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MZ-MMI-based all-optical switch using nonlinear coupled waveguides

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ABSTRACT

We propose an all-optical switch (AOS) based on Mach–Zehnder (MZ) and Multi-mode interference (MMI) using nonlinear closely coupled waveguides. The device operates by switching between two states of coupled waveguides. In first state the refractive index of waveguides are same and light field will completely couple to nonlinear waveguide in half length of coupler and will back in the second half. We will have π phase difference in this procedure and the input field will appear in Bar-state output. In the second state the refractive index of nonlinear waveguide increase with high intensity control field. In this case, we have lower coupling and change in phase. But, we choose the best refractive index change to obtain the phase change of multiple of 2π necessary for Cross-state in output. The beam propagation method is used to simulate the device operation.

1. Introduction

All-optical switches (AOS) are desired devices in optical telecommunication. They can perform a variety of applications, particularly in signal routing and time division signal processing. One of the major advantages of all-optical switches is that they avoid the need for optic–electronic and electronic–optic (o–e–o) conversions. Such conversions not only limit the versatility and transparency of the system, but they introduce errors to signal. In fact, elimination of such o–e–o conversions will result in a major decrease in the overall system cost, since the equipment associated with these conversions represents the main cost associated in today's networks [1]. In recent years different materials and configurations have been employed for the development of optical switches. They can be separated by the physical switching mechanism, such as acousto-optic [2,3], thermo-optic [4], electro-optic [5], and even electro-mechanical in nature [6], depending on the application requirements. MZI is a key component in optical switching devices. The principle of an MZI is splitting the input field into two equal fields which interfere at the output again and can produce the input field in one of two outputs. According to the relative phase values of two splitted fields MZI structure can have output fields in output 1 or 2. Two methods in optical switching based on MZI are applying ring-resonator or semiconductor optical amplifier (SOA) in coupling with MZI arms [7–9]. The other methods of switching based on MZI are using MMI couplers or splitters in arms of MZI [10,11]. The problem of these devices is the requirement of long length for switching. Therefore, these switches cannot be integrated in small chip area. Some researches are done using nonlinear waveguide couplers [12,13]. Switching by a control beam in a nonlinear coupler is explained in [12], but in this switch the control beam has occupied one of the input ports and also one of the output ports. So, the control and input signals will require to be separated. Switching using nonlinear couplers is a well-known method, in which the data signal must experience two different phases in two different power levels to be switched between output ports.

In this paper we propose an all-optical MMI switch based on Mach–Zehnder interferometer and nonlinear directional coupler in one arm of Mach–Zehnder. The device operation is based on switching between two states of nonlinear directional coupler. Switching is done based on changing refractive index with high intensity control field. In state one refractive index of waveguides are same. In this state in according to that length of coupler is equal to $2L_c$ that causes that we have full of input field in output 1 (in Fig. 2). In state 2, we change the refractive index of nonlinear waveguide. In this case, we have a weak coupling and two arms of MZI will be same. So, there is output field in cross-state. The theoretical background of elements of the switch is explained in Section 2. In Section 3, the operation of switch and Simulation results and discussions are reported.

2. Theoretical background

In this section, MMI and nonlinear directional coupler are presented and discussed using mathematical principles.

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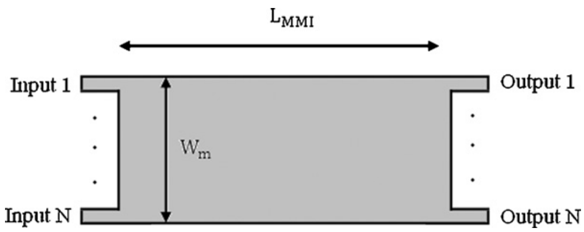

Fig. 1. Basic structure of $N \times N$ MMI coupler.

2.1. Multi-mode interference devices

The MMI devices work based on self-imaging principle. Self-imaging is a property of multi-mode waveguides by which an input field profile is reproduced in single or multiple images at periodic intervals along the propagation direction of the guide. The base structure of an MMI device is a waveguide designed to support a large number of modes (typically ≥3). In order to launch light into and recover light from that multimode waveguide, a number of access single mode waveguides are placed at its beginning and at its end. Such devices are generally referred to as $N \times M$ MMI couplers, where N and M are the number of input and output waveguides respectively [14].

Due to the modes coupling at different phase, light in the MMI region exhibits various distributions as it propagates to different positions determined by L_π, which is the beat length of the first two modes and can be expressed as:

$$L_\pi = \frac{\pi}{\beta_0 - \beta_1} \approx \frac{4n_r W_e^2}{3\lambda_0}, \tag{1}$$

where β_0 and β_1 are the propagation constant of the first two guided modes, n_r is the refractive index of the core layer, W_e is the effective width of the MMI region and λ_0 is the application wavelength [15]. The effective width W_e, takes into account the lateral penetration depth of each mode field, associated with the Goos-Hahnchen shifts at the ridge boundaries. For high-contrast waveguides, the penetration depth is very small so that $W_e \approx W_M$. In general, the effective widths W_e can be approximated by [14]:

$$W_e = W_m + \left(\frac{\lambda_0}{\pi}\right)\left(\frac{n_c}{n_r}\right)^{2\sigma}(n_r^2 - n_c^2)^{-(1/2)}, \tag{2}$$

where $\sigma = 0$ for TE and $\sigma = 1$ for TM. For an $N \times N$ MMI coupler, the optical relative phases of the signals at the output ports are given by:

$$\varphi_{rs} = \frac{\pi}{4N}(s-1)(2N+r-s)+\pi \quad \text{for } r+s \text{ even}, \tag{3}$$

and

$$\varphi_{rs} = \frac{\pi}{4N}(r+s-1)(2N-r-s+1) \quad \text{for } r+s \text{ odd}, \tag{4}$$

where $r = 1, 2, \ldots, N$ is the (bottom–top) numbering of the input waveguides and $s = 1, 2, \ldots, N$ is the(top–bottom) numbering of the output waveguides. An $N \times N$ MMI coupler is shown in Fig. 1.

The propagation direction of $\varphi(y, z)$ is the z direction. It will be seen that, under certain circumstances, the field $\varphi(y, L)$ will be a reproduction (self-imaging) of the input field $\varphi(y, 0)$. We call General Interference to the self-imaging mechanisms which are independent of the modal excitation and Restricted Interference to those which are obtained by exciting certain modes alone. In general interference, all guided modes interfere at $z = 0$. In this case the single images are formed in:

$$L = p(3L_\pi) \text{ with } p = 0, 1, 2, \ldots \tag{5}$$

Direct and mirrored single images of the input field will be formed by general interference at distances z that the p factors are, respectively, even and odd.

The N-fold output will be formed in:

$$L = \frac{p}{N}(3L_\pi) \tag{6}$$

where $p \geq 0$ and $N \geq 1$ are integers with no common divisor.

In restricted interference that includes paired and symmetric interferences selective excitation takes place. In this case the single images are formed in:

$$L = p(L_\pi) \text{ with } p = 0, 1, 2, \ldots \tag{7}$$

for paired interference and in:

$$L = p\left(\frac{3L_\pi}{4}\right) \text{ with } p = 0, 1, 2, \ldots \tag{8}$$

for symmetric interference [14].

2.2. Nonlinear directional coupler

A nonlinear directional coupler includes two waveguides that have a small distance and fully coupling takes place between them in one coupling length. One of these waveguides or both have the nonlinear behaviour means, we can change the refractive index of nonlinear waveguide with a high intensity control field. The evolution of the slowly varying mode amplitudes can be described by the coupled mode equations [16]:

$$-i\frac{dA}{dZ} = \kappa B + \gamma_1 |A|^2 A, \tag{9}$$

$$-i\frac{dB}{dZ} = \kappa A + \gamma_2 |B|^2 B, \tag{10}$$

where κ is the linear coupling coefficient, A and B are the field amplitudes of the waveguides 1 and 2 of the directional coupler and γ_1 and γ_2 are the nonlinear coefficient describing the self-phase modulation, $\gamma = 2\pi n_2 / A_{eff}\lambda_0$ with n_2 being the nonlinear refractive index coefficient, λ_0 being the wavelength in vacuum and A_{eff} the effective modal cross-section in waveguide 1 or 2. First fully coupling takes place in

$$z = L_c = \frac{\pi}{2K}, \tag{11}$$

where L_c is the coupling length.

In the phase matched case, that means the input wavelength and the refractice index of two waveguides be same we will have maximum coupling. But if the refractive index difference of two waveguides increases, coupling will be decreased. In addition to this, we will have change in the phase of fields by changing the difference of refractive indices.

3. Design and simulation results

The proposed structure for all-optical switch is depicted in Fig. 2. This switch consists of two MMI couplers as 3-dB couplers in MZI structure and a nonlinear directional coupler in the lower arm of MZI as a control section for switching. MMI couplers in Fig. 2 have 18 μm width and 850 μm length. Input and output access waveguides have 5 μm width and 100 μm length. Coupling length (L_c) in directional coupler is 473 μm and coupler has $2L_c$ length. The Lower waveguide of directional coupler shows nonlinear behavior

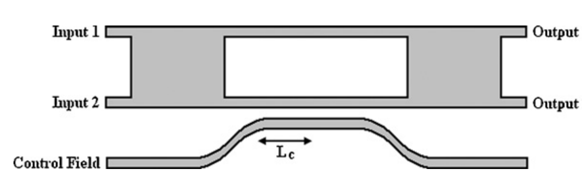

Fig. 2. Proposed structure of all-optical switch.