单频可调谐连续 1342 nm 注入锁频环形激光器

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摘要 为了获得高功率的单频可调谐 1342 nm 激光，研究了一种注入锁频 Nd：YVO$_4$ 环形激光器。以 1.0 W 可调谐单频连续 1342 nm 激光为种子光，"8"字环形谐振腔为从激光器功率腔，基于 PDH（Pound-Drever-Hall）锁频技术实现了环形功率腔的锁定，获得了 8.3 W 的单频连续可调谐 1342 nm 的激光输出。

关键词 激光器；可调谐单频激光器；注入锁频技术；PDH 锁频

1 引　言

1.3 μm 波段激光器可以广泛应用于激光医学、光传感定位、光纤通信以及中红外参量振荡的泵浦源等领域[1-3]。其中 1342 nm 激光器倍频可得到 671 nm 红光[4-5]，它的四倍频 336 nm 光可广泛用于光成像、光医学和光生物学等[6]。

目前，对于单频可调谐的连续 1342 nm 激光器报道较少，实现 1342 nm 波段可调谐的激光器主要有分布反馈式（DBR）或外腔式半导体激光器，他们可实现稳定的频率调谐，但出射功率较低，大都在毫瓦级，因此想要获得高功率可调谐的 1342 nm 激光输出，需要采用放大技术对种子光进行放大。现有的放大手段有锥形放大、拉曼光纤放大[7]、注入锁定放大和多级行波放大等，但这些技术大都针对其他波段[4,8]，在 1342 nm 波段的研究非常少。半导体锥形放大器输出能量低，只有 1 W 左右，且光斑较差。多级行波放大需在种子光注入功率较高的时候才会有高的放大效率，且系统较为复杂。注入锁定放大为固体放大，较其他几种放大有其自身特有的优点，如高增益、高光束质量、低成本等。

本文采用一种注入锁频的方式对可调谐、单频、低功率的 1342 nm 种子激光进行放大。将 1.0 W 的可调谐单频种子光注入四镜环形腔内，得到 8.3 W 的 1342 nm 激光输出。放大后的 1342 nm 激光在能量得到提高的同时，保留了种子激光的光谱特性。

2 实验装置

种子注入锁频激光器是借助具有较好光束质量的主激光器来控制一台具有较高能量的从激光器，由此保证从激光器的输出激光具有主激光器的特性，如单纵模、频率可调谐、高能量和高光束质量等[3]，但其能量要远高于主激光器。它在结构上可分为三个模块：主激光器、从激光器和注入锁频系统，其中主激光器主要输出种子激光，从激光器又叫功率腔，主要对能量较低的种子光激光进行放大，以提高激光能量。

图 1 为整个种子光注入放大激光器的结构示意图，其工作过程为：种子光经隔离器和整形器整形后，经由输入镜 M$_2$ 注入四镜环形功率腔内，当功率谐振腔被激光锁频系统锁频时，即环形腔的光学长度稳定在基频光波长的整数倍时，种子光被成功锁定在从激光器谐振腔内，其功率因干涉增强效应而大幅提高，形成谐振振荡，此时功率腔由双向运转变为沿种子光方向单向运转，并在腔内放大后输出[9]。
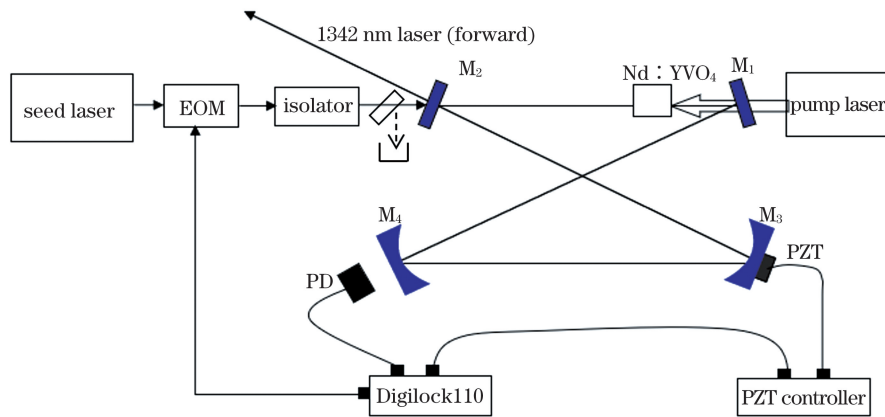
图 1　注入锁频环形激光器实验结构图

Fig. 1　Experimental setup for injection-locked ring laser

种子光是由德国 TOPTICA 公司生产的可调谐倍频半导体激光器（型号为 DLC-TA PRO）所提供。主振荡光为外腔式半导体激光器出射的 1342 nm 红外光，经锥形放大器放大。其最大功率为 1.2 W，波长连续可调，波长可调谐范围为 1320～1500 nm，不跳模可调谐范围为 30～50 GHz。

功率腔的泵浦源采用光纤耦合的激光二极管（LD），它的中心波长为 880 nm，相比于传统的 808 nm 泵浦源，它可有效地减少晶体的热效应[5]。光纤输出的抽运光经耦合系统后纵向注入 YVO₄-Nd：YVO₄ 键合晶体工作物质中，聚焦光斑大小为 $600~\mu m$。

从激光器采用四镜环形谐振腔结构，平面镜 M_1 镀 880 nm 增透膜和 1342 nm 高反膜。腔镜 M_2 为输入耦合镜，镀 1342 nm 透反膜，该膜的透过率决定种子光耦合入腔内的光强。M_3 和 M_4 为平凹面镜，曲率半径为 100 mm，镀 1342 nm 高反膜。四个腔镜均镀有 1064 nm 高透膜，主要为了抑制该波长激光在腔内起振。实验采用的 YVO₄-Nd：YVO₄ 键合晶体为增益介质，降低了晶体的热效应，晶体的两端面镀有 880 nm、1342 nm 和 1064 nm 增透膜。M_5 为 45°反射镜，对 1342 nm 激光的透过率为 99%，可监测种子光的波长和环形激光腔内逆向出射的激光。

锁频系统主要利用 PDH（Pound-Drever-Hall）锁频技术[10-13]对功率腔进行精确锁定，电光调制器（EOM）由美国 New Focus 生产，其调制频率为 25 MHz。控制系统为德国 Toptica 公司生产的 Digilock110。M_3 腔镜上配有压电陶瓷（PZT），由德国 PI 公司生产。

3　实验结果与分析

将种子光经模式耦合后注入从激光谐振腔内，在 M_2 腔镜后用光谱仪（日本 YOKOGAWA 公司生产，型号为 AQ6370C）测量激光的光谱，如图 2 所示。图 2（a）为种子光的光谱线，其波长为 1342.11 nm，其谱线单色性较好，此时功率腔内还未形成激光振荡。图 2（b）为没有种子光时从激光器的谐振腔开始振荡所获得的激光谱线，波长为 1342.15 nm，因为腔内未加单向器等，谐振腔为驻波腔，模式较差，为宽带的多模激光。图 2（c）为功率腔未锁定时种子光光谱和从激光器光谱，从图中可以清晰地看到两个单独分开的光谱，由此可知种子模和功率腔的多模激光未相互影响。图 2（d）为锁定后 1342 nm 放大光的光谱，其波长为 1342.11 nm，放大后模式和种子光波长一致，此时可以判断种子光对从激光器进行了很好的控制，且功率得到大幅度提高。在初始阶段，从激光器的腔内有许多可能起振的纵模频率，它们均可能在自发辐射噪声中建立振荡，此时即为宽带的自然模（1342 nm）。如果没有种子光的注入，自然模将在功率腔内开始振荡并形成激光（1342.15 nm）输出，此时激光为双向输出。在 PDH 锁频基础上，种子光（1342.11 nm）注入从激光功率腔内，腔内与种子光模式相同的纵模功率（或光子数）将会因种子光的注入而极快增加，迅速超过腔内的其他所有模式，形成与种子光模式一致的 1341.11 nm 激光，此时功率腔内的激光由原来的双向输出变化为与种子光方向一致的激光输出。成功实现注入锁频的关键因素是种子模增益要超过自然模增益，这样即可实现种子光在功率腔的频率锁定，同时提高激光输出的功率和单色性。

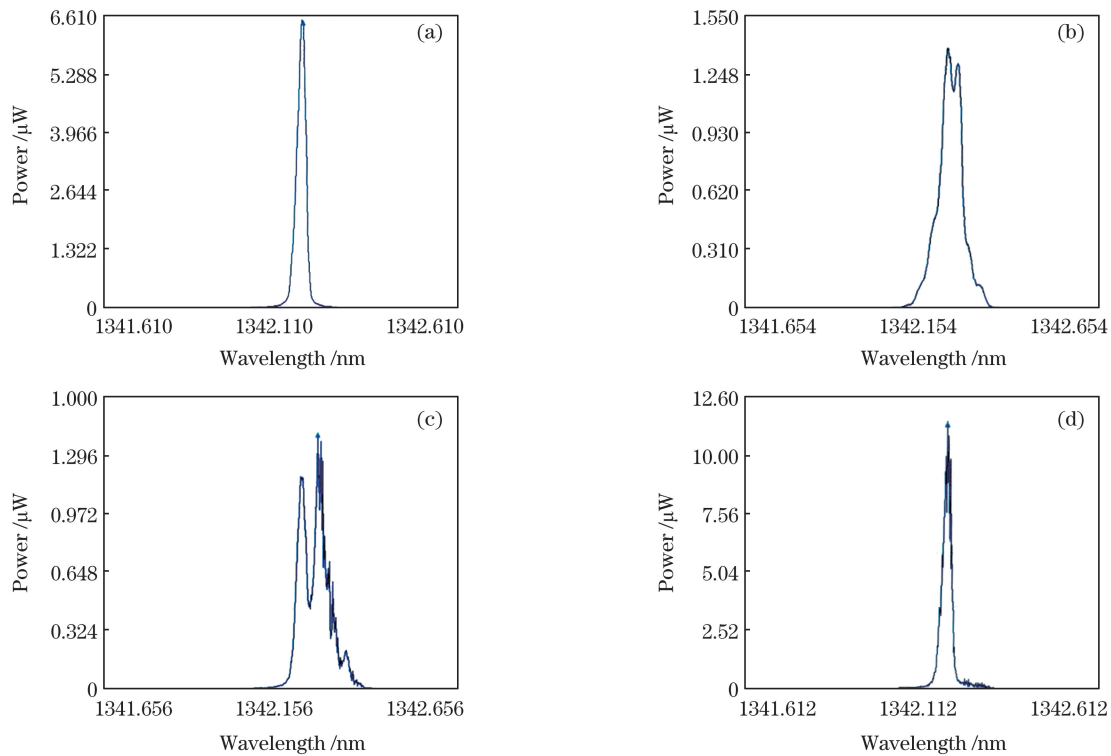接着，通过扫描干涉仪（型号为 SA210-12B，美国 Thorlabs 公司）对 1342 nm 放大光进行了频率特性测量，结果如图3所示，从图中可以看出激光器

图 2　种子光注入锁定实验光谱采集图。(a)种子光光谱(1342.11 nm)；(b)从激光器光谱(1342.15 nm)；(c)未锁定时两光谱线(1342.11 nm 和 1342.15 nm)；(d)锁定后激光光谱(1342.11 nm)

Fig. 2 Spectra of injection locking experiment of seed laser. (a) Spectrum of seed laser (1342.11 nm)； (b) spectrum of ring laser (1342.15 nm)； (c) unlocked spectrum (1342.11 nm 和 1342.15 nm)； (d) injection-locked spectrum (1342.11 nm)
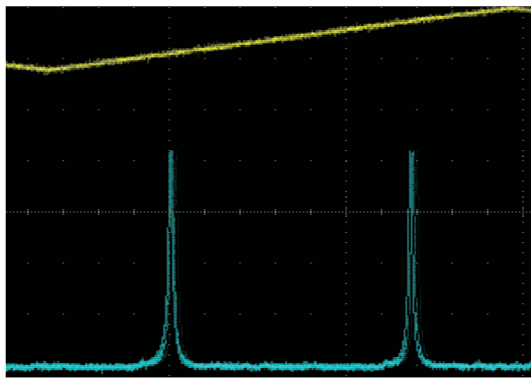
图 3　激光的频率特性图

Fig. 3 Laser frequency property

表 1　不同透过率输入耦合镜时腔内光谱相对强度比较

Table 1 Relative strength of the spectrum with different transmittance of input coupling mirror

T_2/％	2	4	7	10	20
Injection-locked Power /W	6.0	6.4	8.3	6.65	Unlocked

处于单频运转，谱线宽度约 240 MHz。

种子光进入从激光器谐振腔内后，其注入腔内的功率和输入耦合镜的透过率有很大的关系，即要满足阻抗匹配[4]。不同的透过率，对注入锁定放大的影响也不同。实验中，将 1.0 W 的种子光注入腔内，就实验室中几种具有不同透过率 T_2 的输入耦合镜 M_2 进行实验，其数据如表 1 所示，从表中可以看出，锁定放大后，透过率为 7％的耦合镜实验效果较好，对于透过率为 20％输入镜，因为信号峰太低，噪声大，未能成功锁定。

对于透过率为 7％的输入镜，又进行了种子光和从激光功率的锁定放大实验。从激光器在无种子注入的时候双向运转，沿着种子光的方向定为正向，另一个方向为逆向。其中图 4 给出系统锁频前后的功率随着种子光功率的变化关系，此时保持从激光器功率腔的功率不变，正向激光功率为 3.1 W，逆向功率与正向基本相同。种子光功率为 49 mW时，功率较小，锁频效果较差，此时种子模与从激光器的自然模功率相差较大，正向功率仅增加370 mW，属于未全部锁定状态，逆向的激光能量只有小部分转化为正向激光能量。随着种子光功率增大，逆向光的能量逐步转化为正向输出，正向激光功率逐渐增大，锁频也更加稳定，在 1.0 W 时，正向总功率达到 8.3 W。因此在注入锁定放大实验中，提高种子光功率是增加放大效率和稳定性的有效途径。
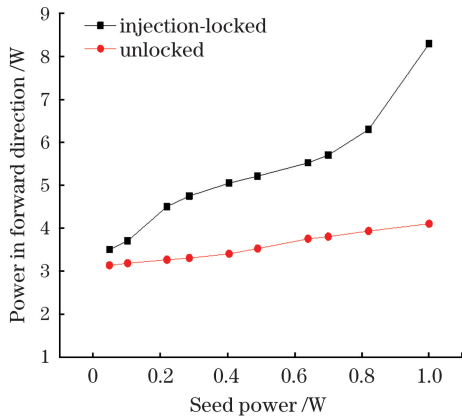
图 4 激光锁频前后输出功率随着种子光功率的变化

Fig. 4 Output powervarying with different seed power of injection-locked and unlocked laser

图 5 为种子光功率注入为 1.0 W 时，随着从激光器功率增大，系统锁频前后的功率变化曲线。圆点曲线代表未锁频前功率腔双向运转总功率与种子光功率的和，方块曲线为锁频后输出的总功率。从图中可以看出，当系统锁定时，功率腔的双向运转变为沿种子光注入方向的单向运转，且整体功率增大，即出现了放大现象。随着从激光器功率增大，注入锁定放大功率也增大，在泵浦功率为 35 W 时，功率腔双向运转总功率为 6.1 W，锁定后，功率腔双向
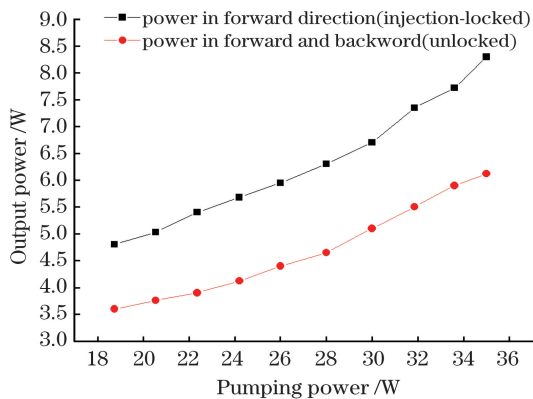
运转因种子光的调制变为单向运转，放大后最大功率为 8.3 W。受功率腔功率和系统噪声的限制，继续加大电流，放大功率不再增加。

图 6 给出激光器为锁频状态时，正向激光功率随种子光波长改变时的变化情况。调节种子光的波长，使其在一定范围内不跳模连续调谐。从激光器波长不变，改变种子光波长时，两者之间的频差即频率失谐量发生变化。当种子光注入为 1.0 W，从激光器未锁定状态的单侧功率为 1.8 W。激光完全锁定后，输出最高功率为 4.8 W，波长为 1342.15 nm。当注入种子光的波长从 1342.15 nm 向长短波两个方向改变时，即频率失谐量不断增大，正向功率会降低，直到 1.8 W 时，从激光器完全失锁。整个激光器调谐范围为 1342.05～1342.25 nm，即 ±0.10 nm。继续保持种子光注入功率不变，使从激光器在未锁定状态的单侧功率增大到 2.8 W。激光器锁定后，最大功率为 7.8 W，调谐范围为 1342.09～1342.21 nm，即 ±0.06 nm，相比 1.8 W 时调谐范围变小。注入种子光能量不变时，从激光器的能量增大，使得整个激光器的调谐范围变小，也可以说增加调谐范围的有效途径是增大注入种子光的能量。

图 7 为激光器自由运转输出功率在 8.3 W 时

图 5 激光锁频前后输出功率随着泵浦功率的变化

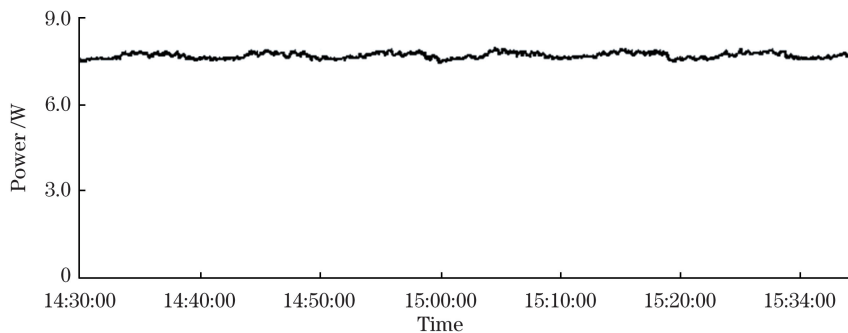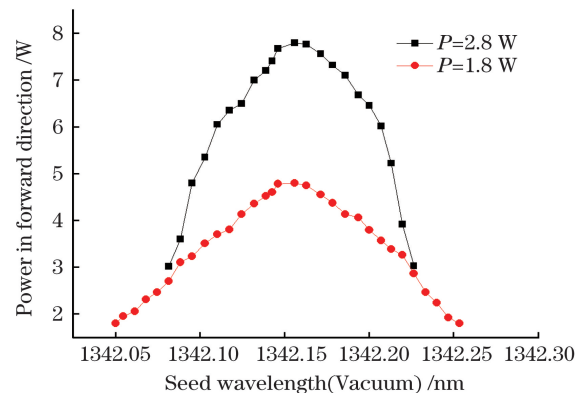Fig. 5 Output power varying with different pump power of injection-locked and unlocked laser

图 6 激光的波长调谐曲线图

Fig. 6 Tuning curves of laser wavelength

图 7 激光器的功率稳定性测量图

Fig. 7 Power stability of the laser

测得的功率稳定性曲线，1 h 内功率波动小于 2%。激光稳定性受 PDH 锁频的影响较大，需对外部谐振腔进行封闭保护，以尽量减小外界环境的扰动和机械振动等对系统的干扰。

4　结　　论

报道了以 1342 nm 可调谐连续光为种子光，通过"8"字环形结构的功率腔获得单频可调谐 1342 nm 红外光的研究。分析了种子光注入锁频激光器中放大参数的影响，通过调整不同透过率的输入镜和注入种子光功率大小来研究功率腔的放大变化情况，在 1.0 W 的种子光注入条件下，获得了最高 8.3 W 单频连续单频 1342 nm 激光输出。

在以后的实验中，可以改进从激光器腔结构，使功率腔自身功率增大，从而增加整个系统的放大功率，还可以增加锁频精度、降低系统噪声影响、提高种子光功率来获得更高功率、更大调谐范围和更稳定的可调谐 1342 nm 红外光。

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A Tunable CW Single-Frequency 1342-nm Injection-Locked Ring Laser

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Abstract

Objective　At present, distributed Bragg reflector (DBR), distributed feedback (DFB) laser, or external cavity diode laser (ECDL) is usually used to realize a tunable single-frequency laser output in 1.3 μm. However, the output power of these diode lasers is as low as several mW. Some studies used a 1.3-μm laser for an effective selective atom stimulation; hence, a higher output power of the lasers was needed. This work presents an injection-locked Nd：YVO$_4$ ring laser that can effectively improve the power of a CW single-frequency 1342-nm laser with wavelength tuning. The amplified 1342-nm laser retains most of the spectral characteristics of the seed laser. This injection-locked Nd：YVO$_4$ ring laser has the advantages of high gain and high beam quality and is very easy to realize. As a consequence of the high power, the doubling frequency of 1342 nm (671-nm red light) and the quadruple frequency (336-nm UV light) can be obtained more easily for some other works.

Methods　An injection-locked Nd：YVO$_4$ ring laser was studied herein. Three modules were considered, namely the seed laser, the laser amplifier, and the Pound-Drever-Hall (PDH) frequency locking system. The seed laser provides the injection source. While the PDH system is being unlocked, the seed laser is reflected away from the cavity because it does not match the resonant conditions of the power cavity. Conversely, while the PDH system is locked, the seed light can be injected into the amplifier cavity and effectively amplified. In this work, a seed laser with output power of the order of mW, good beam quality, and good stability was used. After the injection-locked amplification, the laser retained the spectral characteristics of the seed light, including the single longitudinal mode and the adjustable wavelength. Meanwhile, the laser energy and the beam quality were improved. In this study, a tunable 1.0 W CW single-frequency 1342-mm laser was used as the seed light, and an 8-type ring resonator was used as the amplifier cavity. The injection-locked Nd：YVO$_4$ ring laser was realized, based on the frequency locking technology of the PDH. The seed laser was amplified by the amplifier cavity, and the output power was significantly increased.

Results and Discussions　A 1.3-μm seed laser is successfully injected into the amplifier cavity, and an effective laser amplification with the PDH frequency locked is realized (Fig. 2). At the same time, the frequency characteristics of the 1342-nm output laser are measured by an F-P scanning interferometer. The 1342-nm laser is operated at a single frequency. The spectral line-width is approximately 240 MHz (Fig. 3). We inject 1.0 W of seed light into the amplifier cavity and perform experiments on the input coupling mirror with different transmittances. We achieve a good experimental result with 7％ transmittance of the coupling mirror (Table 1). We also perform an optimization experiment of the laser output power with different seed light powers using 7％ transmittance of the input mirror. With the increase of the seed light power, the amplified laser power gradually increases, and the frequency locking becomes more stable. The total amplified output power of the 1342-nm laser reaches 8.3 W, when the power of the seed laser is 1 W. Therefore, increasing the seed light power seems to be an effective method of increasing the amplification efficiency and stability (Fig. 4). The maximum output power is 8.3 W with the 35-W pump laser (Fig. 5). Following the increase of the pump power ($>$ 35 W), the amplified laser output power decreases with the pump power because of the noise in the laser system. We also investigate the laser tunability. The tuning range is 1342.05—1342.25 nm when the power of the seed laser is 1 W, with 4.8 W as the highest output power. The tuning range of the output laser is 1342.09—1342.21 nm, which is smaller than 4.8 W (Fig. 6), when the power of the seed laser is 1.0 W, with 7.8 W as the highest output power. The experiment result demonstrates that the tuning range of the amplified laser decreases with the increase of the output laser. Increasing the energy of the injected seed laser is likely to be an effective method of increasing the tuning range. The innovative result obtained in this work is the demonstration of an easy and effective method of constructing a tunable CW single-frequency 1342-nm injection-locked Nd： YVO$_4$ ring laser with the maximum power output of 8.3 W. Some experiment results are also presented in this paper.

Conclusions An injection-locked Nd：YVO$_4$ ring laser is studied herein. The influence of the amplification parameters, including the different transmittances of the input mirrors and the different powers of the injected seed light of the injection-locked ring laser, is analyzed. The maximum output power of the CW single-frequency 1342-nm laser is 8.3 W, which is obtained with the 8-type ring cavity at the power of the seed laser of 1.0 W. Characteristics such as high power, high beam quality, and continuous wavelength tunability are observed. The structure of the amplifier cavity will be optimized in subsequent experiments. We expect to acquire a wider tuning range with higher power and more stability of the CW single-frequency 1342-nm laser by increasing the frequency locking accuracy, reducing the system noise, and improving the seed light power.

Key words lasers; tunable single-frequency lasers; injection-locking technique; Pound-Drever-Hall locking

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