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All-optical logic gates based on wavelength conversion in a nonlinear directional coupler

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ABSTRACT

In this paper, we theoretically investigate all-optical logic gates based on wavelength conversion in a nonlinear directional coupler. The switching of a weak continuous-wave (cw) light is controlled by two pump lights, as a result, the information on the pump light transfers to the cw light by controlling different combinations of the two pump lights. Firstly we study the switching characteristic of the device and select in a way to provide the best average values of Xratio. Finally we realize logic operations $C = A \oplus B$ and $D = \overline{A \oplus B}$. The Xratio is higher than that of the ordinary methods and the all-optical logic gates based on wavelength conversion exhibit high switching contrast and have a better switching characteristic.

1. Introduction

Nonlinear optical devices have attracted considerable attention because of their applicability as future high-speed all-optical signal-processing devices [1–4]. Among these devices, nonlinear directional couplers (NLDCs) have been studied for their use as an ultrafast all optical switching processor [5–10]. Jensen analyzed the NLDC theoretically in 1982 and therefore he foresaw the use of a nonlinear directional coupler as an optical switch [11]. The NLDCs have diverse applications, such as dispersion compensation modules [12], optical power splitters [13] and nonlinear optical switches [14–17]. One of the most widely used applications is as a logic gate. All-optical switch is the key component of all-optical network and many applications have been investigated recently, such as ultrashort pulse lasers, optical exchanger in time multiplexed system, optical switch device for network monitoring and protection [18]. In 1998, Diez et al. demonstrated all-optical switch for time division multiplexing (TDM) and wave division multiplexing (WDM)/TDM systems in a 640 Gbit/s demultiplexing experiment [19]; they presented a novel interferometric switch that exhibits high linearity, high switching contrast, low noise, wide bandwidth and low crosstalk.

All optical logic gates using optical Kerr effect as a switching mechanism have been intensively studied theoretically. In 2006, Fraga and his co-workers investigated three different asymmetric dual core nonlinear directional couplers which includes an increasing and a decreasing self-phase modulation profile (SPM) and they implemented various logic gates such as AND, OR, and XOR gates by controlling the nonlinearity [20]. In 2011, Sarma studied the soliton switching in a high as well as low birefringent nonlinear directional coupler, and he found that the coupler could be used as a soliton switch even at an input peak power less than the critical power of switching by a judicious choice of the polarization angle [21].

Wavelength conversion is one of the core technologies of all optical networks and addresses a number of key issues in wavelength division multiplexed networks including transparency, interoperability, and network capacity [22]. Wavelength converter can transfer data from one wavelength to another. Based on the technique of wavelength conversion, one can realize different logic operations. In 2006, Wang Jian's group experimentally verified a new idea for 40 Gbit/s wavelength conversion within the 1.5 μm band based on sum-frequency generation (SFG) in a periodically $LiNbO_3$ waveguide and observed a logic NOT gate [23]. In 2004, Sugimoto et al. have demonstrated the fabrication of a novel optical fiber with an ultra-high nonlinearity using a bismuth oxide (Bi_2O_3)-based glass material and successfully obtained a high nonlinearity of $\gamma \sim 1360\ W^{-1}\ km^{-1}$ [24]. In 2005, Lee and his coworkers experimentally demonstrated the use of fabricated 1-m-long bismuth oxide-based nonlinear optical fiber (Bi-NLF) with an ultra-high nonlinearity of $\gamma \sim 1100\ W^{-1}\ km^{-1}$ for wavelength conversion of optical time division multiplexing (OTDM) signals [25].

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In our scheme, in a nonlinear directional coupler which is constructed from a Bi_2O_3-based glass material with an ultra-high nonlinearity, the information on the pump light will transfer to the weak cw light with diverse wavelength because the on–off of the weak continuous-wave (cw) light is controlled by two pumps which carry information. The aim of this works is to investigate theoretically all-optical logic operations based on wavelength conversion in a nonlinear directional coupler.

In our scheme, to avoid the damage to the fiber, the coupler is constructed from a Bi-NLF. Due to the ultra-high nonlinearity of the fiber, the threshold power of switching can reduce. This paper is organized as follows: In Section 2, we introduce the theoretical model and solve the coupled equations. Section 3 is the contribution about the analysis of the switching characteristics and various logic functions based on wavelength conversion in a nonlinear directional coupler. Section 4 is the conclusion.

2. Theoretical model

As shown in Fig. 1, the arms of the coupler are made of two Bi-NLF I and II. Here a weak cw light and a pump light with high power p_1 which is the input signal amplified are coupled into channel I by WDM in port A, and in port B we only input a pump light with power p_2 which is also the input signal amplified. Because the wavelength of the pump light is different from that of the weak cw light, the pump light p_1 and p_2 still remain in channel I and II, respectively. Two pumps perform cross-phase modulation (XPM) to the cw light in core I and core II due to Kerr effect, such that the original symmetry coupler is changed into an asymmetric coupler for the difference between p_1 and p_2. The coupler behaves as linear device at low power level and when the pump power reaches a threshold power, the splitting ratio is approaching 1:1 due to evanescent coupling and XPM. If the pump power is higher than the threshold power, the XPM will prevent the weak cw light from switching between two cores in the coupler.

Using the coupled nonlinear Schrödinger equations, and neglecting the time-related items, we can get the following coupled equations [26]:

$$\frac{dA_1}{dz} = i\kappa_{12}A_2 + i\beta_1A_1 + 2i\gamma p_1A_1 \tag{1}$$

$$\frac{dA_2}{dz} = i\kappa_{21}A_1 + i\beta_2A_2 + 2i\gamma p_2A_2, \tag{2}$$

where β_1, β_2 are the propagation constants of channel 1 and channel 2, respectively, κ_{12} and κ_{21} are the coupling parameters, p_1 and p_2 are the light power of two pumps.

Performing the transformation $A_1 = B_1\exp[i(\beta_1+\beta_2)z/2]$, $A_2 = B_2\exp[i(\beta_1+\beta_2)z/2]$ and we can obtain simpler equations

$$\frac{dB_1}{dz} = i\kappa B_2 + i\xi_1B_1 \tag{3}$$

$$\frac{dB_2}{dz} = i\kappa B_1 + i\xi_2B_2, \tag{4}$$

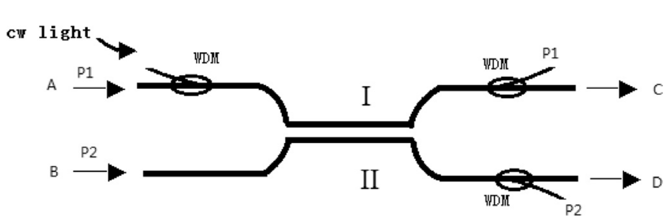

Fig. 1. Schematic of all-optical logic gates based on wavelength conversion.

in the equations, because the two fiber cores are the same, we make the coupling parameters $\kappa_{12} = \kappa_{21} = \kappa$, $\Delta\beta = (\beta_1 - \beta_2)/2$, $\xi_1 = \Delta\beta + 2\gamma p_1$, $\xi_2 = -\Delta\beta + 2\gamma p_2$.

According to Eqs. (3) and (4), we can suppose that the boundary conditions $B_1(z=0) = B_{10}$, $B_2(z=0) = B_{20}$ and get the following results:

$$B_1(z) = e^{ik_1z}\left[B_{10}\cos(k_2z) + i\left(\frac{\gamma(p_1-p_2)}{k_2}B_{10} + \frac{\kappa}{k_2}B_{20}\right)\sin(k_2z)\right] \tag{5}$$

$$B_2(z) = e^{ik_1z}\left[B_{20}\cos(k_2z) - i\left(\frac{\gamma(p_1-p_2)}{k_2}B_{20} - \frac{\kappa}{k_2}B_{10}\right)\sin(k_2z)\right], \tag{6}$$

where $k_1 = \gamma(p_1+p_2)$, $k_2 = [\gamma^2(p_1-p_2)^2 + k^2]^{1/2}$, here we make an approximate $\Delta\beta=0$.

Lastly, we use the extinction ratio (Xratio) to judge the logic function of the system. The extinction ratio of an on–off switch is ratio of the output power in the on state to the output power in the off state. This radio should be as high as possible. It can be expressed by

$$X_{ij} = \frac{\int_{-\infty}^{\infty}|B_i|^2dt}{\int_{-\infty}^{\infty}|B_j|^2dt}, \quad (i,j=1,2) \tag{7}$$

If the extinction ratio uses dB as a unit, Eq. (7) is changed as follows:

$$\mathrm{Xratio[dB]} = 10\log_{10}X_{ij}. \tag{8}$$

We define the transmission which is used to describe the switching performance:

$$T_i = \frac{\int_{-\infty}^{\infty}|B_i|^2dt}{\int_{-\infty}^{\infty}|B_{10}|^2dt} \quad (i=1,2) \tag{9}$$

3. Results and discussion

3.1. Switching characteristics

As mentioned above, in order to reduce the pump power, the arms of the coupler is constructed from a Bi_2O_3–based optical fiber with high nonlinearity, which corresponds to nonlinear coefficient $\gamma = 1360\ \mathrm{W^{-1}\,km^{-1}}$ [24]. Here the coupling coefficient of the device is $\kappa=5\ \mathrm{m^{-1}}$; the corresponding coupling length is $L=\pi/(2\kappa)$; the pump power p_1 is ranged from 0 to 30 W. The wavelengths of the pump light p_1 and p_2 are taken as 980 nm, while the wavelength of the weak cw light is 1550 nm. Figs. 2 and 3 show the transmission as a function of the pump power p_1 and p_2, and they can be obtained from Eq. (9).

In Fig. 2, a pump p_1 input from port A, meanwhile a low cw light is added into port A by a WDM. While, in port B there is no input. With the increase of the pump power p_1, it will produce Kerr effect and XPM in the coupler. It is clear that the output route is changed when the pump power p_1 is about 2.9 W, and we call the pump power as threshold power (p_{pth}).

In Fig. 3, a pump p_1 and a weak cw light are coupled into channel I; in port B there is no cw light input and we input a pump p_2=2.9 W. Because the wavelength of the pump light is different from that of the weak cw light, the pump p_1 and p_2 retain in channel I and II, respectively; two pumps perform the XPM to the cw light in core I and core II, respectively. We can see in Fig. 3, the splitting ratio is approaching 1:1 due to evanescent coupling and XPM when p_1=0, p_2=2.9 W and p_1=5.8 W, p_2=2.9 W. When $0 < p_1 < 2.9$ W, most of the weak cw light power will transfer to