InP-based Monolithically Integratable Optical Waveguide Isolator

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Abstract – The experimental realization of an InP-based integratable optical isolator is presented. By using a transversely magnetized ferromagnetic metal film as the electrical contact of an active optical waveguide structure, non-reciprocal loss of the TM-polarized guided waveguide mode is induced. Based on this principle we designed, fabricated and characterized an optical isolator which is easily integratable with standard InP-based active devices. Experimentally, an isolation ratio of 32 dB/cm has been obtained.

Keywords – optical isolators, magneto-optics, photonic integrated circuit (PIC)

I. Introduction

An optical isolator - a device through which light can pass in one direction, but not in the opposite - is an important component in many laser-based optical systems. By blocking optical feedback in the laser, an isolator is indispensable for eliminating one of the main noise sources in a traditional telecom link. The non-reciprocity caused by magneto-optical effects is the basis of such devices. Magneto-optics deals with phenomena arising as a result of the interaction between light and magnetized matter.

Current optical isolators are free-space bulk components. Developing a planar waveguide-based integrated optical isolator - in the form of a chip - is a long-time sought goal in the field of photonics. Such a device would greatly reduce the manufacturing cost of laser diode packages by reducing the number of optical components and by eliminating the expensive beam alignment techniques needed when using an external, bulk isolator in the package. Furthermore, integrated optical isolators will be indispensable for future photonic integrated circuits (PIC's), assembling a multitude of the most diverse optical functions on a single chip.

Until recently, all research in this domain concentrated on designing an integratable isolator with waveguide structures made of the same materials as their bulk free-space counterparts, being rare-earth ferromagnetic iron garnets. Several stand-alone optical waveguide isolators with sufficiently high isolation ratios have been reported [1]. However, integration with traditional III-V semiconductor substrates, such as InP and GaAs, which are used for the fabrication of semiconductor lasers, has encountered great difficulties. The most popular approach nowadays to integrate this garnet-based material with InP-substrates makes use of direct wafer bonding [2], resulting in no considerable cost reduction compared to the current bulk isolators.

A couple of years ago, a completely new integrated isolator concept was theoretically proposed [3-4] and in 2003, we demonstrated the feasibility of this approach [5-6]. Here, we describe the development of an improved device, with a considerable increase in isolation ratio.

II. Theoretical concept

Basically, the novel optical isolator is an InP-based semiconductor optical amplifier (SOA), with a ferromagnetic metal contact very close - in the order of 300nm - to the active region. By transversely - perpendicular to the light propagation direction and in the plane of the metal contact - magnetizing this metal film, non-reciprocal optical absorption of the TM-polarized guided modes of the active waveguide structure is induced. Electrical pumping of the component, with the ferromagnetic metal film as the electric contact of the underlying SOA, can compensate all optical absorption in the forward propagation direction. The result is an optical component which, being transparent in one propagation direction, while still providing net loss in the opposite, is isolating. Figure 1 is a schematic illustration of this device.

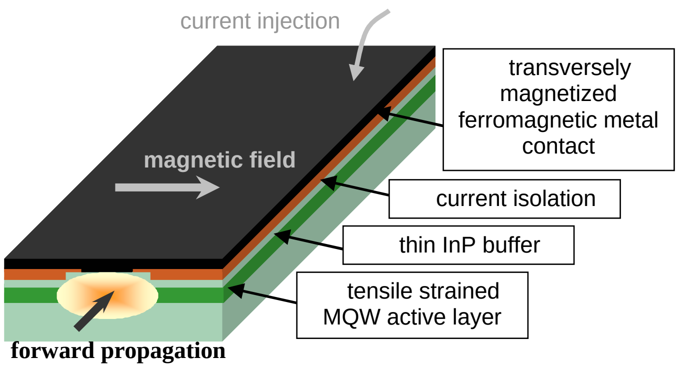

Figure 1: illustration of the novel integratable optical isolator

The advantage of this concept over the traditional, garnet-based approach is obvious. The isolator basically has the same structure as the laser that it is to be integrated with, so monolithic integration - integration of different optical elements on one planar substrate - is easy and no degradation of the isolating performance is expected. In addition, as ferromagnetic films can easily be deposited on III-V semiconductor layers, this optical waveguide isolator can be fabricated using standard InP-SOA processing techniques.

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III. Experimental Realization

Based on this theoretical concept, we successfully designed, fabricated and characterized a monolithically integratable optical isolator. As the ferromagnetic metal film fulfills two functions - it provides the electrical contact of the SOA and it is the source of the non-reciprocal, magneto-optical effect - both its electrical and magneto-optical properties are of primary importance for the device performance. A low resistive ohmic metal-semiconductor contact has been developed for a ferromagnetic metal with a high value of the magneto-optical parameter at the operation wavelength of 1.3μm. In addition, the magnetic behavior of the ferromagnetic film has been an issue that required study, especially with respect to its magnetic remanence. Furthermore, to provide the strong TM-polarization selective material gain needed to compensate the loss in the forward propagation direction, a novel active layer structure has been developed. The final device is an InGaAlAs-based tensile strained multi-quantum well structure topped with a $Co_{90}Fe_{10}$ ferromagnetic metal film, with an optimized metal-semiconductor contact scheme.

The isolator design is done with an in-house developed photonic simulation tool [7], extended with a package for perturbative magneto-optical waveguide calculation [3], similar to [6]. Theoretically, the designed isolator has an isolation ratio of 82.5 dB/cm.

The fabricated components have been characterized in a transmission regime; TM-polarized laser light is injected in the device at one of both isolator facets and the output power is detected at the other. The device is transversely magnetized with an external electromagnet and is electrically pumped to compensate the absorption. In order to determine the isolating behavior of the component, one can compare the output power at each of the two facets while injecting light at the other. However, it is equivalent and much easier to switch the magnetization in the ferromagnetic film between both transverse directions and detect the emitted power at the same facet. An experimental result is shown in Figure 2, where ‘forward’ and ‘backward’ each corresponds with one transverse magnetization direction. There is a clear difference in output power between both directions, which indicates optical isolation. By calculating the power ratio between forward and backward direction, the isolation ratio, which determines the device performance, is extracted. The highest isolation ratio obtained is 32dB/cm. When performing the same experiment with TE-polarized laser light, identical power levels for both magnetization directions are obtained. This is a persuasive argument that the observed power shift is indeed the non-reciprocal effect.

Comparing the experimental results with the design value of the isolation ratio shows a difference of a factor 2.5. It is however believed that this discrepancy can be significantly reduced by optimizing the processing scheme of the devices.

As the final isolator is designed to work in remanent regime - without an external magnetic field applied - it is the isolation ratio in remanence that determines the actual device performance. Figure 3 illustrates that the remanent isolation ratio (at 0 Oe) is quasi-identical to the saturation value (at ±500 Oe). The output power is detected while looping the magnetization in the ferromagnetic metal through its entire hysteresis cycle at a fixed pumping current.

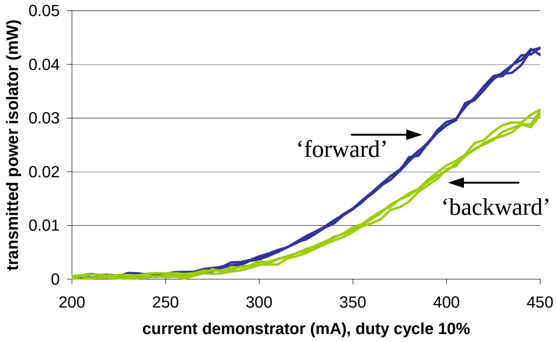

Figure 2: transmitted power for both transverse magnetization directions.

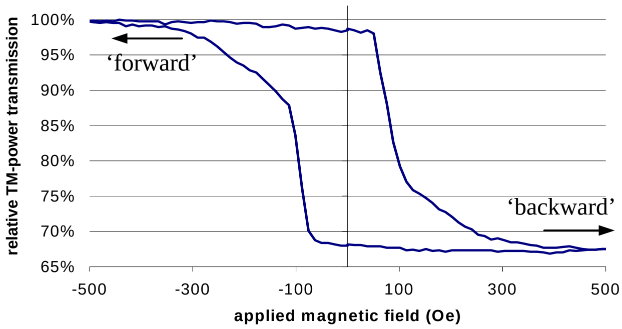

Figure 3: relative transmitted power, detected while looping the magnetization through its hysteresis cycle.

IV. Conclusion and Outlook

We have designed, fabricated and characterized a monolithically integratable optical waveguide isolator with an experimental isolation ratio of 32 dB/cm. We believe that optimization of the processing scheme combined with optimization of the considered ferromagnetic metal should result in improved isolator performance and fully practical devices with isolation ratios over 20 dB.

Acknowledgement

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References

[1] R.M. Osgood et al., “Progress in Integrated Optical Isolators”, in Integrated Photonics Research, OSA Technical Digest (Optical Society of America, Washington DC, 2000), pp. 274.

[2] H. Yokoi et al., “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. Takenaka et al., “Proposal of a Novel Semiconductor Optical Waveguide Isolator”, Proc. of 11th Intern. Conf. on Indium Phosphide and related materials, pp.289-292, May 1999.

[4] W. Zaets et al., “Optical Waveguide Isolator based on Non-Reciprocal Loss/Gain of Amplifier Covered by Ferromagnetic Layer”, IEEE Photon. Technol. Lett., Vol. 11, pp. 1012-1014, August 1999.

[5] M. Vanwolleghem et al., “Experimental Verification of a Novel Integrated Isolator Concept”, ECOC-IOOC, 6, Italy, p.78-79 (2003).

[6] M. Vanwolleghem et al., “First Experimental Demonstration of a Monolithically Integrated InP-Based Waveguide Isolator, OFC 2004, United States, p. TuE6 (2004).

[7] CAMFR, freely available at http://www.sourceforge.net/camfr