Amplifying AlGaInAs/InP Waveguide Optical Isolator with 99dB/cm Non-reciprocal Propagation

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Significant advance of the state-of-the-art performance of a TM-mode amplifying optical waveguide isolator, operating at 1300nm wavelength, has been achieved. The magneto-optical Kerr effect induces non-reciprocal modal absorption in a semiconductor optical amplifier with a magnetized ferromagnetic metal contact. Current injection in the active structure compensates the loss in the forward propagation direction. Monolithic integration of this isolator with active photonic devices is straightforward. The improvement comes from the combination of a novel AlGaInAs/InP active material, the metal alloy $Co_{50}Fe_{50}$ *and modification of the device fabrication. Design, fabrication and characterization are presented.*

Introduction

An optical isolator avoids one of the main noise sources in an optical communication system by blocking optical feedback in the laser source. Current commercial isolators are bulk components requiring collimating lenses and expensive alignment techniques when applied in a laser diode package. Development of an integrated laser-isolator system is highly desirable as it would reduce cost and size and enhance mechanical and thermal stability. Traditional research focuses on applying ferrimagnetic garnets to induce non-reciprocity [1]. The interest in this class of materials comes from their unique combination low optical loss at telecom wavelengths and a considerably strong magneto-optical (MO) effect, the source of the non-reciprocity. Stand-alone devices with large isolation strengths have been reported. The integration with III-V host material however remains an issue. The best reported result demonstrated isolation not higher than 5dB in a device of several millimeters long [2].
A novel concept for a - TM-mode - monolithically integrated optical isolator was theoretically proposed in 1999 [3] and experimentally demonstrated in 2003 [4]. Recently, an equivalent concept for TE-polarization has been proposed and demonstrated [5]. A high value of the non-reciprocal effect has been shown, however, with insertion losses that are still very high. In this paper we present the development of an improved TM-mode component combining a high value of the isolation ratio with reduced insertion loss.

Theoretical Concept

The optical waveguide isolator basically is a semiconductor optical amplifier (SOA) with a ferromagnetic metal contact very close to the active region. Lateral magnetization - perpendicular to the light propagation direction and parallel to the metal-semiconductor interface - of the metal film induces a non-reciprocal shift of the complex refractive index of TM-polarized guided modes, caused by the MO Kerr effect. In other words, the modal

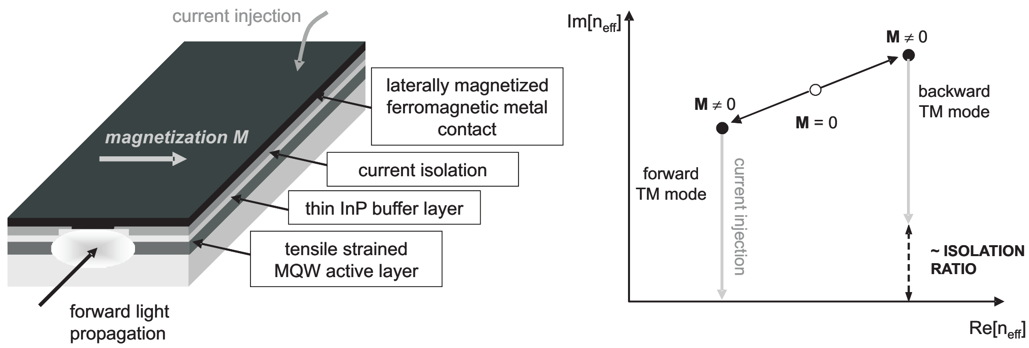

Figure 1: Schematic lay-out and principle of operation of the waveguide optical isolator.

absorption is dependent on the propagation direction. Electrical pumping of the device, with the ferromagnetic metal as the electrical contact compensates the loss in the forward propagation direction. The result is an optical component which, being transparent in one while providing loss in the opposite direction, is isolating. Fig. 1 illustrates the device structure and the operation principle. The advantage of this approach over the garnet based components is obvious. As the isolator basically has the same structure as the laser source it is to be integrated with, monolithic integration is possible. In addition, the ferromagnetic film can easily be sputter-deposited and the fabrication of the entire component can be done with standard III-V processing.

Design and Fabrication

In [4] we reported on the first experimental demonstration of this isolator concept. Using this component as a starting point, the isolator building blocks have been optimized. The amplifying waveguide core needed to compensate the loss induced by the MO metal film is a novel AlGaInAs/InP multi-quantum well (MQW) structure. Built-in tensile strain realizes TM-selective material gain while suppressing TE-gain. At 1300nm wavelength AlGaInAs/InP MQW active material is known to have considerably better gain performance than the more common InGaAsP/InP material [6], used in [4]. Consequently the current needed for transparency in the forward propagation direction is lower or, equivalently, the InP cladding thickness can be reduced - resulting in a higher isolation strength - for the same value of the forward transparency bias current. The optimized active core is built up of 10nm tensile strained (-1.16%) wells (9QWs), 20nm strain compensating compressively strained (+0.64%) barriers and optimized separate confinement heterostructure (SCH) layers [6]. Experimental determination of the gain-current density relation was done on 6 QWs broad area (BA) lasers. A low transparency current density of less than $60 A/cm^2$ has been demonstrated.
The ferromagnetic metal film fulfills two functions: it is the source of the MO non-reciprocal effect and it acts as the electric contact for the underlying SOA. The optical (complex refractive index) and MO (Voigt parameter) constants of $Co_{50}Fe_{50}$ have been experimentally extracted at the operation wavelength of 1300nm. It was demonstrated [7] that this equiatomic compound combines a higher MO effect with less optical absorption, compared with the $Co_{90}Fe_{10}$ alloy used in [4]. A hybrid p^{++} Be-doped InGaAsP/InGaAs contact structure has been developed that realizes an ohmic electrical contact and has only minimal optical absorption at 1300nm wavelength.

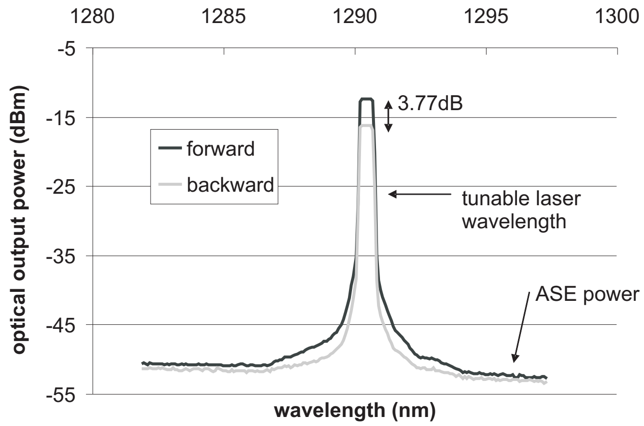

Figure 2: Output signal for saturation in both lateral magnetization directions, showing 99dB/cm non-reciprocal absorption.

The design of the geometric device parameters - the thickness of InP-cladding layer and SCH layers - has been done through 1D simulations using an optical mode solver [8], extended with a perturbation based algorithm for MO waveguide calculation [9]. The applied design strategy was to find the combination of thickness values that maximize the non-reciprocal effect for a fixed, moderate value of the transparency current density ($10kA/cm^2$).
The optimized active structure was grown with metal organic vapor phase epitaxy (MOVPE) on a n^+ Si-doped InP substrate. It was topped with a 280nm thick Be p-doped InP layer and the optimized contact structure. The sputter-deposited 50nm thick $Co_{50}Fe_{50}$ film, capped with a 40nm/150nm Ti/Au protective bilayer was patterned through standard lift-off into 2.5μm wide stripes. Ridge waveguides were defined with CH_4:H_2 reactive ion etching (RIE), using these metallic stripes as an etch mask. With this technique, full covering of the ridge with MO metal is achieved. Processing imperfections caused the actual metallic stripe width to be considerably larger, resulting in wider waveguide stripes ($\approx 3.5\mu$m) hence lateral bimodality of the waveguides.

Characterization

Characterization of this component can be done by evaluation of transmitted optical power for saturation in both lateral magnetization directions - switching the magnetization direction is equivalent to switching between forward and backward propagation direction. An external cavity tunable laser (6dBm output power) is used as the input laser source and the output signal is detected with a spectrum analyzer (resolution bandwidth 0.5nm). The waveguide isolators have a cavity length of 380μm and no AR-coatings have been deposited on the device facets. The pulsed bias current is 175mA (pulse width 0.1μs, duty cycle 10%). The 3.77dB difference in intensity between 'forward' and 'backward' direction is equivalent to an isolation ratio of 99dB/cm. We believe that the difference between this experimental result and the design value of 152dB/cm is mainly due to the lateral bimodality of the waveguides. The injected - TM-polarized - laser light couples to both the zeroth and first order guided modes. The non-reciprocal effect induced on the fundamental mode is considerably higher than that on the first order mode, as the overlap with the ferromagnetic metal of the latter is lower. The output signal is a mixture of both

modes and therefore the actual non-reciprocal effect is lower than what can be achieved with this design, provided the device is laterally monomodal.
The current needed for transparency can easily be estimated from the measurement of the threshold current of these - non AR-coated - isolators, combined with the calculation of the current needed to compensate the mirror losses, for which the experimental gain-current density relation and the simulated value of the optical confinement served as input. The threshold current of 215mA corresponds to an estimated bias current of 130mA. 1D simulation predicted a value of 121mA.

Conclusion

In conclusion, we have demonstrated 99dB/cm isolation on an optical isolator that can be monolithically integrated with a laser diode. Moderate injection current suffices for transparency of forward propagating light. Good agreement between theoretical and experimental performance is found, with identification of the causes of the remaining discrepancy.

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