中国激光

国产 25 μm/400 μm 啁啾倾斜光纤光栅传输功率突破 4 kW

王蒙[1,2,3*]，田鑫[1,2]，赵晓帆[1,3]，叶云[1,2]，饶斌裕[1,2]，奚小明[1,2,3]，王小林[1,2,3]，陈子伦[1,2,3]，王泽锋[1,2,3**]

[1]国防科技大学前沿交叉学科学院，湖南 长沙 410073；
[2]脉冲功率激光技术国家重点实验室，湖南 长沙 410073；
[3]高能激光技术湖南省重点实验室，湖南 长沙 410073

摘要 啁啾倾斜光纤光栅(CTFBG)在高功率光纤激光受激拉曼散射抑制中有重要的应用。在 25 μm/400 μm 光纤上研制了可承受 4.35 kW 激光功率的 CTFBG，这是目前国内外已报道的最高功率水平。CTFBG 的插入损耗小于 0.3 dB，最高功率下的温升仅为 7.5 ℃，温升系数约为 1.72 ℃/kW，表明其具有承受更高激光功率的能力。

关键词 激光器；光纤激光器；受激拉曼散射；光纤光栅；啁啾倾斜光纤光栅
中图分类号 TN248 **文献标识码** A **doi**：10.3788/CJL202149.0615001

受激拉曼散射(SRS)是制约高功率光纤激光系统功率提升的主要因素之一。到目前为止，国内外学者已提出多种抑制 SRS 的方法，主要包括增大光纤模场面积[1]、采用光谱选择性光纤[2-3]和使用光谱滤波器件[4-13][如长周期光纤光栅(LPFG)和啁啾倾斜光纤光栅(CTFBG)]。LPFG 可以将前向传输的纤芯模耦合到前向传播的包层模中，通过设计合理的光栅参数，可以实现对纤芯 SRS 产生的 Stokes 光的滤波。但是，对于大模场双包层光纤，一般存在几个模式，LPFG 纤芯中容易发生基模与高阶模之间的耦合，影响光束质量。此外，LPFG 对外界温度和应变非常敏感，其光谱特性会受影响，进而影响 SRS 抑制的效果和稳定性。CTFBG 将前向传输的纤芯模耦合到后向传输的包层模中，纤芯模之间的耦合非常弱，因此对光束质量的影响非常小。此外，CTFBG 对温度和应力的灵敏度要低很多，所以具有更好的光谱稳定性，更有利于 SRS 的抑制。因此，利用 CTFBG 抑制 SRS 的研究报道较多。

2017 年，国防科技大学首次报道了 CTFBG 抑制光纤激光 SRS 的实验[5]，引起了国内外的广泛关注[6-12]。2019 年和 2020 年，南京理工大学和加拿大麦吉尔大学分别将 CTFBG 的承受功率提升到千瓦量级[9-10]。2021 年，中国工程物理研究院研制的 25 μm/400 μm CTFBG 可承受 3.4 kW 的激光功率[11]。2017 年以来，国防科技大学在大模场双包层 CTFBG 的制备和高功率光纤激光系统 SRS 的抑制两个方面开展了大量的研究工作，通过不断优化刻写工艺，实现了低插损、高抑制比的千瓦级 CTFBG[12]。近期，国防科技大学通过进一步优化光栅刻写参数和退火工艺，并设计高效的制冷封装夹具，在 25 μm/400 μm 的载氘光纤上制备了可承受 4.35 kW 激光功率的 CTFBG，这是国内外已报道的最高功率水平。CTFBG 性能良好，插入损耗 <0.3 dB，温升系数仅为 1.72 ℃/kW，表明其具有承受更高激光功率的能力，对于高功率光纤激光系统 SRS 的抑制具有重要的意义。

收稿日期：2021-10-29；**修回日期**：2021-11-22；**录用日期**：2021-11-29

基金项目：国家自然科学基金面上项目(11974427，12004431)、湖南省自然科学基金杰出青年科学基金项目(2019JJ20023)、湖南省科技创新人才计划科技创新领军人才项目(2021RC4027)、脉冲功率激光技术国家重点实验室主任基金项目(SKL2020ZR05，SKL2021ZR01)、湖南省研究生科研创新项目(CX20200046)

通信作者：*gfkdqy@163.com；**zefengwang_nudt@163.com

CTFBG 采用紫外激光加相位掩模板的方法进行刻写，图 1 为测得的传输光谱。可以看到，其中心波长约为 1133.5 nm，3 dB 带宽约为 7 nm，中心波长处的滤除深度>20 dB。我们自行搭建了图 2 所示的主振荡功率放大器系统，并对 CTFBG 进行了测试。种子源的中心波长为 1080 nm，采用 981 nm 的半导体激光双端抽运的方式进行激光放大，CTFBG 接于后向泵浦合束器输出光纤与包层光滤除器之间。

测试平台是课题组现有的一套高功率光纤激光放大器，由于使用了 25 μm/400 μm 的掺镱光纤和特殊波长 981 nm 的半导体泵浦源，并优化了增益光纤长度，因此在 4 kW 下传输时既没有观测到受激拉曼散射，也没有模式不稳定效应产生。本实验重点进行了 CTFBG 的功率承受能力和稳定性的测试(CTFBG 对 SRS 的抑制在之前的研究中已经得到充分的验证，包括千瓦级系统[9,11-12])，结果如图 3 所示。从图 3(a)可以看到，当最大输入功率为 4348 W时，CTFBG输出端测得的功率为 4158 W

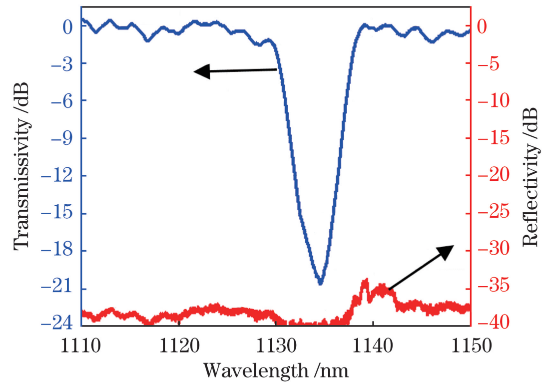

图 1　自研 25 μm/400 μm CTFBG 的传输谱测量结果

Fig. 1　Measured transmission spectra of home-made 25 μm/400 μm CTFBG

(如右下角的实验照片所示)，插入损耗小于 0.3 dB，此时光栅的最高温度为 27.5 ℃，温升系数仅为 1.72 ℃/kW。4348 W 为国内外报道的 CTFBG 最高承受功率。当 CTFBG 输出端功率约为 4105 W 时，进行了 10 min 的稳定性测试，结果如图 3(b)所示，初步验证了 CTFBG 的高功率运行稳定性。

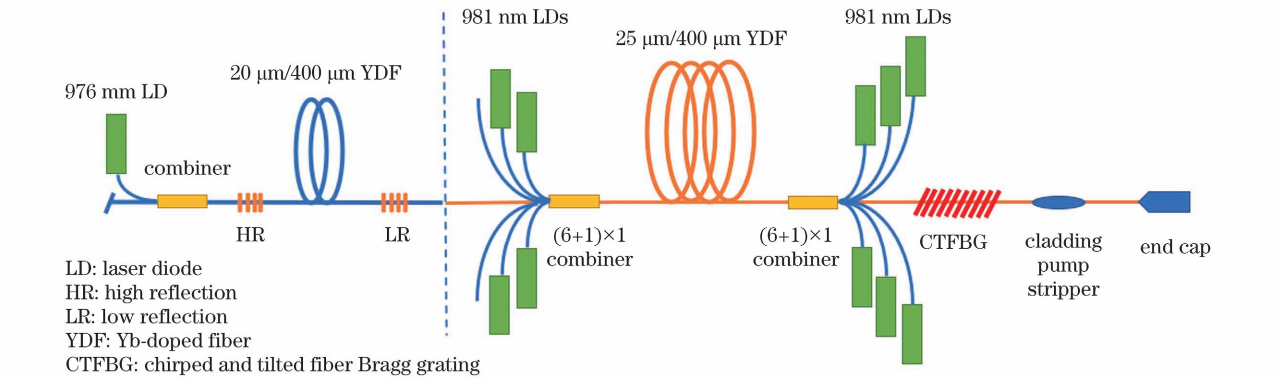

图 2　基于主振荡功率放大器的 CTFBG 测试系统

Fig. 2　Measurement system for CTFBG based on master oscillator power amplifier

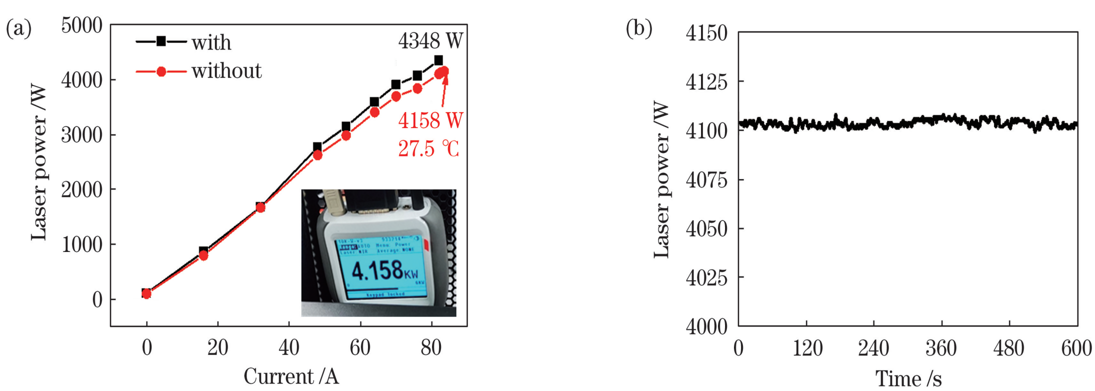

图 3　CTFBG 的实验结果。(a)接入 CTFBG 前后的输出功率及 CTFBG 的热像图；(b)高功率水平下的输出功率随时间的变化

Fig. 3　Experimental results of CTFBG. (a) Output power with or without CTFBG and thermal image of CTFBG; (b) output power versus time under high power level

本文报道了国内外最高功率水平的 CTFBG，插入损耗小于 0.3 dB，温升系数仅为 1.72 ℃/kW，实现了大于 4 kW 的稳定工作，对于推动国产高功率 CTFBG 研制、进一步提升光纤激光系统的输出功率有重要意义。同时，将其置于高功率光纤激光器的输出端，有望增加系统的传输距离，对于高功率光纤激光器的应用有很大的促进作用。后续，我们将在更大芯径的光纤上制备 CTFBG，进一步改进制备工艺，增加抑制带宽和抑制深度，降低插入损耗，使其在国产高功率光纤激光系统中发挥更重要、更广泛的作用。

参 考 文 献

[1] Wang Y, Xu C Q, Po H. Analysis of Raman and thermal effects in kilowatt fiber lasers[J]. Optics Communications, 2004, 242(4/5/6): 487-502.

[2] Zenteno L, Wang J, Walton D, et al. Suppression of Raman gain in single-transverse-mode dual-hole-assisted fiber[J]. Optics Express, 2005, 13(22): 8921-8926.

[3] Kim J, Dupriez P, Codemard C, et al. Suppression of stimulated Raman scattering in a high power Yb-doped fiber amplifier using a W-type core with fundamental mode cut-off[J]. Optics Express, 2006, 14(12): 5103-5113.

[4] Jiao K R, Shen H, Guan Z W, et al. Suppressing stimulated Raman scattering in kW-level continuous-wave MOPA fiber laser based on long-period fiber gratings[J]. Optics Express, 2020, 28(5): 6048-6063.

[5] Wang M, Zhang Y J, Wang Z F, et al. Fabrication of chirped and tilted fiber Bragg gratings and suppression of stimulated Raman scattering in fiber amplifiers[J]. Optics Express, 2017, 25(2): 1529-1534.

[6] Wang M, Liu L, Wang Z F, et al. Mitigation of stimulated Raman scattering in kilowatt-level diode-pumped fiber amplifiers with chirped and tilted fiber Bragg gratings[J]. High Power Laser Science and Engineering, 2019, 7(1): 132-137.

[7] Wang M, Wang Z F, Liu L, et al. Effective suppression of stimulated Raman scattering in half 10 kW tandem pumping fiber lasers using chirped and tilted fiber Bragg gratings[J]. Photonics Research, 2019, 7(2): 167-171.

[8] Tian X, Zhao X F, Wang M, et al. Influence of Bragg reflection of chirped tilted fiber Bragg grating on Raman suppression in high-power tandem pumping fiber amplifiers[J]. Optics Express, 2020, 28(13): 19508-19517.

[9] Jiao K R, Shu J, Shen H, et al. Fabrication of kW-level chirped and tilted fiber Bragg gratings and filtering of stimulated Raman scattering in high-power CW oscillators[J]. High Power Laser Science and Engineering, 2019, 7: e31.

[10] Lin W, Desjardins-Carrière M, Sévigny B, et al. Raman suppression within the gain fiber of high-power fiber lasers[J]. Applied Optics, 2020, 59(31): 9660-9666.

[11] Song H Q, Yan D L, Wu W J, et al. SRS suppression in multi-kW fiber lasers with a multiplexed CTFBG[J]. Optics Express, 2021, 29(13): 20535-20544.

[12] Zhao X F, Tian X, Wang M, et al. Fabrication of 2 kW-level chirped and tilted fiber Bragg gratings and mitigating stimulated Raman scattering in long-distance delivery of high-power fiber laser[J]. Photonics, 2021, 8(9): 369.

[13] Li F Y, Li Y, Song H Q, et al. National optical fiber material devices achieve high SRS suppression ratio of 20.88 kW output[J]. Chinese Journal of Lasers, 2021, 48(21): 2116002.
李峰云, 黎玥, 宋华青, 等. 全国产光纤材料器件实现高 SRS 抑制比 20.88 kW 输出[J]. 中国激光, 2021, 48(21): 2116002.

Transmission Power of Homemade Chirped and Tilted Fiber Bragg Grating on 25 μm/400 μm Fiber Exceeding 4 kW

Wang Meng[1,2,3*], Tian Xin[1,2], Zhao Xiaofan[1,3], Ye Yun [1,2], Rao Binyu[1,2], Xi Xiaoming[1,2,3], Wang Xiaolin[1,2,3], Chen Zilun[1,2,3], Wang Zefeng [1,2,3**]

[1] *College of Advanced Interdisciplinary Studies, National University of Defense Technology, Changsha, Hunan* 410073, *China*;

[2] *State Key Laboratory of Pulsed Power Laser Technology, Changsha, Hunan* 410073, *China*;

[3] *Hunan Provincial Key Laboratory of High Energy Laser Technology, Changsha, Hunan* 410073, *China*

Abstract

Objective Stimulated Raman scattering effect (SRS) is one of the major restrictions upon the further improvement of output power in fiber laser systems. So far, many methods have been explored for SRS suppression in fiber laser systems, such as enlarging the fiber effective mode area, the application of spectrally selective fibers, and using lumped spectral filters. The usage of a chirped and tilted fiber Bragg grating (CTFBG) has attracted much attention in recent years due to its all-fiber structure, flexible design, and good stability. A CTFBG can couple the forward core modes to the backward-propagating cladding mode. Based on the reasonable design of a CTFBG, the Stokes light of the core can be first coupled to the cladding and then leaks into the air, and thus the SRS filtering and suppression are realized. In 2017, the groups from National University of Defense and Technology have proposed and applied a CTFBG to suppress SRS for the first time. Up to now, a kW-level CTFBG with a low loss and a high rejection ratio has been realized and applied. However, it is still unable to meet the needs of a high-power fiber laser system in these years. Therefore, the development of CTFBGs with the ability to handle a higher power laser is an imminent necessity.

Methods The CTFBG used in our experiment is fabricated with the ultraviolet laser phase mask method. The double cladding fiber with a core/cladding size of 25 μm/400 μm is utilized. The CTFBG had a filtering depth of >20 dB, a center wavelength of 1133.5 nm, and a 3 dB bandwidth of 7 nm (Fig. 1). The stability of the CTFBG is tested at the output of a master oscillator power amplification (MOPA) fiber laser system.

Results and Discussions The CTFBG supports the maximum signal laser power of 4.35 kW with an insertion loss of less than 0.3 dB. With the CTFBG working, a mere temperature rise of 7.5 ℃ upon the CTFBG device is recorded at the maximal output (Fig. 3(a)). The output power is very stable during a burn-in test of 10 min at the maximum output power (Fig. 3(b)), which indicates the CTFBG can work stably and satisfy the application requirements in a high power fiber laser system.

Conclusions This paper reports the CTFBG with the ability to support the highest power laser at home and abroad. The CTFBG on 25 μm/400 μm fiber supports the more than 4 kW laser power with an insertion loss of less than 0.3 dB and a high thermal handling capacity (~1.72 ℃/kW). It is of great significance to promote the development of domestic high-power CTFBGs and expand their applications in high power fiber laser systems.

Key words lasers; fiber laser; stimulated Raman scattering; fiber grating; chirped and tilted fiber grating