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中国激光

飞秒激光直写高反射率中红外光纤布拉格光栅

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摘要 采用飞秒激光逐线直写法，在氟化物光纤中制备出了窄带宽、高反射率的中红外光纤光栅，其中心波长为 2964.34 nm，3 dB 带宽为 1.24 nm，反射率高达 99.27%。该工作有利于构建“全光纤化”中红外光纤激光器，对推动国内中红外光纤激光器核心器件的全自主化具有重要意义。

关键词 激光技术；光纤布拉格光栅；光纤激光器；中红外激光器；氟化物光纤

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1 引 言

中红外光纤激光器因光束质量高、光电转换效率高、散热性能好、有望全光纤化等优点而备受关注，在医疗健康、大气通信、红外对抗等领域具有广泛的应用。通常选择声子能量低且传输损耗小的氟化物光纤作为中红外激光产生和传导的介质。空间腔镜式激光器结构存在耦合效率低、鲁棒性差、氟化物光纤端面易潮解等问题[1-3]。基于氟化物光纤的光纤布拉格光栅（FBG）可用于构建全光纤化激光器，并能有效解决上述问题[4]。已报道的制备方法主要有飞秒激光相位掩模板法、飞秒激光逐点法、飞秒激光逐线法和飞秒激光逐面法。2006 年，Grobnic 等[5]采用 800 nm 飞秒激光结合相位掩模板方法，首次在 ZBLAN 光纤中实现了 FBG 刻写。2013 年，Bérubé 等[6]和 Gross 等[7]分别研究了飞秒激光脉冲诱导氟化物玻璃产生折射率改变的物理机制。同年，Hudson 等[8]首次采用飞秒激光逐点法在 ZBLAN 光纤中直写了光栅，并将该光栅用于 2.9 μm 单频激光产生。2015 年，Fortin 等[9]利用氟化物 FBG 实现了 2.94 μm 的 30 W 全光纤化激光输出。2018 年，Goya 等[10]利用 513 nm 飞秒激光器在双包层掺 Er^{3+}：ZBLAN 光纤上逐面刻写了中心波长为 2799 nm、反射率达 97% 的 FBG。同年，Aydin 等[11]利用 FBG 作为腔镜获得了双向泵浦的 41.6 W 中红外激光输出。2019 年，Bharathan 等[12]通过飞秒激光直写并结合退火处理，制备了 99.98%高反射率的 FBG，中心波长为 2893.8 nm。国内关于中红外氟化物光纤光栅的制备研究鲜有报道，亟需对这一关键器件的制备技术展开研究。本文采用飞秒激光逐线直写法，在氟化物光纤中直接制备出了中心波长为 2964.34 nm、反射率达 99.27%的中红外 FBG。该工作有助于提高中红外光纤激光运转的稳定性和可靠性，并拓宽中红外光纤激光技术的应用范围。

2 实验方法及装置

2.1 实验方法

由于氟化物光纤不具备光敏性，因此难以采用传统的紫外曝光法进行 FBG 刻写。而飞秒激光直写方法不依赖于光纤的光敏性，可以直接在光纤中刻写波导，所以飞秒激光直写法是目前刻写氟化物 FBG 的首选方法。飞秒激光直写法可分为飞秒激光相位掩模板法、飞秒激光逐点法、飞秒激光逐线法和飞秒激

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光逐面法。其中，飞秒激光相位掩模板法具有简单、高效、所制备的光栅光谱特性好等优点，但该方法需要定制掩模板，掩模板的造价昂贵且无法根据需要对光栅参数进行灵活调整。飞秒激光逐点法通过在纤芯中刻写一系列等间距点，实现 FBG 刻写。该方法速度快，效率高，一根光栅的制作往往只需要几秒就能完成。但是单个刻点产生的折射率调制区域大小与纤芯截面大小相差较大，会在 FBG 透射谱的短波方向产生较大的米氏散射损耗[13]。相比之下，飞秒激光逐线法与飞秒激光逐面法所刻写的光栅与纤芯的交叠程度更大，这两种方法所产生的米氏散射损耗相对更小。飞秒激光逐面法主要分为两种。一种方法是通过对光纤纤芯进行二维扫描来实现的，但这种方法效率低，刻写时间长。另一种方法是通过使用柱透镜扩展光斑宽度，实现逐面刻写。但是由于实验场地的限制，光路中难以加入柱透镜。飞秒激光逐线法相比其他方法，具有效率高、成本低、刻写参数灵活可控、所制备的光栅光谱特性好等特点。所以实验采用飞秒激光逐线法制备氟化物 FBG。

2.2　实验装置

FBG 的刻写及光谱监测装置如图 1 所示。飞秒激光光源采用 Ligtht Conversion 公司生产的 PHROS-PH1 系列激光器。激光器的中心波长为 1026 nm，重复频率为 200 kHz，脉冲宽度为 290 fs，单脉冲能量大于 200 μJ。通过二倍频器将激光转换为 513 nm 的绿光激光，转换效率大于 50%。出射激光通过可控的衰减器进行能量衰减。衰减后的飞秒激光通过二色镜与显微成像系统共轴入射到物镜中。物镜采用 50 倍干式物镜，数值孔径为 0.42。利用真空吸附装置，通过夹具将光纤固定在高精度三轴位移平台上。三维位移平台采用 Arotech 公司生产的高精度位移平台。其中位移平台 XY 轴位于 ABL1500 空气轴承平台上，定位精度为 ±400 nm。三维位移平台 Z 轴为 ANT130-5 直线电机，垂直位移台，定位精度为 ±1.5 μm。通过计算机控制高精度三维位移平台运动，进而实现光栅刻写。光纤光栅测试装置由超连续谱光源、耦合透镜和光谱仪组成。超连续谱光(波长为 0.5～3.1 μm)通过一对耦合透镜(透镜材质为 CaF_2，焦距 f=15 mm)耦合到刻有 FBG 的 ZBLAN 光纤中，末端直接接入光谱仪中进行透射光光谱测试。

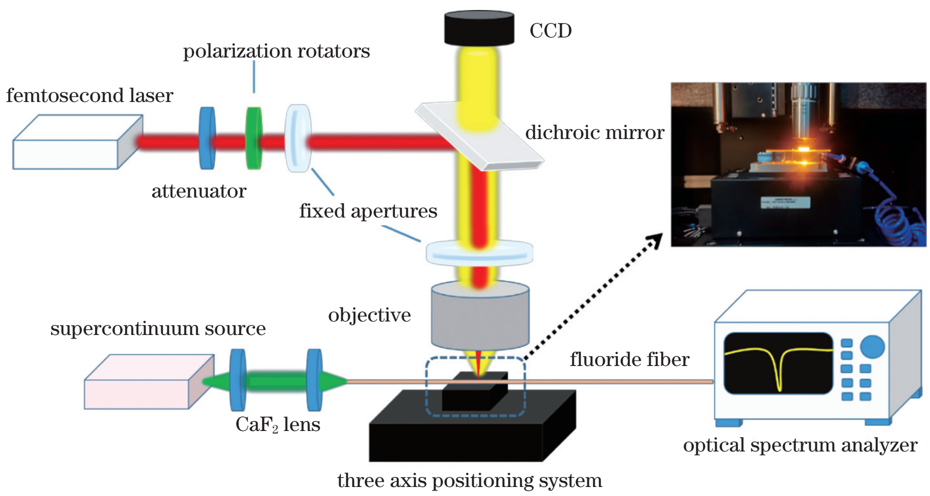

图 1　中红外 FBG 刻写装置及光谱监测装置

Fig. 1　Experimental setup for MIR FBG inscription and spectral monitoring

3　实验结果及分析

图 2 为不同能量条件下刻写的光栅条纹。从左至右激光单脉冲能量分别为 83，100，116，133，150，166，183 nJ。单脉冲能量越高，条纹越清晰，对比度越高。单脉冲能量越大，线宽越宽，相邻条纹之间越容易发生重叠，如 183 nJ 能量下刻写的光栅条纹，光栅质量下降。由于激光器功率存在抖动，因此我们将激光单脉冲能量衰减至 150 nJ 进行实验。

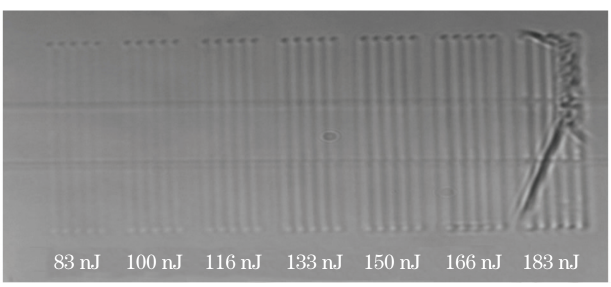

图 2　不同能量条件刻写的光栅条纹

Fig. 2　Grating fringes written under different energy conditions

实验使用 Le Verre Fluore 公司生产的 ZBLAN 单模光纤（纤芯直径为 14 μm，外包层直径为 250 μm）进行 FBG 刻写。实验中将 513 nm 飞秒激光脉冲衰减至 150 nJ，刻线扫描速度为 100 μm/s。FBG 的刻线长度为 50 μm，周期间隔为 1.994 μm。图 3(a)所示为显微镜下观察到的 FBG 图像。图 3(b)所示为 FBG 截断后显微镜下的光纤横截面，可见飞秒激光聚焦后的刻线覆盖了纤芯。

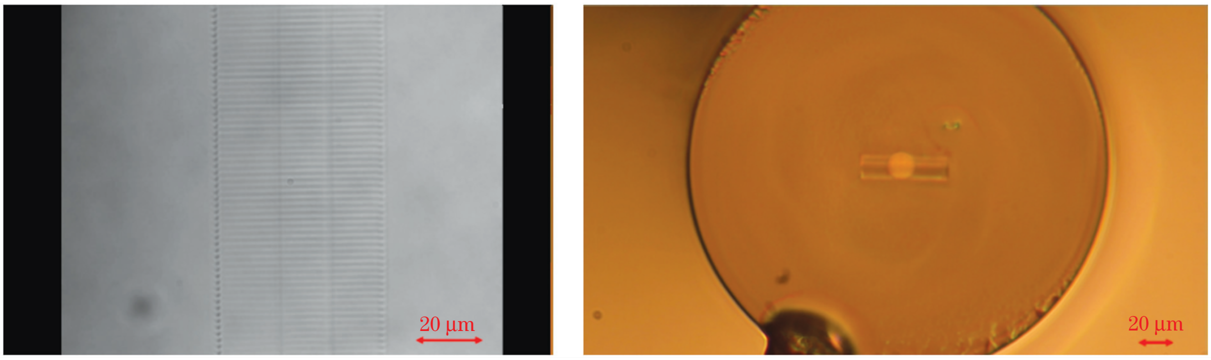

图 3　显微成像图。(a) FBG；(b) FBG 截断后的光纤截面

Fig. 3　Microscopic images. (a) FBG; (b) cross section of fiber after FBG modification

图 4 所示为所刻写的不同长度的 FBG 的透射谱，光栅长度分别为 2.991，3.988，4.985，5.982 mm，对应的反射率分别为 48.2%、63.47%、81%、99.27%，FBG 长度与反射率呈正比关系。所刻写的不同长度的 FBG 的中心波长存在漂移，这是因为 FBG 的中心波长不仅由条纹的周期间隔决定，激光所聚焦的光斑点大小以及功率都会对条纹质量产生影响，从而影响中心波长。在实际刻写过程中，难以保证每次激光聚焦的光斑质量以及激光功率都完全一致，所以不同批次制备的 FBG 会存在小范围内的中心波长漂移。

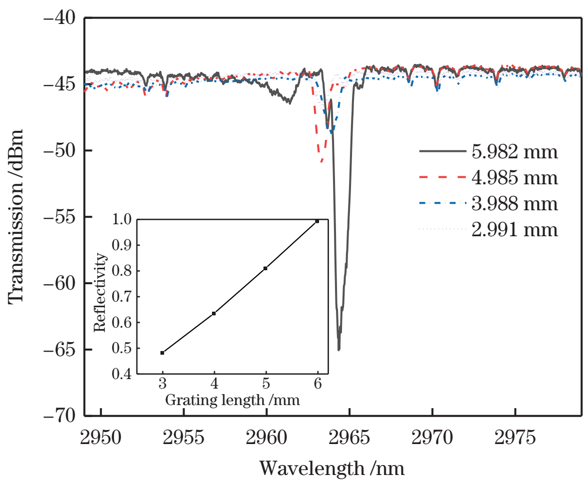

图 4　不同长度的 FBG 透射光谱

Fig. 4　FBG transmission spectra under different lengths

其中，5.988 mm 长的 FBG 响应峰的中心波长为 2964.34 nm，调制深度达 21.38 dB，反射率达 99.27%，3 dB 带宽为 1.24 nm。折射率调制深度[14]为

$$\Delta\lambda = \lambda_B S\sqrt{\left(\frac{\Delta n}{2n_0}\right)^2 + \left(\frac{1}{N}\right)^2}, \tag{1}$$

式中：$\Delta\lambda$ 为 FBG 光谱响应的半峰全宽；λ_B 为光纤布拉格光栅反射光在自由空间中传输时的中心波长；光栅条纹可见度 S 取决于 FBG 的反射率大小（反射率为 100% 时，$S=1$，反射率较小时，$S=0.5$）；n_0 为纤芯的平均有效折射率；N 为 FBG 的总周期数；Δn 为折射率的调制深度。根据(1)式和上述数据，可计算出折射率调制深度为 $\Delta n = 7.66\times10^{-4}$。

表 1 汇总了飞秒激光制备的中红外光纤光栅的参数。本文通过飞秒激光逐线直写法制备的 FBG 为二阶结构，利用较短的长度获得了>99%的反射率。对比文献[12]、[15]和[16]，我们的刻线速度更快，这对于降低 FBG 的制备成本具有一定意义。根据折射率调制产生机理，我们可以把 FBG 分为两类[17]。一类是 Type-Ⅰ 型 FBG，由多光子吸收产生色心变化，该类 FBG 在高温下会被直接擦除。而另一类是 Type-Ⅱ 型 FBG，高能量激光作用于材料，激光能量高于材料的损伤阈值(I_{th})，使得材料局部熔融再固化，产生损伤型 FBG。此类光栅具有较高的温度稳定性，只有温度高于材料的熔点时才会被擦除。由于刻写采用的激光为高斯光束，高斯光束边缘区域的光强较弱，激光能量低于 I_{th}，会在条纹边缘处产生 Type-Ⅰ 型调制。而 Type-Ⅱ 型 FBG 在高温条件下会消去光栅中光强低于 I_{th} 时产生的色心缺陷，Δn 和条纹对比度较高。在对 FBG 进行退火处理后，带宽和反射率还有进一步优化的可能[12,18]。

表 1 飞秒激光制备的中红外光纤光栅的参数

Table 1 Parameters of MIR fiber grating prepared by femtosecond laser

Fiber	Speed /(μm·s^{-1})	Pulse energy /nJ	Length /mm	Wavelength /nm	Reflectivity /%	Reference
Ho^{3+}/Pr^{3+}:ZBLAN	80	270	15	2880	50	[15]
Dy^{3+}:ZBLAN	—	240	11	3388	96	[19]
Er^{3+}:ZBLAN	—	—	—	3425	96	[18]
Er^{3+}:ZBLAN	—	150	2.5	2799	97	[10]
Er^{3+}:ZBLAN	—	—	4	2838	99	[20]
ZBLAN	20	125	13	2894	99.98	[12]
InF_3	20	225	8	4020	95.2	[16]
ZBLAN	100	150	5.98	2964	99.27	This work

飞秒激光直写的优点在于可以灵活改变光栅参数。通过修改光栅的周期间隔，将光栅周期改为 2080 nm，采用相同的刻写参数进行刻写，得到图 5 所示的透射深度达 20.54 dB，反射率达 99.12%，3 dB 带宽为 1.3 nm，中心波长为 3090 nm 的 FBG 透射谱。在透射谱中，响应主峰右侧存在一个中心波长为 3091.2 nm、深度为 6.62 dB 的旁瓣。该 FBG 在应用于激光器中时，由于主峰比旁瓣高 13.92 dB，主峰增益增大，旁瓣处所产生的寄生振荡得到有效的抑制。所以采用传输光波长更长的 InF_3 光纤作为刻写样品，调节光栅周期，进一步在长波方向上刻写 FBG 是完全可行的。本文所制备的 FBG 的响应峰位于 Dy^{3+} 的荧光发射光谱区域中，在掺 Dy^{3+} 光纤激光器中将有更多的应用[21-24]。

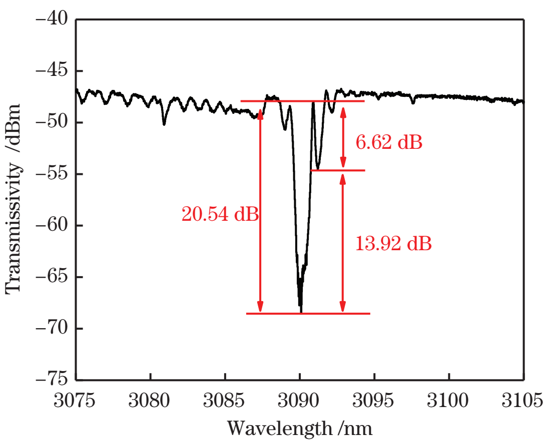

图 5 中心波长为 3090 nm 的 FBG 透射谱

Fig. 5 Transmission spectrum of FBG at central wavelength of 3090 nm

4 结 论

基于飞秒激光逐线直写法，采用 50 倍干式物镜刻写，研究了不同激光单脉冲能量对刻写光栅条纹的影响。选取单脉冲能量 150 nJ、刻线扫描速度 100 μm/s、FBG 的刻线长度 50 μm、周期间隔 1.994 μm 作为刻写参数。基于氟化物光纤制备出了窄带宽、高反射率的中红外 FBG，其中心波长为 2964.34 nm，反射率高达 99.27%。通过调节刻写 FBG 的周期间隔，实现了中心波长为 3090 nm、反射率高达 99.12%的中红外 FBG 制备，且该方法有望实现更长波段的 FBG 刻写。

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High Reflectivity Mid-Infrared Fiber Bragg Grating by Femtosecond Laser Direct Inscription Method

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Abstract

Objective Mid-infrared fiber lasers have attracted much attention due to high beam quality, high photoelectric conversion efficiency, excellent heat dissipation performance, and prospect of all-optical fibers. They have important applications in ranging, remote sensing, medical and health care, absorption spectroscopy, atmospheric communication, polymer materials processing, infrared countermeasures, and basic science. A fluoride fiber with a low phonon energy and a low transmission loss is usually chosen as the medium for producing and conducting a mid-infrared laser. The structure of the space cavity mirror laser has such problems as low coupling efficiency, poor robustness, and easy deliquescence of fluoride fiber end faces. A fiber Bragg grating (FBG) based on fluoride fibers can be used to construct all-fiber lasers, which can effectively solve the above problems. However, the preparation of a mid-infrared fluoride fiber Bragg grating has not been reported in China. It is urgent to study the preparation technology of this key device. In this work, a mid-infrared FBG with a central wavelength of 2964.34 nm and a reflectivity of 99.27% is directly prepared in a fluoride fiber by femtosecond laser line-by-line direct writing method. This work is helpful to improve the operation stability, reliability and miniaturization of a mid-infrared fiber laser, and promote the application of corresponding mid-infrared fiber laser technologies.

Methods In this paper, an FBG is prepared by femtosecond laser direct inscription method, and a 513 nm femtosecond laser is selected as the source. The fiber moves uniformly through a high precision three-dimensional displacement platform. The FBG testing device consists of a supercontinuum source, a coupled lens, and a spectrometer. The supercontinuum source (0.5–3.1 μm) is coupled to a ZBLAN fiber with an FBG through a pair of coupling lenses (lens material of CaF_2, focal length $f=15$ mm), and the end is directly connected to the spectrometer for transmission spectral testing. By comparing various preparation methods of FBGs, the femtosecond laser line-by-line inscription method has the advantages of high efficiency, low cost, flexibility, and good spectral characteristics. We choose the femtosecond laser line-by-line inscription method to achieve the preparation of a mid-infrared FBG. By studying the effects of laser energy and grating length on the preparation of an FBG, the appropriate writing parameters are selected. The preparation of FBGs with different central wavelengths is realized by changing the period interval of each FBG.

Results and Discussions By comparing the grating fringe qualities under different pulse energies (Fig. 2) and FBG lengths (Fig. 4), a second-order FBG with a physical length of 6 mm is written under 150 nJ energy and 100 μm/s inscription speed at 2964.32 nm central wavelength (corresponding to a grating pitch of 1.994 μm). The resulting transmission spectrum of the FBG is shown in Fig. 4. It reveals a strong and sharp Bragg resonance with a reflectivity of 99.27% at 2964.34 nm. The refractive index modulation depth is 7.66×10^{-4}. We study the effect of grating length on the reflectivity of a grating. The reflectivities of gratings with different lengths of 2.991 mm, 3.988 mm, 4.985 mm, and 5.982 mm are 48.2%, 63.47%, 81% and 99.27%, respectively. The grating length is linearly related to its reflectivity. Compared with other works, this paper uses shorter length and faster writing speed to inscribe a high reflectivity FBG (Table 1). In addition, by modifying the grating period interval, we change the grating period to 2080 nm and adopt the same writing parameters. We inscribe an FBG with a reflectivity of 99.12% at 3090 nm (Fig. 5). In the transmission spectrum, there is a side lobe with a central wavelength of 3091.2 nm and a depth of 6.62 dB to the right of the main response peak. When the FBG is applied to the laser, because the main peak is 13.92 dB higher than the side lobe, the gain of the main peak increases, and the parasitic oscillation generated at the side lobe can be effectively suppressed. Therefore, it is completely feasible to write an FBG in the direction of long wavelength by using an InF_3 fiber with a long transmission wavelength as the writing sample and adjusting the grating pitch. The response peak of an FBG prepared in this paper is located in the region of the Dy^{3+} fluorescence emission spectrum, and it has more applications in Dy^{3+} doped fiber lasers.

Conclusions In this study, we use the femtosecond laser line-by-line method and a 50 × dry objective to study the influence of laser pulse energy on grating fringes. The pulse energy of 150 nJ, the inscribe speed of 100 μm/s, the line length of 50 μm, and the period pitch of 1.994 μm are selected as writing parameters. A mid-infrared FBG with narrow bandwidth and high reflectivity is prepared based on a fluoride fiber. The central wavelength is 2964.34 nm and the reflectivity is up to 99.27%. The mid-infrared FBG with a central wavelength of 3090 nm and a reflectivity of 99.12% is prepared by adjusting the period pitch of this FBG. And it is expected to achieve a long band FBG writing by this method. This work is beneficial to the construction of an "all-fiber" mid-infrared fiber laser, which is of great significance to promote the autonomy of the core device of a mid-infrared fiber laser in China.

Key words laser technique; fiber Bragg grating; fiber laser; mid-infrared laser; fluoride fiber