International Journal of Latest Technology in Engineering, Management & Applied Science (IJLTEMAS)
Volume VI, Issue VI, June 2017 | ISSN 2278-2540

Simulated Characteristics of a Nonlinear Directional Coupler Based Optical Switch

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***Abstract*-This paper presents a nonlinear directional coupler for optical power switching. The theoretical study has been done to study the coupling characteristics of the nonlinear directional coupler. Variation of the coupling coefficients with wavelength have been done, and found that, out of all four coupling coefficients, nonlinear coupling coefficient (equivalent to self-phase modulation) decreases with the wavelength. The wavelength dependency of the critical power is studied. We have study the variation of coupling coefficients with the width of waveguide and realized that single mode waveguide with smaller core width have lower critical power. Here, we have proposed a noble design of NLDC with asymmetric waveguide along the length with lower critical power as compare to the symmetric waveguide directional coupler.**

***Keywords*: Directional coupler; waveguide; critical power; optical switch; coupling coefficient**

I. INTRODUCTION

The nonlinear directional coupler (NLDC) has many interesting applications in integrated optical system, such as in optical computing and ultra-fast communication systems. Optical switching is very important for high speed telecommunication and silica is a promising material for optical switching. Optical switching using the optical Kerr effect in single mode fiber has been reported in [1-2]; however, silica has very small nonlinear coefficient. Due to small nonlinearity, very long (few kilometers) fibers were used for switching purpose. To overcome the need for long fiber length, materials with high third order nonlinearity have been employed by various researchers. A nonlinear directional coupler with chalcogenide (ChG) material was first proposed by Jensen in 1982 [3]. ChG glasses are low-phonon-energy materials and are transparent from the visible to the infrared region. These glasses have been used in a large number of applications such as fiber amplifiers, diffraction gratings, optical switching, and waveguide fabrication [4-6]. Application of ChG glass fibers in ultrafast optical switches has been reported, and the switching efficiency has been studied with optical Kerr shutter experiments [7]**.** The NLDC with ultrafast laser inscriptions technique in gallium lanthanum sulphide glasses has also been presented experimentally [8]. A comparison study of Beam Propagation method and coupled mode theory for NLDC has been presented [9]; here the author has presented dependence of critical power on width of coupling region. All the researches have been done on linear coupling coefficient variation with propagation distance [10-12].

In this paper, we present a noble design of nonlinear directional coupler to reduce the optical switching power. To study the switching properties of NLDC, coupled mode theory has been used. The switching ability of NLDC depends on input coupled power and coupling between the two waveguides of the directional coupler. This coupling is affected by wavelength of the input light, length of the coupling region, spacing between the two waveguides and width of each waveguide of directional coupler. We have investigated how coupling coefficients influence switching power. We have presented a noble design of directional coupler to reduce the optical switching power.

In Section II, we show theoretical description by using coupled mode theory. In section III, we present numerical results and discussion. In section IV, we proposed a design of NLDC, followed by conclusion in Section V.

II. THEORETICAL DESCRIPTION

As a switching device, directional coupler consists of two interacting single-mode waveguides. These two single-mode waveguides placed close to each other in such a way that the coupling between their evanescent fields occur. When input power is low, it will couple into the second waveguide of the directional coupler at the coupling length ($L_c = \frac{\pi}{2K_2}$).

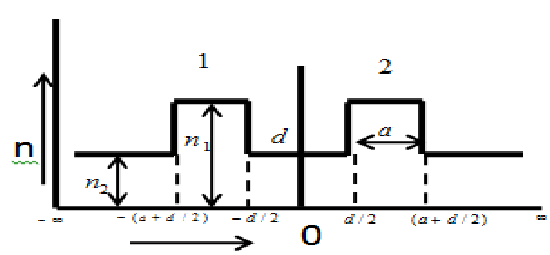

Figure 1: Refractive index profile of directional coupler

As we increase the input power, nonlinear effects change the coupling length and cause less light to be coupled into the second waveguide. As power reaches above the critical value, the light remains in the first waveguide, therefore, the directional coupler will work as an optical switch. Thus, a change in input intensity can cause light to be switched from one waveguide to the other at the output of the device. To study the characteristics of NLDC, the coupled mode theory has been used. The refractive index profile of the NLDC is shown in figure 1.

Refractive index profile for the directional coupler,

$$n(x) = n_1 \quad \text{for } -(a+\frac{d}{2}) < x < -(\frac{d}{2}) \text{ and } \frac{d}{2} < x < (a+\frac{d}{2})$$

$$n(x) = n_2 \quad \text{for other values of } x$$

Refractive index profile for waveguide 1,

$$n_{wg}(x) = n_1 \quad \text{for } -(a+\frac{d}{2}) < x < -(\frac{d}{2})$$

$$n_{wg}(x) = n_2 \quad \text{for other values of } x$$

Refractive index profile for waveguide 2,

$$n_{wg}(x) = n_1 \quad \text{for } \frac{d}{2} < x < (a+\frac{d}{2})$$

$$n_{wg}(x) = n_2 \quad \text{for others values of } x$$

To solve the propagation problem for two single mode symmetric waveguides using coupled mode theory, one gets following equations [3]:

$$i\frac{\partial A}{\partial z} = K_1 A + K_2 B + (K_3|A|^2 + 2K_4|B|^2)A \qquad (1)$$

$$-i\frac{\partial B}{\partial z} = K_1 B + K_2 A + (K_3|B|^2 + 2K_4|A|^2)B \qquad (2)$$

where A and B are the normalized amplitudes of the mode fields of waveguides1 and 2, respectively and coupling coefficients are as follows:

$$K_1 = \frac{\omega}{4\pi P_0}\int_{-\infty}^{\infty}\psi_1^* \Delta n_1^2 \psi_1 dx \qquad (3)$$

$$K_2 = \frac{\omega}{4\pi P_0}\int_{-\infty}^{\infty}\psi_1^* \Delta n_2^2 \psi_1 dx \qquad (4)$$

$$K_3 = \frac{n\omega n_2}{\pi P_0}\int_{-\infty}^{\infty}|\psi_1|^4 dx \qquad (5)$$

$$K_4 = \frac{n\omega n_2}{\pi P_0}\int_{-\infty}^{\infty}|\psi_1|^2|\psi_2|^2 dx \qquad (6)$$

From improved coupled mode theory [13], we have used the nonlinear perturbation theory.

$$\Delta n_1^2 = (n^2(x,y) - n_{wg}^2(x,y)) + \varepsilon_0 c n_0^2 n_2 |\psi_1|^2$$

$$\Delta n_2^2 = (n^2(x,y) - n_{wg}^2(x,y)) + \varepsilon_0 c n_0^2 n_2 |\psi_2|^2$$

ψ_1 and ψ_2 are the electric fields of the two modes, $k_0 = 2\pi/\lambda$, λ is wavelength; β is the propagation constant in the waveguide; $n_1 = 2.398$ and $n_2 = 2\text{x}10^{-18}$ m^2/W are linear and nonlinear refractive indices respectively; P_0 is the normalized input power; c is velocity of light; ε_0 is the free space electric permittivity; Δn_1^2 and Δn_2^2 is the perturbing refractive index of waveguides. Here a_1=6μm and a_2=8μm is the core diameter of each waveguide, d=9μm is the spacing between two waveguides. K_1 is due to the overlap of the mode field with the adjacent waveguide. K_2 arises due to the linear coupling between two fields of adjacent waveguide. K_3 is the strongest nonlinear term, and arises due to nonlinear interaction with itself. It is equivalent to self-phase modulation. K_4 arises due to nonlinear interaction of one mode field with the mode field of adjacent waveguide.

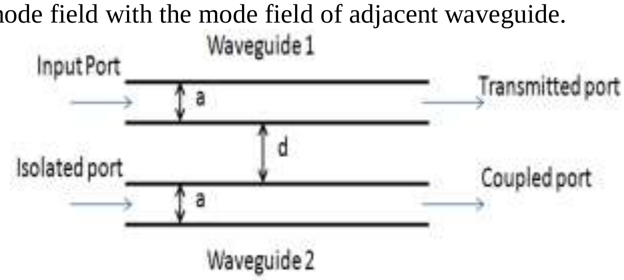

Figure 2: Schematic of nonlinear directional coupler.

III. NUMERICAL RESULTS AND DISCUSSION

Numerical simulations have been carried out by solving coupled mode equations (1) and (2).

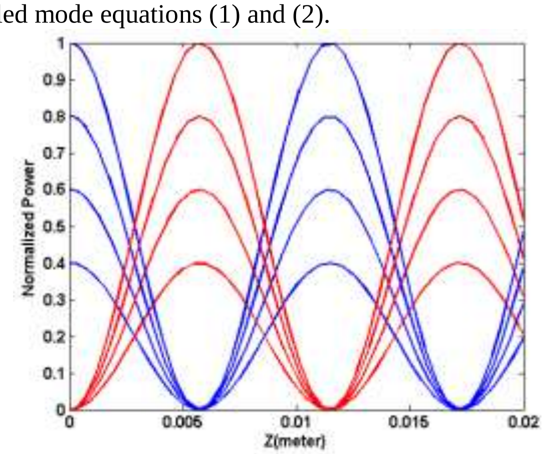

Figure 3: Transmitted and coupled power in the waveguide 1 and waveguide 2

Normalized power passing through the waveguide has been shown with propagation distance into the two waveguides of directional coupler.

Figure 3 shows the transmitted and coupled normalized power of the nonlinear directional coupler, when the nonlinear coupling coefficients K_3=0, and K_4=0. It means there is no coupling due to third order nonlinearity and hence directional coupler should behave like a linear directional coupler. Hence, plot is also equivalent to well-known linear directional coupler. Here the optical power couples and decouples between the two waveguides with a constant coupling length for all input powers. Figure 4(a) and 4(b) shows that the normalized power propagates along the Waveguide 1 in nonlinear directional coupler. It shows input output characteristics of nonlinear directional coupler for various input powers at wavelength 1064nm and 800nm respectively. From the comparison of these two figures, one can see that input output characteristic of NLDC changes at lower value of power at wavelength 800nm than at wavelength 1064nm. Hence the critical power of NLDC at wavelength 800nm is small as compare to the wavelength 1064nm.

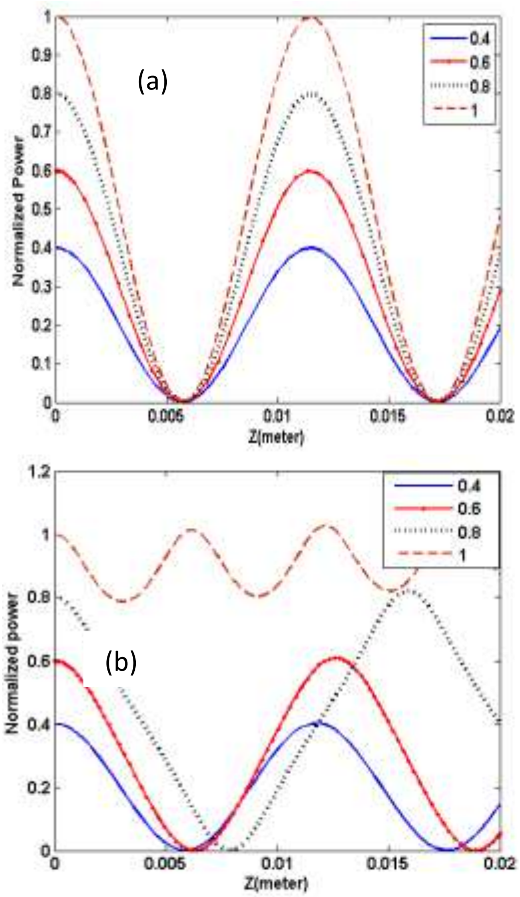

Figure 4: Transmitted normalized power in waveguide1 along the directional coupler at wavelength 1064nm (Fig. a) and at wavelength 800nm (Fig. b) for five different input powers.

Above the critical value, the directional coupler does not allow coupling into second waveguide. This is because of the decoupling induced by nonlinear refractive index; nonlinearity arises between the two waveguides of directional coupler, which drives the two waveguides out of phase. In this way, it works as an optical switch. For optical switching, it requires high Kerr nonlinearity.

In a conventional linear directional coupler, there are two coupling coefficients K_1 and K_2. Switching behavior of linear coupler is very sensitive to interaction length and the wavelength of operation. We have studied nonlinear directional coupler with high third order nonlinearity. We have studied the variation of all four coupling coefficients with wavelength and different input powers. Figure 5(a) shows the variation of linear coupling coefficient K_1 with wavelength. K_1 increases with wavelength but it remains same for all input powers. Figure 5(b) shows the variation of linear coupling coefficient K_2 with wavelength. It also increases with wavelength but does not depend on input powers.

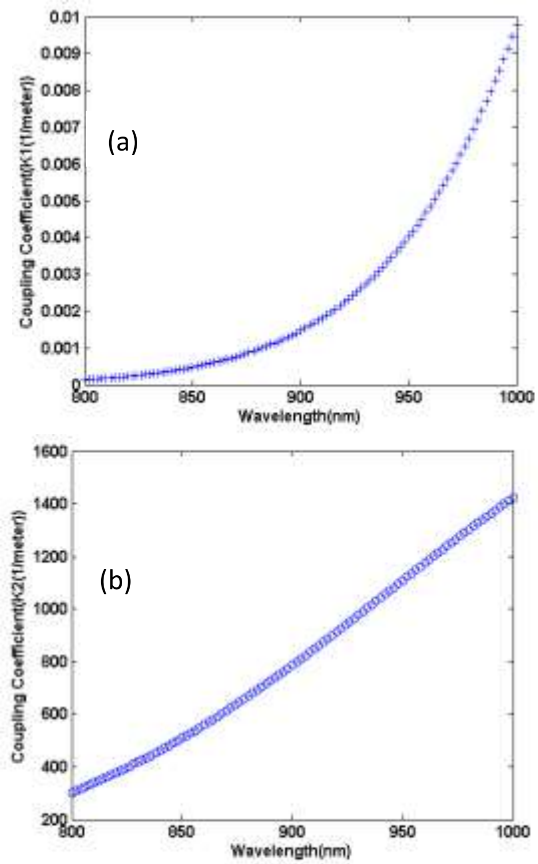

Figure 5: Variation of linear coupling coefficient K_1 (fig. a) and K_2 (Fig. b) with wavelength.

Figure 6(a) shows variation of nonlinear coupling coefficient K_3 with wavelength for five different input powers. Here we can see that, as we increase the wavelength, the nonlinear coupling coefficient decreases. As discussed earlier that, K_3 is due to nonlinear interaction in the same waveguide that is equivalent to self-phase modulation. This is because; when the wavelength increases, the power confinement in the waveguide decreases. Hence the nonlinear interaction in the same waveguide decreases due to which coupling coefficient decreases. Figure 6(b) shows the variation of K_4 with wavelength; like the linear coupling coefficients, it also increases with wavelength.

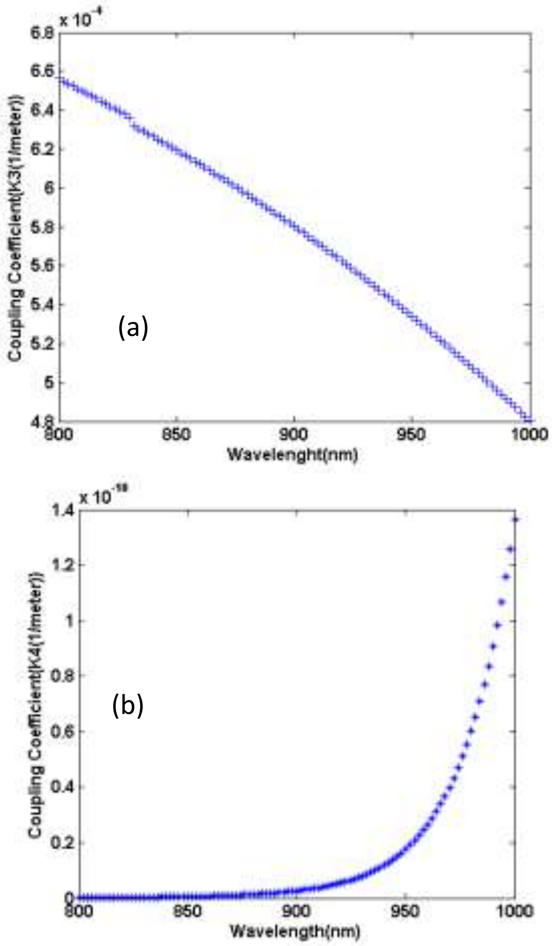

Figure 6: Variation of nonlinear coupling coefficient K_3 (Fig. a) and variation of K_4 (Fig. b) with wavelength.

Here we can see for the same input power, the directional coupler at wavelength 800nm shows switching behavior but at wavelength 1064nm it does not show switching behavior. Thus, we can conclude that switching behavior of NLDC depends upon K_3 because only K_3 is high at wavelength 800nm. On the other hand, all other coupling coefficients are low at wavelength 800nm as compare at wavelength 1064nm. Hence to reduce the switching power we need to increase the K_3 coupling coefficient. Figure 7 shows the variation of critical power with wavelength. Here we can estimate the percentage increment of critical power with respect to the wavelength. Critical power increased more than 70% when wavelength increases from 800nm to 1050nm.

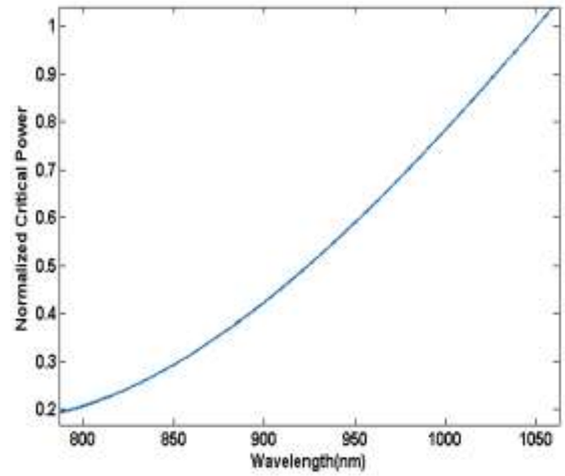

Figure 7: Variation of critical power with wavelength.

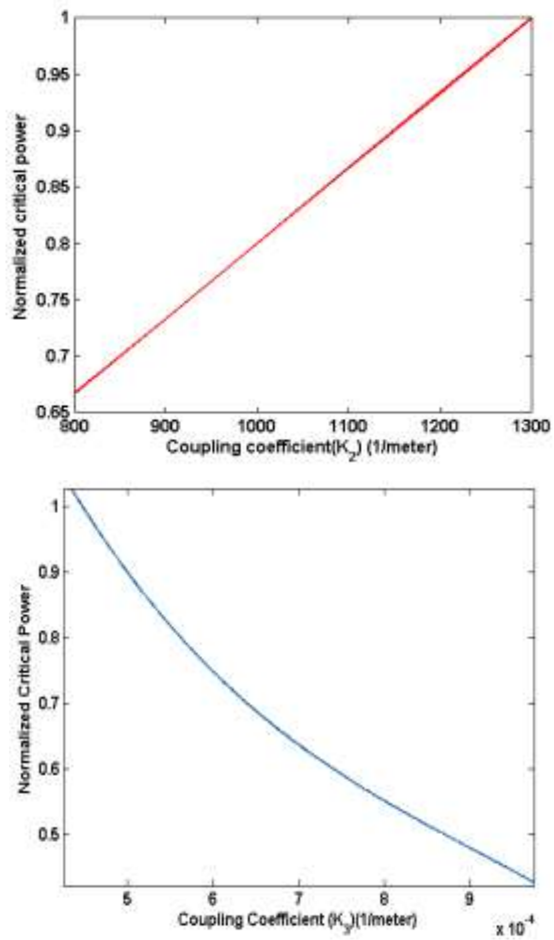

Figure 8: Fig. (a) and Fig. (b) showing variation of normalized critical power with linear coupling coefficient (K_2) and nonlinear coupling coefficient (K_3) respectively.

Figure 8(a) and 8(b) showing the variation of linear coupling coefficient (K_2) and nonlinear coupling coefficient (K_3) with critical power. Critical power linearly increasing with K_2 and linearly decreasing with K_3. Hence, for lower switching power, K_3 should be high and K_2 should be small.

IV. PROPOSED DESIGN OF NLDC

We have proposed a noble design of NLDC. In this NLDC the spacing between two waveguides remains same along the length of NLDC but the width of each waveguide reduces along the length. The schematic of NLDC is shown in figure 9. The variation of coupling coefficient K_3 with the width of waveguides is shown in figure 10. Coupling coefficient K_3 increases as we decrease the width of waveguide. Hence to reduce the switching power one should use directional coupler with smaller core width.

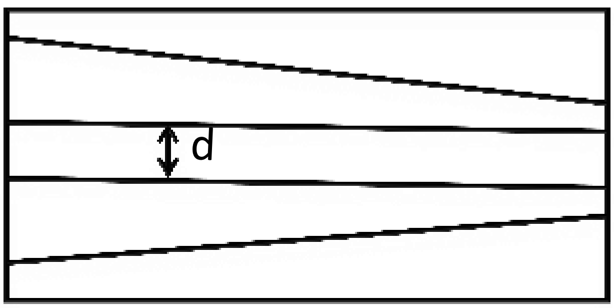

Figure 9: Schematic of nonlinear directional coupler.

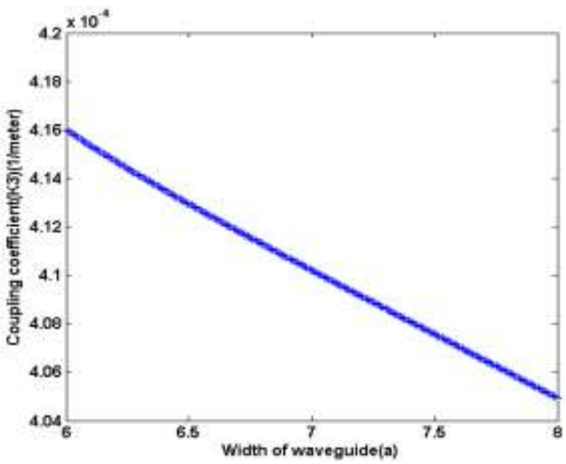

Figure 10: The variation of coupling coefficient K3 with the width of waveguides

This structure has advantages over a symmetric structure along the length. Coupling into the single mode waveguide with large core width is more convenient as compare to smaller core width. Nonlinear interaction area increases as compare to symmetric waveguide of smaller width. Fabrication of larger core width waveguide is also easy.

V. CONCLUSION

In this paper, we have studied the NLDC by using nonlinear coupled mode equations for optical power switching. The NLDC behave as an optical power switch above the critical power. We have presented variation of the coupling coefficients with wavelength. It is found that, out of all four coupling coefficients, nonlinear coupling coefficient (equivalent to self-phase modulation) decreases with wavelength. The quantitative increment of critical power with wavelength is shown. For better optical switching, NDLS should have small wavelength and high nonlinear coupling coefficient K_3 and small linear coupling coefficient K_2. We have study the variation of coupling coefficient with the width of waveguide. We realized that single mode waveguide with smaller core width have more nonlinear coupling coefficient (K_3). We have shown a noble design of NLDC with asymmetric waveguide along the length.

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