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Hybrid magneto-optical mode converter made with a magnetic nanoparticles-doped SiO_2/ZrO_2 layer coated on an ion-exchanged glass waveguide

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This paper describes the possibility to achieve a TE-TM mode conversion in a magneto-optical hybrid waveguide operating at $\lambda = 1550$ nm. This hybrid device is made by coating a SiO_2/ZrO_2 layer doped with magnetic nanoparticles on an ion-exchanged glass waveguide. Soft annealing (90 °C) and UV treatment, both compatible with the ion exchange process, have been implemented to finalize the magneto-optical film. Optical characterizations that have been carried out demonstrated the efficiency of these hybrid structures in terms of lateral confinement and mode conversion. Indeed, TE to TM mode conversion has been observed when a longitudinal magnetic field is applied to the device. The amount of this conversion is discussed taking into account the distribution of light between the layer and the guide, and the modal birefringence of the structure.
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The rapid progress of data transmission capacities has led to the development of optical communication techniques via glass fiber in the near infrared. The light sources that are used are usually III-V laser diodes, which must be protected from the reflected light by optical isolators. To obtain such a function, the most commonly used materials are magnetic iron garnets because they combine a high specific Faraday rotation with relatively low optical losses in the near infrared region.[1] However, these materials are not compatible with classical technologies used to realize planar integrated devices. Therefore, isolators using these materials cannot be integrated monolithically into planar lightwave circuits because the temperature required for the crystallization of magnetic iron garnet is usually too high (>740 °C).[2] To overcome this problem, many studies are currently carried-out to develop magneto-optical materials compatible with existing integrated optics technologies.[3,4] A very interesting approach consisting of using magnetic semiconductors materials to realize nonreciprocal devices integrated on semiconductors substrate has been proposed by Zayets *et al.*[5] Indeed, an isolation ratio of about 25 dB at $\lambda = 750$ nm has been shown, using a $Cd_{1-x}Mn_xTe$ layer coated on GaAs substrate.

Nevertheless, no approach has allowed the full integration of a magneto-optical material with glassy material waveguides which can not stand temperature higher than 500 °C. Recently, the realization of composite magneto-optical thin films made of silica-type matrix prepared via a low temperature sol-gel process and doped by magnetic nanoparticles has been demonstrated.[6] In this approach, instead of creating nanocrystals inside the thin film by a high temperature annealing, already crystallized cobalt ferrite ($CoFe_2O_4$) nanoparticles are dispersed inside a silica sol-gel solution. Magneto-optical thin films are obtained by dipping a substrate in this solution and baking it at 90 °C during 1 h. Using Pyrex^{TM} substrate, promising magneto-optical characteristics illustrated by a specific Faraday rotation of 310°/cm and a refractive index of 1.51(@1550 nm) have been reported.[6,7]

In this letter we report how such a magneto-optical layer can be used with glassy integrated circuits in order to realize hybrid mode converter.

In magneto-optical waveguides, a non-reciprocal effect similar to the Faraday rotation in free space can be achieved by TE-TM mode conversion under a longitudinal magnetic field. The maximum efficiency of such effect is R_M[8]

$$R_M = \frac{|\kappa|^2}{|\kappa|^2 + (\Delta\beta/2)^2}, \tag{1}$$

where κ is the coupling coefficient and $\Delta\beta$ (°/cm) is the phase mismatch between TE and TM mode: $\Delta\beta = 2\pi\Delta N_m/\lambda$ and ΔN_m is the modal birefringence. In the case of a planar waveguide the coupling coefficient can be approximated by

$$\kappa \cong i\Theta_F, \tag{2}$$

with Θ_F(°/cm) being the specific Faraday rotation of the magneto-optical material constituting the waveguide. With the composite magneto-optical films used as planar waveguides, a TE-TM mode conversion should reach a R_M factor of 22% at $\lambda = 1550$ nm with a volume fraction of nanoparticles of 1.5% in the layer (56% at $\lambda = 820$ nm).[6] Such planar magneto-optical converters are promising, but in order to go further on the integration of this material, we have moved our composite approach to the glass ion-exchanged integrated technology, which is one of the prominent technologies in the field of integrated optics. This is due to the

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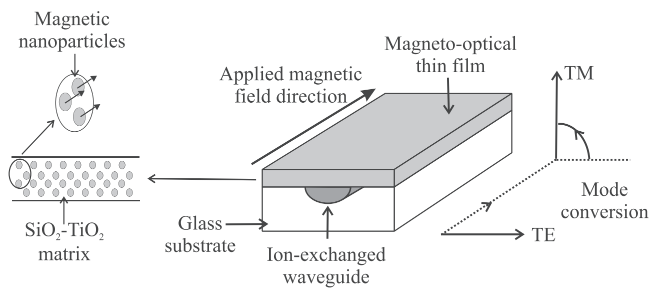

FIG. 1. Schematic of the integrated magneto-optical mode converter.

potentiality of glass materials, the robustness and versatility of the fabrication processes, the low cost of the fabricated devices and, last but not least, their remarkable performances. Indeed, this technology has largely demonstrated its capacity to form channel waveguides and realize integrated optical functions with compactness, stability, and low losses allowing the realization of many high quality devices that are currently on the market such as optical amplifier, couplers or DFB microlaser.[9,10] In 2004, Gardillou *et al*. demonstrated the possibility to associate a thin amplifying layer with a glass ion-exchanged waveguide in order to obtain a hybrid silicate/phosphate glass optical amplifier with 4.25 dB of gain.[11] Epoxy-free wafer bonding has also been successfully used to realize a polarization-insensitive Bragg filter on ion-exchanged waveguide.[12] In such a hybrid structure, the active layer thickness is limited by the required single mode operation of the device and by the interaction of light with the ion-exchanged waveguide, which must be strong enough to ensure an efficient lateral confinement of the guided mode.

Adapting this hybrid structure principle, our aim has been to realize integrated magneto-optical devices by coating a composite magneto-optical layer on an ion-exchanged glass waveguide as shown on Fig. 1.

The refractive index of the ion-exchanged waveguide varies from 1.58 at the surface to 1.50 in the deep substrate (@1550 nm).[10] These values are close to that of the magneto-optical layer $\sim$1.51.[6] That should insure a good hybrid distribution of light in the structure. Furthermore, the refractive index of this layer can be tuned from 1.5 to 1.57 by adjusting the chemical precursors composition.[13] In addition, the temperature of the thermal treatment required to finalise the magneto-optical layer is less than 120 °C, which avoids any change of the refractive index distribution of the ion-exchanged waveguide.

The first goal of our work was to obtain a hybrid mode propagation presenting a good lateral confinement in the structure. The second and the major one is to study the possibility to demonstrate TE-TM mode conversion with this structure.

The magneto-optical layer has been realized by the same method as the one used in our previous works,[6,7] the sol-gel process, which is based on hydrolysis and condensation reactions. The starting materials are photopolymerizable organically modified silicon alcoxide, zirconium alkoxide, and methacrylic acid. To obtain a magneto-optical material, a magnetic fluid has been added into the sol. It is made of cobalt ferrite ($CoFe_2O_4$) nanoparticles that have a mean size of about 9 nm. A photoinitiator (IRGACURE 651) was added in order to promote the starting of the polymerization under UV-light exposure. Using the dip-coating technique, a layer was coated onto a GO14 (by TeemPhotonics SA) glass substrate containing straight channel waveguides made by a silver/sodium ion exchange of 4 min at 330 °C through an alumina (Al_2O_3) mask with diffusion aperture widths ranging from 0.7 to 10 μm. Finally, the hybrid structure has been annealed during 60 min at 90 °C, and UV treated ($P = 1$ mW/cm^2) at $\lambda = 365$ nm and $\lambda = 254$ nm, respectively, during 25 min for both wavelengths. The thermal annealing partially eliminates the organic residuals in the mineral network of the layer while the UV exposure leads to the creation of the organic network by the photopolymerisation of the methacrylate groups (breaking of the carbons double covalent bonds C=C).

The optical properties of the deposited layer have been assessed by *M*-lines spectroscopy,[14] on a part of the wafer without any ion-exchanged waveguide (pure glass): the refractive index n and the thickness h of the magneto-optical layer has been measured: $n = 1.518 \pm 0.001$ (@ 1550 nm) and $h = 2.6\ \mu$m$\pm$ 10 nm. The specific Faraday rotation of the layer has also been measured using a classical free space ellipsometer with a light direction perpendicular to the film plane.[6] Its saturated value is $\Theta_F = 155°$/cm (@1550 nm), associated to a nanoparticles volume fraction of 0.7%. This rotation value is high enough to ensure at least 90° of rotation on a centimetre-long waveguide.

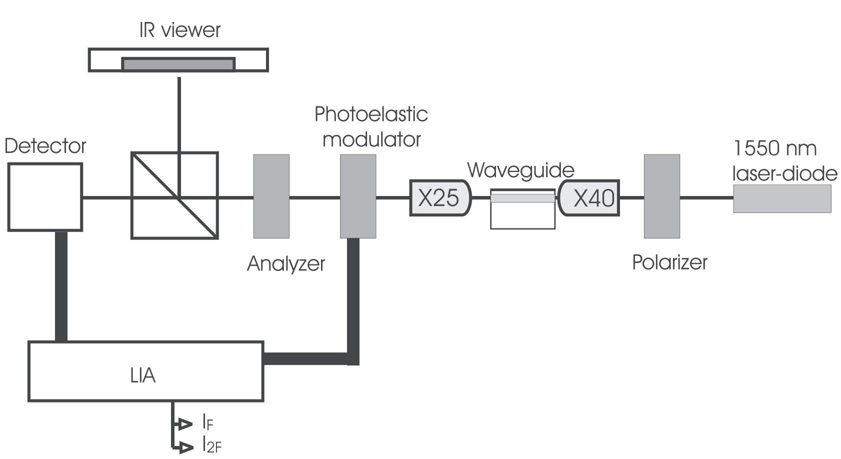

FIG. 2. Experimental configuration used for optical and magneto-optical measurements on the hybrid structures.

FIG. 3. Output light intensity of the hybrid structure (@1550 nm).

In order to characterize the hybrid magneto-optical waveguide, its facets have been diced and prepared to allow a good injection efficiency. The experimental set-up that has been used is given in Fig. 2. The light beam from a laser is polarized and injected in the sample through a microscope objective. At the output, the collection is made using another microscope objective. The beam is then passing through a photoelastic modulator, an analyser, a beam splitter, and a detector. With the light issued from one part of the splitter, a picture of the beam distribution at the output of the hybrid structure is obtained by a camera.

The output intensity detected by this IR camera is presented in Fig. 3. The light has propagated along 1 mm of the hybrid structure, which ion-exchanged waveguide has a diffusion aperture of 4 μm.

This picture shows that the hybrid structure can support the propagation of a light beam with no major extinction, what evidences the good optical compatibility of the magneto-optical layer with the glass ion-exchanged waveguide. Moreover, the almost circular shape of this output intensity assesses the lateral confinement of the guided mode.

The polarimetric arrangement depicted in Fig. 2 has been used to measure the magneto-optical mode conversion. A linearly polarized light is injected in the sample. Due to the longitudinal magnetic field applied to the hybrid waveguide a TE/TM mode conversion is generated, which results at the output as an elliptical state of polarization. The direction of this elliptical polarization is rotated by an angle θ with respect to the input direction, and it is characterized by an ellipticity ε. The modulation generated by the photoelastic modulator (F = 50 kHz) produces an output light intensity which can be expressed by Fourier series[15]

$$I = \frac{1}{2}\left[I_0 + I_F\cos(2\pi f_F t) + I_{2F}\cos(2\pi f_{2F} t) + \cdots\right]. \quad (3)$$

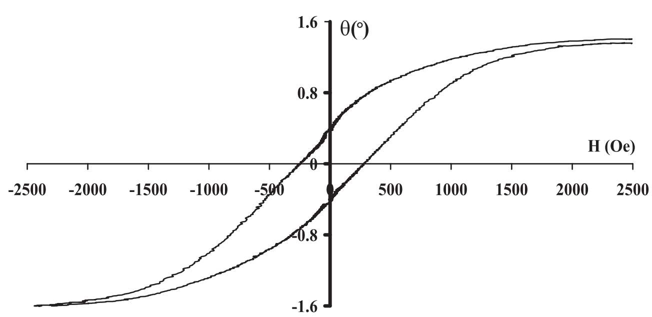

FIG. 4. Magneto-optical mode conversion in the hybrid structure ($\lambda = 1550$ nm).

The synchronous lock-in amplifier referenced to the photoelastic modulator allows the determination of the intensities I_F and I_{2F}. With such a polarimetric arrangement and for low values of the rotation and ellipticity, one can easily demonstrate that the first harmonic I_F and the second one I_{2F} are, respectively, proportional to ε and θ.[6] Thus, the analysis of the emergent light intensity by the lock-in amplifier allows the determination of the magneto-optical rotation according to the intensity of the magnetic field.

The magneto-optical mode conversion of the hybrid structure is reported in Fig. 4 in terms of the Faraday rotation θ as a function of the applied magnetic field. To vary the intensity of this latter, the distance of the permanent magnet to the device has been varied while a hall effect sensor was used to monitor the field amplitude.

The curve of Fig. 4 presents a nonreciprocal variation of the rotation angle as a function of the magnetic field, which is the typical behaviour of the Faraday effect for a ferromagnetic material. A hysteresis phenomena due to the "hard magnetic" behaviour of the cobalt ferrite nanoparticles[16] can be also observed on this curve. The coercitive field of this effect, about 300 Oe, is identical to the one obtained on composite layers in free space configuration.[6] Thus, the result reported in Fig. 4 proves that it is possible to achieve a nonreciprocal mode conversion in a hybrid structure based on ion exchange glass technology. It confirms that the composite approach is a promising way to realize integrated nonreciprocal devices.

Moreover, the hysteresis phenomenon means that even if no magnetic field is applied, a magneto-optical mode conversion exists as a permanent effect (~25% of the maximum value, however 60% can be obtained using assisted magnetic field dip coating[17]). This property could be of high interest to realize self-biased devices that would not require the integration of a permanent magnet.

The saturated rotation obtained for field higher than 2000 Oe is about 1.5° for a propagation length of 1 mm. This value is obviously far from the specific Faraday rotation of the magneto-optical layer: 155°/cm. In fact when in guided configuration, the efficiency of such mode conversion depends on the modal birefringence ΔN_0 and the coupling coefficient K through Eq. (1). Using the perturbation method detailed by Johlen *et al.*,[18] the fundamental modal birefringence of the hybrid waveguide has been measured to be $\Delta N_0 = 7.7.10^{-4} \pm 1.10^{-4}$. Concerning the coupling coefficient, its general expression is given by (with propagation direction along Oz)[8]

$$\kappa = \frac{\omega\varepsilon_0}{4\sqrt{P_{TE}P_{TM}}}\iint_{MO} E_{TE}^{*}.\varepsilon_{xy}^{m0}.E_{TM}\,dxdy, \quad (4)$$

ε_{xy}^{m0} being the off-diagonal element of the magneto-optical material permittivity tensor. It is linked to the refractive index n and the specific Faraday Θ_F rotation through

$$\varepsilon_{xy}^{m0} = \frac{n\lambda.\Theta_F}{\pi}. \quad (5)$$

P_{TE}, P_{TM} are the power associated to TE and TM modes, respectively. ω is the frequency corresponding to the vacuum wavelength λ. Expression (4) demonstrates that the coupling coefficient depends on the quantity of the field that is interacting with the magneto-optical layer. Using a semi-vectorial mode solver (Optitools from OPTIWAVE), such a confinement has been calculated to be 17%, leading to a coupling coefficient of 26°/cm. Combined with the birefringence value, it gives a modal conversion of 1.7° for a propagation length of 1 mm. This value is in good agreement with the one that has been measured and reported in Fig. 4.

To improve the magnitude of the modal conversion and reach the 45° that are required for the realization of an optical isolator, the modal birefringence of the hybrid structure could be decreased and/or the amount of optical field interacting with the magneto-optical layer could be increased. This optimization is currently being carried-out.

To conclude, this work demonstrates that, using a composite silica-based magneto-optical layer, it is possible to achieve a TE/TM mode conversion in an integrated hybrid structure made with ion exchange glass technology. The use of fully crystallized magnetic nanoparticles dispersed in a sol-gel solution eliminates the high thermal annealing which is classically necessary to get a magnetic non-reciprocal behaviour. The magnitude of the conversion 1.5° obtained at a wavelength $\lambda = 1550$ nm is limited by the structure modal birefringence and a quite low coupling coefficient. These parameters are currently being optimised via numerical simulations.

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