Calculation for Transmittivity of One-Dimensional Photonic Crystal: A Comprehensive Review

Usmita Banerjee, Rajashee Khan, Avisek Maity, Barnisa Chottopadhyay, Arpan Deyasi, Sanjay Pal
Department of Electronics & Communication Engineering
RCC Institute of Information Technology
Kolkata, India

Abstract— In this paper, a comprehensive review work is carried out on numerical analysis for transmittivity of one-dimensional due to its immense applicability in photonic integrated circuit. Detailed literature survey is made for analyzing the tuning possibility of proposed bandpass filter by this structure for both normal and polarized incidence of electromagnetic wave. Structural parameters are also modified within the suitable range considering practical limit for study of the shift of passband around centered wavelength. Brief mathematical modeling is also presented, and a few works of the authors in this regard are added, which speaks for the importance of the present state of work. By highlighting the significant development in the field of photonic circuit through the implementation of photonic crystal, this paper aims to present the overall technical details carried out by eminent researchers in a short brief method.

Keywords- Transmittivity; One-dimensional photonic crystal; Bandpass filter; Polarized incidence; tunable bandwidth.

I. INTRODUCTION

Photonic crystal is a multilayer periodic arrangement, constructed by periodic arrangement of dielectric materials [1-3] with alternating regions of higher and lower dielectric constants where localization of propagating electromagnetic wave can be obtained by thicknesses and refractive indices of the materials. Several experimental techniques are already implemented by various workers and corresponding optical properties achieved are also reported for comparative study in a recent survey [3], and new material is proposed to enhance the spontaneous emission. This property can restrict electromagnetic wave within a certain range of wavelength allowing bandpass filter [4] characteristics in the crystal, due to the formation of photonic bandgap, may be exhibited in one, two or three dimensions. Since realization of three-dimensional microstructures are not very easy at near-infrared and optical wavelengths [5], so main focus is on 1D and 2D structures due to their possible various applications in the domain of optical communication [6-10]. Photonic crystal fibre, a revolutionary concept, has been realized due to the advancement in microelectronic technologies in the last decade, can be used in integrated photonics [11], high power technology [12], sensing [13], quantum information science [14] etc. Role of material composition plays a crucial role in the context [15-16] of designing photonic crystal fibres and other notable devices for different communication applications.

In this paper, a comprehensive review has been conducted based on the research of transmittivity using photonic multiple quantum well structure for normal and oblique incidence of p and s-polarized e.m wave considering the dependence of material parameters on material composition and operating wavelength. Mathematical modelling done by the present authors is incorporated to understand the generalized modelling approach. Works on bandpass filter characteristics are re-examined with specific attention on photonic crystals.

II. WORKS ON TRANSMITTIVITY CHARACTERISTICS

Difference in refractive indices appears as a quantum well, where multiple layers can be depicted as Photonic Multiple Quantum Well (PMQW). According to Jiang’s [17] work, quantized states are available in photonic crystal due to photonic confinement, and transmission property can be explained by resonant tunnelling. Chen [18] computed the transmission coefficient using plane-wave expansion method in combination with multiple-scattering techniques. The transmission peaks indicate that a quantized frequency relation has been satisfied through the existence of quantized photonic states. Different confined roles on the different photonic levels are proved to be played by the finite potential barrier.

Fabrication and characterization of 1D photonic MQW structures using porous Si, along with reflectance spectra are analyzed by Xu [19] at lower wavelength region and later in visible spectra [20] as well. Control of film thickness to change the resonant wavelength is essential for conventional multi-layer dielectric filters. This difficulty in fabrication of a mosaic of multiple narrow spectral band transmission filters monolithically was removed by adjusting the spectral transmission of a multi-layer dielectric filter by drilling a periodic array of subwavelength holes through the stack. Shambat [21] and other researchers modelled a photonic crystal filter as a monolithic, six-band optical filter for measuring narrow spectral bands in the optical system.

Lousse [22] analyzed polarization properties of photonic crystal slab mirror for angular incidence, and indicated reflectivity occurs over a sizable angular range for TE and TM...
mode polarizations. They were also able to show that such mirror can be designed as a polarization splitter with a complete contrast to reflect one polarization completely, while allowing cent percent of the other also. Transfer matrix technique is used by Rudziński [23] for fundamental analysis of electromagnetic wave propagation inside 1D photonic crystal for both TE and TM mode of propagation. Optical transfer matrix technique can measure the effect of refractive index of dielectric material on transmission spectra [24] for designing multi-narrow channel band filter.

The fact that a photonic bandgap quantum confined structures can be considered as a high-Q resonant cavity whose reflectivity is dependent on cavity modal frequency, was suggested by Lin [25]. Computation of Transmission coefficient [26] can be obtained considering multiple-scattering techniques which indicate its possibility for filter application. This concept is well utilized for designing quantum-well photodetector by Kalchmair [27-28]. Dhingra and other researchers showed that these MQW structures can be used in photonic integrated circuits [29]. Ming [30] calculated the effect of dimension variation of different slabs on transmission property, and also effects of the coupling between resonance photonic states. Omni-directional reflector and transmission filter are realized centered at 1.55 μm wavelength using Si/SiO₂ one-dimensional photonic crystals. Photonic band structures in the PCs with and without a defect layer have been also analyzed by researcher Lee and others [31]. The temperature dependence of the omni-directional reflection band in a 1-D photonic crystal of SiO₂/Si composition is proposed, considering thermal expansion effect and thermo-optic effect [32]. As the refractive index and thickness of both materials used in this study are modulated by temperature, the ODR band can be tuned as a function of temperature. With the increase of temperature, it is noted that the ODR band shifts towards the longer wavelength region. They have also found out that by introduction of defects in the periodic structure of the photonic crystal one can obtain localized defect mode inside the forbidden band gap. This property of the photonic crystal guides the flow of light and propagation of photons within the PCs is also manipulated. This property has applications in optoelectronics.

Aly etc. [34] analyzed the transmission spectra of dielectric photonic crystal, and comparative studies are carried out with similar type of metallic structure. They found that the reflection of EM waves through DPC’s exhibit resonance reflection very much similar to the diffraction of X-rays by crystal lattice planes. To achieve photonic band gap the system must have high contrast in the refractive index with negligible absorption of light. The metal which should be used should have large value of dielectric permittivity rather than dielectrics. For low frequency region which starts from zero frequency of the spectrum, MPC exhibit plasmonic band gap. The plasmonic band gap is followed by a first transmission band which have centre wavelength corresponding to Bragg’s condition. Pectu [35] et. al. calculated optical transmission in 1D photonic crystal which is based on the transfer matrix method. Dubey [36] calculated the confinement of light in dielectric wave guides which are bounded to small incidence angle with respect to the waveguide surface. The most important advantage of photonic crystals is the possibility of designing electromagnetic devices.

Song reported transmission and reflection characteristics of in-plane hetero-photonic crystals consisting of two serially connected photonic crystal waveguides with differing lattice constants revealing the fact that light within the common frequency range is transmitted with full efficiency through the waveguides while light is almost perfectly reflected within the gap [37]. Novel filter for reflecting or transmitting electromagnetic waves having wavelength range of approximately 100 nm to 10 cm are disclosed by R. Magnusson [38]. These filters are combination of a dielectric multilayer structure with a resonant waveguide grating and valid for both p and s polarized waves. Winnewisser calculated the spectrum of a freely propagating THz pulse with and without filter, measured by electro-optic sampling in a ZnTe crystal [39]. Wei-Hsiao Lin [40] reported Terahertz spectroscopic properties in a one-dimensional superconductor-dielectric photonic crystal. Calculated results showed that a terahertz multi-channelled transmission filter can be formed within the photonic passband. Estudillo-Ayala [41] and his co-workers found that optical driven source that generate wavelength corresponding to THz frequencies are useful for an enormous number of imaging and sensing applications. They concluded that the local field enhancement effect to efficient THz generation uses either a defect-mode or a band-edge tuning position. The peak conversion efficiency for both polarizations is increased by over two orders of magnitude. Larocheet. al. [42] also theoretically justified that a photonic crystal slab enables efficient polarization conversion in reflection.

The transmission profile of electromagnetic wave in 3-D plasma photonic crystals (PPC’s) was reported by the Finite Difference Time Domain (FDTD) method by Xu [43]. The results were represented in such way that the plasma frequency, plasma collision frequency, layer number, and ratio of radius to crystal lattice constant can influence the transmittivity in the face-centred cubic (FCC) and face-centred tetragonal (FCT) lattice woodpile structure PPC’s. Due to the unique characteristics of plasma i.e. plasma has the complex frequency dependent permittivity and being a frequency dispersive medium, there are many special electromagnetic properties with PPCs. The frequency band of the transmittivity attenuation can be affected by plasma frequency.

Wu and co-researchers introduced a new general function photonic crystals (GFPC’s) [44], having arbitrary refractive index of medium as a function of space position and showed a different transmittivity from conventional PCs. They studied the effect of different incident angle, the number of periods and optical thickness on the transmittivity and obtained new results which are different from the conventional PCs. A new quantum theory was introduced by Xiay-Yao Wu [45] to study 1D photonic crystal. Quantum transform matrix, quantum dispersion relation and quantum transmittivity, are compared with classical dispersion relation and classical transmittivity finding the classical and quantum dispersion relation and transmittivity alike. The various applications of PCs had been proposed for the improved of the performance of optoelectronic and microwave devices such as high-efficiency semiconductor laser, right emitting diodes, waveguides, optical filters, high-Q resonator, antennas, optical limiters and amplifiers etc.
Calligaris reported a tunable bandpass optical filter fabricated with multiple-phase-shifted Bragg resonator using InGaAs/InP coupled asymmetric quantum wells [3] which he expected to be useful for high-speed Wavelength Multiplexed Communication Systems. GaAs/AlGaAs material composition based PBG structure is theoretically considered [46] for modeling HBT at lower wavelength region. Suitability of semiconductor heterostructure over conventional PC has been revealed [26, 42-43, 47-51].

Linear defect was introduced in narrow bandpass terahertz wave filter using photonic crystals by Li [48]. Two-photon polymerization is used to yield embedded defects in 3-D silicon photonic crystals by Stephanie [49] obtaining high-resolution 3-D features, first formed within a silica colloidal crystal, followed by a high-index replication step and removal of the opal template. In an optically thin dielectric slab, patterned with a two-dimensional array of air gaps, three-dimensional finite-difference time-domain analysis of localized defect modes was previously done by Painter and co-researchers [50].

Incorporation of metamaterial modifies the optical filter property [32] of 1D PC structure, which has recently been established. Effect of refractive index of materials on transmission spectra [24] for designing multi-narrow channel band filter was analyzed using transfer matrix technique by Gao and other researchers. Theoretical study of optical properties of a multilayer Fabry-Perot narrow band transmission filter containing a metamaterial negative-index defect was also done [51]. Optical transmission at higher frequency was also studied using negative refractive index material [52].

III. MATHEMATICAL MODELING

Consider the smallest unit of 1D photonic crystal structure where forward and backward propagating waves are given by:

\[ a_2 = r_{21} a_1 + r_{12} b_2 \]
\[ b_2 = t_{12} b_1 + t_{21} a_1 \]

where \( r \) and \( t \) are reflectivity and transmittivity in passing from layer \( i \) to layer \( j \).

For s-polarized incident wave at angle \( \theta \), interface reflectivities are given by

\[ r_{12} = -r_{21} = \frac{n_1 \cos(\theta_1) - n_2 \cos(\theta_2)}{n_1 \cos(\theta_1) + n_2 \cos(\theta_2)} \]

(4)

From the wave equations, transfer matrix corresponding to the interface can be obtained as

\[ M_{1,2} = \frac{1}{r_{21,12}} \begin{pmatrix} 1 & r_{21,12} \\ r_{21,12} & 1 \end{pmatrix} \]

(5)

Considering the phase factor of the field propagating through uniform medium, propagation matrix is given as

\[ P_{1,2} = \begin{pmatrix} \exp[j k_{1,2} d_{1,2}] & 0 \\ 0 & -\exp[j k_{1,2} d_{1,2}] \end{pmatrix} \]

(6)

where \( d \) is the propagation length in \( i \)th layer, and \( k \) is the wavevector in that layer. Thus, transfer matrix for the elementary cell is

\[ M = M_{1,2} P_{1,2} \]

(7)

For a perfectly periodic medium composed of \( N \) such elementary cells, the total transfer matrix for such a structure is

\[ M_{\text{tot}} = M_N \]

(8)

Transmission coefficient is given by

\[ T = \frac{1}{M_{11}^2 (\text{tot})} \]

(9)

Optical gain factor (\( \gamma \)) may be written as a function of effective refractive index as

\[ n_{\text{eff}} = n + j \gamma \]

(10)

IV. WORK DONE BY THE AUTHORS

Design of bandpass filter characteristics in the transmittivity profile of 1-D Photonic Multiple Quantum Well (PMQW) for polarized light (TE and TM mode) [53-54] and also for normal mode [55] centred at 1.55\( \mu \)m was reported for application in Optical Communication. The PMQW structure was considered as a periodic arrangement of GaN/Al\(_x\)Ga\(_{1-x}\)N composition serving as alternating layer of lower and higher refractive indices respectively. Adachi’s model [56] has been
followed for material composition and Transfer Matrix Theorem [18] has been implemented for computation of transmittivity. An increase in layer number can serve as better filtering [54]. Filtering effects are tuned with dimensional variation and material composition [53, 57].

Later works reveal better efficiency of semiconductor heterostructure over conventional photonic crystal of SiO$_2$-Air [57-59]. Bandwidths of the filters are also calculated in THz frequency which certifies better tunability of GaN/Al$_x$Ga$_{1-x}$N filters [60]. Dimensional variations prove narrower bandwidth can be achieved for heterostructure at certain well and barrier widths. Continuous variation of barrier and well dimensions reveals the fact more appropriately. Effect of optical gain factor in regard.

V. CONCLUSION

In summary, a detailed review work is presented on calculation of transmittance of one-dimensional photonic crystal structure, and based on that, work already performed by the group of authors. Though it is very difficult to make a complete literature survey on the title mentioned, but authors tried to make a comprehensive work on that matter. The proposed system, also mentioned in a few papers based on the theoretical analysis carried out by the authors, reveals better performance compared to the conventional material set when used as photonic filter in integrated circuit. Suitable tuning of layer dimensions and material compositions play a key role in this regard.

REFERENCES


[33] B. Suthar, V. Kumar, A. Kumar, V. Kumar, and A. Bhargva, “Thermal Tuning of Omni-directional Reflection Band in Si-based 1D Photonic Crystal”, International Journal of Recent Advances in Physics, vol 3, pp. 9-16, 2014.


