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Scattering parameters of a non-reciprocal magneto-optical integrated coupler used as an isolator

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Abstract. We theoretically investigate a non-reciprocal magneto-optical integrated slab directional coupler. The scattering parameters of the structure are derived in the frame of the Coupled-Mode Theory ~~(CMT)~~. By properly designing the coupler, it is possible to achieve a perfect non-reciprocity (with 100% contrast) between the two directions of propagation. Other operating points can also be defined, especially since modal dispersion in the spectral domain is naturally taken into consideration.

1 Introduction

Couplers are important components of photonic circuits. Using magneto-optical materials as constituents of such systems allows one to design non-reciprocal devices, such as nonreciprocal Mach-Zehnder interferometers or nonreciprocal directional isolators [1, 2]. In this communication, we discuss the principle and the operating conditions of such an isolator based on two coupled magneto-optical waveguides with opposite directions of magnetization.

2 Magneto-optical coupler

The coupler consists of two parallel slab waveguides of equal thickness h made of a bigyrotropic magnetic medium B. Both the spacer of thickness d separating the waveguides and the surrounding space are made of the same isotropic, non-magnetic medium A (Fig. 1). Propagation occurs over a coupling length L along the z-axis. Time dependence is taken as $\exp(+i\omega t)$. Both guides are magnetized at saturation along the y-axis, in an "anti-parallel" transverse configuration.

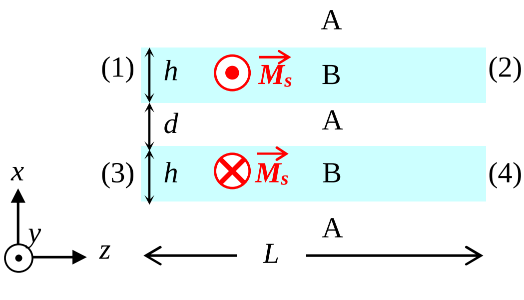

Fig. 1. System of two coupled bigyrotropic slab waveguides (1) in the "anti-parallel" transverse magnetic configuration. The width of both magnetic guiding layers (B) is h, that of the dielectric isotropic spacer (A) is d. L denotes the interaction length. The input-output ports are numbered from (1) to (4).

In the frame of the Coupled-Mode Theory, the coupling constant χ between two phase-matched slab waveguides can be retrieved by evaluating the modal propagation constants β_e and β_o of the *even* (slow) and *odd* (fast) super-modes, since $\chi = (\beta_e - \beta_o)/2$.

According to previous calculations reported in [3], a system made of coupled bigyrotropic slab waveguides in the anti-parallel transverse magnetic configuration becomes non-reciprocal: the two waveguides remain perfectly phase-matched, but the coupling constant depends on the direction of propagation. Let us call χ^+ and χ^- the coupling constants along the z-axis from the left to the right or from the right to the left, respectively. In a non-dissipative system, they are real and positive, with $\chi^+ < \chi^-$.

Besides, considering the spectral effects of modal dispersion, we derive an expression for χ^+ and χ^- that can be linearized around a given operating wavelength.

3 Non-reciprocal *S*-parameters

3.1 *S*-parameters and signal flow-graph

The scattering matrix expresses output fields (b_p) in terms of input fields (a_p). The signal flow graph is the graphical representation of the same connections (Fig. 2).

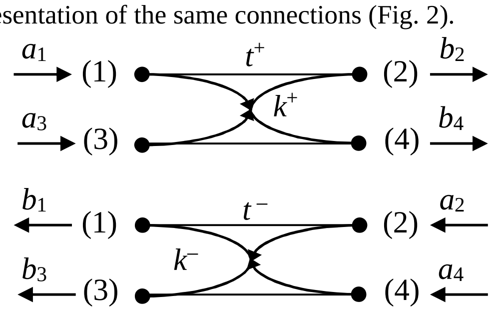

Fig. 2. Signal flow-graph of the directional coupler, in the general case. Input/output fields at port p are denoted (a_p, b_p).

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Since the coupler is directional, no reflection (either direct or cross) is experienced:

$$S_{11} = S_{22} = S_{33} = S_{44} = 0, \quad (1a)$$

$$S_{13} = S_{31} = S_{24} = S_{42} = 0. \quad (1b)$$

The remaining S-parameters are: from the left to the right, $S_{21} = S_{43} = t^+$, $S_{41} = S_{23} = k^+$; from the right to the left, $S_{12} = S_{34} = t^-$, $S_{14} = S_{32} = k^-$. We get eventually:

$$\begin{pmatrix} b_2 \\ b_4 \end{pmatrix} = \begin{pmatrix} t^+ & k^+ \\ k^+ & t^+ \end{pmatrix} \begin{pmatrix} a_1 \\ a_3 \end{pmatrix} \text{ and } \begin{pmatrix} b_1 \\ b_3 \end{pmatrix} = \begin{pmatrix} t^- & k^- \\ k^- & t^- \end{pmatrix} \begin{pmatrix} a_2 \\ a_4 \end{pmatrix} \quad (2)$$

with

$$t^+ = \cos(\chi^+ L) \exp(-i\,\beta^+ L), \quad (3a)$$

$$k^+ = -i \sin(\chi^+ L) \exp(-i\,\beta^+ L), \quad (3b)$$

$$t^- = \cos(\chi^- L) \exp(-i\,\beta^- L), \quad (3c)$$

$$k^- = -i \sin(\chi^- L) \exp(-i\,\beta^- L), \quad (3d)$$

where $\beta^+ = (\beta_e^+ + \beta_o^+)/2$ stands for the average propagation constant from the left to the right; similarly, from the right to the left, $\beta^- = (\beta_e^- + \beta_o^-)/2$. Numerical calculations show that the values of β^+ and β^- are almost identical, but anyway, they appear only as a global phase term.

It is possible to design the waveguide width h and/or the gap d (as well as the interaction length L) in order to ensure that, for a given wavelength λ_0, $(\chi^+ L)$ and $(\chi^- L)$ are adjusted at will, so that

$$\frac{\chi^+}{\chi^-} = \frac{2q}{2q+1}, \quad \text{with } q \in \mathbb{N}, \quad (4)$$

which ensures that the coupler behaves as a perfect directional isolator.

3.2 Perfect directional isolator

For GGG and Bi:YIG as materials A and B, the condition expressed by Eq. (4) can for instance be satisfied (and perfect isolation be achieved) at $\lambda_0 = 1.5$ µm with $h = 0.62$ µm, $d = 0.155$ µm, and $L = 206.5$ µm, so that:

$$(\chi^+ L) \approx 10\pi, (\chi^- L) \approx 10.5\pi. \quad (5)$$

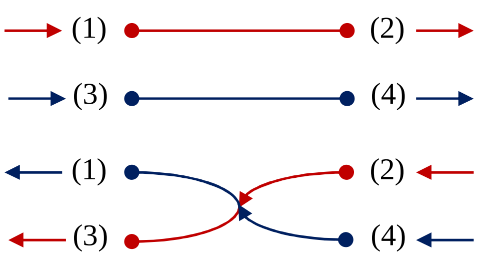

Fig. 3. Illustration of high-contrast non-reciprocity: the material parameters of the coupler can be adjusted in such a way that, for a given operating wavelength, the structure works as a perfect isolator.

As a result, the system becomes highly non-reciprocal, as schematically illustrated in Fig. 3, since

$$|S_{21}|^2 = |S_{43}|^2 = 1, |S_{41}|^2 = |S_{23}|^2 = 0, \quad (6a)$$

$$|S_{12}|^2 = |S_{34}|^2 = 0, |S_{14}|^2 = |S_{32}|^2 = 1. \quad (6b)$$

3.3 Chromatic dispersion and consequences

Once the coupler is designed as a perfect isolator for a given operating wavelength λ_{op}, the knowledge of chromatic dispersion (both modal and material) enables one to assess the bandwidth over which the behaviour remains close to ideal. Around λ_{op}, we write:

$$\chi^{(\pm)} = \chi^{(\pm)}(\lambda_{op}) + (\lambda - \lambda_{op}) (\partial\chi/\partial\lambda), \quad (7)$$

since both coupling constants χ^+ and χ^- exhibit roughly the same value of $(\partial\chi/\partial\lambda)$. Let us start from:

$$\chi^+ L = q\pi + \theta \quad (q \in \mathbb{N}), \quad (8a)$$

$$\chi^- L = q\pi + \pi/2 + \theta, \quad (8b)$$

$$\theta = (\lambda - \lambda_{op}) (\partial\chi/\partial\lambda)\, L. \quad (8c)$$

Then we get:

$$|S_{21}|^2 = \cos^2\theta, |S_{12}|^2 = \sin^2\theta. \quad (9)$$

If we strive to maintain $\sin^2\theta < 0.01$ (which means $|\theta| < 0.1$), then the corresponding bandwitdth $\Delta\lambda$ is:

$$\Delta\lambda \approx \frac{0.2}{(\partial\chi L / \partial\lambda)} \quad (10)$$

Assuming $(\partial\chi/\partial\lambda) \approx 0.07$ µm^{-2}, $\lambda_{op} = 1.5$ µm and $L \approx 206.5$ µm, we get $\Delta\lambda \approx 14$ nm (or, in frequency terms, $\Delta\nu \approx 1.8 \times 10^{12}$ Hz = 1.8 THz).

The same element can also be seen as a building-block to be inserted into more complex structures, such as a non-reciprocal Mach-Zehnder interferometer.

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