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中国激光

大模场铒镱共掺光纤制备及其激光性能研究

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摘要 基于改进的化学气相沉积(MCVD)工艺和溶液掺杂法，成功制备出25 μm/ 300 μm大模场铒镱共掺光纤，并研究了其激光放大性能。该光纤的纤芯数值孔径为0.12，940 nm包层的吸收系数为2.85 dB/m。搭建了全光纤主振荡功率放大(MOPA)结构测试平台，当铒镱共掺光纤长度为8 m，940 nm泵浦光功率为141 W时，输出功率最大为61.7 W，斜率效率达到42%，输出光谱没有观察到明显的放大自发辐射(ASE)。

关键词 激光器；光纤激光器；铒镱共掺；大模场面积光纤；高功率激光

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1 引言

1.5 μm波段激光由于具有“人眼安全”、处于通信传输的第三窗口以及大气传输损耗低等优点[1-3]，被广泛应用于激光雷达、激光测距和光纤通信等领域[4-8]。单掺铒光纤(EDF)在900多纳米处的吸收截面较小且高浓度掺杂极易发生浓度淬灭效应[9]，因此EDF难以用于高功率激光放大。研究人员发现，镱离子在900多纳米处的吸收截面很大[10]，铒镱共掺后，光纤中的镱离子高效吸收泵浦光，并将能量传递给铒离子，大大提高了泵浦转换效率和输出功率。同时，铒镱共掺光纤中镱离子的数量远高于铒离子数量，这使得铒离子被充分分散，能够有效抑制铒离子的浓度淬灭效应。随着铒镱共掺光纤的不断发展，高功率铒镱共掺光纤激光器的输出功率不断提升[11-13]。

目前，国内外主要采用大模场铒镱共掺光纤(LMA EYDF)实现1.5 μm波段高功率激光输出。2020年，Matniyaz等[14]采用Nufern公司生产的大模场铒镱共掺光纤，通过非峰值泵浦实现了302 W的功率输出，光光效率(optical-to-optical efficiency)为56%，但空间光耦合会造成大量泵浦光的损失，而且不利于应用。2021年，王丹等[15]采用CorActive公司生产的铒镱共掺光纤，通过增加1 μm波段辅助腔来抑制1 μm放大自发辐射(ASE)，实现了功率为21.6 W、斜率效率为56.2%的1.5 μm激光输出，但由于采用976 nm激光器进行泵浦，光纤温度较高。2021年，Yu等[16]同样采用大模场铒镱共掺光纤，以1018 nm波段激光进行泵浦，并引入C-band ASE作为辅助信号，实现了1.6 μm处219.6 W的激光输出。典型铒镱激光器的参数如表1所示。这些激光器所采用的铒镱光纤均为国外生产。由于铒镱共掺光纤的核心制造技术长期受到封锁，尚无国产大模场铒镱共掺光纤及基于国产光纤的1.5 μm高功率光纤激光器的报道。

表1 典型铒镱激光器的参数

Table 1 Parameters of typical erbium-ytterbium lasers

Classification	Year	Manufacturing country	Output power /W	Optical efficiency	Reference
Domestic	2021	China	61.7@1550.0 nm	42.7%	–
	2021	Canada	21.6@1548.9 nm	45.7%	[15]
	2021	USA	219.6@1600.0 nm	22.4%	[16]
International	2020	USA	302.0@1562.3 nm	56.0%	[14]
	2016	USA	207.0@1560.0 nm	49.3%	[13]
	2014	Canada	264.0@1585.0 nm	–	[12]
	2007	UK	297.0@1567.0 nm	40.0%–19.0%	[11]

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本文基于改进的化学气相沉积(MCVD)工艺并结合溶液掺杂技术,成功制备出大模场铒镱共掺光纤,分析了预制棒折射率分布及光纤结构。搭建了全光纤主振荡功率放大(MOPA)结构测试平台,研究了大模场铒镱共掺光纤的高功率激光性能。基于国产铒镱共掺光纤实现了 1550 nm 激光的 61.7 W 输出,为 1.5 μm 光纤激光器的国产化打下坚实基础。

2 光纤制备及基本参数

本文基于 MCVD 工艺[17]并结合溶液掺杂技术制备铒镱共掺光纤。首先利用实验室现有的 MCVD 机床设备制备预制棒。在气相掺磷过程中,采用反向沉积工艺提高纤芯 P_2O_5 含量,提高 Yb^{3+} 向 Er^{3+} 的能量传递效率,同时抑制 Er^{3+} 向 Yb^{3+} 的反向能量传递,从而抑制 1 μm ASE 的产生[18-19]。最后,将光纤预制棒匹配合适的八边形石英套管,并拉制成特定尺寸的光纤。

实验制备出 10 μm /130 μm(EYDF1)和 25 μm /300 μm(EYDF2)两种规格的铒镱共掺光纤,光纤径向掺杂浓度如图 1 所示。为了防止泵浦光在包层中以螺旋光的形式存在,通过把石英套管外表面打磨成合适的八边形,将光纤的内包层做成八边形,提高纤芯对泵浦光的吸收。

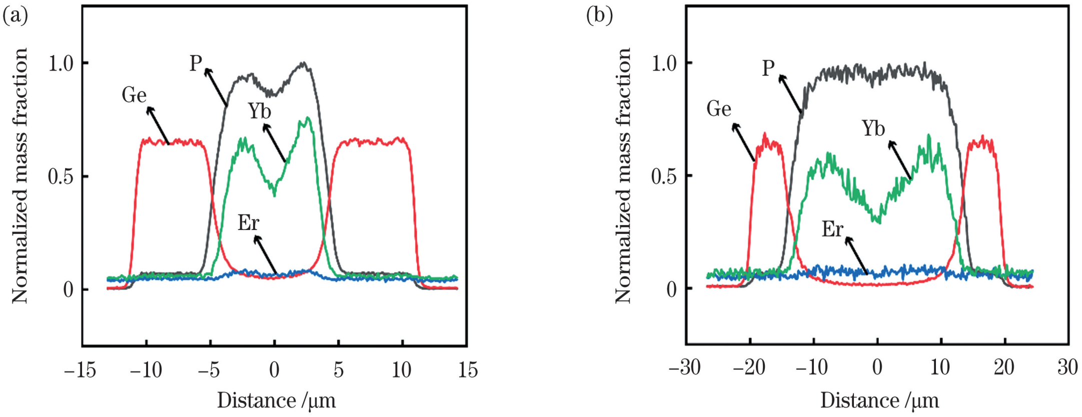


图 1 光纤径向掺杂浓度。(a)EYDF1 光纤;(b)EYDF2 光纤

Fig. 1 Radial doping concentration of fiber. (a) EYDF1 fiber; (b) EYDF2 fiber

两根光纤中心均出现了折射率减小的现象,这是预制棒烧实过程中 P_2O_5 的挥发导致的。适度的折射率减小可以提高光纤的基模模场面积,同时光纤高阶模的弯曲损耗也增大。在纤芯与石英包层间沉积了一段折射率较高的台阶,可以降低纤芯数值孔径(NA),进而优化输出信号的光束质量。通过仿真计算可知,EYDF1 光纤仅包含 LP01 模,EYDF2 光纤包含 LP01、LP02、LP11、LP12、LP21 和 LP31 等模式。两种光纤的截面和折射率剖面分别如图 2、3 所示。其中 EYDF1 光纤纤芯直径为 10.12 μm,包层直径为 128.25 μm,纤芯相对折射率台阶 NA 为 0.10。EYDF2 光纤纤芯直径为 25.01 μm,包层直径为 292.09 μm,纤芯相对折射率台阶 NA 为 0.12。采用截断法测试光纤包层吸收系数,其中,EYDF1 光纤在 915 nm 处的包层吸收系数为 4.50 dB/m,EYDF2 光纤在 940 nm 处的包层吸收系数为 2.85 dB/m。

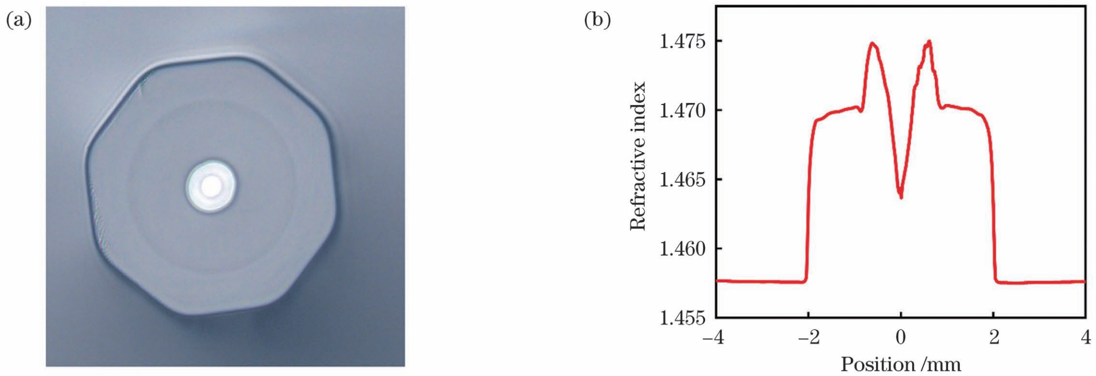


图 2 EYDF1 光纤的截面和预制棒折射率剖面。(a)光纤截面;(b)预制棒的折射率剖面

Fig. 2 Cross section and pre-fabricated rod refractive index profile of EYDF1 fiber. (a) Optical fiber cross section; (b) pre-fabricated rod refractive index profile

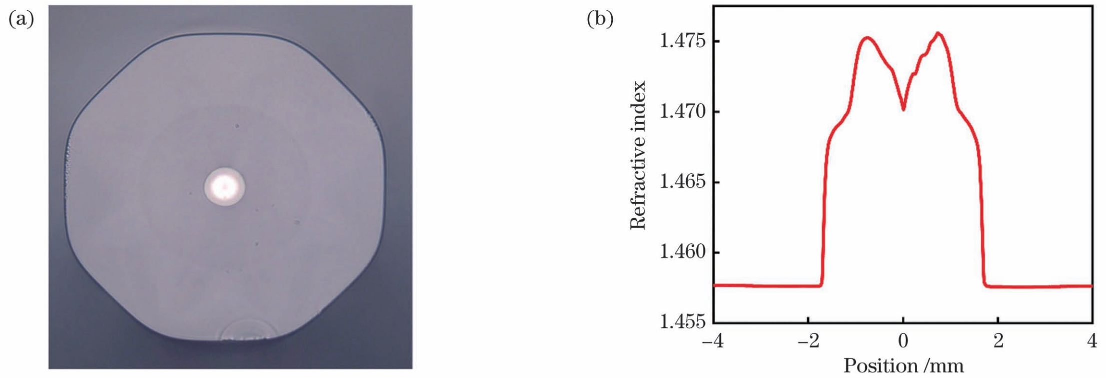
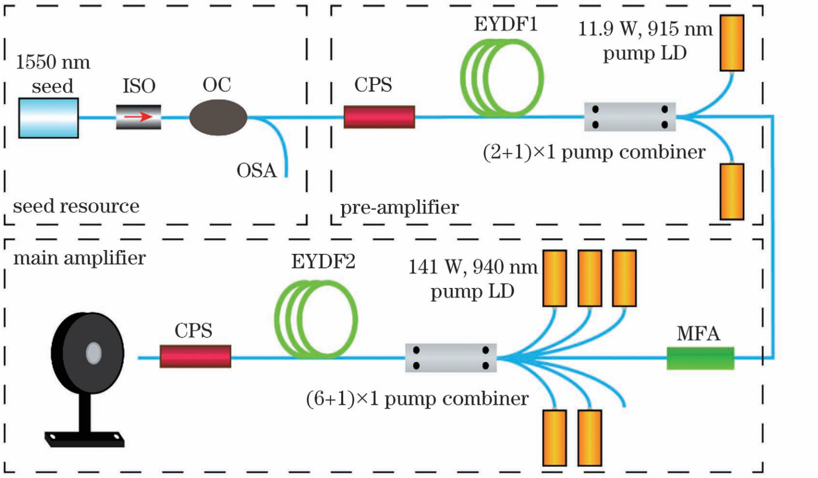


图 3　EYDF2 光纤的截面和预制棒折射率剖面。(a)光纤截面；(b)预制棒的折射率剖面

Fig. 3　Cross section and pre-fabricated rod refractive index profile of EYDF2 fiber. (a) Optical fiber cross section; (b) pre-fabricated rod refractive index profile

3　激光实验装置

实验光路如图 4 所示，功率为 1.13 W、中心波长为 1550 nm 的种子光经过隔离器(ISO)后，被耦合器(OC)的 99%耦合臂传输到预放大级，OC 的 1%耦合臂用于监测种子光光谱和功率。预放大级采用反向泵浦的方式，915 nm 半导体激光器(LD)被反向合束器(PC)的泵浦臂耦合到 EYDF1 光纤中，耦合到光纤中的功率为 11.9 W。经过优化，预放级接入 EYDF1 光纤的长度为 6.8 m，在靠近种子光的输入端使用包层光滤除器(CPS)滤除包层光。预放大级输出的信号光经过反向合束器的输出端进入主放大级的模场适配器(MFA)中。5 个 940 nm LD 被(6＋1)×1 前向合束器耦合到 EYDF2 光纤中，耦合到光纤中的总功率为 141 W。合束器保留一个泵浦臂悬空，用于监测回返光。EYDF2 光纤长度为 8 m，在光纤的输出末端采用 CPS 滤光，并利用量程为 150 W 的功率计探头记录输出激光的功率。本实验中所有悬空光纤均切 8°斜角，EYDF1 光纤和 EYDF2 光纤分别采用风冷和水冷的方式进行主动散热，水冷温度设置为 20 ℃。



ISO: isolator; OC: optical coupler; CPS: cladding pump stripper; OSA: optical spectrum analyzer;
EYDF: erbium-ytterbium doped fiber; LD: laser diode; MFA: mode field adaptor

图 4　全光纤 MOPA 激光器的结构图

Fig. 4　Structural diagram of all-fiber MOPA laser

4　实验结果与讨论

实验采用的种子光功率为 1.13 W，6.8 m 长的 EYDF1 光纤将信号光功率预放大至 5.25 W 时的光谱如图 5(a)所示。经过预放级后，信号光的中心波长为 1550 nm，没有明显的 ASE 杂散光，说明光谱质量良好。图 5(a)显示，光信噪比(OSNR)仅有 17 dB，这很可能是实验中利用散射光测试输出光谱导致的。预放大级的输出激光与泵浦光的功率关系如图 5(b)所示，拟合斜率效率为 38.6%。随着泵浦功率的逐渐提高，预放大级的输出功率稳步上升。

预放大后的信号光被 MFA 和(6＋1)×1 前向合束器耦合到 8 m 长的 EYDF2 光纤中，测得经过 EYDF2 光纤后的剩余信号光功率为 2.9 W。泵浦光被(6＋1)×1 PC 耦合进大模场铒镱共掺光纤中。激光的输出光谱如图 6(a)所示，产生的 1 μm 和 1.5 μm ASE 非常微弱，激光 OSNR 达到 45 dB，这也说明了预放级输出信号具有较好的 OSNR。1.5 μm 激光的输出功率随泵浦功率的变化如图 6(b)所示，最大输出功率达到 61.7 W，拟合斜率效率为42%。电荷耦合

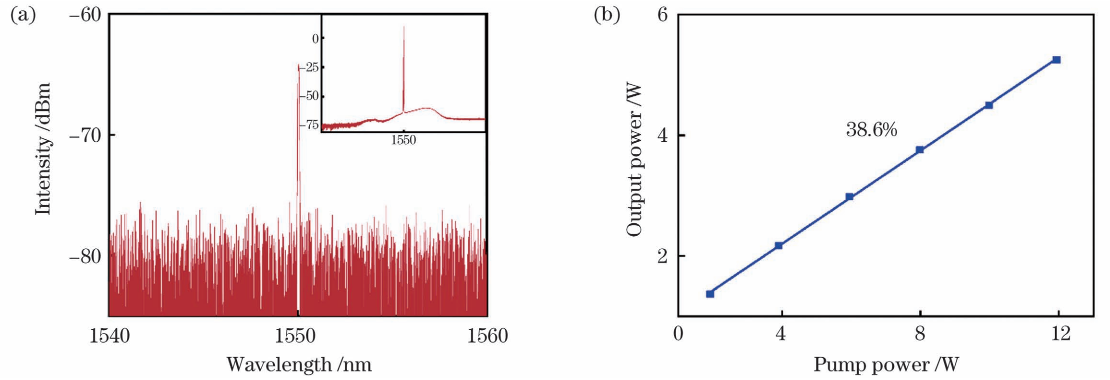


图 5 预放大级的输出激光表征。(a)信号光功率被预放大至 5.25 W 时的光谱(插图为种子光光谱);(b)预放大级的斜率效率

Fig. 5 Output laser characterization of pre-amplification stage. (a)Spectrum when signal power is pre-amplified to 5.25 W with seed light spectrum shown in inset; (b) slope efficiency of pre-amplification stage

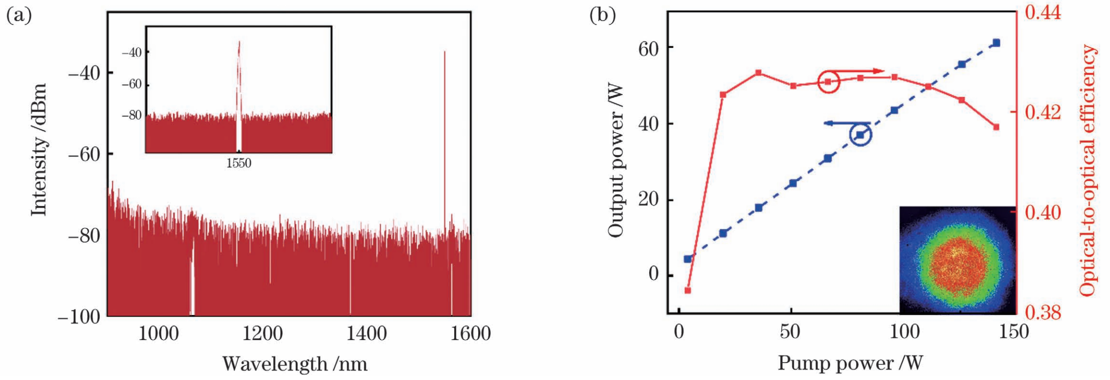


图 6 主放大级的输出激光表征。(a)宽谱范围内的输出光谱(插图为窄谱范围);(b)主放大级的斜率效率、光光效率及激光光斑

Fig 6 Output laser characterization of main amplification stage. (a) Wide output spectrum with narrow spectrum shown in inset; (b) slope efficiency, optical-to-optical efficiency and laser spot of main amplification stage

器件(CCD)捕捉到的激光器放大后输出的光斑如图 6(b)插图所示。随着泵浦功率的逐渐提高,光光效率最大达到 42.7%(泵浦功率为 35.5 W),当泵浦功率大于 100 W 时,光光效率开始下降。光光效率下降的原因可能是此时系统中 1 μm 波段的后向 ASE 开始逐渐升高[20]。随着泵浦功率的增加,光谱质量依然良好,同时输出功率依旧稳步增长,没有明显降低。由此可以看出,通过增加泵浦功率及优化放大器结构和光纤长度,输出功率和斜率效率有望进一步提升。

5 结 论

采用 MCVD 工艺结合溶液掺杂技术,并采用反向 P_2O_5 沉积工艺,成功制备了大模场铒镱共掺光纤。搭建了大模场铒镱共掺光纤放大系统,在 1550 nm 处实现了 61.7 W 的激光输出,斜率效率可达 42%,验证了国产大模场铒镱共掺光纤具有良好的 1.5 μm 激光放大性能。

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Fabrication and Laser Performance of Large Mode Area Erbium-Ytterbium Co-Doped Fiber

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Abstract

Objective With the advent of the industrialization 3.0 era, a 1.5 μm laser has been focused due to its “eye-safe” and low atmospheric transmission loss, which can be widely used in lidar, laser ranging, optical fiber communication and other fields. An erbium-doped fiber (EDF) with a small absorption cross section at 900–1000 nm is difficult to be used for high-power laser amplification. Moreover, concentration quenching is triggered with the increase of the concentration of erbium ions. Previous reports found that ytterbium ions in the erbium-ytterbium co-doped fibers could effectively absorb pump light and transfer energy to erbium ions. Therefore, the pump conversion efficiency and output power are greatly enhanced. Moreover, the number of ytterbium ions in an erbium-ytterbium co-doped fiber is much higher than that of erbium ions, so that the concentration quenching effect is effectively inhibited. In view of these, an erbium-ytterbium co-doped fiber has been the main gain medium for a 1.5 μm laser. A large mode area erbium-ytterbium co-doped fiber is fabricated based on the modified chemical vapor deposition (MCVD) process and the solution doping technology, and its laser amplification performance is also investigated.

Methods In the paper, an erbium-ytterbium co-doped fiber is prepared by MCVD combined with solution doping. The silica rude is prepared through corrosion, deposition, liquid phase doping, drying, vitrification, collapse, burning and other processes in the existing MCVD machine. In the gas phase doping process, the reverse deposition is utilized to improve the content of P_2O_5 in the fiber core. And the doping of P promotes the energy transfer from Yb^{3+} to Er^{3+}. Finally, the fiber prefabricated rod is matched with a suitable octagonal quartz sleeve and pulled into a specific size of fiber. A two-stage all-fiber main oscillation power amplification (MOPA) platform is set up to test the laser performance of the fiber. The MOPA structure contains a 1550 nm continuous laser as seed light, and the 915 nm and 940 nm lasers as pump light.

Results and Discussions Two erbium-ytterbium co-doped fibers of 10 μm/130 μm (EYDF1) and 25 μm/300 μm (EYDF2) are prepared. The cross section and refractive index profile of the fiber are shown in Figs. 2 and 3, respectively. The core for EYDF1 has a diameter of 10.12 μm, the cladding diameter is 128.25 μm, and the relative refractive index step numerical aperture (NA) of the core is measured to be 0.10. For the EYDF2, the core has a diameter of 25.01 μm, the cladding diameter is 292.09 μm, and the relative refractive index step NA is measured to be 0.12. The fiber cladding absorption coefficient is measured to be 4.50 dB/m at 915 nm for EYDF1 and 2.85 dB/m at 940 nm for EYDF2. For the laser experiment, the seed light power is measured to be 1.13 W. Through the 6.8 m long EYDF1, the signal power is pre-amplified to 5.25 W, and its spectrum is shown in Fig. 5(a). After pre-amplification, the central spectrum is stable at 1550 nm without obvious stray light such as amplified spontaneous radiation (ASE). As the scattered light is collected during the spectral test, the optical signal-to-noise ratio (OSNR) is only 17 dB. The output power versus pump power at the pre-amplification stage is plotted in Fig. 5(b), and the slope efficiency is 38.6%. The signal is coupled into an 8 m long EYDF2 through the MFA and the (6+1) × 1 forward pump combiner after pre-amplification, and the remaining signal power is measured to be 2.9 W after EYDF2. The pump light is coupled into the large mode area erbium-ytterbium co-doped fiber by the (6+1) × 1 pump combiner. The optical spectrum at 61.7 W is shown in Fig. 6(a). The 1 μm and 1.5 μm ASEs are too small to observe, and the laser signal-to-noise ratio is measured to be 45 dB. The variation of 1.5 μm laser output power with pump power is shown in Fig. 6(b). The maximum output power is measured to be 61.7 W, and the slope efficiency of 42% is achieved. With the increase of pump power, the maximum optical efficiency is measured to be 42.7% when pump power is 35.5 W. The optical-to-optical efficiency begins to decrease when the pump power is increased to 100 W, which is caused by the increase of the backward 1 μm ASE power. With the increase of pump power, the spectral quality is good, and the output power increases steadily. Therefore, the output power and slope efficiency can be further improved by the increase of pump power and the optimization of fiber length in the future.

Conclusions Large mode area erbium-ytterbium co-doped fibers are successfully fabricated by the MCVD process combined with solution doping. A large mode area erbium-ytterbium co-doped fiber amplification system is established. The 1550 nm laser power of 61.7 W is achieved with a slope efficiency of 42%. It is verified that our large mode area erbium-ytterbium co-doped fiber has a good amplification performance for a 1.5 μm laser.

Key words lasers; fiber lasers; erbium-ytterbium co-doping; large-mode-area fiber; high power lasers