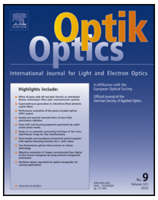
Optik 126 (2015) 436–441

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo



An optimum multimode interference coupler as an all-optical switch based on nonlinear modal propagation analysis

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ARTICLE INFO

Article history:
Received 30 December 2013
Accepted 15 September 2014

Keywords:
MMI
MPA
Switch
Kerr nonlinear effect
Insertion loss

ABSTRACT

This paper proposes the modal propagation analysis (MPA) as a desirable way to study the all-optical switch based on small dimension MMI coupler in nonlinear regime. The finite difference method as a rigorous numerical method applies to solve the nonlinear modal equations and measure the modal propagation constant. The contrast ratio between ON and OFF outputs that is called switching performance gain (SPG) is used to optimize the switch via output width. The results show good efficiency in few micrometer of MMI length and sensitivity of SPG to output width as well as input intensity.

1. Introduction

Multimode interference couplers [1] have recently become key elements of planar integrated circuits in photonics. These couplers have significant features such as low loss and cross-talk [2], high optical bandwidth [3], compact size [4], low sensitivity to input polarization [5], low sensitivity to operating wavelength [6], and tolerance to fabrication errors [7]. MMI couplers have broad applications in photonic complex circuits, one of the important application is all-optical switching especially when operated in the nonlinear regime [8–13].

Researcher on the nonlinear version of MMI [14] for all-optical switching purposes mostly concentrated on the methods based on beam propagation method (BPM) such as Two-mode condition also called zero-gap directional coupler [15], self-guiding phenomena [16] and the variational method [17], these methods cannot predict interference in MMI (while the base of MMI is modal interference), give a qualitative description on the nonlinear MMI and just study the long lengths MMI waveguides when MMI launched by high intensity whereas have the drawback of being large [9–11,16,17]. Long lengths (2 or 3 mm) may show self-guiding just in high intensity that self-focusing is dominate in propagation medium to make a spatial path and neglect interference among modes then self-focusing conducts the beam to the indicated output for performance demonstration. BPM cannot apply in a wide angle or when the refractive index is rapidly varying also in high contrast index (more than 0.1) because of paraxial approximation [18]. Therefore, the modal propagation analysis (MPA) might be the way to study the interference and self-imaging phenomena in nonlinear regime of MMI in details through no approximation in this method and respects to the modes propagation. Of course, a rigorous numerical method should be applied to solve the modal equations and modal propagation constant in MPA. Finite difference method (FDM) is a rigorous method [18] to accomplish MPA in this paper. Our efforts are concentrated on the design of the all-optical switch with the smallest dimension based on nonlinear modal propagation analysis method (NLMPA) [19–22] used the FDM and measuring the contrast ratio between OFF and ON outputs in any states of switching performances to demonstrate the switch efficiency.

In this paper we propose an ultra-compact 2 × 2 switch based on NMPA method. We apply contrast ratio to optimize our switch via output width. Our study shows the switching sensitivity to single waveguides width whereas it is approved by contrast ratio measurement as a function of width. Contrast ratio is named switching performance gain (SPG) that has two advantages, showing the contrast between OFF and ON in any states of switching and shows how bar and cross intensities are same while switching state is changing, additionally this parameter can be used to measure switching efficiency in switches that have already proposed. This regime would be helpful in obtaining the desirable result by study the device on various widths and input intensities.

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http://dx.doi.org/10.1016/j.ijleo.2014.09.009

In this paper; switching is accomplished using phase modulation such as self-phase modulation and cross-phase modulation, as well as energy exchange among guided modes which induced by intense light in multimode waveguide in presence of Kerr nonlinear effect, which leads to a different self-imaging process due to the phases and amplitudes changes of guided modes electric field that lead to different interferences in small lengths. In the second section, we theoretically investigate modal propagation in presence the Kerr nonlinear effect in using a multimode interference waveguides well as electric field at the output facets. Furthermore, we introduce SPG and insertion loss to use in switch characterization. In the third section, the numerical results demonstrate the design capability as ultra-compact switch and optimize our switch via study the insertion loss and SPG as functions of output width then result are discussed.

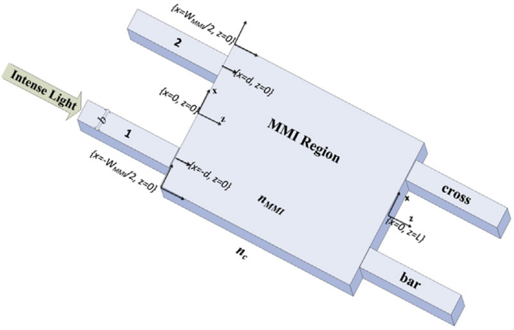

Fig. 1. Schematic structure of (2 × 2) MMI coupler.

2. Modal poropagation in nonlinear multimode interference waveguide

The MMI coupler is introduced to the photonic devices as the simplest structure. Although this device has broad applications in the integrated photonic circuits and telecommunications, these applications increase with the appearance of nonlinear effects due to the change in the modes of electric field in terms of amplitudes or phases. This application exchanges energy among modes [14]. This advantage leads to an ability to control the wave propagation in the medium, contributing to signal processing in all-optical functions [20].

The central region of MMI coupler is the multimode waveguide. The access waveguides, which are usually single mode, are fixed at the input and output facets of the multimode waveguide. The performance of these devices depends on the interference of guided modes, where the complete constructive interference contributes to the formation of the single or multiple self-images at precise distances in the input facet. The interference property of the MMI waveguide intensely depends on the refractive indices of the core and cladding regions of the multimode waveguide. In other words, by varying the refractive index in the core region, modal interferences phenomena are also changed. In fact, by imposing the intense light into the multimode region, core refractive index becomes a function of intensity in presence of Kerr nonlinear effect [14,19], as the result the modes propagate in the different way according to changes of optical properties. By studying this effect in the multimode interference couplers and applying the obtained results, we can design all-optical switch to have small MMIs [22]. In this section, we theoretically study the Kerr nonlinear effect in a MMI coupler by introduce and study the Nonlinear Modal Propagation Analysis (NMPA) method in the central region. Then, we drive the electric field in the output single mode waveguides and introduce the SPG and insertion loss.

2.1. Kerr nonlinear effect in MMI coupler

The schematic structure of the (2 × 2) MMI coupler is shown in Fig. 1, where L_{MMI} and W_{MMI} are the length and the effective width of central region, respectively. n_{MMI} and n_c represent the effective refractive index of core and cladding of the multimode waveguide, respectively.

When an intense input light launches into the MMI region from one input waveguide, the refractive index of the region changes by an amount that is proportional to the intensity of the input light. In fact, varying the intensity of the input light produces a nonlinear change in the refractive index of the MMI region. The change of the refractive index leads to a change in interference of the modes and in the self-imaging formation. In other words, light propagation in MMI region is changed. Notably, the MMI region is isotropic, and the field in this region is a superposition of all the modal fields of the MMI. The details of MPA method are exist anywhere [23], for study the NMPA; whereas in linear regime, the amplitude of the modal fields is constant, in the this nonlinear regime, the amplitude of the modes is considered as a function of propagation direction either shows phases and amplitudes changes in region also exchange energy among modes (in the z direction). Therefore, we follow the conventional MPA while consider the modes amplitudes as a function of propagation direction then solve the nonlinear coupled equations of guided modes to obtain the electric field throughout the MMI region for applying the Kerr effect On MPA and proposing NMPA.

The field distribution of the light in MMI region is expressed by

$$E(x,z,t)=\sum_{\nu=0}^{n} A_\nu(z)e^{j\gamma_\nu x}e^{j\beta_\nu z}e^{(-\omega t+\phi_0)} \tag{1}$$

where ν is the mode number, $A_\nu(z)$ is the amplitude of the νth mode that contains real and imaginary parts, γ_ν and β_ν are lateral and longitudinal propagation constants of the νth mode, respectively. With the appearance of the nonlinear effect in the MMI region, the refractive index of this region changes and takes a nonlinear part. The total refractive index of the MMI region is then given by:

$$n = n_{MMI} + n_2 I = n_{MMI} + n_{Nl} \tag{2}$$

where n_{MMI} is the usual weak-field refractive index of guiding structure (linear term), it denotes the intensity of the input light, and n_{NL} is the nonlinear refractive of the Kerr nonlinear effect determined by the Kerr nonlinear effect. In addition, the interaction of an input light with a nonlinear optical region is expressed in terms of the nonlinear polarization. The total polarization in MMI region is described by [24]:

$$P(t) = \varepsilon_0\{\chi^{(1)}E(t) + \chi^{(3)}E^3(t)\} \tag{3}$$

where $\chi^{(1)}$ and $\chi^{(3)}$ are the linear and nonlinear susceptibilities, respectively. In the Eq. (3), the first term denotes the linear polarization, whereas the second term is the nonlinear polarization. The refractive index induced by the intense input light (i.e., nonlinear refractive index) is proportional to the third-order susceptibility. To consider the light propagation in a nonlinear MMI region, we solve the wave equation in that region as [24]:

$$\nabla^2\vec{E} - \frac{n^2_{MMI}}{c^2}\frac{\partial^2\vec{E}}{\partial t^2} = \mu_0\frac{\partial^2\vec{P}^{Nl}}{\partial t^2}. \tag{4}$$