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Waveguide laser formed in YAG:Nd^{3+} crystal by femtosecond laser inscription.

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ABSTRACT

A technique of direct writing of depressed cladding waveguides by a tightly focused, femtosecond laser beam in laser crystals has been developed. A laser based on a depressed cladding waveguide in a Neodimium doped YAG crystal has been demonstrated for the first time.

Keywords: refractive index change, diode-pumped laser.

1. INTRODUCTION

Femtosecond laser inscription in dielectric materials is an emerging and promising technology which has already proved to be a powerful and flexible tool for optoelectronic components manufacture. Waveguiding structures in some materials, including many types of glass, can be written directly, as the laser exposure produces positive change in refractive index. In crystal materials, the change of refractive index can be either negative or positive.[1-4] Therefore; direct writing of waveguides in crystals is not always possible. At the same time, it would be highly advantageous to adapt the femtosecond inscription approach for making waveguides in crystal media. In particular, laser crystals, such as $Y_3Al_5O_{12}$ (YAG), represent an interesting target in the view of potential applications for development of waveguide lasers. We have found that the refractive index change is predominantly negative in YAG:Nd^{3+} and YAG:Cr^{4+} crystals, making it possible to form the waveguides by defining the depressed index cladding. This approach has been earlier demonstrated in crystals of CaF_2 which shows distinct negative induces refractive index change.[2]

In this paper, we report, for the first time, on the femtosecond inscription of depressed cladding waveguides in a family of laser crystals of great practical importance – YAG:Nd^{3+} and YAG:Cr^{4+} crystals. The core consists of unexposed area whilst the cladding is formed by a number of separate parallel tracks. We demonstrate the first laser based on a laser-inscribed waveguide in a YAG:Nd crystal.

2. FEMTOSECOND LASER INSCRIPTION

The experimental technique was similar to that used previously for femtosecond inscription in glasses and in some crystals.[1-4] An amplified laser system, operating at a wavelength of 800 nm, produced 150 fs-long pulses at a repetition rate of 1 kHz. Laser beam was focused at a depth of 200 μm under a polished surface of the sample using a X40 microscope objective with the numerical aperture of 0.65. Patterning was provided by translation of the sample mounted on a high-precision translation stage. The energy of the pulse arriving at the sample was varied and permanent change of refractive index in the YAG:Nd and YAG:Cr crystals was observed. always kept below the optical damage threshold. Refractive index change was controlled by phase delay measurements[5].

We compared the effect of femtosecond inscription in YAG:$Cr4^{+}$, YAG:Nd^{3+} and undoped YAG crystals. Permanent change of refractive index in the YAG:Nd and YAG:Cr crystals was observe above a certain 'inscription threshold' lying in the range 0.2-1.0 μJ, which corresponds to power density of $(1\text{-}2)\times10^{14}$ W/cm^2 . The inscription threshold for undoped YAG is approximately by an order of magnitude greater. In fig. it is presented images of single tracks inscribed in various crystals at intensity levels just above the inscription thresholds. It is remarkable, that a track, inscribed in the YAG:Nd^{3+} crystal, is very smooth, without any visible defects, while a track in the YAG:Cr^{4+} crystal exhibits worse quality. A track inscribed in the undoped YAG strongly differs from those in the doped crystals. It has remarkable deviations from strain line. Further increase of the inscribing pulse energy leads to a pattern looking like damages. This difference between doped and undoped crystals indicates that the crystal defects define the possibility of

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“smooth” modification of lattices of the YAG crystal, resulting in the well-defined refractive index change. The dopants present in a crystal generate large number of defects and thus facilitate the modification of crystal lattice without optical damage.

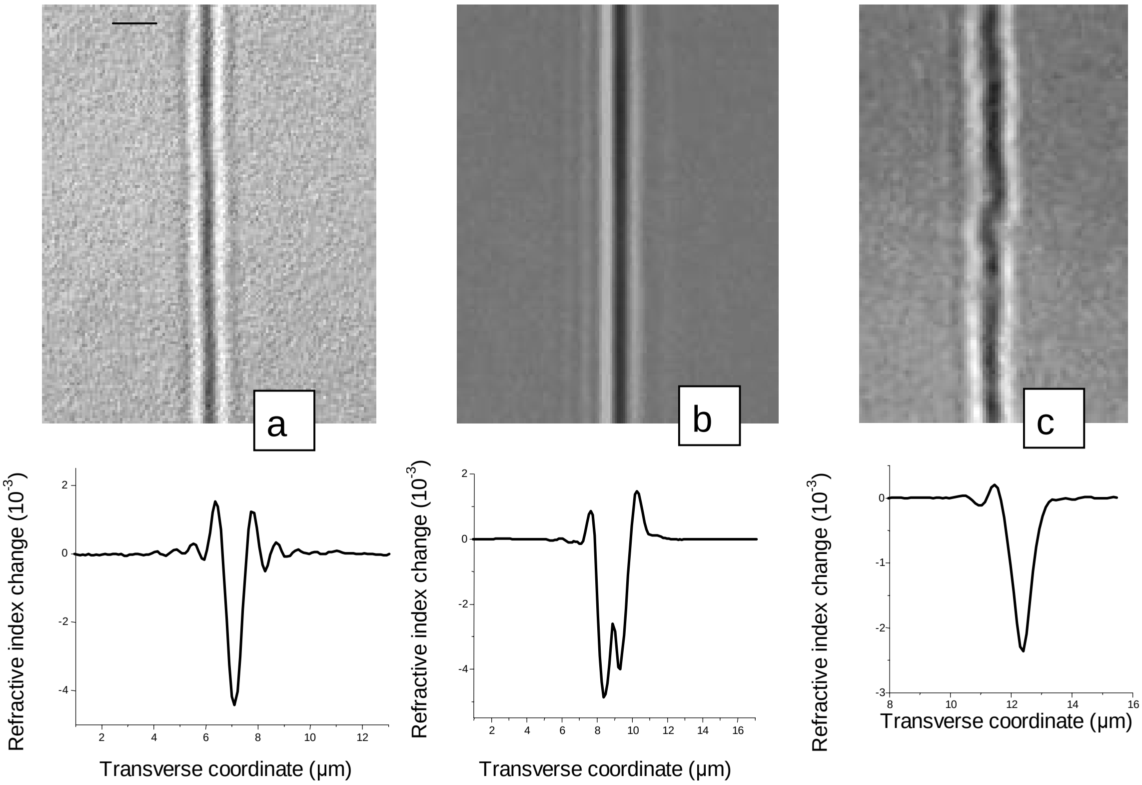

Figure 1: Microscope photographs and refractive index profiles of single tracks in a) YAG:Cr^{4+}; b) YAG:Nd^{3+}; c) undoped YAG

A refractive index change profile of tracks possess complex geometry and include volumes of material with increased and those with decreased refractive index (fig.1.). Typically, the refractive index change is negative in the central area of an inscribed "feature" whether it is a single point or a track, and is positive at the edges of the processed volumes. In our recent study, we observed that a single track inscribed in YAG:Cr^{4+} crystals exhibit waveguiding properties.[4] Obviously, that the waveguide was formed at the edge of a single track. Importantly for this study, we found that in all types of YAG crystals, the refractive index change is negative in the central area of the inscribed "feature" whether it is a single spot or a track.

By writing the tracks around the unmodified central volume of material, a depressed cladding can be produced with the central volume serving as the core of a waveguide. The structure is therefore similar to certain types of microstructured optical fibres. In this study, a waveguide was written in a crystal of YAG:Nd^{3+} with the Neodimium concentration of 0.8 mol.%.

The technique immediately proved to be flexible enough for definition of arbitrarily shaped waveguides. For this study, we produced a rectangular shape waveguide with the core size of 100 μm by 13 μm along X and Y axes accordingly, as shown in fig.2. This particular geometry was chosen in order to approximately match the mode profile of the waveguide with that of a typical pumping laser diode, operating at 809 nm wavelength. One can see that the tracks possess some internal structure (fig.1). However, the change of refractive index, averaged across the cross-section of each track, is always negative, which was established by the phase delay measurements.[5]

The crystal was 10 mm long. The waveguide ends were covered with the dielectric coatings which were highly-reflective (HR) on one side and anti-reflective (AR) on the other side at a wavelength of 1064nm. The HR coating was dichroic and transmitted 90% of pumping emission at wavelength of 809nm.

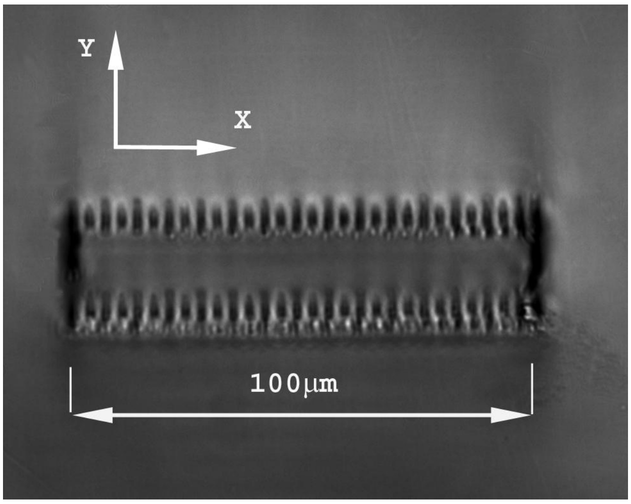

Figure 2. End view of a depressed cladding waveguide inscribed in $YAG:Nd^{3+}$.

2. OSCILLATION EXPERIMENT

The scheme of the waveguide laser is shown on fig.3. The waveguide was pumped through the HR coating facet by a beam from a high-power laser diode (LD). The size of the laser emitting area was 1x200 μm, and a standard cylindrical lens was permanently attached to the LD output. We used a collimator with the magnification of 0.5 in order to couple the laser diode beam into the waveguide. We estimated that the overall coupling efficiency was 65%. A flat mirror was attached directly to the AR side of the waveguide, serving as an output coupler (OC in fig.3) with the transmittance of 24%.

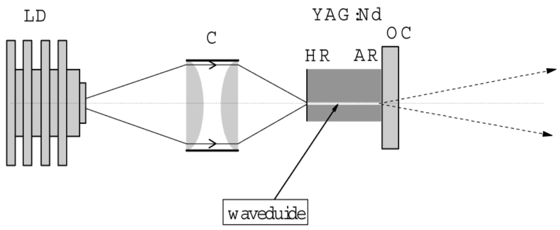

Figure 3: Experimental setups for lasing experiments. Output coupler OC is directly attached to the end of the wavewuide. LD – pumping laser diode, C – collimator.

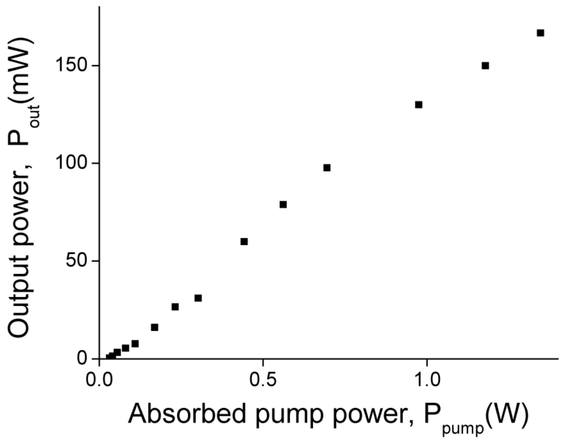

Figure 4: Laser output power as a function of pump power measured with the 24% output coupler.

Alignment of the waveguide and propagation of the pumping beam were monitored under a microscope. The up-conversion emission, produced by the pump, made the waveguide clearly visible and thus helped to optimise the alignment.

Dependence of the laser output on pumping power is shown in Fig.4. The lasing threshold was 30 mW in this configuration, and the power conversion efficiency was 11%. The spectrum of the laser signal was centered at a wavelength of 1064 nm.

By pumping a volume of the crystal beam away from the waveguide, it was possible to obtain lasing in the bulk modes. However, this crystal element was not specially prepared for the bulk mode of operation. Namely , the angle between the opposite crystal facets was relatively large, 2.5 mRad, thus increasing the losses in the corresponding Fabry Perot cavity. As a result, the lasing threshold in the bulk mode was as high as 1 W. The waveguide laser showed a considerably superior performance, having the threshold of only 30 mW.

The field profiles of the laser output were measured at a moderate pump power level of 0.27 W in a configuration with a 6.9% output coupler. The near field image was formed at the input of a CCD camera by an objective with magnification by a factor of 12. The far field images were obtained by placing the camera directly in the laser beam at a distance of 6 cm, exceeding the Raleigh distance. Measured beam images and field profiles are shown in Fig.5. The near field profiles are approximated by Gaussian functions with a good accuracy, as shown by dashed lines in Fig.5a. Mode half-widths, measured at $1/e^2$ intensity level, are 36 μm and 6.6 μm in lateral and transverse directions, respectively. Thus, the laser mode is well confined in the waveguide core. The far field profiles are also well approximated by Gaussian shape with the divergence half-angles of 9.4 mRad and 51 mRad measured in lateral and transverse planes, respectively. These values are very close to the diffraction-limited ones of 9.6 mRad and 47 mRad, calculated from the near-fields, indicating that the waveguide laser oscillates predominantly in the fundamental mode.

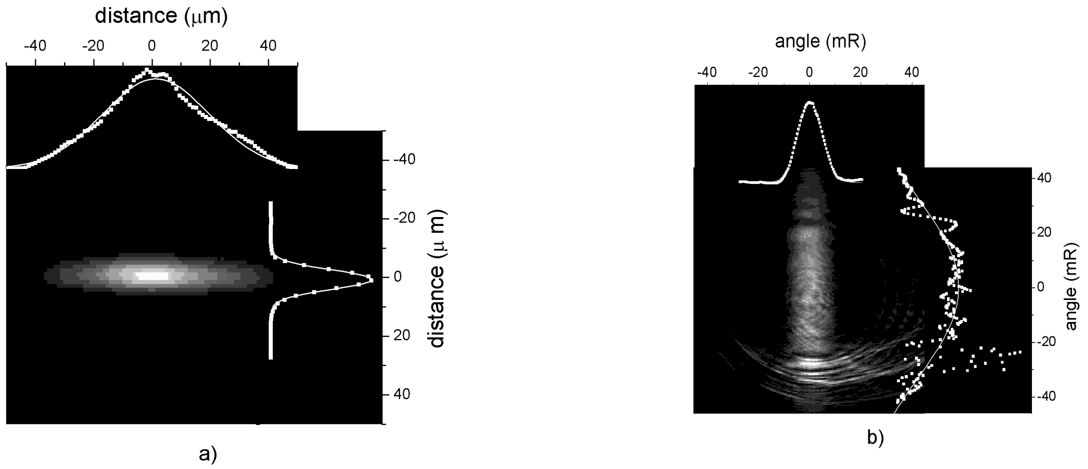

Figure 5: Near field (a) and far field (b) images of the laser beam. Profiles along lateral and transverse directions are shown as scatter graph lined on top and on the right of each image, respectively. Gaussian fitting curves are shown as thin lines.

An additional beam can be seen in the far-field profiles which appears as a circular pattern diffracting in the transverse plane (fig.5b). The centre of symmetry of the pattern coincides with that of the laser mode, but the intensity is not uniformly distributed around the circle. A possible reason for this pattern is the diffraction of the fundamental mode on the complex periodic structure of the cladding.

No degradation of the output power or a beam shape was observed after several tens of hours of laser operation.

4. EFFECTIVE REFRACTIVE INDEX STEP.

Given the good fit of the Gaussian approximation to the measured fundamental mode profiles, one can estimate the effective index step between the core and the cladding in the waveguide. Firstly, we assume a planar waveguide approximation, as the lateral size of the waveguide is much larger than the transverse size. Refractive index profile is considered to be rectangular. The cladding is considered to be thick, which is in line with the above observation of good confinement of the mode within the waveguide.

We note that the laser oscillates in a fundamental mode. Of course, this does not prove that the waveguide would support only one mode in passive regime as well. However, from these measurements we can estimate the waveguide parameter

V_y for the transverse coordinate, and, hence, the value of the effective step of refractive index Δn_y. The waveguide parameter is related to the transverse sizes of the core and the mode as: [6]

$$V_y = \left(\frac{\sqrt{\pi}\rho_y}{2r_{0y}} \right)^{1/2} \exp(\frac{\rho_y^2}{2r_{0y}^2}) \quad (1),$$

where $2\rho_y$ is thickness of the waveguide core (ρ_y =6.5 μm in our case) and $2r_{0y}$ is the transverse size of the fundamental mode (r_{0y} =6.6 μm). Equation (1) yields V_y=1.52. It is is lower, than π/2 — V parameter cutoff value for next order TM_1 and TE_1 modes of step index planar waveguides[6]. Thus, it is an additional evidence, that the laser oscillates in a fundamental mode only. Substituting this value in the definition formula for *V*-parameter:

$$V_y = \frac{2\pi\rho_y}{\lambda}\sqrt{2n\Delta n}, \quad (2)$$

one obtains an estimate for the effective refractive index step as $\Delta n_y = 4\times10^{-4}$.

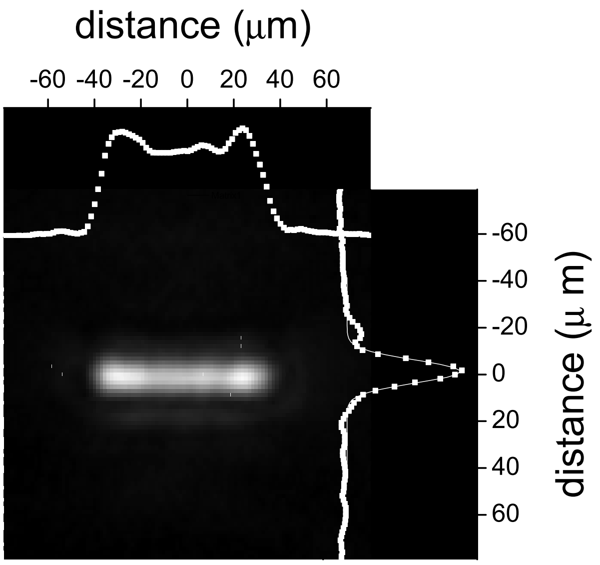

Fig.6. Near field image of luminescence in the 1060nm wavelength range outgoing from an end of the waveguide in passive regime.

Maximal possible profile size of emission field supported by waveguide was estimated in a passive regime, without resonator. For this purpose, the output coupler OC was removed and replaced with filters, blocking pumping emission and Nd^{3+} luminescence in the 940 nm wavelength range. Then near field profile of luminescence in the 1060 nm wavelength range and outgoing from AR coated end of the waveguide was recorded by CCD camera. So as pump emission is absorbed on nearly 0.3 cm -long sector of the waveguide at the HR coated end, luminescence image of the AR coated end is predominatingly formed by emission originating near HR coated end and matched to propagating waveguide modes The near field luminescence image is shown in fig.6. Transverse profile of the image is well approximated by Gaussian with half width equaled to 9.7 μm. It is not strongly higher of oscillation mode (6.6 μm), and excessive size could be explained by presence of additional leakage modes in passive regime, which disappear in multi-passing lasing regime. Thus waveguide obtained is a single mode waveguide.

5. WAVEGUIDE LOSSES

The waveguide losses were estimated following the Findlay-Clay analysis[7] according to which, the lasing threshold power P_{th} depends on the cavity parameters as:

$$P_{th}(\xi) = P_0\left(1+\frac{\xi}{2\alpha L}\right) \qquad (3)$$

Here, the logarithmic output coupling losses ξ is defined as $\xi=-ln(1-T_{OC})$, where T_{OC} is the output coupler transmission. P_0 is the threshold pump power corresponding to the zero output coupling, L is the length of waveguide and α is the waveguide internal loss coefficient.

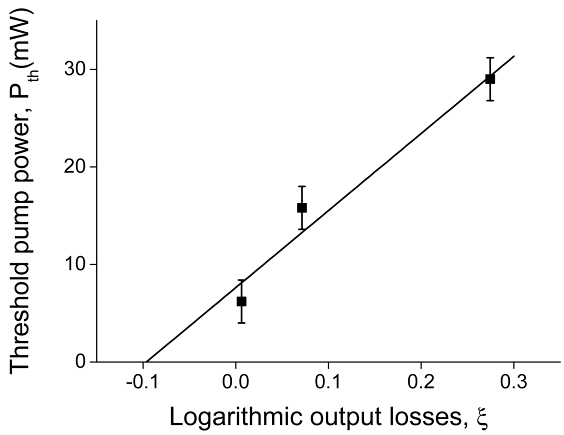

Figure 7. Dependence of the threshold pump power on logarithmic output coupling losses ξ=-ln(1-T_{OC}). Squares – experimental data, solid line – theory.

The first value of lasing threshold, corresponding to the output coupling of 24%, was taken from the measurements described above. At this stage, the threshold measurements were repeated with two other output couplers having transmission coefficients of 0.62 % and 6.9%. Fig.7 shows the measured the dependence of lasing threshold on logarithmic coupling losses ξ. The dependence was approximated by the linear function (3) obtained from the least square calculation under variation of P_0 and α parameters. Thus the waveguide loss coefficient was estimated as α=0.048 cm^{-1}.

6. CONCLUSIONS

In conclusion, technique of refractive index changing by femtosecond laser pulses is adapted to YAG single crystals. Transition metal or rare-earth ions doped to the crystal facilitate process of crystals lattice modification without optical damage. Tracks of permanently changed refractive index have been produced in YAG:Cr^{4+} and YAG:Nd^{3+} crystals by femtosecond inscription and arranged to form depressed-cladding waveguides of a predetermined shape. A low-threshold laser based on such waveguide in the YAG:Nd^{3+} has been demonstrated for the first time. The waveguide losses were estimated to be as low as 0.05 cm^{-1}.

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