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Photonic Crystal Structure

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ABSTRACT

Photonics involves the control of photons in free space or in matter. Photonics replace the electron flow with photonic flow. Photonic crystal has the ability to control the flow of light and their capacity to concentrate light. Sharp bending is observed when an electromagnetic wave enters the photonic crystal. Materials that contain photonic band gap have the potential to manipulate the light. Photonics ICs applied in the range of visible light and near infra-red light. In photonic crystals, it is possible to obtain negative refraction behavior at optical wavelength. This review introduces the concept of photonic crystals, fabrication of photonic crystal by lithography method, bending of electromagnetic wave when propagates through photonic crystal waveguide.

Keywords

Photonic Crystal, Photonic Band Gap, Transversal Magnetic, Transversal Electric.

1. INTRODUCTION

Photonics is a term derived from Greek word “photos” that means light [1]. Photonics is the generation, amplification, emission, transmission, modulation, signal processing, switching and sensing of light. Photonic Crystal (PC) consists of regions with low and high value of dielectric constant. Now-a-days, Photonic ICs are widely applied in the range of visible and near-infrared light.

1.1 The Implementation of Photonics in Various Fields

Light beams are the preferred carriers of energy and information for many applications. For example

1) Coherent light beams (lasers) have a high bandwidth and can carry far more information than radio frequency and microwave signals.
2) Lasers are used for welding, drilling, cutting of metals, fabrics and other materials.
3) Fiber optics allow light to be piped through cables [2].

2. PHOTONIC CRYSTAL

Photonic applications use the photons in the same way that the electronic applications use the electrons. Photonic crystals are based on the principle of periodic arrangement of refractive index variation and this variation controls the movement of photons through crystal. Photonic Crystals have regularly repeating regions of high and low dielectric constant. The characteristics of photons originate through structure depend on the wavelength. The wavelengths that are permit to travel through fiber are known as modes. The group of permitted modes forms a band. Disallowed modes are known as photonic band gaps. Photonic crystals are also known as Photonic Band Gap (PBG) materials. The light sources such as light bulbs or fluorescent strip lights waste 80-95% of electrical energy input. It needs to improve so better light sources are required [3]. Concept of photonics crystal is used to make efficient LEDs. Photonic crystals also improve the operating characteristics of laser diodes. Light sources travels thousand times faster than electrons, so the internet data that is transmitted through photonics can travel longer distances with in fraction of time [4].

2.1 One dimensional Photonic Crystal

One dimensional photonic crystals consist of different layers of dielectric constant deposited together to form band gap in single direction. One dimensional photonic crystal has stacks of identical parallel multilayer segments. They are used as grating that reflect wave of certain frequency [5].

2.2 Two Dimensional Photonic Crystal

Two dimensional photonic crystals include sets of parallel rods as well as sets of parallel cylindrical holes. In 2-D photonic crystals, electromagnetic waves are decoupled into polarized modes. These modes are Transversal Electric (TE) mode and Transversal Magnetic (TM) modes. For TE and TM modes, photonic band gaps occur at different frequency regions but only in selected structures. Both the modes exist at same frequency region give rise to complete photonic band gap [5].

2.3 Three Dimensional Photonic Crystal

Three dimensional photonic crystal structures consist of array of cubes, spheres or holes of various shapes. 3-D photonic crystals control the flow of photons in all three spatial dimensions. Optical properties vary periodically in three directions. In 3D structures, the diffraction and the scattering losses are unavoidable [5].

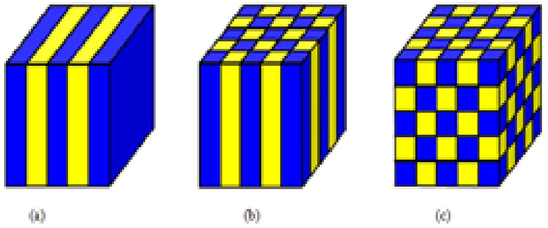

Fig 1: Photonic crystal structures in (a) one dimensional (b) two dimensional (c) three dimensional [5]

3. FABRICATION PROCESS OF PHOTONIC CRYSTAL

The photonic crystals are fabricated using layer-by-layer lithography method. Various lithographic techniques are developed for Si and GaAs to systematically build PCs one layer at a time. The basic idea is to etch a cross section of the PC pattern onto a substrate, backfill the etched holes with SiO_2, then deposit another layer of substrate. This process is repeated for each desired cross section of the PC pattern. After a sufficient number of layers, a minimum of 10 in order to exhibit the desired band gap, the silica is dissolved, leaving a photonic crystal that can have a PBG close to the visible regime. The etching itself is accomplished through e-beam lithography. E-beam lithography uses a focused beam of electrons to drill holes in a given substrate. In this process each hole must be drilled sequentially [6]

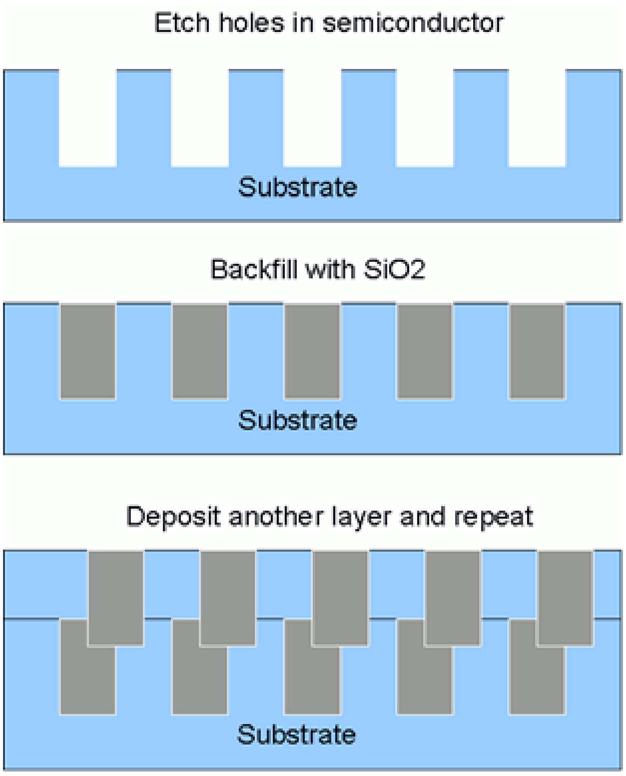

Fig 2: Layer-by-layer lithography technique [6].

4. BRAGG'S REFLECTION IN PHOTONIC CRYSTAL

Photonic crystal consists of two dielectric arranged alternately. Consider a case of light flow into one dimensional photonic crystal. A and B indicates two dielectrics to construct one dimensional photonic crystal as shown in fig 3. The thickness and refractive indices of dielectrics is a, b and n_1, n_2 respectively [6]. The two dielectrics are assumed to be loss-less within the operational frequency range, so the light beam reaching the internal interfaces undergoes only reflection and transmission without any absorption and scattering. As light energy goes off with each reflection, the eventual light energy that goes out the whole crystal will attenuate to be zero after infinite layers. That means that light could be totally reflected after infinite periodic units. Actually, the total reflection can be realized within finite layers if the frequency of light is right in certain band-gap.

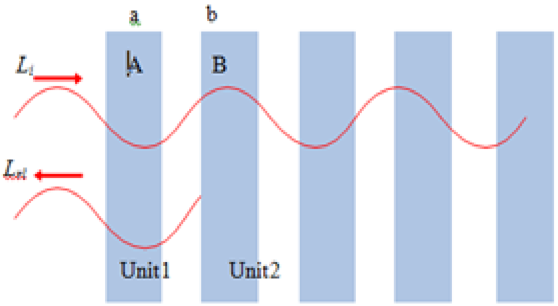

Fig 3: Light flow in one dimensional photonic crystal [7]

When the incident light L_i with wavelength λ propagates into one dimensional photonic crystal, it will be reflected at the interface between the first two units and there comes the reflect light L_{r1}. The difference of optical path between the incident light L_i and the reflect light L_{r1} is expressed as [6]

$$d=2(n_1 \times a + n_2 \times b) \qquad (1)$$

If the optical path difference d satisfies the condition

$$d= 2(n_1 \times a + n_2 \times b) = m\lambda \qquad m=1, 2, 3..... \qquad (2)$$

L_i will superpose with L_{r1} and produce a standing wave, the other reflect lights L_{ri} also join in the standing wave. Then the incident light L_i with wavelength λ is totally reflected, namely the Bragg reflection and forbidden transmitting through the crystal [6].

The central wavelength λ_c of the band-gap is decided by the refractive index, dimension parameters and crystal lattice constant (l). With dimensionless parameters n_1/n_2, a/b and the crystal lattice constant of the photonic crystals central wavelength can be expressed as

$$\lambda_c = 2\left(\frac{n_1 \times a + n_2 \times b}{m}\right) = 2\, n_2 \frac{l}{1+\frac{a}{b}} \left(\frac{n_1}{n_2} \times \frac{a}{b} + 1\right)\frac{1}{m} \qquad (3)$$

where l = a + b and m=1, 2, 3.......

5. PHOTONIC CRYSTAL WAVEGUIDE

Two main designs are commonly used to guide electromagnetic waves along a line viz. metallic pipe waveguides and dielectric waveguides for infrared and visible light. The former waveguides provide lossless transmission only for microwaves, while the later one has large losses at the corners. Through a line defect i.e. a waveguide introduces into a photonic crystal which has a photonic band gap, one can guide light (whose frequencies are within the photonic band gap) from one location to another. Both theoretical simulations and experimental studies have shown that the transmission losses in a PC waveguide are very low for a wide range of frequencies and vanish for specific frequencies, even through a 90 degree sharp bend. Fig 4 shows the electric field pattern when an electromagnetic wave propagates through a photonic crystal waveguide sharp bend with essentially a 100% transmission [8]. For metallic photonic crystal waveguides, studies also show that 85% transmission efficiency can be achieved even through a 90 degree sharp bend [9].

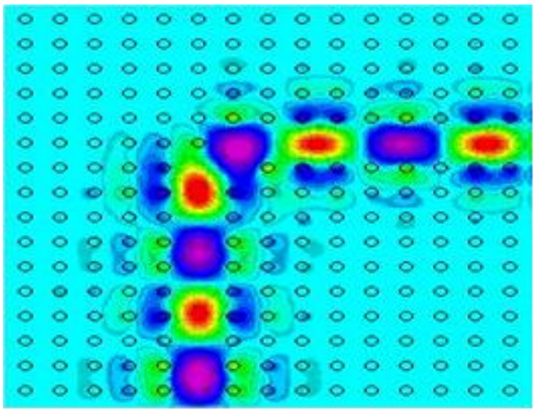

Fig 4: Sharp bends when an electromagnetic wave propagates through photonic crystal [7]

6. NEGATIVE REFRACTION IN PHOTONICS CRYSTAL

Negative refraction occurs in materials which have simultaneous negative permittivity (ε) and permeability (μ). Materials that can bend light in the opposite direction to normal also called left hand materials reverse the way in which refraction usually works, this negative refractive index is due to simultaneously negative permeability and permittivity. A negative refractive index implies that the phase of a wave will be negative rather than positive.

For an electromagnetic wave refractive index can be determined and has a negative value over some frequency range. In photonic crystals, it is possible to obtain negative refraction behavior at optical wavelengths i.e. a refracted beam going to the wrong direction compared to the direction expected on the base of the classical refraction laws. Left-handed media with negative refractive indices result in light focusing characteristics that are different from those of conventional positive refractive optical components [10].

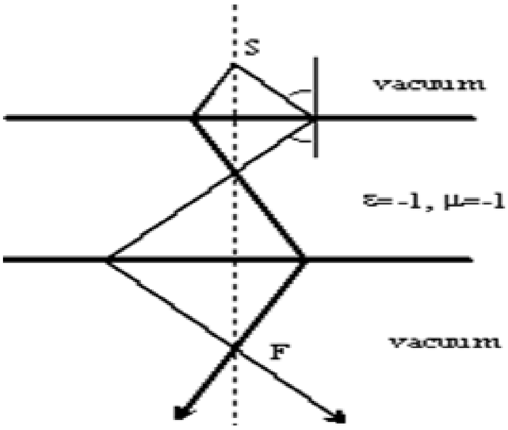

Fig 5: Negative Refraction [10]

7. SILICON AS A PHOTONIC MATERIAL

Optical fiber communication is the process of transporting data on a glass fiber using light at a very high speed. The hardware components are fabricated using materials that are expensive in nature. The goal of silicon photonics is to develop low cost, high volume optical components using standard Complementary Metal Oxide Semiconductor (CMOS) processing. The drawback of silicon is that it cannot emit laser light. Lasers that run optical communications made of more exotic materials such as Indium Phosphide (InP) and Gallium Arsenide (GaAs). Silicon can be used to manipulate light emitted by inexpensive lasers to provide light that has characteristics identical to more expensive devices. This is how silicon lower cost of photonics. Silicon photonic components have applications such as optical communication, optical memory, optical interconnection in computers and optoelectronic instruments [11].

8. SILICON ON INSULATOR (SOI)

SOI wafer consists of three layers viz. Silicon substrate followed by epitaxial layer of Silica (SiO_2), buffer layer which is about 1 micro meter thick and a top crystalline Si layer. In order to get single mode propagation in the top layer, the thickness of top silicon layer is normally between 200 nm to 300 nm. The high refractive index (n), contrast of different materials like silicon (nSi=3.45), silica ($nSiO_2$=1.45) and air (nair=1) is important feature of silicon on insulator technology [12, 13].

8.1 Fabrication of SOI by Separation by Implantation of Oxygen (SIMOX) Process

SOI wafer have single crystal silicon layer formed on insulator such as silicon dioxide (SiO_2). Silicon on insulator is obtained by implantation of oxygen ions, executing annealing treatment for chemical reaction between oxygen ions and silicon atoms to form oxide layers [15]. Enough oxygen needed to implement for forming silicon dioxide. For 200 KeV ion energy, thickness of 200 nm of silicon above buried oxide is obtained [16]. Very high temperature annealing is required after implantation to react oxygen ions with silicon to get silicon dioxide. SIMOX (Separation by Implantation of Oxygen) structures annealed at 13000 C. SOI wafers are obtained by bonding two single crystal silicon substrates [17, 18]. One of which is oxidized and other is not. SOI layer can be formed to a thickness of 0.3 m [14]. Silicon on Insulator technology has good characteristics including low power consumption operation and high sped operation [15].

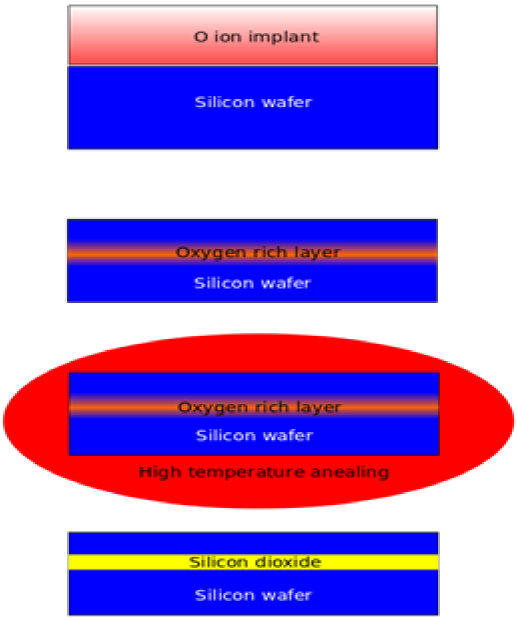

Fig 4: SIMOX Process [14]

9. CONCLUSION

Photonic technology uses photon instead of electrons to process and transfer signal and information. Light travel faster than electrons. Data that is transmitted photonically travel long distances in fraction of time. Electronics is not suitable for operation at very high frequencies or bandwidth but the optical domain is perfectly suited to operate at high frequencies. In photonics crystal, all the components e.g. waveguides, couplers and routers etc. of the optical system are fabricated in the form of a single chip. Photonic Integrated circuits make the optical system more compact as a result system performance increases. Also in metallic photonic crystal waveguide, there is 90 degree sharp bend with full transmission. In addition, silicon photonics can develop low cost, high volume optical components with standard CMOS processing.

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