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基于光栅反馈技术的掺铥光纤随机激光器

朱德才[1,2]，胡耀宗[1,2]，周乐文[1,2]，黄昌清[3]，董新永[1,2]
（1 广东工业大学 信息工程学院，广州 510006）
（2 广东省信息光子技术重点实验室，广州 510006）
（3 中国计量大学 光学与电子科技学院，杭州 310018）

摘　要：提出一种基于光栅反馈技术的掺铥光纤随机激光器。激光器采用半开腔设计，封闭端采用中心波长为1 940 nm的高反射率光纤光栅为激光器系统提供强反馈，增益介质采用1.5 m长的掺铥光纤，泵浦源采用793 nm半导体激光器，开放端采用光纤随机光栅提供随机分布反馈。该光纤随机光栅由飞秒激光逐点刻写技术制备，在10 cm单模光纤上刻写超过6 000个间距随机分布的折射率畸变点，以增强光纤的后向瑞利散射效应。实验测得中心波长为1 940 nm的随机激光输出，其泵浦阈值为2.33 W，在3.8 W泵浦功率下的输出功率为57 mW，光信噪比达56 dB。输出激光在1 h内的波长偏移量小于0.1 nm，功率变化约0.26 dB，具有良好的稳定性。

关键词：光纤激光器；随机激光器；掺铥光纤；光纤光栅；光栅反馈
中图分类号：TN248.1　　**文献标识码：**A　　**doi：**10.3788/gzxb20225111.1114001

0　引言

光纤随机激光器是一种基于光纤中光信号增益和随机分布反馈效应的新型光纤激光器，具有结构简单、无需谐振腔、输出激光空间相干性弱等优点，有望在光传感与通信、无散斑成像、生物医学检测、激光加工、非线性光学研究等领域获得重要应用[1-2]。自2007年第一台光纤随机激光器被报道以来[3]，研究人员对其基础理论和工作机理展开了深入研究[4-8]，通过改变激光器的结构设计、增益机制和光信号反馈方式等，研制出多种不同结构和类型的光纤随机激光器。按照反馈材料和机制的不同，光纤随机激光器大致可以分为空芯填充型[9-10]、瑞利散射型[11-12]和光栅反馈型[13-15]。其中，液芯填充型光纤随机激光器通过在空芯光纤的空气芯中填充包含高散射性颗粒和增益材料的液体，利用光纤的二维限制特性实现随机激光的一维输出，是最原始的光纤随机激光器设计，制备和使用不方便；瑞利散射型光纤随机激光器利用光纤本身对光信号的后向瑞利散射提供分布式随机反馈，反馈效率比较低；光栅反馈型光纤随机激光器则利用反馈效率远高于瑞利散射效应的光纤光栅提供反馈，具有泵浦阈值低、效率高等优点。当前，光纤随机激光器的研究和应用主要集中在1.0～1.6 μm波段，增益介质或机理主要为光纤受激拉曼散射、光纤受激布里渊散射、掺铒光纤、掺镱光纤等。光纤随机激光器的最高输出功率已达百瓦量级[16-18]，并在全光场实时成像、远距离传感、随机比特码生成等领域获得应用[19-22]。

近年来，工作在人眼安全的2 μm波段的光纤激光器受到了广泛关注。该波段包含了1 940 nm附近的水吸收峰，对组织的穿透深度浅，从而使得2 μm波段光纤激光成为包括非侵入手术等医疗过程的有力工具[23-25]。该波段还包含几个大气透明窗口，在自由空间通信、遥感、激光雷达等领域也有重要的应用前景。针对激光在中红外波段的广泛技术需求，光纤随机激光器研发的波长范围也在从常规的1.0～1.6 μm波段向2 μm及以上波段延伸。但是与常规波段相比，光纤随机激光器在2 μm波段必须面对两个不利因素：一是普

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第一作者：朱德才（1996—），男，硕士研究生，主要研究方向为掺铥光纤随机激光器。Email：1397865184@qq.com
导师(通讯作者)：董新永（1975—），男，教授，博士，主要研究方向为光纤随机激光器、光纤放大器，光纤传感。Email：dongxy@gdut.edu.cn

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通光纤在 2.0 μm 的损耗高达 30 dB/km，而且随波长增加而急剧升高[26]；二是光纤瑞利散射的强度与波长的四次方成反比，所以光纤在 2.0 μm 的散射只有 1.0 μm 处的 1/16 和 1.5 μm 处的 1/5。因此，采用石英光纤和瑞利散射的常规技术和方法难以获得高性能的 2 μm 波段随机光纤激光器。为克服以上困难，2015 年，上海交通大学采用纤芯掺锗的高数值孔径光纤为半导体激光泵浦的掺铥光纤提供随机分布瑞利散射反馈，在 4 W 以上的泵浦功率下获得了随机调 Q 激光输出[27]。2016 年，国防科技大学利用 1 942 nm 激光泵浦 150 m 长的高掺锗光纤（二氧化锗浓度 38%），在泵浦功率超过 3 W 时获得了宽带的随机拉曼激光输出[28]。这两个工作都采用了在 2 μm 波段传输损耗相对较低的高掺锗光纤，但弱的瑞利散射依然导致激光器的泵浦阈值高、转换效率低。2021 年，深圳大学将 200 m 单模光纤的瑞利散射与掺铥光纤的主动增益相结合，获得 2 μm 随机激光，但泵浦功率阈值仍然高达 3.5 W[29]。

本文采用 793 nm 半导体激光器作为泵浦源，利用掺铥光纤产生增益放大，采用光纤随机光栅和高反射率光纤光栅构成半开放腔结构光纤随机激光器，在 2 μm 波段实现了阈值功率为 2.33 W、斜率效率为 4% 的窄线宽激光输出。

1 激光器结构和工作原理

提出的基于光栅反馈技术的掺铥光纤随机激光器的结构如图 1 所示，由 793 nm 半导体激光器、793 nm / 2 000 nm 波分复用器（Wavelength Division Multiplexer, WDM）、高反射率光纤光栅（High Reflectivity Fiber Bragg Grating, HR-FBG）、掺铥光纤和刻写在普通单模光纤上的光纤随机光栅构成。所用掺铥光纤（Nufern，SM-TDF-10P/130-HE）的长度为 1.5 m，模场直径为 10 μm，数值孔径为 0.15，对 793 nm 的吸收系数为 3 dB/m；HR-FBG 的中心波长为 1 940.1 nm，3 dB 带宽为 0.25 nm，反射率为 99%，其透射谱如图 2 所示。高反射率光纤光栅作为反射端镜，使激光器成为半开腔结构，可以降低随机光纤激光器的阈值功率。

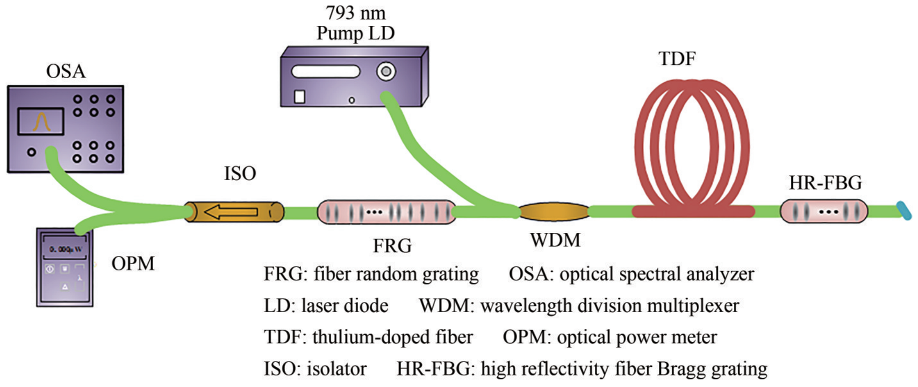

图 1 基于光栅反馈技术的掺铥光纤随机激光器结构

Fig. 1 Configuration of the Tm^{3+}-doped fiber random laser based on grating feedback technology

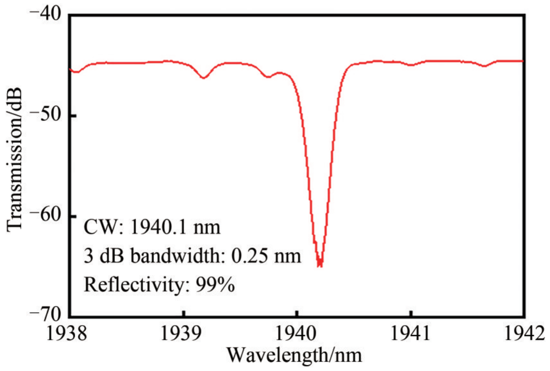

图 2 高反射率光纤光栅的透射谱

Fig. 2 Transmission spectrum of the high-reflectivity fiber Bragg grating

光纤随机光栅是由飞秒激光逐点写入的，其栅区长度为10 cm，纤芯中沿着光纤长度方向具有超过6 000个间距随机分布的折射率畸变点，这些折射率畸变点增强了光纤纤芯轴向折射率的非均匀性，产生了增强的反向瑞利散射效应。光纤随机光栅的制备过程中，超快钛宝石再生放大器的工作波长为800 nm，重复频率为10 Hz，脉冲持续时间为80 fs。采用一个由平凸透镜和面凹透镜组成的光束减缩器来减小激光束宽度，通过光学显微镜的物镜将其产生的飞秒脉冲通过光纤侧面聚焦到SMF-28光纤的纤芯上，而SMF-28光纤被提前安装在一个气浮轴承台（Aerotech）上，以100 μm/s的速度移动。物镜安装在压电工作台上，该工作台沿光纤轴以100 Hz的频率的伪随机方式抖动，其最大位移为2.5 μm。如此沿10 cm的SMF-28光纤引入了超过6 000个折射率畸变点，相邻畸变点的空间间隔在0～3.5 μm范围内随机分布。该光栅的制备应该满足两个基本要求：1）光纤随机光栅写入折射率的调制深度要浅，不至于引起过大的插入损耗；2）写入的折射率畸变点数要足够多，才能产生足够强的瑞利散射，与几公里甚至几十公里单模光纤的瑞利散射达到一个量级。

实验测得光纤随机光栅在2 μm的插入损耗为4.7 dB，虽然损耗的光中仅很少的部分为后向瑞利散射，但其反馈强度可等同于数公里的单模光纤[30]。与之相比，1 km普通单模光纤在2 μm的传输损耗约为30 dB。因此，采用光纤随机光栅可以在短的光纤长度上产生较强的随机分布反馈效应，避免长的普通单模光纤用于2 μm分布反馈所带来大的传输损耗。

在两个光纤光栅外侧的光纤尾端熔接接负8角跳线来消除光纤端面的菲涅尔反射。左端为光纤随机激光器的输出端，与泵浦激光的输入方向相反，可避免在输出激光中混入残余的泵浦光。随机激光器的输出光谱和功率分别用光谱分析仪（OSA，AQ6376）和光功率计来测量。

激光器的工作原理为：掺铥光纤在793 nm泵浦激光作用下产生上下能级集居反转，引起自发辐射效应，其前向传输的自发辐射光中与右端的高反射率光纤光栅波长相同的部分被反射回来，经掺铥光纤放大，然后到达光纤随机光栅，大部分的光经由光纤随机光栅到输出端，少部分光被光纤随机光栅反馈回去，再次进入掺铥光纤被放大并被右端的高反射率光纤光栅反射回来，由此往复形成谐振。随着793 nm泵浦激光功率的提高，当增益能够补偿腔内损耗时，形成随机激光输出。

2　实验结果与讨论

掺铥光纤随机激光器的输出光谱由波长分辨率为0.1 nm的AQ6376光谱分析仪测得。随着泵浦功率逐渐增加，在低于阈值泵浦功率时，只观察到高反射率光纤光栅的反射谱。在泵浦功率达到和超过2.33 W时，观察到激光产生，激光输出峰值波长为1 940 nm，略低于高反射率光纤光栅透射谱的中心波长0.1 nm。这是由于1.5 m掺铥光纤的最大增益波长小于1 940 nm，所以激光产生在高反射率光纤光栅反射谱的短波侧。因此，掺铥光纤随机激光器的阈值功率为2.33 W，阈值前后的光谱如图3所示。

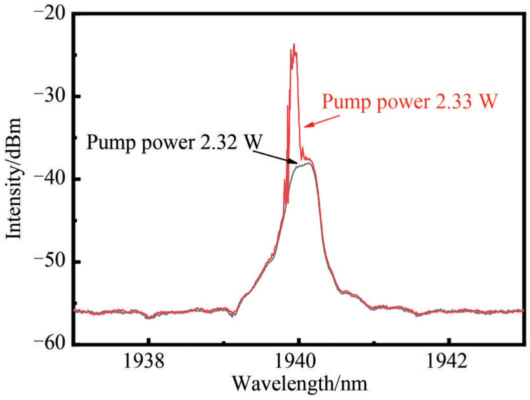

图3　掺铥光纤随机激光器阈值附近的输出光谱

Fig. 3　Output spectra of the Tm^{3+}-doped fiber random laser with pump powers near the threshold

随着泵浦光功率逐渐增大，光纤随机激光器输出光谱中峰值波长处的光强度随之明显增加，不同泵浦功率下的输出光谱如图4所示。在3.8 W泵浦功率下的输出功率为57 mW，光信噪比达56 dB。激光强度增

加的同时，激光器的输出波长在泵浦功率变化过程中保持稳定。这是因为两个光纤光栅都制备在普通单模光纤上，而不是掺铥光纤上，因此其波长不受掺铥光纤在泵浦光作用下温度变化的影响。实验测得掺铥光纤随机激光器的输出功率随泵浦功率的变化呈良好的线性关系，如图5所示，斜率效率约为4%。经测量泵浦源输出尾纤与WDM泵浦端熔接点的插入损耗为3 dB，掺铥光纤与WDM公共端熔接点的插入损耗为4.5 dB。斜率效率不高的主要原因是上述两个熔接点两端光纤的纤芯直径、模场直径、光纤折射率不匹配导致熔接点的插入损耗过大。若不考虑熔接点的插入损耗，按注入掺铥光纤的泵浦功率计算，实际斜率效率可以达到22%，与普通掺铥光纤激光器的斜率效率相近。因此，通过定制尾纤匹配的WDM来减少熔接损耗，可以提高掺铥光纤随机激光器的斜率效率。

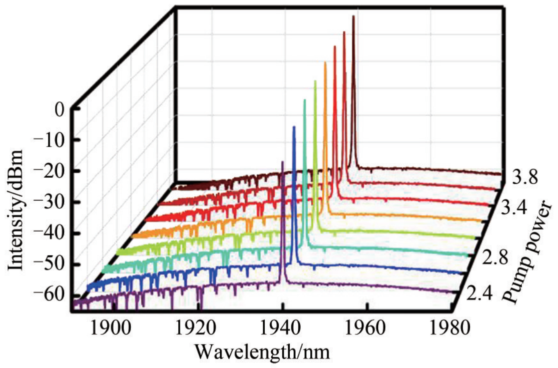

图4　不同泵浦功率下测得的随机激光输出光谱

Fig. 4　Random laser output spectra measured at different pump powers

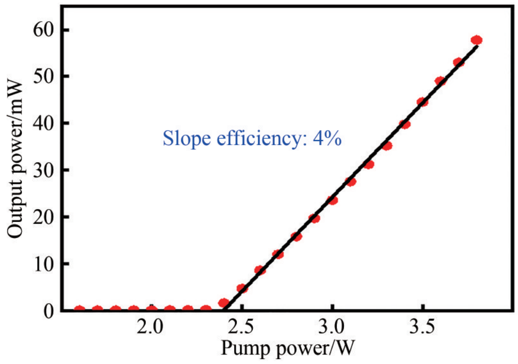

图5　掺铥光纤随机激光器的输出特性

Fig. 5　Output characteristics of Tm^{3+}-doped fiber random laser

为了测试光纤随机激光器输出的时间稳定性，在泵浦功率为3.8 W情况下，每隔5 min记录一次激光的输出光谱和功率，每隔1 s记录一次激光的输出功率，总测量时间为1 h，记录的激光输出光谱如图6所示。实验结果显示，随机光纤激光器的峰值波长漂移小于0.1 nm，低于光谱分析仪的波长分辨率，说明掺铥光纤随机激光器的输出光谱具有良好的稳定性，应该与高反射率光纤布拉格光栅良好的波长选择性反射有关。图7为实验测得的激光输出功率随时间的变化，激光输出功率的最大值为17.62 dBm，最小值为17.03 dBm，最大差异仅为0.59 dB，说明本文的掺铥光纤随机激光器具有良好的输出稳定性。

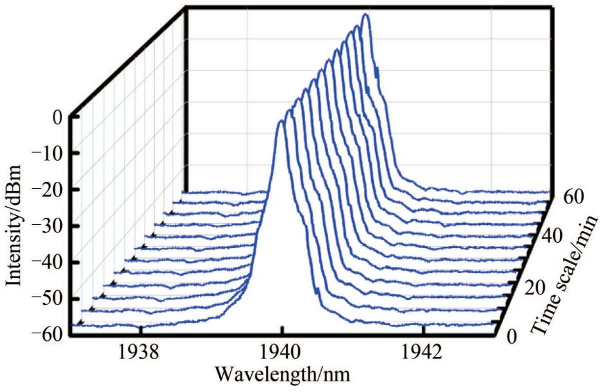

图6　泵浦激光功率为3.8 W时多次测量得到的随机激光输出光谱

Fig. 6　Laser output spectra of multiple measurements at pump power of 3.8 W

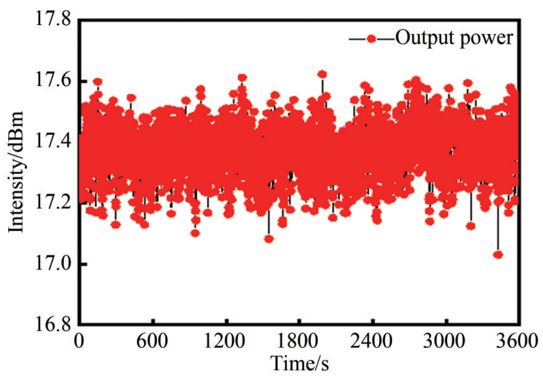

图7　随机激光输出功率随时间的变化

Fig. 7　Output power of the random laser versus time

3　结论

利用光纤随机光栅的增强瑞利散射效应提供分布式随机反馈，结合高反射率光纤光栅的窄带选频滤波作用，在793 nm半导体激光器的泵浦下，以掺铥光纤作为增益介质，获得了结构简单、输出稳定的半开腔结

构 2 μm 波段光纤随机激光器，并对其输出光谱和功率特性做了研究。实验获得光纤随机激光器的峰值波长为 1 940 nm，阈值为 2.33 W，在 3.8 W 泵浦功率下的输出功率为 57 mW，光信噪比达 56 dB。另外，输出激光在 1 h 内的波长偏移量小于 0.1 nm，功率变化为 0.26 dB，具有良好的时间稳定性。

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Tm^{3+}-doped Fiber Random Laser Based on Fiber Grating Feedback Technology

ZHU Decai[1,2], HU Yaozong[1,2], ZHOU Lewen[1,2], HUANG Changqing[3], DONG Xinyong[1,2]
(1 *School of Information Engineering*, *Guangdong University of Technology*, *Guangzhou* 510006, *China*)
(2 *Guangdong Provincial Key Laboratory of Information Photonics Technology*, *Guangzhou* 510006, *China*)
(3 *College of Optical and Electronic Technology*, *China Jiliang University*, *Hangzhou* 310018, *China*)

Abstract: Random Fiber Lasers (RFLs) based on random distributed feedback can operate without a precise resonant cavity, leading to the advantages of simple structure and low production cost. In previous work, random fiber lasers operating in the band of 1.0～1.6 μm have been widely investigated. However, limited by the high transmission loss of ～30 dB/km and the weak Rayleigh scattering efficiency in normal silica fibers, random fiber lasers operating in the band of 2 μm are rarely reported. It's of great fundamental interest to push the random fiber lasers to 2 μm mid-infrared band for their potential applications in the fields including medical surgery, nonlinear optics, material processing, and remote sensing. In this work, a random fiber laser operating in 2 μm band is developed by using a 1.5 m long thulium-doped fiber as the gain medium and a fiber random grating for random distributed feedback with enhanced Rayleigh scattering efficiency. The proposed random fiber laser adopts the half-open cavity design by using a high reflectivity fiber Bragg grating with a central wavelength of 1 940 nm to provide strong feedback to the laser system. A 793 nm semiconductor laser is employed as the pump laser source. The fiber random grating containing over 6 000 refractive index distortion spots was inscribed point by point along with a 10 cm long single-mode fiber by using a Ti: sapphire femtosecond regenerative amplifier with an operation wavelength of 800 nm, a repetition rate of 100 Hz and a pulse duration of 80 fs. The neighboring refractive index distortion points were spaced at a random distance between 7.5 and 12.5 μm. Experimental results show that random laser output at the wavelength of 1 940 nm is achieved with a relatively low threshold power of 2.33 W. Benefit from the enhanced Rayleigh scattering efficiency of the fiber random grating, the pump threshold of the random fiber laser is much lower than that of the previously reported random fiber laser in 2 μm region. With increasing the pump power, an output power of the random fiber laser increases nearly linearly with a slope efficiency of 4%. When the pump power reaches 3.8 W, the output power is 57 mW and the optical signal-to-noise ratio is up to 56 dB. The laser output wavelength remains quite stable during the change of pump power. To further test the stability of the random fiber laser, laser output spectra and powers were measured at an interval of 5 min and one second respectively within 60 min under the fixed pump power of 3.8 W. Good wavelength stability of 0.1 nm and power stability of fluctuation less than 0.26 dB are achieved. The good performance in stability should be related to the good wavelength selectivity and stability of the high-reflectivity fiber Bragg grating in both wavelength and reflectivity. It was fabricated on ordinary single-mode fiber, not the thulium-doped fiber, so its reflection wavelength and reflectivity can keep stable even when the pump laser reaches new heights and changes the temperature of the thulium-doped fiber. The slope efficiency is relatively low if compared with that of the common thulium-doped fiber lasers. It should be related to the relatively large insertion losses, 7.5 dB in total, of the two fiber fusion splicing points between the pump laser source and the thulium-doped fiber. The fiber parameters of the lead-out fiber of the pump laser and the thulium-doped fiber are much different from those of the single-mode fiber of the ports of the wavelength-division multiplexer. However, it can be improved by customizing a wavelength-division multiplexer with matching fiber parameters. Anyway, the proposed random fiber laser provides an effective technical method to develop random fiber lasers in the 2 μm wavelength band with relatively low pump threshold and better performances.

Key words: Fiber laser; Random laser; Tm^{3+}-doped fiber; Fiber Bragg grating; Fiber grating feedback
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