中国激光

33.8 W 高效率中红外 2.8 μm 光纤激光器

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摘要 为了提升中红外光纤激光器的功率和效率，基于掺铒氟化物光纤的高效热管理技术、高性能中红外光纤端帽制备技术和高功率泵浦激光的高效耦合技术，利用高功率 976 nm 半导体激光器，单端泵浦 8 m 长、掺杂铒离子的摩尔分数为 7% 的氟化物增益光纤，实现了 33.8 W 的中红外 2.8 μm 激光输出，据我们所知，这是单端泵浦中红外光纤激光器的最高功率水平，此时激光器的光光转换效率达 26.4%。

关键词 激光器；中红外光纤激光器；单端泵浦；高功率激光；掺铒氟化物光纤

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中红外 2.8 μm 波段掺铒氟化物光纤激光器作为光谱分析、生物医疗以及红外对抗等应用领域的高功率、高亮度激光光源，近年来得到了广泛关注，激光性能得到快速发展[1-4]。表 1 总结了基于高掺铒氟化物光纤的高功率 2.8 μm 波段激光器近年来的重要研究进展[5-11]。目前，高功率中红外光纤激光器的研究报道多数来自加拿大和日本的研究团队，单端泵浦结构的全光纤化激光器的最大输出功率为 30.5 W[8]，双端泵浦结构激光器的最大输出功率为 41.6 W[9]；国内西北核技术研究所（NINT）于 2015 年实现了 10 W 级 2.8 μm 波段光纤激光器[7]，深圳大学于 2021 年基于全光纤结构将 2.8 μm 激光的输出功率提升到 20.3 W[11]。在激光效率方面，由于氟化物光纤的软化温度低、热膨胀系数大，且铒离子对 0.98 μm 波段泵浦光存在激发态吸收（${}^4I_{11/2}\rightarrow{}^4F_{7/2}$）[12]，已报道的中红外 2.8 μm 掺铒光纤激光器在高功率运转下的光光效率通常低于 25%。在谐振腔结构方面，基于光纤布拉格光栅的全光纤化激光器具有更紧凑的系统结构，但中红外光纤光栅的热退化、波长漂移、熔接损耗等问题[8-9]也为实现高功率激光器增加了新的技术难题；相比之下，利用镀膜反射镜作为激光器腔镜同样可实现高功率激光输出，目前的最高功率为日本京都大学通过双端泵浦结构实现的 24 W 输出，光光转换效率为 14.5%[5]。为了实现高功率、高效率的 2.8 μm 波段光纤激光器，除了需要加强

表 1 高功率 2.8 μm 波段掺铒氟化物光纤激光器的研究现状

Table 1 Research status of high-power erbium-doped fluoride fiber lasers emitting at 2.8 μm wavelength band

Year	Ref.	Organization	Laser wavelength / μm	Output power / W	Pump arrangement	Optical-to-optical efficiency / %
2009	[5]	Kyoto University	–	24.0	Dual-end pumping, spatial pump coupling	14.5
2011	[6]	Université Laval	2.83	20.6	Forward pumping, all-fiber configuration	28.2
2015	[7]	NINT	2.79	9.2	Backward pumping, spatial pump coupling	23.0
2015	[8]	Université Laval	2.94	30.5	Forward pumping, all-fiber configuration	16.2
2018	[9]	Université Laval	2.82	41.6	Dual-end pumping, spatial pump coupling in one end	24.2
2019	[10]	Osaka University	2.84	35.4	Dual-end pumping, spatial pump coupling	18.7
2021	[11]	Shenzhen University	2.83	20.3	Forward pumping, all-fiber configuration	14.5
2022	**This work**	**Tianjin University**	**2.87**	**33.8**	**Backward pumping, spatial pump coupling**	**26.4**

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系统热管理外，还需要避免水分子扩散导致的氟化物光纤端面损伤问题[13]，因此高性能光纤端帽对于高功率中红外激光输出至关重要。本文利用镀膜反射镜和自制高性能中红外光纤端帽提供谐振腔反馈，结合高功率泵浦光的高效耦合技术，将单端泵浦中红外光纤激光器的输出功率提升到33.8 W，并获得了＞30 W功率水平下的最高激光效率。

图1为本文采用的中红外光纤激光器系统结构。有源光纤为纤芯直径为15 μm、内/外包层直径为～250 μm/290 μm的掺铒氟化锆（Er:ZrF_4）光纤，掺杂铒离子的摩尔分数为7%，光纤的截止波长为2.5 μm，可保证单横模中红外激光的产生和传输。实验中使用了8 m长的有源光纤以获得充分的泵浦吸收，有源光纤一端平切后被放置在五轴光纤调整架上，与2.8 μm波段的宽带高反射镜（HR mirror，反射率$R>99\%$）空间对接，另一端熔接了长度为500 μm的200 μm/240 μm多模氟化铝（AlF_3）端帽光纤。该AlF_3端帽作为腔镜为谐振腔提供腔反馈，同时还有效避免了2.8 μm激光高功率运转下光纤的端面损伤。实验使用一个976 nm锁波长的高功率半导体激光器（LD）作为泵浦源，泵浦光由纤芯/包层直径为105 μm/125 μm的尾纤输出，经石英非球面透镜准直后，被氟化钙透镜聚焦，经熔接有光纤端帽的一端耦合进激光谐振腔。中红外激光经放置在石英非球面透镜与氟化钙透镜间的二向色镜（DM）反射输出，DM在976 nm处的透过率$T>97\%$，在2.7～2.9 μm波段的反射率$R>94\%$。实验中未观察到镜片膜系的损伤，因此在光纤与高反射镜耦合处未采取特殊保护措施，整个激光系统除泵浦入射端的有源光纤采用水冷散热外，其余部分均采用被动散热方式。

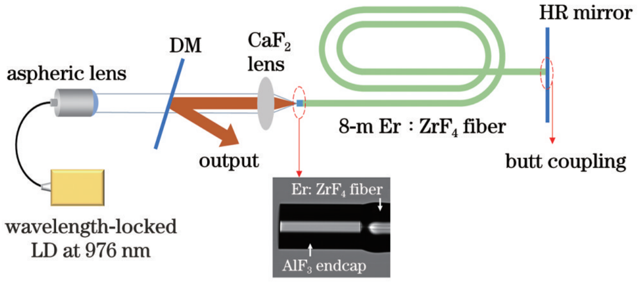

图1　中红外光纤激光器系统示意图

Fig. 1　Schematic of mid-infrared fiber laser system

图2（a）、（b）为激光器输出功率及激光光谱随泵浦功率的变化曲线，其中P_{out}表示激光器输出功率，λ表示激光器的工作波长。当输出功率小于10 W时，激射波长位于2800～2818 nm范围内，激光器斜效率为32.8%，接近～35%的斯托克斯效率极限。随着泵浦功率进一步增加，激光器的斜效率由32.8%逐渐降低到21.7%，这主要是由前述的泵浦光激发态吸收导致的；而激光光谱则逐渐红移，这主要是由激光谐振腔宽带反馈特性以及高激光功率下的信号重吸收效应引起的。当入射泵浦功率达到其最大值128 W时，激光器输出功率达到33.8 W，对应的光光转换效率为26.4%，光谱呈现2865 nm和2871 nm双波长振荡。由于端帽AlF_3材料相比于有源光纤ZrF_4材料具有更为优异的抗潮解能力，且输出端中红外激光功率密度较低，AlF_3端帽在最高输出功率下尚未出现损伤。本实验激光功率的进一步提升主要受限于泵浦功率水平，在更高的泵浦功率下，有源光纤的热管理可能成为新的制约因素。

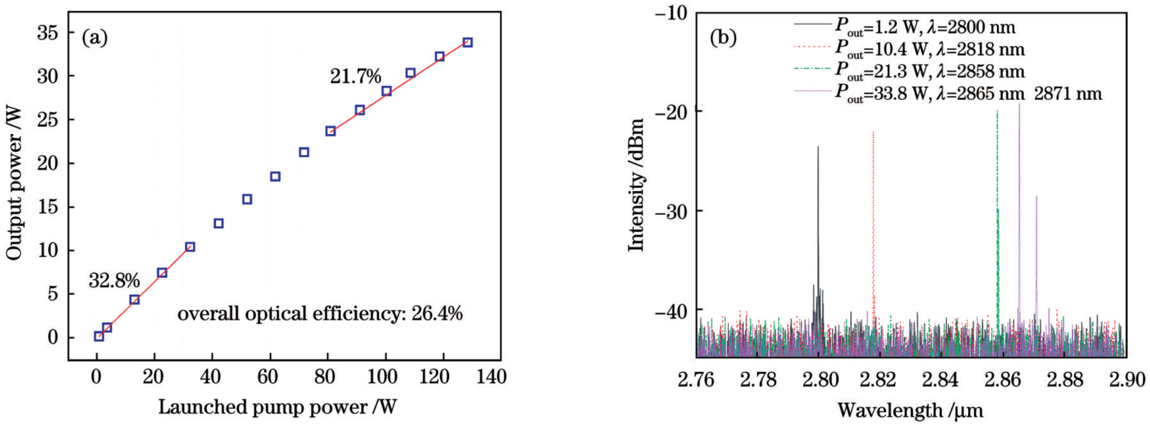

图2　中红外光纤激光器的实验结果。（a）输出功率随泵浦功率的变化曲线；（b）不同输出功率下的激光光谱

Fig. 2　Experimental results of mid-infrared fiber laser. (a) Output power versus launched pump power; (b) laser spectra under different output powers

本文基于单端泵浦结构实现了高功率中红外2.8 μm掺铒氟化物光纤激光器。通过优化泵浦耦合，将激光器在较低功率下的斜效率提升到～33%；通过引入AlF_3端帽，避免了高功率激光运转下光纤端面损伤的问题。据我们所知，这是国内首次实现＞30 W中红外光纤激光输出，同时也是国际上单端泵浦中红外光纤激光器的最高功率水平。

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Efficient 33.8 W Mid-Infrared Fiber Laser Operating at 2.8 μm

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Abstract

Objective The power scaling of mid-infrared (mid-IR) fluoride fiber lasers is difficult to realize because of the low melting temperature of fluoride glass and immature fabrication techniques of mid-IR fiber devices. Mid-IR laser output powers of 30.5 W and 41.6 W at 2.94 μm and 2.82 μm based on single-end and dual-end pumping configurations (Table 1), respectively, have been previously reported. Although fiber Bragg gratings (FBGs) written in fluoride fibers have been developed as cavity mirrors in mid-IR fiber oscillators, the thermal degeneration of grating reflectivity, mismatch of the reflective wavelength, and severe splicing losses with silica fiber create new problems for the power scaling of FBG-based mid-IR fiber lasers. This study introduces a high-power erbium-doped fiber laser at 2.8 μm based on a single-end pumping scheme, where a high-reflective (HR) mirror and Fresnel reflection from the end face of a homemade end cap are used to provide cavity feedback.

Methods Figure 1 shows the experimental setup of the high-power 2.8 μm erbium-doped fiber laser. The active fiber has an erbium dopant mole fraction of 7%, core and inner/outer cladding diameters of 15 μm and ~250 μm/290 μm, and core and inner cladding numerical apertures of 0.12/0.45; the fiber is butt-coupled to an HR mirror on one end and spliced to a 500-μm-long AlF$_3$ fiber end cap on the other end. An end cap with core and cladding diameters of 200 μm and 240 μm, respectively, can efficiently decrease the power density of the high-power mid-IR laser while isolating the water vapor diffusion from the end face of the active fiber, which is essential for high-power laser output. A multimode laser diode with a wavelength stabilized at 976 nm and a maximum output power of 128 W is coupled to the inner cladding of the fluoride fiber using two lenses with optimized focal lengths, where one is for pump light alignment and the other is for focusing light into the fiber. A dichroic mirror, which transmits the pump laser and reflects the back-propagation mid-IR laser, is inserted between the two lenses. Water cooling is applied to the pump coupling end of the erbium-doped fiber for appropriate heat dissipation under a high laser power, while the rest of the optical system is passively cooled.

Results and Discussions When the output power is less than 10 W, the laser slope efficiency is 32.8% with respect to the launched pump power, and the lasing wavelength is red-shifted from 2800 nm to 2818 nm with increasing laser power. The slope efficiency decreases gradually as the laser power increases because of the pump excited-state absorption ($^4I_{11/2}\rightarrow{}^4F_{7/2}$). A maximum output power of 33.8 W is achieved at a launched pump power of 128 W, and dual-wavelength lasing at 2865 nm and 2871 nm is obtained owing to the wide reflection band of the HR mirror and high laser gain of the cavity. Because no damage is observed from the AlF$_3$ end cap at the maximum output power, further power scaling of this fiber laser is limited by the available pump power delivered from a 105 μm/125 μm multimode fiber.

Conclusions With a homemade AlF_3 end cap, a 33.8 W erbium-doped fluoride fiber laser operating at 2.8 μm is demonstrated under the appropriate thermal management of the fluoride fiber. A high optical-optical conversion efficiency of 26.4% is achieved at the maximum output power using high-precision spatial pump coupling. To the best of our knowledge, this is the highest output power achieved using a single-end pumping mid-infrared erbium-doped fiber laser.

Key words lasers; mid-infrared fiber lasers; single-end pumping; high-power lasers; erbium-doped fluoride fiber