Improved integrated waveguide optical isolator using polarization converters

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Recently an optical isolator was reported in InP/InGaAsP, using the magneto-optic effect in an SOA with a ferromagnetic contact. Through the nonreciprocal absorption in the presence of a lateral magnetic field it achieved 4dB isolation. Here a proposal is presented to improve on this performance, by combining non-reciprocal refraction and absorption. It uses the different influence on TE and TM of these effects. With polarization converters, which can be made with very high conversion efficiency, this can be exploited to give 20dB isolation, according to our analysis. A polarization diversity configuration can be applied to obtain polarization independence.

Introduction

In PICs an optical isolator has not yet been satisfactory developed, due to compatibility problems in materials and processing. Most pressing is the need for integrated isolators in PICs based on InGaAsP/InP. Not only would this allow mass production of semiconductor lasers with integrated isolators, but it also opens the way to embedding lasers within larger circuits, without being hampered by optical feedback.

A promising integrated waveguide isolator is investigated the last few years, which is based on a magnetic material on top of a semiconductor optical amplifier, in such a way that mode hybridization occurs between a plasmon and a waveguide mode. The hybrid mode shows a magneto-optic effect; it has a higher loss in one direction. The direction of lowest loss depends on the direction of the magnetic field. The SOA current can be adjusted to provide transparency in the direction of lowest loss. In [1] the isolation obtained in this way is 81 dB/cm, but since the device is limited in length to a few hundred micron the actual isolation is 4 dB. The effect only occurs for the TM-polarization in the geometry used. With different field orientations isolators have been reported for TE-polarization [2] and with non-reciprocal polarization conversion [3].

Here a proposal is made to obtain a higher isolation, of at least 20 dB. It allows any combination of input and output polarization. The magneto-optic effects on absorption and refractive index are used. The proposed device uses the polarization dependence of the effects to influence the direction dependent interference between TE and TM polarized light in one waveguide. Bends are avoided, which reduces the size.

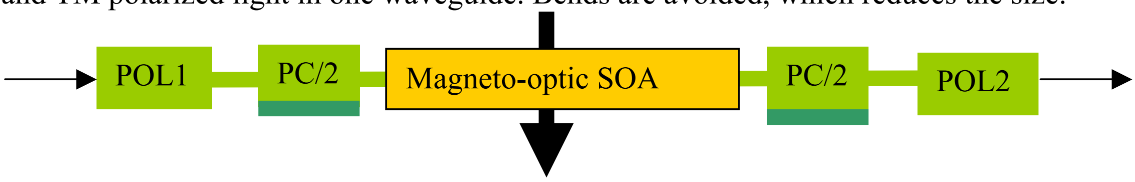

Figure 1: Top view of the proposed waveguide isolator. POL1 and POL2 are polarization filters (either TE- or TM-pass); PC/2 is a 50% polarization converter. The arrow indicates the magnetic field.

The isolator (figure 1) uses passive polarization converters with good performance [4]. For 50% conversion, as needed here, the length of such a converter is about 60 µm.

In the next paragraph a description is given of the operation of the proposed isolator. Next a theoretical treatment is developed and finally a feasibility study is reported, making use of theoretical and experimental results in the literature.

Operation principle

In figure 2 the nonreciprocal behavior of the magneto-optic effect is indicated. It shows that in the presence of a magnetic field there is a difference in the complex refractive index for light propagating in the two directions. This difference occurs for the TM-polarization, for the magnetic field perpendicular to the waveguide and parallel to the chip surface. The TE-polarized mode is not perturbed.

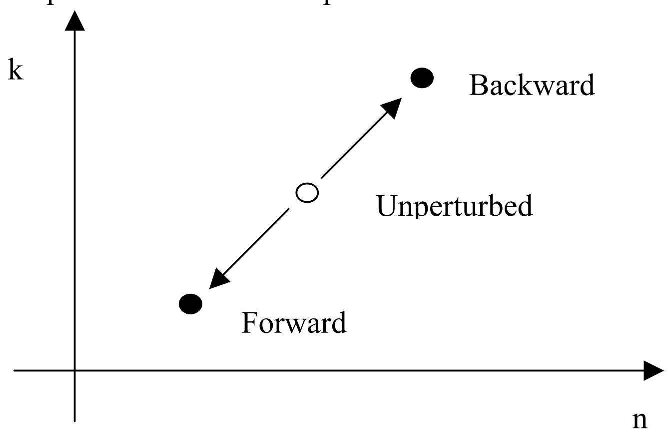

Figure 2: Absorption and refractive index for forward and backward propagating TM polarized modes. The effective refractive index and the extinction coefficient are "n" and "k", respectively.

Both imaginary and real parts of the effective index show non-reciprocity. The best performance for the proposed device is obtained when both effects, the absorption and the phase shift effect, are used together to enhance the isolation. The explanation will be based on the scheme of figure 1, with input and output TM polarized modes.

The TM polarized light is converted in the 50%-polarization converter to equal TE- and TM-fractions, which pass through the magneto-optic SOA. This induces the non-reciprocal phase shift and absorption on the TM-mode. The two fractions recombine into a new polarization state at the second 50%-polarization converter, depending on their respective phase and strength. If e.g. the induced phase shift in the SOA is 0, and power is equal in TE and TM, then the polarization conversion from the 2 PC/2's are added, so TE polarization is obtained, which is subsequently blocked in the output polarizer. If the phase difference is π radians, then the effect of the two polarization converters cancel out, and a TM output is obtained, which passes the polarizer.

It is clear that a non-reciprocal phase shift on the TM-polarization influences the transmission. An opposite $\pi/2$ phase shift for both directions allows one direction to fully pass the device, while the other direction is fully blocked. In general a phase shift of this magnitude is not available. However, this is also not strictly needed. If a full blocking is obtained in one direction then even a much smaller phase shift will allow transmission in the other direction, and thus a large isolation ratio. The price is an extra loss in the through direction, which must be compensated by the SOA. Full blocking requires sufficient control over the relative phase and amplitude of the TE and TM fractions.

By replacing the TM-pass polarizers with TE-pass types, and adjusting the phase differences between TE and TM, also TE isolators are possible. With polarization splitters it is therefore quite straightforward to make a polarization diversity circuit to obtain polarization independent isolation (see figure 3).

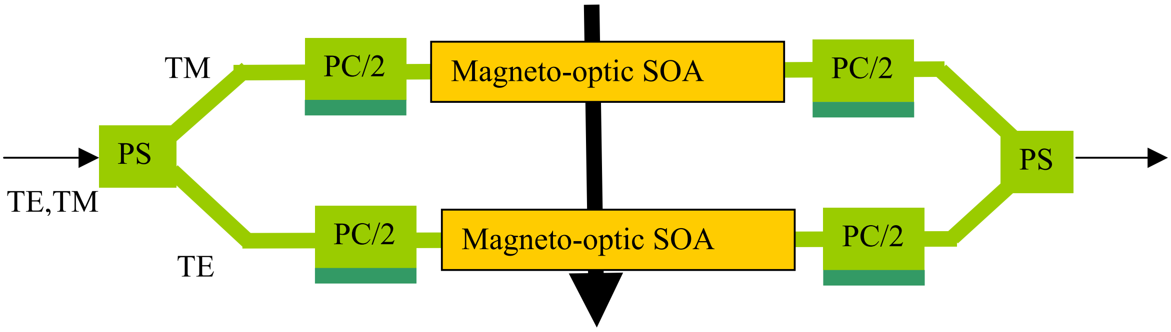

Figure 3: Top view of polarization independent waveguide isolator. PS is a polarization splitter.

Theory

The transfer function of the proposed isolator can be obtained from concatenating the transfer matrices of each of the components in the device. For the magneto-optic SOA it is assumed that the TM-polarization passes with a non-reciprocal attenuation and phase shift, changing the sign of both with direction. The TE-polarization is taken to have the same attenuation and phase shift as the TM-polarization in the "backward" direction:

$$P_{out} / P_{in}(\pm) = \left[0.25e^{\pm 2\alpha} + 0.25e^{-2\alpha} - 0.5e^{\alpha(\pm 1-1)}\cos(\pm\varphi + \varphi)\right] \qquad (1)$$

Here $\pm\alpha$ is the non-reciprocal gain/attenuation factor and $\pm\varphi$ is the non-reciprocal phase shift. The ±-sign indicates the direction; '+' is "forward", '-' is "backward".

The terms on the right hand side are respectively the non-reciprocal absorption/gain for TM, the absorption for TE and the interference between them.

The output in the "-"direction is zero, in the "+"direction it is:

$$P_{out} / P_{in}(+) = \left[0.25e^{2\alpha} + 0.25e^{-2\alpha} - 0.5\cos(2\varphi)\right] \qquad (2)$$

This is clearly optimal if the non-reciprocal phase shift is π/2 radians.

The actual performance of the isolator depends on the control of the phase shift and on the equal attenuation for TE and TM (both $e^{-\alpha}$ in the "backward" direction). In the following feasibility study, based on theoretical and experimental results from the literature, it will be investigated what the tolerances on these parameters are.

Feasibility and discussion

As a starting point a desired isolation ratio of 20 dB is taken. A higher number is not realistic, because integrated polarizers have extinction in this range [5].

The data that available are the following:

- Experimentally an isolation (due to non reciprocal absorption) of 81 dB/cm was found at λ=1.3 μm in [1].
- In [6] theoretically a non-reciprocal refractive index change of 2 10^{-4} and a non-reciprocal absorption of 240 dB/cm were found, at a wavelength of λ=1.55 μm

The 20 dB isolation leads to the following condition, in the presence of errors of $\delta\alpha$ on the attenuation of the TE-mode and of $\delta\varphi$ on the TE/TM phase difference φ_0:

$$\frac{\left[\delta\alpha + 0.5(\delta\varphi)^2\right]}{0.5e^{4\alpha} + 0.5 - e^{2\alpha}\cos(2\varphi)} \leq 0.01 \tag{6}$$

The length of the SOA is 520 μm, as in [1]. The non-reciprocal absorption is 81 dB/cm, but the non-reciprocal refractive index change is taken as 1/3 of the theoretical value (because also the experimental absorption is 1/3 of the theoretically predicted one). From this it follows that α=0.48 and φ=0.17 radians. This means e.g. that $\delta\alpha$ should be smaller than 0.015, or 0.06 dB, if there is no phase error. Thus the power ratio of the TE and the TM mode after the magneto-optic SOA should be defined to within 2.5 %. The phase error $\delta\varphi$, without amplitude error, is 0.17 radians, or 10 degrees. The extra loss in the through direction due to incomplete reconstruction of the polarization is 5.5 dB.

The most critical issue is controlling the relative amplitudes of TE and TM in the magneto-optic SOA. If this can not be controlled by careful fabrication, or adjustment of the SOA-current, an extra polarization depended attenuator or amplifier would be needed.

More tolerance can be obtained if stronger effects or longer devices can be used.

Conclusions

In this paper a proposal is presented for a waveguide optical isolator on InP/InGaAsP. It uses a magnetic contact on top of a SOA to obtain a non-reciprocal effect on both the absorption and phase shift of a TM-polarized mode. With integrated partial polarization converters and polarizers these two effects can be applied to obtain 20 dB isolation if power ratio and phase shifts between TE and TM can be sufficiently controlled.

References

[1] W. Van Parys et al, "Demonstration of 81 dB/cm isolation on an InP-based optical waveguide isolator", in Proceedings of the European Conference on Integrated Optics, 2005, pp. 33-36.

[2] H. Shimizu and Y. Nakano, "First demonstration of TE mode nonreciprocal propagation in an InGaAsP/InP active waveguide for an integratable optical isolator", Japanese Journal of Applied Physics, vol. 43, pp. L 1561-1563, 2004.

[3] J.M. Hammer et al., "Poly-crystalline-metal-ferromagnetic optical waveguide isolator (POWI) for monolithic integration with diode lasers", IEEE Photonic Technology letters, vol. 9, pp. 631-633, 1997.

[4] Y. Zhu, U. Khalique et al," Ultrashort, highly efficient integrated optical polarization converter", in Proceedings of the European Conference on Integrated Optics, 2005, pp. 96-99.

[5] J.J.G.M. van der Tol et al., "A short polarization splitter without metal overlays on InGaAsP-InP", IEEE Photonic Technology letters, vol. 9, pp. 209-211, 1997.

[6] M. Takenaka and Y. Nakano, "Proposal of a novel semiconductor optical waveguide isolator", in Proceedings of the 11th International Conference on Indium Phosphide and Related Materials, 1999, pp. 289-292.