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Highly efficient actively Q-switched Nd:YAG laser

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Abstract: A novel gain medium structure is designed providing Q-switched pulses with high efficiency. The use of an improved corner-side hybrid pump structure achieves a high absorption efficiency of pump light by crossing through the active media 13 times Nd:YAG. A layer of Sm:YAG is bonded around the active media, which suppresses parasitic oscillation and amplified spontaneous emission (ASE) effectively. A high-efficient actively Q-switched laser is successfully realized with a pulse energy of 104 mJ. The corresponding optical-optical conversion efficiency is 30.5%. This is, to the best of our knowledge, the highest optical to optical efficiency for an actively Q-switched Nd:YAG laser at the hundred milli-joules level.

1. Introduction

Diode-pumped actively Q-switched Nd:YAG laser sources with low repetition rate are employed in various fields, such as medical treatment, military application and scientific research [1,2], due to their advantages of high peak power, narrow pulse width, small volume and great reliability. These broad applications, in turn, provide incentive to further improve the basic performance of these light sources, especially the total conversion efficiency [3]. The optical conversion efficiency is constrained by many reasons, such as the quantum defect, absorption of the pump light, ASE, and so on [4,5].

Various approaches have been tried to improve the optical conversion efficiency. One way is to enhance the absorption of pump energy. For side-pumped systems, the key to increase the absorption of the pump energy is to exploit the excited population on the upper level near the side surface where the efficient excitation distributes. Five bounces by total internal reflection are introduced to increase the effective absorption length for the coplanar-pumped slab [6,7]. With a hybrid longitudinal/transversal-pumped zig-zag slab architecture, multiple passes of the pump beam through the active media increases the absorption length. It enables efficient absorption of the pump energy [8]. In the corner-pumped scheme, the multi-pass absorption is realized by the total internal reflection of the pump light in the slab. The incident pump light is absorbed gradually by the central active medium. Therefore, the absorption length is sufficient for high-efficiency absorption, even at a low absorption coefficient and a low doping concentration [9–11]. All these measures lead to the improvement of the conversion efficiency by increasing the absorption path.

The other way to increase the conversion efficiency is to suppress parasitic oscillations and ASE by lowering the ion doping concentration or applying the layer claddings on the gain medium.

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On the one hand, with respect to the saturation of output energy, reduction of Nd^{3+} ion doping concentration reduces the pump gain of the laser medium. As a result, the self-excited oscillation is effectively suppressed and an optical conversion efficiency of 18% can be obtained [12,13]. On the other hand, the use of the thick undoped layer (anti-ASE cap) or claddings on the edge faces allow an increase in the output power [14,15]. A layer consisting of the bonding agent, in which the solid particles like aluminum oxide or magnesium oxide effectively scattered the light, was used in the diode-pumped Q-switched Nd:YAG laser head to suppress the parasitic lasing modes and reduce the ASE [16]. Moreover, because Sm:YAG exhibits a high absorption coefficient at 1064 nm but is highly transparent for the pump at 808nm [17], it is bonded to the core-doped laser rod to suppress ASE and parasitic oscillations [18,19].

Unfortunately, effective absorption of the pump light and suppression of ASE and parasitic oscillation in a simple diode-pumped Q-switched Nd:YAG laser have not yet been achieved simultaneously. Consequently, the optical-optical efficiencies for most Q-switched Nd:YAG lasers have stagnated around 20% [7,8,16–18,20–22].

In this letter, we demonstrate a novel design for the gain medium module surrounded with Sm:YAG cladding with a corner-side hybrid pump structure based on the corner-pumped scheme, which can effectively increase the absorption of the pump and suppression of ASE and parasitic oscillations at the same time. The obliquely-transmitted pump in the gain medium will be reflected back after multiple reflections on the side surfaces of the cladding. Due to the increase in the number of reflections, the pump light travels with a relatively long path in the active media so that the effective absorption path of the pump light is greatly increased. Thus, the absorption efficiency of the pump light is enhanced correspondingly. In order to absorb ASE from the gain medium and shorten the path of amplified parasitic oscillation, the absorbent material Sm:YAG was bonded around the Nd:YAG by the diffusion bonding technique. Consequently, the capacity of energy storage in the gain medium is greatly enhanced and the corresponding optical-optical conversion efficiency is as high as 30.5%.

2. Experimental setup

Figure 1 presents the structure of the gain medium with the pumped laser. The 70 mm long, composite gain medium is fabricated from bulk crystal of Nd:YAG, Sm:YAG and undoped YAG by a diffusion bonding technique. The gain medium has a square active core made of the 0.1at.%Nd:YAG with a 4mm×4mm cross-section. In order to reduce the resonation loss, both of the two ends of the Nd:YAG core are coated with anti-reflection layers at 1064 nm. The angle of these two ends is also cut at 4 degrees relative to the x-y plane to suppress the parasitic oscillation. Four pieces of 3at.% Sm:YAG with thickness of 1mm are thermally bonded around the side surfaces of the core Nd:YAG crystal. Undoped YAG bulk crystals are sequentially bonded to the Sm:YAG crystal as depicted in Fig. 1. Furthermore, both the top and bottom surfaces are coated with SiO_2 film at a thickness of 3μm to reduce reflection loss on the interfaces between the crystal and the air. The two 6 mm×12 mm planes define the entrance faces for pump light and are anti-reflectively coated at 808 nm. The pump light is transmitted into the medium directly. The angle α between the side face and the y-z plane is 3 degrees. The two side faces are high-reflection (HR) coated at 808 nm. The pump lights will be reflected back after multiple reflections and pass through the crystal again. The pump light passes through the gain medium 13 times, which provides the total minimum absorption length of 52mm.

To confirm that the pump light was almost completely absorbed by the designed structure of the gain medium, the pump absorption efficiency and the pump absorption distribution in the gain medium are simulated with the software Zemax. The simulation was carried out under the condition that both the top and bottom surfaces are covered by two pieces of Sm:YAG with different thickness. Only one diode laser stack is inserted at one entrance face and a detector is placed at the other entrance face to measure the residual pump power. The results shown in

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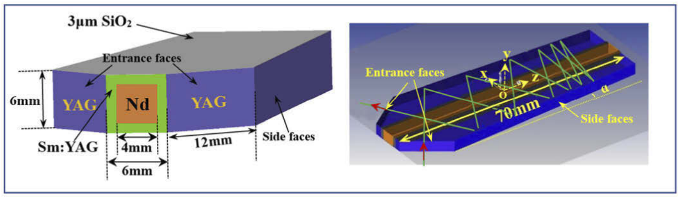

Fig. 1. The structure and the rendering of the gain medium with dimensions.

Table. 1 indicate that the pump power is completely absorbed by the gain medium for all thickness values of Sm:YAG modeled. Based on the simulation, the thickness of the Sm:YAG has little impact on the efficiency of absorption of pump light.

Table 1. Absorption of pump light for the gain medium with different thickness values of Sm:YAG

Thickness	Input power(W)	Absorbed power(W)
0.5mm	1	0.9999
0.8mm	1	0.9998
1mm	1	0.9997
1.5mm	1	0.9986

The thickness of the Sm:YAG is set as 1mm by taking the processing technology and the mechanical strength of the engineered gain medium into consideration. A volume detector is placed to evaluate the distributions of the absorbed pump power. The results of the absorbed pump power distributions in central cross-section of the active media Nd:YAG with doping concentrations of 0.1 at.% and 1 at.% are shown in Fig. 2. It is apparent that the Nd:YAG doped with 0.1 at.% outperforms that of 1 at.% in terms of the uniformity of the absorbed power distribution. In addition, the high gain density of the laser medium can be avoided by decreasing the Nd^{3+} ion doping concentration, which effectively suppresses the self-excited oscillation and improves the conversion efficiency [12,13]. Therefore, a Nd:YAG crystal with low doping concentration of 0.1at.% was selected to increase the pump uniformity and the efficiency.

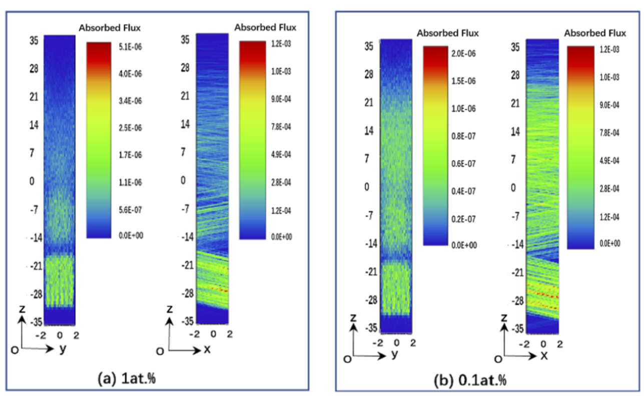

Fig. 2. The pump power distributions in central cross-section of the active media.

The schematic of the Q-switched Nd:YAG laser is presented in Fig. 3. The flat mirror M1 has high-reflection (HR) coating at 1064 nm. The flat mirror M2 was the output coupler and it was specially coated with optimized transmissions of 70% at 1064 nm. The length of the cavity was about 260 mm. The pump sources of two 808 nm diode laser stacks are placed close to the corners, each one consisting of six bars. The beams from the bars are collimated by micro-lens in the fast divergence axis direction. The result is that the divergence is small enough that the pump light will mostly be reflected by the side faces of bonding gain medium, rather than the top and bottom faces, allowing for good pump absorption. The pump beam with size of 10 mm wide by 3.8 mm high is launched. The bars are driven with pulse widths of 230µs at 5 Hz. The stacks provided a maximum pump energy of 369 mJ at 180A. The polarizer was a quartz plate oriented along the Brewster angle. A quarter-wave plate (QWP) was used to realize the polarization status control in the cavity. The Pockels cell electro-optical switch made of KD_*P was driven by electric pulses with a quarter-wave voltage of 3700 V and pulse width of 1 µs, and was synchronized with the LD driver under the control of a four channels digital delay/pulse generator (Stanford Research Systems, DG535). The polarizer, the QWP and the Pockels cell collaboratively achieved pulse-on Q-switching operation in the cavity. In addition, the crystals were wrapped with indium foil and mounted between two metal plates which were maintained at a constant temperature of 25°C by water cooling.

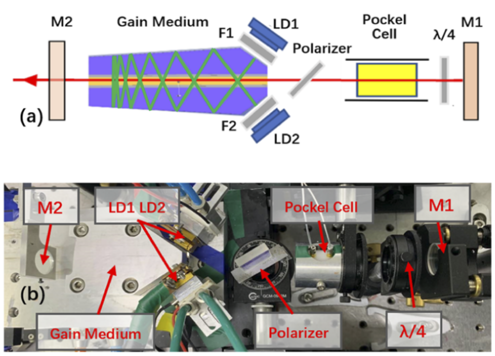

Fig. 3. Experimental setup for EO Q-switched Nd:YAG laser

3. Experimental results

In order to investigate the absorption of pump light, only one stack is mounted and a power meter is placed at the other entrance face to detect the residual pump power. When the stack is operated at 180A, the left pump power is nearly undetectable in the exit face, which indicates that the pump light was almost completely absorbed by the gain medium.

For the purpose of assessing the impact of Sm:YAG crystal on suppressing parasitic oscillation and reducing ASE, the time-resolved fluorescence of gain medium was also measured, and the results were compared with that of the initial stage prototype gain medium, which is roughly the same as the gain medium described in Fig. 1 except that there is no Sm:YAG crystal layer on the upper and lower surfaces. The same pump power of 180A and pump pulse duration of 200 µs were provided to the two different gain mediums. A high speed photodetector and a digital oscilloscope were used to record the time dependence I(t) of the emission from the end of the Nd:YAG at a fixed observation angle. The observed time-resolved fluorescence signals of both gain medium with and without Sm:YAG are shown in Fig. 4.

For the prototype gain medium without Sm:YAG crystal on the upper and lower surfaces, bursts or oscillations appear just 120µs after the start of the pumping. A steeper decay is shown and the decay time is only about 300µs (Fig. 4.(a)). In contrast, for the gain medium with Sm:YAG cladding on the upper and lower surfaces, the intensity of fluorescence increases throughout the pumped time until the end of the 200 µs pump pulse, and the expected exponential energy storage curves were measured. The time of decay is about 600µs, which is much longer than that of the

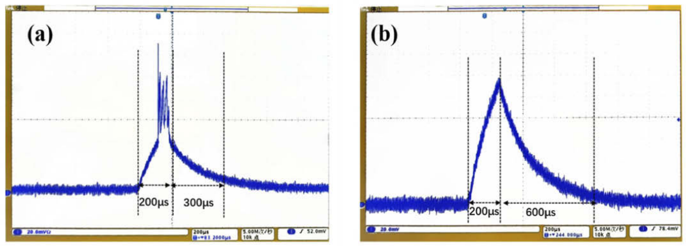

Fig. 4. Comparison of the time-resolved fluorescence measurements of the gain medium without Sm:YAG (a) and with Sm:YAG (b) at the same peak pump power.

prototype gain medium (Fig. 4.(b)). These observed behaviors suggest that parasitic oscillations and ASE in the gain medium with Sm:YAG crystal were suppressed and reduced.

To determine the energy storage capacity of the gain medium with Sm:YAG crystal, we investigated the output pulse energy (at 5Hz repetition rate) in both free-run and Q-switched operation modes. The polarizer, the λ/4 wave plate and the Pockels cell were inserted into the cavity. Under the condition that the Pockels Cell is not driven and the 1/4 wave plate is adjusted, a polarized free-run laser pulse can be produced. The highest pulse energy is 126mJ at 180A with the optimized pump pulse width of 230µs.

As the 1/4 wave plate is adjusted and the Pockels cell is driven by the 1/4 wave voltage, the actively Q-switched output is measured by a laser energy meter. Following the end of the pumping pulse, a quarter-wave electrical voltage is applied on the KD_*P Q-switch crystal so that a linear polarized laser pulse is produced. The maximum pulse energy of 112mJ was obtained in the Q-switch mode at 180A with the pump width of 230µs. It has been found that the output pulse energy of Q-switch mode is higher than that in free-run mode at the beginning. Unfortunately, as the current increases, the growth of the output pulse energy in Q-switch mode slowed and is a little lower than the energy in free-running mode when the pump current is above 150A. The optical-optical (O-O) conversion efficiency begins to drop when the output energy is above104mJ corresponding to a pump current of 170A. However, the highest optical to optical conversion efficiency of 30.5% and the dynamic-to-static ratio (the ratio of output power of Q-switched operation to non-Q-switched operation) of 91.2% were obtained at 170A, which is much higher than the average level [23–25]. To verify the performance of the Q-switch modes at 180A, pump power is provided while the Pockels cell is not driven. No light can be detected and there is no thermally induced depolarization. It appears the 3at.% Sm:YAG layer of 1 mm is too thin to completely absorb the ASE, drastically limiting generated output energy.

In order to further test the effectiveness of Sm:YAG crystal in suppressing parasitic oscillations and reducing ASE, an output pulse energy (at 5 Hz repetition rate) of the prototype gain medium without Sm:YAG crystal on the upper and lower surfaces was also measured in Q-switched operation and the results are also shown in Fig. 5. Above 100A of pump current, the output energy is drastically limited due to parasitic oscillations and ASE caused by the high pump density. The highest pulse energy is only 50mJ at 170A with the same pump pulse width of 230µs, which is less than half the energy of the gain medium with Sm:YAG. These results reconfirm that parasitic oscillations and ASE in the gain medium with Sm:YAG crystal were suppressed and reduced.

The temporal profile of the Q-switched Nd:YAG laser was recorded using a digital oscilloscope with a Si-biased detector (Thorlabs DET025AL/M). Figure 6 shows a typical oscilloscope trace of the expanded shape of a single pulse, with a pulse width of 26 ns (FWHM).

The output beam was focused by a lens with focal length of 150 mm. The $1/e^2$ beam radius was measured with Thorlabs CCD Beam Profiler at several positions when the single pulse energy was 104 mJ. The calculated beam quality factor M^2 is 4.4×4.7(in Fig. 7). No thermally induced

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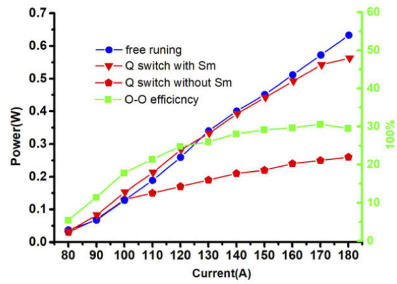

Fig. 5. Laser output vs. current for different running modes and the O-O efficiency

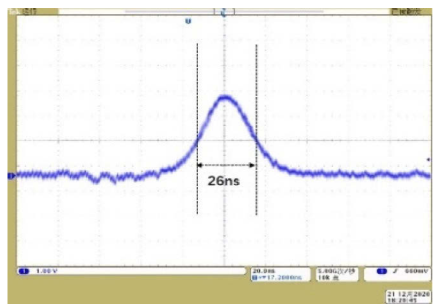

Fig. 6. The temporal pulse shape of actively Q-switched Nd:YAG laser.

depolarization has been proved in the previous part of this paper. To further investigate the reason for the poor beam quality, we increase the pulse repetition rate to 10Hz. The beam quality and the pulse energy have changed very little, which indicating that the influence of thermal lens can be ignored. In our opinion, the poor beam quality is mainly resulted from the large seize of the gain medium which has a square active core with a 4mm×4mm cross-section.

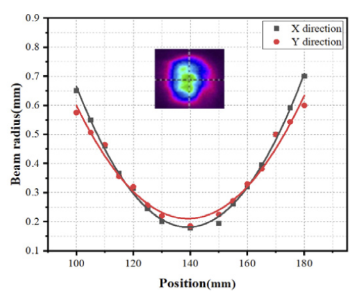

Fig. 7. The output beam quality measurement in a horizontal and vertical direction.

In the future, we plan to fabricate the gain medium with thicker Sm:YAG layers, aiming at improving the conversion efficiency at higher pump energy levels. Moreover, the low absorption coefficient will be compensated by using the 1 at.% Nd:YAG as the operating central wavelength of the pump diode shifted away from 808nm due to the temperature variation [26]. For the beam quality, we are going to improve it by using an unstable resonator with a radially variable-reflectivity output coupler [22].

4. Conclusions

In conclusion, we have designed and built a Q-switched laser that provides high total conversion efficiency. The use of a novel corner-side hybrid pump structure gives high absorption efficiency of pump light. A layer of Sm:YAG is bounded around the active medium Nd:YAG to suppress parasitic oscillation and reduce ASE effectively. The output lasing pulses with the energy of 104mJ (the pulse repetition rate of 5 Hz), the pulse width of 26 ns (FWHM), and M^2=4.4×4.7 was obtained. The optical-to-optical conversion efficiency and the dynamic–static ratio were 30.5% and 91.2%, respectively. To the best of our knowledge, this is the highest efficiency obtained from an actively Q-switched Nd:YAG laser at the hundred milli-joules level. This provides a significant improvement over typical O-O efficiency levels of around 20% achieved without this method. This is the first demonstration of a method that simultaneously improves absorption efficiency and reduces ASE energy losses.

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Disclosures. The authors declare no conflicts of interest.

Data availability. Data underlying the results presented in this paper may be obtained from the authors upon reasonable request.

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