基于随机光栅的掺铥光纤随机激光器研究

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摘要　采用能增强瑞利散射效率的光纤随机光栅作为掺铥光纤随机激光器的随机分布反馈介质，光纤环镜下激光器形成半开腔结构，在 793 nm 半导体激光器泵浦下，实现了波长为 1951 nm 的单波长随机激光输出。激光器的泵浦阈值功率为 2.1 W，比已报道的相同泵浦波长的掺铥光纤随机激光器的阈值低 40%。在泵浦功率为 6 W 时，获得的激光输出功率为 142.9 mW，边模抑制比为 43 dB，输出激光在 1 h 内的波长偏移量小于 0.1 nm，功率波动小于 3.7 mW，具有良好的稳定性。

关键词　激光器；随机激光器；瑞利散射；掺铥光纤激光器；光纤随机光栅；光纤环镜

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1　引　　言

传统的激光器通常由三部分组成：激光工作物质、泵浦源和光学谐振腔，其中光学谐振腔限制了光子的路径并决定了激光的某些特性，如空间模式结构、方向性和偏振特性等[1]。而随机激光器是一种特殊的激光器，无需严格的光学谐振腔，而是靠无序增益介质中的多重散射来增加光放大的有效路径，最终使增益能够补偿损耗，实现激光的产生和输出[2-5]。由于光的散射通常效率低且没有方向性，因此随机激光器的阈值高、输出方向性差。光纤随机激光器的发明使光被限制在光纤的一维结构中传输，极大地提高了光的反馈和增益效率，降低了泵浦阈值[6-8]。随着相关技术的发展，具有结构简单、制造成本低、功率可定标放大等优点的光纤随机激光器在非线性光学、光传感与光通信、生物医学成像、遥感等多个领域中得到了广泛的关注[9-12]。

2 μm 波段是人眼安全的光波段，该波段包含水分子和许多大气分子的吸收峰以及低损耗的大气通信窗口，因此，2 μm 激光器在激光雷达、激光测距和外科手术等领域中具有特殊的优势[13]。目前，2 μm 波段的光纤随机激光器已经引起关注。光纤随机激光器通常利用光纤中的背向瑞利散射作为随机反馈机制，结合光纤中的分布式受激拉曼或受激布里渊散射效应产生的增益，在光纤单一介质中产生随机激光[14-16]。然而，单模光纤瑞利散射的强度与波长的四次方成反比，普通石英光纤在 2 μm 波段的传输损耗高达 30 dB/km，且随波长的增加呈指数式升高[17]，所以与常规 1.0～1.5 μm 波段的光纤随机激光器相比，2 μm 波段的光纤随机激光器更难实现[18]。

为了克服以上困难，文献[19]采用 150 m 的高掺锗光纤（纤芯的二氧化锗摩尔分数为 38%）作为增益介质，在泵浦功率超过 3 W 的条件下实现了基于拉曼增益的宽带随机激光输出。文献[20]采用具有高增益的掺铥光纤作为增益介质，使用纤芯掺锗的高数值孔径光纤提供随机分布瑞利散射反馈，在泵浦功率高于 4 W 的条件下获得了调 Q 随机激光输出。文献[21]利用长距离单模光纤提供瑞利散射并结合掺铥光纤增益放大，在 793 nm 泵浦激光的激励下获得了 2 μm 波段的随机激光，泵浦阈值功率为 3.5 W。以上工作均采用长的光纤（普通单模光纤或高掺锗光纤）作为随机分布反馈介质，由于瑞利散射效率低及光纤传输损耗高，随机激光器的泵浦阈值和转换效率等指标难以提高。

本文利用飞秒激光逐点写入制备的光纤随机光栅作为掺铥光纤随机激光器的随机分布反馈介质[22-23]，结合光纤环镜下形成的半开放腔随机激光器结构，降低了激射阈值[24]，在 793 nm 泵浦激光的激励下，获得了波长为 1951 nm、阈值功率为 2.1 W 的随机光纤激光输出。

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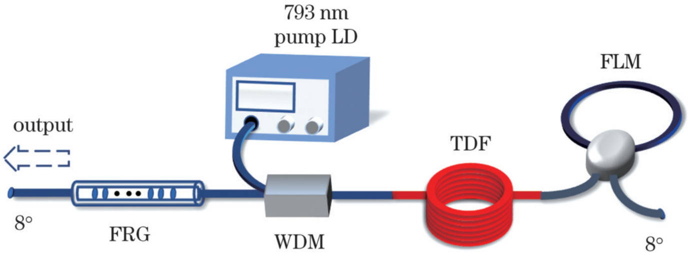
2 激光器结构与原理

掺铥光纤随机激光器的结构如图 1 所示。输出波长为 793 nm 的泵浦激光器通过 793 nm/2000 nm 的波分复用器(WDM)泵浦一段 1.5 m 长的掺铥光纤。掺铥光纤的另一端连接一个由 3 dB 光纤耦合器同端尾纤熔接而成的光纤环镜以提供强反馈,从而形成半开放腔结构的随机光纤激光器。WDM 的信号输入端连接光纤随机光栅,提供弱的随机分布反馈。光纤随机光栅的另外一端为激光器的输出端,连接一根输出端面切角为 8°的跳线,以避免光纤输出端面的菲涅耳反射对激光器的影响。掺铥光纤随机激光器的输出光谱和功率分别用光纤光谱分析仪和光功率计测量。



FRG: fiber random grating; WDM: wavelength division multiplexer;
LD: laser diode; TDF: thulium-doped fiber; FLM: fiber loop mirror

图 1 掺铥光纤随机激光器的结构示意图

Fig. 1 Structural diagram of thulium-doped fiber random laser

我们利用飞秒激光将光纤随机光栅逐点刻写在 10 cm 长的普通石英单模光纤的纤芯上,光栅包含约 6000 个随机分布的折射率调制点。所用的飞秒激光源为超快钛宝石再生光放大器,工作波长为 800 nm,重复频率为 10 Hz,脉冲宽度为 80 fs。飞秒激光脉冲通过光学显微镜的物镜从单模光纤侧面聚焦到纤芯,光纤被提前安装在一个 Aerotech 气浮平移台上,以 100 μm/s 的速度移动。物镜则安装在压电微位移工作台上,该工作台沿光纤轴向以 100 Hz 的频率作伪随机方式抖动,其最大位移为 2.5 μm。按照此办法在 10 cm 长单模光纤上引入了超过 6000 个的折射率畸变点,相邻畸变点的空间间隔在(10±2.5)μm 范围内随机分布。这些折射率调制点极大地增强了单模光纤纤芯折射率的纵向非均匀性,所以光纤的反向瑞利散射效应得到了极大的增强,可以在较短的光纤上获得与数千米长的普通单模光纤等效的反向瑞利散射信号[25]。虽然随机光栅越长、刻写密度越大,折射率调制点数就越多,所引起的瑞利散射增强效果也越强,但是其长度往往受到制备系统的限制,而且折射率调制深度也不能太大,否则会引起大的光传输损耗,从而降低激光器的输出功率。

实验中泵浦激光通过波分复用器进入掺铥光纤中,使掺铥光纤中铥离子的上下能级粒子数反转,从而引起自发辐射。前向传输的自发辐射光经过光纤环镜反射回来后,被掺铥光纤放大,然后传输到光纤随机光栅中,光纤随机光栅产生的随机分布后向散射光会再次被掺铥光纤放大,并由光纤环镜反射,依次往返。随着泵浦激光功率的逐步增加,当掺铥光纤提供的增益能够弥补光的损耗(即达到或超过阈值)时,就会发生谐振,产生随机激光输出。

3 实验结果与讨论

实验采用波长分辨率为 0.1 nm 的光谱分析仪对激光器的输出光谱进行测量。从 0 W 开始逐渐增加泵浦功率,当泵浦功率低于阈值时,在光谱仪上只观察到一个弱的宽带放大的自发辐射(ASE)光谱。当泵浦功率增加到 2.10 W 时,在光谱仪上观察到约 10 条紧密排列、间隔固定的多波长窄线宽激光谱,这是瑞利散射和级联受激布里渊散射共同作用的结果[26-28]。随着泵浦功率的继续升高,输出光谱变为宽带激光输出,这与光纤中的非线性光学效应如四波混频、自相位调制、交叉相位调制等所引起的光谱展宽有关,而且光谱展宽会反过来压制受激布里渊散射引起的不稳定性,使输出激光变得稳定[29-30]。由图 2 可见,宽带激光谱上仍有一些细小的尖峰存在,可解释为多个窄线宽激光经非线性展宽、重叠后遗留的痕迹。对比文献[21]中同样使用 793 nm 激光泵浦的掺铥光纤随机激光器,本文

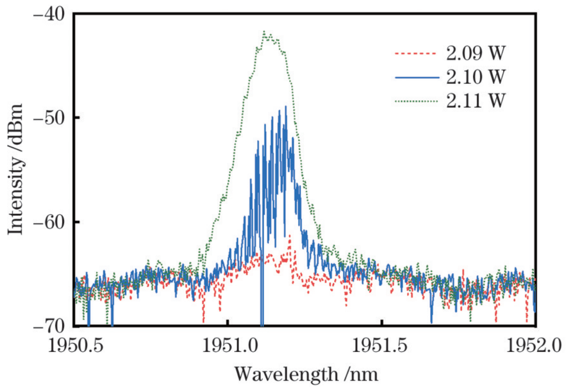


图 2 随机激光器在阈值功率附近的输出光谱

Fig. 2 Output spectra of random laser near threshold power

所报道的掺铥光纤随机激光器的阈值功率要低约40%。这主要得益于光纤随机光栅的高效随机反馈以及激光器的半开放腔结构设计。

图3给出了泵浦功率为2.0～6.0 W时测得的激光输出光谱。可以看出，当泵浦功率超过阈值后，激光器的输出光谱维持单峰输出，激光的峰值强度逐渐增大。当泵浦功率增加到3.0 W时，在离主峰0.2 nm的长波长侧可观察到新的模式被激发。当泵浦功率达到3.5 W时，右峰开始占主导地位，输出激光的中心波长从1951.2 nm偏移至1951.4 nm，随后保持稳定的单峰输出直至泵浦功率达到4.5 W。在4.6～4.8 W的泵浦功率下，出现两个模式的激烈竞争，可同时测量到两个输出激光峰。随着泵浦功率的继续增加，激光的中心波长重新回到1951.2 nm，并保持稳定的单波长随机激光输出直至泵浦功率达到最大值6 W。

所以，在整个泵浦功率增加的过程中，光纤随机激光器的输出存在两个模式的竞争，在绝大多数情况下为单波长输出，仅在模式跳变前观测到双波长同时存在的不稳定输出光谱。这种现象与掺铥光纤随机激光器中提供随机分布反馈的光纤随机光栅密切相关。

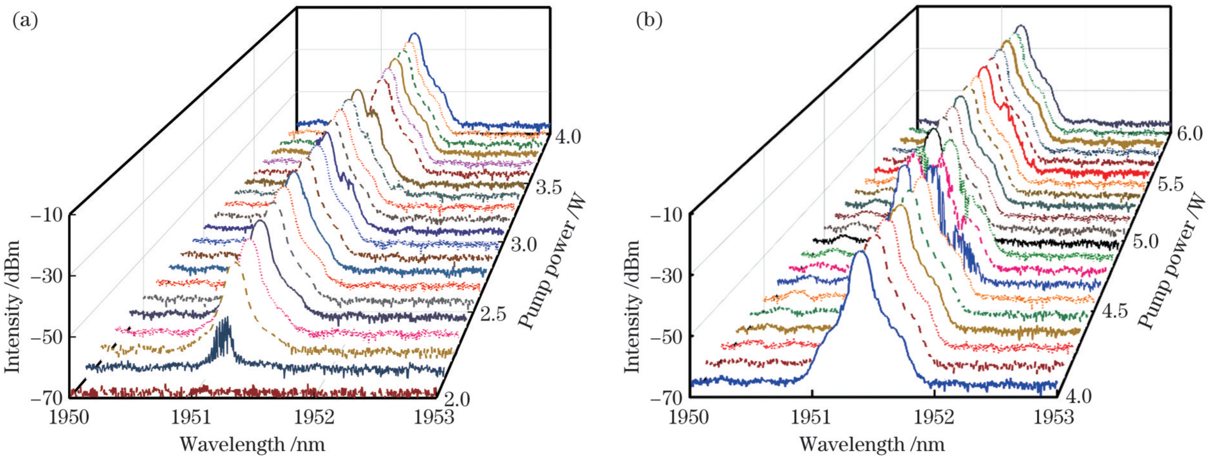


图3　不同泵浦功率下测得的激光输出光谱。(a) 2.0～4.0 W；(b) 4.0～6.0 W

Fig. 3　Laser output spectra measured at different pump powers. (a) 2.0−4.0 W; (b) 4.0−6.0 W

光纤随机光栅是一种特殊的一维随机反馈介质，光波在其中传播时受到较强的随机分布式散射作用，与掺铥光纤另一端的光纤环镜一起，产生空间上互相交叠的多个闭合式共振腔。由于结构中没有添加光滤波器进行波长的限制，随着泵浦功率的增加，掺铥光纤引入的光学增益超过腔内损耗的共振腔会率先产生激光发射，并对其他共振腔产生的激光纵模产生抑制作用，形成单波长激光输出。而泵浦功率的持续增加使得腔内的激光能量增加，同时掺铥光纤的最大增益波长也发生变化，对激光器中的模式竞争产生影响。当前一个激射的模式在竞争中不再占主导地位时，就会发生模式跳变，导致输出激光的中心波长发生漂移[31]。

图4给出了实验测得的光纤随机激光器的输出功率随泵浦功率的变化曲线。当泵浦功率超过阈值功率2.1 W后，输出功率随泵浦功率的增加呈线性增长，斜率效率为3.9%。这个斜率效率的值与普通光纤激光器相比显得较低：一方面是由于泵浦激光波长比所激发的激光波长短太多，即使量子转换效率高达100%，功率转换效率也只有40.6%；另一方面是由于实际耦合进掺铥光纤的泵浦激光功率远低于泵浦激光器的输出功率。在实验过程中，在泵浦激光器尾纤与WDM泵浦端的熔接点、WDM公共端与掺铥光纤的熔接点处均观测到明显的红光漏出，说明存在较大的熔接损耗。经测量，两个熔接点的插入损耗分别为3.0 dB和4.5 dB。因此，当泵浦光功率为6.0 W时，仅有1.07 W的泵浦光进入到掺铥光纤中。产生这两个大的熔接损耗的主要原因是泵浦激光器的输出尾纤与WDM泵浦端尾纤、掺铥光纤与WDM公共端尾纤在纤芯直径、模场直径和折射率等参数上不匹配。因此，通过定制尾纤匹配的WDM可以降低损耗并提高激光器的效率。如果去除了熔接点所带来的插入损耗，激光器的斜率效率可达20.6%，与普通掺铥光纤激光器的斜率效率相近。

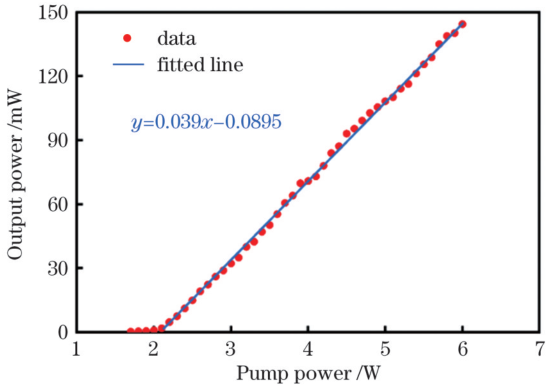


图4　激光器的输出功率随泵浦功率的变化

Fig. 4　Output power of laser versus pump power

为了研究掺铥光纤随机激光器的输出稳定性，我们将泵浦功率维持在6.0 W，在1 h内每5 min记录一

次随机激光的输出光谱和输出功率，总共获得13组数据，结果如图5、6所示。由图5可见，光纤随机激光器的输出激光在1 h内的中心波长偏移量为0.03 nm，小于实验中所使用的光谱分析仪的波长分辨率0.1 nm。由图6可以见，激光输出功率的中间值为142.9 mW，功率波动小于3.7 mW。以上结果表明，掺铥光纤随机激光器的输出具有良好的稳定性。

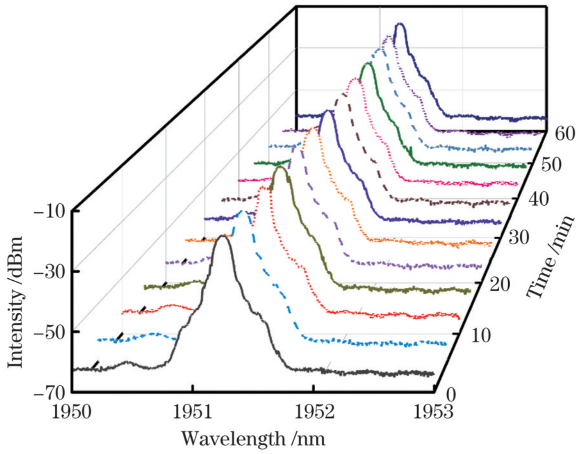


图5　泵浦功率为6.0 W时不同时间下测得的激光输出光谱

Fig. 5　Laser output spectra measured at different time when pump power is 6.0 W

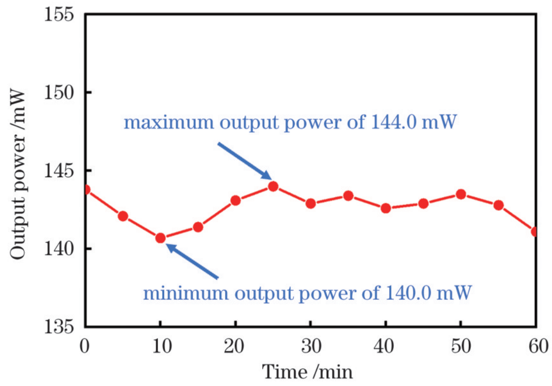


图6　泵浦功率为6.0 W时不同时间下测得的激光输出功率

Fig. 6　Laser output power measured at different time when pump power is 6.0 W

4　结　　论

采用飞秒激光逐点写入的光纤随机光栅作为随机反馈介质，利用掺铥光纤进行增益放大，结合光纤环镜，使得光纤随机激光器形成半开放腔结构，获得了输出波长为1951 nm的掺铥光纤随机激光器。得益于光纤随机光栅所提供的高效随机分布反馈及半开放腔结构，激光器所需的反馈光纤长度大幅缩短，泵浦阈值功率仅为2.1 W，比已报道的相同泵浦波长的掺铥光纤随机激光器的阈值低约40%。在6.0 W泵浦功率下，获得的输出激光的功率为142.9 mW，边模抑制比为43 dB，输出激光具有良好的稳定性。

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Thulium-doped Fiber Random Laser Based on Random Grating

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Abstract

Objective The 2 μm wavelength band is an eye-safe optical band that contains the absorption lines of water molecules and many atmospheric molecules as well as the spectrum windows for atmospheric communications. Therefore, fiber lasers in the 2-μm-band have been widely studied for their potential applications in fields such as lidar, laser ranging, and surgery. Currently, random fiber lasers (RFLs) have attracted extensive research attention owing to their simple structure and low spatial/temporal coherence properties. These fibers usually utilize back Rayleigh scattering as the random feedback mechanism, combined with the distributed Raman or Brillouin gain in the fiber, to generate random lasers in a long single-mode fiber. However, the Rayleigh scattering intensity of the single-mode fiber is inversely proportional to the fourth power of the wavelength, and the transmission loss is as high as 30 dB/km at 2 μm. Compared with the common RFLs operated at 1.0–1.5 μm, RFLs operated within the 2-μm-band are rarely reported, as they are highly difficult to realize. In this work, an RFL operated in a 2 μm region is demonstrated using a thulium-doped fiber as the gain medium and a random fiber grating for random distributed feedback with enhanced Rayleigh scattering efficiency. A laser output of wavelength 1951 nm is achieved with a relatively low pump threshold of 2.1 W.

Methods The proposed RFL is formed using a 793 nm pump laser, 793 nm/2000 nm wavelength-division multiplexer, fiber loop mirror, 1.5-m-long thulium-doped fiber, and random fiber grating. The random fiber grating containing over six thousand index modulation points along a 10-cm-long single-mode fiber is inscribed using a femtosecond Ti: sapphire regenerative amplifier, which is operated at a wavelength of 800 nm with a repetition rate of 100 Hz and a pulse duration of 80 fs. The neighboring refractive index modulation points are spaced at random distances between 7.5 μm and 12.5 μm. The random fiber grating provides an enhanced backward Rayleigh scattering, equivalent to that achieved from a several-km-long optical fiber. The thulium-doped fiber provides strong amplification, and the fiber loop mirror helps to form a half-

open laser cavity structure. Therefore, a low pump threshold is expected for the proposed RFL.

Results and Discussions It is found that the threshold pump power is 2.1 W, which is approximately 40% lower than that previously reported for a thulium-doped random fiber laser with the same pump wavelength and nearly the same lasing wavelength. At the threshold power, the laser output spectrum contains many stochastic narrowband wavelength components or spikes (Fig. 2). When the pump power slightly exceeds the threshold, a quasi-continuous wave is generated. Based on previous studies, the generation of stochastic spikes is related to the combined effects of distributed Rayleigh scattering and cascade-stimulated Brillouin scattering, while nonlinear spectral broadening arising from nonlinear interactions, such as frequency mixing and cross-phase modulation, can broaden and superimpose the spikes and further suppress the stimulated Brillouin scattering process. Mode competition and hopping are observed between two laser modes with different peak wavelengths of 1951.2 nm and 1951.4 nm when the pump power is approximately 3.5 W and 4.5 W, respectively (Fig. 3). The output power increases almost linearly with the pump power, with a slope efficiency of 3.9% (Fig. 4). When the pump power reaches 6.0 W, the laser output power is 142.9 mW, the optical-signal-to-noise ratio is up to 43 dB, and the wavelength and power fluctuations of the output laser within 1 h are less than 0.1 nm (Fig. 5) and 3.7 mW (Fig. 6), respectively, demonstrating good stability. The relatively low slope efficiency is predominantly caused by the high loss of the pump laser power from the output to the net injection into the thulium-doped fiber, of approximately 7.5 dB. The mismatching fiber connection introduces the high loss, and therefore, this problem may be resolved by customizing a WDM made of fibers whose parameters match those of fibers to be connected, i.e., the output fiber of the pump laser and the thulium-doped fiber. If the insertion loss is minimized, the slope efficiency of the laser may reach 20.6%, which is close to the slope efficiency of ordinary thulium-doped fiber lasers.

Conclusions In this work, a thulium-doped fiber random laser operated at 1951 nm is demonstrated using a random fiber grating as the distributed random feedback medium. Owing to the enhanced Rayleigh scattering provided by the random fiber grating, a random fiber laser with a relatively low threshold power of 2.1 W is achieved, which is approximately 40% lower than that of the previously reported thulium-doped random fiber laser with the same pump wavelength. When the pump power reaches 6.0 W, the output power of the random laser reaches 142.9 mW, and the optical-signal-to-noise ratio is up to 43 dB. The stability of the laser output is relatively good, as the wavelength shift and power fluctuation are less than 0.1 nm and 3.7 mW, respectively, over the testing period of one hour.

Key words lasers; random lasers; Rayleigh scattering; thulium-doped fiber lasers; fiber random grating; fiber loop mirror