Omnidirectional Reflection Characteristics of Photonic crystal

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Abstract : In this paper, we review the structure of photonic crystal, their concept, design and analysis. Beginning with analysis of 1D periodic dielectric structures and their properties followed by introduction to defect in the perfect periodicity. Then the effect of number of periods,additional materials and filling fraction is analysed. In this paper the reflection characteristics of photonic crystal is observed. Under certain condition, one dimensional dielectric lattice displays total reflection of the incident light. The thickness of the layers, the refractive indices should be carefully chosen for better reflections. This will find application in photonic reflector mirrors. The simulation results show the reflection coefficient for different cases.

***IndexTerms* - photonic crystal; band gap; lattice constant. reflection coefficient, transmission coefficient.**

I. INTRODUCTION

For many years semiconductor technology revolutionized in creating miniaturized components of electronic circuits. But light has several advantages over electron. It can travel in a dielectric material at higher speed than electron in metals. The bandwidth is large. Interference between light particle is less which reduces losses. Thus light can be used as carrier instead of electrons.

Photonic crystals are periodic structures constructed using alternating layers of high and low dielectric structures. The propagation of electromagnetic radiation in periodic media exhibits many interesting and useful phenomena. These phenomena are employed in many optical electronic devices including high reflectance mirrors, lasers, Bragg gratings and optical filter Periodic media are any optical structures whose dielectric and permeability constants, reflecting the translational symmetry are periodic functions of position. Photonic crystal consists of periodic

Nanostructure which contain regularly repeating regions of low and high refractive indices. Light propagates through this structure or not depends on the wavelength. A spectral range of large reflectivity is known as stop band. In this way light can be controlled and manipulated in any way. This finds application in LEDs and LASERs.

1.1 CONCEPT OF PHOTONIC CRYSTALS

For many years semiconductor technology revolutionized in creating miniaturized components of electronic circuits. But light has several advantages over electron. It can travel in a dielectric material at higher speed than electron in metals. The bandwidth is large. Interference between light particle is less which reduces losses. Thus light can be used as carrier instead of electrons.

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$$\varepsilon(x) = \varepsilon(x+a) \quad (1)$$
$$\mu(x) = \mu(x+a) \quad (2)$$

Where a is any arbitrary lattice vector. The equations state that the medium looks exactly the same to an observer at x as at x+a.The propagation of optical waves in a periodic medium is described by Maxwell’s equations.

$$\nabla_x H = jw\varepsilon E \quad (3)$$
$$\nabla_x E = jw\mu H \quad (4)$$

Where ω is the angular frequency of light. The equations remain the same after x+a is substituted for x in the operator ∇ and ε and μ.

$$Ex(x)=Ex(x+a) \quad (5)$$
$$Hx(x)=Hx(x+a) \quad (6)$$

This is known as Bloch theorem.

$$\omega = \omega(k)$$

In the spectral regime where K is real, optical waves can propagate in the periodic medium without loss. They can be considered the equivalent in periodic media of plane waves in the case of homogeneous media. The intensities of these waves are periodic functions of positions in the medium. There exists spectral regimes where k is a complex vector; the optical waves in this case become evanescent. These spectral regimes are photonic band gap where optical waves cannot propagate in periodic medium. Dielectric optical structures that exhibit forbidden bands are known as photonic band gap structures.

1.2 PHOTONIC BANDGAP

Photons behaving as wave do (or do not) propagate through the Photonic crystal depending upon the relation between its physical dimension and the wavelength of the propagating wave. Allowed wavelengths that propagate through the crystal form a band called photonic band. Group of wavelengths that are blocked from propagating through the crystal form a photonic band gap (PBG).

Light propagating in a high dielectric material is reflected at the interface of low dielectric material. This limits the degree of miniaturization of optical components. A periodic potential exists due to dielectric media. The property of photonic crystal is decided by the nature of the defect which alters the periodicity.

Photonic crystal acts as a mirror for a light with a frequency in the specified range. Multiple reflection and refraction occurs at each interface. The variation is only in one direction. Smaller the contrast smaller will be the gap.

Two materials with refractive index n1 with thickness d1 ,n2 with thickness d2 ; a=d1+d2

The gap is maximised when n1d2=n2d2

d1=an2/(n1+n2)

The mid gap frequency

$$\omega_m = \frac{n_1 + n_2}{4 n_1 n_2} \cdot \frac{2\pi c}{a}.$$

The corresponding wavelength 2πc/Wm satisfies the relation λm/n1=4d1 And λm/n2=4d2 which means that the individual layers are exactly quarter wavelength in thickness. For this reason, this type of multilayer film is called a quarter wave stacks. The gap is maximum for a quarter wave stacks as reflected wave s from each layer are exactly in phase at the midgap frequency.

When d1=d2=0.5a the gap is 51.9%.When d1=0.217, the structure would be a quarter wave stack with 76.6% gap. When d1=0.2a which is nearly a quarter wave stack the computed gap is 76.3%.

Electromagnetic modes are not allowed to have frequency in the gap. The wave amplitude decays exponentially into the crystal as evanescent wave. It is like a Bloch mode with complex vector. The imaginary part of the wave vector causes the exponential decay. Minimal penetration is obtained for the quarter wave stack.

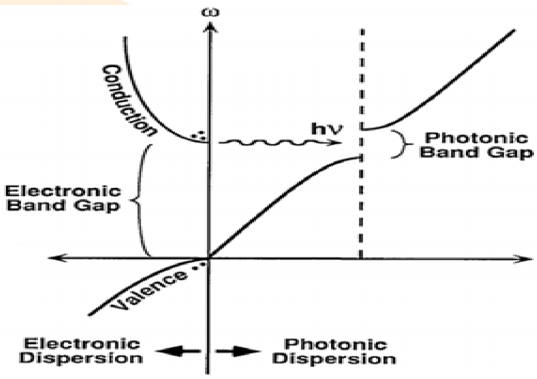

Fig 1:Photonic Bandgap

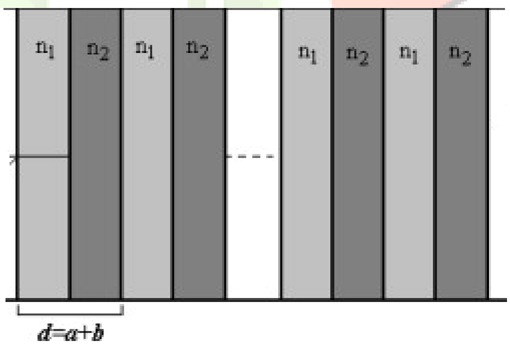

Fig 2: Alternate layers of two dielectric medium

Each of the plane reflects only a very small fraction of incident plane wave.The total scattered wave consists of a linear superposition of all these partially reflected waves. The diffracted beams are found when all these reflected waves add up constructively.[2]Let Δ be lattice constant which is the period of index variation in space. The path difference for rays reflected from two adjacent planes is 2Δ sinΘ where Θ is the angle of incidence measured from the planes.Constructive interference occurs when the path difference is an integral number of wavelength λ/n in the medium, so that

2Δ sinΘ=m(λ/n) , m=1,2,3…..

Where n is the averaged index of refraction of the periodic medium and m is an integer.Beam diffraction occurs for certain values of Θ which obeys the Braggs law so that reflections from all planes add up in phase.

2k sinΘ=m(2π/Δ) , where k is the wavenumber of the light beam in the medium k=2πn/ λ.The term 2π/Δ is known as the grating wavenumber.

Fig 2 shows schematic diagram of a periodic layered medium consisting of alternating layers of two different materials with refractive indices n1 and n2 and thicknesses a and b respectively. Δ =a+b is the period.The photonic bandgap occurs at Re[kΔ]=m π.If W0 is the centre of photonic bandgap such that k1a=k2b=π/2 A structure with this condition is known as a quarter wave stack.

When the frequency of incident wave falls in the photonic bandgap,the Bloch wave generated in the periodic medium is known as an evanescent wave which cannot propagate in the medium. The electric field amplitude decays exponentially. The power flow along the z axis is zero. Thus the energy of the incident beam will be totally reflected and the medium acts as a high reflectance mirror for the incident wave. By properly designing the periodic layered medium it is possible to achieve near unity reflectance for some selected spectral region.

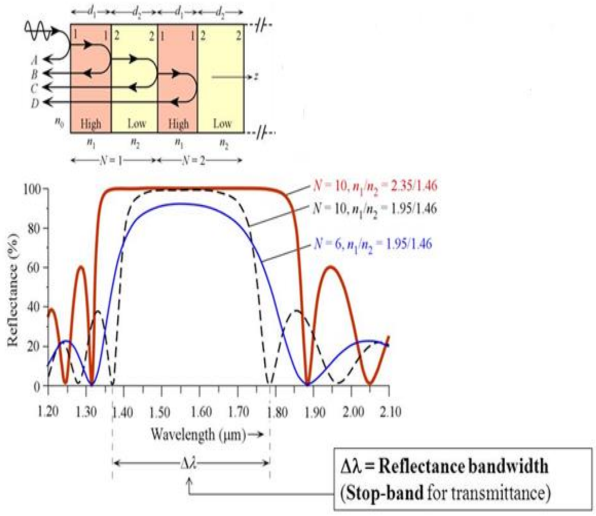

Fig 3:Reflectance Characteristics

1.3 EFFECT OF DEFECT IN THE SYSTEM

The reflectance in the photonic bandgap is near unityfor a bragg reflector with a substantial number of periods.At the centre of the bandgap each period of the layered mediumis approximately an integral multiple of half waves.In the case of quarter wave stack ,each period is an exact half wave at the centre of the photonic bandgap.The light waves will be highly reflected since successive reflections from the neighbouring periods will be in phase with one another and therefore will be constructively superimposed.Fig 3 shows 10 period Bragg Reflector and different refractive index.

For a quarter wave stack,the fundemental photonic bandgap is given by $\Delta Wgap = W0\frac{4}{\pi}\frac{n2-n1}{n2+n1}$

Where W0 is the centre of the bandgap.Stopband is proportional to the index (n2-n1). Thus a narrow band reflection filter can be obtained by using a quarter wave stack with small index difference (n2-n1).However a high reflectance at the center of the band requires a large number of periods due to the small (n2-n1).

A narrowband spectral filter is obtained by using half wave layer sandwiched between two quarter wave stacks.

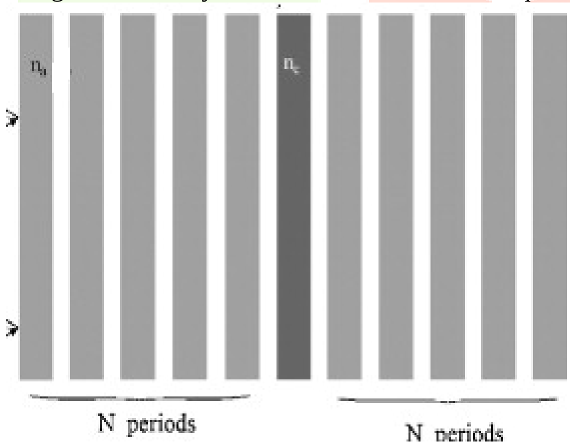

Fig4:Two stacks separated by another layer.

The structure may also be viewed as a quarter wave stack with a defect at the centre of the stack.Omnidirectional reflector is a perfect mirror for light from any direction with any polarization within a specified frequency range.In this range there are no propagating solutions of of Maxwell's equations.[3].The parameters varied are n1,n2 and a/Δ.For each value of n1 and n2/n1 there is a value of a/Δ that maximizes the range.For omnidirectional reflection the index ratio should be reasonably high(>1.5) and the indices themselves must be higher(by>1.5) than that of ambient medium.The materials should also have a long absorption length for the frequency range of interest where path length of the reflected light along the crystal surface is long.crystal.

The photonic crystal can also be designed using alternate layers of superconductor and dielectric The structure gives 100% reflection for a wide range of wavelength of the electromagnetic spectrum.

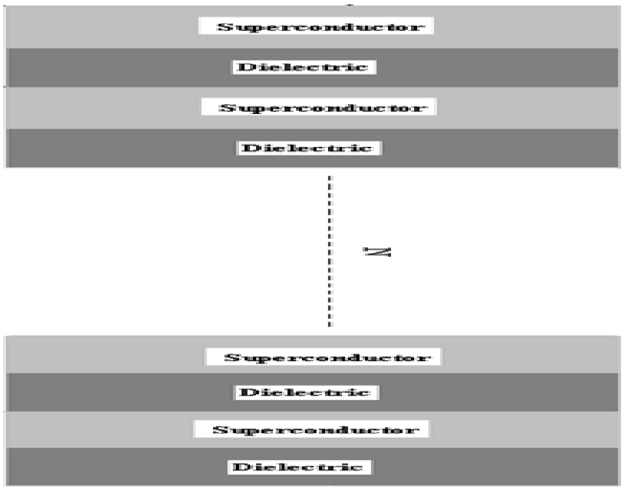

Fig 5: Schematic presentation of superconductor/ dielectric periodic structure.

When angle of incidence increases, it is observed that the range of band gaps and reflectance of the given structure increases. But the band structures and reflectance of the considered structure are shifted towards the higher frequency range. The role of dielectric constant and magnetic permeability also influence the photonic band gap.[5]. The reflection bandwidth is larger when dielectric constant is greater than magnetic permeability.

It is shown that under certain conditions a one dimensional dielectric lattice displays total omnidirectional reflection of incident light. The predictions are verified experimentally using a Na_3AlF_6/ZnSe multilayer structure developed by means of standard optical technology. The structure was found to have a reflection coefficient of more than 99% in the range of incident angles 0–86^0 at the wavelength of 632.8 nm for s-polarization [6]. a lattice consisting of 19 layers of Na3AlF6 (*n*1=1:34) and ZnSe is fabricated. The thickness of each layer was *d*1 and *d*2 is 90 nm and the period of the lattice *d*1 +*d*2is 180 nm. The following table gives commonly used dielectric material and their corresponding refractive indices.

TABLE 1

Material	Refractive Index
Air	1
Cryolite	1.3
Silicon dioxide	1.45
Titanium Oxide	2.65
Silicon	3.4
Germanium	4

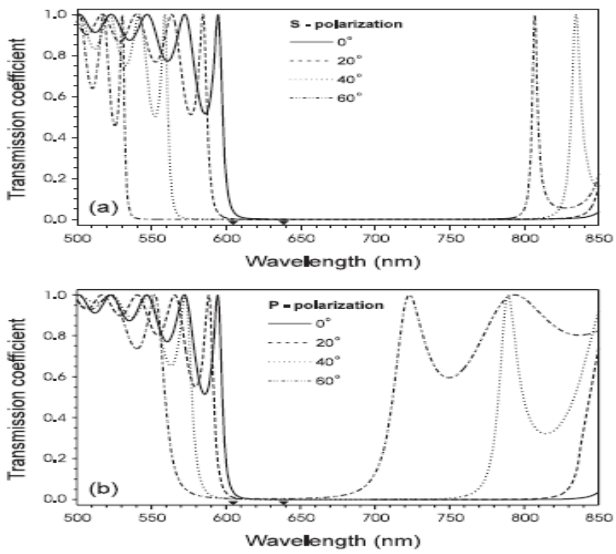

Fig 6:Transmission spectra of Na3AlF6=ZnSe 19-layer structure measured for s-polarized (a) and p-polarized (b) light at different 60^{0}dash-dotted line).

Wavelength division multiplexing devices are needed to divide and combine incident signals of different wavelength in optical integrated circuit. Graded index photonic crystals have a hyperbolic secant refractive index profile through which the incident wavelengths follow typical trajectory. Due to gradual variation of refractive index profile light is emerged at different location with different exit angles. This is used in the design of wavelength selective media to separate three to seven different wavelengths.

The photonic crystal is fabricated using photolithography process.[7] The response is changed for different lattice constant and filling fractions. An increase in the optical contrast n1/n2 where n1 and n2 are the refractive indices of the alternate layers or number of periods of regular structure is employed to extend photonic band gap range. Reflection bands can be extended by merging two or more photonic crystals. A composite photonic crystal by adding two with same lattice constant but with different filling fractions and a composite photonic crystal with different lattice constant and same filling fraction. The second photonic crystal will have a photonic band gap range covering the regions of transmission between the photonic band gaps of first.

The dielectric based photonic crystal restrict the wide usage of materials. They have low rejection rate per layer so a large number of layers are needed for application requiring high isolation purposes .At low frequencies these crystals become impractical due to their relatively large dimensions. These problems are solved by introducing metals to photonic crystals. The metals are perfect reflectors at microwave frequencies and are superior over dielectrics only devices. Defects can be introduced to further enhance the performance.

In order to increase the photonic band gap either refractive index contrast is increased or heterostructure is used. Band gap can also be increased by adding third material along with the two in each period. This is called ternary photonic crystal. This is used to design a tunable optical filter and an optical sensing device. This also can use a metallic silver for additional benefit.[9]. If the thickness of the metal layer is increased, then it will reflect almost all waves like a purely metallic reflector.

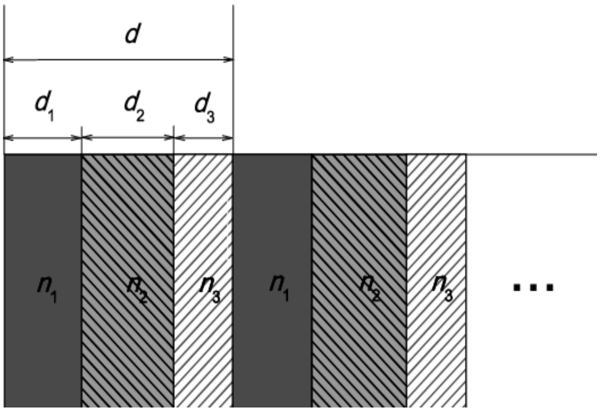

Fig 7:Ternary photonic crystal

II. ACKNOWLEDGMENT

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