Optimization of a monolithically integrated ferromagnetic-metal-clad InP-based optical waveguide isolator

M. Vanwolleghem[1], **W. Van Parys**[2], **P. Gogol**[1], **R. Baets**[2], **P. Beauvillain**[1]
[1] Institut d'Electronique Fondamentale, UMR CNRS 8622, Université Paris-Sud, 91405 Orsay CEDEX, France.
[2] Department of Information Technology, Faculty of Applied Sciences, Ghent University, St-Pietersnieuwstraat 41, B-9000 Ghent, Belgium.

Five years ago a new concept for a straightforwardly monolithically integrated optical waveguide isolator has been predicted[i]. The approach is based on the idea that for monolithic integration the isolator structure should be very similar to that of the laser it is to be integrated with. If in a standard InP-based optical amplifier (SOA) a transversely magnetized ferromagnetic metal is placed very close to the guiding region, the evanescent tail of the guided ground TM mode overlaps with the magneto-optic (MO) metal and the MO Kerr effect induces a non-reciprocal complex shift of the complex effective index of the guided mode. The modal absorption will be different in both propagation directions. The remaining loss in the forward direction can be compensated by current injection in the active material. The result is a component which, being transparent in one while providing loss in the opposite direction, is isolating and which can be straightforwardly monolithically integrated with InP-based active photonic devices (see Fig. 1). On top of that, as opposed to traditional approaches for an integrated optical waveguide isolator, which are based on non-reciprocal interferometric structures in the transparent Be:YIG/GGG material system, this concept has the advantage that it works directly on the modal absorption of the guided modes, hence not needing an interferometer to obtain backward extinction.

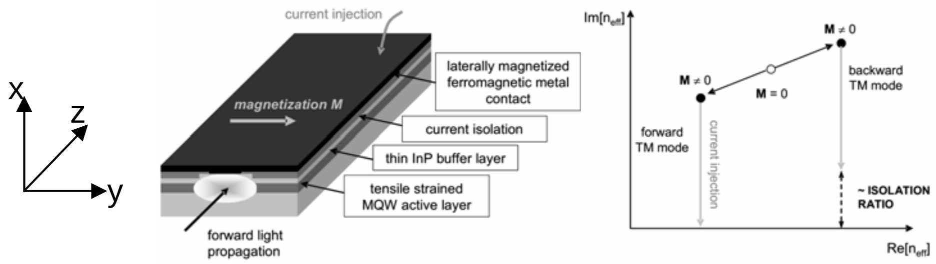

Fig.1 : Schematic representation of the integrated optical isolator and operation principle.

Previously, we reported successful experimental observation of the non-reciprocal TM absorption effect[ii-iii], and of the growth and characterization of tensile-strained InAlGaAs multi-quantum-well (MQW) layers providing sufficient TM gain for forward loss compensation and sufficient TE gain suppression. Here we describe the design of an optimal layer structure for this type of integrated optical waveguide isolator and compare three different CoFe alloy compositions, $Co_{90}Fe_{10}$, $Co_{50}Fe_{50}$ and pure Fe. The layer structure consists of a 1.3μm AlGaInAs/InP MQW (9 wells at –1.16% tensile strain) surrounded by lattice-matched InGaAsP (λ_g = 1.0μm) guiding layers. The following logarithmic material gain-current density relationship was observed for the strained wells[iv]

$$G_{\mathrm{QW}} = 464 \ln\left(\frac{J}{0.525}\right) \quad \text{in 1/cm (with } J \text{ in kA/cm}^2) \tag{1}$$

We have demonstrated that the non-reciprocal absorption shift can be modelled with sufficient precision using a perturbation formalism using the following overlap integral[v]:

$$\Delta\alpha[\mathrm{dB/cm}] \approx -\frac{0.3}{\lambda[\mathrm{cm}]} \Re\left[\iint g E_x E_z \mathrm{d}S \Big/ \iint E_x H_y - E_y H_x \mathrm{d}S\right], \tag{2}$$

with g the complex MO gyrotropy constant and λ the operation wavelength of the device. On the other hand, the needed current density for forward loss compensation, J_{transp}, is found by directly

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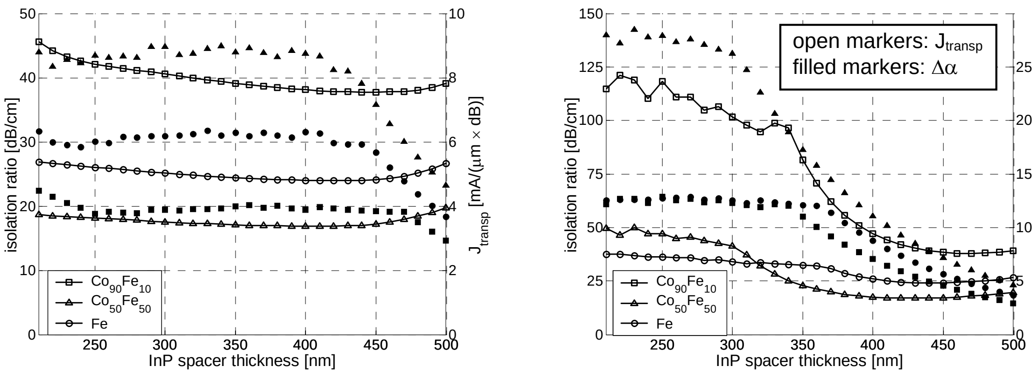
using (1) when calculating the zero order guided TM mode. These two device parameters, $\Delta\alpha$ and J_{transp}, determine the behaviour of the device. It is clear that these will vary as a function of 1.) the thickness of the InP buffer layer between the metal and the active layer, of 2.) the thickness of the guiding layers surrounding the MQW region, and 3.) as a function of the used ferromagnetic magneto-optic metal (via its optical absorption and its gyrotropy constant *g*). The MO constant *g* as well as the complex refractive index *n* of the three CoFe alloy compositions at 1300nm have been previously experimentally characterized.[vi]

Using $\Delta\alpha$ and J_{transp}, the optimality of the layer structure can be expressed by three different Figures of Merit (FoM). The available non-reciprocity and/or loss-compensating gain is optimally used when either the total length per dB of isolation (FoM = $1/\Delta\alpha$), or the total current (per width of the active layer) per dB of isolation (FoM = $J_{transp}/\Delta\alpha$), or the product of these latter two (FoM = $J_{transp}/(\Delta\alpha)^2$), is minimized. We performed such optimisation calculations on the mentioned layer structure using an open-source slab mode solver,[vii] extended with the perturbation formula (2). Fig. 2 shows an example of the kind of calculations. By varying the guiding layers for each value of the thickness of the InP spacer so that one of the above FoM's is minimized, the optimally available non-reciprocity and needed transparency current is found at each thickness of the buffer layer.



(a) (b)

Fig. 2: optimisation of (a): the needed current , (b): the length × current product.

These curves show that from a certain InP buffer thickness on (depending on the metal used and the FoM considered), there is a saturation-like behaviour of the optimally obtainable non-reciprocity. This is a result of the need for thicker guiding layers around the MQW in order to keep the current or the length×current product minimal for low thicknesses of the InP spacer. It can also be seen that the equi-atomic CoFe composition invariably gives the best results. This is mainly a result of the higher absolute value of the gyrotropy of this composition. Contrary to popular belief, pure iron only performs as strong as $Co_{90}Fe_{10}$. Even though we have proven that it is mainly explained by its lower absolute value for *g*, this is partially compensated by its considerably lower optical absorption, allowing much thinner guiding layers around the MQW for an optimal transparency current that can compete with that of $Co_{50}Fe_{50}$. It will also be shown how the complex behaviour of the field product E_xE_z in (2) in this amplifying waveguide can be brought in better accordance with the complex phase of *g*, in order to further optimise the non-reciprocal effect.

In conclusion, these optimisation calculations show that this integrated isolator concept is capable of realizing a very competitive 20dB isolation in a length of only 4.0mm and needing only 65mA/(μm active layer width), when using $Co_{50}Fe_{50}$. Shorter device lengths are possible when using a length×current FoM, but this comes at the cost of higher transparency currents.

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