中国激光

稳定单纵模运转的低噪声环形复合腔光纤激光器

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摘要 报道一种可实现稳定单纵模运转的低噪声环形复合腔掺铒光纤激光器。利用保偏光纤抗外界扰动能力强的特性，精细地优化复合腔参数以拓宽有效纵模间隔。对经隔震绝热封装后的激光器采取温度补偿，可对复合腔自由光谱范围(FSR)进行微调，使得复合腔激光器可更精准地运用 Vernier 效应来有效抑制跳模，进而该激光器可实现 14 h 以上无跳模的稳定单纵模连续运转，输出激光的信噪比高达 80 dB，线宽窄至 400 Hz。此外，还首次测量了环形复合腔掺铒光纤激光器在自由运转下宽频段内强度噪声和频率噪声特性，测量结果表明，该激光器在 1 mHz～1 MHz 宽频段内的强度噪声和频率噪声低，在 1 mHz～10 Hz 频段，强度噪声和频率噪声均优于典型分布 Bragg 反射(DBR)光纤激光器的噪声水平，且弛豫振荡频率也更低。

关键词 激光器；光纤激光器；环形复合腔；保偏光纤；单纵模；线宽；噪声

中图分类号 TN248 **文献标识码** A **doi**：10.3788/CJL202148.0501017

1 引 言

低噪声窄线宽单纵模光纤激光器在引力波探测[1]、原子分子物理[2-3]、时频传递[4]及精密测量[5-6]等领域具有重要应用。迄今的单纵模光纤激光器主要分为分布反馈(DFB)[7]、分布 Bragg 反射(DBR)[8]、环形腔[9]三种结构方案。DFB 和 DBR 光纤激光器均采用短腔长的线形腔设计，可实现长期无跳模的单纵模运转，但短腔结构限制了腔内增益光纤的储能，不利于获取高输出功率，且谐振腔品质因数(腔 Q 值)难以提高，使得激光器自由运转下的线宽一般在 kHz 以上[7-8,10]。环形腔光纤激光器在原理上可以采用长腔长的谐振腔结构，这不仅可以通过增加增益光纤长度来提高输出功率，同时还有利于在腔内插入各种光电器件，实现对单纵模激光进行频率调谐和反馈控制等功能[11-12]。并且，通过运用腔长相对较长的环形腔，可提升光纤激光器谐振腔的 Q 值，这将有利于获取更窄的自由运转下的激光线宽[13]，也有利于降低激光器弛豫振荡频率[14]，进而便于进一步通过采用光电反馈控制抑制弛豫振荡峰。但是，具有较长腔长的环形腔极易受外部环境噪声扰动的影响，导致环形腔光纤激光器存在着跳模等单纵模运转不稳定的问题。尽管人们发展出了复合谐振腔结构，利用复合腔的 Vernier 效应增大有效纵模间隔[11-12,15-16]，并辅以窄带滤波[16-18]或运用掺杂光纤可饱和吸收效应[12,15]等，在一定程度上抑制了环形腔光纤激光器的跳模；还通过采用抵抗外界扰动能力强的保偏光纤构建环形复合腔[19]，有效延长了无跳模单纵模运转时间。但迄今的环形腔光纤激光器在自由运转下的无跳模连续运转时间也仅数小时[15,17]，使得这种在原理上具有优良性能的环形腔光纤激光器难以满足实际应用需求。

本文报道一种可稳定单纵模运转的低噪声环形

收稿日期：2020-10-14；**修回日期**：2020-11-17；**录用日期**：2020-11-27

基金项目：国家重点研发计划(2017YFB0405100，2017YFB0405200)、中国科学院战略性先导科技专项(B 类)(XDB21010300)、国家自然科学基金(61805258，61377044)、先进激光技术安徽省实验室主任基金(20191001)

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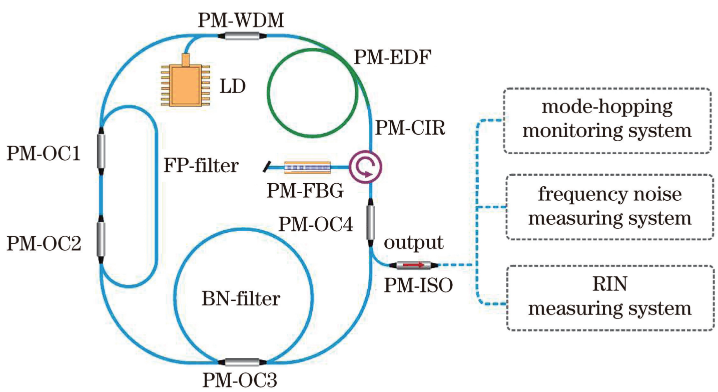
复合腔掺铒光纤激光器。将展示如何利用抗外界扰动能力强的保偏光纤优化复合环形腔参数，以拓宽有效纵模间隔；如何通过对经隔震绝热封装后的激光器进行温度控制来微调复合腔的自由光谱范围(FSR)，以精准地运用 Vernier 效应来抑制跳模，实现激光器长期稳定的单纵模运转；在此基础上，通过测量该激光器宽频段范围的强度和频率噪声，对这种环形复合腔光纤激光器的噪声特性进行表征。

2　激光器设计与研制

图 1 为设计并研制的全保偏环形复合腔单纵模掺铒光纤激光器的示意图。复合腔由在环形主腔中插入的 Fabry-Perot(F-P)型和带阻型辅腔构成，该复合腔结构能巧妙地利用三个谐振腔的透射特性增大复合腔的有效纵模间隔[15]。激光器内所用增益光纤为一段 0.66 m 长的保偏掺铒光纤(PM-EDF；Nufern PM-ESF-7/125)，在 975 nm 处的吸收为 20 dB/m，该 PM-EDF 由一只保偏尾纤输出的功率为 600 mW 的 975 nm 半导体激光器经保偏波分复用器(PM-WDM)泵浦。主腔中插入了一只快轴截止的保偏环行器(PM-CIR)，其公共端接入了一只反射率为 99%、3 dB 带宽为 0.1 nm(～12.3 GHz)的 1560 nm 保偏光纤光栅(PM-FBG)，以在主腔中构建出窄带滤波器，减少增益带宽内的潜在纵模数。为抑制外界环境扰动对 PM-FBG 反射特性的影响，采用 FBG 温度补偿技术[20]对该 PM-FBG 进行封装，封装后的中心波长随温度变化约为 1 pm/℃(～120 MHz/℃)。此外，该环行器还可使复合腔内的光波单向传输，并抑制正交偏振态之间的耦合。主腔中插入了由一对相同耦合比的保偏光纤耦合器(PM-OC1、PM-OC2)构成的 F-P 型辅腔，利用其窄带谐振透射峰滤出潜在起振的优势主腔谐振纵模；还插入了由一只耦合比为 50∶50 的 PM-OC3 构成的带阻型辅腔，利用其阻带来抑制经 F-P 型辅腔选取的处于 PM-FBG 滤波带宽内的多余优势主腔纵模。PM-OC1、PM-OC2 及 PM-FBG 的闲置尾纤端口均进行斜 8°处理以防止光纤端面反射。另一只耦合比 50∶50 的 PM-OC4 用作激光耦合输出，为防止外部反射，在该耦合器输出端后接入一只保偏隔离器(PM-ISO)。



PM: polarization-maintaining; EDF: erbium doped fiber; FBG: fiber Bragg grating; OC: optical coupler; WDM: wavelength division multiplexer; ISO: isolator; CIR: circulator; LD: laser diode; FP-filter: F-P type secondary cavity filter; BN-filter: band-notch type secondary cavity filter; RIN: relative intensity noise

图 1　全保偏环形复合腔光纤激光器的结构

Fig. 1　Structure of the all-PM compound ring cavity fiber laser

由于保偏光纤抵抗外界扰动能力强，能够在实验室环境下通过可重复的实验对复合腔参数进行优化设计。实验优化时，在相距极近的众多主腔模中先利用 F-P 型辅腔极窄的透射峰滤出潜在起振的优势纵模，随后使用带阻型辅腔的阻带对滤出的多余优势主腔模进行抑制；同时根据主腔长度精细地对各辅腔长度进行设计和优化，使其满足 Vernier 效应拓宽复合腔有效纵模间隔的要求[11,17]。根据上述优化设计方法，先尽可能地缩短主腔腔长，以增大主腔 FSR，优化后的主腔腔长约 2.26 m，对应的 FSR 约 92 MHz，使得在 FBG 的 3 dB 带宽(0.1 nm)内大约包含 133 个主腔纵模。然后，结合 F-P 型辅腔所用 PM-OCs 耦合比对其谐振透射峰带宽和透过率的影响[21]，通过兼顾透射峰带宽和透过率的原则来优化 PM-OC1 和 PM-OC2 的耦合比，其透射峰的 3 dB 带宽内只包含一个主腔纵模，优化后的 F-P 型辅腔所用两只 PM-OCs 的耦合比均选取 70∶30；在确保满足 Vernier 效应前提下，也尽可能地缩短

F-P 型辅腔的腔长，F-P 型辅腔的实际腔长约 0.49 m，相应的 FSR 约为 422 MHz，这样，经 Vernier 效应就可将复合腔的有效纵模间隔拓宽为约 1.2 GHz，使得 FBG 的 3 dB 带宽内包含的主腔纵模数由 133 个减少为 10 个；由于掺铒光纤为均匀加宽为主并伴有一定非均匀加宽效应的增益介质，轻微的非均匀加宽会导致纵模之间的竞争效应，故利用带阻型辅腔来抑制这种潜在的纵模竞争，优化后的带阻型辅腔腔长约 1.86 m，对应的 FSR 为 111 MHz，经 Vernier 效应就可将复合腔的有效纵模间隔进一步拓宽到 12.3 GHz 以上，最终确保在 FBG 带宽内仅有一个优势纵模起振，实现单纵模运转。

采用聚四氟乙烯和铝板对参数优化后的激光器进行了振动和声波隔离的绝热封装，以抑制外界环境扰动的影响，并且，封装后的激光器配备了精密温控单元。通过改变控制温度，可对构成复合腔的主腔和辅腔的腔长或 FSR 进行微调，使其能更精准地符合 Vernier 效应要求，从而有效抑制跳模。对于优化后的激光器的各腔长，当温度变化 ΔT 时，各腔 FSR 的变化量为 $\Delta F_{\mathrm{FSR}}=-\frac{c}{n\cdot L}(\alpha+\beta)\cdot\Delta T$，其中 α 和 β 分别为光纤的热膨胀系数和热光系数，n 为光纤折射率，L 为腔长。因此，由于各腔的长度不同，随着温度的改变，各腔对应的 ΔF_{FSR} 也不同[22]，当控制温度在室温附近改变 0.05 ℃时，可在 40～200 Hz 范围内对主腔和辅腔的 FSRs 进行精细微调，这样通过调节控制温度，主腔起振纵模能够精准地对应于 F-P 型辅腔透射峰中央，带阻型辅腔的阻带峰也可有效地抑制其他潜在起振主腔纵模，最终使得主腔起振纵模在与其他潜在主腔起振纵模竞争中处于更优势地位，实现激光器长时间单纵模无跳模运转。不仅如此，当 F-P 型辅腔透射峰精准对齐主腔起振纵模时，复合腔将具有低损耗特性，从而利于提升激光腔的 Q 值，使得激光器具有窄线宽和低噪声特性[13-14]。

3 测试结果与讨论

采用两种 F-P 扫描干涉仪对封装后的光纤激光器在实验室环境(25±1)℃下的单纵模运转特性进行测试，其中 FSR 和精细度分别为 1.5 GHz 和 200(SA200-12B，Thorlabs)、10 GHz 和 150(SA210-12B，Thorlabs)，测试结果均表明，激光器均可实现单纵模运转。图 2(a)是 FSR 为 1.5 GHz 的 F-P 扫描干涉仪对激光器的测量结果，清晰地展现了单纵模输出特性，但是实验观察的无跳模连续运转时间为 7～20 min。利用 F-P 扫描干涉仪观察发现，适当调整激光器的控制温度，激光器无跳模连续运转时间会大幅延长，表明对激光器施加温度补偿，确实可精细地微调复合腔的各腔长，使其能更精准地满足 Vernier 效应要求，进而抑制跳模产生。

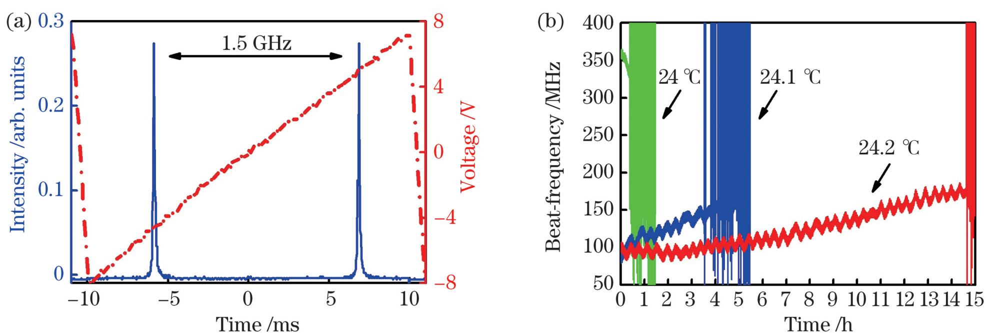


图 2 研制的激光器单纵模运转特性监测。(a) F-P 扫描干涉仪测量的单纵模运转特性；(b)一台可长期稳定单纵模运转的可调半导体激光器与所研制的激光器相拍产生的拍频信号

Fig. 2 Single-longitudinal-mode characteristics monitored by the designed laser. (a) Single-longitudinal-mode characteristics measured by the F-P scanning interferometer; (b) beat frequency signals between a long-term stable single-longitudinal-mode adjustable diode laser and the designed laser with a frequency counter

为了考察所研制的激光器单纵模连续运转时间的长短，采用频率计数器(53220A，Agilent)自动记录下可长期稳定单纵模运转的可调半导体激光器(8164B，Agilent)与所研制的激光器输出激光在 1.5 GHz 带宽光电探测器(EOT；ET3000A)上产生的拍频信号。图 2(b)为频率计数器自动记录的在不同激光器控制温度下的拍频信号随时间的变化关系，其中，拍频信号发生突变意味着激光器发生了跳模。由图 2(b)可见，对于不同的控制温度，所研制的激光器单纵模连续运转时间不同，当控制温度设

定为 24.2 ℃时，激光器可实现大于 14 h 的无跳模单纵模连续运转。这是迄今自由运转环形腔单纵模光纤激光器单纵模连续运转所能达到的最长时间。值得注意的是，14 h 的无跳模单纵模连续运转已能满足大多实际应用要求。

图 3(a)为光谱分析仪(OSA；AQ6370D，Yokogawa)测得的激光器输出光谱，激光输出中心波长为 1560.470 nm，信噪比高达 80 dB。高信噪比主要得益于激光器的高 Q 值和快轴截止的全保偏结构，有效抑制了激光起振偏振方向上放大的自发辐射(ASE)。图 3(a)插图所示为激光器经 PM-OC4 端口的输出功率(P_s)随泵浦功率(P_p)之间的变化关系，可见激光器阈值泵浦功率低，仅 42 mW，表明腔损耗小，这同样得益于 F-P 型辅腔透射峰与主腔起振纵模之间的精准对齐。当泵浦功率为 600 mW 时，PM-OC4 端口的输出功率达 50 mW，且未出现饱和现象，表明输出功率还可进一步提升。图 3(b)为基于 50 km 长单模光纤延迟线的标准自外差系统对输出激光线宽的测量结果，由经洛伦兹拟合后的实测数据所知，输出激光的 20 dB 和 3 dB 线宽分别为 8 kHz 和 400 Hz，这进一步表明激光器具有极高的 Q 值。

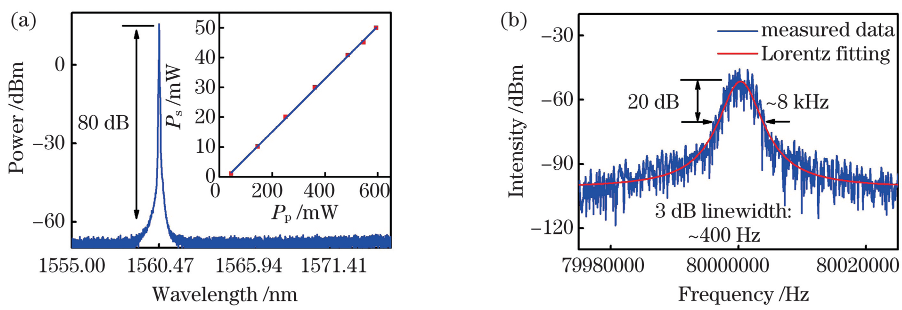


图 3 研制的激光器的输出特性。(a) OSA 测得的激光器输出光谱，插图为激光器输出功率随泵浦功率的变化；(b)标准自外差系统对输出激光线宽的测量结果

Fig. 3 Output characteristics of the designed laser. (a) Laser output optical spectrum measured by the OSA, the insert shows the laser output power varying with pump power; (b) measured results of the output laser linewidth using a standard self-heterodyne system

受 1 Hz 以下频段噪声测量持续时间长的限制，迄今未见关于自由运转环形复合腔单纵模光纤激光器宽频段噪声特性测量的报道。由于所研制的激光器能实现长期无跳模运转，对这种自由运转环形复合腔单纵模光纤激光器的宽频段噪声特性进行测量，并与已报道的典型 DBR 光纤激光器噪声水平[23]进行比较。对复合腔光纤激光器的测量方法与测量设备均与文献[23]相同。

图 4 为实测的环形腔光纤激光器在 1 mHz～50 MHz 宽频段内的相对强度噪声(RIN)功率谱密度(PSD)。总体上，环形腔光纤激光器的 RIN 特性与 DBR 光纤激光器相似，低频处的功率谱均会因热噪声影响呈 $1/f$ 趋势滚降[5]，实测 1 mHz 处的噪声水平为 1.7×10^{-2} $\mathrm{Hz}^{-1/2}$，与 DBR 光纤激光器相近；在 10 Hz～1 kHz 频段，受声波噪声影响呈尖峰[24]，实测 1 kHz 处的噪声水平为 1.4×10^{-7} $\mathrm{Hz}^{-1/2}$，与 DBR 光纤激光器几乎一致；在高频段均趋于散粒噪声极限[24]。但是在 1 mHz～10 Hz 频段，环形复合腔激光器强度噪声明显低于 DBR 激光器，主要原因是该频段的主要噪声来源是热效应[25]，DBR 激光器为短腔结构，增益光纤为高掺杂，增益系数高，非辐射弛豫造成局部产热快，而玻璃材料导热性相对较差，导致掺杂光纤内局部热积累严重；而环形腔的长腔结构使得所用增益光纤的增益系数低，非辐射弛豫造成的局部产热较慢，缓解了光纤的自热效应[26]，最终在该频段环形复合腔激光器的强度噪声低于 DBR 激光器。由图 4 还可看出，相较于 DBR 光纤激光器，环形腔光纤激光器具有更低的弛豫振荡频率和更快的弛豫振荡衰减速率，这是因为具有长腔结构的环形复合腔光纤激光器具有更高的 Q 值和更长的腔寿命。正因为如此，环形腔激光器的弛豫振荡峰对应的频率低至 123 kHz，且在 1 MHz 频率附近，已趋于散粒噪声极限值 1.58×10^{-8} $\mathrm{Hz}^{-1/2}$。

图 5 为实测的环形腔光纤激光器在 1 mHz～1 MHz 频段内的频率噪声功率谱密度，其中处于 1 mHz～10 Hz 频段的频率噪声通过已知噪声特性的 1560 nm 单纵模光纤激光器的参考激光经外差拍频法测得[23]。同样，环形腔光纤激光器的频率噪声谱变化趋势在总体上也与 DBR 光纤激光器相似，频率噪声水平也几乎相当。但是与强度噪声一样，

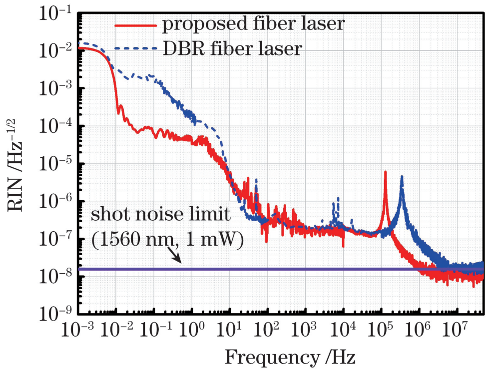


图 4 实测的环形腔光纤激光器在 1 mHz～50 MHz 宽频段内的 RIN 功率谱密度和 DBR 光纤激光器强度噪声的测量结果[23]

Fig. 4 Measured RIN power spectrum density of the ring cavity fiber laser in the wide frequency range of 1 mHz–50 MHz and the measurement results of intensity noise of DBR fiber laser[23]

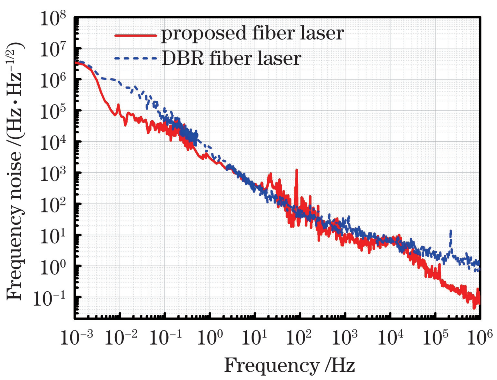


图 5 实测的环形腔光纤激光器在 1 mHz～1 MHz 宽频段内的频率噪声和 DBR 光纤激光器频率噪声[23]

Fig. 5 Measured frequency noise of the ring cavity fiber laser in the wide frequency range of 1 mHz–1 MHz and frequency noise of DBR fiber laser[23]

在 1 mHz～10 Hz 频段，环形复合腔激光器的频率噪声也低于 DBR 激光器，这同样是因为环形腔的长腔设计有利于抑制基本热噪声[5]，得益于环形腔光纤激光器的快轴截止的全保偏结构和高 Q 值腔设计对腔内 ASE 的有效抑制(信噪比高达 80 dB)，使得环形复合腔光纤激光器的频率噪声在 1 MHz 处就降为 0.1 Hz/$\sqrt{\text{Hz}}$，明显快于 DBR 光纤激光器频率噪声随分析频率下降的速度。此外，由 Domenico 的 β 算法[27]，容易由实测的频率噪声功率谱计算出激光半峰全宽(FWHM)，由此计算得到 3 dB 线宽为 439 Hz，与延迟自外差法实测到的线宽基本吻合。

4 结　论

报道了一种可稳定单纵模运转的低噪声环形复合腔光纤激光器。采用抵抗外界扰动能力强的保偏光纤构建复合环形腔时，在实验室环境下精细地优化复合腔参数，使其接近利用 Vernier 效应拓宽复合腔有效纵模间隔的要求，这使得激光器经隔震绝热封装后，通过调整控制温度微调复合腔的 FSRs，就能精准地运用 Vernier 效应来有效抑制跳模，实现长期的单纵模稳定运转。所研制的全保偏复合环形腔光纤激光器的无跳模单纵模运转时间已达 14 h 以上，是迄今为止环形腔光纤激光器获得的最长单纵模稳定运转时间。得益于环形腔的高 Q 值，输出激光信噪比高达 80 dB，3 dB 线宽约 400 Hz。根据该环形复合腔光纤激光器的单纵模长期运转特性，首次测量了这类激光器宽频段噪声。结果表明，环形腔光纤激光器在 mHz 至 MHz 频段内强度噪声和频率噪声低，但因环形腔的长腔结构，增益光纤的增益系数低，强度噪声和频率噪声在 1 mHz～10 Hz 频段均低于 DBR 激光器。而因环形腔的高 Q 值特性，环形腔光纤激光器具有比 DBR 光纤激光器更低的弛豫振荡频率，且在分析频率大于弛豫振荡频率后，频率噪声随分析频率升高下降的速度更快。

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Low-Noise Compound Ring Cavity Fiber Laser with Stable Single-Longitudinal-Mode Operation

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Abstract

Objective Low-noise narrow-linewidth single-longitudinal-mode (SLM) lasers have several important applications in many fields, such as gravitational wave detection, atomic and molecular physics, time and frequency transfer, and precision measurement. Currently, SLM fiber lasers are divided into three main types: distributed feedback, distributed Bragg reflection (DBR), and ring cavity laser. Among them, the ring cavity laser, which employs a long cavity design, facilitates increase in cavity gain to improve output power using relatively high-gain fibers. A ring cavity laser can also be used in other applications such as frequency tuning and feedback control by simply inserting optical components into a cavity. Moreover, the Q-value of a fiber-laser resonator can be increased by employing a long ring cavity. This long cavity helps in obtaining a narrow free-running laser linewidth and reduces the relaxation oscillation frequency of the laser. This is useful in suppressing a relaxation oscillation peak through photoelectric feedback control. However, a long ring cavity is easily affected because of external-environment noise disturbances, which leads to SLM instability, e. g., mode hopping. Thus far, the achieved continuous operation time of a free-running compound ring cavity fiber laser without mode hopping is only several hours. Therefore, although in principal, a fiber-laser source exhibits excellent performance, it cannot meet practical application requirements. In this study, a low-noise narrow-linewidth-ring erbium-doped fiber laser operating in a SLM and maintaining its polarization is reported.

Methods A polarization-maintaining (PM) fiber′s strong ability to resist environmental disturbances allows the parametric optimization of a compound ring cavity through repeatable experiments in a laboratory. During experimental optimization, Fabry-Perot (F-P) type very narrow resonant transmission peaks of a secondary cavity are used to filter potentially oscillating dominant longitudinal modes from a large number of nearby main-cavity modes. Then, notch bands of the band-notch type secondary cavity are used to suppress excess dominant main-cavity modes, which are filtered using the F-P type secondary cavity. Length of each secondary cavity can be designed and optimized according to the length of the main cavity so that it meets the Vernier-effect requirements to broaden the effective longitudinal mode spacing of a compound ring cavity. During laser optimization, a vibrational acoustic wave and a thermal-isolation design are employed to protect the laser from environmental vibrations and thermal disturbances. Length of each cavity in a compound ring cavity fiber laser can be fine-tuned to strictly meet the Vernier-effect requirements by changing the control temperature of a laser. Thus, mode hopping is efficiently suppressed.

Results and Discussions After optimizing the cavity length and employing the vibrational acoustic wave and thermal-isolation design, the laser is capable of performing the SLM operation at room temperature [Fig. 2(a)]. By fine-tuning the length of each cavity through temperature compensation, the laser is capable of achieving continuous SLM operation without mode hopping for more than 14 h. To the best of our knowledge, this is the longest SLM free-running time ever achieved using the proposed laser type [Fig. 2(b)]. By adopting a laser cavity structure that maintains the laser polarization and exhibits a high-Q design, the laser output signal-to-noise ratio measured is up to 80 dB [Fig. 3(a)], and linewidth is approximately 400 Hz [Fig. 3(b)]. The long-term SLM operating characteristics of the compound ring cavity fiber laser designed by our experiment allowed us to measure its broadband noise characteristics. The relative intensity noise-power (Fig. 4) and frequency noise-power spectra (Fig. 5) of the ring cavity fiber-laser type were measured in the mHz–MHz frequency band for the first time. The noise measurement results demonstrate that the proposed laser exhibits excellent noise characteristics, similar to those of the DBR fiber laser. Moreover, its intensity noise and frequency noise are lower than those of the DBR fiber laser in the 1 mHz–10 Hz frequency band. Additionally, its relaxation oscillation frequency is lower than that of the DBR fiber laser.

Conclusions A low-noise compound ring cavity fiber laser with stable SLM operation is proposed in this study. Using PM fibers with strong resistance to external disturbances, compound ring cavity parameters were accurately optimized to achieve a broad effective longitudinal mode spacing. After fabricating vibration isolation and thermal insulation packaging, temperature control was adopted to further fine-tune the FSRs of a compound ring cavity. Then, the Vernier-effect requirements were strictly followed to suppress mode hopping. Finally, the proposed laser was capable of achieving long-term SLM stable operation for more than 14 h, which is the longest SLM stable operation time ever achieved by a compound ring cavity fiber laser to the best of our knowledge. Owing to the laser high-Q characteristics, its output signal-to-noise ratio is up to 80 dB, and 3-dB linewidth is approximately 400 Hz. The long-term SLM-operation characteristics of the compound ring cavity fiber laser allowed us to measure the noise behavior of the laser type. The noise measurement results demonstrate that the compound ring cavity fiber laser exhibits low intensity and frequency noise in the mHz–MHz frequency band. Compared with a typical DBR fiber laser, the proposed laser exhibits lower relaxation oscillation frequency, relative intensity noise, and frequency noise in the 1 mHz–10 Hz frequency band.

Key words lasers; fiber laser; compound ring cavity; polarization-maintaining fiber; single-longitudinal-mode; linewidth; noise

OCIS codes 140.3500; 140.3510; 140.3560; 140.3570