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Compact quasi continuous pumped Nd:YAG Q-switched solid laser

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Abstract: A compact end-pumped Electro-optical Q-switched Nd:YAG laser was designed in this paper. In order to achieve compact construction, laser diode arrays(LDAs) with collimated fast axes were used as pumping source. A spherical lens with a focal length of 40 mm and a cylinder lens with focal length of 25 mm were used as a group for the coupling lens. The LDAs' beam profiles on the incident and exit faces were calculated using Tracepro software. The simulation results indicate that when taking a Φ6 mm×30 mm Nd:YAG with a doping concentration of 1.0at.% as the gain medium, the spots on the incident and exit faces were 5 mm (slow-axis) ×4.5 mm(fast-axis) and 3 mm(slow-axis) ×6 mm(fast-axis), respectively, and the absorption pumping power was about 83%. Dynamic temperature field distributions of Nd:YAG larer in 360 s at 22 ℃ and 60 ℃ were simulated by Ansys software. Output pulsed energy of 30 mJ and 25 mJ were achieved while the repetition frequencies were 30 Hz and 50 Hz, corresponding to a slope efficiency of 11.6% and 14.71%. The pulse durations were 18 ns and 16 ns, respectively. The experimental results show that the designed compact laser in this paper can achieve stable pulse laser output.

Key words: solid laser; Nd:YAG crystal; electro-optic Q-switch; quasi continuous pumped

紧凑型准连续泵浦调 Q Nd:YAG 激光器

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摘要:本文设计了一种紧凑型端面泵浦电光调 Q Nd:YAG 激光器。为实现激光器整体结构紧凑,以快轴准直后的半导体激光器叠阵(Laser Diode Arrays,LDAs)作为泵浦源。使用焦距分别为 40 mm 和 25 mm 的球面镜和柱面镜将泵浦光耦合至 Nd:YAG 晶体内。利用 Tracepro 软件模拟了晶体入射端面和出射端面的光场分布。在采用 Φ6 mm×30 mm、掺杂浓

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度1.0at.%Nd:YAG晶体作为增益介质时,入射与出射泵浦光斑分别为5 mm(慢轴)×4.5 mm(快轴)和3 mm(慢轴)×6 mm(快轴),吸收效率为83%。利用Ansys软件模拟了在22 ℃和60 ℃条件下Nd:YAG激光器壳体在360 s内的温度场动态分布。实验结果表明,本文设计的紧凑型激光器可以实现稳定的脉冲激光输出。在重复频率分别为30 Hz和50 Hz条件下,获得了单脉冲能量为30 mJ和25 mJ的单脉冲输出,对应脉冲宽度分别为18 ns和16 ns,斜效率分别为11.6%和14.71%。实验结果表明,本文设计的紧凑型激光器可以实现稳定的脉冲激光输出。

关 键 词:固体激光器;Nd:YAG晶体;电光调Q;准连续泵浦

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1 Introduction

Pulsed lasers with output wavelength of 1 μm are widely used in the military, scientific research, the civil environment and other fields, with usages such as laser ignition, laser ranging, laser radar detection and laser cutting[1-6]. Electro-optical Q-switches can be used to generate pulsed lasers under high gain conditions and are widely used in solid-state lasers[7-12].

Pumped Nd:YAG crystals mainly achieve laser output in two ways: side pumping[13] and end pumping[14]. The side pumping method is limited by the length of the pump light's absorption path. Compared with end pumping, side pumping has low absorption efficiency, thereby limiting the laser's conversion efficiency. In 2017, Wu Wentao *et al*. at the Harbin Institute of Technology achieved laser output by side-pumping Nd:YAG crystals. When the pump energy was 1.8 J and the pulse width was 2 ms, the output energy was 2 mJ and the repetition frequency was 5 kHz using cavity emptying technology. The light conversion efficiency was 11%[13].

Compared with the side pump structure, the end-pumped laser crystal has the advantages of good pattern matching and high absorption efficiency. In 2012, Chang Lang *et al*. at Beijing University of Technology achieved 22.7 W, 1 064 nm pulsed laser by using end-pumping Nd:YAG crystal fiber-coupled laser diode(LD) as the pump source and electro-optic Q-switched modulation with a pump power of 59.5 W and a repetition rate of 10 kHz. The light conversion efficiency was 38.1%. At a repetition rate of 2 kHz, the maximum pulse energy and the narrowest pulse width were found to be 5.1 mJ and 14.5 ns, respectively[15]. In 2017, Ma Jian *et al*. used a fiber-coupled LDAs end-pumped Nd:YAG crystal and electro-optic Q-switch to obtain a maximum pulse energy of 11 mJ and a repetitive frequency of 100 Hz at a pump energy of 84.3 mJ. The corresponding slope efficiency was 18.6%[16].

Although fiber-coupled LDAs end-pumping can be used to achieve a better beam quality and higher efficiency, it is difficult to achieve miniaturization of the laser structure due to the volume limitations of the pump source. Direct pumping of the gain medium with free space output LD is one of the effective ways to solve this problem. In 2007, the US Army Laboratory Night Vision Laboratory directly pumped Nd:YAG laser crystals with light-guided LDAs and used an electro-optic Q-switch to achieve pulsed laser outputs of 50 mJ and 100 mJ, corresponding to a repetition rate of 20 Hz[17]. In 2018, Peng Chao and others from Beijing University of Technology used a light guide to couple 4 kW multi-wavelength LDAs into an Nd:YAG crystal. A pulse output of 37 – 74 mJ could be obtained in the range of 25 – 55 ℃, corresponding to a repetition frequency of 5 – 20 Hz[18]. It can be seen that large energy output can be obtained by using LDAs end-pumped Nd:YAG, but there are few reports on using Ansys simulations to attain the dynamic temperature field distribution of an Nd:YAG shell.

In this paper, a two-lens coupled pump optical pulse laser is studied. A semiconductor laser output was directly coupled from free space into an Nd:YAG crystal using a ball lens and a cylindrical

lens, and Q-switching was done using a potassium dideuterium phosphate(DKDP) electro-optical crystal. The temperature field distribution of the designed Nd:YAG laser shell was simulated by Ansys software. At ambient temperatures of 22 ℃ and 60 ℃, after 360 s, the maximum temperature of the shell reached 45 ℃ and 75 ℃, respectively, 23 ℃ and 15 ℃ higher than initial ambient temperature, which meets the temperature difference allowed by the TEC′s normal operation. Using the proposed housing, the designed Nd:YAG laser attained a maximum pulse energy of 30 mJ and 25 mJ at a repetition frequency of 30 Hz and 50 Hz, respectively.

2　Experimental Equipment

Fig. 1 is a schematic diagram of the experimental setup of the Nd:YAG laser used in the experiment. The pump source is an 8-Bar LDAs (Focus Light Technologies; FL000581) with a center wavelength of 808 nm and a spectral line width of 3 nm. Fiber rods with diameter of 200 μm were used to compress the angle of divergence in the LDAs′ fast axis direction. The divergence angle was less than 5° after fast axis compression and the Bar strip spacing was 0.73 mm. At a supply current of 200 A, the peak output power was 1 100 W. In order to evenly distribute the pump light in the Nd:YAG crystal, the pump light was coupled into the laser crystal using a spherical mirror with a focal length of $f=40$ mm and a cylindrical mirror with a focal length of $f=25$ mm. The focusing lens was adjacent to the incident end face of the crystal.

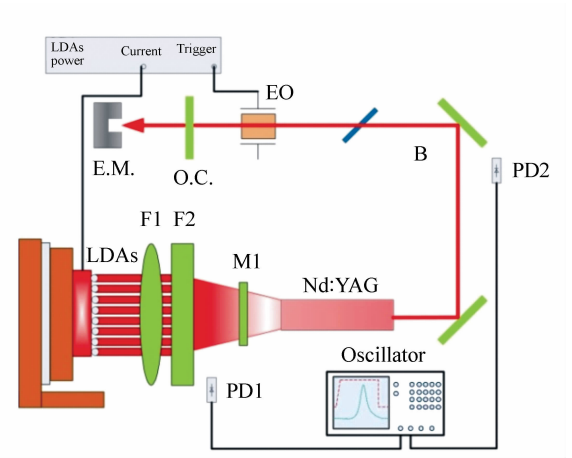
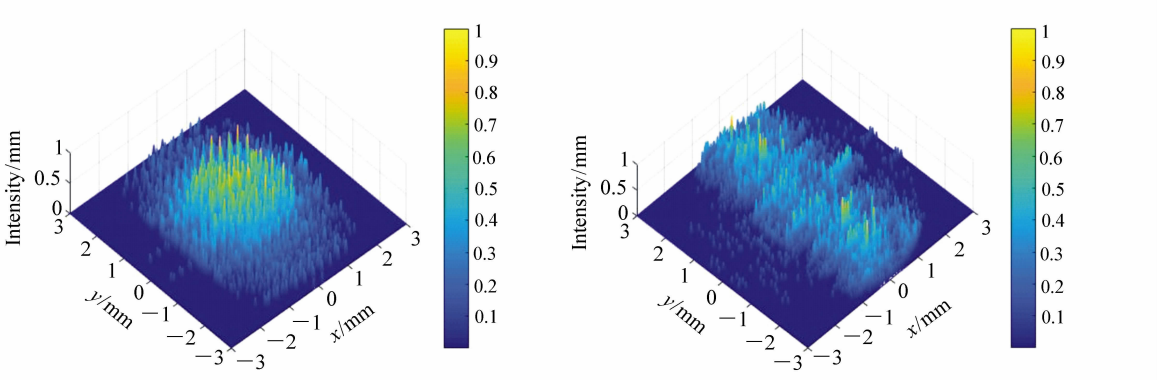


Fig. 1　Schematic of the experimental setup

图 1　实验装置示意图

In order to fully absorb the pump light and to improve the efficiency of the laser, Tracepro software was used to calculate the absorption of different lengths of Nd:YAG crystal. When the crystal length was 30 mm, the absorption efficiency exceeded 83%. Considering the influence of the size of the pump light and the thermal effect of the end face,



(a) Nd:YAG 入射端面
(a) Input end surface of Nd:YAG

(b) Nd:YAG 出射端面
(b) Output end surface of Nd:YAG

Fig. 2　Normalized distribution of the pump source at Nd:YAG end surface

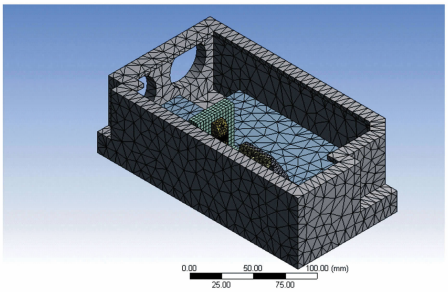
图 2　Nd:YAG 晶体端面泵浦光归一化强度分布

we selected a Nd:YAG crystal with a diameter of 6 mm. Fig. 2(a) and 2(b) show the normalized distribution of the pump light at the input end face and the output end face of the Nd:YAG crystal, respectively.

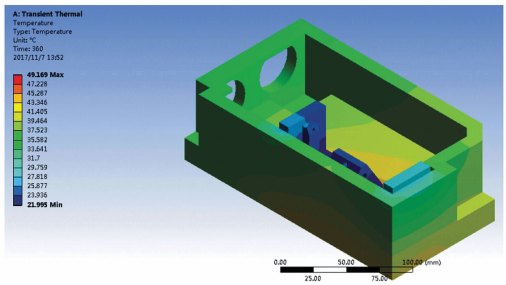
The pump light at the Nd:YAG crystal's input end face has a spot size(FHWM) of 5.0 mm(slow axis) × 4.5 mm(fast axis). Since the optical parameter product of the LDAs' fast axis and slow axis is greatly different, and because of the reflection of the pump light inside the crystal, the spot(FHWM) of the pump light at the output end surface is 3 mm (slow axis) × 6 mm(fast axis) after passing through the Nd:YAG crystal.

The cavity is a flat cavity structure with a length of 325 mm. The input mirror(M1) is coated with an antireflection film in the 808 nm band and a reflective film in the 1 064 nm band. O. C. is an output coupler with transmittances of 60% and 70% at 1 064 nm.

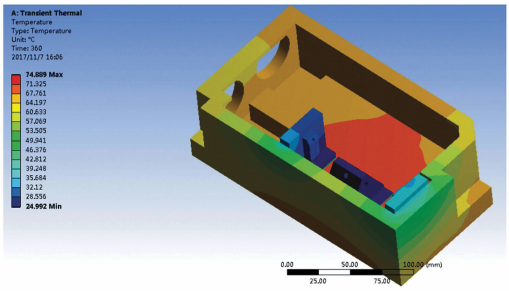
The gain medium is an Nd:YAG crystal with a doping concentration of 1.0at.%. The crystal size is Φ 6 mm × 30 mm and the end faces are plated with antireflection films of 808 nm and 1 064 nm. In order to improve the heat dissipation capabilities of the crystal, the side of the crystal is wrapped with indium foil and fixed by a copper fixture. The temperature of the crystal is controlled to (25 ± 2) ℃ using thermo-electric cooler(TEC). The oscillating light in the cavity is set to a linear polarization state by inserting a film-type polarizing beam splitter thin film polarizer(TFP) into the cavity. A DKDP crystal is used as the electro-optic Q-switch(LeiLingJiGuang; ϕ 8 × 20 mm) and a quartz lens and a Teflon plastic seal are used to prevent deliquescence. The DKDP crystal's end face and sealed quartz lens are coated with 1 064 nm anti-reflection film.



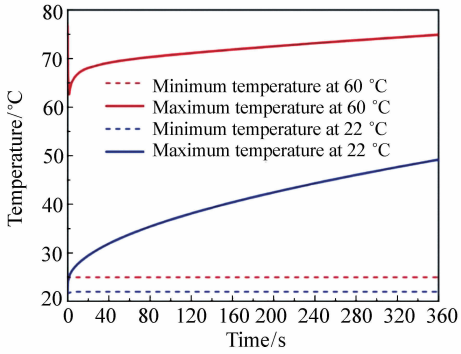
(a) 网格划分结果
(a) Grid division results



(b) 温度场分布(初始温度为 22 ℃)
(b) Temperature distribution (Initial temperature of 22 ℃)



(c) 温度场分布(初始温度为 60 ℃)
(c) Temperature distribution (Initial temperature of 60 ℃)



(d) 时间-温度变化图
(d) Diagram of time-temperature relation

Fig. 3 Dynamic thermal simulation of Nd:YAG shell

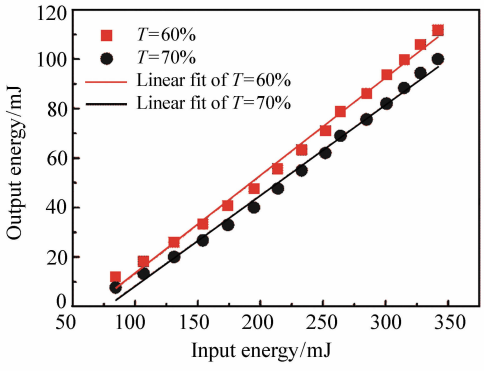
图 3 Nd:YAG 壳体动态热学模拟计算

In order to make the laser compact and portable, and so that it can function normally in high- and low-temperature environments, it is necessary to consider the temperature field distribution of the laser under adiabatic conditions. The heat source of the laser is LDAs and Nd:YAG crystal and the generated heat is mainly transmitted to the laser′s casing. Therefore, the housing of the laser is not only used to affix the components within the laser but also to absorb heat. Based on this, we designed an Nd:YAG laser housing and performed dynamic thermal calculations on it. In order to reduce the complexity of the calculations, the non-heat source parts, such as the lens and the electro-optic Q-switch are ignored. The designed shell module was simulated using Ansys software, and the results are shown in Fig. 3. The housing is made of aluminum alloy material(T4) and has a size of 220 mm(length) ×110 mm(width) ×68 mm(height) and a total weight of 2.2 kg.

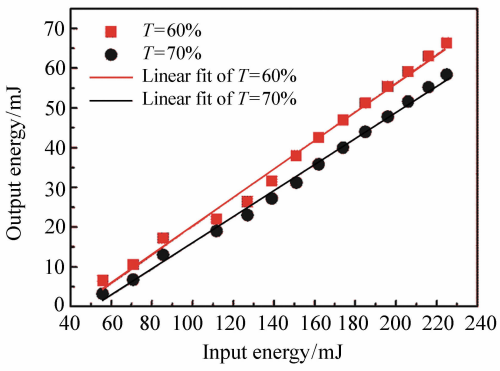
Since the TEC is used to cool the LDAs and the crystal fixture, the thermal load calculation for the housing should consider not only the heat load of the LDAs and the crystal fixture but also the heat generated by the TEC itself. LDAs and laser crystals were separately cooled using TEC(TEC1-06308)(TEC1-12706). During operation, in consideration of the excessive current, the heat is reversely conducted. Therefore, during the cooling process, the current is usually controlled such that it does not exceed 80% of its capacity. When the heat source was applied to the casing, the heat load power of the LDAs portion and the laser crystal portion was set to 30 W and 10 W, respectively. After the frame was analyzed by the Ansys software′s frame-making program, the number of frame nodes was found to be 36 970 and the number of frames was 16 416. The initial temperature was 22 ℃ and 60 ℃ to approximate ambient temperatures, and the shell was insulated. The simulation results are shown in Fig. 3. When the initial temperature was 22 ℃ and 60 ℃ respectively, the maximum temperature after 360 s reached 45 ℃ and 75 ℃, respectively. The temperature difference from the initial temperature was 23 ℃ and 15 ℃, which meets the allowable temperature difference during normal operation of the TEC.

3　Experimental Results and Discussion

The output obtained by the LDAs′ end-pumped Nd:YAG crystal is shown in Fig. 4. The LDAs operate quasi-continuously. At 30 Hz and 50 Hz, the voltage pulse widths are 300 μs and 200 μs, respectively; and the corresponding duty cycles are 0.9%



(a) 重复频率 30 Hz, 泵浦脉宽 300 μs
(a) Repetition frequency of 30 Hz, pulse width of pumping light of 300 μs



(b) 重复频率 50 Hz, 泵浦脉宽 200 μs
(b) Repetition frequency of 50 Hz, pulse width of pumping light of 200 μs

Fig. 4　Output characteristics of directly pumped crystals

图 4　直接泵浦晶体的输出特性

and 1.0%, respectively. It can be seen from Fig. 4 that as the pump energy increases, the output pulse energy increases linearly, and no ground state bleaching or gain saturation occurs. The laser operates stably.

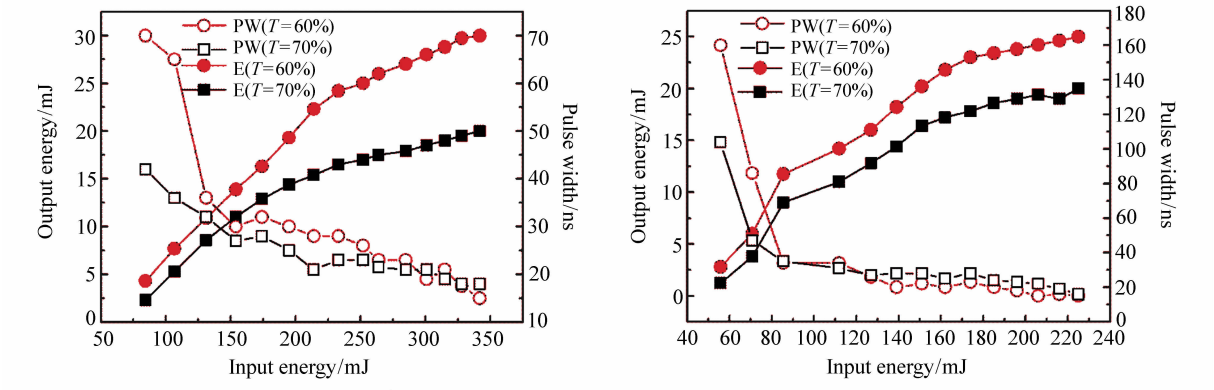
In order to achieve higher laser conversion efficiency, the pump pulse width should be greater than the Nd:YAG upper-level lifetime (about 230 μs). When the LDAs work normally, the duty ratio should satisfy <1.0%. Thus the pulse width should be slightly larger than the pump level lifetime at a duty cycle of less than 1.0%, in order to ensure maximum population inversion. Therefore, when the LDAs are retransmitted at 30 Hz and 50 Hz, the pump pulse widths are set to 300 μs and 200 μs, respectively.

When the LDAs are at a repeated frequency of 30 Hz and the output coupler's transmittances are 60% and 70%, the designed Nd:YAG lasers have corresponding slope efficiencies of 43.29% and 38.76%, respectively; and the output pulse energies are 111.7 mJ and 100 mJ, respectively.

When the LDAs are at a frequency of 50 Hz and the output coupler's transmittances are 60% and 70%, the designed Nd:YAG lasers have slope efficiencies of 29.51% and 25.96%, and the output pulse energy is 66.4 mJ and 58.4 mJ.

Compared with the repetitive frequency of 30 Hz, the slope efficiency of the pump with a repetitive frequency of 50 Hz is slightly reduced, which is mainly due to the increase of the duty ratio corresponding to the operation of the LDAs from 0.9% to 1.0%. At identical pump powers, compared to the continuous pumped Nd:YAG laser, the low-duty cyclical pulse-pumped Nd:YAG pump power is more efficient, and the crystal is subjected to lower average pump power, resulting in a relative higher density of ground state particles. So the quasi-continuous pumped laser has a large gain. It is difficult to insert the acousto-optic Q-switch into the cavity to make the loss exceed the gain and achieve high-efficiency Q-switching. Therefore, a DKDP with an extinction ratio of 500:1 is used. The electro-optical Q-switch is used to achieve the Q-switching of the laser and create pulsed output.

Due to the electro-optic Q-switch, the oscillation light in the resonant cavity needed to be linearly polarized. Therefore, a TFP is inserted into the experimental cavity where the insertion loss is less than 5%. The triggering signal provided by the power supply is used to control the opening time of the electro-optic Q-switch, thereby attaining the Q-switching operation. The corresponding output results are shown in Fig. 5.



(a) 重复频率 30 Hz, 泵浦脉宽 300 μs
(a) Repetition frequency of 30 Hz, pulse width of pumping light of 300 μs

(b) 重复频率 50 Hz, 泵浦脉宽 200 μs
(b) Repetition frequency of 50 Hz, pulse width of pumping light of 200 μs

Fig. 5 Output results of Nd:YAG laser with an electro Q-switch

图 5 Nd:YAG 激光器调 Q 时输出结果

When the repetition frequency of the pump source is 30 Hz, the pulse width is 300 μs, the maximum input energy of the pump light is 342 mJ, and the output coupler's transmittance is 60%, the maximum single pulse energy of the Nd:YAG laser is 30 mJ, the pulse width is 18 ns, the efficiency is 11.63% and the light-to-light conversion efficiency is 8.77%. When the output coupler's transmittance is increased to 70%, the maximum single pulse energy output of the Nd:YAG laser is 20 mJ, the corresponding pulse width is 15 ns, the slope efficiency is 7.75%, and the light-to-light conversion efficiency is 5.85%, as shown in Fig. 5(a). The laser spot output by Nd:YAG is 4.2 mm(fast axis) × 1.7 mm (slow axis), and the divergence angle is 1.8 mrad. When the pump energy is less than 200 mJ, the pulse energy output during Q-switching increases linearly with the pump energy. As the pump energy continues to increase, the laser's slope efficiency decreases.

When the output coupler's transmittance is increased to 70%, the slope efficiency is further lowered. This is due to the decrease in gain due to the insufficient number of ground state particles in the laser crystal, which causes the slope efficiency of the laser to decrease. The slope efficiency can be increased by reducing the output mirror transmittance but this also increases the optical power density in the cavity, which may damage the optical film inside.

In Fig. 5(b), when the pump pulse width is reduced to 200 μs, the maximum input energy of the pump light is 225 mJ, the output coupler's transmittance is 60%, the maximum single pulse energy of the Nd:YAG laser is 25 mJ, the pulse width was 16 ns, the slope efficiency is 14.71%, and the light-to-light conversion efficiency is 11.11%. When the output coupler's transmittance is increased to 70%, the maximum single pulse energy of the Nd:YAG laser is 20 mJ, the pulse width is 15 ns, the slope efficiency is 11.76% and the light-to-light conversion efficiency is 8.89%. The Nd:YAG output laser spot size is 4.8 mm(fast axis) × 2.8 mm (slow axis) and the divergence angle is 1.1 mrad. Compared with the 30 Hz repetition frequency, the divergence angle is lower, mainly because the thermal lens effect is weakened due to the decrease in pump energy, thus reducing the divergence angle. For output transmittances of 60% and 70%, the slope efficiency is still lower when the pump energy is higher than 170 mJ, which is for a similar reason to that of Fig. 5(a). The damage threshold of the cavity optical film is the main reason for the energy limitation of the Q-switched pulse output of the laser.

At equal output coupler's transmittances, the output energy at the repetition frequency of 30 Hz is higher than that of 50 Hz. The pump pulse width used at 30 Hz is 300 μs, which is slightly higher than the upper-level life time of Nd:YAG crystal. At 50 Hz, the pump pulse width is 200 μs. The pump pulse width is smaller than the lifetime of the crystal. So the inverted population does not reach the maximum limit of the crystal; while the the inverted population reaches the limit at the pulse width of 300 μs at 30 Hz, more than that of 50 Hz, so the single pulse output energy is larger.

4　Conclusion

In this paper, Tracepro software is used to simulate the normalized pumped light of a Nd:YAG crystal's input end face and output end surface. Nd:YAG laser housing is designed and the temperature distributions of the initial temperature for 360 s continuous operation at 22 ℃ and 60 ℃ are simulated using Ansys software. The temperature rise is 23 ℃ and 15 ℃, respectively, which satisfies the temperature difference allowed by the TEC during normal operation. Simulation results show that the

laser structure using the housing can achieve stable and efficient pulsed laser output. A pulsed laser output with a maximum energy of 25 mJ is obtained at a repetition frequency of 50 Hz by delaying the trigger signal loaded into the electro-optic Q-switch. The corresponding pulse width is 16 ns and the corresponding slope efficiency and light-to-light conversion efficiency are 14.71% and 11.11%, respectively. At a repetition frequency of 30 Hz, a pulsed output with a maximum energy of 30 mJ is obtained. The corresponding pulse width is 18 ns, and the corresponding sope efficiency and light-to-light conversion efficiency are 11.63% and 8.77%, respectively.

——中文对照版——

1 引 言

1 μm 脉冲激光器在军事、科研、民用等领域应用广泛,如激光点火、激光测距、激光雷达、激光切割[1-6]。电光 Q 开关在高增益条件下可以用于产生脉冲激光,被广泛用于固体激光器中[7-12]。

泵浦 Nd:YAG 晶体实现激光输出主要有侧面泵浦[13]和端面泵浦[14]两种方式。侧面泵浦方式受泵浦光吸收路径长度的限制,较端面泵浦方式吸收效率低,故其激光转换效率受限。2017 年,哈尔滨工业大学武文涛等人采用侧面泵浦方式泵浦的Nd:YAG晶体,在泵浦能量为 1.8 J,脉宽为 2 ms 时,通过腔倒空技术实现输出能量达 2 mJ,重复频率为5 kHz;光光转换效率为 11% 的激光输出[13]。

相对于侧面泵浦结构,端面泵浦激光晶体具有模式匹配好,吸收效率高等优点。2012 年,北京工业大学常亮等人采用光纤耦合半导体激光器(Laser diode, LD)作为泵浦源,端面泵浦键合 Nd:YAG晶体,利用电光 Q 开关调制,在泵浦功率为 59.5 W,重复频率为 10 kHz 的条件下,输出 22.7 W的 1 064 nm 的脉冲激光,光光效率为 38.1%。在 2 kHz 的重复频率时,获得最大的脉冲能量和最窄脉冲宽度分别为 5.1 mJ 和 14.5 ns[15]。2017 年,上海光学精密机械研究所马剑等人采用光纤耦合激光器叠降(LDAs)端面泵浦 Nd:YAG 晶体,并采用电光调 Q 技术,在泵浦能量为 84.3 mJ 时获得了最大脉冲能量为 11 mJ,重复频率为 100 Hz,对应的斜效率为 18.6% 的激光输出[16]。

虽然使用光纤耦合 LDAs 端面泵浦方式可以获得更好的光束质量和更高的效率,但是由于受到泵浦源体积限制,难以实现激光器结构小型化,而采用自由空间输出的 LD 直接泵浦增益介质可有效解决该问题。2007 年,美国陆军实验室夜视实验室利用光导管耦合 LDAs 直接泵浦 Nd:YAG 激光晶体,并采用电光调 Q 技术,先后获得了 50 mJ和 100 mJ 的脉冲激光输出,对应重复频率为 20 Hz[17]。2018 年,北京工业大学的彭超等人采用光导管将 4 kW 多波长 LDAs 耦合至Nd:YAG 晶体内,在 25 ~ 55 ℃内可获得 37 ~ 74 mJ 的脉冲输出,对应重复频率为 5 ~ 20 Hz[18]。由此可以看出,采用 LDAs 端面泵浦Nd:YAG可获得大能量输出。

通过调研发现,有关利用 Ansys 模拟计算 Nd:YAG壳体动态温度场分布报道较少。本文研究了一种双透镜耦合泵浦光脉冲激光器。由球透镜和柱透镜将自由空间输出的半导体激光直接耦合至 Nd:YAG 晶体内,利用磷酸二氘钾(Potassium dideuterium phosphate, DKDP)电光晶体调 Q。利用 Ansys 软件模拟计算了设计的 Nd:YAG 激光器壳体温度场分布。在环境温度为22 ℃和 60 ℃条件下,360 s 后激光器壳体最高点温度分别达到 45 ℃和 75 ℃,与初始环境温差分别为 23 ℃和 15 ℃,满足半导体制冷器(Thermo Electric Cooler, TEC)正常工作时所允许温差。利用该壳体,设计的 Nd:YAG 激光器在重复频率分别为 30 Hz 和 50 Hz 条件下,得到了最大脉冲能量分别为 30 mJ和 25 mJ 的激光输出。

2　实验装置

图 1 为实验所用 Nd:YAG 激光器的实验装置示意图。泵浦源为由 8 个 Bar 条构成的 LDAs(炬光科技,;FL000581),中心波长为 808 nm,谱线宽度为 3 nm。采用直径为 200 μm 的光纤棒在 LDAs 快轴方向压缩发散角,快轴压缩后发散角小于 5°,Bar 条间距为 0.73 mm。在供电电流为 200 A时,峰值输出功率为 1 100 W。为使泵浦光在 Nd:YAG 晶体内均匀分布,采用焦距为 f = 40 mm的球面镜和焦距为 f = 25 mm 的柱面镜将泵浦光耦合至激光晶体内,聚焦透镜紧邻晶体入射端面。

为充分吸收泵浦光,提高激光器的效率,利用 Tracepro 软件计算 Nd:YAG 晶体不同长度的吸收情况。结果显示:当晶体长度为 30 mm 时吸收效率超过 83%;同时考虑到泵浦光的尺寸与端面热效应的影响,选择直径为 6 mm 的 Nd:YAG 晶体。图 2(a)和 2(b)分别为 Nd:YAG 晶体入射端面和出射端面的泵浦光归一化后的分布。

泵浦光在 Nd:YAG 晶体入射端面的光斑尺寸为 5.0 mm(慢轴) × 4.5 mm(快轴),由于 LDAs 快轴与慢轴方向的光参数积相差较大,以及泵浦光在晶体内的反射作用,经过Nd:YAG晶体后,泵浦光在晶体出射端面光斑尺寸为 3 mm(慢轴) × 6 mm(快轴)。

谐振腔采用平平腔结构,腔长为 325 mm。输入镜(M1)镀有 808 nm 波段的增透膜以及 1 064 nm波段的反射膜。O. C. 为输出镜,在 1 064 nm波段透过率为 60% 和 70%。

增益介质是掺杂浓度为 1.0at.% 的 Nd:YAG 晶体,晶体尺寸为 Φ 6 mm × 30 mm,端面镀有 808 nm与 1 064 nm 波段的增透膜。为提高晶体的散热能力,晶体侧面使用铟箔包裹并由铜夹具固定,用 TEC 将晶体温度控制在(25 ± 2) ℃内。通过在腔内插入薄膜型偏振分光片(TFP),使谐振腔内的振荡光处于线偏振态。采用 DKDP 晶体作为电光 Q 开关(雷凌激光;ϕ8 × 20 mm),并采用石英镜片及特氟龙塑料密封以防止潮解,DKDP 晶体端面和密封的石英镜片均镀有 1 064 nm 波段增透膜。

为了使激光器小型便携,且在高低温环境下均能够正常工作,需要考虑激光器在绝热条件下的温度场分布。激光器的热源有 LDAs 以及 Nd:YAG晶体,产生的热主要传导到激光器壳体上。因此,激光器的壳体不仅用于固定激光器内部元件,同时需要吸收激光器内热量。据此,设计了 Nd:YAG 激光器壳体,并对其进行动态热学计算。为降低有限元计算的复杂程度,忽略透镜及电光 Q 开关等无热源部分。利用 Ansys 软件对设计的壳体模块进行模拟,结果如图 3 所示。壳体采用铝合金材料(T4),尺寸为 220 mm(长) × 110 mm(宽) ×68 mm(高),总重量为 2.2 kg。

由于采用 TEC 对 LDAs 及晶体夹具进行制冷,所以壳体热负载计算时不仅要考虑 LDAs 和晶体夹具的热负载,还要考虑 TEC 本身所产生的热。采用 TEC(TEC1-06308)(TEC1-12706)分别对 LDAs 和激光晶体进行致冷。在实际使用过程中,考虑到电流过大会使热量反向传导,因此,在实际致冷过程中,电流通常控制在不超过满负载的 80%。在对壳体加载热源时,LDAs 部分与激光晶体部分的热负载功率分别设为 30 W 和 10 W。采用 Ansys 软件自带网格划分程序对壳体进行网格划分后,网格节点数为36 970个,网格数为 16 416 个。采用初始温度分别为 22 ℃和60 ℃来近似环境温度,壳体与外界绝热,模拟结果如图 3所示。由图 3 可见,初始温度分别为 22 ℃和 60 ℃时,360 s 后壳体最高点温度分别达到 45 ℃和 75 ℃,与初始温度温差为 23 ℃和 15 ℃,满足 TEC 正常工作时所允许温差。

3　实验结果与讨论

LDAs 端面泵浦 Nd:YAG 晶体获得的输出结果如图 4 所示。LDAs 采用准连续工作方式,在 30 Hz 和 50 Hz 时,电压脉冲宽度分别为 300 μs 和 200 μs,对应的占空比分别为 0.9% 和 1.0%。从图 4 中可以看出,随着泵浦能量的增加,输出脉冲能量线性增加,未出现基态漂白或增益饱和现象。激光器处于稳定工作状态。

为获得较高的激光转换效率,泵浦光脉宽应

大于 Nd:YAG 上能级寿命(约 230 μs)。由于本实验所用 LDAs 正常工作时,占空比应小于 1.0%,因此泵浦脉宽应该在占空比小于 1.0% 的条件下略大于上能级寿命,以保证获得最大的反转粒子数。本文中,LDAs 在重复频率分别为 30 Hz和 50 Hz 时,泵浦脉冲宽度分别设置为 300 μs和 200 μs。

LDAs 在重复频率为 30 Hz,输出镜透过率为 60% 和 70% 时,设计的 Nd:YAG 激光对应的斜效率分别为 43.29% 和 38.76%,输出脉冲能量分别为 111.7 mJ 和 100 mJ。

LDAs 在重复频率为 50 Hz,输出镜透过率分别为 60% 和 70% 时,设计的 Nd:YAG 激光对应的斜效率分别为 29.51% 和 25.96%,输出脉冲能量分别为66.4 mJ和 58.4 mJ。

相对于重复频率 30 Hz 的情况,重复频率为 50 Hz 的泵浦光泵浦时斜效率略有降低,这主要是由于 LDAs 工作对应的占空比由 0.9% 提高至 1.0%。在同等泵浦功率下,与连续泵浦的 Nd:YAG 激光器相比,低占空比脉冲泵浦的 Nd:YAG 泵浦功率高,并且晶体受到的平均泵浦功率较低,基态粒子数密度相对连续泵浦时高,因此准连续泵浦工作的固体激光器增益较大,很难通过腔内插入声光 Q 开关使损耗超过增益,实现高效调 Q,因此采用消光比为 500:1 的 DKDP 电光 Q 开关来实现激光器的调 Q,从而实现脉冲输出。

由于电光 Q 开关工作时,需要使谐振腔内的振荡光呈线性偏振,因此,本实验腔内插入一 TFP,插入损耗小于 5%。通过电源提供的触发信号来控制电光 Q 开关打开时间,从而实现调 Q 工作,对应的输出结果如图 5 所示。

当泵浦源重复频率为 30 Hz,脉冲宽度为 300 μs,泵浦光最大输入能量为 342 mJ,输出镜透过率为 60% 时,Nd:YAG 激光器输出最大单脉冲能量为 30 mJ,脉冲宽度为 18 ns,斜效率为 11.63%,光光转换效率为 8.77%。当其余条件不变,输出镜透过率增加至 70% 时,Nd:YAG 激光器输出的最大单脉冲能量为20 mJ,对应的脉冲宽度为 15 ns,斜效率为 7.75%,光光转换效率为 5.85%,如图 5(a)所示。Nd:YAG 输出的激光光斑为 4.2 mm(快轴)×1.7 mm(慢轴),发散角为 1.8 mrad。当泵浦能量小于 200 mJ 时,调 Q 时输出的脉冲能量随泵浦能量线性增加,随着泵浦能量增大,激光器的斜效率降低。

当将输出镜透过率增加至 70% 时,斜效率进一步降低。这是由于激光晶体基态粒子数不足导致增益下降,从而使激光器的斜效率下降。可以通过降低输出镜透过率来提高斜效率,但会增加腔内光功率密度,从而可能对谐振腔内的光学薄膜造成损伤。

在图 5(b)中,泵浦脉冲宽度降低至 200 μs 时,泵浦光最大输入能量为 225 mJ,输出镜透过率为 60% 时,Nd:YAG 激光器输出最大单脉冲能量为 25 mJ,脉冲宽度为 16 ns,斜效率为 14.71%,光光转换效率为 11.11%。当输出镜透过率提高至 70% 时,Nd:YAG 激光器输出最大单脉冲能量为 20 mJ,脉冲宽度为 15 ns,斜效率为 11.76%,光光转换效率为 8.89%。Nd:YAG 输出激光光斑尺寸为 4.8 mm(快轴)×2.8 mm(慢轴),发散角为 1.1 mrad。与 30 Hz 重复频率相比,发散角有所减小,主要是由于泵浦能量降低使得热透镜效应减弱导致的。对于 60% 和 70% 的输出透过率,泵浦能量高于 170 mJ 时斜效率仍降低,这与图 5(a)原因类似。谐振腔光学薄膜损伤阈值是激光器调 Q 脉冲输出能量受限的主要原因。

在相同输出镜透过率时,30 Hz 重复频率的输出能量高于 50 Hz 重复频率。30 Hz 时使用的泵浦脉宽为 300 μs,略高于 Nd:YAG 晶体的上能级寿命,而在 50 Hz 时泵浦脉宽为 200 μs,泵浦脉宽小于晶体上能级寿命,因此反转粒子数没有达到晶体最大极限;而在 30 Hz 的 300 μs 脉冲宽度时反转粒子数达到极限,比 50 Hz 时多,所以单脉冲输出能量更大。

4 结 论

本文利用 Tracepro 软件模拟了自由空间泵浦 Nd:YAG 晶体入射端面及出射端面泵浦光归一化后的光场分布。设计了 Nd:YAG 激光器壳体并利用 Ansys 软件模拟了初始温度分别在 22 ℃ 和 60 ℃ 条件下连续工作 360 s 内的温度场分布,壳

体最高点温升分别为 23 ℃和 15 ℃,满足 TEC 正常工作时所允许温差。模拟结果表明,使用该壳体负载的激光器结构可以实现稳定、高效的脉冲激光输出。为获得大能量脉冲激光输出,通过对加载到电光 Q 开关中的触发信号延迟,在 50 Hz 重复频率时获得最大能量 25 mJ 的脉冲输出,对应的脉冲宽度为16 ns,对应的斜效率与光光转换效率分别为 14.71% 和 11.11%。在重复频率为 30 Hz 时获得了最大能量 30 mJ 的脉冲输出,对应的脉冲宽度为18 ns,对应的斜效率与光光转换效率分别为 11.63% 和 8.77%。

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