Optik 126 (2015) 404–407

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

Optical pulse controlled two mode interference coupler based logic gates

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ARTICLE INFO

Article history:
Received 19 September 2013
Accepted 24 April 2014

Keywords:
TMI
Optical logic gates
MMI

ABSTRACT

In this paper, an optical pulse controlled 1×2 two mode interference (OTMI) coupler having silicon core and GaAsInP cladding has been introduced as NOT and AND gates. The coupling characteristics of OTMI coupler are analyzed by using a simple mathematical model based on sinusoidal modes. It is seen that the length of OTMI based logic gate is eight times lower than that of existing MMI coupler based logic gates and the effect of power imbalance on fabrication tolerances of the device is also less than that of MMI device.

1. Introduction

In recent years, optical processors have become essential for address recognition, label swapping, and data encryption in optical domain for present day's high speed communication. All optical logic gates are key components for these applications and these logic gates have been demonstrated using optical fibers [1], semiconductor optical amplifiers [2], photonic crystals [3,4], dielectric microring resonators [5,6] and multimode interference (MMI) coupler [7]. Out of these, MMI coupler has been focused for the implementation of optical logic gates because of simple configuration and polarization insensitivity. Compactness of optical logic gates has been made by using silicon waveguide with silica cladding [8], directional couplers (DC) with semiconductor based nonlinear waveguides [9] and nonlinear optical loop mirror [10]. But it is observed that the fabrication of these devices [8–10] with exact design parameters is not impossible and the slight deviation of these device parameters (during fabrication) will affect much more on the performance because of having more number of waveguide parameters [8–10]. In this direction, we have already shown [11] that two mode interference coupler has higher fabrication tolerance than other compact devices.

Most of the recent works on all optical integrated optical devices are based on high index contrast waveguide materials such as GaAsInP (III–V compounds) [12], silicon [5,6,8,13], etc. Out of these materials, silicon is a promising material for the fabrication of these devices because of compatibility with matured conventional IC technology, compactness, polarization insensitivity, etc. Recently all optical flip-flop based on micro-disk laser using silicon nanowire is reported [12] but it has complicated structure requiring more number of fabrication steps.

In this paper, we have proposed optically controlled two mode interference coupler as a NOT and AND gate. The dependency of the coupling characteristics on the applied optical pulse has been shown. In optical logic operation of the coupler, no power is treated as a bit 'O' whereas signal power is treated as a bit '1'. The fabrication tolerances of OTMI coupler is shown and compared with existing optical logic gate based on MMI coupler.

2. Device concept

The detailed theory and applications of conventional two mode interference coupler have been studied by many researchers [11,14,15]. For the use of TMI coupler in all optical devices, the propagation of two excited modes in TMI region are required to be controlled by optical pulse. Fig. 1 shows optical pulse controlled two mode interference coupler consisting of two mode coupling region of width 2 w and coupling length L_C and single mode input access waveguide (waveguide-1) of core width w and two single mode output access wave guide (3rd and 4th) of same width and thickness. It is already seen by previous authors [16] that GaAsInP material shows non-linear refractive index change with fast recovery time ~1 ps and the non-linear index co-efficient is $n_{nl} = -2 \times 10^{-3}\ \mu m^2\ W^{-1}$ at wavelength $\lambda = 1.53\ \mu m$. The core is made up of silicon material with refractive index n_1 (which is not changed with applied optical pulse in the cladding). The cladding is made up of GaAsInP material and its refractive index $n_2(E)$,

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http://dx.doi.org/10.1016/j.ijleo.2014.04.100
0030-4026/

II. **Device concept**

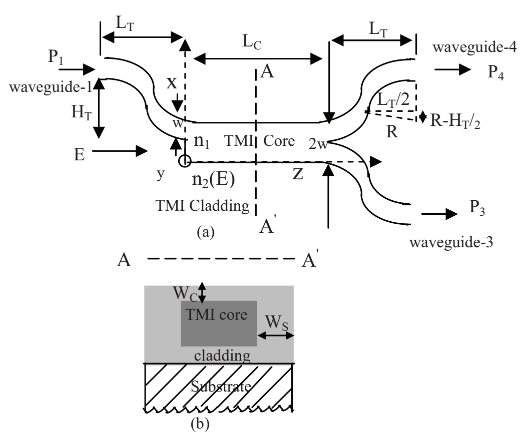

Fig. 1. Schematic of optically controlled two mode interference coupler using channel waveguide with TMI core of width 2 w and length L_c. (a) Top view and (b) cross-sectional view in TMI region along line AA′.

depending on applied optical pulse of energy E (unit in Joule) generated by KCl: Tl^0 laser [16,17]) is expressed as,

$$n_2(E) \approx n_2(0) + \frac{n_{nl}.E}{1.065A_{\text{eff}}.T_w} \tag{1}$$

where, T_w is width of pulse at half maximum power of pulse and A_{eff} is obtained from the figure as $(2W_S + 2w)(2W_C + w) - 2w^2$ which is basically cladding cross-sectional area (where W_C is upper cladding width which is same as lower upper cladding width, W_S is side cladding width) of TMI. In the figure, the input power, P_1 is launched to TMI region at waveguide-1 and the output power at waveguide-3 and 4 are P_3 and P_4 respectively, which are controlled by applied optical pulse energy E in the cladding region (as discussed earlier). The transition length L_T of the access waveguide (along z direction) of bending radius R and height H_T is obtained from the figure as $L_T = \sqrt{H_T(4R - H_T)}$.

Since the lateral dimension (along axis) in TMI region is approximately two times larger than the transverse dimension, it is assumed that the waveguide is to be single mode in transverse direction and has the same behavior everywhere in the TMI region. So the problem can be analyzed by considering 2D structure where lateral (x-axis) and horizontal characteristics of mode propagation are considered. As per principle of TMI phenomena, two excited modes are fundamental mode and first order mode which travel along the direction of propagation and the input field (launched through input access waveguide) is expressed in terms of mode field distribution of two excited modes in 2D as,

$$H(x + w, 0) = \sum_{i=0}^{1} b_i^T H_i(x + w) \tag{2}$$

where, b_i^T = ith mode field excitation coefficient of proposed TMI coupler. The mode excitation coefficients are obtained from Fourier series coefficients of odd periodic functions. The $H_i(x + w)$ represents mode field of ith mode of TMI region at $z = 0$. Again the mode field at the output access waveguides of width, w, is assumed to be single mode 0. The mode field at the output waveguides is contributed by two excited modes guided in TMI region. The power transferred to 3rd and 4th output access waveguide with application of optical pulse of energy E are written as,

$$\left.\begin{aligned} \frac{P_3}{P_1} &= \left|\frac{H_1(x, L, E)}{H(x + w, 0)}\right|^2 \\ \frac{P_4}{P_1} &= \left|\frac{H_2(x + w, L, E)}{H(x + w, 0)}\right|^2 \end{aligned}\right\} \tag{3}$$

where, $$H_1(x, L, E) = \sum_{i=0}^{1} c_{1,i}^T H_i(x) \exp[j\{\beta_0(n_1, n_2(E)) - \beta_i(n_1, n_2(E))\}]$$

$$H_2(x + w, L, E) = \sum_{i=0}^{1} c_{2,i}^T H_i(x + w) \exp[j\{\beta_0(n_1, n_2(E)) - \beta_i(n_1, n_2(E))\}]$$

The $c_{1,i}^T$ and $c_{2,i}^T$ are coefficients of field contribution of ith mode for 3rd and 4th output waveguide respectively, evaluated by using a simple mathematical model based on sinusoidal modes [9]. The $\beta_0(n_1, n_2(E))$ and $\beta_1(n_1, n_2(E))$ are the propagation constants of fundamental mode and first order mode respectively, obtained with application of optical pulse of energy E. The phase difference between two excited modes application of optical pulse of energy is written as

$$\Delta\phi_T(E) = \Delta\phi(0) + \frac{2\pi L}{\lambda}[\Delta n_1^{\text{eff}}(E) - \Delta n_0^{\text{eff}}(E)] \tag{4}$$

where, $\Delta\phi(0)$ is the phase difference between fundamental and first order mode without application of optical pulse in cladding region written as

$$\Delta\phi(0) = \{\beta_0(n_1, n_2(0)) - \beta_1(n_1, n_2(0))\}L$$

where, $\beta_0(n_1, n_2(0))$ and $\beta_1(n_1, n_2(0))$ are the propagation constants for fundamental mode and first order mode respectively, obtained without application of optical pulse of energy. The $\Delta n_1^{\text{eff}}(E)$ and $\Delta n_0^{\text{eff}}(E)$ are effective refractive index change of first order mode and fundamental mode respectively written as

$$\Delta n_1^{\text{eff}}(E) = n_1^{\text{eff}}(0) - n_1^{\text{eff}}(E) \tag{5}$$

$$\Delta n_0^{\text{eff}}(E) = n_0^{\text{eff}}(0) - n_0^{\text{eff}}(E) \tag{6}$$

where, $n_0^{\text{eff}}(0)$ and $n_0^{\text{eff}}(E)$ are effective refractive indexes for fundamental mode determined by using Eq. (1) and dispersion equations [17] without and with application of optical pulse of energy E respectively. $n_1^{\text{eff}}(0)$ and $n_1^{\text{eff}}(E)$ are effective refractive indexes for first order mode determined by using Eq. (1) and dispersion equation without and with application of optical pulse of energy E respectively. The coupling length required to get π phase shift due to application of optical pulse of energy E (i.e. $\Delta\phi(E) = \pi$) is written as,

$$L_C = \frac{\lambda}{2\{\Delta n_1^{\text{eff}}(E) - \Delta n_0^{\text{eff}}(E)\}} \tag{7}$$

The variation of effective refractive index change $\Delta n_i^{\text{eff}}(E)$ (where suffix $i = 0,1$ represents fundamental and first order mode respectively) with optical pulse energy E obtained by using Eqs. (1), (6)–(7) and dispersion equations for $n_1 = 3.5$, $n_2(0) = 3.17$, $w = 0.398$ μm $L_C = 778.5$ μm and $T_w = 25.4$ ps are shown in Fig. 2. It is seen from the figure that for both the modes, effective refractive index change $\Delta n_i^{\text{eff}}(E)$ increases with increase in optical pulse energy E and the rate of increase of $\Delta n_i^{\text{eff}}(E)$ with respect to E for first order mode is less than that for fundamental mode. The figure also shows the phase change $\Delta\phi(E)$ versus optical pulse energy in