Q-switched pulse laser generation from double-cladding Nd:YAG ceramics waveguides

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Abstract: This work reports on the Q-switched pulsed laser generation from double-cladding Nd:YAG ceramic waveguides. Double-cladding waveguides with different combination of diameters were inscribed into a sample of Nd:YAG ceramic. With an additional semiconductor saturable absorber, stable pulsed laser emission at the wavelength of 1064 nm was achieved with pulses of 21 ns temporal duration and ~14 µJ pulse energy at a repetition rate of 3.65 MHz.

OCIS codes: (230.7380) Waveguides, channeled; (140.3540) Lasers, Q-switched; (160.5690) Rare-earth-doped materials.

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1. Introduction

Rare earth doped yttrium aluminum garnet (RE:YAG) ceramics is a latest developed gain media for high power solid state lasers, owing to its excellent lasing properties [1]. Compared with its single-crystalline partners, RE:YAG ceramics possess similar fluorescence ability and can be produced in larger homogenous volumes. Efficient high power operation of the neodymium doped YAG (Nd:YAG) ceramic lasers have been realized under configuration of continuous wave [2], Q switching [3] and mode locking [4]. Except for these bulk laser systems, Nd:YAG ceramics are also used as the gain media for the active devices in integrated photonics [5, 6].

Waveguide lasers and amplifiers are the basic active devices, for integrated optics. As a basic component of these active devices, waveguide structures confine light within micrometric or sub-micrometric scales and can obtain higher optical intra-cavity intensities compared with bulk [7–9]. Until now, few fabrication techniques have been used for waveguide fabrication in YAG ceramics, such as ultrafast laser writing or ion implantation/irradiation [5, 10]. The ultrafast laser writing technique is a well known waveguide fabrication method [11]. Ultrafast laser written waveguides, depending on the relative location of the waveguide and writing tracks, could be classified into Type I waveguides (in the positive refractive index changed track) [12], Type II stress-induced waveguides (typically between two written tracks with negative index change) [13] and Type III waveguides (in the core surrounded by tracks) [14]. More recently, a new structure, so called double-cladding waveguides, has been reported, which is a tubular cladding surrounded by another concentric cladding with larger size [15]. With this structure, the performance of the laser oscillation was modified by the diameter of the outside tubular cladding. For example, the slope efficiency of the 1030 nm laser emission was increased from 38% to 63% as diameters of outer claddings varied from 100 μm to 200 μm.

The pulse laser with high peak power density and good flexibility is significant for applications of medicine and nonlinear optics. Pulse fiber lasers could be achieved by the conventional Q-switches, such as acousto-optic modulators (AOM) and solid-state saturable absorbers, which simply replaces one end mirror of the fiber laser [16]. And compact fiber pulse laser could be easily incorporated into a variety of material processing applications. Compared with fiber laser, the waveguide laser has much smaller size and higher integration level. With the extremely short cavity length of waveguide laser, it enables pulse widths well below 1 ns under Q-switched operation. Hence, it is attracting to analyze the Q-switching performance in the waveguide laser devices. So far, Q-switching has been demonstrated in the ion-doped laser crystal waveguide [17–19].

In this paper, we report on the Q-switched pulsed laser generation based on double-cladding Nd:YAG ceramic waveguides fabricated with a femtosecond laser beam. This kind of waveguide has the ability to enhance the laser performance of single cladding waveguides. Different inner and outer diameter of the claddings were used inscribed into the Nd:YAG

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ceramics by the femtosecond laser. Adhering a semiconductor saturable absorber to one end facet of waveguides, Q-switched operation with stable pulse duration and pulse power was demonstrated.

2. Experiments

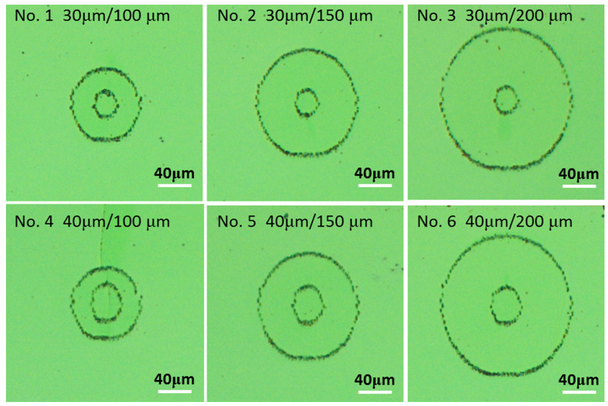

Fig. 1. Cross-section microscope image of the femtosecond laser inscribed double cladding Nd:YAG ceramics waveguides Nos. 1-6, which are composed of inner and outer concentric tubular claddings. The diameters of the double cladding waveguides are No. 1 30µm/100µm, No. 2 30µm/150µm, No. 3 30µm/200µm, No. 4 40µm/100µm, No. 5 40µm/150µm and No. 6 40µm/200µm, respectively.

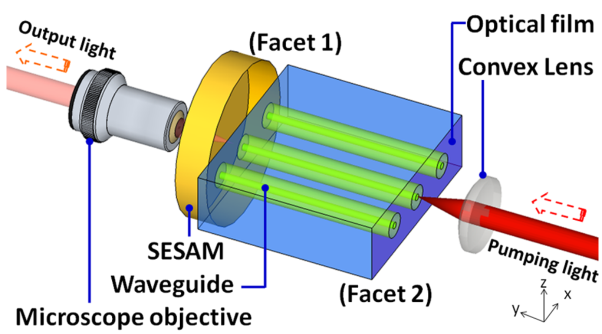

Fig. 2. Schematic plot of the experimental setup for the pulsed laser generation in the double-cladding Nd:YAG ceramic waveguides.

The Nd:YAG ceramic used in this work is doped by 2 at.% Nd^{3+} ions (obtained from Baikowski Ltd., Japan) and was cut into dimensions of 10 × 7 × 2 ($x \times y \times z$) mm^3 with the biggest facets optically polished. Waveguide structures in Nd:YAG ceramic were fabricated by the ultrafast laser writing method. In the process of the experiment, a linearly polarized femtosecond laser (120 fs pulse duration) from an amplified Ti:Sapphire laser system (Spitfire, Spectra Physics, USA) was applied for the inscription. And the pulses have a central wavelength of 800 nm at 1 kHz repetition rate and 1 mJ maximum pulse energy. The detailed experimental process is the same as that reported in [15]. According to the diameter of the inner and outer cladding, waveguides are numbered as shown in Fig. 1: the combination of the diameter of the inner and outer tubular cladding are No. 1 30µm/100µm, No. 2 30µm/150µm, No. 3 30µm/200µm, No. 4 40µm/100µm, No. 5 40µm/150µm and No. 6 40µm/200µm, respectively. To estimate the refractive index change (Δn) of the waveguide, we measured the angle of aperture of the guided mode in the far-field at wavelength of 1064 nm, which have a maximum far-field angular aperture of ~8°. Based on the method described in [20], the refractive index change in the tubular central waveguide is estimated to be ~0.008. The scattering loss of the waveguides, which is induced by the surface roughness of the

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waveguide walls, was measured by the Fabry-Perot method. A red laser (632.8 nm) was used as the detecting light, provided that the absorption of Nd:YAG ceramics at this wavelength can be neglected. According to the measurements, the loss was 1 ± 0.2 dB/cm in waveguides No. 1, 2, 3, and 1.5 ± 0.2 dB/cm in waveguides No. 4, 5, 6.

After inscription, end facets of the sample perpendicular to waveguides were optically polished. For the purpose of pulsed laser generation, both facets were particularly designed. As shown in Fig. 2, facet 1 was adhesion to a semiconductor saturable mirror (SESAM) with ~95% reflectance for the laser Q-switching. Facet 2 was coated by an optical film with a reflectivity of >99% at 1064 nm and a transmission of >98% at 810 nm. A continuous laser at the wavelength of 810 nm was chosen as the pump source, which comes from a tunable Ti:Sapphire laser (Coherent MBR 110). With a convex lens (focal length is 25 mm), the pumping laser was coupled into the inner-cladding waveguide through facet 2. The diameter of the focused light was around 20 μm, which insure that the pumping light will not be coupled into the outside cladding waveguide. The generated laser light passed through the SESAM and was collected by a 20 × microscope objective lens (N.A. = 0.4).

3. Results and discussion

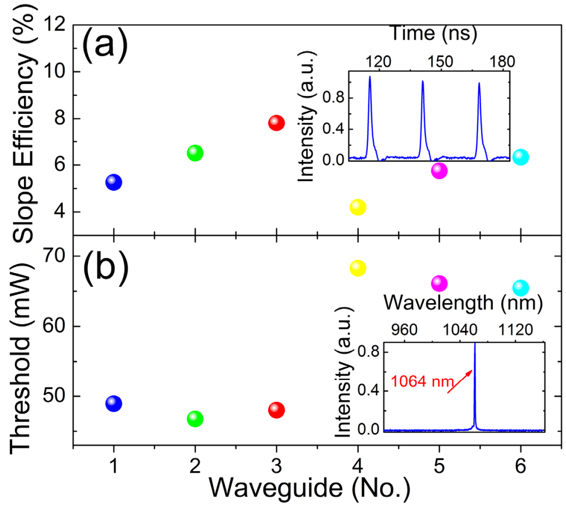

Fig. 3. Slope efficiency (a) and threshold (b) of the output pulsed laser as a function of the waveguide Nos. The pulse train and the laser oscillation spectra of the pulsed laser are shown in the inset of (a) and (b) in the waveguide No.3.

Laser emission was obtained from the six waveguides. As depicted in the insets of Fig. 3, the output laser of waveguides was the pulse laser at the wavelength of 1064 nm with the pumping power above the laser threshold. And the timing jitter is hardly observed with the maximum power of pumping laser. Figure 3 shows the slope efficiency, the lasing threshold and the spectra of the generated pulsed lasers of the double-cladding waveguides. The slope efficiency was measured to be $\Phi_{30/200}$≈7.8%, $\Phi_{30/150}$≈6.5%, and $\Phi_{30/100}$≈5.2% for the 30 μm inner core waveguides in comparison with $\Phi_{40/200}$≈6.3%, $\Phi_{40/150}$≈5.7%, and $\Phi_{40/100}$≈4.2% for the 40 μm inner core ones. The average threshold (launched power) is ~47 mW and ~66 mW for the 30 μm and 40 μm inner core cladding waveguides, respectively. It seems that the slope efficiency increases in waveguides with the same inner core, as the diameters of outer claddings increase from 100 μm to 200 μm. In turn, the threshold is determined by the size of inner core and it is independent on the outer cladding size. Compared with waveguides with the same diameter of outer cladding, the generated laser has lower threshold and higher slope efficiency in cladding waveguides with smaller inner core. In our opinion, the inner and outer cladding of double-cladding waveguides play different roles in the laser generation. The inner cladding is the laser output volume, whose cross section determines the intensity in the Fabry-Perot laser resonator. Hence the laser threshold is determined by the inner cladding. Meanwhile the outer cladding confines more pumping light into the whole structure inducing higher laser output power. So, simultaneous smaller inner and larger outer cladding will lead to better laser performance (lower threshold and higher slope efficiency).

Figure 4 exhibits the propagation mode of the generated laser in the waveguides. Due to the tubular waveguide structure, the modal profile of waveguide propagation modes is nearly a circle, which is similar to the propagation modes in a fiber. When increasing the diameter of the inner waveguide from 30 μm to 40 μm, the propagation modes are still symmetrical and single mode but the FHWM (full width at half maximum) increased from 17.8 μm to 26.7 μm. Taking into account the symmetrical single mode and the adjustable mode size, cladding waveguides have the potential to be excellent candidates to combine with fiber pump systems due to their better mode matching with the optical fiber.

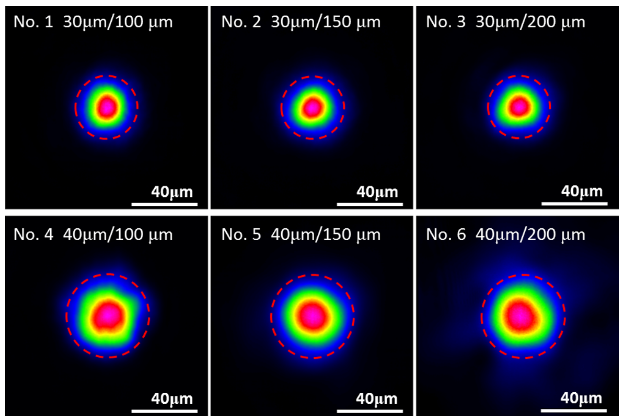

Fig. 4. Near-field modal profiles of the laser emission at 1064 nm from the double-cladding waveguides numbered 1, 2, 3, 4, 5, and 6. The red dashed lines indicate the position of the fs-laser inscribed tubular inner claddings.

To simplify the discussion, we take the waveguide No. 3 as an example to describe the pulse laser performance in double-cladding waveguides, which has the highest slope efficiency and the smallest threshold. Figure 5 demonstrated the output characteristics of the Q-switched pulsed laser. With the maximum launched power, the total average output power and repetition rate reached 48 mW and 3.65 MHz respectively (Fig. 5 (a)). Depending on the increasing of pump power, there is a nearly linear dependence of average output power corresponding to the slope efficiency of 7.8%. It should be noted that the value of the slope efficiency is reduced when operating in Q-switching mode. Without adhering the SESAM at the end facet of the waveguides, the slope efficiency of the output continuous wave laser from waveguide No. 3 is ~60%. The significant reduction results from the high reflection of the saturable absorber, which was used as the output mirror.

Figure 5 (b) shows the pulse energy and duration as a function of launched power, which are measured by the photodiode with resolution ~2 ns. The pulse energy (J_{pul}) was calculated from the pulse repetition rate (f_{rep}) and the average output power (P_{ave}) following the equation below:

$$J_{pul} = \frac{P_{ave}}{f_{rep}} \tag{1}$$

Far from the threshold, the pulse energy increases and finally saturates to ~13.4 nJ. Similarly, the pulse width of the Q-switched waveguide laser becomes constant (~22 ns) with high pump powers. Near the threshold, the value of pulse energy and width was tuned by the pump power. In this waveguide structure, the relaxation oscillation was observed with the

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pumping power near the threshold. Hence, we believe the unstable output of laser near the threshold could be attributed to the relaxation oscillation effect.

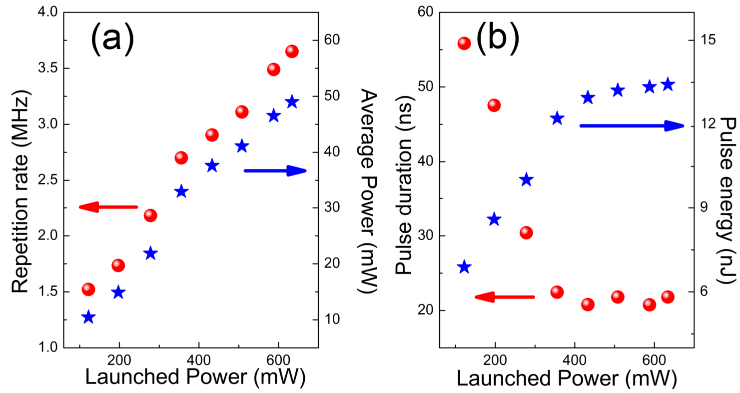

Fig. 5. Results for the generated pulsed laser from No. 1 waveguide by the Q-switching method using a SESAM as the out-coupling mirror. Repetition rate, average output power (a), pulse duration and pulse energy (b) as a function of launched pump power.

The model for passively Q-switched laser has been demonstrated in [21] and [22]. Based on their argument, the equations for the pulse width and pulse energy could be expressed as below:

$$E_p \approx \frac{h\nu_L}{\sigma_L} A\Delta R\eta_{out} \tag{2}$$

$$\tau_p \approx \frac{3.52T_R}{\Delta R} \tag{3}$$

where E_p is the pulse energy; $h\nu_L$ is the photon energy at the lasing wavelength; σ_L is the emission cross section of the laser material; A is the cross section of pumped volume; ΔR is the modulation depth of the SESAM; η_{out} is the output coupling efficiency; τ_p is the pulse duration; T_R is the cavity round-trip time. As one can see, all the parameters are decided by the material ($h\nu_L$, σ_L) and the structure of waveguide (A, ΔR, T_R, η_{out}), which are constants for a certain waveguide. Hence, the pulse width and pulse energy are independent of the pump power and become constant values at high pumping power, which has a very good agreement with our experiment results.

4. Conclusions

In conclusion, Q-switching pulsed laser generation was realized in double-cladding Nd:YAG ceramics waveguides with a SESAM as output mirror. Symmetrical single mode laser oscillation was observed at the wavelength of 1064 nm. The pulsed laser oscillation threshold was 47 mW for the 30 µm inner core waveguides. The maximum repetition rate and average power achieved were 3.65 MHz and 48 mW respectively.

Acknowledgments

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