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ANALYSIS OF THE CHARACTERISTICS OF TRIANGULAR CORRUGATED OPTICAL WAVEGUIDE

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ABSTRACT

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Transmittance and Reflectance characteristics of a periodically triangular corrugated optical waveguide are presented on the principle of mode coupling between forward and backward propagating waves. According to the principle of mode coupling, the forward and backward propagating waves are coupled by a coupled mode equations. The coupled mode equations are applied to the corrugation section of the triangular corrugated waveguides and by solving the equations of reflectance and transmittance have been calculated. In addition to, the transmittance and reflectance or elimination characteristics of this waveguide have been visualized and analyzed by computer programming. Furthermore, it has been decided that triangular corrugated optical waveguide can be used as optical filter in optical fiber communication system.

Keywords: optical waveguide, corrugation section, optical fiber communication system

INTRODUCTION

Communication is defined as the transfer of information from one place to another (Senior, et al. 1999). In optical fiber communication, the information is transferred from one place to another as a light signal (Yariv, *1998)*. Optical waveguide is a structure that guides a light wave from one place to another (Yariv, *1998)*. In waveguide there exist a discrete set of field pattern for each frequency which are maintained during propagation. These patterns are called propagation modes. Each mode may have a unique propagation velocity (Ghatak, et al. *1999)*. Depending upon the propagation modes, patterns of the electric field varies both in propagation direction and along the direction perpendicular to the direction of propagation (Hill, et al. *1978)*. Periodic corrugated optical waveguide is a periodic due variation in refractive index in guiding layer (Yariv, *1998)*. In case of theoretical optical waveguide, edges are straight but practically there exists some ripples in the edges (Yariv, *1998)*. Some power of transmitting signal radiate through these ripples of the practical optical waveguide. This is why power confinement of the waveguide decreases for all wavelengths of the optical signal and the efficiency of the optical waveguide decreases. The ripples cannot be eliminated completely from this waveguide. If the ripples are added in a definite shape to the optical waveguide edges, then some wavelengths are radiated out completely through these ripples while some other wavelengths are confined through the waveguide guiding layer (Figure 1).

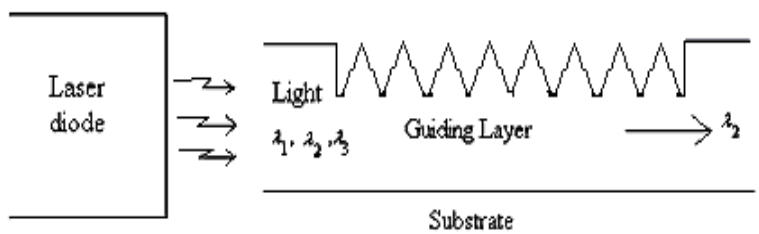

Figure 1. Use of triangular corrugated waveguide

As a result the losses of the waveguide are minimized and efficiency of the optical waveguide increases (Yariv, *1998)*. The ripples or corrugation in definite shapes are square triangular, sine etc. In section-2 of this paper, mathematical analysis of triangular corrugated optical waveguide will be presented. In section-3, visualizations and analysis of the

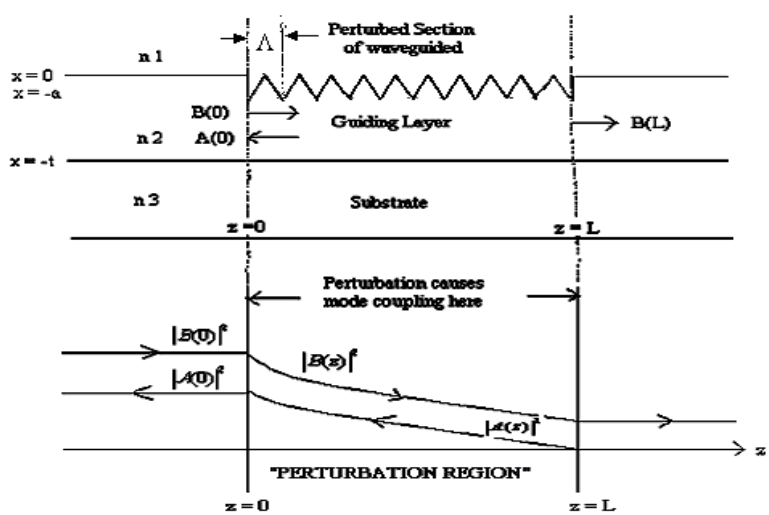

Figure 2. A Triangular corrugated section of an optical waveguide with incident, reflected and transmitted intensities in the corrugated section

Transmittance and Reflectance characteristics of the triangular corrugated optical waveguides will be shown. In section-4 of this paper, results of this analysis will be shown. In section-5, conclusion of this paper will be shown.

MATHEMATICAL ANALYSIS OF TRIANGULAR CORRUGATED OPTICAL WAVEGUIDE

Equations of coupled mode theory and coupling co-efficient for the triangular corrugated optical waveguide

When a light signal is incident to the corrugation section of this type of waveguide, some wavelengths of incident light are reflected back from different positions of corrugation section due to variation in refractive index and some other wavelengths transmitted through the waveguide. Constructive interference will be occurred among those reflected wavelengths that follows the Bragg law $\beta = \frac{l\pi}{\lambda}$ where l is a integer (Ghatak, et al. *1999).* In this way forward propagating wave $A(z)$ and backward propagating wave $B(z)$ in the propagation direction z have been formed (Figure2). The propagating modes in one optical waveguide may be coupled if there exist two types of waves say forward going and backward going (Yariv, *1998).* The coupled mode equation describe coupling between modes due to a spatially periodic index distribution within the same waveguide (Yariv,*1998).*The basic equation of the coupled modes theory interrelates the complex amplitudes of the forward and backward waves as follows (Yariv, *1973)*

$$\frac{dA}{dz} = \kappa B e^{[-i2(\Delta\beta)z]}, \qquad \frac{dB}{dz} = \kappa A e^{[i2(\Delta\beta)z]} \quad \text{..... (1)}$$

where $\kappa = \text{coupling co-efficient}$, $\Delta\beta = \beta - \beta_0 = \beta - \frac{l\pi}{\Lambda}$, $z =$ value in z-axis.

For triangular corrugation $\kappa_T = \kappa$ and the equation of the coupling co-efficient

$$\kappa_T = \frac{\omega\varepsilon_0}{2l^2\pi^2}.C_S^2 \left[\begin{array}{l} n_1^2 \left\{ \left(\frac{q_S^2}{4h_S^2} - \frac{1}{2h_S} \right) \sin(2h_S a) + \left(\frac{q_S}{2h_S^3} - \frac{q_S}{2h_S^2}\cos(2h_S a) \right) + a\left(\frac{1}{2} + \frac{q_S^2}{h_S^2} \right) \right\} \\ -\frac{\Delta n^2}{a} \left\{ \begin{array}{l} \left(\frac{a q_S^2}{2h_S^3} - \frac{q_S}{4h_S^3} - \frac{a}{4h_S} \right) \sin(2h_S a) + \left(\frac{q_S a}{2h_S^2} - \frac{1}{8h_S^2} + \frac{q_S^2}{4h_S^4} \right) \cos(2h_S a) \\ + \left(\frac{a}{2} + \frac{1}{8h_S^2} + \frac{q_S^2 a}{h_S^2} - \frac{q_S^2}{4h_S^2} \right) \end{array} \right\} \end{array} \right] \quad \text{..... (2)}$$

where $C_S = 2h_S \left(\frac{\omega\mu}{|\beta_S|[t + (1/q_S) + (1/p_S)](h_S^2 + q_S^2)} \right)^{1/2}$, $\beta_s \approx n_2 k_0$, $k_0 = \frac{2\pi}{\lambda}$, $h_s \to \frac{\pi s}{t}$

s =1, 2, 3, ….. = transverse mode number and $\frac{q_s}{h_s} \approx \left(n_2^2 - n_1^2\right)^{\frac{1}{2}} \left(\frac{2t}{s\lambda} \right)$

For coupling, the corrugation period Λ is so chosen that for $l = 1,2,3,.....$, $\Delta\beta = 0$.Thus $\Delta\beta = \beta - \frac{l\pi}{\Lambda} = 0$ and $\Lambda = \frac{l}{2}\lambda_0$,where $\lambda_0 = \frac{2\pi}{\beta} =$ guide wavelength of s-mode.

It follows straightforwardly from eq^n-1 that $\frac{d}{dz}\left(|B(z)|^2 - |A(z)|^2 \right) = 0$ .Thus the total electromagnetic power carried by the modes is conserved (Yariv, *1998).*

Solution of the coupled mode equation

To find the solution of the coupled mode equation (eq^n-1), consider a waveguide with triangular corrugated section of length L as shown in Figure 2. In Figure2 the symbols a =corrugation depth, n_1=refractive index of cladding layer, n_2 =refractive index of guiding (core) layer, n_3 =refractive index of substrate. A wave with amplitude $B(0)$ is incident from the left on the corrugated section and a wave with amplitude $A(0)$ is reflected from the end of the corrugated section due to a spatially periodic index distribution. At $z = 0$, both $B(0)$ and $A(0)$ persist maximum value.

At $z = L$, $B(L)$ contain minimum value and $A(L) = 0$. A plot of mode power $|B(z)|^2$ and $|A(z)|^2$ is also shown in Figure 2. For sufficiently large arguments of the *cos* and *sin* functions, the incident mode power drops off exponentially along the corrugation region. This behavior is due not to absorption but to reflection of power into the traveling wave. Even we lunch a forward propagating wave, both forward and backward waves will generate.

The solutions of the coupled mode equation (Eq^n.1) is performed by using value $A(L) = 0$ and boundary condition

$$\frac{d}{dz}\left(\frac{dA}{dz}\right) = \kappa B(-i2\Delta\beta)e^{-i2\Delta\beta z} + \kappa e^{-i2\Delta\beta z}\frac{dB}{dz}$$

$$\Rightarrow \frac{d^2A}{dz^2} + i(2\Delta\beta)\kappa\frac{dA}{dz}\frac{1}{\kappa}e^{i(2\Delta\beta)z}e^{-i(2\Delta\beta)z} - \kappa e^{-i(2\Delta\beta)z}\kappa A e^{i(2\Delta\beta)z} = 0$$

$$\Rightarrow \frac{d^2A}{dz^2} + i(2\Delta\beta)\kappa\frac{dA}{dz} - \kappa^2 A = 0 \quad \text{.....(3)}$$

The solution of the coupled mode equation by using Eq^n-3 is

$$A(z)e^{i\beta z} = B(0)\frac{i\kappa e^{i\beta_0 z}}{-\Delta\beta\sinh SL + iS\cosh SL}\sinh[S(z-L)] \quad \text{.....(4)}$$

$$B(z)e^{-i\beta z} = B(0)\frac{e^{-i\beta_0 z}}{-\Delta\beta\sinh SL + iS\cosh SL} \times \left\{\Delta\beta\sinh\left[S(z-L)\right] + iS\cosh\left[S(z-L)\right]\right\} \quad \text{.....(5)}$$

where $S = \sqrt{\kappa^2 - (\Delta\beta)}$

For each value of l, there exists a gap whose center frequency ω_0 satisfies $\beta(\omega_0) = \frac{l\pi}{\Lambda}$ The exceptions are values of *l* for which κ is zero. We can approximate $\beta(\omega)$ near its Bragg value $\frac{l\pi}{\Lambda}$ by $\beta(\omega) \approx (\omega/c)n_{eff}$, where n_{eff} is an effective index of refraction.

The result is $\Delta\beta L = \left[(\omega - \omega_0)L/c\right]n_{eff}$, where $\omega_0\left(=\frac{2\pi c}{\lambda_0}\right)$, the mid gap frequency, is the value of $\omega\left(=\frac{2\pi c}{\lambda}\right)$ for which the unperturbed β is equal to $\beta_0 = \frac{l\pi}{\Lambda}$ and n_{eff} = effective refractive index.

Transmittance of the triangular corrugation section

It is known that, Transmittance, $T_{eff} = \frac{\text{Power of the transmitted wave}}{\text{Power of the incident wave}}$

Thus Transmittance for the corrugation sections $T_{eff} = \left|\frac{B(L)}{B(0)}\right|^2$ .....(6)

By using Equ.5 and Equ.6, the Transmittance for the triangular corrugation section has been calculated as

$$T_{eff} = \frac{(\kappa L)^2 - (\Delta\beta L)^2}{(\kappa L)^2\cos^2 h\left(\sqrt{(\kappa L)^2 - (\Delta\beta L)^2}\right) - (\Delta\beta L)^2} \quad \text{.....(7)}$$

where $\Delta\beta L = \left[(\omega - \omega_0)L/c\right]n_{eff}$

Reflectance of the triangular corrugation sections

It is known that, Reflectance, $R_{eff} = \dfrac{\text{Power of the Reflected wave}}{\text{Power of the incident wave}}$

Thus Reflectance for the corrugation sections $R_{eff} = \left|\dfrac{A(0)}{B(0)}\right|^2$ .....(8)

By using Eq^n.4, Eq^n .5 and Eq^n.8, the Reflectance for the triangular corrugation section has been calculated as

$$R_{eff} = \frac{(\kappa L)^2 \sin^2 h\left(\sqrt{(\kappa L)^2 - (\Delta\beta L)^2}\right)}{(\kappa L)^2 \cos^2 h\left(\sqrt{(\kappa L)^2 - (\Delta\beta L)^2}\right) - (\Delta\beta L)^2} \quad \text{.....(9)}$$

Visualizations And Analysis of The Transmittance And Reflectance Characteristics of The Triangular Corrugated Optical Waveguide Using MATLAB

Now visualizations of the transmittance and reflectance characteristics of such a periodic waveguide will be shown by using Eq^n-.7, Eq^n-9 and Table 1.

Transmittance and Reflectance characteristics of a corrugated section

The transmittance and reflectance characteristic of such a periodic waveguide is visualized in Figure 3 by using Eq^n .7, Eq^n .9 and Table 1. From the Figure 3 it is observed that at a particular wavelength, the transmittance is minimum and reflectance is maximum while at some other wavelengths, the transmittance is maximum and reflectance is minimum of this waveguide. Thus triangular corrugated waveguide acts as a high reflectivity mirror. So we can say that, triangular corrugated optical waveguide can be used as an optical filter. Selection of any desired λ to be passed through the corrugated waveguide is depending on coupling constant κ of such waveguide. We can change κ by varying different parameters such as *a*, *t*, n_2, L and Λ etc.

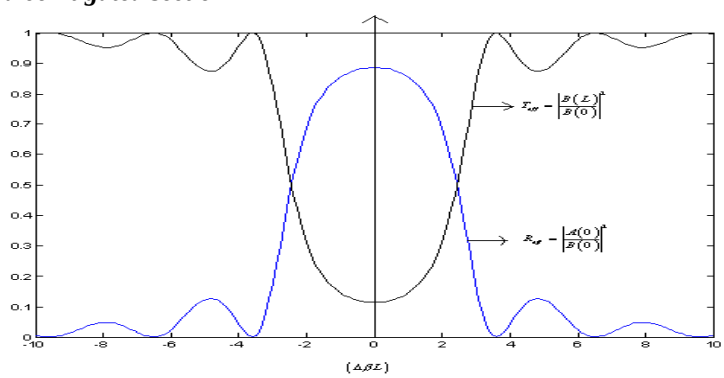

Figure 3. Transmission and reflection characteristics of a triangular corrugated section as a function of the detuning $\Delta\beta L = \left[(\omega - \omega_0) L / c\right] n_{eff}$ for $(\kappa L = 1.75)$

Table 1.different parameters, thier symbols and numerical values for analyzing

Parameter	**Symbol**	**Value**
Refractive index of cladding layer	n_1	1.48
Refractive index of guiding(core) layer	n_2	1.5
Refractive index of substrate.	n_3	1.485
Integer	l	1
Transverse mode number	s	0
Corrugation depth	a	0.5 μ m
Width of guiding(core) layer	t	4 μ m
Total length of corrugation section	L	50 μm
Effective refractive index	n_{eff}	1.482
Operating wavelength	λ	1 μ m

Visualizations and analysis of reflectance characteristics by varying corrugation period Λ

Visualizations of reflectance characteristics for different corrugation period Λ is shown in Figure4 by using Eq^n-.9.

It is observed from Figure 4 that for corrugation period $\Lambda = 10\mu m$, reflectance is only 76% but for $\Lambda = 8\mu m$ it is almost 99%. So the reflectance of this corrugated waveguide increases for decreasing corrugation period Λ and the value of corrugation period Λ is very effective on the reflectance characteristics of triangular corrugated waveguide.

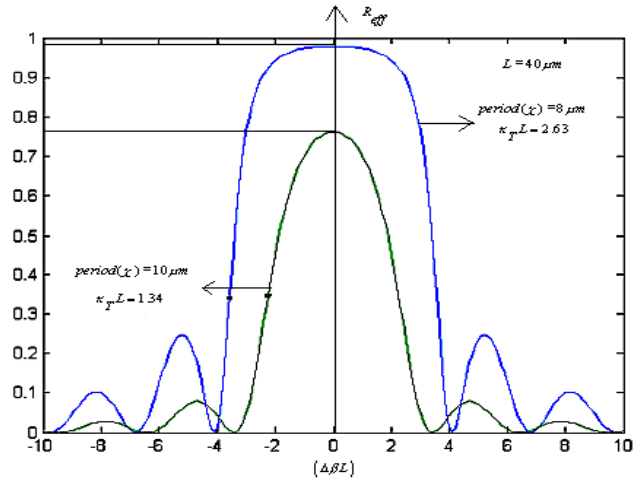

Figure 4. Reflectance characteristics for different corrugation period Λ

Visualizations and analysis of reflectance characteristics by varying corrugation depth a

Visualizations of reflectance characteristics for different corrugation depth a are shown in Figure5 by using Eq^n-9. It is observed from Figure5 that for corrugation depth $a = 0.5\mu m$, reflectance is only 88% but for $a = 1\mu m$, it is almost 44%. So the reflectance of this corrugated waveguide decreases for increasing corrugation depth a and the value of corrugation depth a is very effective on the reflectance characteristics of triangular corrugated waveguide.

Visualizations and analysis of reflectance characteristics by varying waveguide thickness t

Visualizations of reflectance characteristics for different waveguide thickness t are shown in Figure 6 by using Eq^n.9. It is observed from Figure 6 that for waveguide thickness $t = 4\mu m$, reflectance is only 78% but for $t = 5\mu m$ it is almost 32%. So the reflectance of this corrugated waveguide decreases for increasing waveguide thickness t and the value of waveguide thickness t is very effective on the reflectance characteristics of triangular corrugated waveguide.

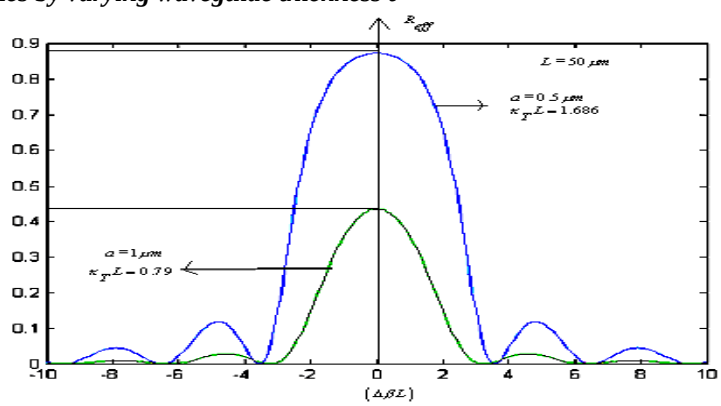

Figure 5. Reflectance characteristics for different corrugation depth a

Visualizations and analysis of reflectance characteristics by varying corrugation length L

Visualizations of reflectance characteristics for different corrugation length L is shown in Figure7 by using Equation 9.

It is observed from Figure 7 that for corrugation length $L = 60\mu m$, reflectance is 94% but for $L = 40\mu m$,it is almost 76%. So the reflectance of this corrugated waveguide decreases for decreasing corrugation length L and the value of corrugation length L is less effective on the reflectance characteristics of triangular corrugated waveguide.

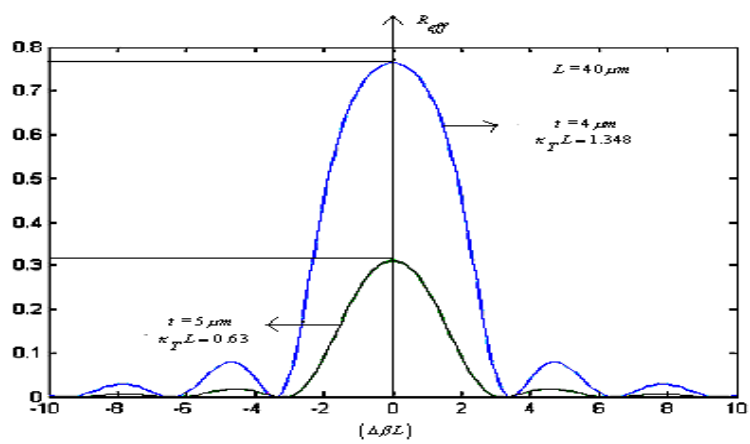

Figure 6. Reflectance characteristics for different waveguide thickness t

Visualizations and analysis of reflectance characteristics by varying guiding layer refractive index n_2

Visualizations of reflectance characteristics for different guiding layer refractive index n_2 is shown in Figure 8 by using Equ.9. It is observed from Figure 8. that for guiding layer refractive index $n_2 = 1.6$, reflectance is 28% but for $n_2 = 1.5$,it is almost 99%. So the reflectance of this corrugated waveguide increases for decreasing refractive index of guiding layer n_2 and the value of guiding layer refractive index n_2 is very effective on the reflectance characteristics of triangular corrugated waveguide.

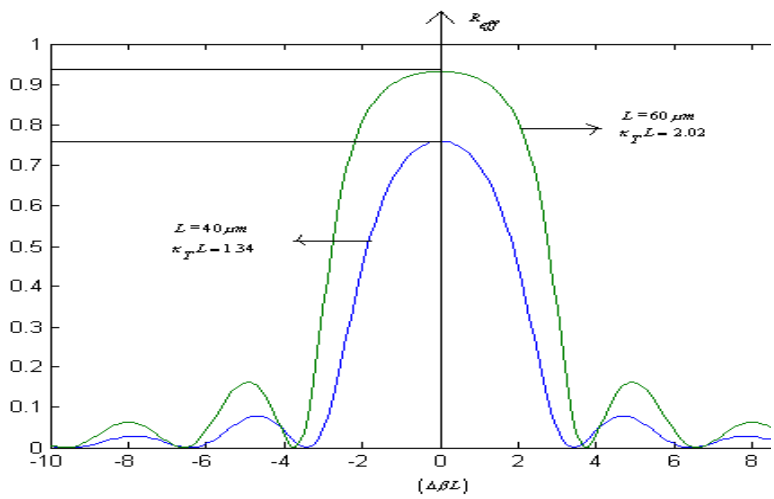

Figure 7. Reflectance characteristics for different corrugation length L.

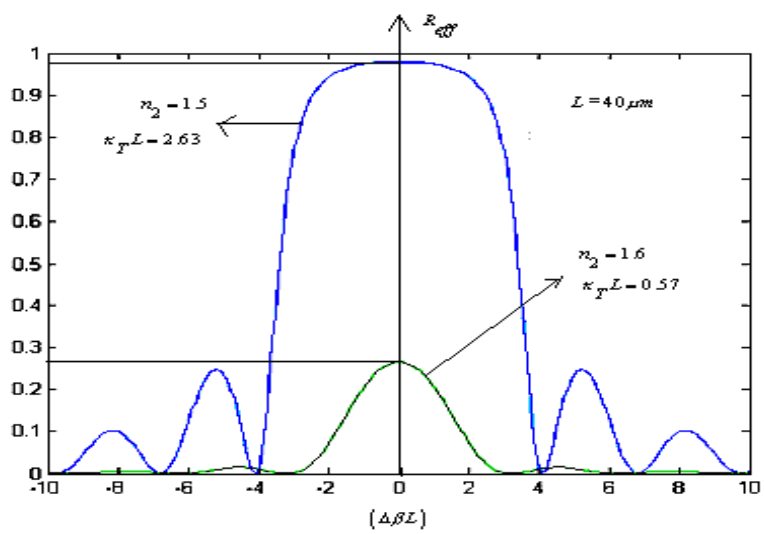

Figure 8. Reflectance characteristics for different guiding layer refractive index n_2

RESULTS

By mathematical analysis, we have determined that the value of corrugation depth a, waveguide thickness t and guiding layer refractive index n_2 is very effective on the reflectance characteristics of triangular corrugated waveguide. The reflectance of this corrugated waveguide decreases for increasing corrugation depth a, waveguide thickness t and the reflectance of this corrugated waveguide increases for decreasing corrugation period Λ, refractive index of guiding layer n_2. The value of corrugation period Λ and corrugation length L is less effective on the reflectance characteristics of triangular corrugated waveguide. From characteristics of Triangular corrugated optical waveguide, we have decided that it can be used as a optical filter. In this research paper, our main goal is to analyze a triangular corrugated optical waveguide as optical filter. To do this, the coupled mode equations are applied the corrugation section of this type of waveguide and the value of coupling co-efficient is calculated. Then the equations of transmittance and reflectance are calculated and visualized by computer programming (MATLAB). By varying different parameters such as corrugation depth**,** waveguide thickness, guiding layer refractive index, corrugation period and corrugation length, the reflectance characteristics of triangular corrugated waveguide have been observed. It is seen that the value of corrugation depth a, waveguide thickness t and guiding layer refractive index n_2 is very effective on the reflectance characteristics of triangular corrugated waveguide while the value of corrugation period Λ and corrugation length L is less effective on the reflectance characteristics of triangular corrugated waveguide. From the manufacturing point of view of optical waveguide it is easier to fabricate triangular corrugated optical waveguide than conventional waveguide in which some ripples exist in the edges. As reflectance characteristics of triangular corrugated waveguide is better, reflected light from corrugated section will be near monochromatic than transmitting beam. If we collect these beam and focus to a point using lens, we will get light of near single frequency. Thus triangular corrugated optical waveguide acts as optical filter.

REFERENCES

Ajoy Ghatak, K. & Thyagarajan. *1999.* "Introduction to Fiber Optics,"*First South Asian Edition.*

Gowar, J. *1998.* "Optical communication sysrtem," *2nd edition.*

Hill, K.O. Y. Fujii, D.C. Johnson, and B. Kawasaki., *1978*. "Photo sensitivity in optical fiber waveguides: Application to reflection filter fabrications," *Appl.Phys.Lett.32:646-649.*

Hill,K.O. B.Malo, F.Bilodeau, and D.C. Johnson. *1993.* "Photo sensitivity in optical fibers," *Ann.Rev.Mater.Sci,23:125-157.*

Khun,L., M.L.Dakss, P.F. Heidrich, and B.A. Scott. *1970.* "Deflection of optical guided waves by a surface acoustic wave," *Appl.phys. Lett.17:265.*

Senior, J. *1999.* "Optical fiber Communication,"*2nd Edition.*

Stoll,H. and A. Yariv, *1973*. "Coupled mode analysis of periodic dielectric waveguides," *Opt.Comm,8:5,*

Yariv, A. *1998.* Optical Electronics in Modern Communications, *fifth Edition.*

Yariv,A., *1973*" Coupled mode theory for guided wave optics", *IEEE J. Quant.Elec. 9:919.*

Kashyap.,R. *1994.* "Photo sensitive optical fibers: Devices and applications," *Optic.Fiber Technol., vol. 1, pp.17-34*.

Elachi., C. *1976.* "Waves in active and passive periodic structure: A review, "*in Proc. IEEE, vol., 64, pp.1666-1698.*