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Optical losses measurements in $GdCa_4O(BO_3)_3$ waveguide deposited by laser ablation

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Abstract

Planar optical waveguides were fabricated by pulsed laser deposition of $GdCa_4O(BO_3)_3$ thin films on quartz substrates. The surface morphology of the obtained thin films was investigated by using atomic force microscopy (AFM). It is shown that the surface is rather homogeneous and does not display any macroscopic particles and the average surface roughness was evaluated to be in the range of 4-5 nm. The optical properties were studied by prism-in coupling technique (m-lines). Two guided modes for TE polarization and TM polarization are excited and the film refractive indices and thickness are determined.

1. Introduction

There is considerable interest in developing thin films for integrated optics for several applications include second-harmonic generation, high speed modulators, and gain devices. Thin films devices offer physical characteristics potentially superior to diffused waveguides fabricated in bulk materials. As an example, large index changes between substrate and film enable highly confining waveguides to be formed [1]. In addition, the high confinement in thin film waveguides creates the potential for fast, low voltage-electro-optic switching, facilitated by the small electrode separation allowed due to the small dimensions of these waveguides [2].

Generally, the development of new laser sources requires the research and manufacture of new nonlinear materials with large non-linear coefficients and a wide transparency band. For this purpose, oxoborates of calcium and gadolinium $GdCa_4O(BO_3)_3$, currently named GdCOB, has been discovered [3]. This material has very attractive nonlinear optical properties which make it more interesting such as its wide transparency range (0.3-2.6 μm) [2], its high optical damage threshold (1GW/cm2 at 532 nm) [4] and its chemical stability. It also offers new possibilities in the frequency conversion by phase matching type I [5] and self-frequency conversion to generate visible laser beams [6]. Second harmonic generation (SHG) of infrared laser emission is a common way to achieve visible and UV radiation. The doping of the GdCOB by rare earth ions [7,8] (Yb3 +, Nd3 +) makes this material a good candidate for the second harmonic generation (SHG) of very high-energy laser sources.

Indeed, the GdCOB is easily elaborated as bulk material by the Czochralski method [9]. However, despite its complex chemical composition, its growth as thin films [10,11] was performed using the laser ablation method. The method of pulsed laser deposition (PLD) is intensively used in material research, as well as the industry, for developing thin films and coatings of special materials, such as: ferroelectrics, superconductors, oxides, polymers, complex hybrid metal-organics, etc. This simple, yet versatile thin film deposition method can be applied to such materials that are not suitable to process by other technique. The deposited thin films can combine the intrinsic properties of the material with those of the waveguide to improve the performance of the optoelectronic components.

In this work, we present the morphological and optical study of the GdCOB thin films deposited on quartz substrate by laser ablation. The surface topography was examined by non-contact atomic force microscopy (AFM). The optical study is carried out by prism coupling [12] to determine the optogeometrical parameters as well as by CCD camera in the visible range to measure the optical losses due to the diffusion of the light through the waveguide.

2. Experimental details

The studied thin films were grown on quartz substrates by Pulsed Laser Deposition [13,14]. The PLD system consists of ArF excimer laser and a vacuum chamber. A laser (λ=193 nm) with a pulse rate of 5Hz, pulse duration of 23 and energy density of 0.8 J/cm2 was directed at the $GdCa_4O(BO_3)_3$ ceramic target. The target-to-substrate distance was 30 mm. The substrate was heated resistively to 650°C. The pressure of the chamber was 0.3 mbar which makes it possible to have thin films of $GdCa_4O(BO_3)_3$ with a Ca/Gd ratio equal to 4 [9]. A more detailed description and schematic diagram of PLD has been published elsewhere [15,16]. The growth time is 5 hours to obtain quite thick thin films and so that the obtained thickness must be greater than the threshold thickness below which no mode will be excited.

If the deposition time is less than five hours, the obtained films will have a small thickness and consequently less than two modes will be excited and subsequently the determination of the refractive indices and the thickness will be impossible.

3. Results and Discussion

3.1. Morphological study

The surface topography of the $GdCa_4O(BO_3)_3$ thin films is studied by non-contact atomic force microscopy. This study showed that the film obtained under the mentioned conditions has a homogeneous surface with the presence of numerous islands which form a dense granular structure (Figure 1). However, several particles with a size up to 1 µm are observed and the measured surface roughness is in the order of 4 to 5 nm. This value can be estimated as low considering the relatively large thickness (820 nm) which was measured by Rutherford backscattering spectroscopy (RBS). Moreover, since the diffusion losses are closely related to the surface roughness of the thin films, we therefore predict low optical losses.

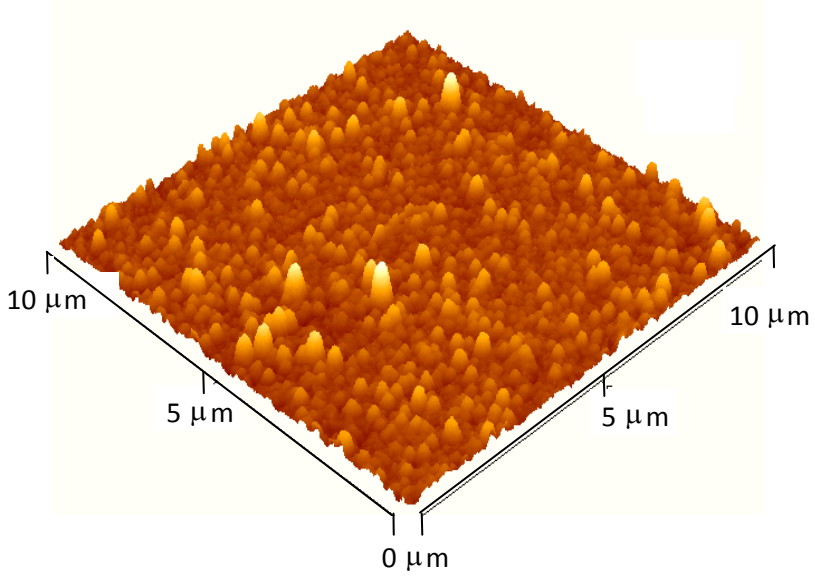

Figure 1: Atomic force microscopy scan of the surface of GDCOB film surface

3.2. Optical study

3.2.1. Determination of the optogeometrical parameters

The optical study carried out using prism coupling technique [17] with a He-Ne laser (λ= 632.8 nm) has shown the feasibility of a waveguide structure formed by the deposition of the GdCOB thin film on a quartz substrate. The quartz is chosen because its refractive indices (no = 1.5518 and ne = 1.5428 at 632.8 nm) are

lower than those of GdCOB. This condition is necessary to excite guided modes. Moreover, if the index difference between the film and the substrate is large; the light confinement becomes better [18,19].

The results show that two guided modes were excited for each transverse polarization: transverse electric (TE) and transverse magnetic (TM). Fig. 2 illustrates the spectrum of the guided modes in TM polarization. The observed third mode is a leaky mode which propagates in the substrate since it has an effective index lower than the substrate refractive index. The sharpness of the reflectivity dips indicates a good confinement of the light into the waveguide [20]. This is an indication of the good microstructural quality of the studied film. Moreover, even if the large film thickness (820 nm by RBS), the number of the guided modes is not consequent since the small index difference between the film and the substrate. The number of guided modes is largely related to the difference in index between the film and the used substrate and related to the value of studied film thickness. This justifies that despite the obtained film thickness is enough important, the coupling prism method has permitted the excitation only two guided modes for each polarization (TE and TM).

The angular positions of these modes make it possible to calculate the effective indices which, by injecting them into standard guided mode dispersion equation, we can calculate the refractive indices as well as the film thickness. From these modes spectra (Fig.2) we computed the effective refractive indices N_m given by:

$$N_m = n_p \sin\left[A_p - \arcsin\left(\frac{\sin\alpha_m}{n_p}\right)\right]$$

Where n_p is the refractive index of the prism, α_m is the external angle of incidence and A_p is the prism angle. Using a prism with well known optical parameters A_p and n_p , the accuracy of N_m particularly depends on that of the synchronous angle. With $\Delta\alpha$=0.01° an accuracy of ΔN_m better than 0.005 can be obtained. The thin film optical parameters are then related to the effective mode indices by the following dispersion relationship:

$$\frac{2\pi d}{\lambda}\left(n^2 - N_m^2\right)^{\frac{1}{2}} = m\pi + artg\left[\left(\frac{n}{n_a}\right)^{2\rho}\left(\frac{n_m^2 - n_a^2}{n^2 - n_m^2}\right)\right]^{\frac{1}{2}} + artg\left[\left(\frac{n}{n_s}\right)^{2\rho}\left(\frac{n_m^2 - n_s^2}{n^2 - n_m^2}\right)\right]^{\frac{1}{2}}$$

For the TE mode ρ=0 and for the TM mode ρ=1, where d is the film thickness, λ is the wavelength of the light in vacuum, na and ns are respectively, the air and substrate refraction indices and m the mode numer.
We found for the studied GdCOB thin film n_x = 1.666 ± 0.005, n_y = 1.673 ± 0.005 and n_z = 1.680 ± 0.005. This result evidence a value on refractive indices that is very close to the bulk value of GdCOB [21] with a small difference in order of 3%. The measured thickness is 860 ± 20 nm which is in a good agreement with the value obtained from RBS measurements.

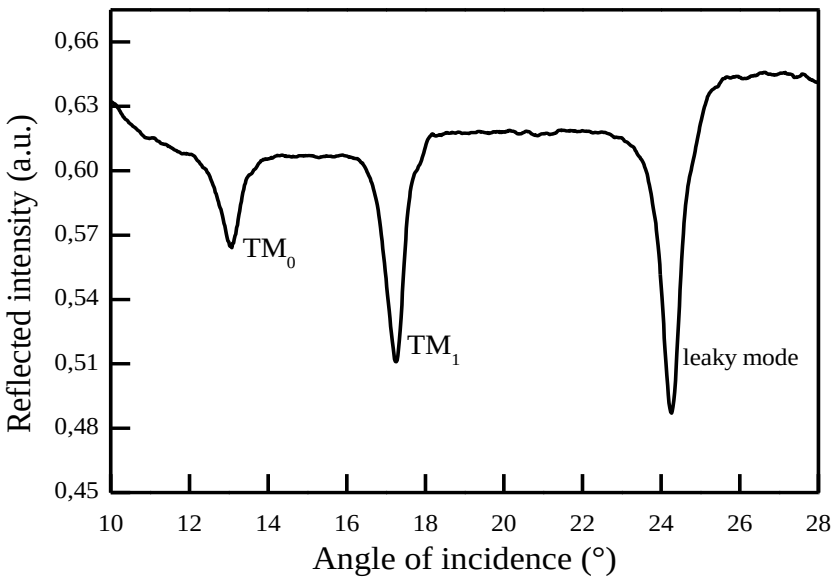

Figure 2: Typical TM guided mode spectrum of GdCOB thin film on quartz substrate

3.2.2. Optical losses measurements

The optical losses types which occur during light propagation in waveguides are radiation, absorption, or diffusion losses. All these losses types are present in different degrees independently of the films growth

method. In practice, radiation losses occur when the waveguide thickness is close to of the threshold thickness, or when its refractive index is close to index substrate. However, absorption losses arise from stoichiometry defects, anionic deficiency (for example oxygen) or impurities which have absorbing effects. On the other hand, diffusion losses arise from inhomogeneities in the material, such as structure or composition local changes (discontinuity of refractive index or thickness), irregularities at film-substrate interface, presence of impurities (dust), residual stresses (cracks) or a high surface roughness. All losses types present a great handicap of the waveguides and limit their performances.

Several techniques allow the measurement of the attenuation coefficients in the waveguides [22,23]. In this work, propagation loss measurements (at 632 nm) have been performed by using a CCD camera to collect the light intensity scattered from the waveguide surface as a function of the propagation distance in the waveguide.

The CCD camera is placed in front of the waveguide plane. It is added to the experimental prism coupling method and it makes possible to record the trace of propagated light when a mode is excited. The captured image is then treated by a computer equipped with an image analysis program (wima-TSI). We thus obtain the scattered light intensity I(x) as function of position x. Two hypotheses are considered in this study: the first is that the diffused light intensity is proportional to light guided intensity at the same position [24] and the second is that the diffusion is uniform along the waveguide.

Figure 3 shows the light propagation line in the studied waveguide for the fundamental modes TE_0 and TM_0. The appearance of these propagation lines illustrates the presence of particles and diffusing defects. The intensity of the diffused light as a function of the propagation distance for the two fundamental TE_0 and TM_0 modes is shown in Figure 4. This figure is obtained from the both propagation lines images, corresponding to TE_0 and TM_0 modes, which have been treated by wima-TSI. The diffusion losses (in $dB.cm^{-1}$) will be determined by adjusting the curves by the following function:

$$I(x) = I_0 \exp\left(10^{\frac{-ax}{10}}\right)$$

Where I_0 and a are, respectively, intensity diffusion light at x = 0 abscissa point and diffusion losses.

The measured diffusion losses values for TE and TM excited modes are given in table 1. We observe that, whatever the polarization, the diffusion losses increase when guided mode order increases. This can be explained from a geometrical optics description by the increase of the number of reflections undergone by the guided wave when mode order increases.

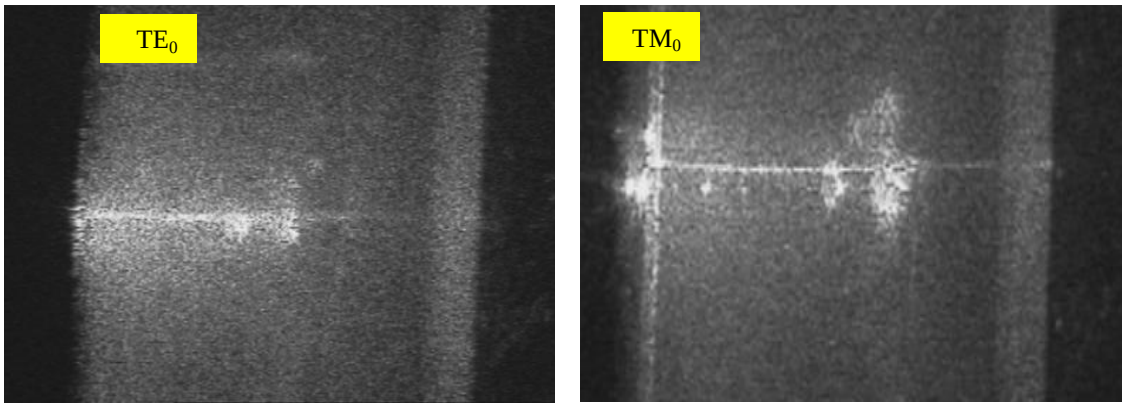

Figure 3: Light propagation line for the fundamental modes TE_0 and TM_0 captured by CCD camera in GdCOB waveguide

We also observe that, despite the low measured surface roughness (4-5 nm), the losses diffusion values are quite high (greater than 1 $dB.cm^{-1}$). Indeed, the necessity of depositing multilayer films so that its thickness is greater than threshold thickness and that it allows, subsequently, the excitation of least two guided modes (our studied film is grown in two stages of ablation: the first for three hours and the second for two hours) has probably induced the growth of an inhomogeneous film disrupting the guiding quality. Consequently, the thickness effect is no longer negligible because the obtained thickness is 860 nm; from which the diffusion losses in volume become greater.

Moreover, The Rutherford backscattering spectroscopy (RBS) does not make possible to determine the boron content in GdCOB thin films because of the low boron atomic mass. Therefore, absorption optical losses should

not be overlooked, since they generally come from an anionic deficiency, lack of stoichiometry or impurities presence. This may explain the fact that even with a homogeneous surface condition and a low roughness; we can have significant optical losses.

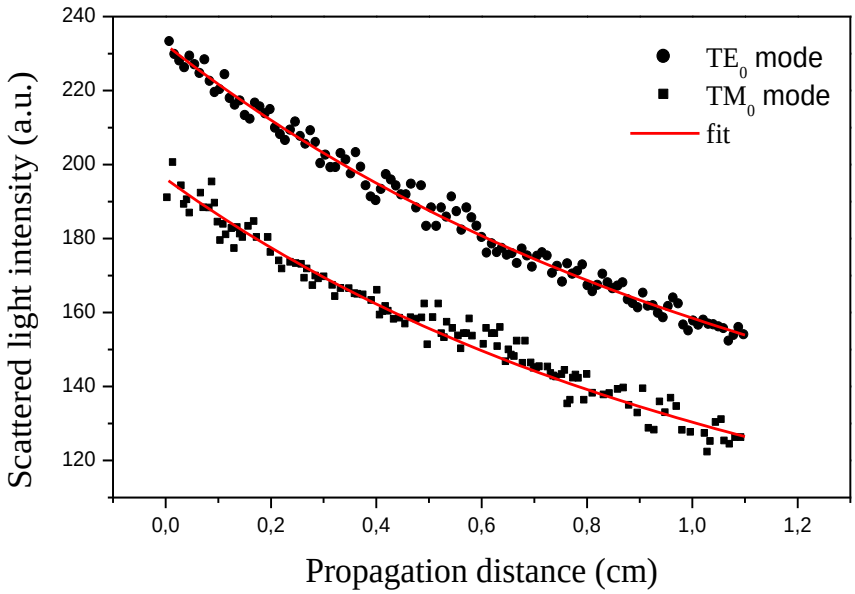

Figure 4: Intensity of the scattered light as a function of the propagation distance for both fundamental TE_0 and TM_0 modes

Table 1 : Diffusion losses values for the two guided modes for each TE and TM polarizations

Polarisation	Mode order	Diffusion losses (dB/cm)
TE	0	2,09 ± 0,13
	1	3,35 ± 0,13
TM	0	2,28 ± 0,21
	1	4,22 ± 0,21

Conclusion

In this paper, we presented a morphological and optical study of GdCOB thin films deposited on quartz substrate by pulsed laser ablation technique. The AFM scans show that the surface roughness of studied film is in order of 4-5 nm. The optical study performed by prism coupling shows the feasibility of waveguides and two modes were excited for each polarization (TE and TM). On the other hand, the measured refractive indices (at 632.8 nm) are closely alike of those of bulk GdCOB which indicates a good compactness of the elaborated thin film. Finally, the optical losses diffusion, measured by CCD camera, are approximately equal to 2 $dB.cm^{-1}$ (at 632.8 nm) for both fundamental TE_0 and TM_0 modes. The optimization of growth parameters will improve the composition of the elaborated films and reduce optical diffusion losses as much as possible.

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