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飞秒激光刻写的10 kW级啁啾倾斜光纤布拉格光栅

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摘要 啁啾倾斜光纤布拉格光栅（CTFBG）是高功率光纤激光系统中抑制受激拉曼散射（SRS）的关键器件。使用飞秒激光在50 μm/400 μm光纤上研制了可承受10 kW激光功率的CTFBG。CTFBG插入损耗为0.03 dB，制冷后的功率温升系数仅为2.4 ℃/kW，验证了飞秒激光刻写的CTFBG具有优异的功率承受能力。

关键词 光纤光学；飞秒激光；高功率光纤激光器；受激拉曼散射；光纤布拉格光栅；啁啾倾斜光纤布拉格光栅
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光纤布拉格光栅（FBG）在高功率光纤激光器中具有重要应用[1]。一方面，FBG可以作为光纤振荡器的腔镜，起到选频和耦合输出的作用，并推动光纤振荡器向全光纤化方向发展[2-4]。另一方面，特殊结构的FBG，例如啁啾倾斜光纤布拉格光栅（CTFBG），可以作为全光纤滤波器，对高功率光纤激光中的受激拉曼散射（SRS）效应进行抑制，从而提高光纤激光器的输出功率与光谱纯度[5-7]。腔镜用FBG和CTFBG的功率承受能力是关键性能指标，决定其能否在更高功率的光纤激光器中发挥作用。传统的高功率FBG的制备方法为紫外激光相位掩模板法，在刻写FBG前后要分别对光纤进行载氢与退火处理，这使得FBG的制备周期普遍较长。更重要的是，当退火处理不彻底时，FBG中残留的氢分子和羟基化合物会吸收激光并发热，导致FBG极易在承受高功率激光时烧毁。目前，基于紫外激光刻写的腔镜用FBG和CTFBG的最高承受功率分别为8 kW级[2]和4 kW级[8]，CTFBG的功率承受能力还有很大的提升空间。然而，紫外激光制备的高功率CTFBG已经面临瓶颈，需要采用特殊的退火方法[6]、复刻写技术[7]等来提高CTFBG的承受功率，故其制备周期、工艺复杂性与经济成本都显著增加。

飞秒激光刻栅技术的发展[9]为制备高功率FBG提供了新的方案。飞秒激光可直接在光纤中刻写FBG，这不仅缩短了FBG的制备周期，也避免了FBG中氢气和羟基化合物的吸收发热问题。此外，飞秒激光刻写的FBG具有耐高温的优点[10]，其对高功率激光引起的温升也具有更好的鲁棒性。目前，国内外均有基于飞秒激光刻写高功率腔镜用FBG的报道[3-4]，其最高承受功率也达到了8 kW级[4]。2022年，国防科技大学南湖之光实验室报道了基于飞秒激光刻写的CTFBG[11]，并在高功率光纤激光器中验证了其抑制SRS的效果与功率承受能力[12-13]。目前基于飞秒激光刻写的高功率CTFBG都是刻写在20 μm/400 μm光纤中，其承受功率未超过4 kW。近期，国防科技大学南湖之光实验室通过优化飞秒激光刻栅系统，在50 μm/400 μm大芯径光纤中刻写了CTFBG。搭建了10 kW级高功率光纤放大器，并将CTFBG置于放大器的输出端，承受了10 kW的信号光功率。CTFBG的插入损耗为0.03 dB，封装制冷后的最高温度为52 ℃。

采用飞秒激光相位掩模板技术在剥除涂覆层的50 μm/400 μm光纤中刻写了CTFBG，刻写系统与文献[11]基本相同。所用的啁啾相位掩模板的啁啾率为2 nm/cm、周期为1586 nm。图1展示了CTFBG的光

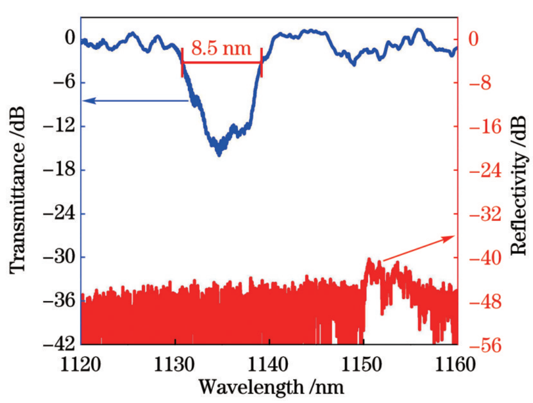

图1 CTFBG的测量光谱
Fig. 1 Measured spectra of CTFBG

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谱。其滤除带的中心波长为 1137 nm，3 dB 带宽为 8.5 nm，滤除深度约为 15 dB。使用自行搭建的级联泵浦光纤放大器测试CTFBG的功率承受能力，如图2所示。放大器采用纯后向泵浦结构，其种子源输出波长为1080 nm，泵浦源为一组1018 nm的光纤激光器，有源光纤为芯包直径从24 μm/200 μm到48 μm/400 μm的锥形掺镱光纤（YDF），激光经过包层光滤除器（CLS）与光纤准直器（QBH）后输出，在CLS前插入CTFBG滤除拉曼光。

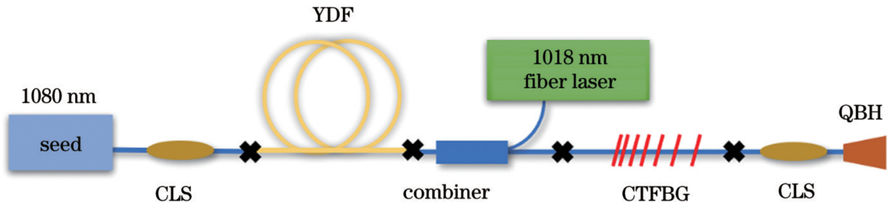

图 2　基于 10 kW 光纤放大器的 CTFBG 测试系统

Fig. 2　Test system for CTFBG based on 10 kW fiber amplifier

实验结果如图3所示。图3（a）展示了插入CTFBG前后最大功率下的输出光谱。CTFBG的滤除带宽为12 nm，最大滤除深度为10 dB，这与图1光谱中CTFBG的滤除宽度与深度有所差异，原因在于CTFBG对基模与高阶模拉曼光的滤除效果不同[14]。图1是使用模式匹配器测量得到的CTFBG的基模透射谱，而在50 μm/400 μm光纤中拉曼光分布在基模与高阶模中，实际CTFBG滤除效果受基模与高阶模的共同影响。图3（b）展示了插入CTFBG前后的输出功率变化曲线以及输出激光光斑图。插入CTFBG后，激光器输出功率由10170 W下降到10090 W，斜率效率（η）由81.2%下降为80.7%，CTFBG的插损为0.03 dB。输出光束质量轻微退化，光束质量因子（M^2）由3.35增大到3.46。在激光器多次功率放大过程中，CTFBG出现了自退火效应[3,13]，其温升特性趋于稳定后，对CTFBG进行了高效制冷封装并使用热像仪测量温度，结果如图3（c）所示。CTFBG的功率温升系数为2.4 ℃/kW，10 kW输出功率时的温度为52 ℃，表明CTFBG还具有承受更高功率的潜力。

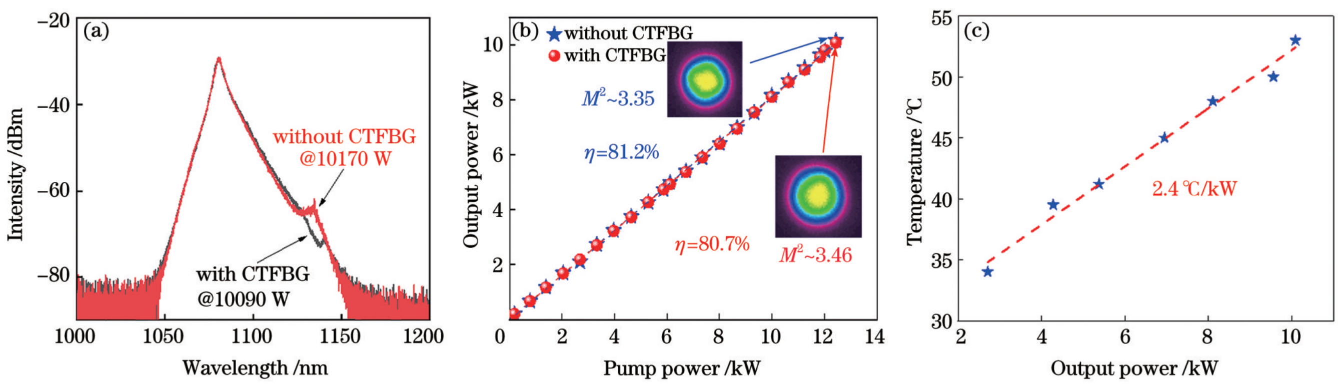

图 3　测试结果。（a）加入 CTFBG 前后的输出光谱；（b）输出功率与激光光斑图；（c）CTFBG 的温度变化

Fig. 3　Test results. (a) Output spectra without and with CTFBG; (b) output power and laser beam profile; (c) temperature variation of CTFBG

本文报道的基于飞秒激光刻写的CTFBG承受了10 kW的信号光功率，其插入损耗为0.03 dB，功率温升系数为2.4 ℃/kW。研究结果表明：飞秒激光刻写的CTFBG具有优异的功率承受能力。今后将进一步优化10 kW级CTFBG的滤除带宽与深度，增强其SRS抑制效果。

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Femtosecond-Written 10-kW Chirped and Tilted Fiber Bragg Gratings

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Abstract

Objective Fiber Bragg gratings (FBGs) have important applications in high-power fiber lasers. FBGs can act as cavity mirrors for fiber oscillators, playing a role in frequency selection and coupling output and promoting the development of fiber oscillators toward all-fiber fiber structure. In addition, special FBGs, such as chirped and tilted FBGs (CTFBGs), can act as all-fiber filters to suppress stimulated Raman scattering (SRS) in high-power fiber lasers, improving the output power and spectral purity of fiber lasers. The power handling capability is the key performance index for mirror FBGs and CTFBGs. The traditional fabrication method for mirror FBGs and CTFBGs is the ultraviolet (UV) laser phase mask method; however, hydrogen loading and thermal annealing treatment are required in this method, which leads to a long FBG fabrication period. In addition, if thermal annealing treatment is not complete, the residual hydrogen molecules in the FBG would absorb high-power lasers, limiting the power handling capability of FBGs. With the development of femtosecond (fs)-laser inscribing technology, a new scheme has emerged for fabricating high-power CTFBGs. An fs-laser can directly inscribe a CTFBG in the fiber; hence, the fiber does not need hydrogen loading and annealing treatment, which not only shortens the fabrication period but also avoids the heating caused by incomplete annealing. Moreover, CTFBGs written by fs-lasers have better tolerance to the temperature increase caused by high-power lasers.

Methods A CTFBG is written using fs-laser phase mask technology. Figure 1 shows the spectrum of the CTFBG. The filtering band central wavelength of the CTFBG is 1137 nm, with a 3-dB bandwidth of 8.5 nm and a filtering depth of approximately 15 dB. The homemade high-power fiber amplifier with a maximum output power of 10 kW is used to test the CTFBG, as shown in Fig. 2.

Results and Discussions Figure 3(a) shows the output spectra at maximum output powers with and without the CTFBG. The CTFBG has a maximum filtering depth of 10 dB and a filtering width of 12 nm. Figure 3(b) shows the output power variation with and without the CTFBG, as well as the output laser beam profile. After inserting the CTFBG, the output power decreases from 10170 W to 10090 W, and hence the insertion loss of the CTFBG is 0.03 dB. The output beam quality degrades slightly, and the beam quality factor (M^2) increases from 3.35 to 3.46. The CTFBG with a cooling package has a small thermal slope of 2.4 ˚C/kW, as shown in Fig. 3(c).

Conclusions A CTFBG written by a fs-laser is introduced at the output end of a 10-kW fiber laser to test its power handling capability. The CTFBG has an insertion loss of 0.03 dB and a small thermal slope of 2.4 ˚C/kW. This study shows that the fs-laser-written CTFBG has excellent power handling capability, which will further promote the development and application of CTFBGs.

Key words fiber optics; femtosecond lasers; high-power fiber lasers; stimulated Raman scattering; fiber Bragg gratings; chirped and tilted fiber Bragg gratings