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亚纳秒 Zig-Zag 板条激光器实现 500 Hz 焦耳量级输出

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摘　要：亚纳秒激光因其对光电器件的损伤优于纳秒激光和飞秒激光，而被广泛应用于光电对抗领域。然而，在常规水冷条件下实现输出数百赫兹焦耳级亚纳秒激光还面临较大的挑战。笔者课题组面向国防重大需求，结合端面泵浦微片晶体百皮秒激光产生技术和多程多级板条激光放大技术，对板条激光器的放大性能进行大量的实验研究，并提出了温控双端泵浦技术，弥补双端泵浦结构的缺陷。实现板条激光器单脉冲能量 952 mJ，重复频率 500 Hz 的激光输出，这将为光电对抗系统所需的高重频大能量激光提供优质光源。

关键词：板条激光；　双端泵浦；　高重频；　亚纳秒

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高能高重频亚纳秒激光凭借其优于纳秒激光的高功率以及优于飞秒激光的高稳定性已广泛应用于工业[1−2]、医疗、军事[3] 和科研领域。研究发现亚秒激光对光电器件的完全损伤阈值均低于纳秒激光和飞秒激光[4]，因此高重频大能量亚纳秒固体激光在光电对抗领域具有突出优势。目前常规水冷条件下，高重频激光器单脉冲能量已突破百毫焦级[5−6]。为进一步提升百皮秒固体激光器的单脉冲能量获得更高亮度激光稳定输出，克服因高重频热累积引起的热效应导致常规水冷条件下难以实现高重频 (≥500 Hz) 焦耳级亚纳秒脉冲放大输出的难题。笔者课题组结合端面泵浦微片晶体百皮秒激光产生技术和多程多级板条激光放大技术，采用 Zig-Zag 板条激光放大器将二维热效应简化为一维热效应，使热效应得到了极大程度抑制。

2022 年初，笔者课题组设计了一种百赫兹大能量板条固体激光四程放大器。放大器采用低掺杂 Nd:YAG 作为增益介质，利用板条端面泵浦结构，基于单脉冲能量为 1.1 mJ，脉冲宽度为 491 ps 的信号光和 907 mJ 的 808 nm 二极管泵浦条件下，输出单脉冲能量为 100 mJ，重复频率为 200 Hz 的亚纳秒脉冲激光[7]。2022 年 6 月，通过增加两级双端泵浦板条放大器，在泵浦总能量为 10.87 J (一级 870 mJ，二级 5.26 J，三级 4.74 J) 时输出 1.07 J@200 Hz 的亚纳秒激光输出。

近期，笔者课题组通过优化光路及设计双端泵浦结构，并提出温控双端泵浦技术，如图 1 所示。这种结构省略泵浦光隔离，缩小双端泵浦模块的体积，但也存在逃逸泵浦光 (未被增益介质吸收从板条另一端逃逸的泵浦光) 损坏另一端泵浦模块的风险。因此笔者课题组研究了端面泵浦结构中逃逸泵浦光能量随半导体激光阵列 (LDA) 泵浦电流的变化过程如图 2(a) 所示。逃逸泵浦光能量随泵浦电流的变化有较大的变化。这是由于泵浦光的峰值波长会随泵浦电流的增加而出现红移 (向长波长方向移动)，泵浦电流从

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0~350 A 逐渐增加时，泵浦光峰值波长从 802 nm 增加到 809 nm，而 Nd:YAG 的较强吸收峰在 808.6 nm 附近，超过 808.6 nm 时吸收急剧下降，导致泵浦光未被完全吸收，从另一端面逃逸。高泵浦电流下峰值波长超过 808.6 nm，逃逸泵浦光就会剧增，这种条件下极易损伤泵浦模块。研究发现 LDA 制冷温度也可调节泵浦光的峰值波长。笔者通过控制 LDA 制冷温度实现了对逃逸泵浦光的能量控制，有效避免泵浦模块的损伤。笔者课题组利用温控双端泵浦技术，通过一级板条单端泵浦 (制冷温度 25 ℃)、二级板条双端泵浦 (制冷温度 23 ℃) 和三级板条双端泵浦 (制冷温度 25 ℃)，将种子光从 3.12 mJ 放大至 952 mJ，如图 2(b) 所示 (一级板条和二级板条以及三级板条的放大能量测试位置均位于三级板条之后 1.5 m 处)，重复频率为 500 Hz，脉冲宽度为 680 ps。该系统输出的数百赫兹焦耳级亚纳秒激光是目前板条激光器领域输出的最高参数。这项工作将为高能短脉冲激光器提供有效的泵浦冷却方案，确保其稳定运行，进而为高重频大能量亚纳秒板条激光器应用于光电对抗领域铺平道路。

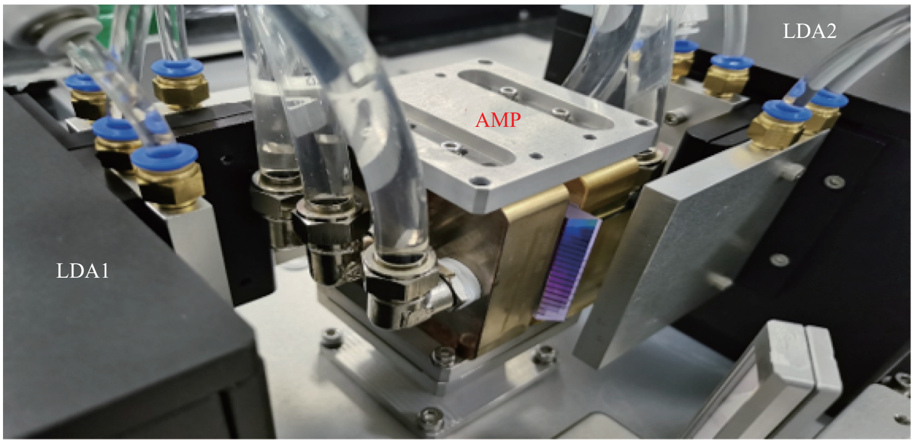

图 1 双端泵浦结构

Fig.1 Double ended pump structure

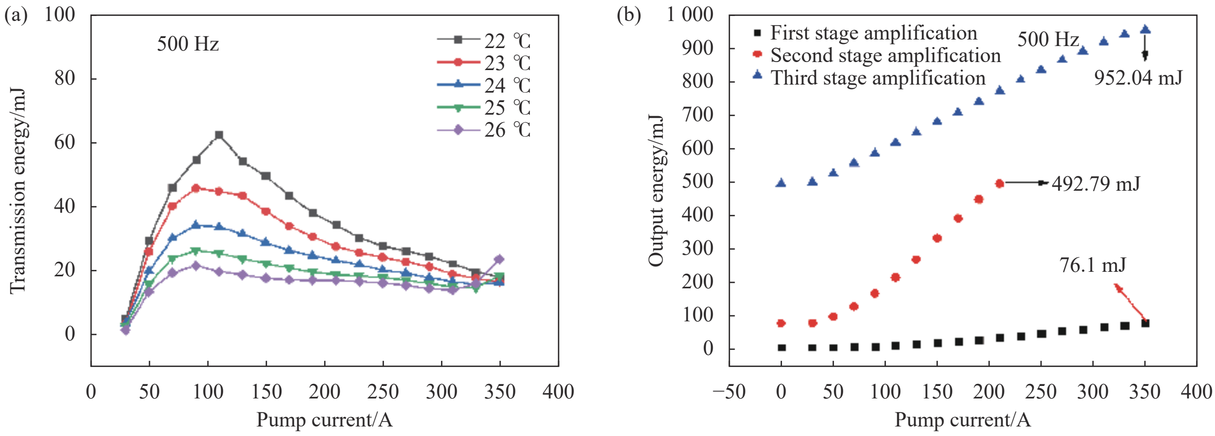

图 2 板条放大结果 (a) 逃逸泵浦光能量随泵浦电流和 LDA 制冷温度的变化图; (b) 不同泵浦电流下的放大结果

Fig.2 Slab amplification result (a) variation of escape pump light energy with pump current and LDA refrigeration temperature; (b) Amplification results at different pump currents

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500 Hz Joule-level output by sub-nanosecond Zig-Zag slab laser

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Abstract:

Objective The high-energy, high-repetition-rate sub-nanosecond lasers have been widely applied in various fields such as industry, military, and scientific research due to their superior peak power compared to nanosecond lasers and enhanced stability compared to femtosecond lasers. Researchers have discovered that sub-nanosecond lasers have a lower threshold for causing complete damage to optoelectronic devices compared to nanosecond and femtosecond lasers. Therefore, high-repetition-rate, high-energy sub-nanosecond solid-state lasers offer significant advantages in the field of optoelectronic countermeasures. Currently, under conventional water cooling conditions, the single-pulse energy of high-repetition-rate lasers has surpassed the hundred-millijoule level. However, for optoelectronic countermeasure applications, higher repetition rates and higher single-pulse energies are required to improve the hit rate on rapidly moving targets. Thus, the breakthrough of higher repetition rates and high-energy sub-nanosecond lasers is urgently needed.

Methods This paper presents the realization of Joule-level sub-nanosecond laser output by combining end-pumped microchip crystal picosecond laser generation technology and multi-pass multi-stage slab laser amplification techniques. Initially, the microchip laser is pre-amplified through a three-stage end-pumping process, scaling the microjoule-level energy to millijoule-level. Subsequently, the shaped laser beam with a size of 2×18 mm^2 is injected into a first-stage single-end-pumped slab amplifier system. The amplified laser is then transmitted through a first-stage imaging and beam expanding system before being injected into a second-stage dual-end-pumped double-pass amplifier system. Finally, the laser is further amplified through a third-stage single-pass booster amplifier in the slab configuration. This study presents the design of a dual-end pumping structure (Fig.1), with the omission of the isolation system.

Results and Discussions In the dual-end-pumping structure, the energy of the leaked pump light can directly cause damage to the pumping module. In this study, experimental results revealed significant fluctuations in the energy of the leaked pump light with variations in the pump current and pump module cooling temperature

(Fig.2(a)). Therefore, by controlling the cooling temperature of the pumping module, it is possible to regulate the energy of the leaked pump light at different pump currents, thereby avoiding damage to the pumping module and eliminating the need for complex isolation devices. Using the temperature-controlled dual-end pumping technique, the research team amplified the seed light from 3.12 mJ at 500 Hz to 952 mJ (Fig.2(b)) with pulse width of 680 ps, under the conditions of a first-stage and second-stage pump cooling temperature of 25 ℃, and a second-stage pump cooling temperature of 23 ℃. The amplification energy levels in Fig.2(b) were measured after the output of the third-stage slab amplifier. The sub-nanosecond laser output with Joule-level energy and a repetition rate in the hundreds of hertz achieved by this system represents the highest parameters currently achieved in the field of slab lasers.

Conclusions This paper reports a high-repetition-rate, high-energy Nd:YAG low-doped slab laser. The laser utilizes a high-power master oscillator power amplifier (MOPA) structure, with a single longitudinal mode microchip laser as the seed source, and achieves amplification through a three-stage slab system with beam shaping. The study demonstrates that the leaked pump light in the dual-end-pumped slab amplifier can damage the pumping module. However, precise control over the energy of the leaked pump light can be achieved by controlling the cooling temperature of the pumping module, effectively avoiding damage to the pumping module. In this work, using temperature-controlled dual-end pumping technique, we amplify the seed light from 3.12 mJ at 500 Hz to 952 mJ with a pulse width of 680 ps. This work provides an effective pump cooling solution for high-energy, short-pulse lasers, ensuring their stable operation, thereby paving the way for the application of high-repetition-rate, high-energy sub-nanosecond slab lasers in the field of optoelectronic countermeasures.

Key words: slab laser; dual-end pumping; high-repetition rate; sub-nanosecond

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