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Operation principle of self-phase compensated optical waveguide isolator

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ABSTRACT

A theory is developed for the self-phase compensated optical waveguide isolator recently reported in the literature. The operation principle of such device is explained in terms of synchronization of phase and power conversion. The effect of balancing phase mismatches of the two convertors on achieving a proper percentage of mode conversion is revealed. The way to make use of the phase mismatches of different sections to accommodate the different requirements in phase relationship for the reciprocal and nonreciprocal mode convertors is discussed. The theory is extended to the case where phase compensator is used. It is demonstrated that the introduction of phase compensator separates the adjustment of phase from the adjustment of power for the mode convertors so that relaxes fabrication tolerances of such devices. An isolator consists of three phase mismatched waveguide sections is designed and simulated. The simulation results confirm the self-phase compensation theory.

1. Introduction

In optical communication, scattered wave in the guide has influence on the operation of active devices such as semi-conduct laser or optical amplifier, and consequently, the performance of the system could be affected. Optical isolator is a device to suppress such effect so that to improve the stability of the system. Optical circulator is used in splitting and recombining different transmission routes. These devices are commercially available as bulk micro-optical components in the market. It is beneficial to integrate optical components such as light sources, isolators, circulators, modulators, amplifiers and couplers etc. on a single chip in many applications. To alleviate the integration problem, the development of integrated waveguide isolators and modulators for use in such applications is important [1–6].

In the investigation for such integrated, compact devices, several schemes were proposed. The first concept of waveguide isolator is based on nonreciprocal TE-TM mode conversion [7,8]. The nonreciprocal Faraday rotation of magnetooptical materials is the basis of such device. When adapting to waveguide optics, the planar format of guiding structure breaks the symmetry of bulk optical devices. Invariably this leads to a structurally induced birefringence and, consequently, a phase mismatch between TE and TM modes arises.

The main problem in the design of such waveguide isolator is the phase mismatch. It was believed that phase matching has to be adjusted very precisely so that the required isolation can be achieved. Numerous attempts have been made to solve this problem [9–15]. Full phase match has been demonstrated possible by Wolfe et al. [11]. However, quite complicated manufacturing processes are involved in the preparing of the waveguide. The tolerances in the manufacturing make it impractically difficult to achieve the required control of each component of the birefringence. A quasi phase matching solution was proposed by Hutchings [2] as an alternative. But it is noted in the literature that a small relaxation like this in the phase-matching criteria is insufficient.

The enormous difficulties of achieving precise phase matching have led to the investigation of other isolator concepts, including those based on nonreciprocal Mach–Zender interferometer [16,17], on nonreciprocal couplers [18], on nonreciprocal multimode imaging [19,20], and on nonreciprocal amplification [21], etc. However, none of the multitude of prior attempts has so far been translated into a marketable technology, in spite of the strong technological need for on-chip optical isolators.

A scheme that could withstand birefringence is always desirable. The first waveguide isolator technology operating in the presence of phase mismatch was proposed by Dammann et al. [12]. However, in that scheme the through direction is not properly taken care of. The wave passing the first polarizer and the magnetooptic waveguide in the through direction is elliptically polarized. Thus the wave can only partially pass the second polarizer and an intrinsic insertion loss is resulted. In addition to that, the two polarizers are oriented at an angle of 45° with each other, with neither of them pointing in the direction of the waveguide's main axis. Dammann's scheme is therefore difficult to implement in the format of integrated devices.

Recently, a new scheme that could operate in the presence of phase mismatch with better performance and easier manufacturing than Dammann's scheme was reported [23]. It was demonstrated that the

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troublesome phase-matching condition for the TE-TM mode conversion could be got rid of without any degradation on the performances of the isolator. The main features of the scheme include the balance between the phase-mismatches of the reciprocal and the nonreciprocal mode convertors, and the redirecting of the effects of phase-mismatches to the creation of a phase jump, which is essential in accommodating the different phase requirements of the two different convertors. The phase matching requirement for each individual mode convertor becomes unnecessary. The use of this scheme enables a waveguide isolator to be built from the principle of Faraday rotation in the presence of phase mismatch. It overcomes the problem of phase mismatch without any complication to the system, so that simplifies the construction of waveguide isolator of this type significantly.

In this work, a theory for the self-phase compensated isolator reported in [23] is developed. The evolution of amplitudes and phases of the TE and TM modes in different sections of the isolator is analyzed. The effect of birefringence on mode power conversion is revealed. The way to make use of the phase mismatch of the guide to adjust the phase relationship between the two modes to suit the different requirements of the two convertors is discussed. Furthermore, an extension of the self-phase compensation scheme is proposed for the use of phase compensator in such isolator. The phase compensator provides a fine tuning on the phase so that the adjustment of phase relationship could be separated from the adjustment of power relationship for the convertors, therefore relaxes the tolerance of manufacturing of such devices. In the presence of phase mismatches, the phase compensator would be shortened because the phase mismatches of the two convertors also have contribution towards the phase adjustment. An isolator consists of a reciprocal convertor, a nonreciprocal convertor, and a phase compensator is designed and simulated. An insertion loss of −0.157 dB and an isolation of −32.1 dB are obtained.

2. The coupled mode theory

For linear, continuous, homogeneous media, Maxwell's equations for time-harmonic waves, of the form $\exp(j\omega t)$ are

$$\nabla \times E = -j\omega\mu_0 H \tag{1}$$

$$\nabla \times H = j\omega\varepsilon_0[\varepsilon]E \tag{2}$$

where ε_0 and μ_0 are the, respective, permittivity and permeability of free space, E is the electric vector, H is the magnetic vector and D is the displacement vector. For a magneto-optical material, $[\varepsilon]$ is the relative permittivity tensor

$$[\varepsilon] = \begin{bmatrix} \varepsilon_{xx} & \varepsilon_{xy} & \varepsilon_{xz} \\ \varepsilon_{yx} & \varepsilon_{yy} & \varepsilon_{yz} \\ \varepsilon_{zx} & \varepsilon_{zy} & \varepsilon_{zz} \end{bmatrix} \tag{3}$$

In this paper, the investigation concerns the longitudinal configuration in which the magnetization points along the propagation direction. For this case, $\varepsilon_{xx} \approx \varepsilon_{yy} \approx \varepsilon_{zz} \equiv \varepsilon_r$, $\varepsilon_{xz} = \varepsilon_{zx} = \varepsilon_{yz} = \varepsilon_{zy} = 0$, $\varepsilon_{xy} = -\varepsilon_{yx} = j\varepsilon_r Q$, where Q is the saturation magnetooptic coefficient induced by the externally applied magnetic field. If the refractive index varies slowly along z, the approximation $\partial\varepsilon_r/\partial z \approx 0$ can be used and the x and y components E_x E_y then become decoupled from the z-component E_z. After these considerations and some lengthy manipulations, we get the wave equation for the principal electric field components E_x and E_y:

$$\frac{\partial}{\partial x}\left(\frac{1}{\varepsilon_r}\frac{\partial(\varepsilon_r E_x)}{\partial x}\right) + \frac{\partial^2 E_x}{\partial y^2} + \frac{\partial^2 E_x}{\partial z^2} + \varepsilon_r k_0^2 E_x + \frac{\partial}{\partial x}\left(\frac{1}{\varepsilon_r}\frac{\partial \varepsilon_r}{\partial y}E_y\right) + j\varepsilon_r Q k_0^2 E_y = 0$$
$$\frac{\partial^2 E_y}{\partial x^2} + \frac{\partial}{\partial y}\left(\frac{1}{\varepsilon_r}\frac{\partial\left(\varepsilon_r E_y\right)}{\partial y}\right) + \frac{\partial^2 E_y}{\partial z^2} + \varepsilon_r k_0^2 E_y + \frac{\partial}{\partial y}\left(\frac{1}{\varepsilon_r}\frac{\partial \varepsilon_r}{\partial x}E_x\right) - j\varepsilon_r Q k_0^2 E_x = 0 \tag{4}$$

In order to reveal the mechanism underpinning the finding of [23], we turn to the perturbation theory for the development of an analytical description for the operation of the isolator. The terms $\frac{\partial}{\partial x}\left(\frac{1}{\varepsilon_r}\frac{\partial\varepsilon_r}{\partial y}E_y\right)$ and $\frac{\partial}{\partial y}\left(\frac{1}{\varepsilon_r}\frac{\partial\varepsilon_r}{\partial x}E_x\right)$ account for polarization coupling due to geometric effects, the terms $j\varepsilon_r Q k_0^2 E_y$ and $j\varepsilon_r Q k_0^2 E_x$ account for polarization coupling due to magnetooptic effects. In the unperturbed situation the waveguide supports stationary, uncoupled modes. Furthermore, for weakly guiding, the uncoupled modes of the waveguide can be classified into categories of quasi-TE and quasi-TM modes. Suppose that the waveguide cross-section is in the x–y plane and that the wave propagates, predominantly, along the z-direction. The field components of the quasi-TE and quasi-TM modes can be expressed as $E_y = \Xi_y(x,y)\exp(-j\beta_{TE}z)$ and $E_x = \Xi_x(x,y)\exp(-j\beta_{TM}z)$, where $\beta_{TE,TM}$ is the corresponding propagation constant, and $\Xi_{x,y}(x,y)$ is the eigenmode of the waveguide that satisfies Eq. (4) in the absence of the other polarization component.

Suppose the waveguide is cut at corners deliberately, geometric coupling will be introduced into the system. On the other hand, if magnetooptic material is used in the construction of the waveguide, magnetooptic coupling has to be considered. In most cases these coupling terms are so small that they can be treated as perturbations. Eq. (4) can therefore be solved with the first order perturbation method with good accuracy. The stationary solutions $\Xi_{x,y}(x,y)$ are the zeroth order quasi-TM and quasi-TE solutions, and start from which the influence of coupling can be considered. According to the first order perturbation theory, the mode profile $\Xi_{x,y}(x,y)$ and the propagation constant $\beta_{TE,TM}$ will not be affected but the amplitude of the mode is allowed to vary. Ignoring the possibility of coupling to the continuum of radiation modes, and assuming the unperturbed system can only support one single quasi-TE mode and one single quasi-TM mode, then the solution takes the form

$$\begin{aligned} E_x &= A_x(z)\Xi_x(x,y)e^{-j\beta z} \\ E_y &= A_y(z)\Xi_y(x,y)e^{-j\beta z} \end{aligned} \tag{5}$$

where $\beta = (\beta_{TE} + \beta_{TM})/2$. Substitution of Eq. (5) into Eq. (4) leads to

$$2j\beta\frac{\partial A_x}{\partial z}\Xi_x = \frac{\partial}{\partial x}\left(\frac{1}{\varepsilon_r}\frac{\partial\varepsilon_r}{\partial y}\right)A_y\Xi_y + j\varepsilon_r Q k_0^2 A_y \Xi_y - \beta^2 A_x\Xi_x + \beta_{TM}^2 A_x \Xi_x \tag{6a}$$

$$2j\beta\frac{\partial A_y}{\partial z}\Xi_y = \frac{\partial}{\partial y}\left(\frac{1}{\varepsilon_r}\frac{\partial\varepsilon_r}{\partial x}\right)A_x\Xi_x - j\varepsilon_r Q k_0^2 A_x \Xi_x - \beta^2 A_y\Xi_y + \beta_{TE}^2 A_y \Xi_y \tag{6b}$$

The paraxial approximation has been invoked. The power flows along the z direction. It is convenient to define $A_{x,y}$ in such a way that $|A_{x,y}|^2$ corresponds to the power carried by the quasi-TE and quasi-TM modes respectively, which implies that $\frac{1}{2}\frac{\beta}{\mu_0\omega}\int\left|\Xi_x\right|^2 dxdy = \frac{1}{2}\frac{\beta}{\mu_0\omega}\int\left|\Xi_y\right|^2 dxdy = 1(\text{Watt})$.

Taking the product of Eq. (6a) with $\Xi_x^*(x,y)$ and Eq. (6b) with $\Xi_y^*(x,y)$ for integration from $-\infty$ to $+\infty$. The result is,

$$\begin{aligned} \frac{\partial A_x}{\partial z} &= \kappa_{xy}A_y - j\Delta_\beta A_x \\ \frac{\partial A_y}{\partial z} &= \kappa_{yx}A_x + j\Delta_\beta A_y \end{aligned} \tag{7}$$

where $2\Delta_\beta = \beta_{TM} - \beta_{TE}$ is the phase mismatch between the two polarization components, and

$$\kappa_{xy} = \frac{1}{2\beta\iint\left|\Xi_x\right|^2 dxdy}\left[-j\iint\frac{\partial}{\partial x}\left(\frac{1}{\varepsilon_r}\frac{\partial\varepsilon_r}{\partial y}\right)\Xi_x^*\Xi_y dxdy + k_0^2\iint\varepsilon_r Q\Xi_x^*\Xi_y dxdy\right]$$

$$\kappa_{yx} = \frac{1}{2\beta\iint\left|\Xi_y\right|^2 dxdy}\left[-j\iint\frac{\partial}{\partial y}\left(\frac{1}{\varepsilon_r}\frac{\partial\varepsilon_r}{\partial x}\right)\Xi_x\Xi_y^* dxdy - k_0^2\iint\varepsilon_r Q\Xi_x\Xi_y^* dxdy\right]$$