ECIO'05: 12th EUROPEAN CONFERENCE ON INTEGRATED OPTICS
- ABSTRACT -

DEMONSTRATION OF 81dB/cm ISOLATION ON AN InP-BASED OPTICAL WAVEGUIDE ISOLATOR

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SUMMARY

The paper describes the design, fabrication and characterization of an InP-based, monolithically integratable optical isolator with a demonstrated isolation strength of 81dB/cm.

KEYWORD

optical isolator, integrated optics, magneto-optical Kerr effect, SOA

ABSTRACT

INTRODUCTION

In a traditional optical telecom link, an optical isolator blocks optical feedback in the laser and, as such, eliminates one of the main noise sources in the system. Current optical isolators are free-space bulk components. Developing a planar, waveguide-based integrated optical isolator 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 the development of an integratable isolator with waveguide structures made of rare-earth ferromagnetic iron garnets, the same materials as their bulk free-space counterparts. Several stand-alone optical waveguide isolators with sufficiently high isolation ratios have been reported [1]. However, integration with traditional III-V semiconductor substrates 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], not resulting in a considerable cost reduction compared to the current bulk isolators. A couple of years ago, a completely new concept for a – TM-mode – integrated isolator was theoretically proposed [3-4]. We experimentally demonstrated this approach in 2003 [5-6]. Recently, an equivalent concept for TE-polarization has been proposed and demonstrated [7]. This paper describes the development of an improved TM-mode device, with a considerable increase in isolation ratio.

THEORETICAL CONCEPT

The novel optical isolator basically is an InP-based semiconductor optical amplifier (SOA), with a ferromagnetic metal contact very close - in the order of 300nm - to the active region. Lateral magnetization of this metal film induces non-reciprocal optical absorption of the TM-polarized guided modes of the active waveguide structure, caused by the transverse MO Kerr effect. Electrical pumping of the component, with the ferromagnetic metal film as the electrical contact for 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. In figure 1 a schematic illustration of the optical isolator and its operation principle is given.

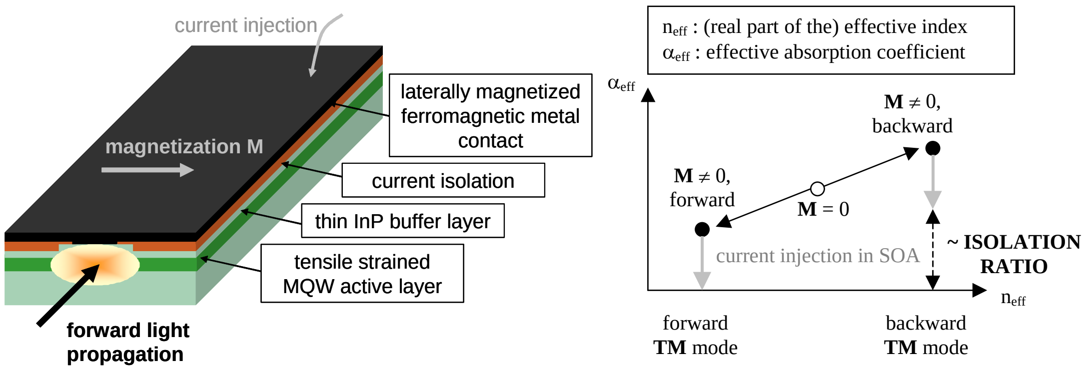

Figure 1: structure and operation principle of the novel optical isolator

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

DESIGN AND FABRICATION

Based on this theoretical concept, a monolithically integratable optical isolator has been designed and fabricated. As the ferromagnetic metal film fulfils two functions - it is the source of the non-reciprocal MO effect and it provides the electrical contact for the SOA - both its MO and electrical properties are of primary importance for the device performance. The optical and MO constants of the metal under study, $Co_{50}Fe_{50}$, have been experimentally extracted at the operation wavelength of 1.3µm [8]. Furthermore, a low resistive ohmic metal-semiconductor contact has been developed for this ferromagnetic metal. 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 active region is an InGaAlAs-based tensile strained (-1.16%) multi-quantum well (MQW) structure (9 QW's), with strain-compensating barriers and surrounding separate confinement heterostructure (SCH) layers [9]. Built-in tensile strain realizes TM-selective material gain, while TE-gain is suppressed. Figure 2 gives the experimental modal gain – current density relation for the active material system, measured on 6 QW broad area (BA) lasers, demonstrating a low transparency current density of less than $60A/cm^2$ per well.

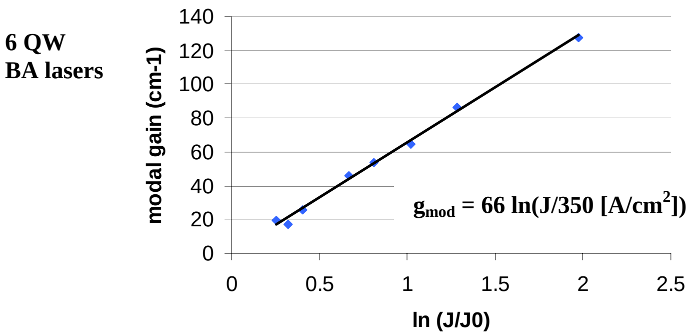

Figure 2: characterization of the active layer material

An in-house developed photonic simulation tool [10], extended with a package for perturbative MO waveguide calculation [11], has been used to calculate the optimum thickness of the InP cladding layer and the SCH layers, for a chosen value of the current density needed for transparency. A moderate forward transparency current density of $10kA/cm^2$ corresponds to a theoretical value for the isolation ratio of 152dB/cm.

The semiconductor layers have been grown with a metal organic vapor phase epitaxy process (MOVPE). A 50nm ferromagnetic $Co_{50}Fe_{50}$ contact was sputter-deposited and capped off with a protective Ti/Au bilayer defined through standard lift-off techniques. This layer stack has been processed with CH_4:H_2 RIE etching into ridge waveguide amplifiers (width 2.5µm) with the metal used as the etch mask to realize complete covering of the waveguide ridge with $Co_{50}Fe_{50}$. In the actual component however, processing imperfections occurred, causing the ridge to be wider (±3.5µm).

CHARACTERIZATION

The most fundamental characterization method for the fabricated components consists of coupling light in the isolator and detecting the output power under lateral magnetization reversal [12] – switching between both magnetization directions is equivalent to switching between forward and backward propagation direction. This is however a laborious method, not suited for a first, quick characterization of the devices. Here, an alternative method has been used, based on non-reciprocal lasing of the waveguide amplifiers.

The isolator – without an antireflection coating on the cleaved facets – is electrically pumped above threshold and the output power is measured under lateral magnetization reversal. Above threshold, the cavity losses are compensated by the material gain. This results in a simple extraction formula for the non-reciprocal absorption. If in the ASE-based formula given in [5] the roundtrip gain is set to unity, one finds the following expression for the isolation ratio:

$$isolation\ ratio\left[\frac{dB}{cm}\right] = \frac{10}{\ln 10}\frac{2}{L[cm]}\ln(optical\ power\ ratio) \qquad (1)$$

According to this formula, the only parameters that determine the isolation are the cavity length L and the ratio of detected power in forward to backward propagation direction. In figure 3 an example of such an isolation measurement is given. The left graph of figure 3 shows the output power for (pulsed) injection currents up to 500mA at saturation magnetization in either lateral direction, or – equivalent – in either light propagation direction. The right graph is found by taking the ratio of forward to backward optical power. Close to threshold, the power ratio increases with current. This can be understood by considering that the mentioned fabrication imperfections cause the waveguide amplifiers to be laterally bimodal, with both the zeroth and the first order with an important contribution to the total output power. This is experimentally confirmed by far field measurements of the output signal. A consequence of this bimodality is that, close to threshold, the threshold condition isn't fulfilled for a considerable fraction of the output power, hence the extraction method doesn't hold in this current region. For a correct determination of the isolation strength by applying formula (1), the optical power ratio must be measured at high injection current.

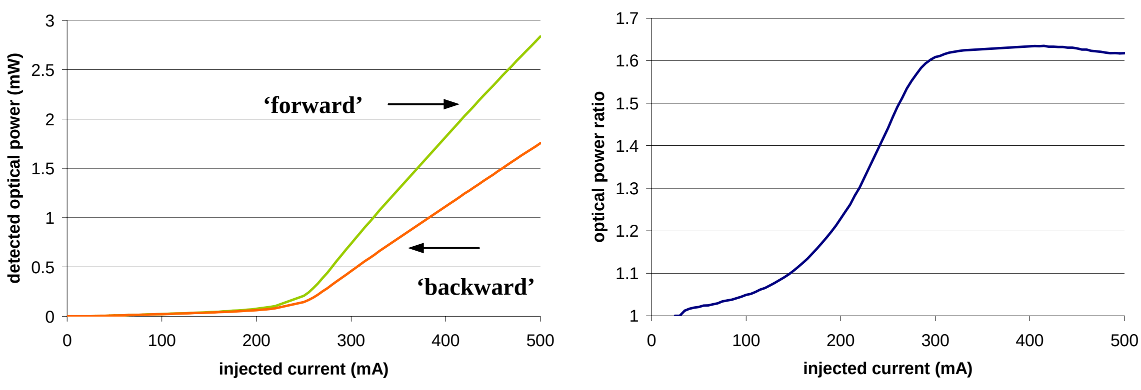

Figure 3: extraction of isolation strength: optical power and power ratio at different injection currents

A value for the optical power ratio of 1.625 has been demonstrated on a 520µm long device, which is equivalent to an isolation ratio of 81dB/cm. The corresponding threshold current equals 230mA.

Comparing the experimental isolation ratio with the design value indicates a discrepancy of a factor 1.9. Several possible reasons can be distinguished for this difference. The lateral bimodality of the active waveguide results in an extracted value for the isolation ratio that is a weighted average of the isolation of both the zeroth and first order TM-polarized guided modes. The overlap of the first order mode with the magnetized ferromagnetic metal is smaller than that of the fundamental mode, causing the non-reciprocal absorption difference of the first order

mode to be considerably smaller. In addition, the design is done with a 1D simulation tool, while it is obvious that the fabricated component is explicitly two dimensional, due to the fabrication imperfections. A third source of errors is the uncertainty of 7% on the extracted value for the magneto-optical constant of $Co_{50}Fe_{50}$.
Comparison between the designed transparency current of 180mA and the measured threshold current of 230mA shows that theory and experiment are in good agreement in terms of transparency of the forward propagating light.

CONCLUSION

We designed, fabricated and characterized an InP-based monolithically integratable optical isolator. An isolation ratio of 81dB/cm has been demonstrated, applying a quick characterization method based on non-reciprocal lasing of the waveguide amplifiers. Far field measurements of the optical output show that higher order mode effects play a role on the fabricated devices. This results in an extracted value for the optical isolation strength that is below what can be achieved with this design.

ACKNOWLEDGEMENT

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

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