Polymeric photonic quasicrystal: octonacci sequence and elasto-optic effect

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Abstract
Here we would like to discuss the light transmission modulation by the one-dimensional polymeric quasi-multilayer which is formed according to substitutional generalized Octonacci with PMMA and PS as the constituent materials. In particular, we will present some theoretical findings using the well-known transfer matrix method. The width of the PBG, the inter-band spacing and the depth of the PBGs can be managed by choosing the appropriate generation number, whereas the number of the major PBGs is the same for all the considered generation numbers. Regarding the position of the PBGs, we found that, with an increase in generation number, the aroused PBGs are shifted symmetrically towards the designed frequency. It also reveals the aroused forbidden frequency band can be manipulated by changing the applied hydrostatic pressure. With an increase in pressure, the frequency spectra are shifted to a higher frequency. In addition to this, we also found that as the thickness of the polymers increases the PBGs are red-shifted. The proposed structure could be another possible system for optical device design specially multi-band tunable optical reflectors.

Keywords Elasto-optic effect · Octonacci sequence · Transmission dynamics

1 Introduction
Photonic crystal (PhC) is an artificially engineered, periodic structure with the dielectric constants periodically varying in space. Yablonovitch (1987) and John (1987) independently proposed the concept of such superstructure in 1987, which affect the propagation...
of photons analogously to electrons in a crystal and this may result in the appearance of what is being called a photonic bandgap (PBG) (Soukoulis 2012; Prather et al. 2009; Jena et al. 2016). The PBG of PhC suffers from being sensitive to the lattice structure for instant breaking the periodicity of the structure generates allowed states that are strongly localized around the defect in the PBG. Whilst modulation following a deterministic generation rule gives rise to a photonic quasicrystal (PQC) Shechtman et al. (1984) may practice for the same. Besides, the similar functionalities as periodic counterparts, such as PBG, negative refraction, the transmission properties of electromagnetic waves (EM) waves in PQC give some extraordinary results (Mnaymneh and Gauthier 2007) like their branching band structures (Vardeny et al. 2013; Nayak et al. 2020). The more widely studied PQC are the Fibonacci (Nayak et al. 2019; Padhy et al. 2020), Thue-Morse (Nayak et al. 2019), Cantor (Ali 2017), Double-period (Nayak et al. 2019) and Rahimi (2016). However, research in Octonacci PQC (Nayak et al. 2017) has been so far mainly limited to theoretical investigations of multilayered structures. This sequence has a geometric origin: the octagonal Ammann-Becker tiling is ruled by the Octonacci sequence.

A tunable PhC or PQC in which the PBG, as well as the defect-mode, can be tuned as desired by controlling parameters such as the refractive index (Gong and Hu 2014). Therefore, the use of constituent building blocks with relatively more complex dielectric constants than simply losslessness can provide an extra degree of freedom in the design of tunable PhCs and PQC. In this line, the resent focus on those PhCs and PQC whose dielectric properties can be controlled by the external influences such as magnetic field, electric field, temperature, pressure due to magneto-optic effect (Nayak 2020; Rashidi et al. 2020; Nayak et al. 2020; Shiri et al. 2019; Zhang et al. 2013), electro-optic effect (Schmidt et al. 2005), thermo-optic effect (Nayak et al. 2020; Jena et al. 2021) and elasto-optic effect (Nayak 2021; Jena et al. 2019; Nayak et al. 2017) respectively. The elasto-optic phenomenon is well observed in transparent polymers such as polyamide-imide films (PAI), polyvinyl butyral. (PVB) polystyrene (PS) and polymethyl methacrylate (PMMA) and therefore is well accepted for practicing photonic structures. In this regard, polymer-based PCs and PQC are interesting alternatives that can be used at very high-frequency bands (Jena et al. 2019) particularly in the THz or mid-infrared (10 – 100 THz) bands and has employed in very advanced applications such as infrared free-space communications, biomedical, and environmental sciences, safety monitoring and many more.

In the present work, we explore the transmission spectra and the possibilities of aroused new PBGs from the Octonacci quasicrystal (Nayak et al. 2017) which is composed of PMMA and PS (Jena et al. 2019). The dielectric constant of such polymer can be tuned by the applied hydrostatic pressure. First, we present the structures under investigation and describe shortly the computational method we used in Sect. 2. Our results about the transmittance spectra of light as well a detailed discussion over them are in Sect. 3. Final conclusions are given in Sect. 4.

2 Methodology

The geometrical PQC structure in this paper consists of a one-dimensional Octonacci quasicrystal in an air environment, as illustrated in Fig. 1. Layer A, with thickness $d_A$ (quarter wave condition), is fulfilled by PMMA, and is characterized by a hydrostatic pressure dependent refractive index $n_A$. Layer B, with thickness $d_B$ (quarter wave condition), is fulfilled by the PS, and is characterized by a hydrostatic pressure dependent refractive index
The Octonacci sequence is created by the recurrence relation (Nayak et al. 2017) $O_n = \{O_{n-1}O_{n-2}O_{n-1}\}$ for the generation number, $n \geq 3$, with initial condition: $O_1 = \{A\}, O_2 = \{B\}$. For the theoretical method employed for the transmission simulations of such structure we refer to Ref. Born and Wolf (2013). Briefly, the characteristic matrix corresponding to the $i^{th}$ layer is

$$M[i] = \begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix}$$

(1)

and the characteristic matrix of the quasisequence is

$$M[T] = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix} = \prod_{i=1}^{N} M[i]$$

(2)

where, $N$ is the number of layer to required to construct the sequence and can be calculated by the recurrence relation, $N_n = 2N_{n-1} + N_{n-2}$ for $n \geq 3$, where $N_1 = 1$ and $N_2 = 1$. Finally, the transmittance, $T$, of the quasicrystal is calculated through the transmission coefficient which is the amplitude of the right propagating wave in the substrate region.

3 Result and Discussions

We now intend to investigate the transmittance spectra in generalized Octonacci one-dimensional PQC by using the calculations of the previous section. The considered PQCs are stacked of two types of layers namely, $A$ (PS) and $B$ (PMMA) Jena et al. (2019) according to the substitution rules of the Octonacci sequences (Nayak et al. 2017). We compute the transmission properties of light incident normally through the air on the considered multi-layer structures. It is investigated under the influence of the parameters of the constituent materials such as the thickness of the layers and the applied external hydrostatic pressure. The pressure dependant refractive index of PS and PMMA is taken from Ref. Jena et al. (2019). The structure is designed at 61.25 THz which corresponds to $d_A=780$ nm and $d_B=830$ nm. The observation frequency range is fixed from 20 to 100 THz.

Figure 2 illustrates the transmittance of the Octonacci multilayer, $S_n$ at generation number, $n = 4$ (blue), 5 (green), 6 (red), 7 (black) and 8 (cyan) versus the frequency. For the Octonacci multilayer, $n = 4$ (blue), oscillation in transmission with four dips at unit transmittance is noted. Such behavior is aroused because of the spatial variation in the refractive index of two optically transparent materials. At $n = 5$ (green) these dips are intensified.
with some additional deeps. In addition, these dips are symmetrically shifted toward the designed frequency i.e. 61.25 THz. With the increase in $n$, these four dips transformed to PBGs in the direction of propagation (Z-axis). A Fig 3 presents the numerical results of increasing the hydrostatic pressure from 0 to 200 MPa on the same sequences, except the $n = 4$, represents in Fig 2. In detail, The Octonacci multilayer, $n = 5$ at ‘a’, 6 at ‘b’, 7 at ‘c’ and 8 at ‘d’, respectively. In all the cases, it was found that, increase in external hydrostatic pressure, the refractive index contrast decreases (Jena et al. 2019), causing the PBG to be blue-shifted which is given an opportunity for tunable multiband reflector design.

To realize the effect on the forbidden region introduced by the variation of the layer thicknesses of the polymeric Octonacci quasiperiodic structures, we consider the same sequences employed for Fig. 3, Octonacci multilayer, $O_n$ at generation number, $n = 5$, 6, 7 and 8 at hydrostatic pressure, $P = 0$ MPa and at a fixed hydrostatic pressure, $P = 100$ MPa. At first, we start our analysis to examine the effect of thickness on transmittance spectrum with respect to the changes in PMMA layer from 390 nm (one by eighth wave condition) to 1070 nm (half-wave condition) whereas the thickness of PS is kept constant to 830 nm (quarter-wave condition). The transmission spectrum for Octonacci multilayer, without any hydrostatic pressure, $P = 0$ MPa, $O_n$ at generation number, $n = 5$, 6, 7 and 8 are depicted in Fig. 4a. Whereas in Fig. 4b the same for $P = 100$ MPa are depicted. From Fig. 4a, we
observe that the aroused PBGs experience a redshift and become narrow as the PMMA layers thickness increases. Moreover, the frequency spacing between also decreases with an increase in it. While observing the effect of hydrostatic pressure in Fig. 4b, where hydrostatic pressure is equal to 100 MPa, similar behavior of the transmittance spectra is observed. Whereas the presence of hydrostatic pressure shift the PBGs to the blue side as we showed in Fig. 3. These appeared modifications in the position and width of the forbidden regions aroused because of intrinsic consequences of each constituent element.

In order to realize the effect on the forbidden region introduced by the variation of the layer thicknesses more clearly, we examine how the forbidden regions can be controlled with respect to the changes in PS layer thickness from 415 nm (one by eighth wave condition) to 1245 nm (half-wave condition) whereas the thickness of $d_A$ is kept constant to 780 nm (quarter-wave condition). The transmission spectrum for Octonacci multilayer, without any hydrostatic pressure, $P = 0$ MPa, $O_n$ at generation number, $n = 5, 6, 7$ and $8$ are depicted in Fig. 5a. Whereas in Fig. 5b the same for $P = 100$ MPa.
are depicted. From Fig 5, a very close response to the changes in PMMA layer thickness is observed. These alike appeared modifications in the position and width of the forbidden regions aroused because of the chose the polymeric material with very close dielectric constant to design the stack.

Then, we investigate the PQC where the addition of PMMA and PS is taken as constant. Here, the total thickness to form a period is 1610 nm. Figure 6 displays the transmittance spectra with an increase of PMMA layer thickness from 390 nm (one by eighth wave condition) to 1070 nm (half-wave condition) whereas the thickness of the PS layer is calculated with reference to PMMA layer thickness. The transmission spectrum for Octonacci multilayer, without any hydrostatic pressure, \( P = 0 \) MPa, \( O_n \) at generation number, \( n = 5, 6, 7 \) and 8 are depicted in Fig. 6a. Whereas in Fig. 6b the same for \( P = 100 \) MPa are depicted. It can be found from the results that the PBGs within the frequency region is shifted to a higher frequency when PMMA layer thickness increases.

In this case, the thickness of the PMMA layer increases while the thickness of the PS layer decreases correspondingly. Therefore, the variation in PBG shown in Fig. 6 is the combination of the increase in the thickness of PMMA and the decrease in the thickness of the PS layer. As the previous study reflects that the increase in thickness of any layer (PMMA or PS) causes the shift in PBG towards lower frequency. Therefore, the decrease in the thickness of the PS layer causes the shift towards higher frequency. From Fig. 6, it is clear that overall the PBG shifted towards higher frequency suggests, the variation in PBG is more effective in case of reduction in the thickness of any layer compared with the increase in the thickness.

While the changes in the bandwidth of the PBGs are quite interesting, they are quite changes of PBGs in trend to our previous two cases, variation of PMMA as well as PS thickness. Moreover, the slope of PBGs are found to be more as from simple variation of PMMA and PS layer thickness. Therefore, in accordance with the application, the edge of the PBGs and their width can be effectively tuned by altering the thickness of both layers is suggested.

\[ \text{Fig. 6} \] Transmittance, \( T \) in Colour map as a function of incidence frequency [THz] and thickness of the PMMA layer [nm] for the polymeric Octonacci photonic quasicrystal, \( O_5(i), O_6(ii), O_7(iii) \) and \( O_8(iv) \), at both the panel (a) and (b). In panel (a) \( P = 0 \) MPa whereas \( P = 100 \) MPa in panel (b). Here, the sum of the thickness of the PMMA and PS is always kept constant to 1610 nm in both of the panels.

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4 Applications

The proposed structure can be employed for various optoelectronic applications such as tunable multi-channel filters and hydrostatic pressure sensors. In the following, we discuss one of these major applications i.e. tunable multi-channel filter. Here, the tunable multi-channel filter is designed using the Octonacci sequence having generation number eight, $O_8$. As depicted in Fig. 1, the transmission spectrum of the $O_8$ has four major PBGs in different frequency bands hence acting as a multi-channel filter. This transmission spectrum is further incorporated with the hydrostatic pressure in order to study the behaviour of the bands B1, B2, B3 and B4 across the frequency spectrum as shown in Fig. 7. It is observed that there is a shift in bandgaps with an increase in pressure as shown in Table 1, where the $f_{B1}$, $f_{B2}$, $f_{B3}$ and $f_{B4}$ are the central frequencies of the respective bands of the $O_8$ multi-channel filter. In Fig. 8 this data is plotted which gives an intuition regarding the frequency of the bands across the frequency spectrum with application of the hydro-static pressure. From Fig. 8 it can be observed that the $O_8$ multi-channel filter with the different shift of operating frequency across the spectrum, where frequency shift of $B_4 > B_3 > B_2 > B_1$ as observed in Fig. 8.

| Pressure (MPa) | Central frequency (THz) |
|---------------|-------------------------|
|               | $f_{B1}$    | $f_{B2}$    | $f_{B3}$    | $f_{B4}$    |
| 0             | 35.64       | 50.42       | 71.3        | 86.16       |
| 50            | 35.98       | 50.91       | 72.07       | 87          |
| 100           | 36.34       | 51.43       | 72.79       | 87.87       |
| 150           | 36.71       | 51.95       | 73.52       | 88.76       |
| 200           | 37.09       | 52.49       | 74.28       | 89.67       |

Fig. 7 Transmittance spectra of polymeric Octonacci photonic quasicrystal having generation number 8 under the influence of different hydrostatic pressure.
5 Conclusions

The transmittance of the one-dimensional polymeric Octonacci structure is investigated with the change of applied hydrostatic pressure and the layer thickness of the constituent materials using the characteristic matrix. By comparing the transmittance spectra of different generation numbers \( n \), we try to highlight the importance of PBG formation in PQC. We found that, initially, at \( n = 4 \), the Octonacci distribution introduces four transmission dips in the computed frequency band and these are transformed to PBGs as the generation number increases. Moreover, an additional effect is also noticed, i.e. the aroused PBGs are shifted symmetrically toward the designed frequency, but the shift is found to be very minimal. While studying the impact of hydrostatic pressure we found that the formed PBGs in the transmission spectra of the PQC changed for different applied hydrostatic pressure and shifted to the right with an increase in it. The increase in thickness of the structure is imposed a mixed response on the aroused PBGs. More clearly, with an increase in both PMMA and PS layer thickness, the PBGs are shifted to lower frequency and become very very marginally wider. On the other hand, the PBGs are shifted to a higher frequency with an increase in PMMA layer thickness while the addition of PMMA and PS layer thickness is always kept constant to 1610 nm.

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Declarations

Conflict of interest The authors have not disclosed any competing interests.

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