Thermo-optic Effects on Three Waveguide Directional Couplers

by Ary Syahriar

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ABSTRACT

We studied the thermo-optic effects in detuned antisymmetric three waveguide directional couplers analytically, we analyzed the effects on switching operation on several temperature changes, which cause different switching characteristics, especially the value of propagation constant mismatch. Based on this research, it concluded that the system with three identical waveguides in which the beam launched into middle waveguide is better system to withstand cross state condition in higher temperature. Note that the system's limit changes of propagation constant mismatch in which could hold the cross state performance is $\Delta\beta$ = -0.4 – 0.4 before heated, $\Delta\beta$ = -1.4 – 1.4 after heated 10°C and $\Delta\beta$ = -2.7 – 2.7 after heated 20°C.

Keywords: thermo-optic effect, detuned antisymmetrically three-guide directional coupler, cross state, propagation constant mismatch.

1. INTRODUCTION

Two waveguide directional coupler is the common optical coupler components used in optical communcation system. It has two input ports and two output ports, and is composed of two closely spaced waveguides. By placing a third waveguide between the two waveguides is what this paper analyzed. One advantage of using this scheme is that it can reduce the physical length of the device significantly from conventional system due to minimum coupling length requirement[1]. But at the time of fabrication, frequent imperfections happen in the making of coupling length of the coupler. In this manner, to balance it out, the propagation constant mismatch or $\Delta\beta$ between two interacting waveguides or the coupling constants can be varied electrically to match the imperfection[2]. Then the optical beam is switched completely from one waveguide to another (cross state) without changing the coupling length which function of propagation direction. In this paper, Applying three silica (SiO_2) waveguides of an optical switch are identical and equally spaced and used 1550 nm in wavelength, we examine the switching mechanism for cases where an initial power/beam is launched into a waveguide one and into a waveguide two. For each power-launched case, switching voltage is applied so that the overall index is detuned antisymmetrically. After the system is detuned, we observing temperature dependence as function of propagation constant mismatch where the cases are heated every 10°C from assume the initial temperature is 25°C to 45°C.

2. TEMPERATURE EFFECT ON REFRACTIVE INDEX

The thermo-optic effect is a phenomenon by which the refractive index of a substance changes with temperature. In most used material like silica glass, this effect is characterized by an increase in the refractive index as the temperature rises. Since absolute refractive index is generally a function of both wavelength and temperature, it is important to know refractive indices at the optical system's design operating temperature. Further, for large, refractive, optical components, spatial variation of both a material's refractive index and its thermo-optic coefficient (dn/dT) can be potentially damaging to optical system performance[3].

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Differentiating the Lorentz-Lorenz equation with respect to temperature, gives the temperature dependence of refractive index[4]. Decreasing density with temperature decreases refractive index, whereas a positive change in polarizability with temperature incerases refractive index. Therefore, high thermal expansion materials such as the alkali and thallium halides have negative thermo-optic coefficients, whereas low thermal expansion materials such as diamond and silicon carbide have positive thermo-optic coefficients (TOC). Due to small contribution of thermal expansion coefficient (TOE) to influence the switching, so that it can be ignored.

In this study, the typical values of the refractive index of the SiO2 are around 1.4 and at 1550 nm, respectively[5]. Relation between refractive index and thermo-optic coefficient given by[6] :

$$n_T = n_R + (T - R)\left(\frac{dn}{dT}\right) \tag{1}$$

where T is the temperature in ^{0}C, R is the room temperature, n_T and n_R are the refractive index at T and at room temperature, respectively. From equation (1) gives positive TOC on this proposed 7 μm core width planar waveguide-type which the relation between effective refractive index as function of temperature as shown in Figure 1 below.

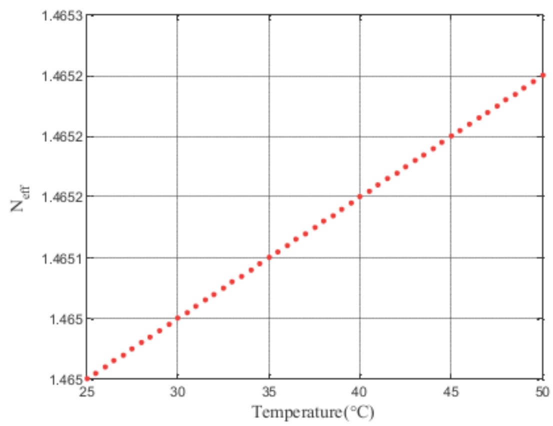


Figure 1. Increases effective refractive index as function of rising temperature for 7 microns width of core SiO_2 planar waveguide-type.

3. THREE WAVEGUIDE DIRECTIONAL COUPLER SYSTEM

Consider the waveguides are identical, symmetric, equally spaced as Figure 2. The coupled-mode equations for this three-waveguide system are described as follows[7]:

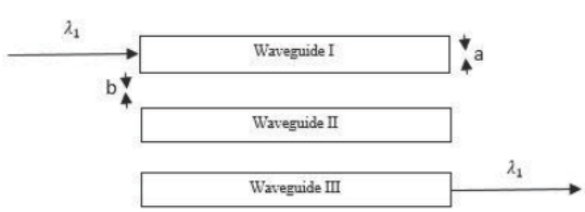


Figure 2. The proposed system of three identical directional coupler on this SiO_2 planar type waveguide where a and b are both 7 microns and refractive index n=1.465 at λ=1550 nm.

$$\frac{d}{dz}A_1(z) = -j\kappa_1 A_2(z)e^{j\Delta\beta_1 z} \tag{2a}$$

$$\frac{d}{dz}A_2(z) = -j\kappa_1 A_1(z)e^{-j\Delta\beta_1 z} - j\kappa_3 A_3(z)e^{-j\Delta\beta_3 z} \tag{2b}$$

$$\frac{d}{dz}A_3(z) = -j\kappa_3 A_2(z)e^{j\Delta\beta_3 z} \tag{2c}$$

Where

$$\Delta\beta_1 = \beta_1 - \beta_2 \tag{3a}$$

$$\Delta\beta_3 = \beta_3 - \beta_2 \tag{3b}$$

β_1, β_2 and β_3 is the propagation constant of each waveguide. $\Delta\beta_1$ and $\Delta\beta_3$ are extent of detuning of β_1 and β_3 from β_2, respectively. Since in this paper, where the case of each waveguide is identical and equally spaced, $\kappa_1 = \kappa_3 = \kappa$.

The solution when $\Delta\beta_1 = \Delta\beta_3 = 0$ can be written as[8] :

1. Initial condition for waveguide 1 as source of power is applied inside of it will be:

$$a(z) = \begin{bmatrix} \frac{1}{2} + \frac{1}{2}\cos\left(\kappa\sqrt{2}z\right) \\ -\frac{1}{\sqrt{2}}\,\mathrm{j}\sin\left(\kappa\sqrt{2}z\right) \\ -\frac{1}{2} + \frac{1}{2}\cos\left(\kappa\sqrt{2}z\right) \end{bmatrix} \tag{4a}$$

2. Initial condition for waveguide 2 as source of power is applied inside of it will be:

$$a(z) = \begin{bmatrix} -\frac{1}{\sqrt{2}}\,\mathrm{j}\sin\left(\kappa\sqrt{2}z\right) \\ \cos\left(\kappa\sqrt{2}z\right) \\ -\frac{1}{\sqrt{2}}\,\mathrm{j}\sin\left(\kappa\sqrt{2}z\right) \end{bmatrix} \tag{4b}$$

From initial condition 1 above, we can get the coupling length by:

$$L_{c1} = \frac{\pi}{\sqrt{2}\kappa}(2m-1) \tag{5}$$

From initial condition 2 above, we can get the coupling length by:

$$L_{c2} = \frac{\pi}{2\sqrt{2}\kappa}(2m-1) \quad (6)$$

It shows that when the initial power is launched into different waveguide, the power will switched to another waveguide at different length, based on Equation (5) and (6) above. When the electric field is applied to waveguide via electrodes, the overall index profile is changed due to the electro-optic effect. In order to analyze the behavior of optical switching, we observing $(\Delta\beta_1, \Delta\beta_3)$ into $\Delta\beta_1 = -\Delta\beta_3 = \Delta\beta$, which is called detuned antisymmetrically.

4. ANTISYMMETRIC DETUNING

Antisymmetric detuning means that the overall β's of both waveguides one and three are changed from that of waveguide two by the same amount but in opposite directions[8]. Therefore, $\Delta\beta_1 = -\Delta\beta_3 = \Delta\beta$.

The solutions for antisymmetric detuning in term of matrix will be[7],

$$\begin{bmatrix} a_1(z) \\ a_2(z) \\ a_3(z) \end{bmatrix} = \begin{bmatrix} c_1 + \frac{\kappa^2}{\kappa'^2} & c_2 & c_3 - \frac{\kappa^2}{\kappa'^2} \\ c_2 & 2c_3 + \frac{\Delta\beta^2}{\kappa'^2} & -c_2{}^* \\ c_3 - \frac{\kappa^2}{\kappa'^2} & -c_2{}^* & c_1{}^* + \frac{\kappa^2}{\kappa'^2} \end{bmatrix} \cdot \begin{bmatrix} a_1(0) \\ a_2(0) \\ a_3(0) \end{bmatrix} \quad (7)$$

Where

$$c_1 = \left(1 - \frac{\kappa^2}{\kappa'^2}\right)\cos\kappa' z - j\frac{\Delta\beta}{\kappa'}\sin\kappa' z$$

$$c_2 = -j\frac{\kappa}{\kappa'}\sin\kappa' z + \frac{\kappa\Delta\beta}{\kappa'^2}(\cos\kappa' z - 1)$$

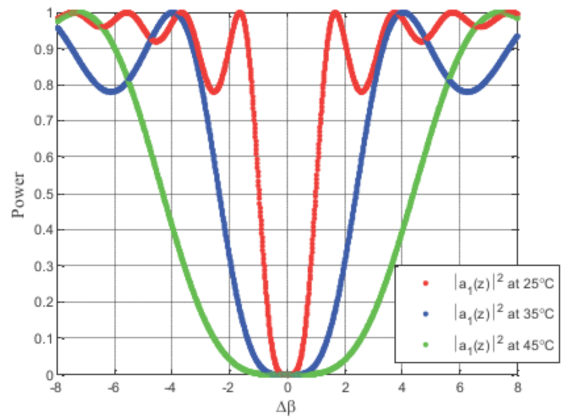
$$c_3 = \frac{\kappa^2}{\kappa'^2}\cos\kappa' z$$

$$\kappa'^2 = \Delta\beta^2 + 2\kappa^2 \quad (8)$$

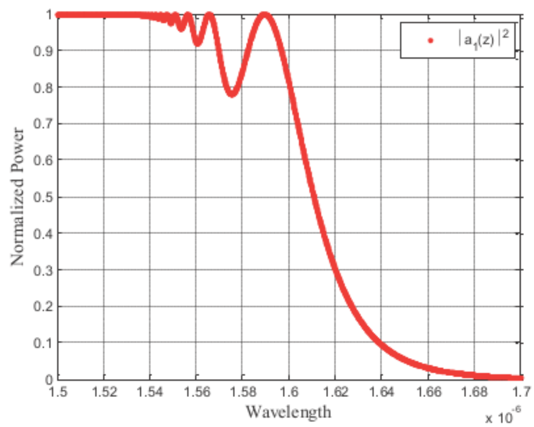
4.1 Initial power launched into waveguide one

Since the light is launched entirely into waveguide one, the initial conditions are $a_1 = 1$, $a_2 = 0$, $a_3 = 0$ at $z = 0$. And for the beam incident on waveguide one to cross over to waveguide three completely at $z = L$, the following conditions are required: $a_1 a_1{}^* = a_2 a_2{}^* = 0$, $a_3 a_3{}^* = 1$. From Eq. (7), the initial conditions equation for detuned antisymmetrically will be

$$\begin{bmatrix} a_1(z) \\ a_2(z) \\ a_3(z) \end{bmatrix} = \begin{bmatrix} c_1 + \frac{\kappa^2}{\kappa'^2} \\ c_2 \\ c_1 - \frac{\kappa^2}{\kappa'^2} \end{bmatrix} \quad (9)$$



(a)



(b)

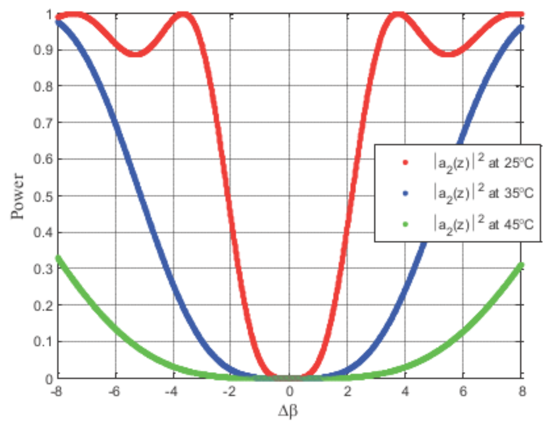
Figure 3. (a) Switching operation in three-guide detuned antisymmetrically in which beam launched into waveguide one system as function of temperature. (b) The relation between normalized power as fuction of wavelength range for optical communication.

Figure 3 (a) above shows how the switching operation on three waveguide system with detuned antisymmetrically in which beam is launched into waveguide one before heated (red line), after heated 10^{o}C (blue line) and heated 20^{o}C (green line) using thermo-optic effect from Equation (1), it will have perfect switched (cross state) to waveguide three only if $\Delta\beta$=0 where z or L_{c1} (coupling length) in Eq. (7) are multiple odd integer. Figure 3 (b) shows the $a_1(z)$ in matrix Equation (9) relates with applicable wavelength. Note from Figure 3 (a), the range in order to keep cross state condition, ($\Delta\beta$ = -0.1 - 0.1) before heated, ($\Delta\beta$ = -0.7 - 0.7) after heated 10^{o}C, and ($\Delta\beta$ = -1.15 - 1.15) after heated 20^{o}C, and requirement for bar state condition, $\Delta\beta$ = 1.732 before heated to 4 after heated 10^{o}C and 7.2 after heated 20^{o}C.

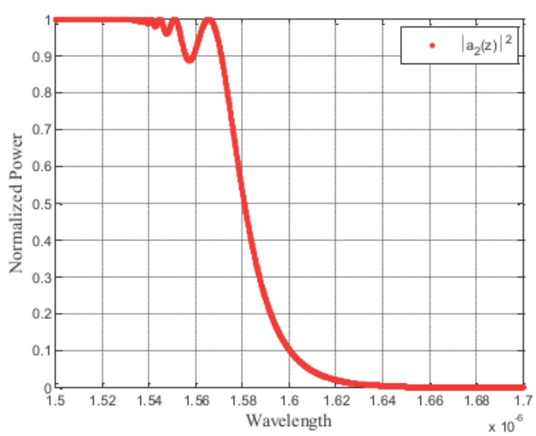
4.2 Initial power launched into waveguide two

Since the light is launched into waveguide two, the initial conditions are $a_1 = 0$, $a_2 = 1$, $a_3 = 0$ at $z = 0$. And for the beam incident on waveguide one to cross over to waveguide three completely at $z = L$, the following conditions are required : $a_1 a_1^* + a_3 a_3^* = 1,\ a_2 a_2^* = 0$. From Eq. (7), the initial conditions equation for detuned antisymmetrically will be

$$\begin{bmatrix} a_1(z) \\ a_2(z) \\ a_3(z) \end{bmatrix} = \begin{bmatrix} c_2 \\ 2c_3 + \frac{\Delta\beta^{2^*}}{\kappa'^2} \\ -c_2^{\,*} \end{bmatrix} \tag{10}$$



(a)



(b)

Figure 4. (a) Switching operation in three-guide detuned antisymmetrically in which beam launched into waveguide two system as function of temperature. (b) The relation between normalized power as fuction of wavelength range for optical communication.

Figure 4 (a) above shows how the switching operation on three waveguide system with detuned antisymmetrically in which beam is launched into waveguide two before heated (red line), after heated 10°C (blue line) and after heated 20°C (green line), it will have perfect switching only if $\Delta\beta$=0. And for bar state condition it will require minimum $\Delta\beta=\sqrt{15}$. But there is no requirement for exact length ratio for switching to occur. Figure 4 (b) shows the $a_2(z)$ in matrix Equation (10) relates with applicable wavelength. Note from Figure 4 (a), the range in order to keep cross state condition, ($\Delta\beta$ = -0.4 - 0.4) before heated and ($\Delta\beta$ = -1.4 - 1.4) after heated 10°C, and ($\Delta\beta$ = -2.7 - 2.7) after heated 20°C, and for bar state requirement condition, $\Delta\beta$ = 3.87 before heated to 8.8 after heated 10°C and turn to 16 after heated 20°C.

5. CONCLUSION

The changes in switching operation on three waveguide directional coupler with detuned based on thermo-optic effect are analyzed. Results are summarized as follows.

1. For the case where the initial power is launched into waveguide one and the system is detuned antisymmetrically, odd integer multiples of L_{c1} are required for the perfect switching.
2. For the case where the initial power is launched into waveguide two and the system is detuned antisymmetrically, is expected to play important role because there are no requirement for exact length ratio for switching to occur. Thus, even in the case where the switch is operated at another waveguide so that a different coupling length may be required, only an adjustment of the applied voltage allows a complete switching operation.
3. From simmulation results, it clearly show us that the systems after heated more impervious to keep the switching performance (cross state) while as it shifting the propagation constant mismatch due to rising temperature, but the system after heated will effecting to the bar state condition where each system has higher $\Delta\beta$ value to satisfy that power completely return back to initial waveguide than before they heated. And the system with three waveguides directional coupler detuned antisymmetrically where the initial power is launched into waveguide two has better cross state condition system at 35°C and 45°C but the system has the biggest requirement value of $\Delta\beta$ for bar state condition compared to the system where the initial power is launched into waveguide one.

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