B. TECH. PROJECT REPORT

On

Experimental realization of 2D photonic crystals with Aluminium Anodization

BY

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DEPARTMENT OF ELECTRICAL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY INDORE

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Experimental realization of 2D photonic crystals with Aluminium Anodization

A PROJECT REPORT

Submitted in partial fulfilment of the requirements for the award of the degrees

of

BACHELOR OF TECHNOLOGY

In

ELECTRICAL ENGINEERING

Submitted by:

Ajay pippal

Guided by:

Dr. Mukesh Kumar

INDIAN INSTITUTE OF TECHNOLOGY INDORE

December 2018

CANDIDATE'S DECLARATION

I hereby declare that the project entitled **"Experimental realization of 2D photonic crystals with Aluminium Anodization"** submitted in partial fulfilment for the award of the degree of Bachelor of Technology in 'Electrical Engineering' completed under the supervision of **Dr. Mukesh Kumar, Associate professor and department of Electrical Engineering,** IIT Indore is an authentic work.

Further, I declare that I have not submitted this work for the award of any other degree elsewhere.

Ajay Pippal

CERTIFICATE by BTP Guide(s)

It is certified that the above statement made by the students is correct to the best of my knowledge.

Dr. Mukesh Kumar (Associate Professor)

<u>Preface</u>

This project report on "**Experimental realization of 2D photonic crystals with Aluminium Anodization"** is prepared under the guidance of **Dr. Mukesh Kumar**.

In this report we have discussed photonic crystal and how can we use this as the platform to fabricate integrated photonic circuits and can also be used in optoelectronics communications as well.

I have tried to the best of my abilities and knowledge to explain the content in a lucid manner. I have added photographs and experimental results to make it more illustrative.

Ajay Pippal

B.Tech. IV Year

Department of Electrical Engineering

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<u>Acknowledgements</u>

I wish to thank **Dr. Mukesh Kumar** for his kind support and valuable guidance. This work has been done in the framework of the IIT Indore project. We would like to acknowledge **Vishal Kaushik, Swati Rajput, Sourabh Jain, Sulabh Srivastava, Lalit Jain, & Surbhi Tidke for** providing their sincere cooperation and guidance to carry out this research. Without their support, this report would not have been possible.

I had a great experience during the project. I got familiar with the branch "Integrated Photonics", and it's several applications in nanophotonic technology and optical communication.

Ajay Pippal

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Abstract

Photonic Crystals (PC) have received continued attention of researchers owing to their distinctive properties with applications in the fields of optical communication, integrated photonic circuits, bio sensing etc. Their fabrication however remains a major challenge, on one hand conventional techniques like Electron Beam Lithography are costly and unsuitable for batch processing, wet chemical methods like Sol-gel on the other hand being cost effective suffers from low refractive index of the polymers. AAO with their ability to create ordered porous structures on alumina are suitable for large area fabrication and can be considered as an attractive alternative to e-beam lithography. AAO films with high density of pores have been fabricated and successfully examined to show optical bandgap similar to the one fabricated by conventional (E-Beam Lithography). Photonic crystal fabricated via Aluminium Anodization can be used to have applications spanning the areas in optical fibre communication, interconnections and bio-chemical sensors etc.

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Chapter 1: Introduction to Photonic crystals

1.1) Introduction

Photonic crystals are the materials patterned with a periodicity in dielectric constant. This periodicity in dielectric constant [1] creates a range of frequencies called A Band Gap [2]. Photons with energy lying in the bandgap cannot propagate through the medium. This provides us the opportunity to shape and mould the flow of light for photonic information technology. Photonic crystal is a new type of optical material in which the refractive index changes periodically. These are periodically structured electromagnetic media, generally possessing Photonic Band Gaps. Photonic Band Gap: Ranges of frequency in which light cannot propagate [3] through the structure. A photonic crystal is a Periodic Optical nanostructure that affects the motion of photons in much the same way that ionic lattices affects electrons in solids. There are artificially multidimensional periodic [4] structures with a period of the order of optical wavelength. Photonic crystal can be made artificially or they can be found in the nature also. In recent years, 2D (PhCs) composed of air holes drilled in a dielectric slab as shown in fir 3(b), and structured in a triangular lattice as shown in fir 3(a), are most commonly used due to fabrication difficulty of other types of photonic crystals (3D). The OPAL in some bracelet contains a natural periodic microstructure responsible for its iridescent colour. It is essentially a natural photonic crystal. The study of photonic crystals is likewise governed by the BlochFloquet theorem [5]. He intentionally introduced defects in the crystal (analogous to electronic dopants) give rise to localized electromagnetic states: linear waveguides and point like cavities.

1.2) Integrated Photonics

Integrated photonics plays a big role in the field of optical communication and optical devices fabrication platform. Devices like waveguides [6], routers [7], couplers [8] and photodetectors are being fabricated with this branch of technology. Photonic crystal gives us the platform to have lots of applications based on its properties. This branch is analogous with the electronic semiconductor technology. Semiconductor technology provides platforms which arises lot of applications similarly photonic crystal also posses' same properties which also produces many applications. The new type of optical material i.e. Photonic Crystal possesses various properties which can be commercially used for various applications like photonic integrated circuits.

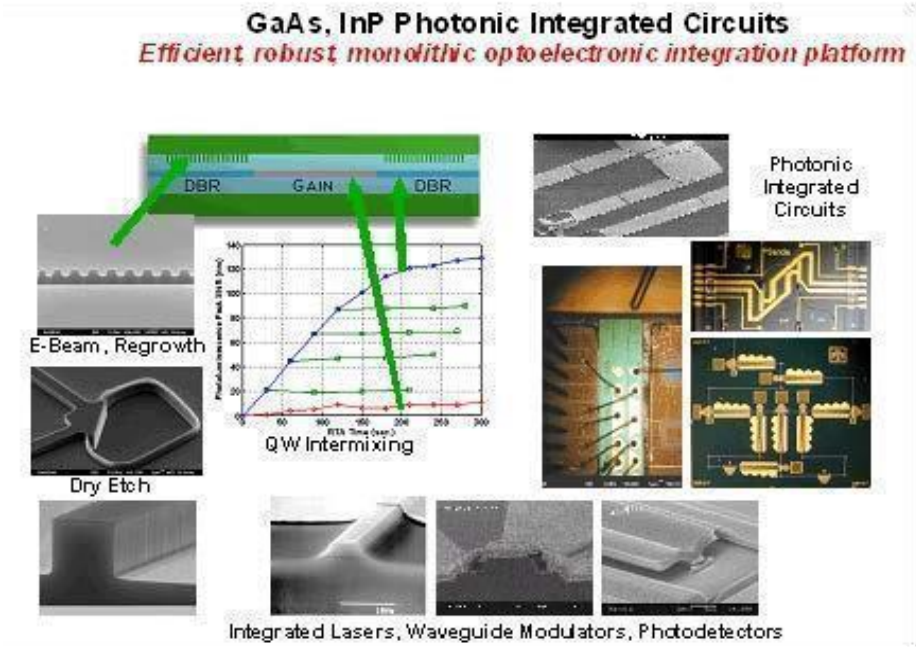


Figure 1: Integrated Photonic circuits.

Source: www.circuitstoday.com

1.3) Comparison to electronic integration

Photonic crystal technology gives us opportunities to integrate optical devices on optical chip based on the properties of photonic crystal. Photonic Integration analogous to electronic integration, there is only the difference of material being used to fabricated Photonic ICs. In electronic integration technology commercially used material are silicon and germanium etc. while in optical communication InP [9] material is widely used. Optical integration produces less wasted energy and less tolerance as compare to electronic integration, due to which it attracts to fabricated optical ICs instead of electronic ICs. Photonic Crystal produces diverse properties which are widely used in optical integration. It produces a photonic band gap similar to semiconductors [10] devices to generating, creating and moulding the flow of light at very small scale, which leads to various interesting platforms.

Chapter 2: Photonic crystal technology

Photonic crystal is a new type of optical material in which the refractive index changes periodically. PhCs are the materials patterned with a periodicity [11] in dielectric constant. This periodicity in dielectric constant creates a range of frequencies called A Band Gap. Photons with energy lying in the bandgap cannot propagate through the medium. This provides us with the opportunity to Shape and Mould the flow of light for photonic information technology [12].

The periodicity in the photonic crystals creates a range of frequencies (known as A Photonic Band Gap) through which the light cannot propagate. Thus**,** the band gap obtained due to the periodicity in the PhCs gives us opportunities to Shape, mould and manipulate the flow of light for photonic information technology. For over fifteen years it has been known that photonic crystals (PCs) can possess a full photonic bandgap (PBG) and can be used to confine and guide light in ultra-small defects such as waveguides, bends and high-Q micro resonators. Moreover, the band structure of PCs can be engineered, enabling wavelength sensitive signal routers and dispersion compensators for WDM applications [13]. Furthermore, the analogy often made between PBG and semiconductor materials, the fundamental platform of the highly successful microelectronics industry, has reinforced the expectation that PCs may offer a compelling platform for photonic integrated circuits (PICs).

Commercial viability of an integrated optical platform requires a market need and technology able to meet required specifications, before factors such as price, novel functionality, and footprint are considered. Mature telecommunication [14] networks have evolved with, and become reliant on, best-of-breed devices offering unprecedented performance. As such, an integrated platform that cannot match the performance of an equivalent system comprised of best-of-breed devices is unlikely to be adopted. We focus on the ability of planar PC technology to meet the performance requirements of telecommunication networks as a necessary, but not sufficient, condition for its commercial viability.

2.1) Type of photonic crystal

There are basically three types of photonic crystal on the basis of their periodicity.

- 1D: Periodicity in one direction.

- 2D: Periodicity in two directions.
- 3D: Periodicity in three directions.

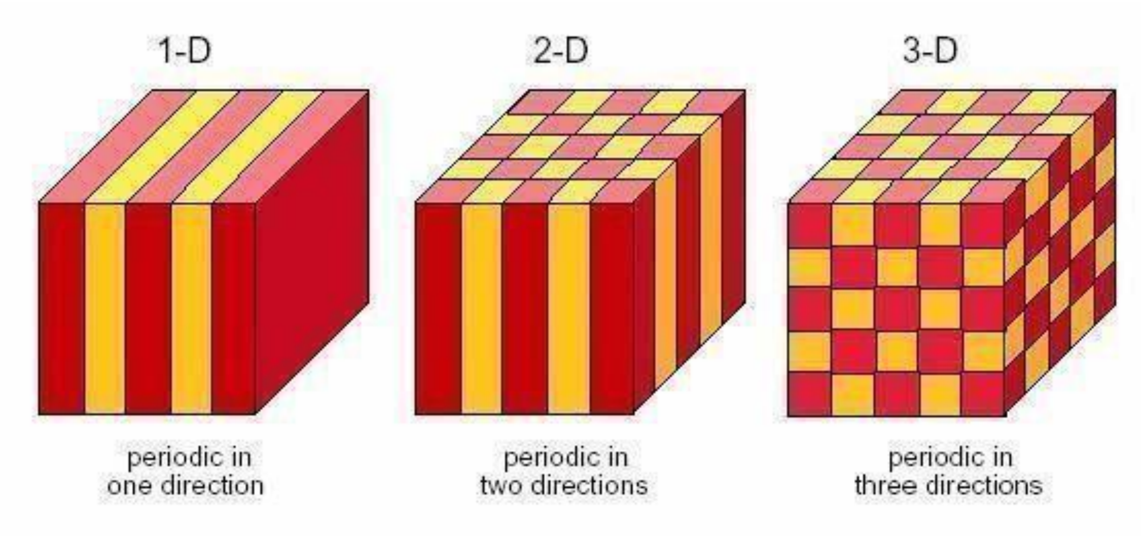


Figure 2: Different types of photonic crystal.

Source: http://emt-photoniccrystal.blogspot.com

2.2) Two-dimensional Photonic Crystals

On the basis of periodicity photonic crystal [15] are classified in three different categories. Here, in my work I have fabricated a 2-D photonic crystal via aluminium anodization and characterized its optical properties.

2D (PhCs) composed of air holes drilled in a dielectric slab as shown in figure 3(b), and structured in a triangular lattice as shown in figure 3(a), are most commonly used due to fabrication difficulty of other types of photonic crystals (3D). An ideal 2D PhC is periodic in two directions and homogeneous in the third. The crystal can have band gaps in x-y direction. We can obtain a 2D photonic crystal via Aluminium Anodization [16] as shown in the fig below figure 3(b).

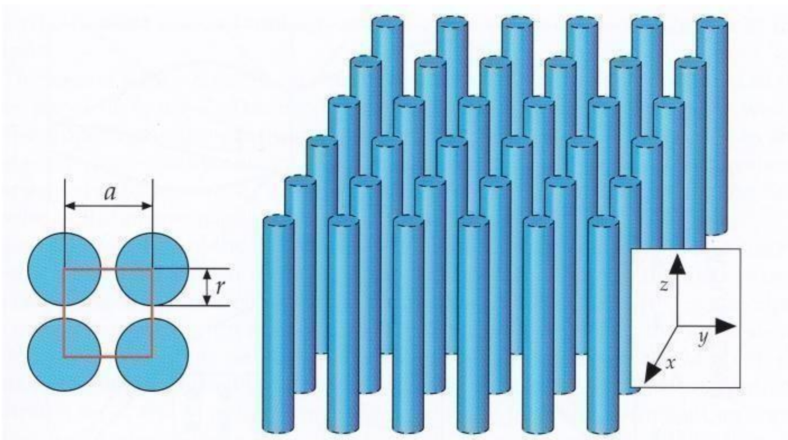


Figure 3: (a) 2-D Photonic crystal (High refractive index rods in air)

Source*: www.iap.unijena.de*

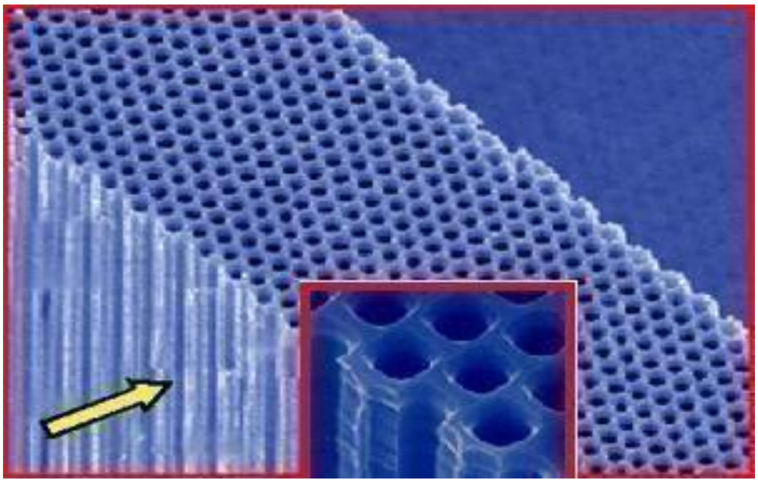


Figure 3: (b) 2-D Photonic crystal (Nanopores in high refractive index slab)

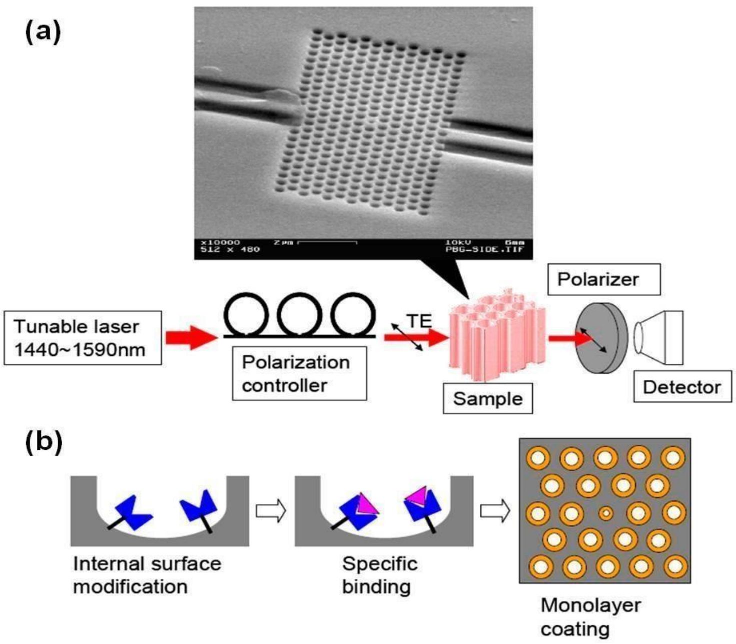
Source: http://www-old.mpi-halle.mpg.deour

Chapter 3: Applications of Photonic Crystals

Photonic crystal technology raised rapidly in the field of optical communication, integrated photonic, In designing nanoscale devices like waveguide, couplers, routers and bio sensing applications as well. Due to diverse properties of photonic crystal it leads us to have the following applications.

3.1) Applications of photonic crystals in refractive index sensing

There have been quite a few demonstrations utilizing PhCs in sensing applications. One of the leading approaches is the use of a 2D PhC cavity. In the work of Lee et al. 73, they demonstrated an ultrasensitive two-dimensional PhC micro-cavity biosensor as shown in figure 4. Coating the surface of the device with proteins of different concentrations resulted in a unique resonance red shift. The experimental results were in good agreement with theoretical computations and with ellipsometry measurements performed on a flat oxidized silicon wafer surface.



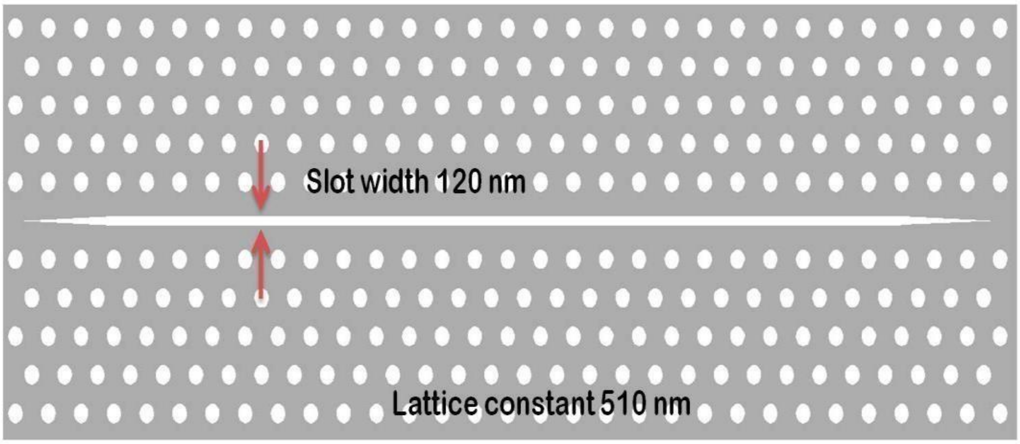
Source: *infoscience.epfl.ch*

Figure 4: (a) SEM image of the sensing PhC device and the experimental setup. (b) Schematic of bio-molecule recognition

3.2) Air slot waveguide and air slot cavity

In most of the cases, the major proportion of the cavity mode energy is confined inside the medium with high dielectric constant such as Silicon. This strongly limits the sensitivity of the sensing application. In contrast to this, the air slot PhC cavity has a large percentage of the cavity mode confined inside the air slot. This cavity mode is highly sensitive to the refractive index changes in the cladding layer. Therefore, air slot PhC cavity is highly interesting for refractive index and biosensing applications. We develop a new type of silicon air-slot PhC cavity for optical refractive index sensing.

The air slot PhC cavity was inspired by the air slot waveguide (as shown in figure 5) The first air slot waveguide was theoretically proposed and experimentally demonstrated by Lipson *et al.* in 2004. They showed that by use of such a structure the field could be confined within a 50 nm wide low-index region with ultra-high intensities.



Source: *infoscience.epfl.ch*

Figure 5: Schematic drawing of a PhC slot waveguide.

3.3) In deigning nanoscale devices: *Waveguides*, *Couplers*, and Routers

There are lots of application of photonic crystal that are being used in different areas like in integrated photonics, bio-sensing and optical communication. The application of PhC allows us to design ***waveguides***, ***couplers***, and ***routers*** on a much smaller scale as shown in figure 6. It is also widely spreading in the field of telecommunications.

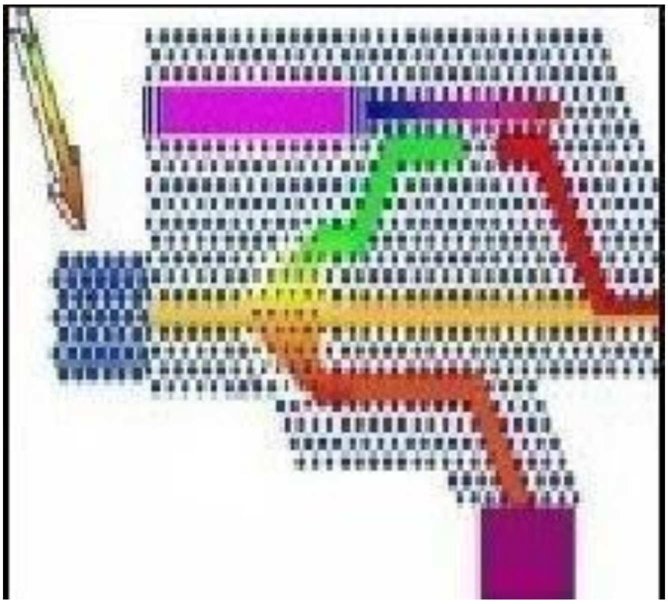


Figure 6: PhC as Waveguide, Couplers and Routers

Source: www.slideshare.net

3.4) Photonic crystal fibre

Photonic crystal fibre (PCF) (as shown in figure 7) is a new type of optical fibre which obtains its waveguide properties from a periodic arrangement of tiny and closely spaced variations of the refraction index which go along the whole length of the fibre.

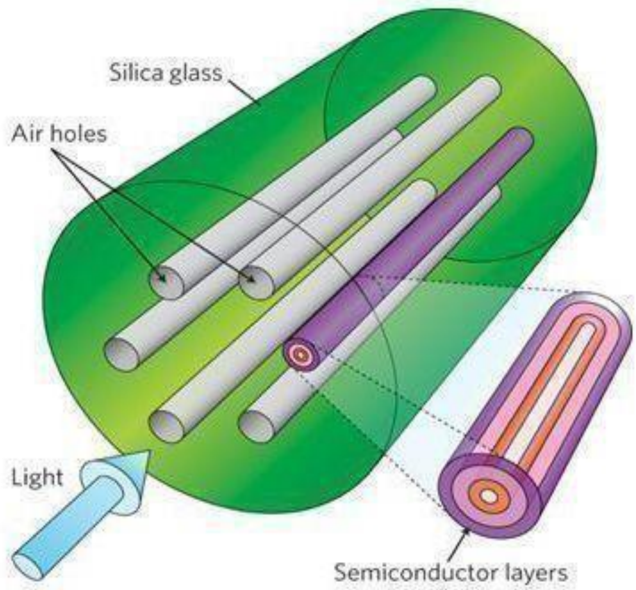


Figure 7: Photonic crystal fibre

Source: www.slideplayer.com

Chapter 4: Objective & Motivation

The concept of photonic crystal plays important role in application areas like optical fibre communication, interconnection and biochemical sensors etc. It also attracts researcher's attention to fabricated nanoscale devices like waveguides, routers, couplers and photo detector as well. Though a 2-D photonic crystal fabrication is done by E-beam lithography which is quite expensive. But few years ago, it was very challenging to fabricate a 2-D photonic crystal with some cheap and economically effective method before coming the Aluminium Anodization process into existence to fabricate a photonic crystal with same feature as E-beam lithography does. This fascinating technique motivates us to fabricate a 2-D photonic crystal. Following are the objectives of my work.

- Fabrication (Synthesising a 2-D PhC)
- Optimization (PhC with different pore size)
- Optical characterisation (Scattering of broadband source light through PhC)

4.1) Anodization Process

Aluminium Anodization process is an electrochemical process which is used to fabricated 2-D photonic crystal as similar as the e-beam process does, this process is a very cheap method and economically a very good choice too. It gives very compatible result with e-beam. Aluminium (Al) is ideally suitable for this process.

Features

Photonic crystal has some salient features like high reflective index contrast, It is the very peculiar property of PhCs that the refractive index of PhCs varies at a different place of the point. Periodicity (Lattice distance) on the scale region of visible to IR, the scale region of periodicity falls in the region of the visible spectrum and near infra-red region. Highly ordered, The PhC obtained via aluminium anodization is highly ordered in period and Uniformity in nanopores. Thickness, it can be controlled with anodization time. Period obtained via aluminium anodization 30 - 300 nm can be obtained for different Voltage.

4.2) Flow chart: Anodization Process

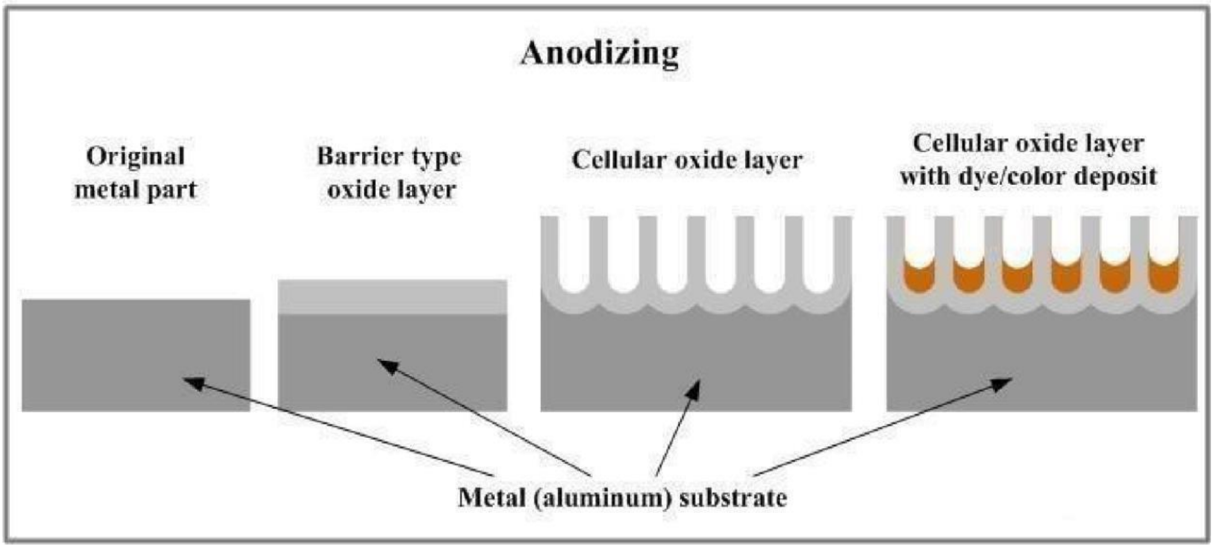


Figure 8: Steps of Aluminium Anodization *Source: www.anodizing.org*

4.3) Experimental procedure and parameters

These are the following steps that need to follow during the experiment.

1. Electropolishing: This is the first step of aluminium anodization in which we are smoothing the surface of Al foil by an electrochemical process. This step has to be done to remove roughness of the thin (~250 um) Al foil. The following parameters are set for this process:

- Time set: 10 min
- The voltage applied: 10 V
- Solution used: PSO4 + H2SO4 + H2O

2. First step Anodization: After, electropolishing next step i.e. Anodization is performed. We simply take two electrodes (Anode & Cathode) in this process, that is placed inside the sonicater. At anode, Al foil is connected and at cathode stainless steel is connected. Then we give DC supply. An electron starts moving from anode to cathode and the currents flow in the circuit. These are the following parameters taken during the experiment for both type of sample.

For first sample A	**For second sample B**
• Solution used: 0.3 M oxalic acid	Solution used: 0.1M Phosphoric acid

- Temp maintained: 33 °C — Temp maintained: 33 °C
- Total time: 2 hours 10 min — Total time: 1 hour
- DC Voltage supply: 38 V — DC Voltage supply: 150 V
- Pore diameter: 90 nm — Pore diameter: 220 nm
- Lattice constant: 110 nm — Lattice constant: 300 nm

3. <u>Selective etching</u>: In the first step anodization, the nanopores obtained in the aluminium slab (AAO film) are in disordered at the top of the surface and in the ordered form in the bottom of AAO film. In order to remove the disordered nanopores from the top selective etching is performed so that we can proceed to second step anodization.

4. <u>Second step anodization</u>: After first step anodization and selective etching, we get SEM images shown in Figure 10: (a) &(b) of the sample with nanopores in the film. The nanopores in the AAO film are in ordered form and now we perform the second step anodization to enhance the depth of these nanopores. The second step anodization involves stripping of anodized film obtained via Aluminium Anodization as shown in figure 8. This needs to be done to remove the disordered nanopores at the top of the surface and then the ordered film of nanopores is obtained in the bottom.

4.4) Anodization Setup

The following setup was made in the optoelectronics lab. It includes a DC source, sonicater, aluminium foil, stainless steel slab, ice cubes to step down the temp, wires chords and chemicals like phosphoric acid, oxalic acid, hydrochloric acid, sulphuric acid etc.

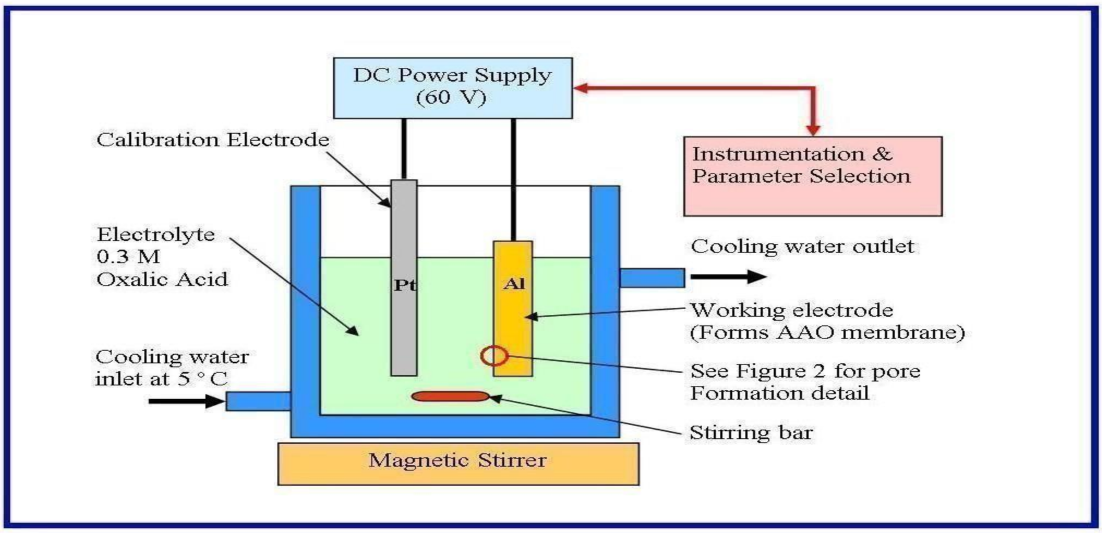


Figure 9: Experimental setup of Aluminium anodization

Source: www.article.sapub.org

There were some changes in the apparatus and the parameters taken during the experiment as shown in figure 9:

- The calibration electrode taken was of stainless steel instead of platinum.
- The DC supply was different for different types of electrolytes.
- The temp was maintained up to 33 °**C** instead of 5 °**C.**
- The whole setup was placed in sonicater.

Chapter 5: Results and Discussion

The results obtained are quite relevant. We obtained two different pore size of photonic crystals. First photonic crystal obtained with oxalic acid as an electrolyte and the other with phosphoric acid as an electrolyte. The diameters of the pores for both type of photonic crystal is 90 nm and 220 nm as shown in figure 10 (b) & (c) respectively. The period obtained for the types of the photonic crystal is 110 nm and 300 nm respectively and falls in a scale region in between visible or near infrared region (850-1650 nm). Centre wavelength for the first and second type of photonic crystal is 1180 nm and 1350 nm as shown in figure 10 (b) & (c) respectively.

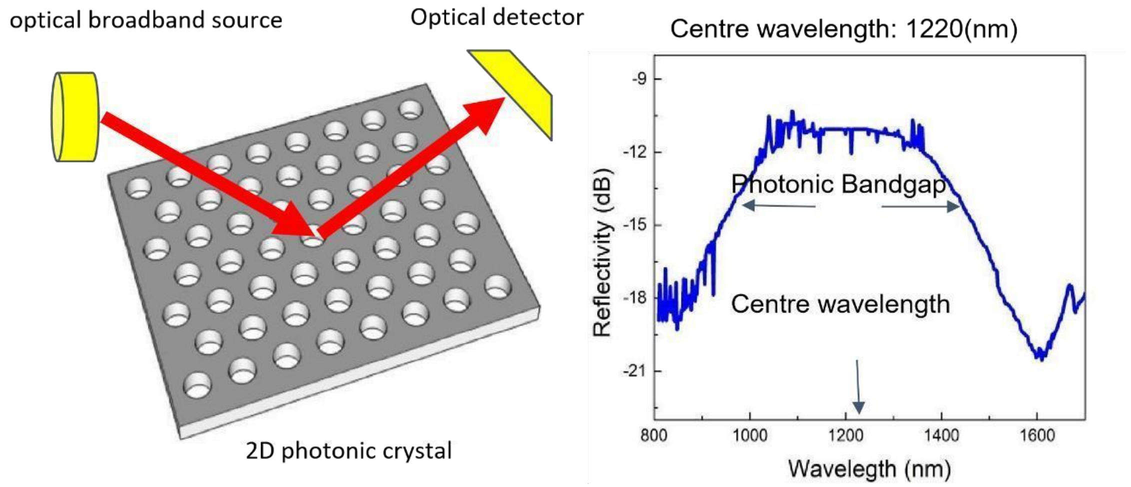


Fig 10: (a)FDTD method lumerical solution

The calculated Reflection spectrum of photonic crystal (by FDTD method, Lumerical sol.) of a Hexagonal photonic crystal with period 300 nm is shown below, whose centre wavelength is 1220 nm as shown in figure 10 (a).

5.1) Scanning Electron Microscope (SEM) image

We have obtained two different pore size photonic crystals SEM images as shown in the figure 10 (b) & (C). The pore diameter and period of PhC in figure 10 (b) are 90 and 110 nm respectively and the pore diameter and period of PhC in figure 10 (c) are 110 and 300 nm. The result obtain are found similar in terms of the properties of photonic crystal.

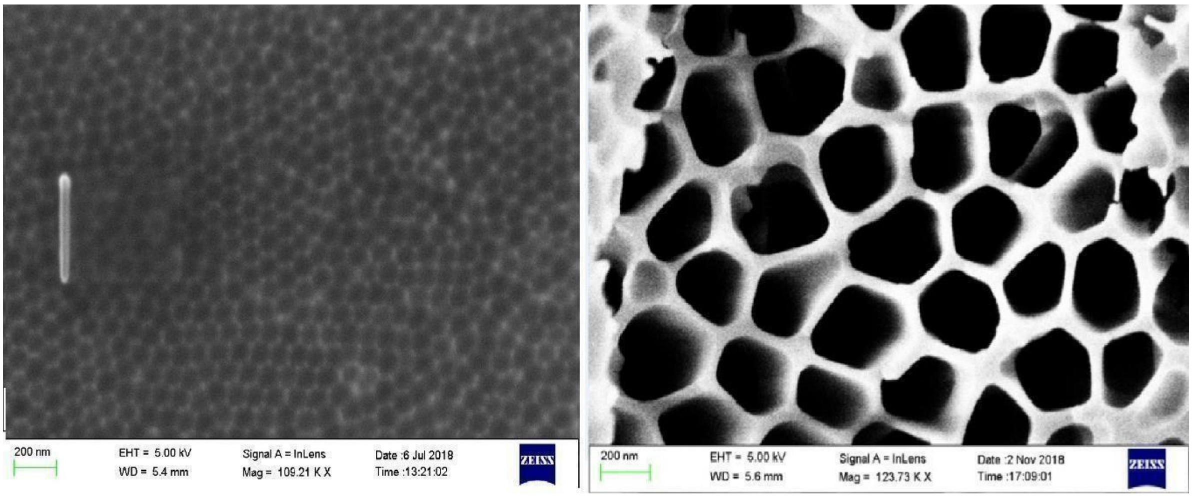


Figure 10: (b) SEM image of first sample (c) SEM image of Second sample

A close analysis of Scanning electron microscopy (SEM) images shows that photonic crystals with period 110 nm(a) and obtained for 300(b) nm are anodization voltages of 40 V and 150V respectively.

5.2) Optical characterisation (Intensity Vs Wavelength)

In optical characterisation, we study the optical behaviour of fabricated PhCs crystals. Photonic crystals fabricated via Aluminium Anodization with different pore size i.e. PhC with pore diameter 90 nm and lattice constant(period) 110 nm and other PhC with Pore diameter 220 nm and lattice constant(period) 300 nm. The optical studies reveal that the shift in centre wavelength will be more for higher lattice constant (period) PhC than the other PhC with less lattice constant(period).

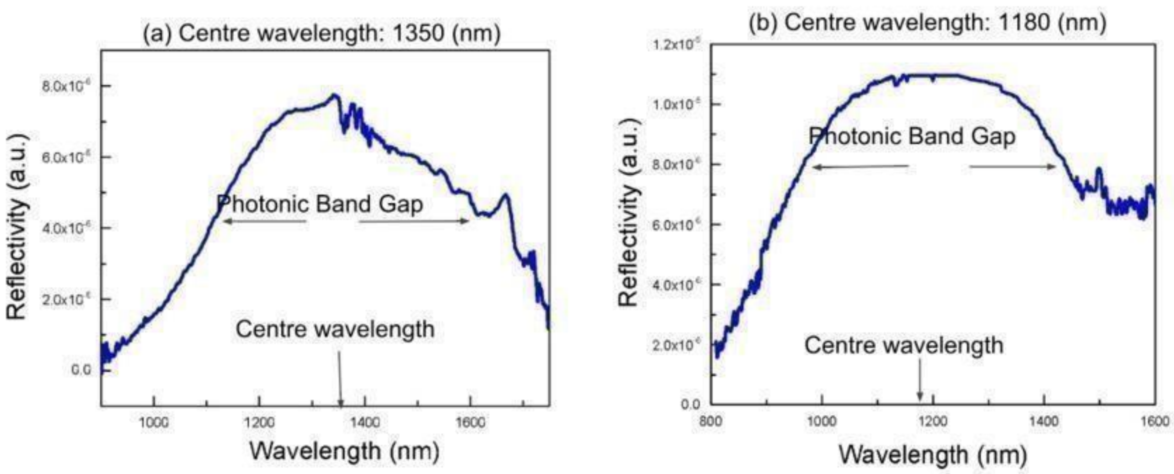


Figure 11: Reflection characteristics of 2-D photonic crystal

Figure 11 (a) & (b) shows the reflection spectrum of the fabricated Photonic Crystal.

The shift in the centre wavelength of photonic band gap corresponding to different lattice constant of the photonic crystal is apparently visible after a careful analysis of reflection characteristics of the photonic crystals.

Chapter 6: Conclusion

Highly ordered Hexagonal array of pores within AAO templates with uniform pore size were successfully prepared via the two-step anodization of Al foil under controlled anodizing conditions. The fabricated structures demonstrate a clear photonic bandgap in the IR region gap similar to the one fabricated with conventional (E-Beam Lithography) methods.

Anodization parameters influencing self-ordering Anodized:

The size of photonic crystal's nanopores are basically depends on the following parameters like Concentration of electrolyte, Voltage applied, temperature and Anodization time. In my work, I have fabricated two different pore size photonic crystal. First photonic crystal was fabricated with 0.3 M of oxalic acid, voltage applied 38 V, temperature maintained up to 38degree, anodizing time2 hour 10 min. This gives the pore size diameter of 90 nm and period of 110 nm. Second photonic crystal was fabricated with 0.1 M of Phosphoric acid, voltage applied 150 V, temperature maintained up to 38-degree, anodizing time 1 hour. This gives the pore size diameter of 220 nm and period of 300 nm. On the basis of the above result, it is concluded that the pore size of photonic crystal can be optimized with above parameters. Thus, Al can be considered as a cost-effective alternative to fabricate photonic crystal. It has various applications in integrated photonics and optical communication. The application of 2D photonic crystal is sharply heading in the field of optical communication, bio-chemical sensing devices and photonic technology.

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