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光学学报

基于飞秒激光制备的啁啾倾斜布拉格光纤光栅

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摘要 啁啾倾斜布拉格光纤光栅(CTFBG)在高功率光纤激光器的受激拉曼散射(SRS)抑制中有重要的应用。利用飞秒激光在纤芯/包层直径为 20/400 μm 的大模场面积双包层光纤(LMA-DCF)中刻写出不同角度的 CTFBG，其最大滤除深度约为 15 dB，最大滤除宽度约为 8.9 nm。飞秒激光刻写 CTFBG 可以显著缩短制备周期，对推动 CTFBG 的研制与发展具有重要意义。

关键词 光栅；飞秒激光；光纤光栅；啁啾倾斜布拉格光纤光栅

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高功率光纤激光器被广泛应用于工业、科研、国防等领域，而受激拉曼散射(SRS)是制约该激光器功率提升的主要因素之一[1]。为了抑制 SRS，研究人员使用具有滤波功能的光纤光栅如长周期光纤光栅(LPFG)[2]、啁啾倾斜布拉格光纤光栅(CTFBG)[3]，滤除 SRS 产生的拉曼光[4-12]。然而，LPFG 对温度、应力和弯曲较为敏感，导致其光谱特性和工作波长易受外界环境影响，进而影响 LPFG 对拉曼光的滤除效果[9-12]。相比之下，CTFBG 具有更好的光谱稳定性，更适合于在高功率光纤激光器中滤除拉曼光[4-8]。传统的 CTFBG 制备方法是紫外激光相位掩模板法[3]。由于紫外激光刻写光纤光栅对光纤光敏性有较高的要求，因此在刻写前后需要对光纤进行载氢和退火处理。载氢与退火处理的时间会随着光纤直径的增大而延长，尤其是在大模场面积双包层光纤(LMA-DCF)上制备 CTFBG 时，其制备周期明显延长。

飞秒激光刻写技术[13-15]为替代传统的紫外曝光法刻写 CTFBG 提供了新的思路。因为飞秒激光对光纤光敏性没有要求，所以其不需要对光纤进行载氢与退火处理，这有效地缩短了 CTFBG 的制备周期。目前，尽管已经有飞秒激光制备啁啾光纤光栅[16-18]和倾斜光纤光栅[19-20]的报道，但是还没有基于飞秒激光制备 CTFBG 的报道。近期，国防科技大学南湖之光实验室大功率光纤激光课题组基于飞秒激光相位掩模板法在 LMA-DCF 中刻写了 CTFBG，其制备周期明显缩短。进一步，刻写了不同倾斜角度的 CTFBG，最大滤除深度约为 15 dB，最大滤除宽度约为 8.9 nm，验证了飞秒激光刻写系统的灵活性与可靠性。

基于飞秒激光相位掩模板法的 CTFBG 刻写系统如图 1 所示。从激光光源发射出的飞秒激光(波长为 515 nm，脉宽为 190 fs，重复频率为 1 kHz，平均功率为 250 mW)沿 X 轴方向射到反射镜(RM)，经反射镜反射后沿 Y 轴方向依次经过柱面镜(CL)(焦距为 25 mm)、啁啾相位掩模板(PM；啁啾率为 2 nm/cm，周期为 1488 nm)和待刻写光纤(纤芯/包层直径为 20/400 μm 的 LMA-DCF)。飞秒激光经过柱面镜后聚焦于光纤纤芯，以保证纤芯处有足够大的能量强度达到折射率调制的阈值。相位掩模板使聚焦后的飞秒激光在纤芯形成周期性干涉条纹，从而诱导条纹的折射率呈周期性变化。由于飞秒激光聚焦后的束腰宽度小于纤芯直径，因此需要扩大光纤的横向折射率调制范围。将待刻写光纤通过光纤夹具(FH)固定在一个压电振动台(PP)上，通过压电振动台使光纤在 XZ 平面倾斜振动，此时飞秒激光将在光纤内部倾斜扫描，从而扩大横向折射率调制范围并形成倾斜光栅结构。同时，反射镜与柱面镜也被固定在一个一维位移台(TS)上，通过将一维位移台沿 X 轴方向运动来实现飞秒激光相对啁啾相位掩模板的扫描，从而增加光栅的刻写长度并引入更大的啁啾量。

CTFBG 刻写过程中的扫描策略示意图如图 2(a)所示，其中绿色(实心)图案为飞秒激光聚焦在纤芯形成的周期性干涉条纹，虚线为干涉条纹的扫描路径。

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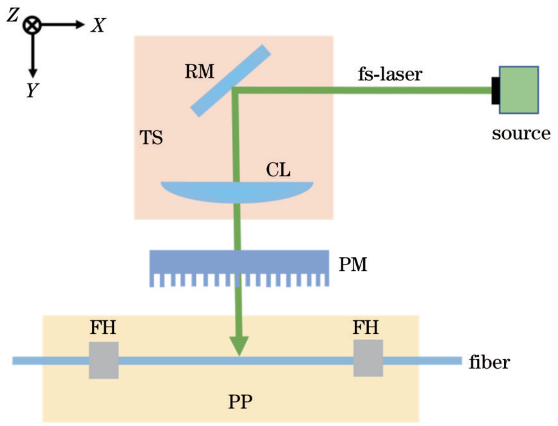

图 1　CTFBG 的刻写系统

Fig. 1　Inscription system for CTFBG

CTFBG 的啁啾量由啁啾相位掩模板决定，但是 CTFBG 的倾角可以灵活方便地进行调节。可以看到，倾角 $\theta=\arctan(\Delta L_X/\Delta L_Z)$，其中 ΔL_X 和 ΔL_Z 分别为干涉条纹在 X 轴方向与 Z 轴方向的扫描长度。因此，通过改变压电振动台的振动长度即可调节 CTFBG 的倾角。随后，刻写出不同倾角的 CTFBG，其栅区长度都为 28 mm。图 2(b)、(c)为两个不同倾角 CTFBG 的显微镜图。可以看到，倾斜光栅结构清晰可见，并且完整地覆盖了纤芯区域。不同倾角 CTFBG 的光谱如图 3 所示。从透射谱可以看到，倾角逐渐增大，会激发更高阶的包层模与纤芯模之间的耦合，并且包层模与纤芯模的耦合系数会随倾角增大而减小，这导致了透射谱中心波长向短波方向移动并且透射谱深度减小。此外，随着

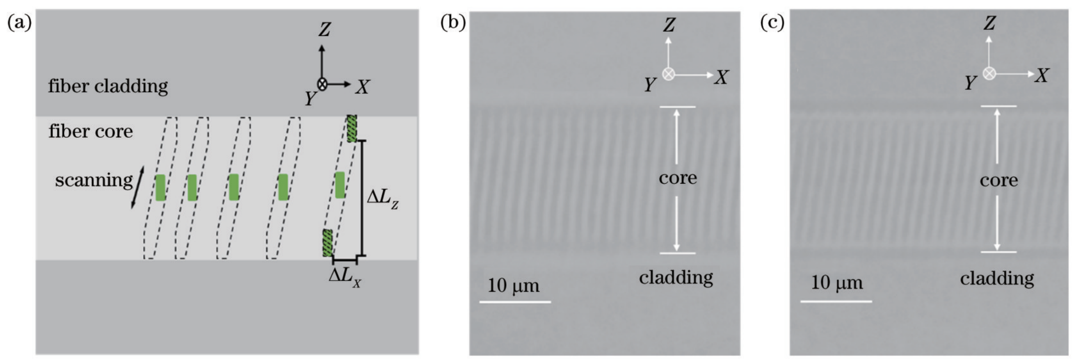

图 2　CTFBG 的示意图与显微镜图。(a)刻写 CTFBG 的扫描策略示意图；倾角为(b) 7.1°和(c) 8.3°的 CTFBG 显微镜图

Fig. 2　Schematic and micrographs of CTFBG. (a) Schematic of scanning strategy for inscribing CTFBG; micrographs of CTFBG with tilt angles of (b) 7.1° and (c) 8.3°

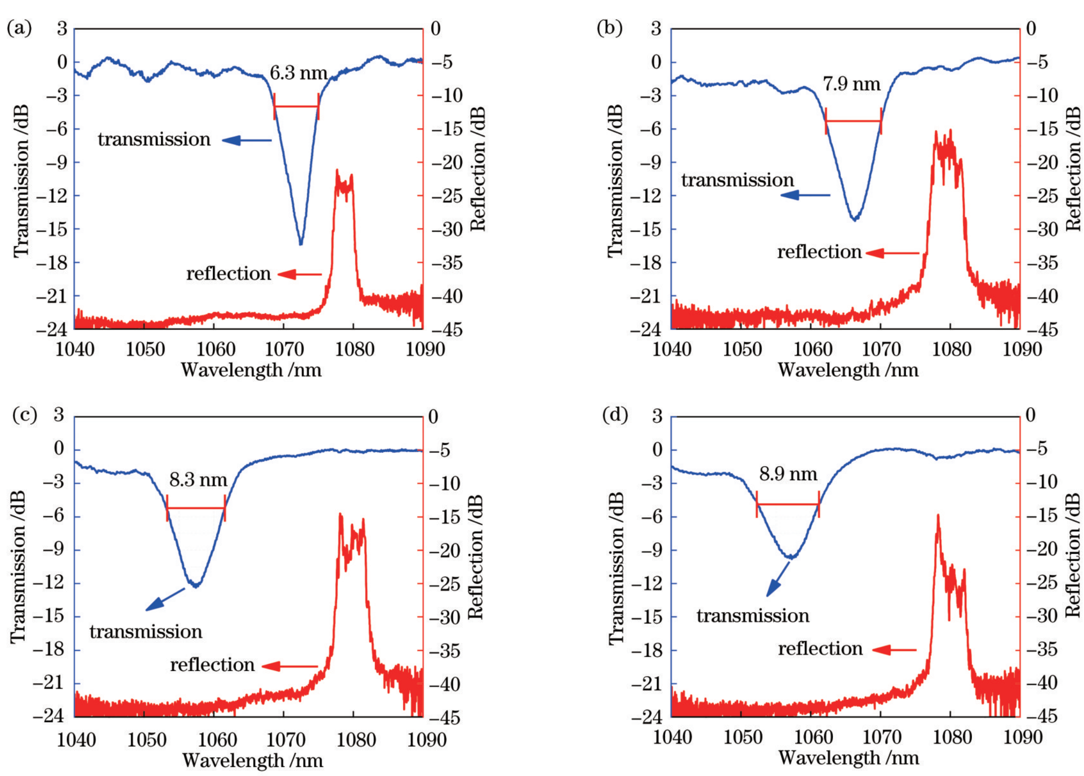

图 3　不同倾角的 CTFBG 光谱。(a) 4.7°；(b) 7.1°；(c) 8.3°；(d) 9.4°

Fig. 3　Spectra of CTFBG with different tilt angles. (a) 4.7°; (b) 7.1°; (c) 8.3°; (d) 9.4°

激发的包层模阶数增大,相邻包层模之间的波长间隔也变大,从而增大了透射谱带宽[3-5]。当倾角为4.7°时,CTFBG的滤除深度最大,约为15 dB;当倾斜角度为9.4°时,CTFBG的滤除宽度最大,约为8.9 nm。观察CTFBG的反射谱可以发现,随着倾斜角度增大,反射峰中心波长没有变化。这是因为基于飞秒激光倾斜扫描方式刻写的CTFBG的光栅周期Λ_g并不会随着倾斜角度的变化而改变,因此CTFBG的反射峰中心波长$\lambda=2n_{core}\Lambda_g$($n_{core}$为纤芯模的折射率)也保持不变。

本文报道了一种基于飞秒激光相位掩模板法的CTFBG刻写系统,并在LMA-DCF上刻写出不同倾斜角度的CTFBG,其最大滤除深度约为15 dB,最大滤除宽度约为8.9 nm。使用飞秒激光刻写CTFBG可以有效缩短制备周期,进一步促进CTFBG的发展与应用。下一步,我们将制备中心波长更长的CTFBG,以验证其在高功率光纤激光系统中的SRS抑制效果。

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Fabrication of Chirped and Tilted Fiber Bragg Gratings with Femtosecond Laser

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Abstract

Objective Up to now, high-power fiber lasers have been widely used in industrial processing, national defense, scientific research, and other fields. However, stimulated Raman scattering (SRS) is one of the main factors limiting the power scaling of such fiber lasers. In recent years, chirped and tilted fiber Bragg gratings (CTFBGs) have been demonstrated to suppress the SRS in high-power lasers by filtering the Raman light. CTFBGs are traditionally fabricated by the ultraviolet laser phase mask method, which requires the fibers to be hydrogen-loaded and thermal-annealed before and after grating inscription, respectively. This process is time-consuming and costly, especially when CTFBGs are fabricated with large-core fibers since the time for hydrogen loading and thermal annealing increases as the fiber core expands. The development of the femtosecond (fs) laser inscription method provides an alternative to the fabrication of CTFBGs. As it has no requirement on fiber photosensitivity, hydrogen loading and thermal annealing are no longer necessary, which greatly shortens the fabrication period of CTFBGs. However, although chirped FBGs and tilted FBGs have been fabricated by fs-lasers, fs-laser-inscribed CTFBGs have not been reported yet, and this paper is expected to fill this research gap.

Method The inscription system for CTFBGs is shown in Fig. 1. The fs-laser emitted from the laser source is reflected by a reflecting mirror and is then focused on a fiber after passing through a chirped phase mask and a cylindrical lens successively. The fiber is fixed on a piezoelectric platform by a pair of fiber holders, and the reflecting mirror and the cylindrical lens are fixed on a one-dimension translation stage. Because the waist width of focal spot is smaller than the diameter of the fiber core, a tilted grating structure can be obtained by the oblique scanning of the fiber with the piezoelectric platform. Moreover, a larger chirp and a longer grating length can be achieved by moving the translation stage along the fiber axis.

Results and Discussions Four CTFBGs with different tilt angles are fabricated, with their micrographs shown in Figs. 2 (b) and 2(c). The tilted grating structure is clear and completely covers the fiber core. Fig. 3 presents the measured spectra of the CTFBGs. The transmission spectra suggest that as the tilt angle increases, the center wavelength moves towards a short wavelength. In addition, the depth decreases while the width increases. However, the Bragg wavelength of the CTFBGs does not change as the tilt angle increases according to the reflection spectra of the CTFBGs.

Conclusions This paper takes the lead in inscribing CTFBGs with different tilt angles in large-mode-area double-cladding fibers with core/cladding diameter of 20/400 μm by fs-lasers, with a maximum filtering depth and bandwidth of ca. 15 dB and ca. 8.9 nm, respectively. This paper is of great significance to the research and development of CTFBGs.

Key words gratings; femtosecond laser; fiber gratings; chirped and tilted fiber Bragg gratings