Design of Ultra Fast Polymer Electro-Optic waveguide Switch for Intelligent Optical Networks

S.Ponmalar, S.Sundaravadivelu

***Abstract*—**Traditional optical networks are gradually evolving towards intelligent optical networks due to the need for faster bandwidth provisioning, protection and restoration of the network that can be accomplished with devices like optical switch, add drop multiplexer and cross connects. Since dense wavelength multiplexing forms the physical layer for intelligent optical networking, the roll of high speed all optical switch is important. This paper analyzes such an ultra-high speed polymer electro-optic switch. The performances of the 2x2 optical waveguide switch with rectangular, triangular and trapezoidal grating profiles on various device parameters are analyzed. The simulation result shows that trapezoidal grating is the optimized structure which has the coupling length of 81μm and switching voltage of 11V for the operating wavelength of 1550nm. The switching time for this proposed switch is 0.47 picosecond. This makes the proposed switch to be an important element in the intelligent optical network.

***Keywords*—**Intelligent optical network; optical switch; electro-optic effect; coupled mode theory; waveguide grating structures

I. INTRODUCTION

OPTICAL networks are growing at unprecedented rates to accommodate the explosion in data traffic brought on by Internet and enterprise applications. Traditional SONET/SDH networks provide high levels of reliability based on mature and stable technologies. However the challenges for these existing networks are bandwidth scalability, efficient bandwidth utilization, lower operational costs, faster provisioning time, protocol and bit rate independence and differentiated services.

Dense wavelength-division multiplexing (DWDM) in optical networks has been rapidly gaining acceptance as a means to handle the explosive bandwidth demands of network traffic. Commercial dense WDM systems are expected to concurrently carry more than 160 wavelengths at data rates of OC-192c and above, for a total of 1.6 Tbps or more.

Even though, bandwidth provided these systems are plenty and inexpensive, a carrier's key challenge is to turn that bandwidth (in THz) into services for customers in a cost-effective and timely way. This is the basic motivation for incorporating intelligence into optical networks. Emerging intelligent optical networks(ION) can provide faster provisioning of light paths, protection and restoration, automatic discovery of network elements and automatic reconfiguration of network[1]. Additionally, when combined with modern service management technologies, these networks open exciting opportunities for delivering new customized optical services directly to end-users, allowing carriers to fully exploit the economics of optical transport[2].

Intelligent optical networking enabled by high capacity Optical Cross Connects (OXCs), optical add-drop multiplexers with software intelligence, grants new methods for managing high capacity core optical networks. Important innovations that OXCs bring to optical networking include switching capacities matching the bandwidth needs of DWDM technologies, automatic topology and resource discovery supporting large random mesh topologies. Since these elements are very much essential to the network, there is a strong need for high speed optical switching devices, which will be the key component of ION.

Optical switches are of growing importance for routing and other functions in optical networks. Optical networks using DWDM need a lot of optical switches, especially for optical cross-connection (OXC) and in optical add-drop multiplexer (OADM). These are the key devices for constructing flexible and low-cost high speed optical networks. Several types of optical switching devices are in use including electro optic switch [3], optomechanical [4][5], thermo optic[6][7], bragg grating switch[8], PLZT electro optic switch[9] and photonic crystal switch[10][11]. Of these switches, one of the most useful is the optical waveguide grating coupler based switch, which is highly stable and reliable. The ability of this architecture to achieve input and output-port counts of over one thousand is the primary driver of the large-scale OXCs based on arrayed 2x2 switch module. In particular, these types of switches provide high application flexibility in network design because of low and uniform insertion loss with low wavelength dependency under various operating conditions. In this paper we propose an optical waveguide switch with different geometry and analyse the switching time and wavelength dependency of the proposed witch and compared the results with existing optical switch.

II. DESIGN OF ELECTRO-OPTIC SWITCH

The structure of a waveguide grating based 2x2 optical switch is shown in Figure 1. It consists of a pair of identical waveguide grating structures which have the same values of reflectivity, length, and periodicity. The rectangular, triangular and trapezoidal shapes of grating structures are projected over the film layer along the direction of propagation (z-direction).

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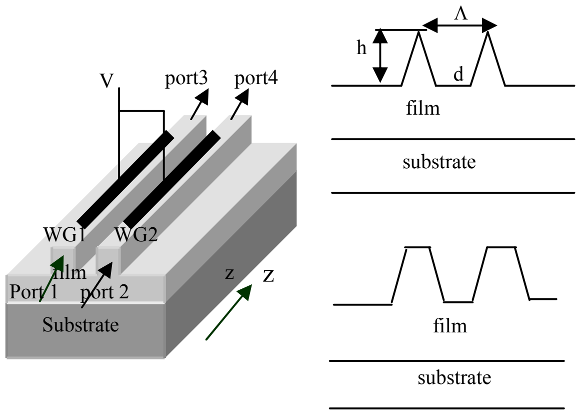

Fig .1 2x2 optical waveguide grating switch

The fig. 1 shows the waveguide core section with light travelling along the waveguide in the direction of arrow on the left. When power is incident on one waveguide, then it excites a linear combination of the symmetric and antisymmetric modes [12]. The excitation would be such as to add the lobes in one waveguide cancel in the other. Since, the propagation constants of two modes are unequal, as the fields propagate through the system, they develop a phase difference. When the accumulated phase difference is π, the superposition of these modes will result in a cancellation in the first waveguide and an addition in the second waveguide. Further propagation over an equal length will result in a phase difference 2π, leading to power transfer back to the first waveguide. Thus, the power exchanges periodically between these two waveguides.

High speed light switching can be attained in structures made of electro-optic materials. When an electric field is applied to electro-optic materials, a change in index of refraction occurs which alters the speed of an optical signal travelling through it. The applied electrical field produces this response by disturbing the electronic polarization of non-centro symmetrically ordered chromophores dispersed in organic matrix material. This effect is called the pockel's effect. The relationship of index change Δn, to applied field is given by [13]

$$\Delta n = \frac{n^3}{2} r_{33} \frac{V}{d} \tag{1}$$

where Δn is the change of the material's optical index of refraction, r_{33} is the electro-optic coefficient and d is electrode width.

When the electro optic (EO) activity of a material is high, less electric field strength is required to change the refractive index. One of the electro optic material that has been used to fabricate a variety of optical components is Lithium Niobate, which has relatively high electro optic coefficient *r33* of ~ 32 pm/V. However, Lithium Niobate has several properties that hinder applications with high data rates. The dielectric constant is high and increases at higher frequency and the speed of light waves and electrical waves are mismatched, which limits operational speed and bandwidth. The electro-optic coefficient is relatively fixed, which limits the operational speed due to the size and complexity of high voltage. The crystal structure is fragile and fixed, which severely restricts the integration of Lithium Niobate devices with other components. Thus, there is a need for new materials that allow high speed, low power operation while providing the opportunity for integration with other optical and electrical components.

Electro-optic polymers are particularly interesting for new device design and high-speed operation [13][14]. Electro-optic polymers have the advantages of high data rate operation, low drive voltage, and broad bandwidth. It has very fast EO response time, very high EO coefficient (r33 up to 300 pm/V), relatively low dielectric constant and closely matched refractive indices (1.4 – 1.7) at optical and RF wavelengths. The advantages of EO polymer material make us to choose it as a base material in the design of electro-optic switch.

Efficient switching is possible by placing planar electrodes on directional couplers consisting of two identical single-mode waveguides close to each other, as shown in figure.2, where electro optic material of refractive index 1.711 is used as the substrate and 1.723 as film. The propagation constant difference between two waveguides is varied by the EO effect with an applied voltage *V*, while the coupling coefficient κ is insensitive to *V* under weak coupling condition. The coupling length *L* for complete power transfer from one waveguide to the other is also defined as $\pi / 2\kappa$ when Δβ=0. The coupler length *l* must be adjusted to be an odd multiple of *L* so that the incident light on waveguide *1* is totally transferred to waveguide *2* at the output when voltage *V* is applied to the electrode which is the crossover state of the switch. When no voltage is applied, $\Delta\beta / \kappa = 2\sqrt{3}$ the power transfer of waveguide 1 to 1 is then obtained which is the through state of the switch.

III. Analysis of Optical Switch by Coupled-Mode Theory

The waveguide gratings structures are analyzed using coupled mode theory[15][16]. In the presence of periodic perturbation, predominant coupling takes place only between those modes with propagation constants β_m and β_n satisfying $\beta_m - \beta_n \cong \pm K = \pm 2\pi/\Lambda$ and coupling to other modes is negligible. Assuming that power gets coupled only among two modes, the total field at any z as

$$E(x,z) = A(z)E_1(x,y)e^{-i\beta_1 z} + B(z)E_2(x,y)e^{-i\beta_2 z} \tag{2}$$

where $E_1(x,y)$,$E_2(x,y)$ are the modal field profiles of the two interacting modes, β_1, β_2 are their corresponding propagation constants and *A*,*B* are amplitude constants of respective waveguides. The coupling between these two modes is described by the coupled mode equations

$$\frac{dA}{dz} = \kappa B e^{i\Gamma z} \tag{3}$$

$$\frac{dB}{dz} = \kappa A e^{-i\Gamma z} \tag{4}$$

where $\Gamma = \beta_1 - \beta_2 - K$ is the phase mismatch and κ is known as the coupling coefficient. The value of κ depends on the waveguide parameters, wavelength of operation, shape of the grating and the extend of periodic perturbation [17].

If $P_1(0)$ is the power launched into port 1 of waveguide 1 at z = 0, then at any value of z the powers propagating in two waveguides are given by

$$P_1(z) = P_1(0)\left(1 - \frac{\kappa^2}{\gamma^2}\sin^2 \gamma z\right) \quad (5)$$

$$P_2(z) = P_1(0)\frac{\kappa^2}{\gamma^2}\sin^2 \gamma z \quad (6)$$

where $\gamma^2 = \kappa^2 + 0.25\Delta\beta^2$ and $\Delta\beta = \beta_1 - \beta_2$. In the above equation, coupling coefficient κ is a measure of strength of interaction between two waveguides which depends on the separation between waveguides, grating height, wavelength of operation and shape of the grating.

The photonic switch made of two waveguides of identical propagation constant has $\Delta\beta = 0$. For such a case

$$P_1(z) = P_1(0)\cos^2(\kappa z) \quad (7)$$

$$P_2(z) = P_1(0)\sin^2(\kappa z) \quad (8)$$

At $z = \pi/2\kappa, 3\pi/2\kappa, 5\pi/2\kappa\ldots, (2m+1)\pi/2\kappa$, the power on the waveguide 1 is $P_1(z) = 0$ and the power on waveguide 2 is $P_2(z) = P_1(0)$, which indicates that the entire power is coupled to waveguide 2. The minimum distance at which the power completely transfers from one waveguide to other waveguide is given by $z = L_c = \pi/2\kappa$ and is referred as the coupling length. Strong interaction implies large value of κ and, hence, a small coupling length.

IV. Results and Discussions

The switching performance of an electro optic polymer waveguide switch is shown in figure.2 for rectangular, triangular and trapezoidal waveguide grating structures with phase matching assumption. The parameters considered in the simulation are refractive index of the film n_f=1.723, refractive index of the substrate n_s=1.711, waveguide spacing d= 4μm, grating height h = 2.5 μm. It can be seen that for complete power transfer from waveguide 1 to waveguide2, the switching time is 0.77 ps, 1.3 ps and 0.235 ps respectively. The trapezoidal waveguide grating structure provides lesser switching time when compared with other grating structures. It is also observed that the switching time of waveguide grating switch is much lesser than other switching technologies like optical MEMS switches[4][5], thermal optical switches [6][7] and PLZT electro optic switches[8][9].

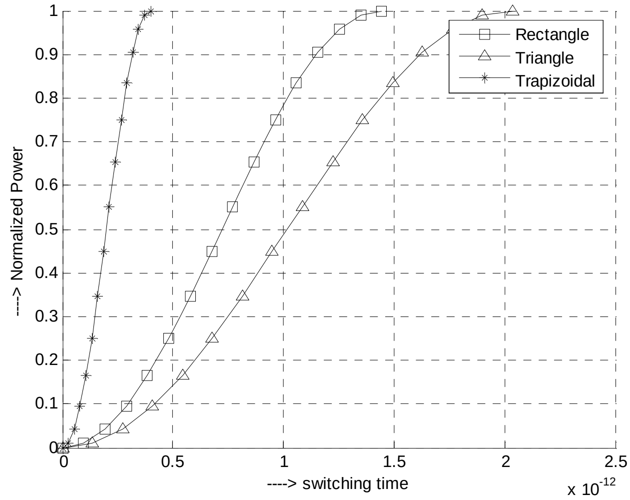

Fig. 2. Power transfer from waveguide 1 to waveguide 2 with n_{core} = 1.723, n_{clad}=1.711

The switching time is an important parameter to be considered in the design of optical switch. The switching time depends on the coupling length which in turn depends on the physical parameter of the structure such as waveguides separation, structure of grating, grating height and refractive indices of film and substrate. The response of switching time of the switch over various device parameters is discussed below.

The fig. 3 depicts the performance of the switch over the spacing between the waveguides. The waveguide spacing is varied from 3μm to 7μm with step size of 0.25μm. It is observed that as the waveguide spacing is reduced, the switching time reduces. It is also seen that trapezoidal grating structure gives much lower switching time when compared with other structures

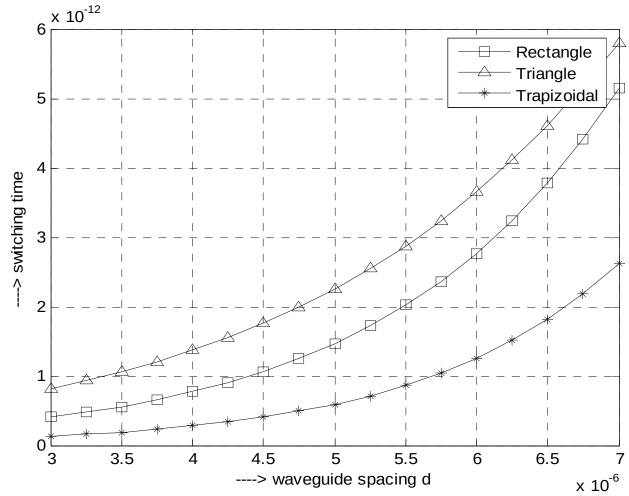

Fig. 3 Switching response of different grating profiles with waveguide spacing

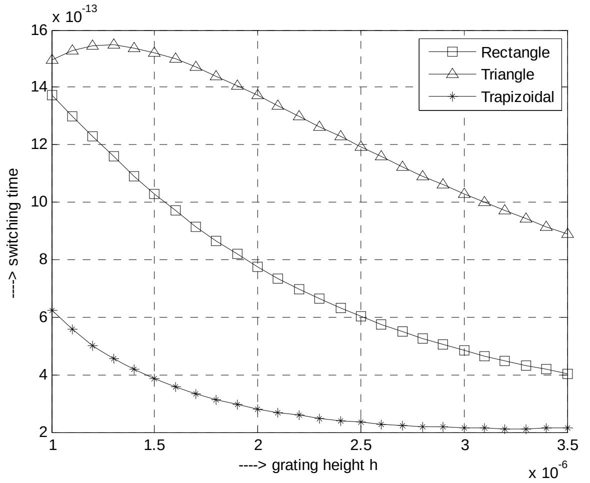

Fig. 4 Switching response of different grating profiles with grating height

The performance of the switch as a function of grating height is shown in figure 4. The grating height is varied from 1µm to 3.5µm. It can be seen that trapezoidal grating structure has fastest switching speed (0.23 ps) for an optimized grating height of 2.5 µm compared to other grating.

The switch is operated over the wavelength regime 900nm to 1600nm and the performance of the switch with operating voltage is studied for all grating profiles and shown in figure 5. It can be seen that the switching time reduces over wavelength till 1510nm for all the grating structure and in the WDM regime the switching is independent of wavelength. Above all trapezoidal grating provides the lowest switching time on the order of 0.2ps.

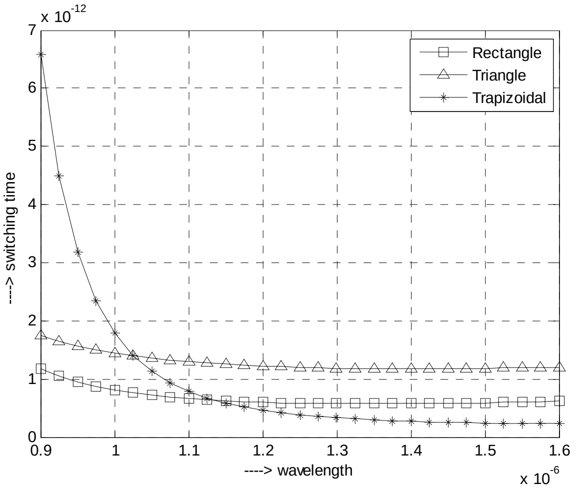

Fig. 5 Switching response of different grating profiles with wavelength

The above simulation results shows that trapezoidal grating structure provide faster switch taking into account all device parameters. So, this structure is considered for the design of the wavelength independent electro optic switch. The switching characteristic is measured by launching a light of wavelength 1550nm to port 1 of the switch. The switching was effected by applying or not applying control voltage to the electrodes. Figure 6 shows the characteristics of the switch in the bar state and cross state for the switch parameters refractive index of film 1.73, refractive index of substrate 1.711, waveguide separation 4µm and grating height 2.5µm. When no voltage is applied to the electrodes, the signal launched in port 1 comes out of port 3 with a coupling length of 81µm which is the bar state of the switch. The cross state of the switch is achieved by applying a control voltage of 11V to the electrodes. The applied voltage makes the relative index difference between the film and substrate to be changed from 0.012 to 0.0075. This index change makes the power launched in port 1 coupled to port 4 with a coupling length of 81µm. This represents the cross state of the switch. The switching time is on the order of 0.47ps. As the switching time is in pico seconds, this type of trapezoidal waveguide grating switch, finds application in fast recovery of intelligent optical networks in case of failure.

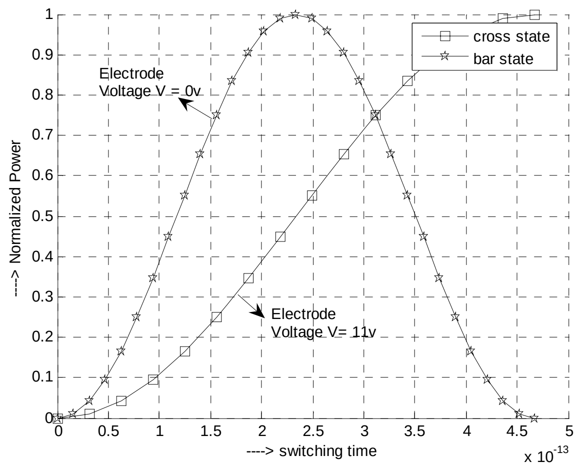

Fig. 6 Switching characteristics of a trapezoidal grating electro-optic switch

Comparison of switching time and wavelength dependency for optical mems switch, thermo optical switch, electro optic switch and newly proposed waveguide grating based polymer electro-optic switch is shown in table 1. It shows that the newly proposed polymer electro-optic waveguide grating switch has very low switching time and wavelength independency when compared with other types of switches.

TABLE I

Switch Type	**Switching Time**	**Wavelength Dependency**
Optical MEMS[3][4]	7 ms	No
Thermal optical switch using coated micro resonator[5][6]	100 ms	Yes
Electronically Switchable Bragg Grating switch[8]	50 ns	Yes
PLZT Electro-optic Switches[9]	10 ns	No
GaAs photonic crystal cavities switching[10]	15 ps	Yes
Photonic Crystal Optical Switch[11]	20 µs	Yes

V. CONCLUSION

The design of 2×2 polymer electro-optic switch is demonstrated. Coupled mode theory is used to study of switching characteristics of the proposed switch with device parameters like waveguide spacing, grating height and grating profile. In this paper we have analyzed rectangular, triangular and trapezoidal waveguide structures for the design of optical switch. The simulation result shows that trapezoidal grating structure provides high speed switching (0.47ps) and also the device length is found to be on the order of 81μm which makes the device compact. The switch is found to be wavelength independent beyond 1400 nm. From the above discussions it is concluded that trapezoidal grating is the optimized structure that can be used for faster provisioning of light paths and protection switching in intelligent optical network.

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