光学学报

飞秒级联啁啾倾斜光纤光栅用于拉曼滤除

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摘要 啁啾倾斜光纤光栅(CTFBG)是高功率光纤激光系统中拉曼光滤除的重要器件。采用飞秒激光级联刻写的方式，在大模场面积双包层光纤(LMA-DCF)中制备了一个带宽约为15.2 nm、滤除深度大于20 dB的CTFBG，将其置于1080 nm高功率光纤激光长距离传输系统的输出端，实现了光谱无拉曼输出，明显提高了输出激光纯度，插入损耗约为0.3 dB，光束质量无明显变化。所提出的利用飞秒激光制备宽带CTFBG的方法可有效滤除光谱中的拉曼光，对CTFBG的研制与应用有重要意义。

关键词 光栅；飞秒激光；高功率激光器；受激拉曼散射；光纤光栅；啁啾倾斜光纤光栅

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为了解决高功率光纤激光系统的受激拉曼散射(SRS)问题[1-2]，研究者们提出了各种各样的方案，其中使用长周期光纤光栅(LPFG)[3-6]和啁啾倾斜光纤光栅(CTFBG)[7-14]作为光谱滤波器件具有简单有效的特点。LPFG对温度、应力和弯曲等因素比较敏感，其光谱稳定性相对较差[15]。相比之下，CTFBG具有更好的鲁棒性，已经得到广泛的研究与应用，并且成功实现了商业化[16-17]。CTFBG的滤除带宽和深度决定了滤除效果，因此增大其滤除带宽和深度是十分必要的。2022年，国防科技大学报道了级联CTFBG的方法，通过级联两个不同倾角的CTFBG可以有效增大CTFBG的带宽[14]。利用传统的紫外激光相位掩模版法制备级联CTFBG具有以下不足：1)在刻写CTFBG前后需要对光纤进行载氢与退火处理，延长了CTFBG的制备周期，增加了制作成本；2)级联刻写不同倾角的CTFBG时需要改变相位掩模版的倾角，并重新校准刻写系统，增大了制备级联CTFBG的操作复杂性；3)级联CTFBG的Bragg反射带宽也会随着滤除带宽的增加而增大，而Bragg反射带宽的增大可能会给拉曼(Raman)光提供反馈，影响CTFBG的滤除效果[11]。

2022年，国防科技大学南湖之光实验室首次报道了基于飞秒激光相位掩模版法的CTFBG刻写系统[18]，为制备级联CTFBG提供了一个更有前景的技术方案。该CTFBG刻写系统具有刻写倾角调整灵活的优点，并且Bragg反射带宽不会随着倾角改变。此外，由于飞秒激光对光纤光敏性没有要求，刻写前后不需要对光纤进行载氢与退火处理，缩短了制备周期。近期，国防科技大学南湖之光实验室采用飞秒激光级联刻写技术在大模场面积双包层光纤(LMA-DCF)中刻写了一个宽带CTFBG用于拉曼滤除实验。CTFBG的滤除带宽达到了15.2 nm，其滤除带中心波长为1135 nm。通过将CTFBG置于1080 nm高功率光纤激光长距离传输系统的输出端，实现了1.4 kW信号光在18 m无源光纤中的远距离传输，并且输出光谱中的拉曼光几乎被完全滤除。

基于飞秒激光刻写CTFBG的实验系统与文献[18]的实验系统基本相同。波长为515 nm、重复频率为1 kHz的飞秒激光经过反射镜反射后，依次正入射到焦距为25 mm的柱面镜和啁啾率为2 nm/cm、周期为1577 nm的啁啾相位掩模版，最后聚焦于待刻写的光纤纤芯。通过压电振动台使光纤倾斜振动，从而在纤芯形成倾斜的光栅栅面。同时，由于反射镜与柱面镜固定在一个一维位移台上，通过移动一维位移台可以实现飞秒激光沿着光纤轴向扫描啁啾相位掩模版，从而增大光栅的刻写长度并引入更大的啁啾量。在飞秒激光沿着光纤轴向扫描的过程中，通过改变压电振动台的振幅可以引入不同角度的倾斜栅面，进而实现级联CTFBG的刻写。级联CTFBG的结构如图1所示，由两段不同倾角的sub-CTFBG Ⅰ和sub-CTFBG Ⅱ组成。图2(a)、(b)分别展示了单级CTFBG和级联

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CTFBG的光谱。单级CTFBG的倾角为6.4°，栅区长度为20 mm；级联CTFBG由两段不同倾角的CTFBG组成，每段栅区长度都为10 mm，角度分别6.9°和5.3°。级联CTFBG与单级CTFBG的栅区总长度都为20 mm，但是级联CTFBG的带宽更大，达到了15.2 nm，同时滤除深度也能保持在20 dB以上。两者的滤除带中心波长都为1135 nm，对应1080 nm信号光产生的拉曼光波长。

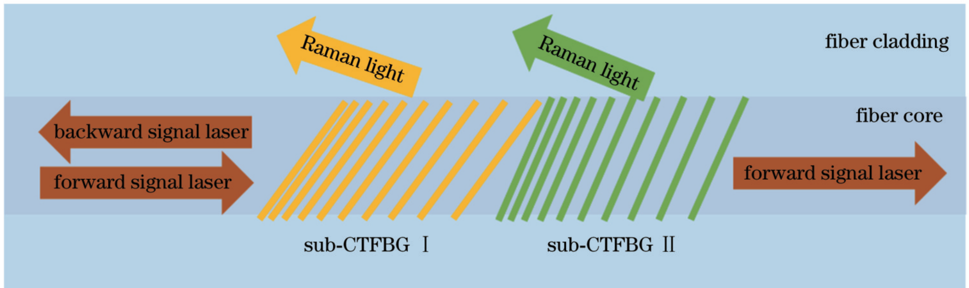

图1　级联CTFBG的结构示意图

Fig. 1　Structure diagram of cascade CTFBG

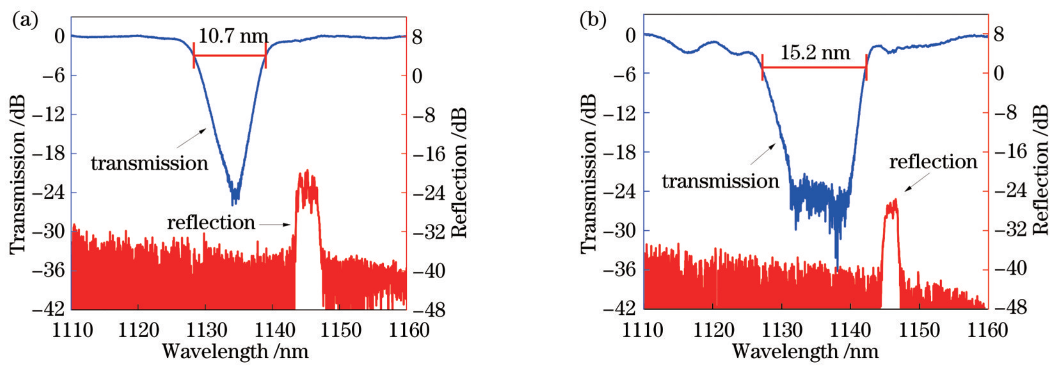

图2　CTFBG的光谱。(a)单级CTFBG；(b)级联CTFBG

Fig. 2　Spectra of CTFBG. (a) One-stage CTFBG; (b) cascade CTFBG

为了测试级联CTFBG滤除拉曼光的效果，搭建了基于高功率光纤激光器的测试系统，如图3所示。测试光源为一台工业用1080 nm连续波高功率光纤激光振荡器，其输出光纤为纤芯/包层直径为20/400 μm的LAM-DCF，总长度约为18 m。输出端有包层光滤除器(CLS)和端帽(QBH)，最高输出功率约为1.5 kW，测量得到的不同输出功率下的输出光谱如图4(a)所示。最高输出功率下，光谱信号光与拉曼光的光强差约为35 dB。将CTFBG插入到CLS前端，同时为了保证测试系统的光纤总长度不变，在加入1 m长的CTFBG后，将无源光纤长度截短为17 m，测量得到的输出光谱如图4(b)所示，插图为最高功率时的输出激光光斑。可以看到，在最大输出功率下，拉曼光几乎被完全滤除，此时光谱的信噪比约为46 dB，拉曼滤除比为11 dB。受限于测试系统产生的拉曼光强度，CTFBG的实际拉曼滤除比小于其透射谱滤除深度。通过对比CTFBG插入前后的振荡器输出功率变化，得到CTFBG的损耗约为0.3 dB。CTFBG插入前后输出激光光束质量因子M^2仅仅从1.45增大到1.51，因此光束质量没有出现明显变化。

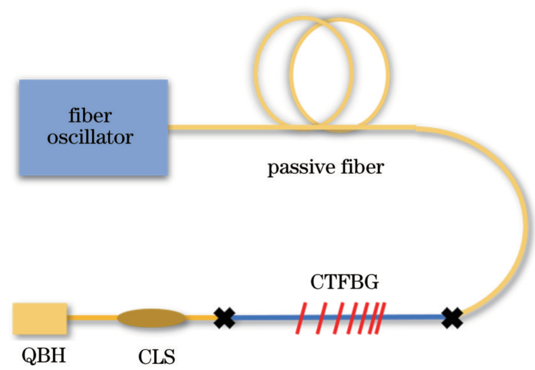

图3　级联CTFBG的测试系统

Fig. 3　Testing system of cascade CTFBG

本文报道了飞秒激光刻写的级联宽带CTFBG，并验证了其在高功率光纤激光器中的拉曼滤除效果。级联CTFBG的滤除带宽达到了15.2 nm，滤除深度大于20 dB。通过将级联CTFBG置于1080 nm高功率光纤激光器的输出端，实现了1.4 kW信号光在18 m长光纤中的远距离传输，同时输出光谱中的拉曼光几乎被完全滤除，最大拉曼滤除比为11 dB，且对输出光束质量几乎没有影响。本文验证了飞秒激光刻写的级联宽带CTFBG具有良好的拉曼滤除效果，对提升光

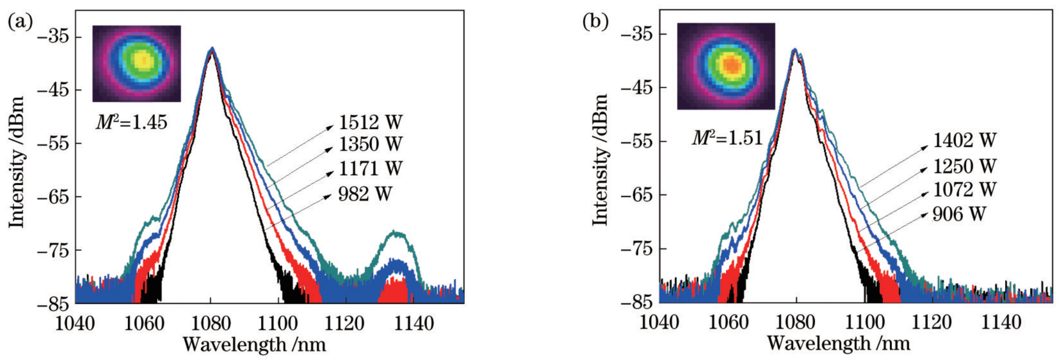

图 4　测试系统的输出光谱与激光光斑图。(a)未加入级联 CTFBG;(b)加入级联 CTFBG

Fig. 4　Output spectra and beam profiles of testing system. (a) Without cascade CTFBG; (b) with cascade CTFBG

纤激光系统的输出功率与传输距离有重要意义。后续将进一步优化飞秒 CTFBG 制备工艺,降低插入损耗,并提高其功率承受能力。

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Femtosecond Cascade Chirped and Tilted Fiber Bragg Gratings for Raman Filtering

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Abstract

Objective The chirped and tilted fiber Bragg grating (CTFBG) is an important component for filtering Raman light in high-power fiber laser systems. The filtering bandwidth and depth of CTFBG determine the filtering effect, so it is necessary to increase its filtering bandwidth and depth. The tandem inscription method can effectively increase the bandwidth by cascading two CTFBGs with different tilted angles. However, the tandem inscription method based on the traditional ultraviolet laser phase mask technology has the following shortcomings. 1) The fiber needs to be processed by hydrogen loading and heat annealing before and after the CTFBG inscription, respectively, which increases the fabrication time and cost. 2) When cascade CTFBGs with different tilted angles are inscribed, it is necessary to change the tilted angle of the phase mask and realign the inscription system, which increases the inscription complexity. 3) The Bragg reflection bandwidth of cascade CTFBG will also increase, which may provide feedback to Raman light and affect the Raman filtering effect of CTFBG. The proposed femtosecond laser inscription system for cascade CTFBG in this paper can effectively overcome the above shortcomings.

Methods The femtosecond laser arrives at the cylindrical lens and the chirped phase mask in turn and finally forms interference fringes on the fiber core. The tilted grating plane is formed by oblique scanning of the fiber via a piezoelectric stage. At the same time, the femtosecond laser scans the chirped phase mask along the fiber axis, thereby increasing the length of the grating and introducing a larger chirp. When the femtosecond laser scans along the fiber axis, the grating planes with different tilted angles can be formed by changing the amplitude of the piezoelectric stage, thereby realizing the inscription of cascade CTFBGs. The schematic of the grating structure of the cascade CTFBG is shown in Fig. 1, which consists of sub-CTFBG Ⅰ and sub-CTFBG Ⅱ with different gratings.

Results and Discussions Figs. 2(a) and 2(b) show the spectra of single-stage CTFBG and cascade CTFBG, respectively. The tilted angle of the former is 6.4° with a grating length of 20 mm. The latter consists of two sections of CTFBG with different tilted angles, and its grating length is 20 mm. The bandwidth of cascade CTFBG is wider than single-stage CTFBG, and the filtration depth can be maintained greater than 20 dB. In order to test the performance of cascade CTFBG for filtering Raman light, a test system is built (Fig. 3). The test source is a continuous-wave high-power fiber oscillator of 1080 nm with a maximum output power of about 1.5 kW and output fiber length of about 18 m. The output spectra measured without and with cascade CTFBG at different output powers are shown in Figs. 4(a) and 4(b), respectively. Raman light is almost completely filtered out by cascade CTFBG at the maximum output power.

Conclusions Here, a CTFBG is fabricated by the femtosecond laser tandem inscription method, and the filtering bandwidth and depth of which are about 15.2 nm and greater than 20 dB, respectively. By introducing the CTFBG at the output end of a high-power fiber laser long-distance transmission system of 1080 nm, the output spectrum without Raman light is realized, which greatly improves the purity of the output laser. This work provides a method for the fabrication of the wideband CTFBG and demonstrates its Raman filtering effect, which is of significance for the development and application of CTFBG.

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