Amplifying Waveguide Optical Isolator

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Abstract—**To eliminate one of the main noise sources in an optical telecom link, it is necessary to protect the lasers from optical feedback by including an optical isolator in the laser diode package. With today's commercial bulk isolators the packaging of a laser diode module represents the largest part in the cost of the module. An isolator that can easily be integrated with its source is therefore highly desirable. A promising scheme consists of an amplifying waveguide covered with a magnetized ferromagnetic metal. Earlier, we demonstrated this concept experimentally. Here we report on the optimization of the isolator. Magneto-optic waveguide calculations revealed a subtle interplay between the waveguide dimensions, the cladding material and the properties of the metal film. Our experimental result of 12.7dB optical isolation combined with full compensation of the internal loss is the best ever obtained. With this performance practical implementation is now within reach.**

Keywords— **optical telecommunication, integrated isolator, magneto-optics**

I. INTRODUCTION

DUE to reflections along an optical telecom link light can be coupled back into a laser sources. This is one of the main sources of noise in this link. It can be avoided by including an optical isolator – a device which is transparent in one direction and blocking the light in the opposite – in the laser diode module. Today's commercial isolators are bulk components with a completely different structure than the semiconductor laser which is basically an optical waveguide. Alignment of both elements in the package requires expensive, sub-micron alignment techniques. As a consequence the packaging of the laser diode module – with the laser and the isolator in it – represents by far the largest part of the cost of the entire module. In addition, this precise alignment makes the use of mass fabrication techniques impossible. The cost of a laser diode could therefore be largely reduced if an optical isolator was developed that can easily be integrated with the laser source.

Research is ongoing for more than 30 years, but no real solution has been found. Some years ago, two Japanese groups have independently proposed the promising concept of an amplifying waveguide optical isolator [1]-[2]. In 2003, we experimentally demonstrated this configuration for the first time worldwide [3]. Continuously improved understanding of this concept resulted in enormous advance of the device performance. In this paper we discuss this optimization.

II. THEORETICAL CONCEPT

The basis of an optical isolator is the non-reciprocal effect, causing the light properties to be dependent on the propagation direction. It is generated by the interaction of light a magnetic field, which is the domain of magneto-optics.

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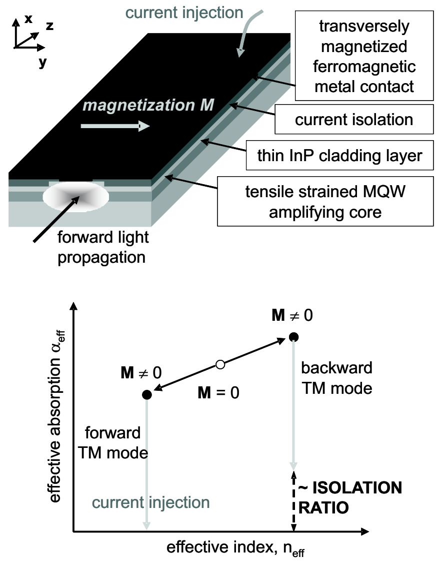

Fig. 1. Schematic lay-out (top) and operation principle (bottom) of the TM-mode amplifying waveguide optical isolator.

The amplifying waveguide optical isolator configuration is based on the idea that an optical isolator can only be easily integrated if its structure is similar to that of a semiconductor laser. Telecom semiconductor lasers are double heterostructure lasers, with a thin gain medium – the waveguide core – sandwiched between a n- and p-doped cladding layer. Pumping of the gain medium is done by electrical current injection through metal contacts at the sides of these cladding layers. Light is guided in the core and amplified if the bias current is sufficient. In standard lasers or amplifiers, the cladding layers are thick enough for metal contact not to be felt by the guided mode, as this would cause extra absorption.

Now, the amplifying waveguide isolator is a semiconductor amplifier with thin (500nm) cladding layers and a transversely magnetized ferromagnetic metal contact. In this case, the guided light overlaps with the magnetized metal. The magneto-optic Kerr effect causes the absorption in the metal to be dependent on the light propagation direction. By sufficient pumping of the gain region the loss in one direction can be compensated, resulting in a device which is transparent in one and absorbing in the opposite direction, i.e. an optical isolator. This operation principle and the lay-out of the isolator is illustrated in figure 1.

III. SIMULATIONS

The performance of the amplifying waveguide optical isolator is obviously determined by the magneto-optic strength and the optical absorption of the ferromagnetic metal film and the amount of material gain that can be provided by the amplifying waveguide core. Optimization of both building blocks has been done in collaboration with external partners. The have been reported earlier [4]-[5]. The optimized heterostructure has a tensile strained AlGaInAs multi-quantum well core (9 wells with a thickness of 10nm) and is covered with a 50nm $Co_{50}Fe_{50}$ metal film.

Apart from these main building blocks the refractive index and the thickness of the cladding layers between the guided core and the metal film needs to be properly designed. Calculations have been done with the in-house developed waveguide solver CAMFR extended with a perturbation algorithm for magneto-optic waveguide simulation. The experimentally determined material parameters of the $Co_{50}Fe_{50}$ (complex refractive index and magneto-optic strength) and of the MQW AlGaInAs core (material gain versus injected current) served as input for these simulations. The relevant figure of merit (FoM) for this type of device is the amount of current required for forward transparency in a device showing 1dB optical isolation.

A rough but very intuitive design rule can be stated like this: as the cladding thickness decreases, both the overall absorption in the metal and the non-reciprocal effect increase due to enhanced overlap of the light with the metal film. As such, an optimal cladding thickness can be found. However, extensive study of the interaction of the waveguide mode with the metal revealed that the situation is much more complex. The actual non-reciprocal effect is determined by a subtle interplay between the phase of the (complex) electric field at the metal-semiconductor interface and the phase of the (complex) magneto-optic constants of the metal. It was only after taking this into account that the amplifying waveguide isolator layer structure could really be optimized.

IV. Experimental Results

Characterization of the amplifying waveguide isolator is done by comparing the light transmission through the device in each of both propagation directions. Unfortunately, it is a difficult job to ensure that the coupling of light in and out of the waveguide device is identical for both propagation directions. To overcome this, we came up with an equivalent but much easier method. Instead of evaluating light that is traveling in both directions, we inspect light in one direction, but change the direction of the applied magnetic field. This gives us a completely equivalent experiment. The input light emitted by an external laser source and the isolators are pumped electrically to overcome the loss in the 'forward' propagation direction. A measurement example is shown in figure 2. The device is 2mm long and is biased with 160mA current. The difference in transmission between the 'forward' signal and the 'backward' signal equals 12.7dB and the loss in the forward propagation direction could be completely compensated (transmission >0dB). This result is the first demonstration of a transparent optical isolator that can straightforwardly be integrated with a semiconductor laser. In addition, the obtained isolation of 12.7dB is the highest value ever obtained on this kind of device.

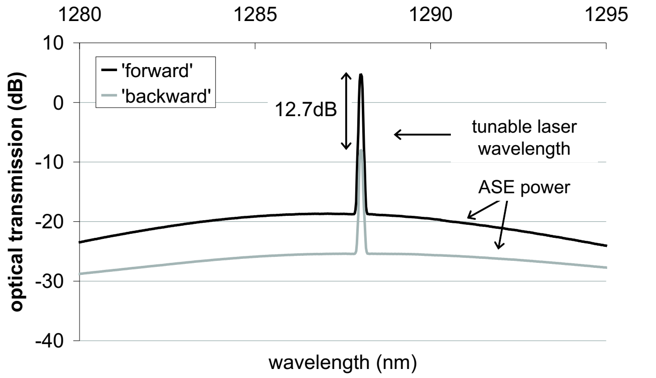

Fig. 2. Spectrum of the isolator transmission in both propagation directions, showing 12.7dB optical isolation; ASE = amplified spontaneous emission.

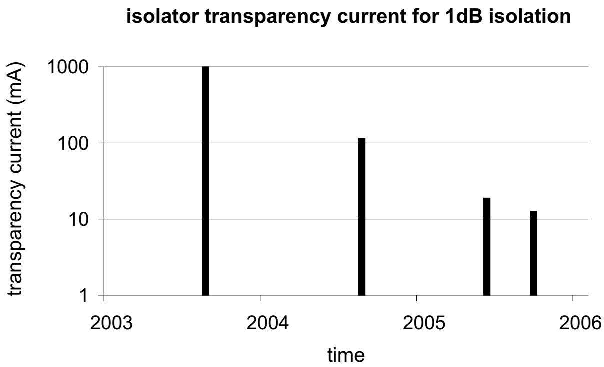

Fig. 3. Evolution of the demonstrated figure of merit with time.

V. Evolution Isolator Performance

Since the first experimental demonstration of the amplifying waveguide isolator mid 2003, the device performance has continuously improved. This is illustrated in figure 3. The current to achieve forward transparency in a device with 1dB optical isolation is plotted versus time. In the three years that have passed since the first demonstration huge improvement of the figure of merit by a factor 80 has been achieved.

VI. Conclusion

Improved understanding of the nature of the amplifying waveguide optical isolator resulted in a major advance of the state-of-the-art. We demonstrated the first transparent optical isolator, monolithically integratable with a laser source. The experimental isolation level of 12.7dB shows that practical implementation of this device is now within reach.

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