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A novel structure for 4-channel all optical demultiplexer using 12-fold photonic quasicrystal

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In this work, a new structure for a 4-channel all optical demultiplexer has been designed, using a 12-fold photonic quasicrystal (PQC). The structure used in this research is composed of air rods of 150 nm in diameter, arranged on silicon nitride substrate with a pitch of 260 nm and lattice constant of 0.25. The area of the structure is only 16 μm^2 which is quite interesting for optical integrated circuit applications. The four channels are separated by introducing some defects to the crystal. Also, superprism effect in PQCs has been investigated by changing the tiling angle of input Gaussian modulated wave. Finally, four channels with spacing of 7.8 nm between channels one and two, 3.6 nm between channels two and three and 7.3 nm between channels three and four, around 0.6 μm as the central wavelength have been separated. The crosstalk level between adjacent channels is about –8 dB for channels one and two, –3 dB for channels two and three and –6.5 dB for channels three and four.

Keywords: photonic quasicrystal, demultiplexer, defect, superprism effect.

1. Introduction

Photonic crystals (PCs) are artificial periodic structures in which the refractive index modulation gives rise to stop-band for electromagnetic waves within certain wavelengths [1]. On the basis of previous studies it is evident that, as the symmetry of photonic crystal increases, the Brillouin zone becomes more circular, resulting in a complete band gap. The highest degree of symmetry found in periodic lattices is six. However, much higher levels of symmetry can be achieved using the complex geometries of photonic quasicrystal (PQC). A complete photonic band gap (PBG) has been observed both theoretically and experimentally in 5, 8, 12-fold PQC [2].

Photonic crystals have potential applications in optical communication, quantum electronic devices, distributed-feedback mirrors, microwave antennas [3], and their unusual optical properties which mostly arise from the existence of PBG can be exploited to control and guide the propagation of light [4].

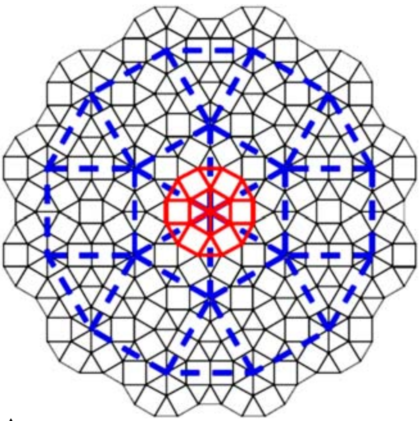
Interest towards integrated optical circuits for optical information processing and optical communication was the motivation to work on optical wavelength demultiplexing devices.

Important factors which should be considered in wavelength demultiplexing devices are: separating several optical channels at different wavelengths with high spectral resolution and low crosstalk level, and also having small size for optical integrated circuit applications.

Different techniques such as those using L-shaped bent waveguides [5], line--defective waveguides, microcavities at the PC's structure, ring resonators [6] and superprism effect [7] have been used to design compact wavelength demultiplexing devices by PCs. For example, the experimental results for superprism-based demultiplexers reported to date show an isolation of 10 dB for only two channels 50 nm apart in wavelength using a 1250 μm^2 structure [8]. Another report demonstrates channel wavelength spacing of 20 nm but with less than 2 dB isolation in a 6300 μm^2 structure and for only two channels as well [9]. And the best report demonstrates a design of a 4-channel optical demultiplexer with the channel spacing of 8 nm and crosstalk level better than –6.5 dB, which is done experimentally using a 4500 μm^2 photonic crystal region [7].

In this work, the Stampfli inflation rule [10] has been used with dodecahedral parent cells (Fig. 1, dashed lines) generating the offspring dodecagons (Fig. 1 solid lines).The resulting arrangement of air rods in the waveguide dielectric layers is generated by placing holes at the vertices as shown in Fig. 2.

We investigate a structure composed of 150 nm air rods arranged on a pitch of 260 nm silicon substrate with lattice constant of 0.25. To model the structure a finite difference time domain (FDTD) method has been used. It has been shown that the band



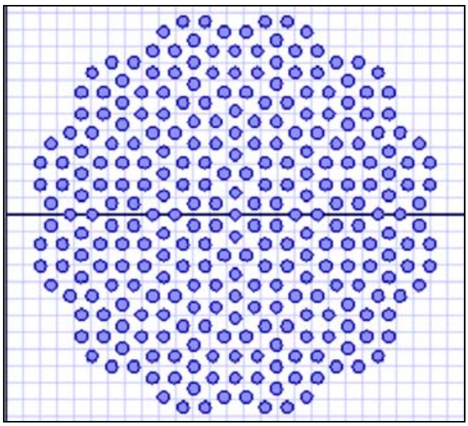


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Fig. 1. Quasicrystal pattern used based on square-triangular tiling, grown using random Stampfli inflation from parent lattice (dashed lines) to produce offspring tiling (solid lines).

Fig. 2. 12-fold PQC structure with air rods placed at the vertices of the arrangement shown in Fig. 1 in silicon nitride substrate.

gap extends from 0.58 μm to 0.62 μm and from 0.64 μm to 0.72 μm for TM electromagnetic incident field with different tiling angle.

We can get different defect wavelengths within the band gap by removing rods from the various positions of the structure [11]. The defects in the crystal have been introduced by removing some rods and successfully 4 channels have been separated at different observation points with acceptable spacing and crosstalk level. The PQC's region is only 16 μm^2 which is quite interesting for optical integrated circuit design purposes.

The final structure is a 4-channel optical demultiplexer, with a channel spacing of 7.8 nm (for channels 1, 2), 3.6 nm (for channels 2, 3), and 7.3 nm (for channels 3, 4).

2. Discussion and results

First, measurements of transmission through the structure have been preformed using FDTD method in order to specify the PBG. The parameters of simulation are as follows:

– Mesh delta X [μm]: 0.01;
– Mesh delta Z [μm]: 0.01;
– Number of mesh cells X: 480;
– Number of mesh cells Z: 2000;
– Time step size [s]: 2.22×10^{-17};
– Number of time steps: 20000;

As shown in Fig. 3, there is a strong attenuation in transmission of EM waves with TM polarization through the crystal. So, the photonic band gap appears to be from 0.58 μm to 0.62 μm and from 0.64 μm to 0.72 μm for different values of incident angle. The transmission characteristics for incident angles of 0°, 15° and 30° are shown in Fig. 3.

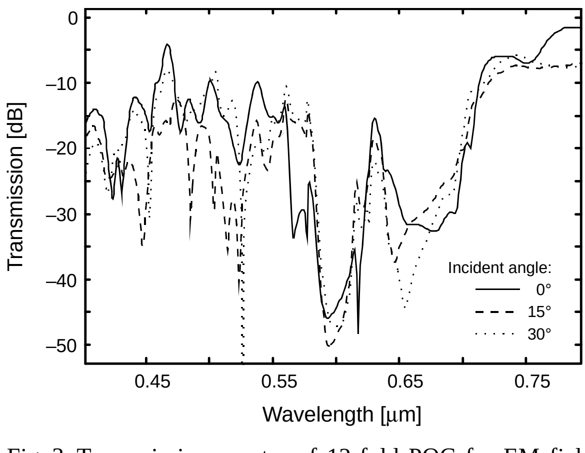

Fig. 3. Transmission spectra of 12-fold PQC for EM field with TM polarization and incident angles of 0°, 15° and 30°. Zero-transmission region at 0.58 μm to 0.62 μm and from 0.64 μm to 0.72 μm is identified.

The defect characteristics of quasiperiodic crystals are more interesting and more useful than the defect states in periodic photonic crystals. Removing one rod from a periodic array would produce one fixed set of localized defect modes. However, for a quasicrystalline arrangement of cylinders, each cylinder is located in a different environment, so that removing one rod from a different location can produce defect states with different frequencies and mode patterns [12]. So, the PQC allows for a higher degree of flexibility for defect mode properties.

In order to design a wavelength demultiplexer an incident EM wave (Gaussian modulated field with central wavelength which is in the band gap of the crystal (0.6 μm) and TM polarization) has been defined and plenty of observation points have been placed at the other side of the structure. The coordinates of observation points are shown in the Table.

Then some rods have been removed from different sites and the effect of defect position on the output waveform at observation points has been studied. Interestingly, different wavelength peaks have been observed at separated positions (observation

T a b l e. Coordinates of observation points which have been used to observe the behavior of structure under different defect sites and incident field.

Observation point	X [μm]	Z [μm]	Observation point	X [μm]	Z [μm]
1	2.16	11.42	11	–0.46	12.6
2	2	11.66	12	–0.78	12.54
3	1.84	11.92	13	–1.02	12.4
4	1.56	12.1	14	–1.28	12.26
5	1.28	12.2	15	–1.52	12.12
6	1.02	12.36	16	–1.72	11.96
7	0.74	12.5	17	–1.94	11.76
8	0.44	12.56	18	–2.1	11.52
9	0.14	12.56	19	–2.28	11.24
10	–0.14	12.6	20	2.28	11.14

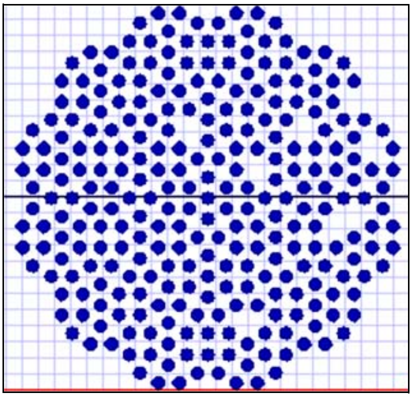

Fig. 4. 12-fold PQC with some defects (removed rods) introduced in the structure in order to excite different modes in band gap of crystal and separate wavelengths at the observation points.

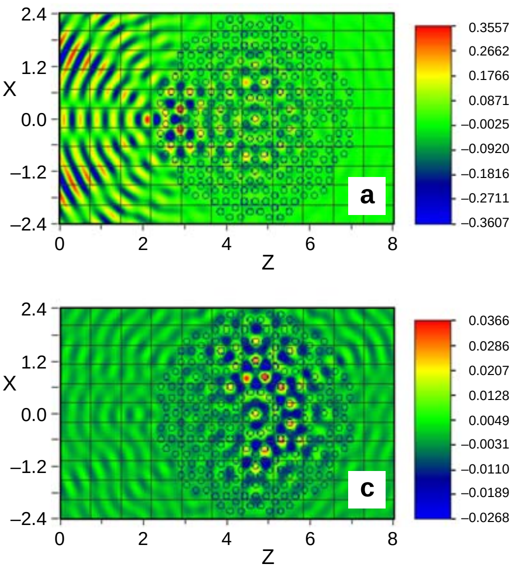

Fig. 5. Different time steps for distribution of Gaussian modulated wave in structure: time step 1000 (**a**), time step 10000 (**b**) and time step 20000 (**c**). The intensity of field is recognizable by the color table on the right-hand side of the figures.

points) on the other side of the crystal with acceptable spatial spacing. Defects profile for the best results achieved in this paper is shown in Fig. 4, and distribution of Gaussian modulated field with TM polarization and central wavelength of 0.6 μm is shown in Fig. 5.

In Figure 5, Gaussian modulated field with TM polarization and central wavelength of 0.6 μm is passing through the structure in *Z* direction. Intensity of field at different sites is shown by colors which are detectable by the measures on the right-hand side of each figure. Some of the time steps are shown in order to clarify the interaction of field with crystal.

When Gaussian modulated wave with TM polarization and central wavelength which appeared at the band gap (0.6 μm), have been used as the input of the structure and also the defect sites have been achieved by successive examinations (Fig. 4), the best result was separating 4-channels with acceptable spacing and crosstalk level at different observation points on the other side of crystal, as shown in Fig. 6.

In Figure 6, channel 1 occurs at observation point number 14 with central wavelength of 0.592 μm, channel 2 occurs at observation point number 7 with central wavelength of 0.599 μm, channel 3 occurs at observation point number 8 with central wavelength of 0.6039 μm, and channel 4 occurs at observation point number 3 with central wavelength of 0.6113 μm. The spacing between channels 1 and 2 is 7 nm, between channels 2 and 3 is 4.9 nm, and between channels 3 and 4 is 7 nm, but between in this figure it is seen that the output waves are a little scrambled.

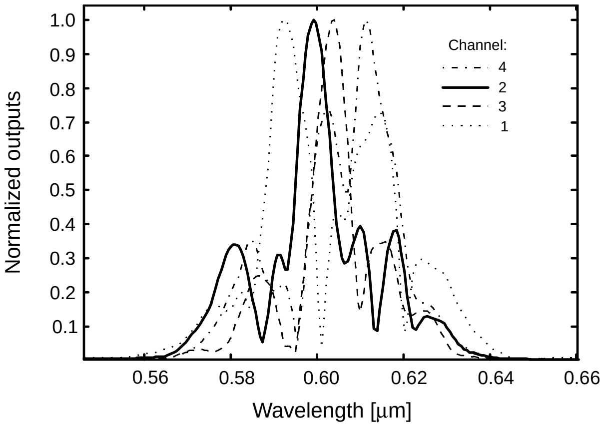

Fig. 6. Normalized output channels.

In the second step, the superprism effect has been investigated for the PQCs. In order to check this effect different tiling angles of incident field were examined and the behavior of the crystal at these angles was studied. With the same defect profile of the previous step, the peak of wavelengths occured at different observation points. Also, by making use of this effect the waveforms were more acceptable.

Then, the field with different tiling angles have been defined and finally, an incident angle of 15° was found, being the best one for this structure with the same defect profile as in the previous step. As can be seen from Fig. 7, the waveform is quite better than in Fig. 6.

In Figure 7, the spacing between channels 1 and 2 is 7.8 nm, between 2 and 3 is 3.6 nm, and between 3 and 4 is 7.3 nm. Channel 1 occurs at observation point 4 and channel 2 occurs at observation point 7, channel 3 at observation point 15 and channel 4 at observation point 17.

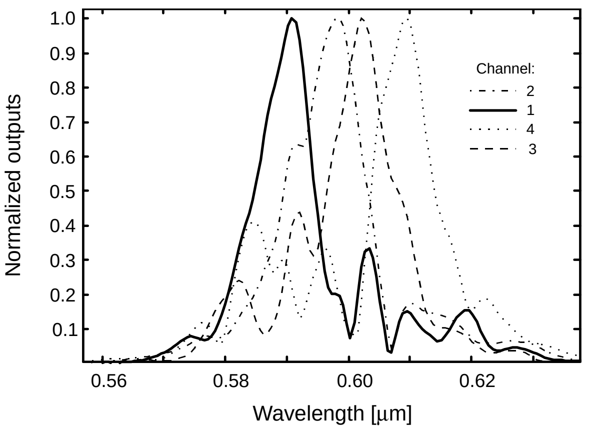

Fig. 7. Normalized output channels with the field tiling angle of 15°.

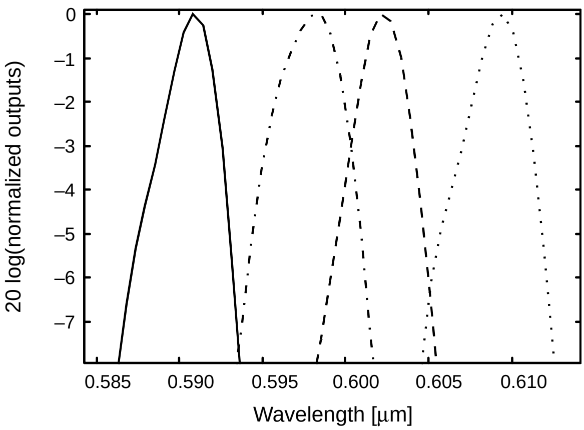

Fig. 8. A dB domain diagram of output channels with incident field angle of 15°.

In Figure 8, a dB domain diagram of output channels can be seen. From this figure it was recognized that the crosstalk between channels 1 and 2 is about –8 dB and the crosstalk between channels 2 and 3 is about –3 dB and between channels 3 and 4 is about –6.5 dB.

3. Conclusions

In this paper, a 4-channel all optical demultiplexer has been designed by introducing defects in the 12-fold photonic quasicrystal structure. Also, superprism effect has been used in order to increase the quality of output channel waveforms by changing the tiling angle of input field. After examining different angles it was found that 15° is the best choice for designed structure with the formation of defects that have been introduced in the crystal. Compared to other structures for demultiplexers designed by other scientists using superprism effect, it can be easily seen that the area of this structure is considerably smaller and the channel spacing and crosstalk level are more acceptable.

References

[1] Gauthier R.C., Mnaymneh K., *Photonic band gap properties of 12-fold quasi-crystal determind through FDTD analysis*, Optics Express **13**(6), 2005, pp. 1985–1998.

[2] Han Zhao, Zaccaria R.P., Jun-feng Song, Kawata S., Hong-bo Sun, *Photonic quasicrystals exhibit zero-transmission regions due to translational arrangement of constituent parts*, Physical Review B **79**(11), 2009, p. 115118.

[3] Agi K., Brown E.R., McMahon O.B., Dill C., III Malloy K.J., *Design of ultrawideband photonic crystals for broadband antenna applications*, Electronics Letters **30**(25), 1994, pp. 2166–2167; Sigalas M., Biswas R., Li Q., Crouch D., Leung W., Jacobs-Woodbury R., Lough B., Nielsen S., McCalmont S., Tuttle G., Ho K.M., *Dipole antennas on photonic band-gap crystals – Experiment and simulation*, Microwave and Optical Technology Letters **15**(3), 1997, pp. 153–158.

[4] MEKIS A., CHEN J.C., KURLAND I., SHANHUI FAN, VILLENEUVE P.R., JOANNOPOULOS J.D., *High transmission through sharp bends in photonic crystal waveguides*, Physical Review Letters **77**(18), 1996, pp. 3787–3790.
[5] NAKA Y., IKUNO H., *Two-dimensional photonic crystal L-shaped bent waveguide and its application to wavelength multi/demultiplexer*, Turkish Journal of Electrical Engineering and Computer Sciences **10**(2), 2002, pp. 245–256.
[6] ZEXUAN QIANG, WEIDONG ZHOU, SOREF R.A., *Optical add-drop filters based on photonic crystal ring resonators*, Optics Express **15**(4), 2007, pp. 1823–1831.
[7] MOMENI B., HUANG J., SOLTANI M., ASKARI M., MOHAMMADI S., RAKHSHANDEHROO M., ADIBI A., *Compact wavelength demultiplexing using focusing negative index photonic crystal superprisms*, Optics Express **14**(6), 2006, pp. 2413–2422.
[8] WU L., MAZILU M., KRAUSS T.F., *Beam steering in planar-photonic crystal: From superprism to supercollimator*, Journal of Lightwave Technology **21**(2), 2003, pp. 561–566.
[9] LUPU A., CASSAN E., LAVAL S., EL MELHAOUI L., LYAN P., FEDELI J.M., *Exprimental evidence for superprism phenomena in SOI photonic crystal*, Optics Express **12**(23), 2004, pp. 5690–5696.
[10] ZOOROB M.E., CHARLTON M.D.B., PARKER G.J., BAUMBERG J.J., NETTI M.C., *Complete photonic bandgaps in 12-fold symmetric quasicrystals*, Nature **404**, 2000, pp. 740–743.
[11] BAYINDIR M., CUBUKCU E., BULU I., OZBAY E., *Photonic band-gap effect, localization, and waveguiding in the two-dimensional Penrose lattice*, Physical Review B **63**(16), 2001, p. 161104(R).
[12] CHAN Y.S., CHAN C.T., LIU Z.Y., *Photonic band gaps in two dimensional photonic quasicrystals*, Physical Review Letters **80**(5), 1998, pp. 956–959.

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