doi:10.3788/gzxb20144303.0314002

LD 泵浦瓦级单模高掺铒中红外光纤激光器

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摘　要:中红外激光在激光医疗、激光光谱学和红外对抗等领域有着广泛的应用前景.为了获得结构紧凑、便携性好的中红外激光源,采用 975 nm 半导体激光器泵浦高掺铒氟化物双包层光纤实现了 2.8 μm 的中红外光纤激光输出.将光纤耦合输出的中心波长为 975 nm 的半导体激光,经过消像差非球面透镜系统耦合进双包层光纤,激光谐振腔由高反镜和具有 4%菲涅耳反射率的光纤端面组成,当注入到增益光纤的泵浦功率高于 0.37 W 时,获得了中红外激光输出.实验结果表明:中红外光纤激光器中心波长为 2.785 μm,谱宽 0.9 nm;工作阈值为 0.37 W,最大输出功率为 0.98 W,斜率效率为 17%,激光工作模式为单模.利用高掺杂浓度铒离子间的能量转移上转换,获得了高效率瓦级单模中红外光纤激光输出.

关键词:中红外;LD 泵浦;掺铒;单模;光纤激光器
中图分类号:TN212,TN248.1　　**文献标识码**:A　　**文章编号**:1004-4213(2014)03-0314002-5

Laser Diode-pumped Watt-level Single Mode Heavily Erbium-doped Mid-infrared Fiber Laser

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Abstract: Mid-infrared lasers have a lot of potential applications, such as laser medicine, spectroscopy and infrared countermeasures. In order to obtain a compact and potable mid-infrared laser source, a diode-pumped fiber laser emitting at 2.8 μm from a heavily erbium-doped ZrF_4-BaF_2-LaF_3-AlF_3-NaF double-clad fiber was demonstrated. A fiber-coupled laser diode centered at 975 nm was coupled into the inner cladding as the pumping source by an achromatic coupling system consisted of two aspheric lenses. The laser cavity was composed of a protected gold mirror butted against the rear end of the active fiber, and the other end with 4% Fresnel reflection. The 2.8 μm lasing was achieved when the launched pump power was higher than 0.37 W. The experimental results indicated that the center wavelength and linewidth of free running were 2.785 μm and 0.9 nm, respectively. Moreover, the maximum output power of the fiber laser working at the transverse-fundamental-mode was 0.98W, corresponding to the slop efficiency of 17%. High efficient watt-level single mode mid-infrared fiber laser was obtained using the efficient energy transfer upconversion processes between Er-Er ions.

Key words: Mid-infrared; Diode-pumped; Erbium-doped; Single mode; Fiber laser
OCIS Codes: 140.0140;140.3480;140.3500;140.3510;140.3613

Foundation item:The Innovation Foundation of State Key Laboratory of Laser Interaction with Matter(No. SKL111106)

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Received: May. 27, 2013; **Accepted**: Aug. 8, 2013

0 Introduction

Recently, the lasers emitting near 3 μm have attracted much attention owing to their potential applications in laser medicine[1], spectroscopy[2], and infrared countermeasures[3-4], etc. Mid-infrared fiber lasers are well-suitable for these applications and prior to other mid-IR laser sources, such as semiconductor lasers[5], solid-state ion-doped crystal and glass lasers[6], optical parametric oscillators and difference frequency generators[7], and gas lasers[8], due to inherent advantages of fiber lasers, including high conversion efficiency, excellent beam quality and, most importantly, compact construction for portable ability[9].

For the great infrared transparency and relatively low phonon energy (550 cm^{-1}) of ZBLAN (53%ZrF_4-20%BaF_2-4%LaF_3-4%AlF_3-20%NaF)[10], the erbium (Er)-doped and Er-praseodymium (Pr)-codoped ZBLAN fiber lasers are promising candidates for construction of a high power, highly efficient and compact mid-infrared fiber laser by employing the emitting on the $^4I_{11/2} \rightarrow {}^4I_{13/2}$ transition at 2.8 μm[11,12]. Thanks to the advances in the semiconductor laser as the pumping sources, significant progresses in the output power of continuous wave (cw) Er-doped and Er-Pr-codoped ZBLAN fiber lasers have been made in the past decade[13-16]. Generally, compared to multi-mode operation, the single-mode output has better beam quality which is required for actual applications mentioned above. In practice, due to relatively low damage threshold of rare-earth doped ZBLAN fiber[2] and the fact that multi-mode fiber has larger core than single-mode one, multi-mode fiber could bear much more pump power than single-mode one. Consequently, for a given output power, single-mode operation needs more efficient operation than multi-mode, which makes the single-mode output a little more difficult.

However, for some reasons, studies on mid-infrared fiber lasers of late-start and low-level at home were carried out since the past two years. Huang *et al*. developed a watt-level cw mid-infrared fiber laser with an Er:ZBLAN fiber in 2012[17]. Nevertheless, the fiber laser was in the multi-mode operation. In this paper, we report a watt-level output power cw mid-infrared fiber laser from singly Er-doped ZBLAN double-clad fiber laser. The fiber laser was single mode, and the slope efficiency was 17.0%.

1 Experimental setup

Partial Er ion and Pr ion energy-levels in ZBLAN glass are depicted in Fig. 1, indicating the processes that are relevant for operation of the high-power diode-pumped heavily Er-doped fiber laser and Er-Pr-codoped fiber laser at the transition $^4I_{11/2}$—$^4I_{13/2}$. GSA, ground-state absorption, ESA, excited-state absorption, ET, energy transfer, and ETU, energy-transfer upconversion. Theoretically, the longer natural lifetime of the lower laser level ($^4I_{13/2}$, 9.0 ms) relative to that of the upper laser level ($^4I_{11/2}$, 6.9 ms) of the 2.8μm transition, also frequently called "self-terminating", the more probably a population bottleneck that inhibits efficient steady-state (cw) lasing in Er: ZBLAN fiber lasers will occur[18]; However, the energy-transfer (ET) processes between Er ions and co-doped Pr ions, and the energy-transfer upconversion (ETU) processes between Er and Er ions, also called lifetime quenching and energy recycling regimes respectively (Fig. 1), have been demonstrated as being able to overcome the population bottleneck efficiently[19]. It has been shown that the energy-recycling regime with its inherent enhancement makes the slope efficiency by a factor of two higher in heavily Er-doped ZBLAN fiber lasers than in Er-Pr-codoped ZBLAN fibers[20]. When the singly Er-doped concentration is higher than a certain value (e. g. > 1 mol. %), the ETU1 process (Fig. 1) leads to a fast depletion of the lower laser level and enables cw operation[21].

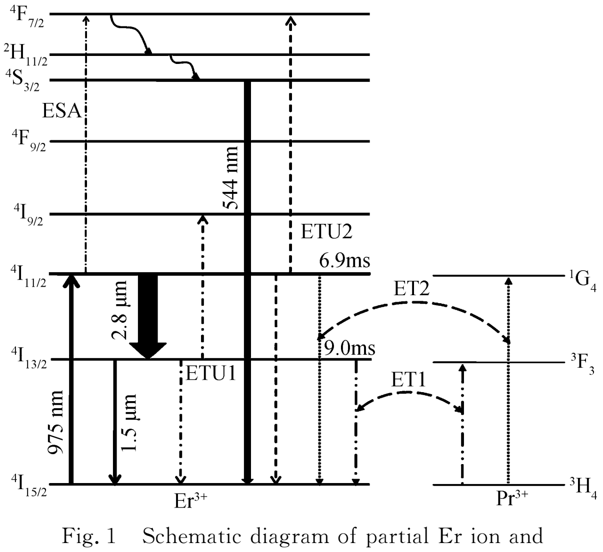

Fig. 1 Schematic diagram of partial Er ion and Pr ion energy-levels in ZBLAN glass

The experimental setup for the heavily Er-doped ZBLAN fiber laser is shown in Fig. 2, L_1 is pumping collimator, L_2 is aspheric lens and L_3 is laser collimator. A fiber-coupled laser diode (LD) was used as a cw pump source and operated at a wavelength of around 975 nm with a maximum output power of 50 W at the fiber end of the laser diode. The output fiber of the laser diode had a core diameter of 105 μm and a numerical aperture (NA) of 0.22. According to the study of energy transfer in high Er^{3+} ion concentration to deplete the population of $^4I_{13/2}$ and solve the population bottleneck for high power 3-μm fiber lasers[19-20], as well as the numerical analysis of optimizing fiber lasers[22], the custom designed active fiber (fabricated by FiberLabs Inc.) was chosen to be a piece of 4.8 m singly Er-doped ZBLAN double-clad fiber. Its core had a diameter of 17 μm and a NA of 0.12, and contained a 60 000-parts-in-10^6 (ppm) molar concentration of ErF$_3$, corresponding to the Er^{3+} ion density of 1.08×10^{27} m^{-3}. The inner cladding of the fiber is rectangle to obtain significantly high effective absorption coefficient[23], and its dimension and NA were 200×250 μm^2 and 0.55, respectively. The diameter of the outer circular cladding was 370 μm. The ends of the fiber were held by fiber chunk holders with a U-shaped groove heat sink. The absorption coefficient of this singly Er-doped ZBLAN fiber was measured to be about 2.45 dB/m, while the background loss was measured to be less than 0.1 dB/m for the laser signal at 2.8 μm. The 975 nm LD pump light went through a collimator (L_1, effective focal length $f_{\mathrm{EFL}}=11$ mm), and then the collimated pump beam was coupled into the inner cladding of the fiber by an aspheric lens (L2, $f=22$ mm). L_1 and L_2 constitute the pumping coupling system. Every side of the lenses was antireflection coated at the pump wavelength. The spot size at the aspheric lens focal point was calculated to be 165 μm. With this pump configuration, the launched pump power was estimated to be approximately 70% of the total power from the laser diode, taking into account the mismatching between the spot size and inner cladding size of the fiber, as well as the transmission of the lenses and dichroic mirror.

In the proposed laser cavity arrangement, a protected gold mirror which had high reflection of about 98% at both 2.8 μm and 975 nm was butted against the rear end of the fiber. Due to the exceptional properties of the ZBLAN fiber, such as fragile and weak mechanics, the active fiber can not be dealt with in a common way. Therefore, a low cost and flexible method was designed to cleave the active fiber end at 0° (angle between optical axis of the fiber and normal vector of the cleaved surface), making Fresnel reflection (4%) of the pumping end work as the laser output port. In front of the pumping end, a dichroic mirror (high reflection $>99.5\%$ at 2.8 μm, high transmission $>95\%$ at 975 nm) was placed with an angle of incidence of 45° to couple out the laser beam. A CaF$_2$ lens with focal length of 50 mm to collimate the laser beam, and an uncoated Germanium plate of 2 mm thickness were located before the detector, acting as the long wavelength pass filter (Transmission about 45% at $>2\mu$m, Transmission about 0 at $<1.8\mu$m) to purify the output. The laser output was measured with a power meter (OPHIR, 3A-P-V1) and a remote infrared spectrum analyzer (Bruker Tensor 37). The spatial profile of the fiber laser spot was captured with an infrared opto-thermal camera.

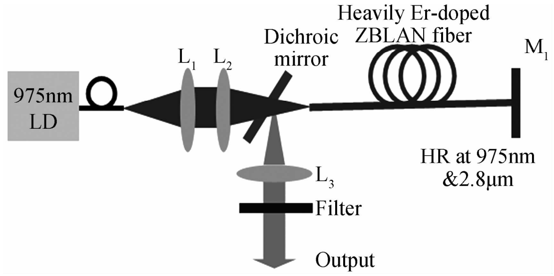

Fig. 2 Schematic diagram of the experimental setup for the diode-pumped heavily Er^{3+}-doped ZBLAN fiber laser

2 Results and discussion

The fiber laser output power as a function of launched pump power is presented in Fig. 3. The solid line is a linear fit for the output over the threshold. Inset, typical spectrum of the fiber laser. As seen from the plot, the maximum output power was 0.98 W and the threshold pump power was determined to be as low as 0.37 W. The slope efficiency was 17.0%, which was roughly half of the Stokes efficiency limit of 34.8%. The optical-to-optical efficiency of 2.8 μm laser output power versus the launched pump power was calculated to be 15.6%, and the corresponding total optical-to-optical efficiency of 2.8 μm laser output power versus the 975 nm laser diode power was around 10.9%, considering the coupling efficiency of the coupling system. The linearity of the plot and no observed saturation clearly indicated that the output power scaling can simply realized by using higher pump powers or more efficient pump coupling techniques. As mentioned before, the maximum pumping power was 50 W. However, the pumping end of the active fiber fused when the LD output power exceeded 9 W, corresponding to launched pumping power larger than 6.3 W. It was difficult to perfectly cleave the fiber in our low cost and flexible way because of the fragile property of ZBLAN fiber. The typical spectrum of the singly Er-doped fiber laser was measured when the laser output power was about 0.11 W. The center wavelength and the linewidth were 2.785 μm and 0.9 nm, respectively. As increasing the pump power, the heat accumulated in the active fiber, and the sublevels of $^4I_{11/2}$ populated. Thus, the output would shift toward longer wavelengths, namely, a little red-shift occurred. Meanwhile, the linewidth was broadened slightly.

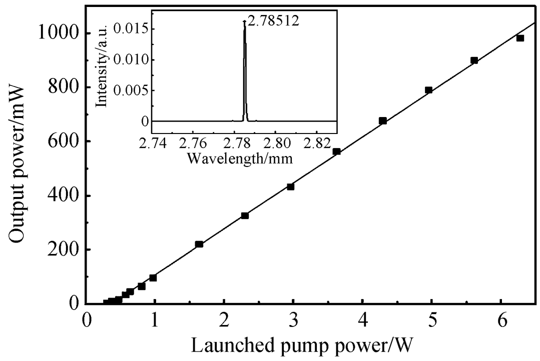

Fig. 3 Output power as a function of launched pump power

Strong green (540 nm band) fluorescence was observed along with the working fiber laser. As illustrated in Fig. 1, this fluorescence was caused by these processes Er^{3+} ions in the $^4I_{11/2}$ level jumped to the $^4F_{7/2}$ level via Excited State Absorption (ESA)[24], followed by rapid non-radiative decay to the $^4S_{3/2}$ level. Subsequent transition occurred from the $^4S_{3/2}$ level to the $^4I_{15/2}$ level, emitting 540 nm photons. This upconversion mechanism represented a detrimental pathway for depopulation of the upper laser level, nevertheless, the rate of ESA was approximately 80 times weaker than 2.8 μm lasing rate[20]. Moreover, the green fluorescence was rather useful as a visual monitor to optimize coupling. As such, the upconversion effect causing the upper level depletion due to the ESA could be ignored.

The custom designed active fiber in our experiment had a V-value of 2.29 at 2.8 μm, which was smaller than 2.41, making our fiber laser operate at transverse-fundamental-mode[25]. We detected the laser beam profile with an infrared opto-thermal camera. The spatial beam profile was shown in Fig. 4, from which one would find that the beam profile has a perfect Gaussian distribution.

In addition, Ref. [2] has summarized the obstacles for obtaining 10 W or tens of watts mid-infrared fiber lasers, such as the fragility, low damage threshold, and low melting point (265 °C) of ZBLAN fibers. The most important and difficult is to cleave the ZBLAN fiber properly. As a consequence, promoting quality of the active fiber pumping end and good heat management are currently supposed to obtain the power and efficiency scaling of mid-infrared ZBLAN fiber lasers.

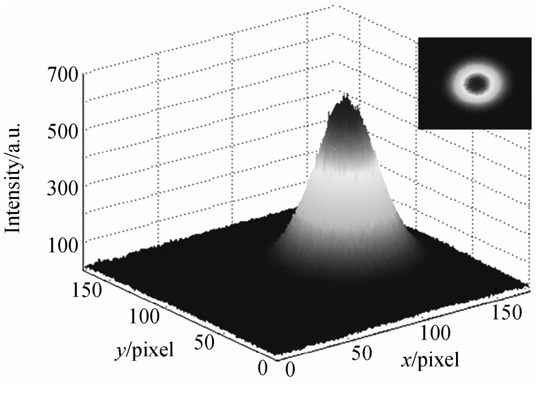

Fig. 4 The spatial beam profile of 2.8μm fiber laser captured by an infrared thermal camera

3 Conclusion

A relatively low threshold watt-level single mode cw output from a heavily Er-doped ZBLAN double-clad mid-infrared fiber laser has been demonstrated. The maximum output power of the fiber laser working at the transverse-fundamental-mode was 0.98 W, corresponding to the slop efficiency of 17%. Further power scaling will be achieved by optimization of the resonator design and the launch efficiency, as well as the wavelength tunability will be expected with a grating as feedback of the cavity in the near future.

Acknowledgement

The authors would like to appreciate helpful discussions with Mengmeng Tao, and thank Wei Zhang and Xiaohong Hu for the preparation of the active fiber, as well as Xiaofeng Wang for the measurement of the spectrum.

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