

InP-Based Monolithically Integrated Optical Waveguide Isolator with 32 dB/cm Isolation

Wouter Van Parys, Mathias Vanwolleghem, Dries Van Thourhout and Roel Baets

Department of Information Technology (INTEC), Ghent University, St-Pietersnieuwstraat 41, 9000 Gent, Belgium

Jean Decobert, Beatrice Dagens and Bruno Thedrez

Alcatel CIT, Route de Nozay, 91460 Marcoussis, France

Roel Wirix-Speetjens and Liesbet Lagae

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

Abstract: Based on the use of a transversally magnetized ferromagnetic metal as the electric contact of an active waveguide structure, a monolithically integrated optical isolator with an isolation ratio of 32 dB/cm is developed.

All traditional approaches towards the development of a waveguide-type optical isolator make use of garnet-based waveguide structures [1]. This implies that integration of an isolator with III-V semiconductor structures has only been realized through direct wafer bonding. Apart from the tight tolerances and cost of such an isolator fabrication technique, it seems that integration causes a severe drop in isolating performance; 19dB isolation is achieved for stand-alone garnet structures [2], while the highest isolation level reached with a wafer-bonded device is 5dB [3]. A new theoretical concept has been proposed in 1999 [4-5] and experimentally demonstrated in 2003 [6-7]. This paper describes the development of an improved device with a considerable increase in isolation ratio.

The TM-polarized eigenmodes of an InP-based semiconductor optical amplifier (SOA) with a transversally magnetized (magnetization $\mathbf{M} \neq 0$) ferromagnetic metal close to the guiding layer undergo non-reciprocal optical absorption, caused by the magneto-optical (MO) Kerr effect. Electrical pumping, with the ferromagnetic metal used as the electric contact of the underlying SOA, can compensate the absorption in the forward propagation direction. The result is a device, which, being transparent in one propagation direction while providing net loss in the other direction, is isolating. Fig. 1 gives a schematic representation the operation principle of the isolator.

In a first step, the key physical parameters needed for the design of the isolator have been experimentally characterized. The optical and MO constants of the considered ferromagnetic metal, $\text{Co}_{90}\text{Fe}_{10}$, have been extracted at the operation wavelength of $1.3\mu\text{m}$. The active region is a novel InGaAlAs based tensile strained (-1.16%) multi-quantum well (9 wells) structure, with strain-compensating barriers and surrounding separate confinement heterostructure (SCH) layers [8]. Built-in tensile strain realizes TM-selective material gain, while TE gain is suppressed. Fig. 2 gives the experimental current density versus modal gain relation for this active material system, measured on 6 QW broad area lasers, demonstrating a low transparent current density of less than 60 A/cm^2 per well. The isolator design is done with an in-house developed photonic simulation tool [9], extended with a package for perturbative MO waveguide calculation [4], similar to [7]. The optimum thickness of the InP cladding layer and SCH layers is calculated, for a reasonable value of the current density needed for transparency in the forward propagation direction (20 kA/cm^2). Theoretically, this isolator has an isolation ratio of 82.5 dB/cm.

The layers have been grown with a metal organic vapor phase epitaxy process (MOVPE) and then processed with CH_4 :RIE etching into ridge waveguide amplifiers with various widths (2 to 7 μm). A 50nm ferromagnetic $\text{Co}_{90}\text{Fe}_{10}$ contact was sputter-deposited and capped off with a protective Ti/Au bilayer defined through standard lift-off techniques. Covering only half the ridge with $\text{Co}_{90}\text{Fe}_{10}$ minimizes the influence of misalignment of the lift-off mask.

In [6-7] the isolator devices are characterized by measuring the generated amplified spontaneous emission (ASE) under magnetization reversal in the $\text{Co}_{90}\text{Fe}_{10}$ layer. Switching the transverse magnetization, by means of an external electromagnet, while detecting the output power from one facet is equivalent to successively measuring forward and backward propagating light. However, a more fundamental characterization method consists of injecting TM-polarized laser light in the device, electrically pumping the device to overcome loss in the forward propagation direction and detecting the transmitted power under magnetization reversal. This method not only avoids the need for a fitting procedure [7] to extract the isolation ratio but also allows for a study of the spectral and dynamic behavior of the device. In Fig. 3 the transmitted TM-power for both propagation directions is given for a range of pulsed injection currents (pulse duration 0.1 μs , duty cycle 10%). To quantify the isolation ratio directly from these measurements, the ASE power component is separately determined and subtracted from the transmitted power. Subsequently the ratio of ‘forward’ to ‘backward’ power is calculated. The model can be described with the following formulas, with α_{mod} the modal loss in the absence of a magnetic field and $\Delta\alpha$ the non-reciprocal difference in optical absorption. Isolation ratios up to 32 dB/cm are achieved.

$$\text{measured ratio} = \frac{\exp([- \alpha_{\text{mod}} + \Delta \alpha / 2] L)}{\exp([- \alpha_{\text{mod}} - \Delta \alpha / 2] L)}, \quad \text{isolation ratio [dB/cm]} = 10 \log(\text{measured ratio}) / L [\text{cm}] \quad (1)$$

Three main reasons can be distinguished for the discrepancy between the calculated and the measured values of the isolation ratio. First of all, there is an error measurement of 20% on the extracted value of the MO constant of $\text{Co}_{90}\text{Fe}_{10}$. Furthermore, the design tool is one-dimensional while the situation is explicitly two-dimensional due to the partial coverage of the waveguide ridges with ferromagnetic metal. A third source of deviations could be higher order mode effects, this issue needing further investigations.

The final isolator is designed to operate in remanent regime (without external magnetic field applied). Therefore, it is the isolation ratio in remanence that determines the actual device performance. Whereas in [7], the remanent isolation ratio is only half the saturation value, for this isolator both values are quasi-identical (Fig. 4).

In summary, we have designed, fabricated and characterized an InP-based monolithically integrated optical isolator with a proven isolation ratio of 32 dB/cm. It can be expected that full covering of the waveguide ridge with ferromagnetic metal would considerably increase the isolation ratio. We believe that optimization of the processing scheme combined with optimization of the considered MO metal should result in improved isolator performance and fully practical devices with isolation ratios over 20 dB.

Acknowledgements

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Figures

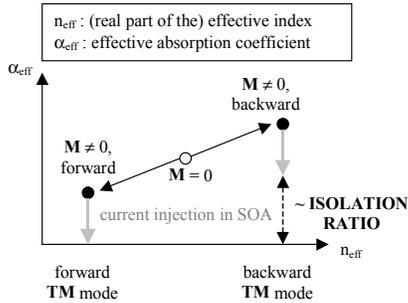


Fig. 1: operation principle of the isolator

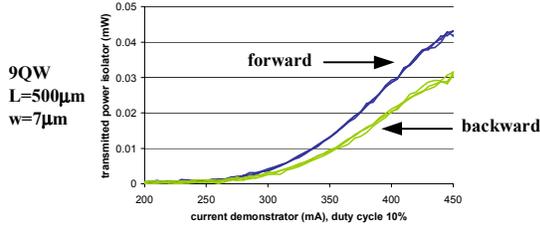


Fig. 3: transmitted TM-power as a function of pulsed injected current

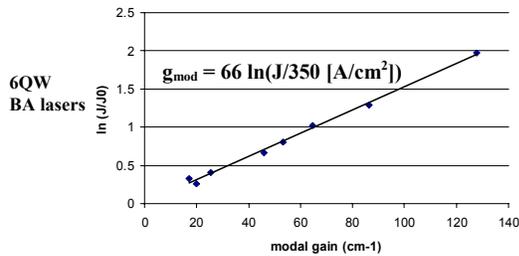


Fig. 2: experimental current density – modal gain relation

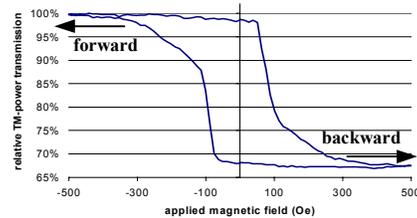


Fig. 4: relative transmitted TM-power as a function of applied external magnetic field

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