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

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ABSTRACT

This paper proposes modal propagation analysis (MPA) as an advantageous approach to studying an all-optical switch based on a small-dimension multimode interference (MMI) coupler at the threshold of the nonlinear regime. The finite-difference method is applied as a rigorous numerical method of solving the nonlinear modal equations and measuring the modal propagation constant. The characterizations of two initial modes demonstrate the changes that are induced by nonlinear effects, such as the conversion of a sinusoidal profile to a Gaussian profile in the direction of propagation, the high oscillation of the induced phase, and a variable shift in wavelength. Furthermore, all of the abovementioned changes manifest differently for each mode. The Gaussian profiles of guided modes accompanied by other observed phenomena lead to more efficient interferences among the modes to demonstrate switching applications at a small MMI length scale. The procedure for designing an optimum switch requires the implementation of a series of several studies of the switching operation based on related parameters, such as the contrast ratio between the ON and OFF outputs, which is called the switching performance gain (SPG); this parameter is used to optimize the switch via the output width, and the insertion loss is used in the same manner. The results indicate the efficiency of the approach at an MMI length of a few micrometers and indicate that SPG is sensitive to both output width and input intensity. To our knowledge, this is the first study to demonstrate power switching using nonlinear modal propagation analysis in the low-intensity nonlinear regime in a configuration created by guided-mode interferences.
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1. Introduction

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

Research regarding nonlinear MMI [14] for all-optical switching has been largely focused on methods based on the beam propagation method (BPM), including switches based on the two-mode condition, also called zero-gap directional couplers [15]; self-guiding phenomena [16]; and the variational method [17]. These methods cannot predict interferences in MMI couplers (although the basis of MMI is modal interference); they provide only a qualitative description of nonlinear MMI and can be used to study MMI waveguides of long length scales, in which the MMI must be induced at high intensity, and the large dimensions and high input intensities of such devices constitute serious drawbacks [9–11,16,17]. Couplers with long lengths (2–3 mm) may exhibit self-guiding only at high intensity, where self-focusing is dominant in the propagation medium, creating a spatial path and permitting interferences among modes to be neglected; the self-focusing then conducts the beam to the desired output to produce the desired switching performance.

The BPM cannot be applied at wide angles or when the refractive index varies rapidly, especially for a high contrast index (more than 0.1), because of the paraxial approximation; there are some algorithms that can be applied to mitigate these limitations in the linear regime, but in the nonlinear regime, all such algorithms that have been reported require high input intensity, long length, and a small contrast index. Therefore, modal propagation analysis (MPA) might offer a superior approach to studying ultra-compact switches because it permits the detailed modeling of the phenomena of modal interference and self-imaging (which serve as the basis of multimode waveguides) in the nonlinear MMI regime without requiring any approximation; thus, analysis based

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on this method may allow the nonlinear mode propagation in multimode waveguides to achieve sufficiently high efficiency to overcome the limitations that have been observed in previous nonlinear MMI switches. Nonlinear modal propagation analysis (NMPA) is an accurate method of studying the propagation of various modes and the interactions among them in the nonlinear multimode region, where a rigorous numerical method is applied to obtain the mode profiles and propagation constant by solving a large number of nonlinear coupled modal equations (the number of equations is equal to the number of guided modes) [18]. Several numerical methods have been proposed to accomplish MPA; the most well known are the finite-difference method (FDM) and finite-element method (FEM). Some authors have reported the validation of the FEM based on comparison with the FDM [19], and some have demonstrated that the FDM is a rigorous method for investigating modal propagation in MMI [20,21]. Therefore, we have chosen to apply the FDM in this work, as in our previous report, in which we presented an ultra-compact nonlinear power splitter based on nonlinear modal propagation [18]. In this previous publication, our method demonstrated the capability of NMPA to overcome the previous limitations on such devices by studying the interference among the guided modes to determine the smallest possible length for a nonlinear power splitter with a large number of outputs.

Here, the presented NMPA [18,22–24] is applied to investigate MMI couplers for all-optical switch applications at ultra-short length scales. Our efforts are focused on the design of the all-optical switch with the smallest possible dimensions based on NMPA to address the problems of miniaturization and intensity in all-optical switches. We use the contrast ratio between the OFF and ON outputs in various states of switching operation to demonstrate the switch efficiency.

We propose an ultra-compact 2×2 switch based on the NMPA method. We use the contrast ratio and insertion loss to optimize our switch via the output width. Our study demonstrates the sensitivity of the switching performance to the output facet width by investigating the contrast ratio as a function of the output width. The contrast ratio, also referred to as the switching performance gain (SPG), has two advantages. First, it expresses the contrast between the ON and OFF outputs in any state of switching and facilitates the determination that the bar and cross intensities are the same when the switching states are in the bar and cross modes, respectively. Second, this parameter can be used to measure the switching efficiency in all types of ON–OFF keyed (OOK) switches. This approach is useful in obtaining meaningful results when studying a device with respect to its output widths and input intensities.

In this paper, switching is accomplished using phase modulation, including both self-phase modulation and cross-phase modulation, as well as wave mixing or energy exchange among guided modes caused by nonlinear refractive effects and nonlinear wave mixing effects, which leads to different types of mode propagation and interference processes with respect to the phase, amplitude, and profile variations of the guided-mode electric field that in turn lead to differences in the image-folding performance. In the second section, we theoretically investigate modal propagation in the presence of nonlinear effects using a multimode interference waveguide with an electric field at the output facets. Furthermore, we introduce SPG and insertion loss for use in switch characterization. In the third section, the modal characterization is presented, and the production of nonlinear effects in wave propagation and interferences in MMI is discussed; the numerical results demonstrate the capability of our proposed design to function as an ultra-compact switch and permit us to optimize our switch via the study of the insertion loss and SPG as functions of the output width. Finally, a summary of the model, the optimization, and the characteristics of the switching operation of our proposed ultra-compact MMI device are presented, in addition to plans for future work.

2. Nonlinear modal propagation in a multimode interference waveguide

The MMI coupler is one of the simplest structures that have been introduced into photonic devices. Although this device already has a broad range of applications in integrated photonic circuits and telecommunications, the number of potential applications increases with the appearance of nonlinear effects caused by changes in the amplitude or phase modes of the electric field [14].

The nonlinear effects in multimode regimes can be classified into two categories: effects that are induced by the exchange of energy between modal waves caused by interactions between excited modes and effects that are related to modal wave interactions with the medium, such as scatterings. The first category includes the generation of harmonics, wave mixing, and nonlinear refraction; thus, some of these effects involve the generation of new frequencies or new wavelengths. In all-optical devices, nonlinear scattering is not efficient because of the lack of acoustic waves. The materials used in waveguides are largely isotropic, and the lowest-order nonlinear effects originate from third-order susceptibility, which is responsible for phenomena such as third-harmonic generation, four-wave mixing, and nonlinear refraction as well as nonlinear absorption. Notably, the third-order susceptibility is a fourth-rank tensor, but in linearly polarized optical waves, only one component contributes to the nonlinear polarization to produce the abovementioned nonlinear effects; this component contains real and imaginary parts, which induce nonlinear refraction and nonlinear absorption, respectively. In nonlinear types of absorption, such as two-photon absorption, photons must be supplied at a sufficiently high rate that there is a reasonable probability that two photons will both be present during the lifetime of the virtual excited state. The photon flux must be high because of the brevity of this virtual lifetime, and therefore, high-power laser beams are required. Therefore, two-photon absorption occurs only at high input intensities, and the threshold depends on the two-photon virtual lifetime.

Here, the most important objective is to apply NMPA to study the nonlinear phenomena that are induced in a multimode waveguide excited by a linearly polarized wave. Such phenomena may induce certain desirable effects on mode propagation and interactions, as discussed below.

The central region of an MMI coupler is the multimode waveguide. Access waveguides, which are typically single-mode waveguides, are located at the input and output facets of the multimode waveguide. The performance of these devices depends on the interference among the guided modes; complete constructive interference contributes to the formation of single or multiple self-images at precise distances in the input facet. The interference properties of an MMI waveguide depend strongly on the refractive indices of the core and cladding regions with respect to the profiles, distributions, propagation constants, and propagation direction of the guided modes. In other words, the modal interference phenomena and propagation can also be changed by varying the abovementioned parameters. In fact, nonlinear effects appear in the MMI when intense light is introduced into the multimode region; nonlinear refraction, or the Kerr effect, causes the core's refractive index to vary as a function of intensity [14,18], and wave mixing and third-harmonic generation create new frequencies and wavelengths. As a result, the modes propagate differently because of the changes in the optical properties of the waveguide. In the next section, we investigate the characteristics

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