Fabrication and characterization of photonic crystals

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1. Introduction

Photonic crystals (PhC) are a periodic arrangement of materials that have different refractive indices, photonic because they directly influence light by its properties, crystal because it follows a certain symmetric arrangement in space. This periodic arrangement, if has its periodicity in the range of the wavelength of the incident light, gives rise to interesting nano-scale optical properties to a PhC. Light propagation can be manipulated and controlled in PhC by tuning the necessary parameters such as dimensions and dimensionality of the lattice, refractive index of the material used, adding impurities or "lattice defects" to the periodic crystal, etc. The concept of molding light propagation is not something new to our world. This has been existing all around us for millions of years in nature as the result of extremely refined biological evolutionary paths. Natural photonic crystals are observed in certain butterflies, for example the Neotropical butterfly genus Morpho, birds with exotic feathers, beetles, marine organisms and even in plants.

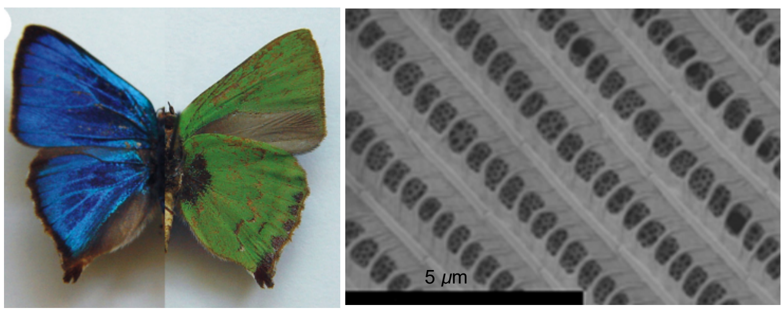


Fig. 1(a) and (b): Composed photographs of male butterfly individuals representing C. remus (left side shows the dorsal surface of the wings, while the right side the ventral side) and the SEM image of the dorsal wing showing the arrangement of scales that leads to a strong blue reflectance.[1]

Only after recent advancement in the field of nanotechnology and microscopy, we are now able to analyse and manufacture PhCs in laboratories which has found several applications in our daily lives in controlling light and its propagation. Broadly, PhC can be classified into three categories based on their symmetry in space. 1D, 2D, and 3D PhC (Fig.2). Recent research has made it quite efficient to fabricate 1D and 2D PhC although it hasn't succeeded too much in making 3D PhC efficiently.

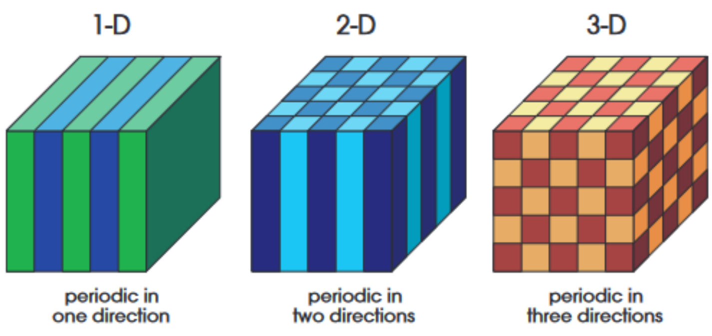


Fig.2 Simple examples of one-, two-, and three-dimensional photonic crystals. The different colors represent materials with different dielectric constants[2]

Fortunately, many interesting properties can be achieved by 2D PhC such as wave guides, resonators, efficient LEDs, "Light insulators" in specific wavelengths, tunable photonic band gaps, etc. Recent research has also extended the fabrication of conventional PhC into colloidal and liquid crystals with interesting applications in printing security patterns in currency notes[3] and magnetic bio-sensors[4]. PhC are in general fabricated by high precision equipments such as Argon-ion milling, Photolithography, and even using self assembly of micro-particles such as polystyrene in colloidal solution. The latter, however is used only for a cost effective synthesis as it is prone to unwanted crystal defects and deformations. A brief overview of the theory, one method of fabrication, characterisation techniques along with the applications of these PhC is discussed in this report.

2. Theory of the physics behind Photonic Crystals

2.1 Transfer Matrix Theory for finite 1D photonic crystals

The theory of Transfer Matrix is an analytical solution of the reflection and transmission of an incident photon based on Maxwell's Equations satisfying certain boundary conditions in the interface between one medium and another. We assume our interface to be as a finite 1D PhC as in Fig.2(a). We encourage the reader to refer Steven J. Byrne[5] for a detailed calculation, only the summarised results of which is discussed below.

A light ray propagating from n_1 to n_2 has the following defined reflection and transmission coefficients depending on its polarisation nature (s- or p-polarised).

$$r_p = \frac{n_2 \text{Cos}(\theta_1) - n_1 \text{Cos}(\theta_2)}{n_2 \text{Cos}(\theta_1) + n_1 \text{Cos}(\theta_2)},\ r_s = \frac{n_1 \text{Cos}(\theta_1) - n_2 \text{Cos}(\theta_2)}{n_1 \text{Cos}(\theta_1) + n_2 \text{Cos}(\theta_2)},\ t_p = \frac{2\, n_1 \text{Cos}(\theta_1)}{n_1 \text{Cos}(\theta_2) + n_2 \text{Cos}(\theta_1)},\ t_s = \frac{2\, n_1 \text{Cos}(\theta_1)}{n_1 \text{Cos}(\theta_1) + n_2 \text{Cos}(\theta_2)} \tag{0.1}$$

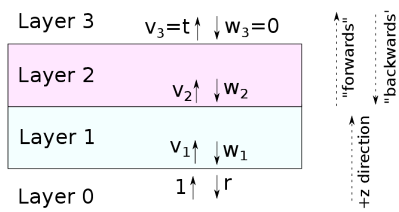


Fig.3 forward and backward wave in a Multi-layer 1D crystal

Now, if we have multiple stacking of the same material as in fig.3, we get a photonic crystal. Considering the forward and backward light at one interface between two materials with refractive indices n_i and n_{i+1}we see that the forward light is the sum of the transmitted ray of the wave in the n-1th interface with an added path difference (corresponding to the distance travelled in n-1th medium), and the ray reflected at that interface. Similarly, the backward light is the sum of the transmitted ray of the reflected wave in the n+1th interface with an added path difference (corresponding to the distance travelled in nth medium), and the ray reflected from the transmitted ray in previous layer. Eqn. (0.2) summarises this:

$$(E_f)_{n+1} = (E_f)_n\, e^{i\,\delta_n}\, t_{n,n+1} + (E_b)_{n+1}\, r_{n+1,n}\ ;\ (E_b)_n\, e^{-i\,\delta_n} = (E_b)_{n+1}\, t_{n+1,n} + (E_f)_n\, e^{i\,\delta_n}\, r_{n,n+1} \tag{0.2}$$

If λ is the incident wavelength, θ_i is the incident angle of the wave, and d_i is the thickness of the medium with RI n_i, the path difference δ_i is given as:

$$\delta_i = \frac{2\,\pi\, n_i}{\lambda} \frac{d_i}{\text{Cos}(\theta_i)}$$

So, we rewrite the relation of the $(E_f)_n$, $(E_b)_n$ with $(E_f)_{n+1}$, $(E_b)_{n+1}$ in the form of matrix as:

$$\begin{pmatrix} (E_f)_n \\ (E_b)_n \end{pmatrix} = \frac{1}{t_{n,n+1}} \begin{pmatrix} e^{-i\,\delta_n} & 0 \\ 0 & e^{i\,\delta_n} \end{pmatrix} \begin{pmatrix} 1 & r_{n,n+1} \\ r_{n,n+1} & 1 \end{pmatrix} \begin{pmatrix} (E_f)_{n+1} \\ (E_b)_{n+1} \end{pmatrix} = M_{n,n+1} \begin{pmatrix} (E_f)_{n+1} \\ (E_b)_{n+1} \end{pmatrix} \tag{0.3}$$

Thus, the final wave, after receiving contribution from all the waves reflected and transmitted within all the interfaces in the crystal, is given by the final transfer matrix $M = M_{0,1}.M_{1,2}.M_{2,3} \ldots M_{n-1,n}$. Note for the first and last matrix, we dont have any phase factor as they are usually assumed to be semi-infinite boundaries. If we assume unit incidence and reflectance r in the first interface, and t transmission and 0 backward wave incident on the nth interface, the equation finally becomes:

$$\begin{pmatrix} (E_f)_0 \\ (E_b)_0 \end{pmatrix} = \begin{pmatrix} 1 \\ r \end{pmatrix} = M \begin{pmatrix} (E_f)_n \\ (E_b)_n \end{pmatrix} = M \begin{pmatrix} t \\ 0 \end{pmatrix} \tag{0.4}$$

This final matrix gives the overall reflectance and transmittance of a light with a particular wavelength. This is a function of wavelength and if we have finite number of matrix multiplications, this can be computed with ease using computational software.

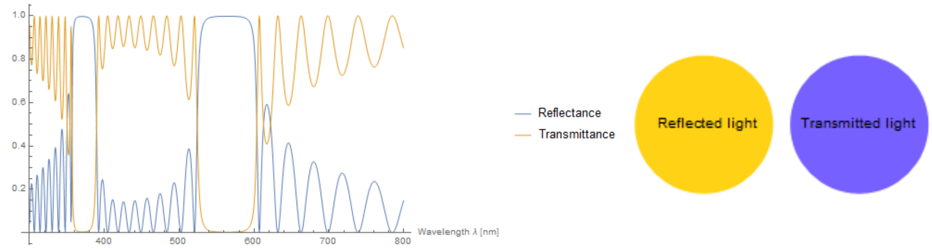


Fig. 4 and 5. The plot of R,T vs λ for a 10-layer 1D photonic crystal with d_1 = 80 nm, d_2 = 200 nm, n_1 = 1.5, n_2 = 2.2, and the color of reflected and transmitted light of the same. (Computed as a part of P441-442 lab course)

We see strong reflectance of incident light at certain wavelengths in visible range that results in a net color produced by the reflected light. This above property can be exploited in 1D biosensors that we will discuss as a direct application of the above phenomenon. This strong reflectance at certain wavelengths occur due to cascading constructive interference of reflected the wave as it enters the material. Hence, hardly any wave is left when it transmits out of the crystal. This can be visualised by plotting the E-field amplitude as it travels inside the crystal:

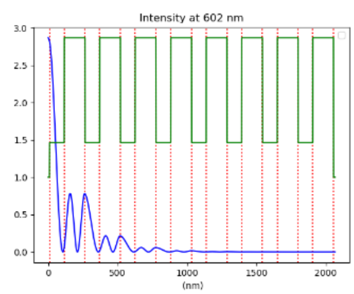


Fig. 6. The plot of E-field of a wave with strong reflection as it travels along the crystal. Refractive index plotted in y-axis and distance inside the crystal in x-axis.

After a few layers, the wave more or less behaves like an evanescent wave that slowly decays with distance. This shows that this specific wavelength cannot exist inside this crystal and this crystal behave like an effective “optical insulator” for these wavelengths. This also brings us to a concept of photonic band gaps that exist in certain wavelengths whish arises due to this in-built symmetry due to the periodic arrangement of refractive indices in our crystal.

■ 2.2 Band Gap theory for photons

The band theory for electromagnetic wave starts with the Maxwell’s equation like any other electromagnetic phenomenon.

$$\nabla\times \boldsymbol{E} = -\partial_t \boldsymbol{B} = i\,\omega\,\mu_0\,\boldsymbol{H}(\boldsymbol{r})\,,\quad \nabla\times \boldsymbol{H} = -i\,\omega\,\epsilon_0\,\epsilon_r\,\boldsymbol{E}(\boldsymbol{r})$$

Combining these two equations by eliminating E we get the master equation for a electromagnetic wave propagating in a non-magnetic (we ignored μ_r) dielectric medium with relative permittivity as a function of position $\epsilon(\boldsymbol{r})$:

$$\nabla\times\frac{1}{\epsilon(r)}\nabla\times \boldsymbol{H}(\boldsymbol{r}) = \left(\frac{\omega}{c}\right)^2 \boldsymbol{H}(\boldsymbol{r}) \tag{0.5}$$

Note that this is an eigenfunction problem of the operator $\Theta = \nabla\times\frac{1}{\epsilon(r)}\nabla\times$ with eigenvalue $\left(\frac{\omega}{c}\right)^2$.

If our lattice has discrete translational symmetry, we have the property that for a translation operator T_s with periodicity ‘s’ such that for a wave, $T_s\, e^{i\,\boldsymbol{k.r}} = e^{i\,\boldsymbol{k.(r+s)}} = e^{i\,\boldsymbol{k.s}}\, e^{i\,\boldsymbol{k.r}} = e^{i\,\boldsymbol{k.r}}$. This gives us the condition that our k can be restricted within -π/s and π/s as $k + \frac{2\pi}{s} \equiv k$. This symmetry in reciprocal lattice space (k-space) arises solely due to our existing discrete translation symmetry in real space. We first note that $e^{i\,\boldsymbol{k.x}}$ is an eigenfunction of our T_s if we have a periodicity in the x-axis. We also see that T_s must commute with Θ as T_s leaves H invariant due to the in built symmetry of our lattice. Hence, the eigenfunctions of Θ can be written as the linear superposition of the eigenfunctions of T_s as:

$$\boldsymbol{H}(\boldsymbol{r}) = \sum_{n\in Z} c_n(y,\,z)\,\boldsymbol{H_0}(y,\,z)\,e^{i\left(k+\frac{2\pi}{s}n\right)x} = e^{i\,k\,x}\sum_{n\in Z} c_n(y,\,z)\,\boldsymbol{H_0}(y,\,z)\,e^{i\,\frac{2\pi n}{s}x} = u(x,\,y,\,z)\,e^{i\,k\,x} \tag{0.6}$$

Where our defined u(x,y,z) is a periodic function in x with periodicity s as it is a superposition expansion of fourier coefficients with periodicity s. Thus, we arrive at an extremely powerful form of Bloch’s Theorem for photons and electromagnetic wave propagating in a PhC that leads us to the concept of allowed and forbidden band gaps as we see in case of electrons moving in a periodic potential of a crystal lattice.

We can obtain the speed of propagation of our light in the medium by taking gradient w.r.t $\mathbf{k}$ in Eq.(0.6) and on rearranging terms after taking inner product with $u_k\, e^{-i\,\mathbf{k}.\mathbf{r}}$ (the fourier coefficient of $u\,(x,\,y,\,z)$):

$$\boldsymbol{v} = \frac{c^2}{2\,\omega}\,\frac{\langle u_k \,|\, (\nabla_{\boldsymbol{k}}\Theta\,)\, u_k\rangle}{\langle u_k \,|\, u_k\rangle} \tag{0.7}$$

Given Θ, we can either solve for our $u\,(x,\,y,\,z)$ numerically or use perturbative effects to finally obtain the dispersion relation (ω vs k plot). In case of a uniform medium, the dispersion relation is a straight line within the First Brillouin Zone ($-\pi/s < k \le \pi/s$). If we introduce non-homogeneous multi-layers, our dispersion curve folds itself flat at the boundaries instead of remaining a straight line and ends up producing what is called a "Photonic Band Gap". This band gap widens if we have more contrast in the refractive index between the materials used to make the multilayer as shown in Fig.7.

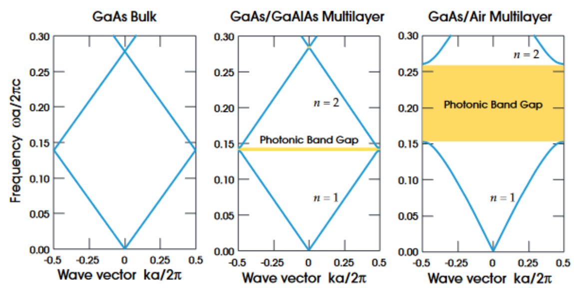


Fig. 7 Dispersion curve for three Ga-As materials. First pure Ga-As, second alternating $\epsilon = 13$ and $\epsilon = 12$, and last alternating $\epsilon = 13$ and $\epsilon = 1$. Note the width of band gap for contrasting refractive index multilayer[b]

This dispersion curve for a 1D PhC tells us that lights of certain frequencies cannot exist in our PhC due to this gap in the calculated dispersion curve. Thus, our PhC acts as an effective insulators in these cases and even if a photon is created (by any means) in the PhC, it decays and behaves like an evanescent wave with an imaginary term in k that leads to this exponential decay. This is also the reason behind why we encounter situations like in Fig.6 in our PhC. Now, given we understand our periodic PhC, what will happen if we manually add defects and break the perfect symmetry of the PhC? This turns out to result in localised frequency modes to exist at the site of defects.

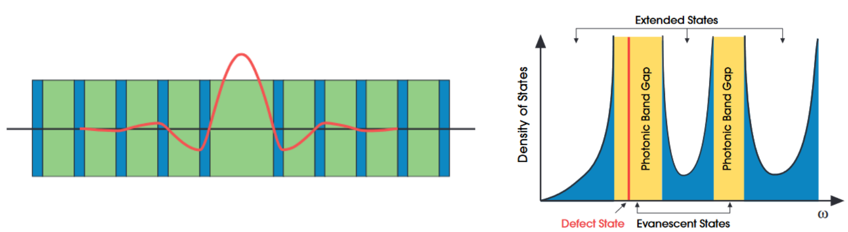


Fig. 8 Localised state in a defective PhC and the introduction of allowed states of certain frequencies in DOS diagram due to the existing defects[f] .

These modes, though present in the forbidden region (band gap), is allowed to exist inside the laterial due to the defects introduced. Thus, we get a small window of frequencies which initially did not exist in the perfectly ordered crystal. This gives us control over allowing certain frequencies and blocking others by cleverly fabricating our PhC with a mixture of symmetry and defects.

3. Fabrication and applications of Photonic Crystals

■ 1D photonic crystals: Fabrication and applications

1D PhC are mainly characterised by the refractive index of the two materials used to make the multi-layer, the thickness of each layer for every periodicity, polarisation nature of the incident light,and the angle of incidence of the light. Based on these factors, we can more or less describe the behavior of almost all 1D PhC. Since these PhC are single dimensional (they are 3D structures with periodicity in 1 dimension) fabrication of these crystals are usually not difficult and does not require too much specialised or precise methods. If our PhC is a thin multi-layer of two solid materials, they can be fabricated by any conventionally used thin film deposition methods such as the evaporation technique, sputtering, and dip/spin coating.

- ***Chemical Bio-sensing: An interesting application of 1D PhC[8]***

Chemical biosensors are materials that result in an induction of a color to the crystal by changing its characteristic properties based on an external stimuli. This stimuli can be an external protein or organic molecule present in our sample solution, a type of bacteria such as E.Coli[9], or any other form of mechanical, thermal, magnetic agitation or even the presence of light of a specific frequency itself! (like presence of UV light creating visible light reflection) These PhC's use special mesoporous nanoparticles of inorganic materials such as silica or TiO_2 layers to achieve this sensing and it has direct applications such as easily identifying the presence of a wanted/unwanted molecule in our solution just by seeing the color change of our crystal.

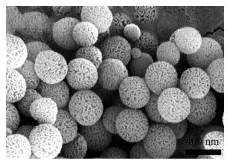


Fig.9 Mesoporous silica nanoparticles. For details of their fabrication, refer Lin-Bing Sun el.al[10]

Once fabricated, it needs no requirement of special handling and can be used by pretty much anyone. Such 1D biosensors are usually termed as Bragg Stacks as they undergo interferences between layers and result in an overall reflection for specific wavelengths similar to the phenomenon in Fig.4. The main principle behind these crystals is the fact that due to its porous nature, it absorbs certain molecules within itself and results in an increased net RI of the layer which changes the reflectance spectra of the PhC and ends up in a colored crystal. To achieve chemical selectivity, the degree of compound uptake has to be closely controlled. The small pore sizes in mesoporous materials allow for selective surface adsorption to have a significant impact on the total uptake of material and sometimes they are also deposited or doped with organic/metal-organic molecules to achieve better resolution and high specificity to sensing the desired compounds. Using this principle, innovations such as "Optical organic nose" are made that senses vapors of organic gases or dilute alcohols in solvents by showing a characteristic light spectrum.

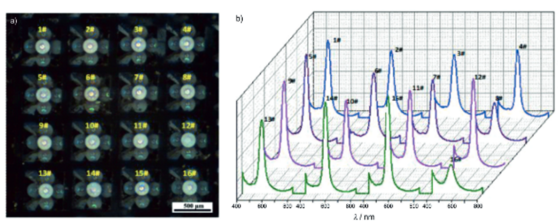


Fig.10 and 11. An organic nose made in a 4x4 array of mesoporous silica showing different light spectrum on adding 16 different alkoxysilanes on each silica.

Another way to exploit Bragg stacks is by changing the thickness of the material by absorbing compounds and result in swelling/shrinking of layers which lead to changes in reflected colors. A case where our Bragg stacks absorb salt ions and result in producing changes in color is made by a multilayer of hydrophobic and hydrophilic copolymers as in Fig. 12. Studies show that such sensors gave an almost linear response in thickness for the log value of the salt concentration in the range from 50 μM to 10 mM.

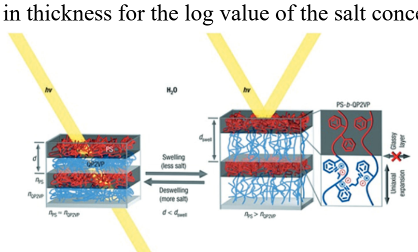


Fig.12 (above). A Photonic gel stack prepared by self-assembly of hydrophilic(blue) and phobic(red) copolymers . Thus, 1D PhC having evolved into so many diverse ways, can be used as a visual cue to translate many physical and chemical triggers which can be easily interpreted by anyone. However these biosensors also face drawbacks that needs to be addressed to make them more practical to use. The main issue faced by these kinds of polymer based bio sensors is their stability and reusability. Since these sensors respond even to a small presence of a reactive molecule of interest, their storage has to be done in a safe environment. Some sensors are seen to undergo irreversible absorption of some molecules in the atmosphere and cause issues in performance. Such irreversible change also calls for recalibration as the same color is not produced after being contaminated by irreversible absorption. This also brings us to the issue of single use of sensors which pose a concern on the environmental protection aspect. Hence, sufficient stability needs to be there in our sensors to be more practical to use.

■ 2D photonic crystals: Fabrication and applications

2D PhC, unlike 1D PhC is characterised better by the photonic band theory than transfer matrix formulation in case of 1D PhC. With that theory equipped, we can see that a 2D PhC is strongly influenced by the structure and geometry of the PhC. On adding defects to our crystals, we also achieve even more interesting features such as guiding light, confining light by totally reflecting it into a defect site of our PhC, and even filter out certain wavelengths by tuning the defect band in the band gap. These characterisations will be extremely useful in preparing optical chips and circuits which we will discuss as an interesting case study of practical applications of 2D PhC.

Now, fabrication of these is not as simple as a 1D PhC since we wish to exploit the symmetry and defects in a 2D surface. It requires a good precision in the prepared PhC as unwanted crystal defects introduced during the fabrication can significantly affect the optical properties of our PhC and destroy the band gaps. Some preferred methods of fabricating 2D PhC are Ar-ion milling Electron-beam lithography, and Photolithogra phy. We shall briefly describe only Ar-ion milling as one efficient method used to fabricate 2D PhC.

▫ *Ar-ion Milling*

Argon ion milling is often used to structure metal or inorganic dielectrics. This type of milling consists of a physical dry etch of the sample surface and eroding exposed areas of the sample by bombarding it with argon ions. A schematic of the used setup is shown in Fig.13. Argon atoms are ionised in a plasma and an applied bias-potential directs a collimated ion beam towards the sample. Argon ions hitting the sample surface transfer their energy to atoms of the sample surface, which are sputtered from the surface. This happens in high vacuum to prevent the scattering of the argon ions in the setup atmosphere and to provide a good collimation and directionality of the milling beam. The acceleration voltage determines the energy of the ions that will be imparted on our sample, and the standard deviation of ion paths from the average beam direction. We can know the number of Argon ions actually hitting the sample by measuring the stage current. If we need to protect specific areas of the sample, SU-8, Az, polystyrene or PMMA resists can be used, since the etching rates of these organic coatings are several orders of magnitudes lower than the etching rates of most inorganic materials. Argon ion milling provides good directionality and with suitable masks high aspect ratios can be achieved.

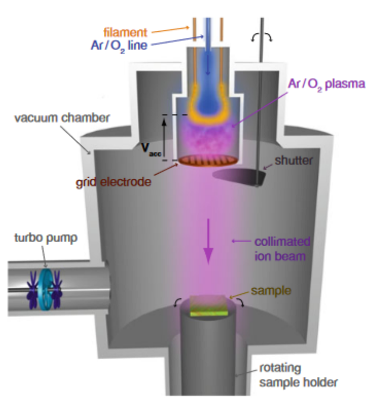


Fig.13 Schematic of the Argon ion milling device. A mixture of argon with ~2% oxygen is ionised in a plasma and directed towards a sample by a bias-potential

Fig.14 shows a GaN sample with periodic honeycomb pattern after being milled by focused ion beams[11].

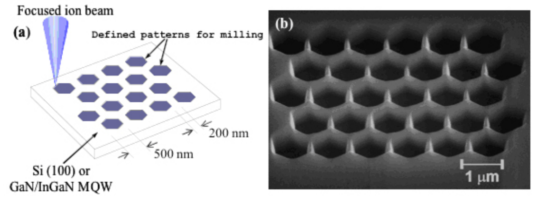


Fig.14 Template of the milling pattern and the experimentally obtained result of the same

Characterisation of 2D PhC also requires more precise characterisation techniques than a conventional spectrometer usually used to get the characterisation of 1D PhC. To get characteristic spectral curve for different regions of our 2D PhC, a Gonio Spectroscope is generally used.

- ***Gonio-Spectroscopy***

This method of spectroscopy characterises our sample by its ability to acquire standard reflected spectrum, transmitted spectrum, diffraction pattern, and forward-backward scattering spectra by placing our detector at different spots as shown in Fig.16. A sketch of the set-up is shown in Fig.15. Sample and detector stage is constructed to be rotated in steps of $<0.1°$ for better resolution in the angle for our reflection, transmission, and diffraction in different geometries, where the incidence and detection angles can be adjusted independently. The light source has its operation spectrum usually in the range of 230–880 nm. From the lamp, the light is coupled into a multimode optical fibre through which our light is transported to our collimator. A n array of ens is placed from the fibre output to collimate the light. Subsequently, after the light interacts with the sample, the resultant light is focused onto an optical fibre which sends the light to the spectroscope. Various samples can be characterised in these four different geometries. For the reference light the following is used as a standardised light for calibrating our spectrometer in the absence of a sample. Reflection measurements of samples with a strong specular reflection a silver mirror of 96% specular reflectance is used as a reference. In transmission measurements the freely propagating light beam serves as reference. Focusing of light using collimator coupled with optical fibres give us an advantage of more precise spectral measurements than our conventional spectrometer.

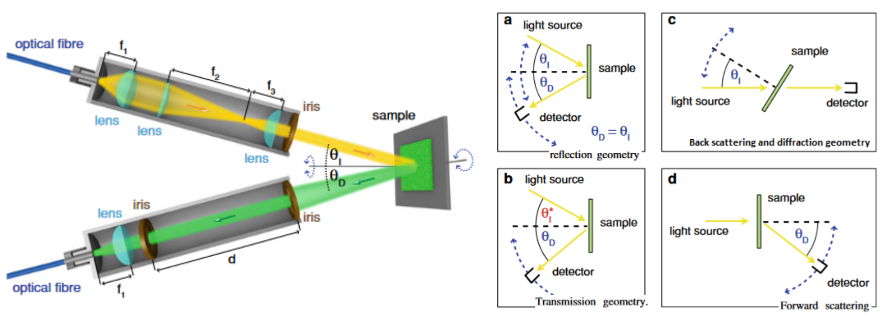


Fig.15 and 16. Sketch of the gonio-spectroscope and the configuration to obtain different spectral data respectively. The sample can be rotated perpendicularly to the plane of incidence to adjust the light incidence angle θ_I. Independently the detector is rotated to vary the detection angle θ_D. In addition, the sample can be rotated around its normal to allow interrogation of its orientation-dependent optical anisotropies

- ***Applications of 2D Photonic Crystals***

- Complete Band Gap and Photonic insulators

2D PhC has several interesting optical properties that can be used in many areas of research and practical life. An interesting application of 2D PhC in contrast to 1D PhC is the existence of a complete band gap in certain 2D structures. In general, our band gap changes with the incident angle and the polarisation nature of light. So the same frequency blocked in a p-polarised light (TM wave) can exist in the crystal if the incident light is s-polarised. High symmetry plot of a conventional hexagonal 2D PhC is given in Fig. 17. We can see that there is no actual photonic band gap common for both TE and TM waves although TE waves individually possesses a band gap. So, this is a PhC with an incomplete band gap. A PhC that blocks certain frequency of light for all polarisation and angle of incidence is termed as a PhC with complete band gap. This acts as a true photonic insulator for these forbidden frequencies.

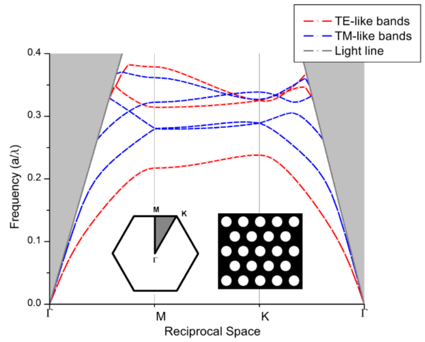


Fig. 17. Dispersion curve for a 2D Hexagonal PhC with Si-substrate and air holes (thickness d = 0.75a, radius r = 0.30 *a*, ϵ_r= 12.605)

A complete band gap photonic crystal can be easily achieved in 3D PhC. But it is usually hard to fabricate them. Alternatively, this property of a complete band gap PhC is achieved using 2D PhC by designing crystals with elliptical holes instead of circular ones. Min Qiu and Sailing He[12] have shown an optimised elliptical holes fabricated in a Ga-As substrate that shows a complete band gap for all polarisation of light.

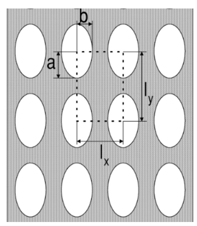


Fig.18 A 2D periodic rectangular array of elliptic air holes in a background material

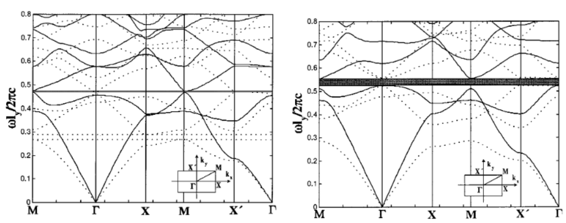


Fig 19 and 20. The band structure with the optimal complete photonic band gap for circular and elliptic air holes respectively in Ga-As material. The solid curves are for the H polarization, and the dotted curves are for the E polarization. The complete band gap is indicated by the shaded area[13]

- Wave guides and wave resonators

Another interesting application of fabricated 2D PhC is the ability to guide, trap and emit photons by creating resonant cavities as a line defect or point defect to our symmetric lattice. Fig. 21 shows a wave guide made by creating a line defect in our 2D PhC. The light travels along this light defect and propagates with no or very little loss as the eigen mode is resonant in the defect sites. A simulation of light propagating in a line defect is shown in Fig. 22.

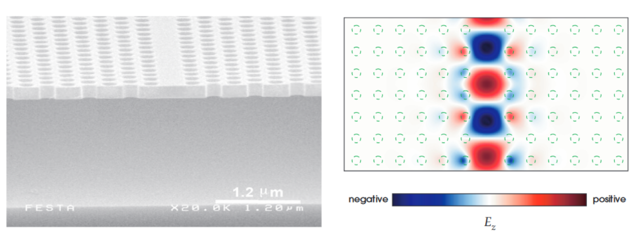
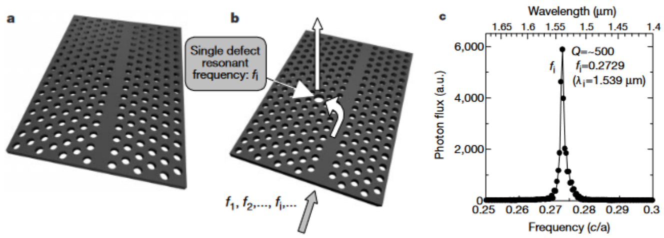


Fig. 21and 22.SEM image of a waveguide formed by a missing row of holes in a suspended-membrane hole slab (Sugimoto et al., 2004). (Image courtesy K. Asakawa). Electric-field (E_z) pattern associated with a linear defect formed by removing a column of rods from an otherwise-perfect square lattice of rods in air acting as a waveguide mode propagating along the defect[14].

Wave resonators can be achieved by introducing point defects near these wave guides. A light of a specific frequency resonates in this defect site as an eigenmode and gets trapped there. High selectivity of frequency in the resonant cavity can be obtained by changing the dimensions of the point defect. Fig. 23 and 24 shows the experimentally fabricated resonant site with a sharp frequency selectivity to exist there.



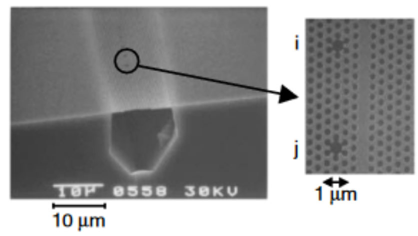
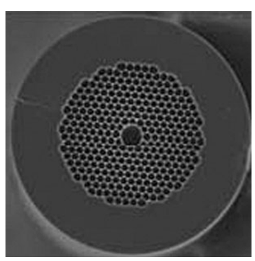


Fig.23 (a,b,c) and 24. Trapping and emission of photons by a single defect in a photonic bandgap, and the experimentally fabricated crystal of the same. a- Two-dimensional triangular lattice slab used as the base PBG structure. Line-shaped defects are introduced to form a straight waveguide. b- A single defect formed at the vicinity of the waveguide with resonant frequency f= 0.2729(c/a) (that is, 1.539 μm for a = 0.42 μm). c- Calculated photon flux trapped from the waveguide and emitted to free space by the single defect.[15]

If we need to transport these light waves to long distances not possible using a wave guide in a substrate then that can also be achieved on the same principles as above using Photonic crystal fibres (PCF). These fibres are made using silica or glass with pores arranged around a hollow core as shown in Fig. 25. The hollow core acts as a resonance site and confines the propagating light within itself. Large scale manufacturing of such crystals is easy and also commercially possible. This is done by stacking tubes of glass (with mm dimensions) in the desired pattern and then stretching it slowly after exposing it to heat and drawing it like a bubble gum. This is possible for glass because it is an amorphous material. After drawing it uniformly and reducing it to micrometer size, it is wound into coils and we can fabricate PCF as long as a few kilometers in just a single stacking.



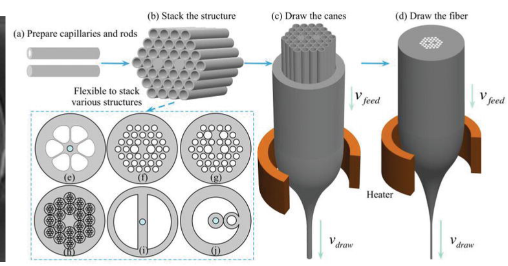
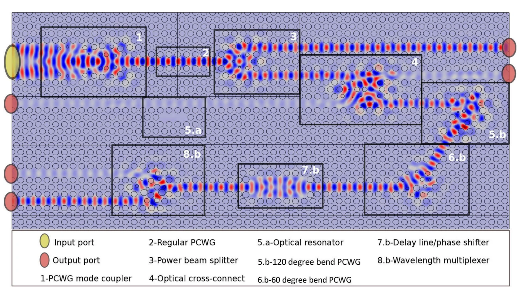


Fig.25 and 26. A silica PCF with air filled holes and a schematic of how nanoscale PCF are made by a drawing process. Courtesy- Thorlabs.

All these materials and components made using PhC can be integrated into what is called an Optical Circuit. These circuits work just like electronic circuits only using light!



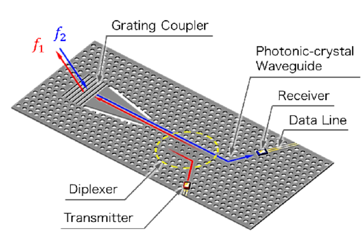


Fig. 27 and 28. (Left) A Ph Circuit with standard components in guiding, changing the direction, multiplexing, deplexing of light. (Right) A Ph circuit to split the input light into two frequencies and send (or receive) it to different receivers using resonant cavities.

This form of processing data is proven to be a lot more power efficient and faster than its electronic analogues. These optical circuits also find lots of applications in experimental quantum computations. Companies have started to manufacture photonic circuits that can solve linear algebra algorithms significantly fast. However, this is still an evolving field and we still haven't optimised the design of circuits by efficiently integrating all components into one chip. Therefore, improvements such as creating in-built electrically pumped lasers using doped semi conductors instead of an external light source, managing the heating effects of these chips in the nano-scale by liquid crystals, etc are being done one step at a time to achieve a fully functional photonic chip that will be available one day for people to buy and use in their computers!

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