Volume: 2 **Issue:** IV **Month of publication:** April 2014

DOI:

www.ijraset.com Vol. 2 Issue IV, April 2014

ISSN: 2321-9653

INTERNATIONAL JOURNAL FOR RESEARCH IN APPLIED SCIENCE AND ENGINEERING TECHNOLOGY (IJRASET)

Calculating Transmittivity of Photonic Multiple Quantum Well for S-Polarized Incidence

Barnisa Chottopadhyay[1], Usmita Banerjee[2], Avisek Maity[3], Arpan Deyasi[4]

[1,2,3,4]Department of Electronics & Communication Engineering, RCC Institute of Information Technology

Abstract*— Novel bandpass filter is proposed using photonic multiple quantum well structure by computing transmittivity for normal and oblique incidence of s-polarized electromagnetic wave. Ratio of thickness of unit cell and material composition of the barrier region is varied to compute the modulation in filter bandwidth using transfer matrix technique for optical communication purpose at 1550 nm. $Al_xGa_{1-x}N$/GaN composition is chosen as unit block of the periodic organization, with $Al_xGa_{1-x}N$ layer as the barrier and GaN as well of the 11-layer structure. Following Adachi's model, refractive index of $Al_xGa_{1-x}N$ is considered as a function of mole fraction and operating wavelength. It is found out that for normal incidence, this structure demonstrate better filter characteristics than oblique incidence. Suitable choice of dimension and Al mole fraction along with variation of incident angle makes it efficient band-pass filter at desired frequency region.

***Keywords*— Photonic Multiple Quantum Well, Transmittance, Transfer Matrix Technique, S-polarization, Band-Pass filter**

I. INTRODUCTION

Photonic crystal is constructed by periodic arrangement of dielectric materials [1-2] 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. This property can be utilized to design novel bandpass filter [3] by restricting e.m wave of certain wavelengths and simultaneously allowing other spectra; possible due to the formation of photonic bandgap, may be exhibited in one, two or three dimensions. Since three-dimensional microstructures are not very easy to realize at near-infrared and optical wavelengths [4], so researchers focus on 1D and 2D structures due to their possible various applications in optical communication domain [5-9]. Photonic crystal fiber is a revolutionary concept, and now realizable due to the advancement in microelectronic technologies. This can now-a-days being used in integrated photonics [10], high power technology [11], sensing [12], quantum information science [13] etc. For different communication applications, designing photonic crystal fibers and other notable devices is very important, and thus role of material composition plays a crucial role in this context [14-15]. Photonic quantum well systems are also studied [16] in recent past to make a comparative analysis between low-dimensional electronic and photonic systems, and resonant tunneling is characterized for this structure.

Fundamental analysis of electromagnetic wave propagation inside 1D photonic crystal was carried out by Rudziński [17] for both TE and TM mode using transfer matrix technique. Effect of refractive index of dielectric material on transmission spectra [18] for designing multi-narrow channel band filter was analyzed by optical transfer matrix technique. Lin [19] suggested that a photonic bandgap quantum confined structures can be considered a high-Q resonant cavity whose reflectivity is dependent on cavity modal frequency. Transmission coefficient is computed [20] considering multiple-scattering techniques, indicates its possibility for filter application. This concept can be utilized to design quantum-well infrared photodetector [21-22]. In this paper, transmittivity of photonic multiple quantum well structure is calculated for normal and oblique incidence of s-polarized e.m wave at 1550 nm considering the dependence of material parameters on material composition and operating wavelength. Width of passband is tuned by changing design parameters for application in optical communication.

II. MATHEMATICAL MODELLING

Consider the smallest unit of 1D photonic crystal structure comprising of GaN/$A_{lx}Ga_{1-x}N$ material composition where forward and backward propagating waves are given by-

$$a_2 = t_{21}a_1 + r_{12}b_2$$
(1.1)

$$b_1 = t_{12}b_2 + r_{21}a_1$$
(1.2)

where r_{ij} and t_{ij} are reflectivity and transmittivity in passing from layer *i* to layer *j*. They are related to the refractive indices of the materials following Fresnel's equation as

$$r_{ij} = -r_{ji} = \frac{n_i - n_j}{n_i + n_j}$$
(2.1)

and

$$t_{ij} = t_{ji} = 2\frac{\sqrt{n_i n_j}}{n_i + n_j}$$
(2.2)

Eq. 2.1 and Eq. 2.2 are valid for normal incidence. The reflectivities *r* and transmittivities *t* are coupled by the relation

$$r^2 + t^2 = 1$$
(3)

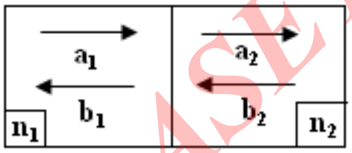


Figure 1: Schematic picture of forward and backward waves in smallest unit of 1D photonic crystal

For s-polarized incident wave at angle θ_1, 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

$$M^T{}_{1,2} = \frac{1}{t}\begin{pmatrix} 1 & r_{21,12} \\ r_{21,12} & 1 \end{pmatrix}$$
(5)

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

$$P_{1,2} = \begin{pmatrix} \exp[jk_{1,2}d_{1,2}] & 0 \\ 0 & -\exp[jk_{1,2}d_{1,2}] \end{pmatrix}$$
(6)

where d_i is the propagation length in i^{th} layer, and k_i is the wavevector in that layer. Thus, transfer matrix for the elementary cell is

$$M = M^T{}_1 P_1 M^T{}_2 P_2$$
(7)

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

$$M_{tot} = M_N$$
(8)

Transmittivity is given by

$$T = \frac{1}{M_{11}{}^2(tot)}$$
(9)

III. RESULTS & DISCUSSION

Using Eq. (9), transmittance of 1D photonic crystal is calculated as a function of wavelength of incident electromagnetic wave. First we consider normal incidence of s- polarized wave, and it is observed that with high al mole composition in barrier region, passband shifts at the left w.r.t centered wavelength. This is plotted in Fig 2. This is due to the fact that with increase of Al percentage (x), bandgap increases, which effectively decreases layer's refractive index. This causes the sharp fall of transmission at lower wavelength, and hence the shift of passband. It may also be noted that with increase of Al mole fraction keeping well and barrier widths constant, transmittivity decreases to a great extent, and thus filter property greatly improves.

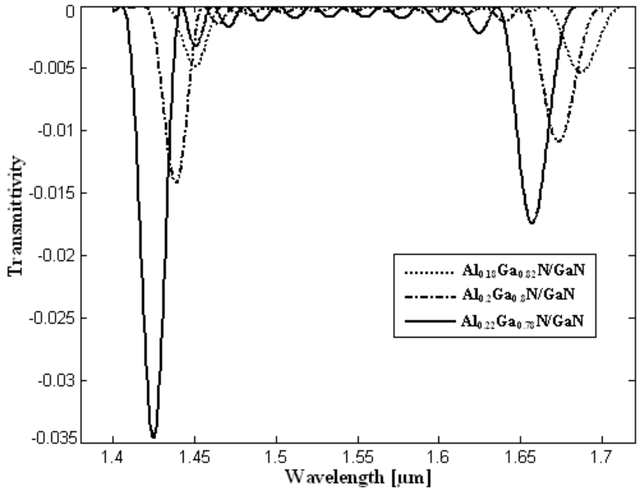


Figure 2: Transmittivity vs wavelength of em wave for normal incidence with constant layer dimensions and different material compositions

By independently varying barrier width and well width, it is found out that bandwidth of the filter can be tuned. By increasing barrier width, passband width decreases monotonically, which results in a narrow band filter. This is shown in Fig 3a. The same nature is observed by increasing well width also; plotted in Fig 3b. This is due to the fact that by increasing thickness of the either of the dielectric slab, periodicity increases, which changes the elementary cell matrix following Eq. (7). Hence the transfer matrix for the structure is modified as expected from Eq. (8), which causes the reduction of wave at the output along the quantized direction with increase of wavelength. This causes the decrease of transmittance, which results reduction of filter bandwidth.

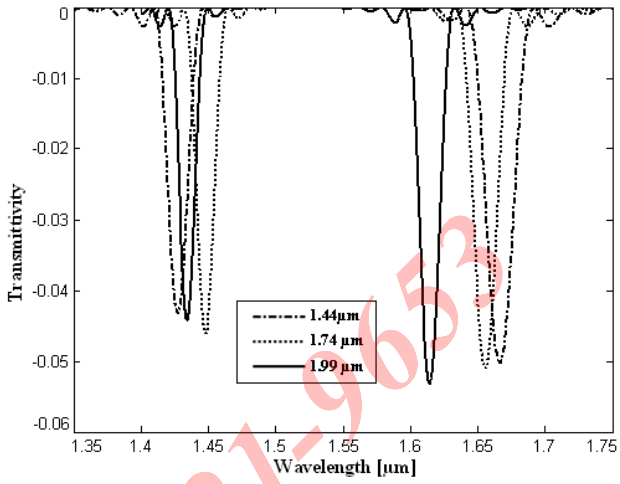


Figure 3a: Transmittivity vs wavelength of em wave for normal incidence for $Al_{0.2}Ga_{0.8}N/GaN$ composition and constant well width but different barrier widths

If normal incidence is changed into oblique incidence, then propagating wave has to traverse longer distance by a factor 1/cosθ (considering θ is the incident angle), and therefore, Brilloiun zone will be smaller by the factor cosθ. Also with increasing angle, the bandgap position will shift towards longer wavelength and at the same time, splitting will be taken place between two dispersion relations. So the bandwidth of the filter will shift towards higher wavelength region, shown in Fig 4a.

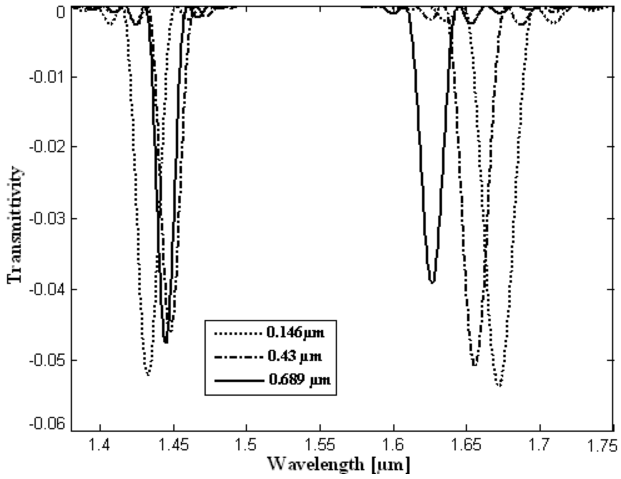


Figure 3b: Transmittivity vs wavelength of em wave for normal incidence for $Al_{0.2}Ga_{0.8}N/GaN$ composition and constant barrier width but different well width

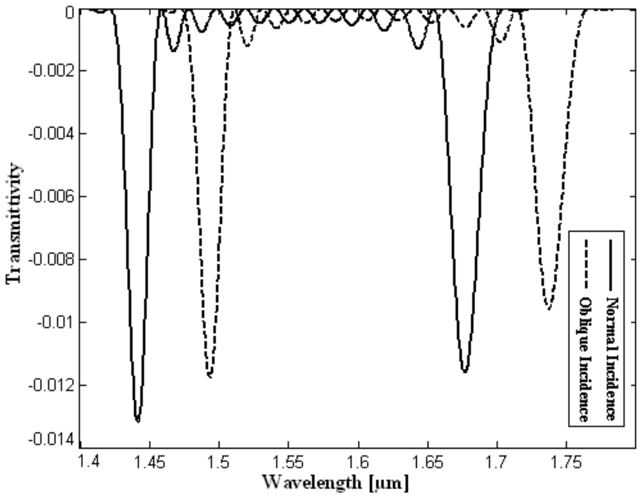


Figure 4a: Comparative study of transmittivity vs. wavelength of em wave for normal and oblique incidence with constant barrier and well widths and $Al_{0.2}Ga_{0.8}N/GaN$ composition

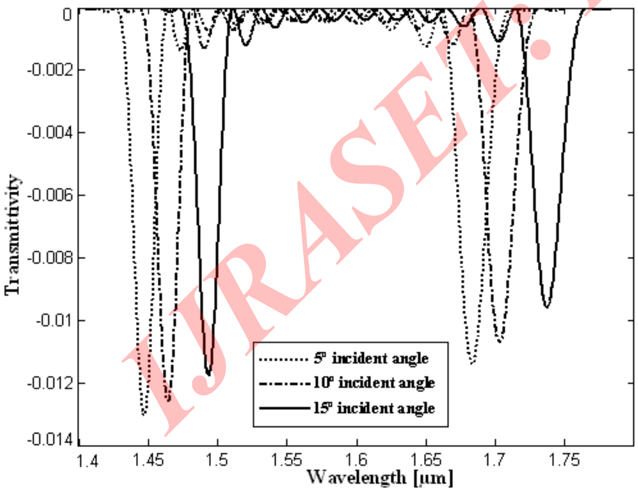


Figure 4b: Transmittivity vs. wavelength of em wave for different oblique incidence angle with constant barrier and well widths and $Al_{0.2}Ga_{0.8}N/GaN$ composition

With gradual increase of incident angle, the filter bandwidth will shift towards more right due to the shift of photonic bandgap. This is plotted in Fig 4b. Here it may be mentioned that for oblique incidence, both the polarized wave can't exhibit a bandgap at any particular wavelength, i.e., the photonic bandgap becomes incomplete.

IV. CONCLUSION

Tranmittance of photonic multiple quantum well structure is computed for normal and oblique incidence of s-polarized electromagnetic wave with centre wavelength at 1550 nm. Computation reveals the fact that slab thicknesses and material composition are two key design features for desired tuning of filter bandwidth. Also variation of incident angle modifies the filter property due to formation of incomplete photonic bandgap. The structure exhibits better filter characteristics for normal incidence than oblique incidence for any material composition, and any width of barrier and well regions when this particular polarization state is concerned. Design parameters can be optimized in such a way that centre wavelength of the proposed bandpass filter will always be surrounded by two photonic bandgap, represented by sudden increases of reflectance in the simulate profiles. This makes it a suitable candidate for optical communication.

REFERENCES

[1] E. Yablonovitch, "Inhibited Spontaneous Emission in Solid-State Physics and Electronics", Physical Review Letters, vol. 58, pp. 2059-2061, 1987.

[2] R. Loudon, "The Propagation of Electromagnetic Energy through an Absorbing Dielectric", Journal of Physics A, vol. 3, pp. 233-245, 1970.

[3] D. Mao, Z. Ouyang and J. C. Wang, "A Photonic-Crystal Polarizer Integrated with the Functions of Narrow Bandpass and Narrow Transmission Angle Filtering", Applied Physics B, vol. 90, pp. 127-131, 2008.

[4] L. C. Andreani, M. Agio, D. Bajoni, M. Belotti, M. Galli, G. Guizzetti, A. M. Malvezzi, F. Marabelli, M. Patrini and G. Vecchi, "Optical Properties and Photonic Mode Dispersion in Two-Dimensional and Waveguide-Embedded Photonic Crystals", Synthetic Metals, vol. 139, pp. 695–700, 2003.

[5] A. Mekis, J. C. Chen, I. Kurland, S. Fan, P. R. Villeneuve and J. D. Joannopoulos, "High Transmission

through Sharp Bends in Photonic Crystal Waveguides", Physical Review Letters, vol. 77, pp. 3787-3790, 1996.

[6] J. C. Chen, H. A. Haus, S. Fan, P. R. Villeneuve and J. D. Joannopoulos, "Optical Filters from Photonic Band Gap Air Bridges", Journal of Lightwave Technology, vol. 14, pp. 2575-2580, 1996

[7] I. S. Fogel, J. M. Bendickson, M. D. Tocci, M. J. Bloemer, M. Scalora, C. M. Bowden and J. P. Dowling, Pure and Applied Optics, "Spontaneous emission and nonlinear effects in photonic bandgap materials", vol. 7, pp. 393-408, 1998

[8] P. Szczepański, "Semiclassical Theory of Multimode Operation of a Distributed Feedback Laser", IEEE Journal of Quantum Electronics, vol. 24, pp. 1248-1257, 1988

[9] J. Hansryd, P. A. Andrekson, M. Westlund, J. Li and P. O. Hedekvist, "Fiber-based Optical Parametric Amplifiers and their Applications," IEEE Journal of Selected Topics on Quantum Electronics., vol. 8, pp. 506–520, 2002.

[10] K. Bayat, G. Z. Rafi, G. S. A. Shaker, N. Ranjkesh, S. K. Chaudhuri and S. Safavi-Naeini, "Photonic-Crystal based Polarization Converter for Terahertz Integrated Circuit", IEEE Transactions on Microwave Theory and Techniques, vol. 58, pp. 1976-1984, 2010.

[11] J. Limpert, T. Schreiber, S. Nolte, H. Zellmer, T. Tunnermann, R. Iliew, F. Lederer, J. Broeng, G.Vienne, A. Petersson and C. Jakobsen, "High Power Air-Clad Large-Mode-Area Photonic Crystal Fiber Laser," Optic Express, vol. 11, pp. 818-823, 2003.

[12] W. Belhadj, F. AbdelMalek and H. Bouchriha, "Characterization and Study of Photonic Crystal Fibres with Bends," Material Science and Engineering: C, vol. 26, pp. 578-579, 2006.

[13] H. Azuma, "Quantum Computation with Kerr-Nonlinear Photonic Crystals", Journal of Physics D: Applied Physics, vol. 41, p. 025102, 2008.

[14] X. Xu, H. Chen, Z. Xiong, A. Jin, C. Gu, B. Cheng and D. Zhang, "Fabrication of Photonic Crystals on Several Kinds of Semiconductor Materials by using Focused-Ion Beam Method", Thin Solid Films, vol. 515, pp. 8297-8300, 2007.

[15] S. K. Srivastava and S. P. Ojha, "A Novel Design of Nano Layered Optical, Filter using Photonic Band Gap Materials", 2nd National Workshop on Advanced Optoelectronic Materials and Devices, pp. 225-230, 2008.

[16] Y. Jiang, C. Niu and D. L. Lin, "Resonance Tunneling through Photonic Quantum Wells", Physical Review B, vol. 59, pp. 9981-9986, 1999.

[17] A. Rudziński, "Analytic Expressions for Electromagnetic Field Envelopes in a 1D Photonic Crystal", ACTA Physics Polonica A, vol. 111, pp. 323-333, 2007.

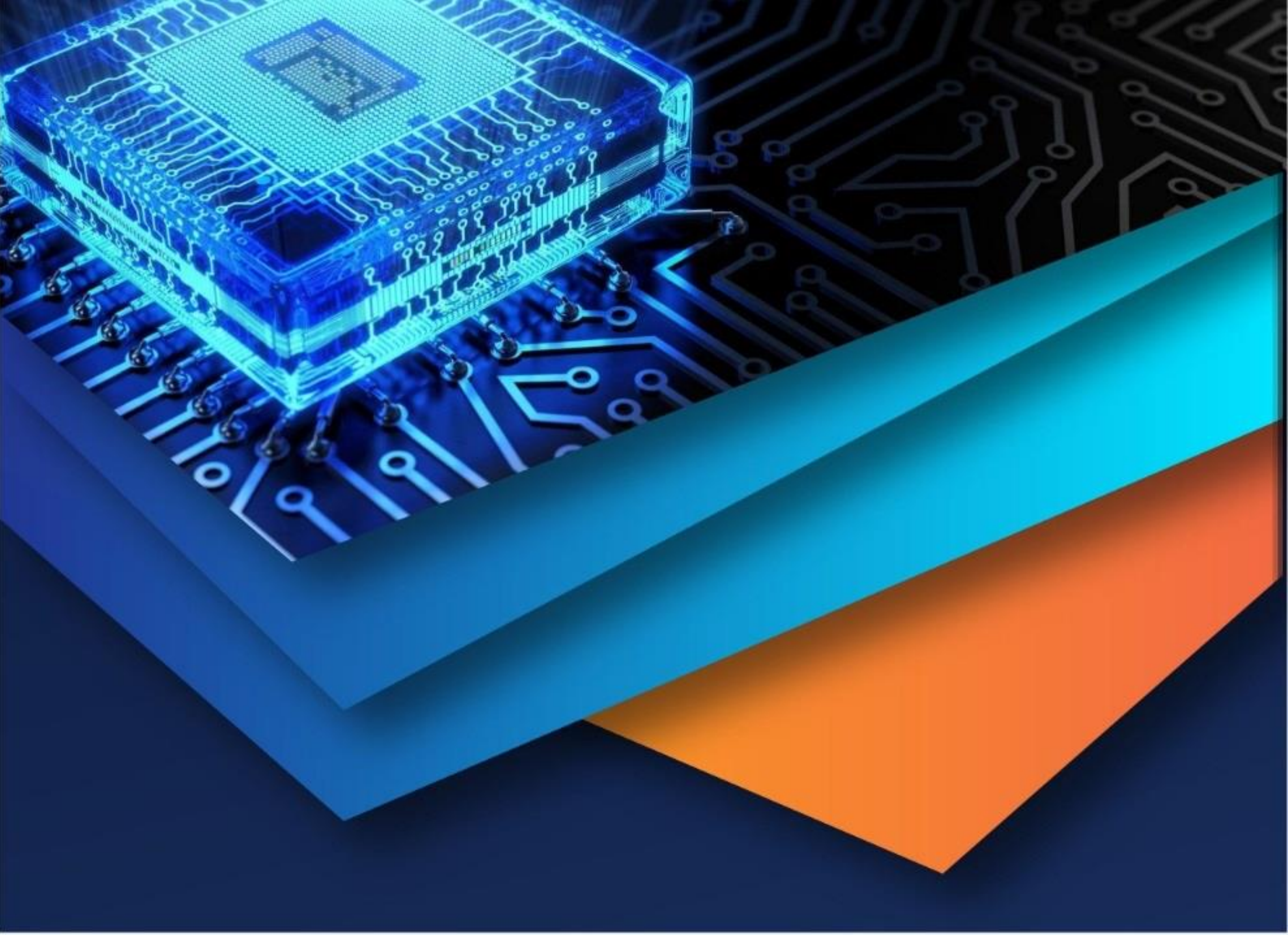
[18] Y. Gao, H. Chen, H. Qiu, Q. Lu and C. Huang, "Transmission Spectra Characteristics of 1D Photonic Crystals with Complex Dielectric Constant", Rare Metals, vol. 30, pp. 150-154, 2011.

[19] S. Y. Lin, V. M. Hietala, S. K. Lyo and A. Zaslavsky, "Photonic Bandgap Quantum Well and Quantum Box Structures: A high-Q Resonant Cavity", Applied Physics Letters, vol. 68, pp. 3233-3235, 1996.

[20] X. Chen, W. Lu and S.C. Shen, "Photonic Resonant Ttransmission in the Quantum-Well Structure of Photonic Crystals", Solid State Communications, vol. 127, pp. 541-544, 2003.

[21] P. Reininger, S. Kalchmair, R. Gansch, A. M. Andrews, H. Detz, T. Zederbauer, S. I. Ahn, W. Schrenk and G. Strasser, "Optimized Photonic Crystal Design for Quantum Well Infrared Photodetectors", Proc. of SPIE, vol. 8425, p. 84250A, 2012.

[22] S. Kalchmair, H. Detz, G. D. Cole, A. M. Andrews, P. Klang, M. Nobile, R. Gansch, C. Ostermaier, W. Schrenk and G. Strasser, "Photonic Crystal Slab Quantum Well Infrared Photodetector", Applied Physics Letters, vol. 98, 011105, 2011.



doi crossref
10.22214/IJRASET

INDEX COPERNICUS
45.98

ISRA JIF
IMPACT FACTOR:
7.129

SJIFactor Scientific Journal Impact Factor
TOGETHER WE REACH THE GOAL
IMPACT FACTOR:
7.429

ISI

INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY