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ON 3D PHOTONIC CRYSTALS: A BRIEF EVALUATION OF THEIR MAIN CHARACTERISTICS FOR VARIOUS TOPOLGIES

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Tendința constantă de miniaturizare a condus la descoperiri teoretice şi aplicații practice în electronică, optică şi mecanică fină (pemițându-ne să anticipăm apariția de noi dispozitive senzoriale, precum şi noi metode de procesare şi transmitere a datelor). La ora actuală, sistemele optice ocupă un loc aparte în domeniul comunicațiilor, dar calitățile lor deosebite le fac să fie foarte atractive, atât pentru dispozitive senzoriale, cât şi pentru procesarea datelor. În ultima decadă s-a remarcat o activitate de cercetare susținută privind anumite structuri regulate cu dimensiuni geometrice comparabile, sau chiar mai mici, decât lungimea de undă a luminii. Astfel de structuri prezintă caracteristici deosebite, lumina interacționând cu ele în mod diferit de sistemele optice clasice, incluzând inhibarea transmisiei şi formarea benzilor fotonice interzise. Aceste structuri regulate sunt cunoscute în literatura de specialitate sub denumirea de cristale fotonice, iar lucrarea de față va trece în revistă o mare parte dintre cristalele fotonice tridimensionale, enumerând tipuri clasice şi comparându-le caracterisiticile intrinseci.

The enduring trend towards miniaturization has lead to many new theoretical discoveries and applications in electronics, optics, and fine mechanics (allowing us to envisage the development of new sensors devices as well as novel ways of data processing and communication). Currently, optical based systems play a central role in communications, but the particular qualities they posses makes them a very attractive candidate for both sensing and processing information. A remarkable development has been observed over the last decade on regular structures having elementary dimensions comparable to, or even smaller, than light waves. Such structures present particular characteristics, as light interacts with them in completely different ways — from what is known from classical optics — like e.g., inhibition of light transmission and photonic band gap formation. These regular structures are known (from the literature) as photonic crystals, and in this paper we will review many 3D photonic crystals by enumerating the basic known types, as well as briefly comparing their intrinsic properties.

Keywords: Photonic crystal (PC), photonic band gap, three dimensional PCs.

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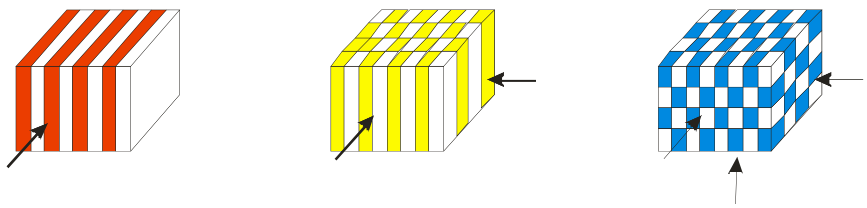
1. Introduction

The electromagnetic phenomena inside PCs were discovered simultaneously by Yablonovitch [1], and John [2] in 1987. Since then, there have been many papers published on this topic [3]-[17]. Meanwhile, the technological capabilities (borrowing from integrated circuits) for the fabrication of special, artificial, micro- (even nano-) structures, have been improved, such as now we can find a plethora of microfabrication recipes.

The physical effect of light propagation through a periodical dielectric structure is valid for one, two or three dimensions of PBG materials (Fig. 1).



(a) (b) (c)

Fig. 1. Basic PBG materials: (a) 1D; (b) 2D; and (c) 3D structures.

(a) (b) (c)

Fig. 2. Specific colors of butterflies coming from the PBG effect: (a) butterfly; (b) detailed view of a wing; and (c) micrometric visualization showing the photonic structures (on the wings).

Before artificial PCs were invented (and fabricated) nature has already been doing its magic with light. In fact, some biological systems are using nanometre-scale structures to produce optical effects based on PBG, like *e.g.*: a species of Brittlestar who use photonic elements composed of calcite to collect light, a Morpho-butterfly who uses multiple layers of cuticle and air to produce their specific colors (see Fig. 2), or some insects who use arrays of elements (nipple arrays) to reduce their reflectivity [18]-[21].

Inside PCs two main scattering phenomena are taking place [9], [22]:

- the “Bragg” (macroscopic) scattering resonance occurring in a periodic structure [23];
- the “Mie” (microscopic) scattering resonance from a single unit cell of the material (occurring at the maximum backscattering).
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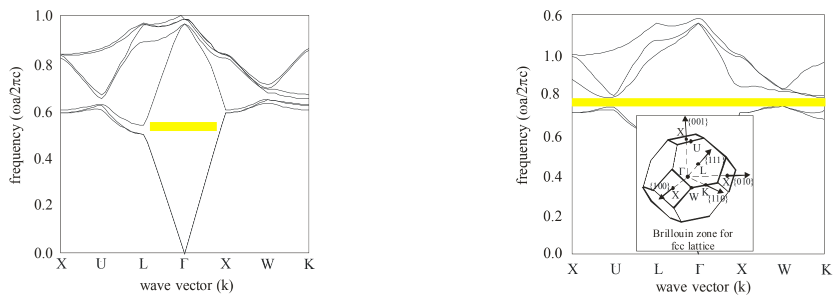

(a) (b)

Fig. 3. (a) A partial PBG (yellow rectangle); and (b) a complete PBG (yellow band) for a 3D structure (inset shows the Brillouin zone for the face centered cubic lattice structure).

The PBG formation can be enhanced by choosing the geometry and material parameters such as both the macroscopic and microscopic resonances occur at the same frequency. Fig. 3 shows the distribution of photon energy states inside a PC (for the face centered cubic lattice structures). The PBG formation is highlighted using yellow (light gray) rectangles. For more details about PBG see [24][32].

Using PCs, unusual (highly nonlinear) phenomena have been reported [33], [34]. The authors of [34], stated that the light traveling through PCs “*leads to interesting propagation phenomena, such as imaging effect*.” In [35] “*the experimental demonstration of imaging by all-angle negative refraction in a 3D photonic crystal*” was shown even at microwave frequencies.

As we can see from Fig. 4(b), a band gap representation occurring in a 2D structure has three main bands: upper, gap (highlighted in yellow), and lower. Each one represents a frequency domain where light is passing through the PC made of dielectric and air interstitials. The lower band is represented by those frequencies corresponding to propagation through dielectric (having high refractive index). The upper band corresponds to air light propagation (low refractive index).

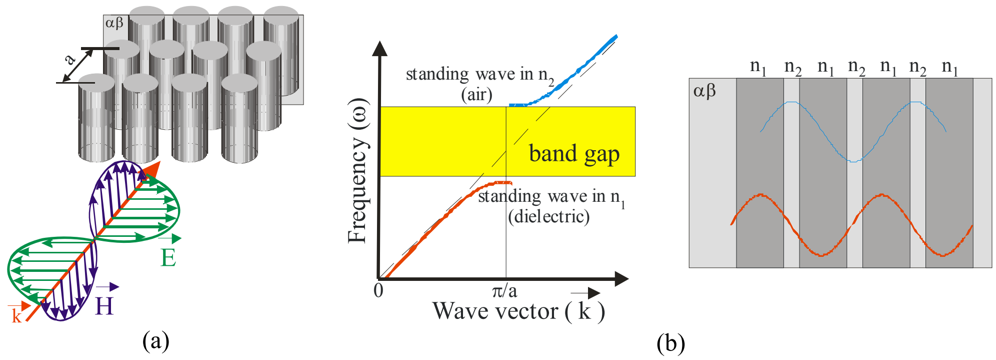

Fig. 4. Wave traveling through a 2D structure: (a) dielectric rods, and (b) formation of the PBG. Here $\vec{\mathbf{H}}$, and $\vec{\mathbf{E}}$ are the magnetic and respectively the electric component of the electromagnetic field, **a** is the lattice periodicity, and **n** represent the refractive index.

The main characteristic of a material which has a PBG behavior is its periodicity ("*a*", or lattice dimension). The gap size can be determined from the refractive index contrast and the filling ratio ("*f*") of the higher index material. Meanwhile, the location of the mid-gap frequency is determined by the lattice constant ("*a*") of the PC (Fig. 4(a) and (b)).

Finally, one more important aspect is the scaling of the PBG: if the PC is scaled by a factor *s*, all frequencies (upper and lower bands, as well as mid-gap "ω_m") will be scaled by *s*, but the ratio gap/mid-gap ($\Delta\omega/\omega_m$) remains the same [36].

2. Characteristics of 3D Photonic Crystals

The inhibition of light in PCs is related to their main characteristics [37], including:

- *Dimensionality*: The number of geometrical dimensions light is constrained to (one, two or three dimensions).
- *Symmetry*: The positioning of the building PC blocks. These will give the symmetry of the lattice. Examples of several 3D symmetries can be found in Bravais lattices: simple cubic, simple hexagonal, body centered cubic, and face centered cubic (Table 1). Other important lattices are formed from Bravais lattices with additional atoms (a typical example is the diamond structure).
- *Topology*: Varying the geometrical (e.g., rod diameters/lattice values) and material parameters (like *e.g.*, switching between direct and inverse structures), one can change the topology [38]. These will strongly affect the PBG. As one example, for the Fcc symmetry we can have: (i) isolated dielectric spheres in air; (ii) interpenetrated dielectric

spheres in air; (iii) isolated air spheres in a dielectric; or (iv) interpenetrated air spheres in a dielectric.

- *Lattice parameters*: These are represented by the periodicity (a) and the geometrical dimensions of the PC (r, c, or L), and all have values in the same range as the wavelengths.
- *Filling ratio*: This is the relative amount of material composing the scattering PCs structure over the total volume of the PC.
- *Refractive index contrast*: This is a measure of the relative difference in refractive indexes of the dielectric and air, being given by $\Delta = \left(n_1^2 - n_2^2\right)/2n_1^2$, where n_1 is the refractive index of the dielectric, and n_2 is the refractive index of the air.

Table 1

3D symmetries

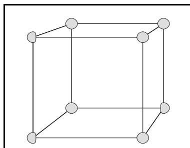	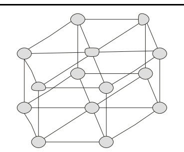	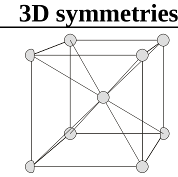	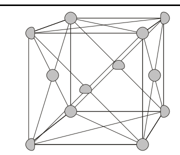	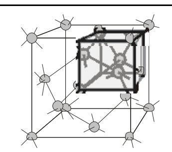
Simple cubic	Simple hexagonal	Body centered cubic	Face centered cubic	Diamond

Table 2 offers a synoptic view of the localization of PBG in 3D PCs, as well as of their fabrications techniques.

Table 2

3D PC structures, some of their PBG localization, and possible fabrication techniques

Structure	*PBG localization (bands)*	*Fabrication technique*	*Reference(s)*
Woodpile		Layer-by-layer, holography	[39]-[42]
Diamond	Between 2nd and 3rd	Nanorobotic manipulation	[37]
Face centered cubic	Between 4th and 5th Between 8th and 9th	Holographic lithography	[43]-[45]
Simple cubic	Between 2nd and 3rd and 5th and 6th	Holographic lithography	[46]
Spiral	Between 4th and 5th	GLancing Angle Deposition (GLAD)	[9], [14], [47]-[49]
Slanted pores	Between 2nd and 3rd	X-ray lithography and template inversion	[50],[52]
Colloidal (opal)	Between 8th and 9th	Self-assembling	[37], [53]-[64]
“Yablonovite”, as a Fcc	Between 8th and 9th	Reactive ion etching	[65]
Pyrochlore	Between 2nd and 3rd	Drilling, etching channels by ion beams, holography	[66], [67]
Network waveguide systems	Many, but some are incomplete	None suggested	[68]

Besides these 3D PC structures, there are a few new and quite interesting ones called hetero-structures, which combine 2D with 3D structures [69]-[71].

3. Properties of 3D PCs

It was shown theoretically that only 3D PCs posses complete PBG. Consequently, if an atom is placed inside such a structure, the energetic state of a photon (which should normally be reflected by the atom) will be binding nearby the atom [27]. This means that, by a smart engineering of a PC it is possible to "control" light. It is known that "control theory" deals with the behavior of dynamical systems, with the desired output known as the reference. When one or more output variables of a system need to follow a certain reference over time, a controller manipulates the inputs to the system to obtain the desired effects at the output(s) of the system. In the case of PCs, the role of the "controller" is played by the way the PCs are designed. Using different PC models, one can amplify or inhibit light in a desired (i.e., "controlled") way.

Table 3 includes many 3D PCs, and for each of them it presents: the 3D PC structure and/or topology; the type of the arms section (when it is the case); the filling ratio *f*; the 3D geometrical values; the center of the PBG (ω_m); the relative size of the photonic band gap ($\Delta\omega/\omega_m$); and the reference(s).

Table 3

Characteristics of several 3D PCs (for various topologies)

Structure	**Sect.**	***f* (%)**	**[x, y, z] (a.u.)**	**ω_m (a.u.)**	**$\Delta\omega/\omega_m$ (%)**	**Ref.**
Simple cubic		79	$r_1=r_2=0.34a$	0.45	16.8	[9]
Body cubic cenered		82	$r_1=0.13a$, $r_2=0.22a$	0.5	16.7	
Face cubic centered		77	$r_1=r_2=0.25a$	0.5	19.5	
Face cubic centered		89	$r_1=0.08a$, $r_2=0.16a$	0.7	17.2	
Face cubic centered		79	$r_1=0.11a$, $r_2=0.16a$	NA	27.8	
Face cubic centered			r=0.3645a	0.95	12.6	[62]
Face cubic centered			r=0.3645a	0.57	1.3	
Face cubic centered	C	78.5	Lx=Ly=0.7, r/a=0.24	0.565	25.1	[42]
Face cubic centered		81.3	Lx=Ly=0.625, r/a=0.23	0.652	26.7	
Face cubic centered -spheres		79	[1.30,1.22,0.27]	0.42	10.6	[14]
Diamond - inverted: 1	Sq	66.7	[0.57, 1.2, 0.57]	0.36	15.4	
Diamond - inverted: 5	Sq	74.6	[1.5, 1.75, 0.57]	0.36	16.6	
Diamond - direct: 3	C	40	[0.81, 1.45, 0.23]	0.33	5.8	
Diamond - inverted: 3	C	79	[1.52, 1.31, 0.25]	0.36	15.4	
Network – direct		17.8	$r_c=0.1$, $r_s=0$	0.6	28.4	
Pyrochlore lattice of dielectric spheres		NA	r/a=0.19	0.45	14	[66] [67]
Pyrochlore lattice of air spheres		NA	r/a=0.27	0.59	26	

Pyrochlore of air rods		NA	r/a=0.23	0.6	25	
Woodpile			c/a=1.414	0.3	27	[40]
Woodpile		80	r/a=0.2	0.55	9	[72]
SP_2 T/[1,1]		80.47	r/a=0.34, c/a=1.73	0.39	13.5	[73]
SP_2 inverted T/[1,1]		80.47	r/a=0.34, c/a=1.73	0.39	13.5	
SP_2 inverted S/[1,1]		80.16	r/a=0.345, c/a=1.4	0.41	24	
Spirals	Sq	NA	[0.71, 1.4, 0.33]	0.41	9	[74]
Spirals	Sq	NA	[0.73, 1.39, 0.34]	0.34	12	
Hexagonal		81.8	Lx=Ly=0.58, r/a=0.22	0.687	26.9	[42]

Here:

- "*direct*" means a structure having $\varepsilon_{sp} = 11.9$, and $\varepsilon_b = 1$ (air) [14];
- "*inverted*" means a structure $\varepsilon_{sp} = 1$ (air), and $\varepsilon_b = 11.9$ [14];
- *C* and *Sq* mean "circle" and respectively "square," representing the type of spiral arms section [14];
- SP_2 is the slanted-pore (*SP*) structure (*2* means the number of pore axes) [73];
- *S* for square, and *T* for triangular [73];
- [*1*, *1*] describes the drilling direction (see [73]).

4. Conclusions

Optical data processing is not only an extremely wide-ranging area, but also a far-reaching and very generous one. It covers both theoretical discoveries and research-and-development advancements, as well as enabling fabrication methods and sophisticated measurement techniques.

The discovery of regular structures known as PCs (long used by Mother Nature) has let to a sustained research effort. This has revealed some of the PCs peculiar optical characteristics—based on the formation of PBGs. Such structures can be used to constraint light propagation onto only one direction [75], [76]. This allows us to envision numerous practical applications among which the most promising (and rewarding) ones are: embedded optical sensors [77], on-chip optical communications [70], [78]-[80], and even optical computations [81].

This paper has briefly reviewed many 3D PCs by enumerating their basic known topologies and various types, as well as comparing their intrinsic characteristics, including their PBG(s). The paper should serve as a quick reference to the state-of-the-art of this fast developing and burgeoning field, which is certainly poised for great expectations in the near future.

Glossary:

Crystal – A solid state of a substance, characterized by a regular arrangement of its constituent atoms (like *e.g.*, simple cubic, body center cubic, face centered cubic, diamond, etc.).

Bravais lattice – A particular type of lattice, which can fill the whole space when repeated.

Photon – A fundamental particle of rest mass zero that is regarded as the quanta of radiated energy (from the Greek word “phōs” *i.e.*, light).

Band – A range of wavelengths between two limits (*e.g.*, in electronics there are: valence, gap and conduction bands of electrons).

Photonic Crystal (PC) – A crystal made of periodically modulated dielectric materials, with a periodicity comparable to the wavelength, which exhibits strong interaction with light.

Photonic Band Gap (PBG) – A range of frequencies for which no electromagnetic wave propagates through a PC.

Bloch wave – The wavefunction of a particle placed in a periodic potential.

Brillouin zone – The volume bounded by those surfaces situated at the same distance from one element of a lattice and its neighbors.

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