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基于种子注入锁定的窄线宽低噪声单频 Nd:YVO_4激光器

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摘 要:采用种子注入锁定放大技术,并结合Pound-Drever-Hall稳频方法,实现了种子光的高稳定放大。实验结果表明,在种子光注入条件下,当泵浦功率为38.12 W时,获得了线宽仅为7.0 kHz、输出功率为13.5 W的单频光,输出功率的不稳定度低于0.18%,且在60 min内的波长漂移仅为132.41 MHz,显著低于自由运行种子光的300 MHz,展现了出色的功率和波长稳定性。

关键词:单频激光器;注入锁定;窄线宽;低噪声;高功率
中图分类号:TN248.1 **文献标识码**:A **doi**:10.3788/gzxb20265503.0314001

0 引言

单频连续波激光器因其窄线宽、低噪声、高相干性等优势,广泛应用于量子信息[1-2]、高精度精密测量[3-4]和激光雷达[5-6]等领域。近年来,随着对高性能光源需求的不断增长,单频激光的研究正持续向更强的时间相干性(更窄线宽)、更优的运行稳定性(频率与功率稳定性提升)、更高输出功率以及更丰富的波长可调性方向推进,已成为激光科学与工程领域的重要研究前沿与热点方向[7-11]。

迄今为止,已经发展出了几种实现单频激光器的技术:非平面环形振荡器(Non Planar Ring Oscillator, NPRO)[12-13]、插入法布里-珀罗(Fabry-Pérot, F-P)标准具的短腔[14-15]、扭摆腔法[16]等,这几种技术受限于晶体热效应和腔型结构等因素,难以同时实现高功率和窄线宽的单频激光输出。相比之下,分布反馈激光器(Distributed Feedback Laser, DFB)和分布式布拉格反射激光器(Distributed Bragg Reflector Laser, DBR),可以实现线宽低于kHz的窄线宽单频激光输出[17-18],同时结合主控振荡器功率放大器可以有效地获得高功率单频激光输出。但是在放大过程中,增益光纤的热负载和非线性效应会导致输出波长漂移,劣化频率稳定性。相比之下,种子注入锁定放大技术[19-20],利用相干增益竞争机制,采用频率锁定技术主动锁定激光腔谐振频率,抑制频率噪声,在未对种子光进行主动稳频的情况下,也能实现高功率稳定性、高频率稳定性的窄线宽单频激光输出。采用种子注入锁定技术的单频激光器可在实现高输出功率的同时兼具低噪声、窄线宽和优异的稳定性。关于连续波单频种子注入锁定放大的研究主要在功率提升和波长扩展两个方向:2005年,德国汉诺威激光研究中心的Frede M团队采用注入锁定放大策略,将低噪声的NPRO种子源的功率首先从2 W放大至12 W,并将其频率精确锁定至高功率谐振腔的振荡模,从而成功实现了输出功率达

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195 W的连续波单频1 064 nm激光输出[21]。2015年，德国凯泽斯劳滕大学通过注入锁定技术实现了17.2 W的单频1 342 nm激光输出，利用单程二次谐波产生5.7 W单频671 nm激光输出[22]；2021年核工业理化研究所张桂侠等人以1.0 W连续单频可调谐激光为种子光，利用Pound-Drever-Hall(PDH)技术注入锁定获得了8.3 W连续单频可调谐的输出激光，1 h内功率波动小于2%[23]；2024年中国科学院理化技术研究所提出一种基于注入锁定技术的888 nm半导体激光器泵浦的高功率单频可调谐1 342 nm Nd∶YVO_4激光器。激光器最大平均输出功率13.9 W，测量的线宽为41 MHz。1 h内功率稳定度为±0.4%，波长波动范围为2.9 pm[24]。种子注入锁定放大后的激光线宽主要取决种子激光线宽，输出激光的功率特性和时域稳定性主要与从激光器和锁定系统有关。

本文采用单频连续1 064 nm光纤激光器作为主激光器，激光二极管泵浦、键合晶体Nd∶YVO_4和四镜环形谐振腔构成从激光器。基于PDH技术，实现了种子光的注入锁定，从而对低功率的1 064 nm种子光实现了低噪声、窄线宽、高稳定性的功率放大。最终获得了功率13.5 W线宽7.0 kHz的单频窄线宽激光输出，放大过程中激光的相频噪声并没有明显提升，同时具有极高的稳定性：60 min内中心波长的抖动带宽132.41 MHz，明显小于种子光60 min内自由运转波长漂移300 MHz，60 min内的功率不稳定性值(Root Mean Square，RMS)小于0.18%。

1 实验装置

图1为实验结构原理图，结构上主要包括三个部分：主激光器、从激光器、频率锁定系统。主激光器使用线宽为5.6 kHz的最大输出功率为100 mW的单频光纤激光器作为种子源，激光器通过隔离器(Optical Isolator，ISO)隔离返回光防止对种子源造成损坏。HR1-HR3为45°反射镜。f为曲率半径1 000 mm的聚焦透镜，实现注入种子光进入谐振腔内的束腰大小与环形腔振荡光束腰大小相同，实现模式匹配。从激光器的结构为“8”字环形腔，M1为平面镜，一面镀有888 nm高透膜，另一面镀有888 nm增透膜，1 064 nm高反膜。M2为平面镜，对1 064 nm的透射率为20%，M2作为从激光器的输出镜，同时也是种子注入的耦合镜。谐振腔的几何长度约为670 mm，凹镜的光学入射角度为10°，基横模在晶体处的理论值为400 μm。M3和M4均为曲率半径100 mm的平凹镜，镀1 064 nm高反膜。泵浦源采用波长888 nm的半导体激光器，耦合输出光学的纤芯直径400 μm、数值孔径为0.22，经焦距为40 mm和100 mm的准直聚焦透镜进行1∶2.5扩束。增益介质采用键合晶体YVO_4/Nd∶YVO_4，可以有效降低晶体的热效应，尺寸大小为3 mm×3 mm×(3+20)mm，晶体的切向是A切，晶体末端设计有一个1.5°的楔角，可以增大σ偏振光的几何损耗，保证π偏振光优于σ偏振光在腔内起振[10]。同时采用半导体制冷器(Thermo Electric Cooler，TEC)控温系统精确控制晶体温度[25]。锁频系统采用Liquid Instruments的Moku Pro设备，种子光通过电光调制器(Electro-Optic Modulators，EOM)进行射频相位调制，Moku系统将光电探测器(Photoelectric Detector，PD)探测到的腔透射信号进行混频解调，获得误差信号，最后通过伺服控制器输出电压驱动压电陶瓷调整激光谐振腔长度，从而完成谐振腔和种子光之间的锁定。

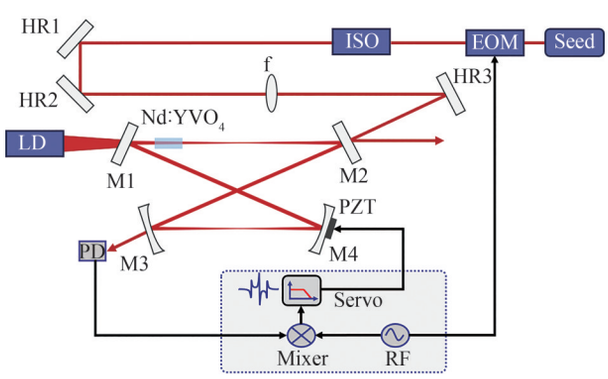


图1 种子注入锁定激光器结构示意图

Fig. 1 Schematic diagram of the seed injection-locked laser

2 实验结果与讨论

实验首先研究了在谐振腔内加入旋光器和二分之一波片时从激光器的输出特性。当输出镜M2透过率为20%时，从激光器单向运转的输出功率随泵浦功率的变化曲线如图2(a)所示。此时，激光器阈值为4.1 W，在泵浦功率为46 W时，可实现16.5 W的1 064 nm激光输出，对应的光光转化效率为35.8%。激光输出功率与泵浦功率呈线性关系，斜效率为39.3%。虽然行波腔单向运作无空间烧孔效应，但是随着泵浦功率的增加，从激光器呈多纵模振荡状态，利用F-P干涉仪对输出激光纵模特性监测结构如图2(b)所示。利用波长计(HighFinesse WS7-60)对其输出的中心波长稳定性进行了测量，最终测得在60 min内中心波长抖动带宽约为2.56 GHz。

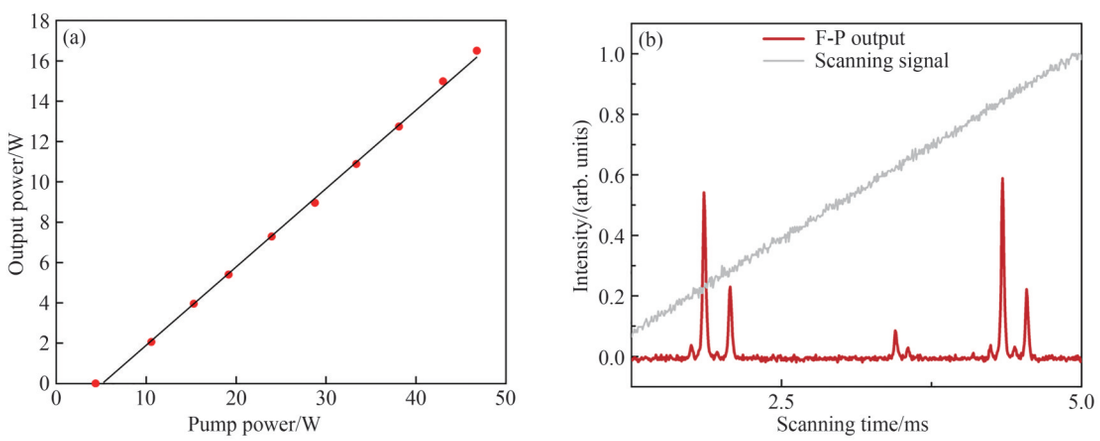


图2 从激光器单向运转时的输出特性。(a)从激光器单向运作时输出功率随泵浦功率的变化；(b)最大输出功率下的纵模结构

Fig. 2 Output characteristics of the slave laser under unidirectional operation. (a) Output power versus pump power during unidirectional operation of the slave laser; (b) Longitudinal mode spectrum at maximum output power

在种子光注入并成功锁频后，对激光器输出功率进行测量，如图3所示，由于种子光功率较低，随着泵浦功率的增加，种子光功率和谐振腔内谐振功率差距增大，导致锁定不完全，从激光器的自由运转模式部分残留，斜效率略有下降。利用F-P干涉仪对注入锁定后输出激光纵模特性监测结构如图3(b)所示，输出激光呈单纵模运转。

后续对激光器的功率和波长稳定性进行了测试，测量了激光器在泵浦功率38 W下稳定运转时的功率稳定性，如图4(a)所示，对应的平均功率为13.4 W，60 min内的RMS小于0.18%。60 min内中心波长抖动

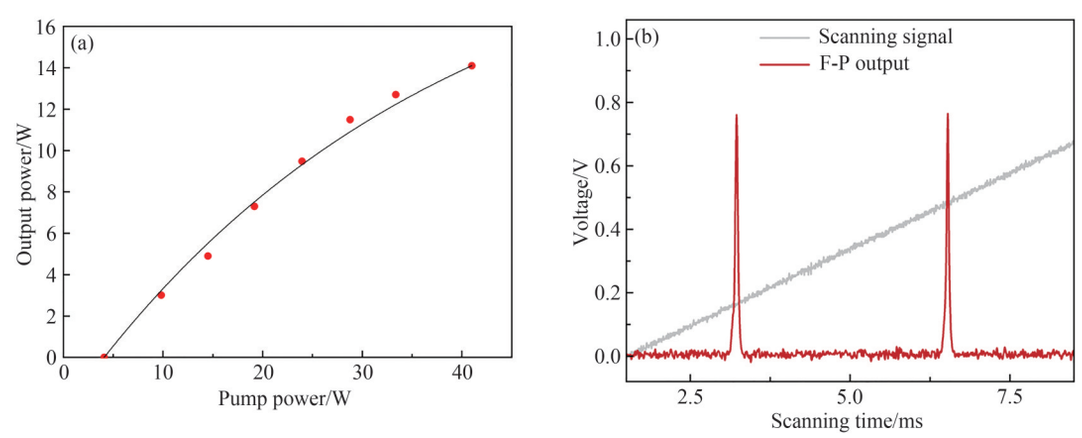


图3 种子注入锁定后输出特性。(a)种子注入锁定后输出功率随泵浦功率的变化；(b)种子注入锁定后输最大输出功率下的纵模结构

Fig. 3 Output performance characteristics under seed injection locking. (a) Output power versus pump power under seed injection locking; (b) Longitudinal mode spectrum at maximum output power under seed injection locking

带宽为132 MHz左右，如图4(b)所示。自由运转的种子光60 min内中心波长抖动带宽为300 MHz左右，在未对种子光施加主动稳频的情况下，放大后波长稳定性相较于种子光自由运转时有明显提升。

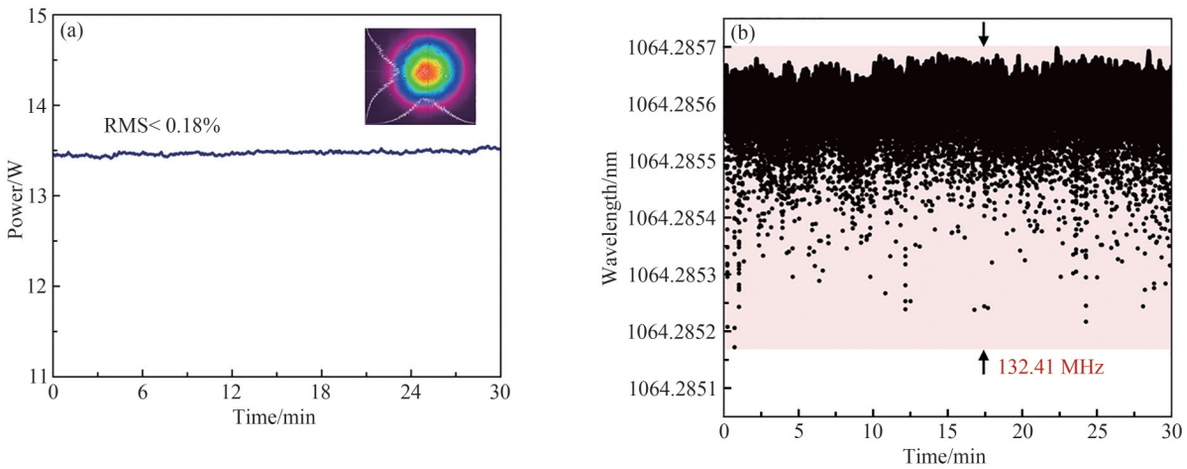


图4 最大输出功率下激光功率稳定性和波长稳定性。(a)功率稳定性；(b)波长稳定性

Fig. 4 Laser power stability and wavelength stability performance at maximum output power. (a) Power stability; (b) Wavelength stability

在锁定稳定状态下，对输出激光进行了线宽测量。测量设备采用的是本实验室基于拍频法自制的实验装置，在该方法中，对比拍频包络谱中的波峰和波谷的幅度差来得到对应的线宽值。在频谱上显示的结果如图5所示，延时光纤长度为1 000 m，为了降低零频附近环境噪声的影响，对比拍频包络中第二峰值和第二谷值的幅度差(Contrast of the Deepest Second Peak and Second Trough, CDSPST)来对线宽进行计算[26-27]，图5(a)为种子光的拍频结果，这里的CDSPST为13.0 dB，对应的线宽约为5.6 kHz。图5(b)为种子注入放大后的拍频结果，这里的CDSPST为12.0 dB，对应的线宽约为7.0 kHz。注入锁定放大后的线宽相比于种子光的线宽略有展宽，可能是由于泵浦源的噪声传递以及从激光器自由运转的残余模式的影响。

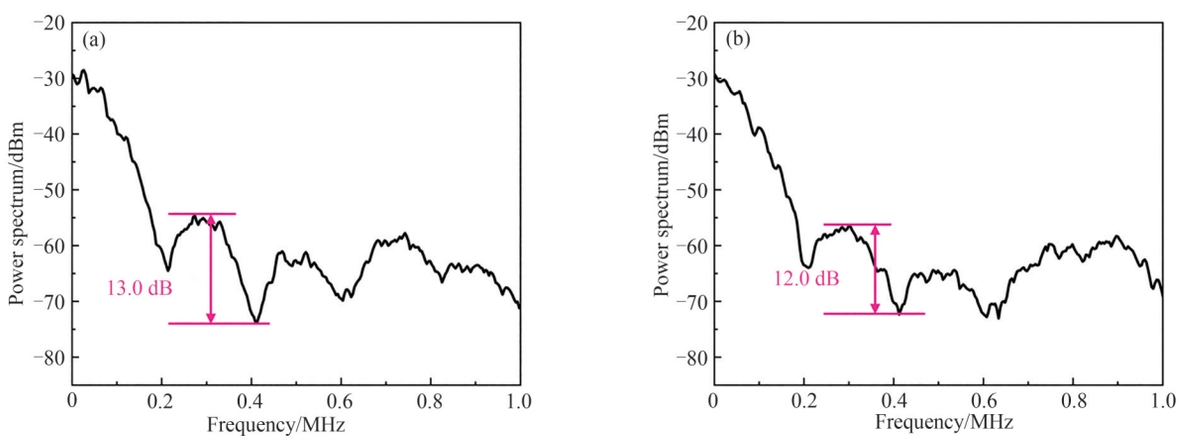


图5 种子光和放大后的线宽相干包络测量结果。(a)种子光相干包络；(b)放大后最大功率下激光泵浦光相干包络

Fig. 5 Measurement results of the coherence envelopes for the seed light and amplified laser output. (a) Coherence envelope of the seed light; (b) Coherence envelope of the amplified laser at maximum output power

为了更全面地评估激光的相干性能与谱线纯度，进一步采用噪声分析仪对自由运转和种子注入锁定后输出激光的相频噪声进行了测量与比较[28-30]。测量结果如图6所示，黑色曲线为单向运转时输出激光的频率噪声，红色曲线为种子注入锁定后输出激光的频率噪声，蓝色曲线为种子光频率噪声。图6可以看到1～100 Hz内，锁定后的相频噪声相较于自由运转时有明显抑制，在百Hz至kHz范围内，激光相频噪声相较于种子光和从激光器自由运转时噪声略有提升，可能由于锁定过程中，压电陶瓷持续往复的伸缩运动引起腔

长持续的抖动，机械振动引入的噪声转换成低频段的频率噪声。如果进一步优化频率锁定参数，在低频段有足够增益的噪声抑制，或将获得更低相频噪声的激光输出。

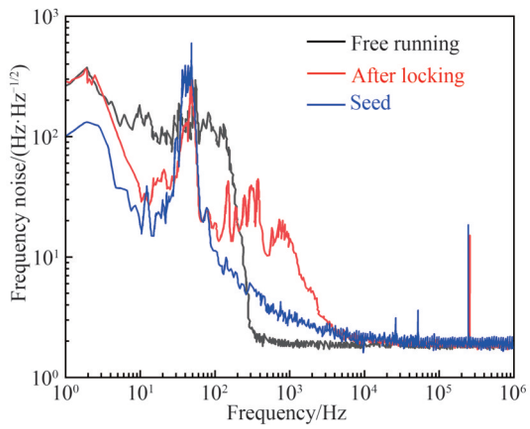


图6　激光相频噪声测量结果

Fig. 6　Laser phase-frequency noise measurement results

3　结论

本文采用种子注入锁定技术，实现了高功率、窄线宽、低噪声且具有优异功率与频率稳定性的单频激光输出。实验获得输出功率13.5 W、线宽约7.0 kHz的高相干单频激光，60 min内功率不稳定度低于0.18%，波长漂移为132 MHz。在未对种子光进行主动稳频的条件下，相比种子光60 min频率漂移300 MHz明显减少，锁定后频率稳定性显著提升。该研究结果表明，种子注入锁定技术能够在保持高功率输出的同时有效抑制相位与频率噪声，为高功率、窄线宽、低噪声单频激光的实现提供了可行途径。未来，通过进一步优化锁定参数，可望获得更高稳定性的激光输出；若结合谐振腔内非线性频率变换技术，还可为特殊波长单频激光光源的构建提供一种高效方案。

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Seed-injection-locked Narrow-linewidth, Low-noise Single-frequency Nd∶YVO_4 Laser

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Abstract: Single-frequency continuous-wave lasers are critically important for advanced applications in quantum information science, high-precision metrology, and lidar systems. These applications demand laser sources that combine a narrow linewidth, low amplitude and frequency noise, and high temporal coherence. A significant challenge in the field is scaling the output power of such lasers while simultaneously preserving their superior spectral purity and high stability. Conventional techniques for achieving single-frequency operation often face limitations in power scaling due to thermal effects and nonlinearities.

This research demonstrates a high-power, single-frequency Nd:YVO_4 laser system utilizing the seed injection-locking technique. A stable, narrow-linewidth fiber laser operating at 1 064 nm serves as the master oscillator. The slave laser is configured as an "8"-shaped ring resonator, which is pumped by an 888 nm diode laser. A composite Nd:YVO_4 crystal is used as the gain medium to mitigate thermal lensing effects. Active frequency stabilization is implemented using the Pound-Drever-Hall (PDH) method. An error signal, derived from the cavity transmission, feeds back to a piezoelectric transducer to control the slave cavity length, thus locking it to the seed laser frequency.

Under optimal injection-locking conditions and at a pump power of 38.12 W, the laser delivers a maximum output power of 13.5 W in a single longitudinal mode. The linewidth of the amplified output is measured to be 7.0 kHz. This represents only a minor broadening compared to the 5.6 kHz linewidth of the original seed laser. The system exhibits excellent power stability, with a root-mean-square power instability of less than 0.18% over a continuous 60-minute period. Furthermore, the frequency stability is significantly enhanced through injection locking. The long-term wavelength drift is reduced to 132.4 MHz, a substantial improvement over the 300 MHz drift observed for the free-running seed laser. A detailed frequency noise characterization reveals effective suppression of noise at low Fourier frequencies (1~100 Hz) in the locked state compared to the free-running slave laser. A slight increase in noise is observed at higher frequency offsets, which is attributed to residual mechanical vibrations from the locking actuator. These results confirm that the seed injection-locking technique successfully amplifies the optical power while maintaining the spectral characteristics of the seed. Crucially, this high stability is achieved without the need for active frequency stabilization of the seed laser itself. This work contributes by achieving a compelling combination of high power (13.5 W), narrow linewidth (7.0 kHz), and high stability at the important 1 064 nm wavelength. A key finding is that this high stability is accomplished without requiring active stabilization of the seed laser itself. The results robustly demonstrate that the seed injection-locking technique is a highly effective method for amplifying optical power while simultaneously preserving and even enhancing the frequency stability and spectral characteristics of the original seed source.

In conclusion, this research successfully realizes a high-power, narrow-linewidth, low-noise single-frequency Nd:YVO_4 laser. The system exhibits outstanding power and frequency stability, making it suitable for demanding applications. The approach provides a viable and practical pathway for developing high-performance single-frequency lasers. Future work will focus on refining the feedback control system to achieve even lower frequency noise. Additionally, the integration of intracavity nonlinear frequency conversion techniques, such as second harmonic generation, could be implemented to produce high-power, single-frequency radiation at other strategically important wavelengths, further expanding the utility of this laser architecture.

Key words: Single frequency laser; Injection locking; Narrow linewidth; Low noise; High power

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