中国激光

自注入锁定外腔超窄线宽半导体激光

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摘要　小尺寸低功耗的超窄线宽半导体激光是相干通信、光纤传感等领域的核心器件。采用品质因子 $Q>10^8$ 且腔长为 7 mm 的法布里-珀罗光腔，设计并封装了波长为 1550 nm 的环形结构的小型自注入锁频激光样机，采用基于 100 km 光纤的自延时外差方法，测得 3 dB 线宽约为 200 Hz，洛伦兹拟合线宽约为 20 Hz。未来可通过提高 Q 值，改进封装，进一步压窄激光线宽，提供比光纤窄线宽激光性能更加优异的小型窄线宽激光产品。

关键词　激光器；自注入锁频；窄线宽；外腔半导体激光；法布里-珀罗光腔；光反馈

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窄线宽激光是相干通信、光纤传感、量子测量等领域的核心器件。与传统光纤窄线宽激光、固体窄线宽激光和片上外腔[1]窄线宽激光所使用的光腔相比，高品质因子(Q)法布里-珀罗(FP)腔具有极低的热效应和非线性效应以及超高的温度稳定性[2-5]，将其用于自注入锁频[6-7]，可以实现超低的相位噪声和频率漂移。过去基于高品质因子 FP 腔的研究采用了体积较大的光腔和反馈自注入锁频光路，仅仅停留在实验室阶段。本文采用了自制的小尺寸高 Q 值光腔，设计制作了体积小于 20 cm^3 的紧凑型外腔窄线宽激光样机，并测试了线宽和频率噪声。

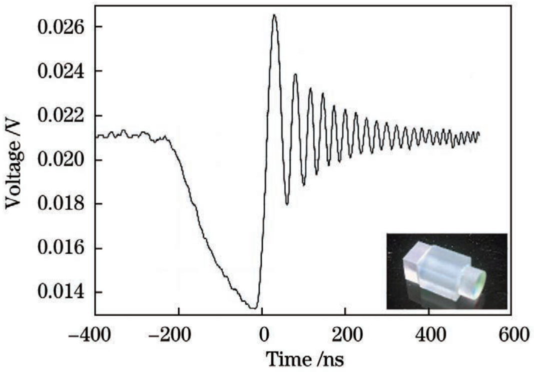

图 1　光腔衰荡法测量的线宽

Fig. 1　Linewidth measured by cavity ring-down technique

图1为我们自主设计并制作的腔长为7 mm的 FP 光腔，腔镜的名义反射率在 1550 nm 波段下达到 99.98%，腔体由石英材质制作。利用线宽约为 400 kHz 的 1550 nm 分布式反馈(DFB)扫频激光，通过光腔衰荡法测量 FP 光腔的光电探测器(PD)信号。可以看出，PD 振荡信号幅度的衰减时间常数为 187 ns，计算得到线宽约为 1.7 MHz，Q 值为 10^8。采用上述 FP 光腔和图 2 所示的环形自注入锁频的拓扑结构，制作了尺寸为 3.8 cm×2.4 cm×2 cm 的窄线宽激光样机，如图 2 左下角所示。我们首先利用透镜(lens)对光源激光进行准直操作，激光从环形器端口 2 输入，从端口 3 输出，在端口 3 输

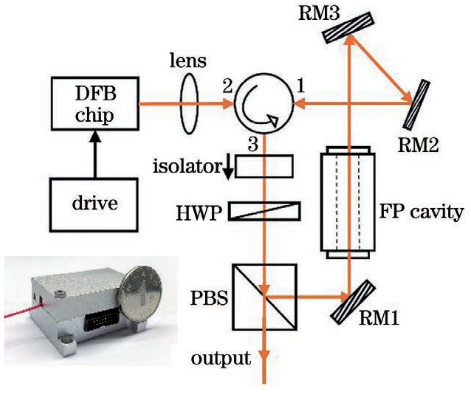

图 2　激光结构示意图

Fig. 2　Structural diagram of laser

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出位置处加入隔离器(isolator)以提高环形器的隔离度。然后再通过调节半波片(HWP)的角度,调节经过偏振控制器(PBS)透射端的输出光强度,PBS 反射的光经过高 Q 值 FP 光腔后,被两面反射镜 RM2 和 RM3 反射,从环形器端口 1 耦合进入到 DFB 芯片中,最终实现激光的自注入锁定。我们采用自制的高精度温控电路控制激光和整体光路的温度,光腔的温度由整体光路温度决定。调节激光电流和温度,使激光保持在光腔基模的自注入锁定状态。

当激光处于自注入锁定状态时,我们分别采用长延时的自延时外差方法和短光纤马赫-曾德尔干涉仪(MZI)鉴频器方法测量激光的线宽和频率噪声。图 3(a)为基于 100 km 光纤的自延时外差方法测量的结果,20 dB 的线宽为 3 kHz,由延时后非相干的同等线宽激光拍频假设可知,对应的 3 dB 线宽为 200 Hz。采用洛伦兹函数拟合频谱曲线,得到近似的本征洛伦兹线宽约为 20 Hz。

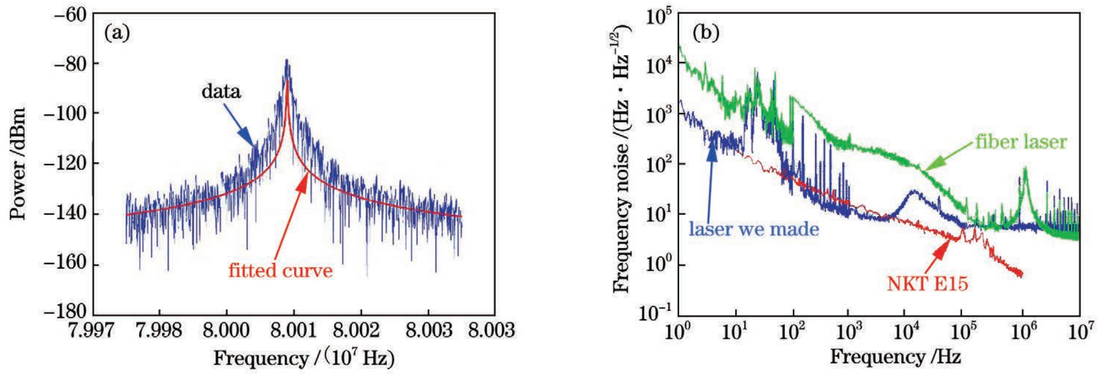

图 3　系统性能。(a)基于 100 km 光纤的自延时外差法测量得到的线宽结果;(b)频率噪声的功率密度谱(对比 NKT E15)

Fig. 3　Performances of system. (a) Linewidth measured by self-delay heterodyne method with 100 km fiber; (b) power density spectra of frequency noise (compared with NKT E15)

图 3(b)为短光纤 MZI 鉴频器测量的激光频率噪声的功率密度谱,根据其频率白噪声极限,得到线宽[8]为 50 Hz。此外,经另一参考单频光纤激光(fiber laser)验证,发现图 3(b)中数十 Hz 频偏处的鼓包为测量仪器的固有噪声。10 kHz 频偏处的鼓包来自所设计的激光样机,其具体成因还有待进一步探究。

最后,通过类似的外腔窄线宽激光拍频的方法,我们在频谱仪上观察到拍频信号在 1～10 s 内的漂移为 10^{-10}～10^{-9},通过改变光腔温度,测得激光频率与温度的依赖关系约为 200 MHz/K。下一步我们将采用反射率更高的反射镜来进一步提高光腔 Q 值,通过密封封装提高封装热稳定性,并进一步降低外腔激光的频率噪声、提高频率稳定度,以期接近或达到 NKT 公司生产的窄线宽激光器 NKT E15 的频率噪声水平。

参　考　文　献

[1] Du Y N, Chen C, Qin L, et al. Narrow linewidth external cavity semiconductor laser based on silicon photonic chip[J]. Chinese Optics, 2019, 12(2): 229-241.
杜悦宁, 陈超, 秦莉, 等. 硅光子芯片外腔窄线宽半导体激光器[J]. 中国光学, 2019, 12(2): 229-241.

[2] Ludlow A D, Huang X, Notcutt M, et al. Compact, thermal-noise-limited optical cavity for diode laser stabilization at 1×10^{-15}[J]. Optics Letters, 2007, 32(6): 641-643.

[3] Zhang W, Stern L, Carlson D, et al. Ultranarrow linewidth photonic-atomic laser[J]. Laser & Photonics Reviews, 2020, 14(4): 1900293.

[4] Peng Y, Shi Q P, Huo H, et al. Realization of narrow linewidth property based on ultra-stable cavity in precision optics teaching [J]. Laser & Optoelectronics Progress, 2017, 54(8): 081402.
彭瑜, 施清平, 霍虎, 等. 精密光学教学中基于超稳腔实现窄线宽性能的方法[J]. 激光与光电子学进展, 2017, 54(8): 081402.

[5] Wang S M, Shang J J, Cui K F, et al. Laser frequency drift control based on refrigeration Fabry-Pérot cavity[J]. Laser & Optoelectronics Progress, 2017, 54(3): 031401.
汪绍茂, 商俊娟, 崔凯枫, 等. 基于制冷法布里-珀罗腔的激光频率漂移控制[J]. 激光与光电子学进展, 2017, 54(3): 031401.

[6] Li H, Abraham N B. Power spectrum of frequency noise of semiconductor lasers with optical feedback from a high-finesse resonator[J]. Applied Physics Letters, 1988, 53(23): 2257-2259.

[7] Zhao Y, Li Y, Wang Q, et al. 100-Hz linewidth diode laser with external optical feedback[J]. IEEE Photonics Technology Letters, 2012, 24(20): 1795-1798.

[8] Tran M A, Huang D N, Bowers J E. Tutorial on narrow linewidth tunable semiconductor lasers using Si/III-V heterogeneous integration [J]. APL Photonics, 2019, 4(11): 111101.

Compact Narrow Linewidth External Cavity Semiconductor Laser Realized by Self-Injection Locking to Fabry-Perot Cavity

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Abstract

Objective Lasers with narrow linewidth and low size-weight-and-power (SWAP) are the key elements for space coherent communication, long range sensing, and quantum technology, etc. Compared with a single frequency fiber laser, a solid state laser and an external cavity diode laser (ECDL) using on-chip optical cavities and hollow Fabry-Perot (FP) cavities possess much lower thermal effects, nonlinear effects, and frequency drifts. In the past, a high performance narrow linewidth laser(NLL) realized by injection locking to a large FP cavity has been demonstrated in the laboratory, however it has never matured into a viable product due to the large FP cavity and optic bench used in the experiment. To take this technology out of laboratory and commercialize it, here we packaged and characterized a compact 1550 nm ECDL employing a miniaturized FP cavity with a high quality factor (Q).

Methods We developed a miniaturized FP cavity with flat and concave mirrors with nominal reflectivity of ~99.98%. The cavity length is 7 mm and we measured its quality factor utilizing the ring-down technique and obtained Q of ~10^8(Fig. 1). We packaged an ECDL with its diagram shown in Fig.2. The light from a DFB chip was firstly collimated and sent to a circulator. The light was reflected, routed toward and coupled to the FP cavity. The transmitted light went through the circulator and was fed back to the DFB chip to form the injection locking. The DFB chip was resided on a small thermo electric cooler and the whole optical system was resided on a large thermo electric cooler. The size of the prototype was 3.8 cm × 2.4 cm × 2 cm. We used a home-made low noise current source to drive the DFB chip and the precise temperature controllers are used to stabilize the temperature of the DFB chip and the whole optic bench. By tuning the current, the DFB laser was injected into the selected fundamental mode of the FP cavity.

Results and Discussions We characterized the performance of the ECDL using two widely adopted methods, i.e., the self-delayed heterodyne method and the frequency discriminator method. With the first method, we used a fiber delay length of 100 km, an AOM with a frequency shift of 80 MHz and obtained the line shape shown in Fig. 3(a). The 3 dB linewidth was estimated to be ~200 Hz and the fundamental Lorentz linewidth was approximately 20 Hz based on the fitting of the baseline. With the second method, we used a commercial product and measured the frequency noise (FN), and the data was plotted in Fig. 3(b) and compared with that of a commercial fiber laser (CoSF-D). Meanwhile, the FN of the NKT E15 fiber laser was also plotted for the purpose of comparison. As was seen, the FN of our ECDL at offset frequency lower than 10 kHz was slightly lower than that of NKT E15. The noise hump at offset frequency between 10 Hz and 100 Hz was from the measurement system as it also appeared in the line of a commercial fiber laser (CosF-D). Finally, we measured the temperature-frequency tuning sensitivity of our ECDL to be around 200 MHz/K, which was much lower than those of materials used in a fiber laser, a solid state laser and an on-chip ECDL.

Conclusions We have shown an ECDL based on injection locking of DFB chip to a compact high Q FP cavity, and it is a viable way to obtain a high performance NLL with low SWAP and low cost. This first prototype we have packaged has shown frequency noise comparable to that of the well-known NKT E15 fiber laser at offset frequency of ＜10 kHz. By improving the Q of the FP cavity and implementing an advanced packaging technique，we believe its performance can surpass that of the NKT X15 fiber laser.

Key words　lasers；self-injection frequency locking；narrow linewidth；external cavity semiconductor laser；Fabry-Perot cavity；optical feedback

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