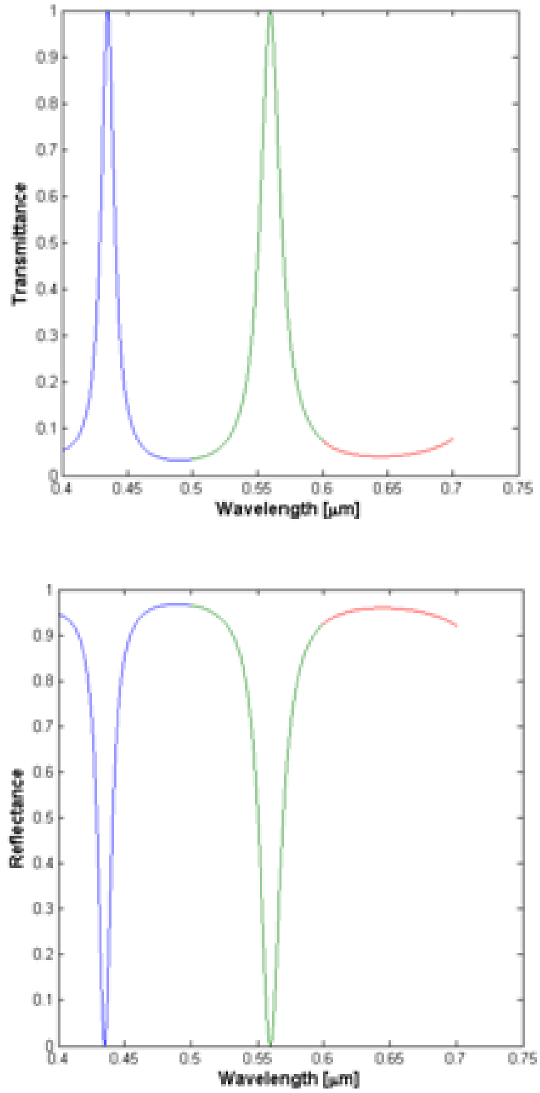
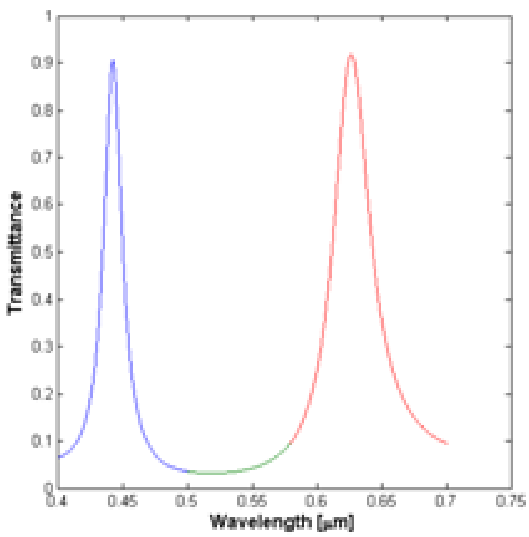


Fig. 3 reflectance and transmittance spectra of proposed filter with $n_{d1} = 3$, $d_{d1} = 250(nm)$, $n_{d2} = 2.9$ and $d_{d2} = 200(nm)$ which transmit Blue and Green colors spectra and reflects Red color spectra.

Consider a mode with frequency inside the band gap, As we know Defect layer permit localized modes to exist with frequency inside photonic band gap these modes must exponentially decay when enters into the crystal and also periodic structure on both side of the defect behave like frequency-specific mirror and any modes with frequency inside the band gap in defect layer trapped between multilayer film on both sides of the defect as illustrated in figures 3, 4 and 5 by increasing defect layer refractive indices modes on the left hand side of band gap in Fig .1 or modes with high frequency pull down into the band gap and moves toward lower frequency with increasing defect layer refractive indices because of Perturbation theory [10] , [11].

As we know by subtracting green light spectra from white light we can produce Magenta, for catching this goal and producing Magenta we change second defect layer reflective indices to $n_{d2} = 2.1$. In this condition as illustrated in Fig.4 our structure transmits blue and red colors spectra and reflects green color spectra which mean we tuned localized modes for producing Magenta with changing defect layer refractive indices. Moreover as illustrated in figure 5 by increasing second defect layer refractive indices to $n_{d2} = 3.7$, three localized modes with RGB colors wavelength pull down into band gap. Our structure with this future transmits RGB color spectra and reflects others. As far as we know Red, green, and blue are the primary additive colors and also in television and computer or any other medium RGB is the basic color model that projects the color.



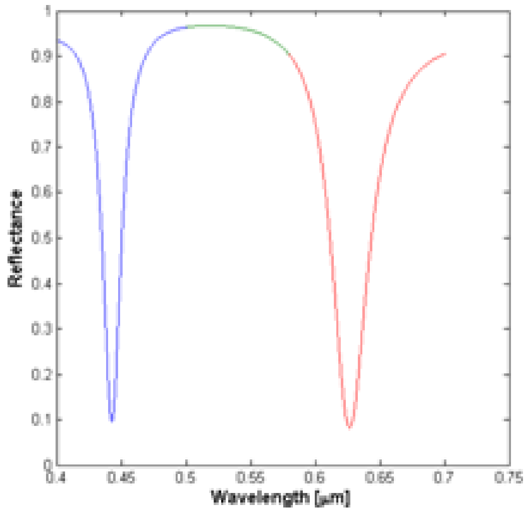
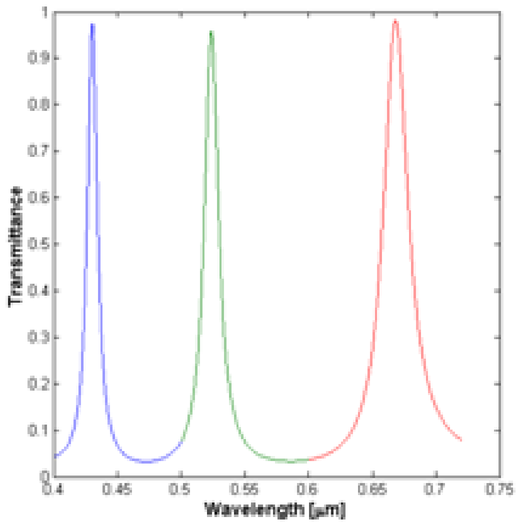


Fig.4 reflectance and transmittance spectra of proposed filter with $n_{d1} = 3$, $d_{d1} = 250(nm)$, $n_{d2} = 2.1(nm)$ and $d_{d2} = 200(nm)$ which transmit Blue and Red colors spectra and reflects Green color spectra.



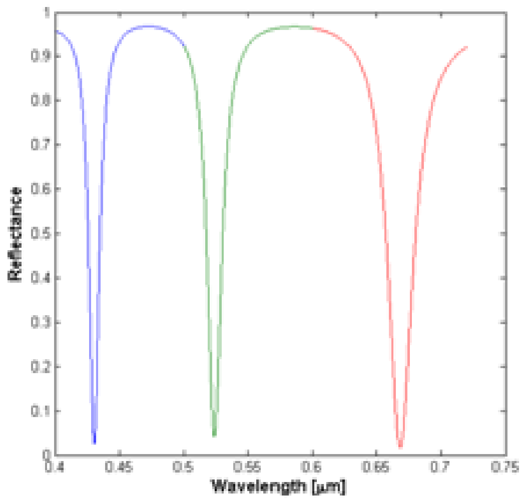


Fig.5 reflectance and transmittance spectra of proposed filter with $n_{d1} = 3$, $d_{d1} = 250(nm)$ $n_{d2} = 3.7$ and $d_{d2} = 200(nm)$

which transmits Blue, Green and Red colors spectra and reflects others.

With adjusting correct value for defect layer reflective indices our filter can used for passing in one color spectra and reflecting others , for example if we choose $n_{d2} = 1.05$ our filter transmits Blue color spectra and reflects other colors spectra as illustrated in Fig.6. and also with changing second defect layer refractive indices to 1.6 our structure transmits Green and reflects others as illustrated in Fig.7.

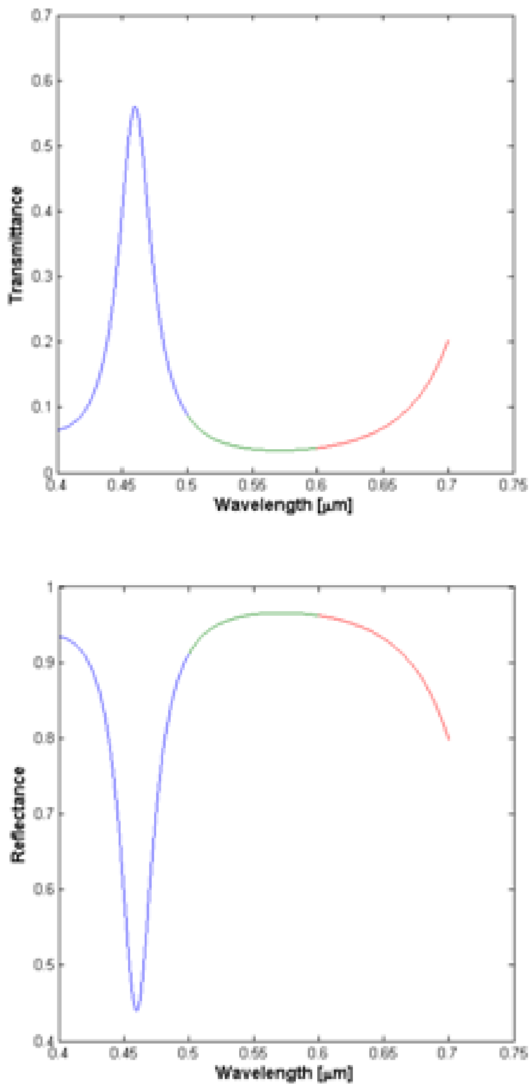


Fig.6 reflectance and transmittance spectra of proposed filter with $n_{d1} = 3$, $d_{d1} = 250(nm)$, $n_{d2} = 1.3$ and $d_{d2} = 200(nm)$ which transmit Blue color spectra and reflects Red and Green colors spectra

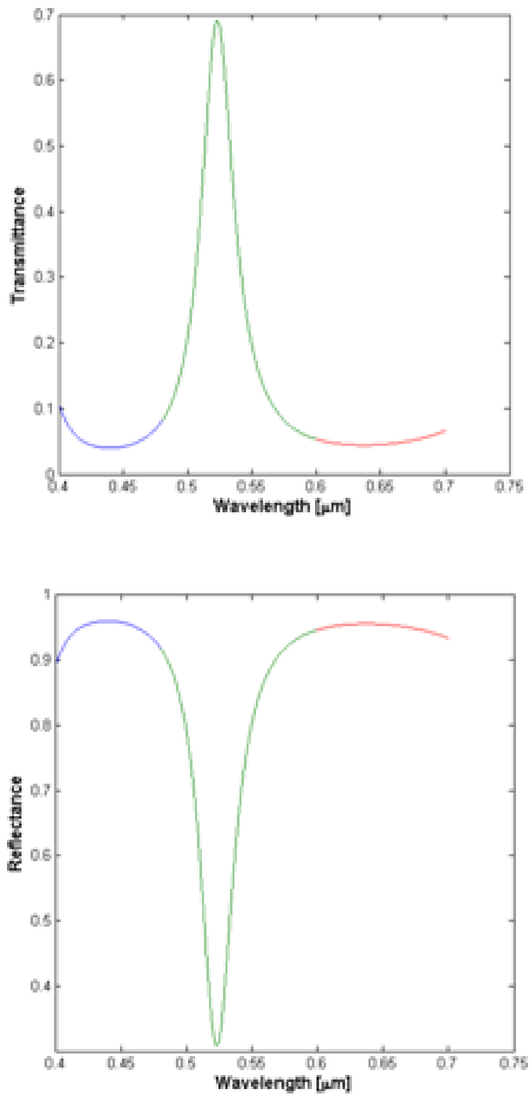


Fig.7 reflectance and transmittance spectra of proposed filter with $n_{d1} = 3$, $d_{d1} = 250(nm)$, $n_{d2} = 1.$ 6and $d_{d2} = 200(nm)$ which transmits Green color spectra and reflects Red and Blue colors spectra

A defect in one dimensional crystal photonic can be formed by changing the thickness of a single layer and also we can tune localized modes in PBG by changing the defect layer thickness. As the thickness of defect layer increase, the frequency will decrease, because the modes has more space to oscillate and also as the thickness of defect layer increases, a train of discrete modes are pulled down into the PBG from upper bands [10]. As illustrated in figure 8 by increasing first defect layer thickness to $d_{d1} = 320\ (nm)$ and increasing second defect layer refractive indices to $n_{d2} = 3.7$ three localized modes with RGB colors wavelength pull down into band gap. In this condition and in comparison to Fig.5 our structure have a better performance for selecting RGB colors. By increasing first defect layer thickness to 320 *(nm)*our structure total width increases to 1.94 (μm) .With $d_{d1} = 320\ (nm)$ and by changing second defect layer refractive indices as above we can tune localized modes for selecting different color spectra.

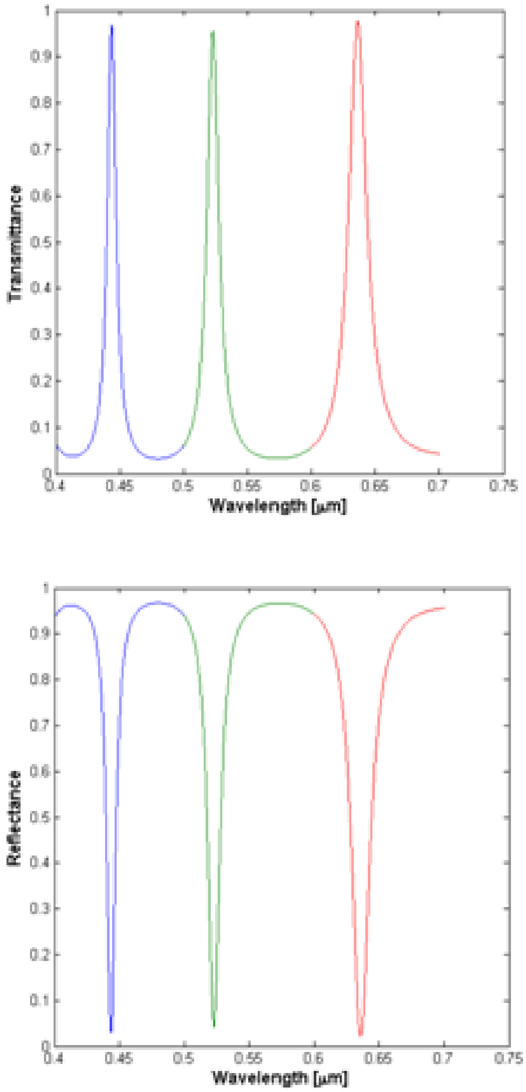


Fig.8 reflectance and transmittance spectra of proposed filter with $n_{d1} = 3$, $d_{d1} = 320(nm) n_{d2} = 3.7$ and $d_{d2} = 200(nm)$ which transmit Blue, Green and Red colors spectra and reflects others.

Conclusion

In summary, by introducing defect layer into one-dimensional crystal photonic, we proposed high efficiency tunable biomedical band pass filter in visible light region which lies in wavelength rang of 400-700 nanometers. With this structure we embody various colors by selecting a specific wavelength in visible light region and also we tuned localized modes in PBG for RGB wavelength with changing the defect layer refractive index.

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