Experimental Verification of a Novel Integrated Optical Isolator Concept

W. Van Parys[1], M. Vanwolleghem[1], D. Van Thourhout[1], R. Baets[1], R. Wirix-Speetjens[2], L. Lagae[2], B. Thedrez[3], F. Lelarge[3] and O. Gauthier-Lafaye[3]

[1] Department of Information Technology, Ghent University
St. Pietersnieuwstraat 41, 9000 Ghent, Belgium
Fax: +32 92643593, Email: wouter.van.parys@intec.ugent.be

[2] Interuniversitair Micro-Elektronica Centrum, IMEC vzw
Kapeldreef 75, 3001 Leuven, Belgium

[3] Alcatel CIT
Route de Nozay, 91460 Marcoussis, France

Abstract

The experimental demonstration of a novel integrated optical isolator concept is presented. By using a transversely magnetized ferromagnetic metal as the electric contact of an active waveguide structure, the transverse magneto-optic Kerr effect induces non-reciprocal loss of the TM guided mode. Based on this principle we designed, fabricated and characterized the first version of an optical isolator easily integrable with standard InP-based active devices. Experimental results on these first demonstrators show an isolation ratio of 2.0 dB/mm.

1. Introduction

The development of a waveguide-type optical isolator continues since more than 20 years. However, since all traditional approaches make use of garnet-based waveguide structures, integration of an isolator with III-V structures, such as InP and GaAs, which are used for the fabrication of lasers, is today only realized through direct bonding. Apart from the obvious increase in cost by using this technique, it seems that integration causes a severe drop in isolating performance; 19dB isolation is achieved for stand-alone garnet structures [1], while the highest isolation level reached with a wafer-bonded device is just 5dB [2].

In 1999, Nakano et al. [3] theoretically proposed a new concept for an integrated optical isolator. In this paper, the experimental verification is discussed. We start with a short theoretical overview of the principle. In a second part, experimental results achieved on first generation demonstrator devices are given.

2. Theory

The dielectric tensor of a magnetized magneto-optical material can be written as:

$$\hat{\varepsilon} = \hat{\varepsilon}_0 + \begin{bmatrix} 0 & 0 & -iN^2Q \\ 0 & 0 & 0 \\ iN^2Q & 0 & 0 \end{bmatrix} \qquad (1)$$

where we assume that the magnetization is in the transverse y-direction. N is the complex refractive index of the medium, Q is the complex magneto-optical Voigt parameter, which is in a very good approximation proportional to the magnetization **M**. $\hat{\varepsilon}_0$ is the (diagonal) dielectric tensor in the absence of the magnetic field.

If an optical waveguide is covered with a transversely magnetized magneto-optical layer sufficiently close to the core, the propagation constant of a TM-polarized guided mode is changed. The transverse magneto-optical Kerr effect is responsible for this phenomenon. Through perturbation theory, with the non-diagonal elements of $\hat{\varepsilon}$ taken as perturbation, we find:

$$\delta\beta = \frac{2\pi}{\lambda}(\delta n_{eff} + i\delta k_{eff}) = \frac{\int_{MO\,material} \frac{Q}{N^2} \mathrm{Re}\left(h_{0,y} \frac{dh_{0,y}}{dx} \right) dx}{\int_{waveguide} \left| h_{0,y} \right|^2 \mathrm{Re}\left(\frac{1}{n(x)^2} \right) dx} \qquad (2)$$

where the z-axis is along the propagation direction, $h_{0,y}$ is the transverse component of the magnetic field if no magnetization is present and $n(x)$ is the complex refractive index of the waveguide structure. It is easy to see that that the effective index correction $\delta\beta$ is independent of the travelling direction of the guided mode. After all, a forward-backward transformation corresponds to a sign change of the transverse magnetic field components, but in equation (2) the field components occur in pairs. As a consequence, the propagation constants of forward and backward travelling mode are no longer exact opposites:

$$\beta_f = \beta + \delta\beta \;\text{ and }\; \beta_b = -\beta + \delta\beta \qquad (3)$$

with β the unperturbed propagation constant of the forward propagating guided mode. This implies that the modal absorption is different for both directions.

This principle can be used to realize an integrated optical isolator. By compensating the loss in the forward direction by using an active core region, a structure is created that is transparent in one and absorbing in the other propagation direction. Figure 1 illustrates the operation principle. It is clear that the magneto-optical material has to fulfill two functions; on one hand, it is the source of the non-reciprocal effect and on the other hand it must serve as a metal contact for the underlying active structure.

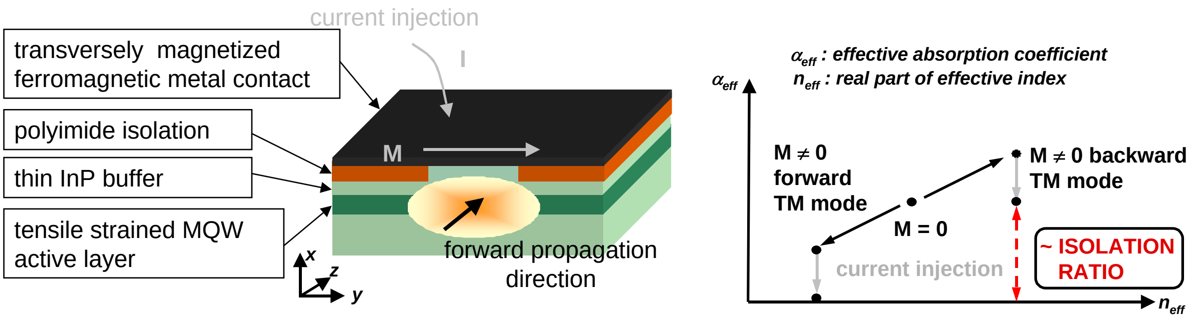

Fig 1. device structure (a) and operation principle (b) of the novel integrable isolator

The advantage of this concept over the traditional, garnet-based approach is obvious. The isolating structure has basically the same structure as the laser that the isolator is to be integrated with, so monolithic integration is easy and no degradation of the isolating performance is expected.

3. Experimental verification

For the practical realization of a device based on this concept, two key aspects needed thorough examination. The active region, responsible for the loss compensation of the TM guided mode, must provide high polarization selective material gain. For this, a tensile strained multi-quantum well active structure was designed and optimized in the InGaAsP/InP material system. The second basic aspect of the device is the study and optimization of the magneto-optical layer, with respect to its optical, magneto-optical, magnetic and electrical properties. At this moment only one magneto-optical metal alloy was considered, $Co_{90}Fe_{10}$. Optically and magneto-optically the complex refractive index N and complex Voigt parameter Q are experimentally measured at the operation wavelength of 1.3μm. Furthermore, as the device must work in the remanent magnetization regime, the magnetic anisotropy is studied, by measuring the magnetic hysteresis both for a magnetization direction perpendicular to and parallel with the stripes. On the electrical side, the influence of the semiconductor-metal contact on the I-V characteristic of the device needs to be as low as possible. We designed a contact structure with the CoFe alloy with a low contact resistivity of $10^{-5}\Omega cm^2$. The device structure is illustrated in figure (1a). An InGaAsP tensile strained multi-quantum well active region is covered with a thin InP buffer layer. On top there is the optimized semiconductor-metal contact structure with the magneto-optical metal alloy $Co_{90}Fe_{10}$.

The design of the structure basically comes down to finding the optimal thickness of the InP buffer between the active core and the magneto-optical layer. The closer the guiding region to the metal layer, the larger the TM modal overlap with the magneto-optical metal and the larger the non-reciprocal effect. At the same time however, the metal absorbs more light and more loss is to be compensated in the active region. The optimal thickness is in the order of 250nm.

A first experimental characterization of the non-reciprocal device is to measure the influence of the magneto-optical layer on the amplified spontaneous emission (ASE) in the active region. The ASE-power emitted at one facet is detected while looping the transverse magnetization of the CoFe film through its entire hysteresis cycle. Practically, this is done by looping the magnetic field of an external electromagnet between H_s and $-H_s$, the fields needed to saturate the magneto-optical film in either transverse direction. From equation (2) it is clear that the light absorption is proportional to the magnetization. Therefore, we expect that a plot of the detected TM-polarized ASE-power versus the applied magnetic field reflects the magnetic hysteresis of the $Co_{90}Fe_{10}$ layer. At the same time the TE response should be flat. The experimental result presented in figure 2 is clearly consistent with these theoretical predictions.

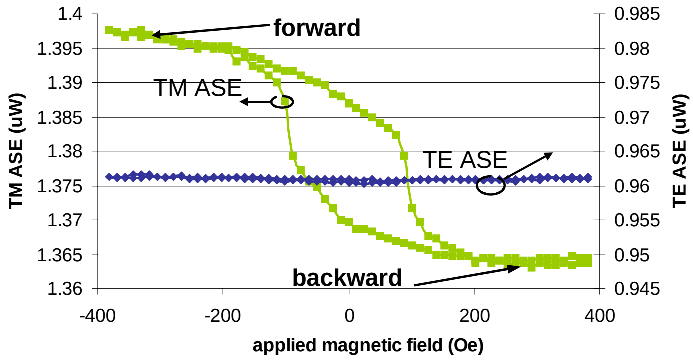

Fig 2. First qualitative verification of the isolator concept by polarization selective ASE-power detection

From these ASE measurements it is possible to extract the isolation ratio of the device. The experiment is repeated for a number of different device lengths L and current injection levels J. The measured ratios of the 'forward' to the 'backward' TM ASE-power are fitted to a theoretical non-reciprocal ASE-model with independent variables J and L. This leads to the extraction of the unknown parameters, being the isolation ratio $\Delta\alpha$ and the parameters of the gain-current density relation. The best result obtained with the first generation demonstrator devices gives an isolation ratio of 2.0dB/mm.

Improvement of the isolator performance is possible by developing an active structure with a higher differential gain, allowing the InP spacer to be thinner. Further increase in isolation ratio might be achieved by optimizing the magneto-optical layer.

4. Conclusion

We have designed, fabricated and characterized a monolithically integrable optical isolator based on a novel concept. An isolation ratio of 2.0dB/mm is measured, which proves the feasibility of the concept. Further optimization procedures are identified.

Acknowledgement

This research has been carried out in the framework of the European Union IST research program ISOLASER.

References

[1] J. Fujita, M. Levy, R.M. Osgood, Jr., L. Wilkens and H. Dötsch, "Waveguide Optical Isolator Based on Mach-Zehnder Interferometer", Applied Physics Letters, Vol. 76, No. 16, pp. 2158-2160, April 2000

[2] H. Yokoi, T. Mizumoto, N. Shinjo, N. Futakuchi and Y. Nakano, "Demonstration of an Optical Isolator with a Semiconductor Guiding Layer that was obtained by use of a Nonreciprocal Phase Shift", Applied Optics, Vol. 39, No. 33, Nov. 2000, pp. 6158-6164.

[3] M. Takena and Y. Nakano, "Proposal of a Novel Semiconductor Optical Waveguide Isolator", Proc. of the 11th International Conference on Indium Phosphide and Related Materials, May 1999, pp. 289-292.