飞秒激光刻写 FBG 实现 3.2 kW 单模光纤振荡器

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摘要　采用飞秒激光相位模板动态刻写技术，在非载氢大模场双包层光纤(纤芯直径/内包层直径为 20 μm/ 400 μm)上制备了中心波长约为 1080 nm 的光纤布拉格光栅对。高反射光纤布拉格光栅的反射率大于 99%，低反射光纤布拉格光栅的反射率约为 10%。利用这对光纤布拉格光栅搭建了高功率全光纤激光振荡器，实现了 3.2 kW 近单模激光输出，光束质量(M^2)约为 1.28，斜率效率约为 77.9%。这是国内飞秒激光刻写的光纤布拉格光栅首次实现千瓦级以上的激光输出，研究结果对高功率光纤布拉格光栅的制备和高功率光纤振荡器的发展都有重要的意义。

关键词　光纤光学；飞秒激光；光纤布拉格光栅；高功率光纤振荡器

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由于光纤激光振荡器具有结构紧凑、抗回光能力强、操作简单等特点，在切割、焊接等工业加工领域受到青睐[1-2]。光纤布拉格光栅(FBG)是大功率光纤振荡器的核心器件，决定了振荡器光谱和输出功率等性能[3]。目前全光纤结构光纤振荡器的最高功率为日本藤仓公司在 2020 年所报道的 8 kW[3]，国内于 2020 年和 2021 年分别实现了全光纤结构光纤振荡器的 6 kW 与 7 kW 的功率输出[4-5]，未来振荡器输出功率的进一步提升受限于 FBG 等器件的承受功率、非线性效应以及模式不稳定效应。目前，大功率光纤振荡器所用的 FBG 主要是通过紫外掩模板曝光法进行刻写[6]。为了提高光纤的光敏性，在 FBG 刻写前需要对光纤进行预载氢，刻写完成后还需要对 FBG 进行退火处理，以去除光纤中残留的氢气[7]。退火后，光栅的光谱会不可避免地发生变化，反射率也会减小。若退火不完全，光纤中残留的氢气将导致 FBG 发热严重，进而光纤无法承受高功率激光的加载。近年来，飞秒激光加工技术的发展为刻写高功率 FBG 提供了新的途径[8-11]。目前关于将飞秒激光与相位模板技术结合刻写大功率 FBG 的研究鲜有报道。2019 年，Krämer 等[12]利用在大模场双包层(纤芯直径/内包层直径为 20 μm/ 400 μm)掺镱光纤上刻写的高反射 FBG，实现了 1.9 kW 的振荡器。2020 年，该课题组在大模场双包层(纤芯直径/内包层直径为 20 μm/ 400 μm)传能光纤上分别刻写了高/低反 FBG，实现了 5 kW 的激光输出[13]。目前，国内还没有利用飞秒激光刻写大功率 FBG 的相关报道。本文利用飞秒激光相位模板动态扫描技术，实现了双包层大模场 FBG 的刻写。基于该 FBG 搭建的光纤振荡器，在 FBG 未加任何封装措施的情况下，实现了最高输出功率超过 3.2 kW 的激光输出。此时 FBG 的温度约为 40 ℃，振荡器的最高输出功率存在进一步提升的可能。

图 1(a)所示为飞秒激光相位模板动态刻写系统示意图，其中 MFA 为模场适配器，DCF 为双包层光纤，OSA 为光谱仪，ASE 为自发辐射光源。所用

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飞秒激光的波长为 515 nm，重复频率为 1 kHz，单脉冲能量约为 250 μJ，飞秒激光光斑直径约为 3 mm。柱面透镜将激光光斑沿垂直于光纤的方向压缩，以提高焦点处的能量密度；振镜调整光斑在纤芯中的聚焦位置，以实现快速对准；受限于光斑尺寸，刻写过程中沿光纤方向移动光斑以增加 FBG 长度。相位掩模板的中心波长为 1487 nm，啁啾率为 0.5 nm/cm，用其刻写的 FBG 在 1080 nm 附近发生二阶谐振。图 1（b）所示为刻写的 FBG 对的透射谱，高反射（HR）FBG（反射率＞99%，3 dB 带宽约为 1.6 nm）的栅区长度约为 4 cm，低反射（LR）光栅的栅区长度（反射率约为 10%）约为 3 mm。

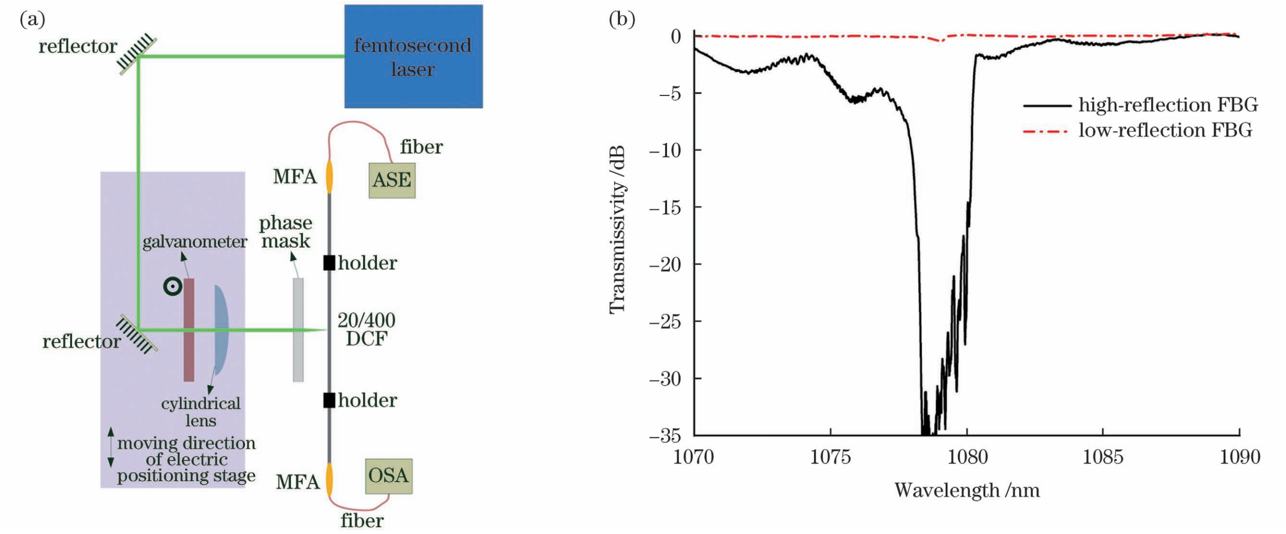

图 1　FBG 的刻写。（a）飞秒激光相位模板动态刻写系统示意图；（b）高反射 FBG 与低反射 FBG 的透射光谱

Fig. 1　Inscription of FBG. (a) Schematic of femtosecond laser phase mask dynamic writing system; (b) transmission spectra of high-reflection FBG and low-reflection FBG

图 2（a）所示为基于飞秒刻写光栅所搭建的振荡器系统，其中 QBH 为石英端帽，LD 为激光二极管，YDF 为掺镱光纤，CPS 为包层光滤除器。整个系统采用双向泵浦的方式，两个泵浦信号合束器位于高反射与低反射 FBG 之间，所用掺镱光纤（YDF）的长度为17 m，为了测试方便，振荡器的两端分别

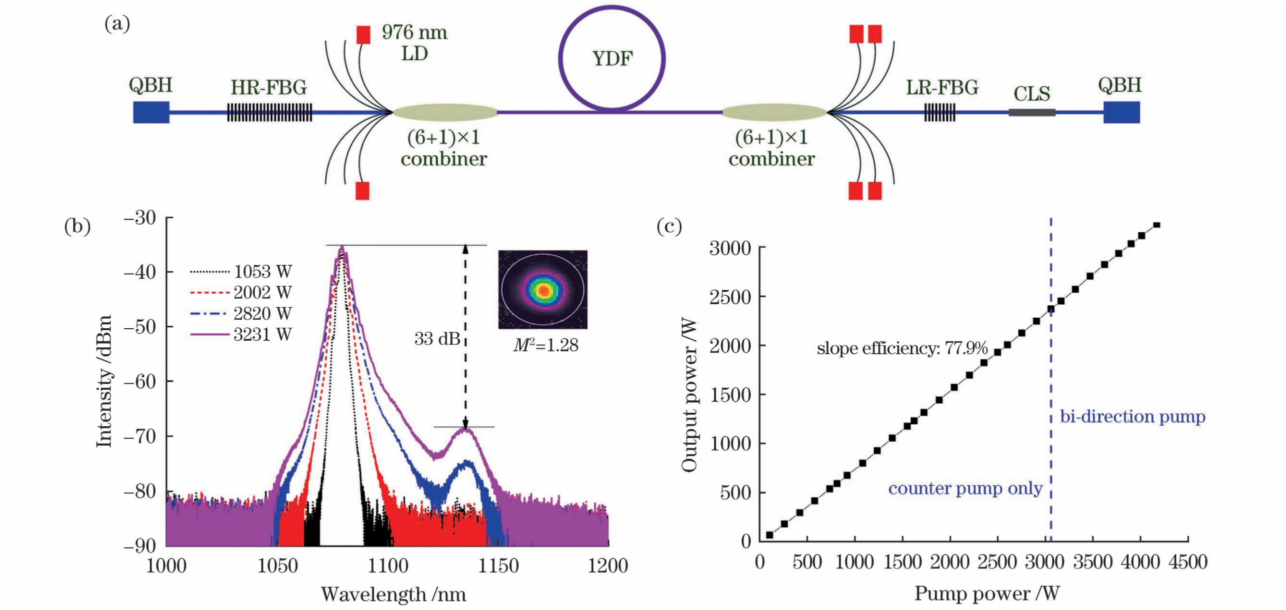

图 2　高功率激光实验。（a）振荡器系统图；（b）不同输出功率下的光谱（插图：输出功率为 3231 W 时的光斑）；（c）振荡器输出功率随泵浦功率的变化

Fig. 2　High power laser experiment. (a) Schematic of oscillator; (b) laser spectra under different output powers (inset: beam profile at output power of 3231 W); (c) relationship between output power of oscillator and pump power

熔接了端帽。图 2(b)所示为输出端信号光在不同功率下的光谱，激光的中心波长为～1079.2 nm，光谱的带宽随着功率的增加而增加，当输出功率大于 2568 W 时，在～1135 nm 附近可观察到受激拉曼散射(SRS)的光谱成分，当最高输出功率为 3231 W 时，信号光强度比 SRS 光强度大 30 dB 以上，测量得到此时的光束质量因子(M^2)约为 1.28，插图为输出功率为 3231 W 时所对应的光斑。图 2(c)所示为信号光功率随泵浦功率变化的曲线，激光器的斜率效率为 77.9%。当泵浦功率为 4170 W 时，振荡器的最高输出功率为 3231 W，此时测得高反 FBG 的温度为 40 ℃，低反 FBG 的温度为 42 ℃。

利用飞秒激光相位模板动态刻写技术制备的高反射与低反射 FBG，搭建了高功率光纤振荡器，实现了 3.2 kW 的功率输出，此时拉曼斯托克斯光的强度比信号光的强度低 33 dB。这是国内基于飞秒激光刻写的 FBG 首次实现千瓦级以上激光输出，对于推动高功率光纤激光器核心器件的全国产化以及提升振荡器的功率具有重要的意义。

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3.2 kW Single-Mode Fiber Oscillator Based on FBGs Inscribed by Femtosecond Laser

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Abstract

Objective Due to the characteristics like simple structure and easier operation, high power fiber oscillators have been largely utilized in national defense industry and industrial processing. The reported highest output power of an oscillator is more than 8 kW and this value can be further elevated in the future. Fiber Bragg gratings (FBGs) play an important role in these oscillators because the output power is directly influenced by the quality of FBGs. The most common method to fabricate FBGs used in oscillators is based on ultraviolet exposure, however, cumbersome processes like hydrogen-loading and annealing are unavoidable, which complicates the fabrication process. Moreover, the annealing process may deteriorate the spectrum of an FBG and a small amount of hydrogen may still remain in the fiber even after annealing, which results in a heat load in the oscillator system. In recent years, the femtosecond laser machining technique has been drastically improved, which provides a potential for FBGs fabrication. Until now, the reports about femtosecond laser inscribed FBGs used in high power oscillators are very limited. Only researchers from Jena University have reported the relevant investigations. For example, the researchers have proposed a 1.9 kW fiber oscillator by inscribing a chirped FBG in the double cladding ytterbium doped fiber with a core/inner-cladding diameter of 20 μm /400 μm in 2019, and a 5 kW oscillator by inscribing a pair of FBGs in the double cladding fiber with a core/inner-cladding diameter of 20 μm /400 μm using the phase mask scanning technique. At present, there is no relevant reports on writing a high power oscillator with FBGs inscribed by a femtosecond laser in China. The researches on this area need to be urgently carried out to find the best way to write high power oscillators with FBGs.

Methods The FBGs used in our experiments are fabricated by the femtosecond laser phase mask scanning method (Fig. 1(a)). The wavelength of the femtosecond laser is 515 nm, the repetition rate is 1 kHz, the pulse energy is about 250 μJ, and the beam diameter is 3 mm. A cylindrical lens is utilized to compress the beam size vertical to the fiber axis, and the galvanometer in the inscription system can realize the vibration of beam spot vertically to the fiber axis. Limited by the scale of beam profile, the focus of the femtosecond laser should be scanned along the fiber axis, if the length of the FBG is longer than 3 mm. The double cladding fiber with a core/inner-cladding diameter of 20 μm/400 μm is utilized to inscribe the FBGs. The period of FBGs is decided by the phase mask. The pitch of phase mask is 1487 nm and the chirped rate is 0.5 nm/cm. The reflectivity of a high-reflection FBG is over 99% and that of a low-reflection FBG is about 10% (Fig. 1(b)). Using this pair of FBGs, we construct an oscillator, and a bi-direction pump scheme is selected to inject the pump light (Fig. 2(a)). Co-pumping and counter-pumping combiner is placed in the cavity.

Results and Discussions The maximum output power of the oscillator is 3231 W with a pump power 4170 W, and the beam quality factor (M^2) is 1.28. The slope efficiency is about 77.9%. When the output power is higher than 2568 W, the Raman-Stokes light becomes obvious, and the intensity of the Raman-Stokes light is 33 dB below the laser intensity when the output power reaches 3231 W (Fig. 2). The temperature of FBGs is around 40 ℃ at the operation power of 3231 W. No roll-over of output power or efficiency is observed during the power scaling process. The maximum output power is only limited by pump power. For the reason that there still exist pump ports in unoccupied combiners, the output power can be further scaled up in the future.

Conclusions In this paper, we demonstrate a high power fiber oscillator based on a pair of 20 μm /400 μm large mode area double cladding fiber Bragg gratings fabricated by a femtosecond laser together with a phase mask. The reflectivity of the high-reflection FBG is more than 99%, and that of the low-reflection FBG is about 10%. The slope efficiency of the fiber oscillator is 77.9%, and the maximum power output is more than 3.2 kW. To the best of our knowledge, the kW level class fiber oscillator using FBGs fabricated by a femtosecond laser has never been reported in our nation before, and our research works fill the vacancy in this field, which is meaningful in fabrication of high power FBGs.

Key words　fiber optics; femtosecond laser; fiber Bragg grating; high power fiber oscillator