Tri-wavelength laser generation based on neodymium doped disordered crystal waveguide

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Abstract: We demonstrate a tri-wavelength laser generation from a Nd-doped calcium niobium gallium garnet disordered crystal waveguide. The laser threshold obtained was 83 mW of launched pumping laser corresponding to a slope efficiency of 5.1%. According to the laser spectrum, the output light was found to be a tri-wavelength laser, with wavelengths of 1058 nm, 1060 nm and 1064 nm, respectively. The stability of the output laser was investigated, which found that the output laser was a continuous laser.

OCIS codes: (230.7380) Waveguides channeled; (140.3460) Lasers; (160.5690) Rare-earth-doped materials.

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1. Introduction

As a new disorder laser crystal, neodymium-doped calcium niobium gallium garnet (Nd:CNGG) have attracted a continuous attention owing to its excellent properties on fluorescence and thermal properties [1–7]. It provides significant inhomogeneous broadening of fluorescence in the absorption and emission spectra, which is similar to the Nd-doped glass. In addition, it has comparable thermal features to the ordered crystal, such as Nd:YAG, Nd:GGG, and Nd:YVO_4. Owing to the different sites of Nd-doped ions in the crystal, multi-wavelength lasers could be generated with Nd:CNGG crystal as gain medium. As reported in Ref [8, 9], tri-wavelength laser has been excited around the wavelength of 1060 nm based on the disorder crystal in the bulk laser system, which have the wavelength interval within several nanometers. According to such small wavelength intervals, the terahertz (THz) radiation has the potential to be generated associated with the appropriate nonlinear crystal [10].

Lasers based on waveguide platforms can be achieved with low pump thresholds and comparable efficiencies with respect to the bulks [11–17], benefiting from the compact active volume of the media and well confined light fields. However the waveguide fabrication technologies in gain media are difficult for many materials. For Nd:CNGG crystal, only ion implantation method has been applied for waveguide fabrication, however, due to the relatively high propagation loss (~3 dB/cm), no laser emission was observed [18, 19].

Femtosecond (fs) laser inscription has been proved to be an efficient method to produce the waveguide structure in gain media [20, 21]. Depending on the shape of waveguides, these waveguides could be divided into Type I waveguides (in the positive refractive index changed track), Type II stress-induced waveguides (typically between two written tracks with negative index change) and Type III depressive cladding waveguides (in the core surrounded by tracks) [22–25]. In this work, we used the fs laser inscription to fabricate the cladding waveguide in Nd:CNGG crystal. Based on this structure, a tri-wavelength laser emission was observed at 1058 nm, 1060 nm and 1064 nm, which indicates that different frequencies at 0.58, 1.04 and 1.62 THz have the potential to be generated with a suitable nonlinear material.

2. Experiments

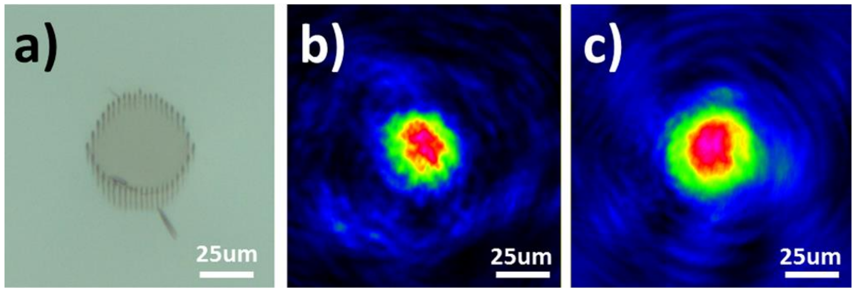

Fig. 1. (a) Cross section of the inscribed Type III waveguide in Nd:CNGG crystal; the measured modal profile (TM_{00}) of the pumping laser at wavelength of 804 nm (b) and the output laser ~1060 nm (c).

The Nd:CNGG crystal used in this work was doped by 2 at.% Nd^{3+} ions and cut into dimensions of 1.5 × 10 × 9.9 ($x \times y \times z$) mm^3 with the largest facets optically polished. The waveguide was fabricated by the fs laser writing. During the fabrication process, a linearly polarized 120 fs pulse laser, which is at a central wavelength of 800 nm with 1 kHz repetition rate and 0.84 μJ pulse energy from an amplified Ti:Sapphire laser system (Spitfire, Spectra Physics), was focused inside the crystal through a 40 × microscope objective (N.A. = 0.65). Along the z axis of the sample, the motorized stage moved the sample at a constant speed of 500 μm/s and a damage track was produced inside the crystal. Then we modified the focusing depth and repeated this process many times with ~3 μm separation between adjacent tracks. After multiple parallel scans at certain depths and lateral positions, a circular waveguide surrounded by damage tracks was formed, which confine the light in the central core of the tubular structure. After that, the two end facets were polished. Figure 1(a) shows the cross-section of the waveguide from one of the polished end facets. As one can see, the dark vertical lines are the inscribed damage tracks, which typically have lower refractive index compared with the Nd:CNGG crystal. And the light could be confined in the middle of this structure. The propagation loss of this waveguide was measured by the method reported in Ref [26]. at the wavelength of 1064 nm, which was assumed to be ~1.5 dB/cm.

Figure 2 shows the experimental configuration for the continuous Nd:CNGG laser generation from the waveguide. A continuous wave tunable Ti:Sapphire laser was applied as pumping source, which could tune the wavelength from 804 nm to 824 nm. The intensity and polarization of the pumping laser was modulated by an intensity modulator constituted by a Glan-Taylor prism and two pairs of waveplates (one half-wave plate placed previous to the Glan-Taylor prism and the other following the prism in order to rotate the polarization of the beam). Focused by a convex lens with a focal length of 20 mm, the pumping laser was coupled into the cladding waveguide. Two specially designed mirrors (M1 and M2) were adhered to the end-facets of the sample in order to form the laser resonator with the waveguide. M1 has high reflectivity between 1050 nm and 1070 nm (>99%) and a transmission of 99% in the range of 800 nm and 830 nm. Meanwhile, Mirror 2 was coated with films of 90% reflectivity around 1060 nm and 99% reflectivity between 800 nm and 830 nm. The generated laser was collected by a long working-distance microscope objective and separated by a monochrometer. In order to analysis the stability of the output laser, a photodiode was used to detect the output power connecting to an oscilloscope for a time interval of more than 20 min.

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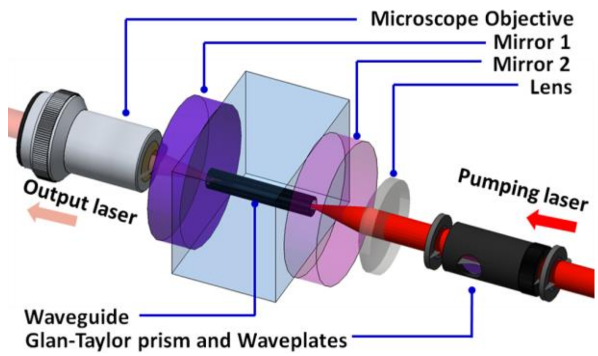

Fig. 2. The experiment setup for the continuous tri-wavelength waveguide laser generation.

3. Results and discussion

As depicted in Fig. 1(a), the diameter of the waveguide structure is 35 μm. Due to the large size of the waveguide and assuming the typical values of the refractive index change at the damage tracks (~1 × 10^{-3}), the behavior of the waveguide is expected to be multi-mode at the wavelength of ~810 nm, in agreement with the experimental observations. However, laser oscillation could only be obtained when the propagation mode of the pumping laser (around 810 nm) is the lowest (single) mode of the waveguide. It can be explained that single modes for the pump and the laser wavelengths have the better mode overlap in the resonant cavity, which have the mode FWHM (full width at half maximum) of ~20 μm (pumping) and ~23 μm, respectively. Figures 1(b) and 1(c) show the propagation modal profiles of the pumping and the output laser with the polarization along *z* axis (TM mode). As one can see, the shape of the propagation modes was nearly symmetrical single mode with a diameter of ~35μm for both pumping (~804 nm) and oscillating laser (~1060 nm). The laser performance and the optical properties were similar for both TE and TM polarizations.

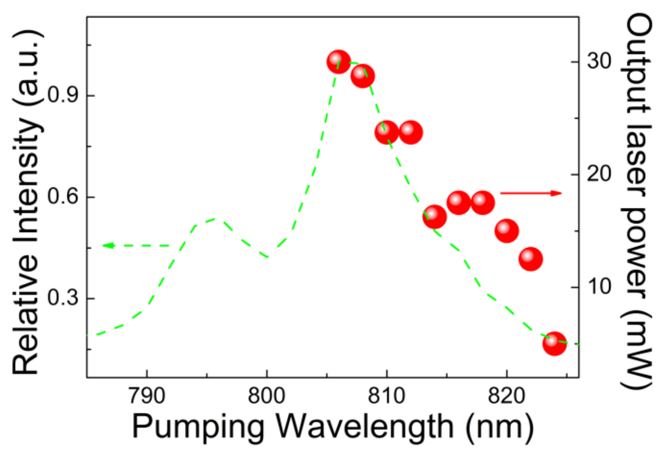

Fig. 3. Maximum power of the output laser as a function of the wavelength of the pumping laser (red dots); absorption spectrum of the Nd:CNGG crystal around 808 nm (green dashed line).

Figure 3 shows the measured absorption spectrum of the crystal. As one can see, Nd:CNGG crystal has a wide absorption spectrum from 785 nm to 824 nm with a maximum value at the wavelength of 804 nm. Tuning the wavelength of the pumping laser from 804 nm to 822 nm, we measured the power of the output laser as a function of the pumping wavelength with the same launched power (~640 mW). The measured values were also pointed in Fig. 3. With 804 nm pumping light, the output power reaches the maximum (~30

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mW). This value gradually decreased to zero along with the wavelength adjustment to 824 nm, which has a similar variation trend with the absorption spectrum. The abnormal increasing within the region of 815 nm - 817 nm was supposed to be induced by the variation of waveguide coupling efficiency.

To simplify the discussion, we would like to take the 804 nm laser as the pumping source to analyze the generated laser. With an optical spectrograph (measurement error around 2 nm), we measured the spectrum of the output laser shown in Fig. 4. A tri-wavelength laser oscillation was observed at wavelengths of 1058 nm, 1060 nm and 1064 nm, respectively. Because of the accommodation of Nd ions into different lattice positions, Nd:CNGG crystal has a broad emission spectrum around 1060 nm. And there are three emission lines at the wavelength of 1067 nm, 1062 nm and 1060 nm with the emission cross section of 5.2, 5.3 and 5.4×10^{-20} cm^2, respectively as reported in Ref [6]. According to the similar values of the emission cross section, the tri-wavelength laser could be excited based on Nd:CNGG crystal. However, the measured wavelength of the tri-wavelength laser has a slight wavelength shift (~2 nm) compared with values in Ref [6]. We believe it was induced by the measurement error of our spectrograph.

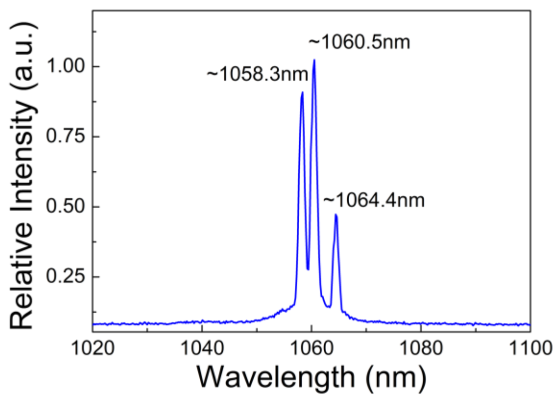

Fig. 4. The laser emission spectra of Nd^{3+} ions at $^4F_{3/2}\rightarrow{}^4I_{11/2}$ transition obtained from the output laser (blue line).

As shown in Figs. 5(a) and 5(b), the power of the total output light and the partial powers at different wavelengths were pointed as a function of the absorbed pump power with an output mirror of 10% transmittance. For the total output light [Fig. 5(a)], the maximum output power was 30 mW under a launched power of 640 mW, leading to a laser slope efficiency of 5%. According to different wavelength measurements, the maximum output power at 1058 nm, 1060 nm and 1064 nm were 14 mW, 13 mW and 3 mW, respectively. For the 1058 nm wavelength, the waveguide laser had a pump threshold of 83 mW and a slope efficiency of 2.3%. At 1060 nm, the pump threshold of 804 nm light was 114 mW, and the slope efficiency of laser oscillations was 2.3%. With respect to 1064 nm, the pump threshold was 231 mW, and the slope efficiency of laser oscillations was 0.6%. The laser threshold at 1064 nm is relatively higher compared with other two wavelengths; meanwhile the 1058 nm and 1060 nm laser emissions have closer threshold values. Besides, the variation of 1060 nm and 1064 nm laser power with launched pump power seems not to follow a linear trend. As the emission cross section of these three wavelengths have the similar values. So the generated waveguide lasers at different wavelengths should have the similar behavior, such as the threshold and slope efficiency. In this work, different laser thresholds and non-linear slope efficiencies were observed, which indicates that there is a competition between the three wavelengths.

As a difference from the bulk laser, the operation power of the waveguide laser is relative low (commonly less than 1 W) and the intensity inside the waveguide is very high. Hence the pulsed laser emission is often observed, induced by relaxation oscillations or nonlinear effects

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[27–29]. In order to prove the continuous laser operation, the output power was detected by a photodiode connected to an oscilloscope for a time interval of 20 min. As depicted by Fig. 6 in the temporal scale of nanoseconds, the results reveal continuous operation and instability less than ± 0.25%.

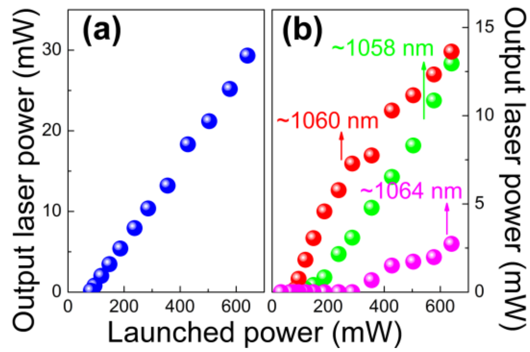

Fig. 5. Power of the total output waveguide laser (a) and partial powers for the different wavelengths (b) versus the launched pumping power.

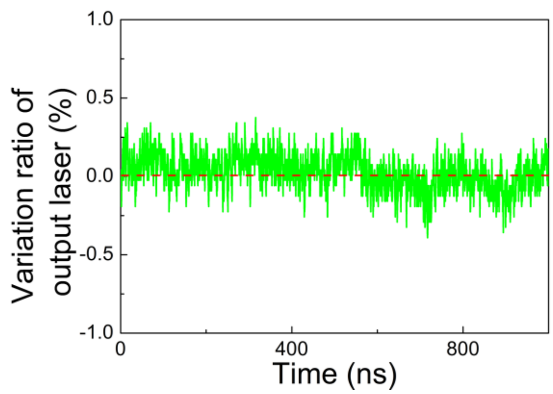

Fig. 6. The variation ratio of the total output laser power as a function of time, measured by a photodiode and an oscilloscope with resolution ~2 ns.

4. Conclusions

In conclusion, a Type III waveguide was formed inside Nd:CNGG crystal by the ultrafast laser inscription method. With pumping laser at wavelength of ~804 nm, tri-wavelength laser oscillation was observed in the Nd:CNGG crystal waveguide for the first time. The threshold and slope efficiency were 83 mW and 5%, respectively. The output laser from this Nd:CNGG waveguide was found to be stable continuous laser.

Acknowledgments

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