中国激光

可连续调谐的窄线宽外腔半导体激光器

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摘要 可快速连续调谐的小尺寸窄线宽外腔半导体激光器是调频连续波（FMCW）激光雷达、量子技术等领域的核心器件。通过紧凑的反馈光路设计，采用腔长为2.5 mm的法布里-珀罗腔（FP腔）反馈压窄线宽，并结合压电陶瓷（PZT）进行腔长扫描，组装了波长为1550 nm的小型化可调频的激光样机。采用光纤长度为1 m的马赫-曾德尔干涉仪，在重复频率为0.1、1.0、10.0 、100.0 kHz下分别测得激光器无跳模的连续调谐范围为25.0、21.6、18.0、10.0 GHz。基于20 km长光纤的延时自外差法，测得3 dB线宽约为10 kHz。未来通过更加紧凑的光路设计，可以获得更大调频范围的超窄线宽激光。

关键词 激光器；连续调频；法布里-珀罗外腔半导体激光；自注入锁定

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可大范围快速连续调频的窄线宽激光是远距离激光传感[1]、精确测距[2]、连续波激光雷达[3]、量子技术[4]以及光学原子钟[5]等所需的核心器件。相对于固体、光纤等激光器，半导体激光器结构简单，体积小，引入外部腔体的半导体激光器在压缩线宽的同时还兼具了调谐的功能[6]，其应用前景较为广阔。传统使用衍射光栅的Littrow结构外腔半导体激光器[7]通过压电陶瓷（PZT）可实现10～20 GHz的快速连续波长调谐，但该激光器体积较大，结构可靠性差，线宽通常在100 kHz～1 MHz量级。利用片上微环谐振器的半导体激光器[8]，通过热光效应可实现超过30 GHz的连续调谐范围，相应波段的线宽约为30 kHz。本文采用自制的腔长为2.5 mm的小尺寸法布里-珀罗腔（FP腔），使用PZT扫描腔长，并通过电路控制系统同步改变半导体激光芯片的波长，当重复频率低于1 kHz时获得了超过20 GHz的无模式跳变的连续调频窄线宽激光输出，继续提高重复频率到100 kHz，连续调频范围仍在10 GHz以上。激光模块封装在体积小于3 cm^{3}的蝶形管壳中，并对激光线宽进行了测试。

图1（a）为我们组装的可调谐窄线宽外腔半导体激光器样机。通过紧凑的光路设计，使用定制的微型光学元器件，我们研发了尺寸为20.8 mm×12.7 mm×8.9 mm的蝶形封装激光器。本实验采用双端输出的1550 nm分布式反馈（DFB）激光芯片，并通过自主研发的电路板进行激光器的电流和温度控制，激光器内部结构示意图如图1（b）所示，其中PD为光电探测器，

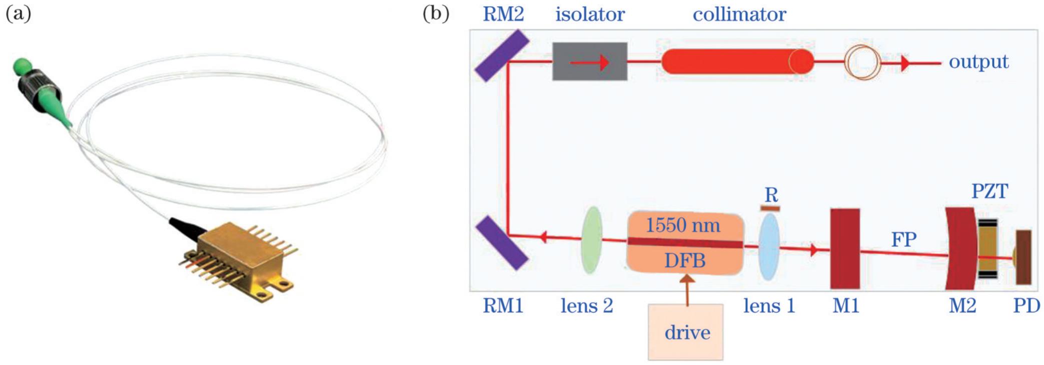

图1 激光器结构示意图。（a）样机；（b）内部结构示意图

Fig. 1 Schematic of laser structure. (a) Prototype; (b) schematic of internal structure

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R 为电阻。这些光学元器件放置在一块基板上，并使用半导体制冷片（TEC）进行整体的温度控制。首先，我们使用硅透镜（lens 1）对芯片出射的激光进行准直，并通过固定在硅透镜上的电阻加热来控制相位。准直光入射到 FP 腔中，之后从腔镜 M1 一端透射出的光回到 DFB 激光芯片中，即可实现自注入锁定。为有效避免腔镜 M1 的直接反射光干扰激光器的运转，准直光应以小角度斜入射到 FP 腔中。光腔由两面反射镜组成：输入端为平面镜 M1，厚度为 200 μm，腔镜的名义反射率在 1550 nm 处达到 97.5%；输出端为平凹镜 M2，曲率半径约为 5 mm，反射率达到 99.8%。平凹镜与 PZT 粘接在一起，通过在 PZT 上施加电压可改变腔长。PZT 的驱动电压为 0～45 V，最大自由行程位移约为 2 μm。PZT 的膨胀和收缩可带动平凹镜移动，从而进行腔长扫描以实现连续调频。之后在 DFB 芯片的另一端用透镜 2 再次进行准直，并通过两面反射镜（RM1 与 RM2）的反射将光束耦合到准直器中。而在准直器前加入隔离器可以提高隔离度，减小反射光对激光器运转的干扰。

在激光模块封装进管壳后，我们对激光器进行了测试。通过信号发生器对激光芯片的电流进行扫描，平凹镜 M2 透射出的锁定信号会被光电探测器接收，连接在示波器上即可观察到自注入锁定的图像，如图 2 所示。

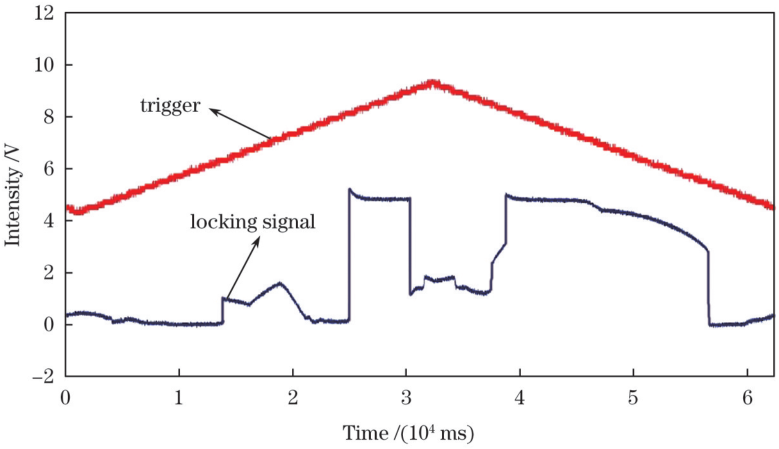

图 2　自注入锁定信号图

Fig. 2　Self-injection locking signal chart

之后逐渐减小电流扫描幅度，调节激光器的温度和相位，使其处于单一模式的自注入锁定状态。接下来使用基于 10 km 长光纤的延时自外差法测量了线宽，如图 3 所示，从频谱仪上测得 20 dB 处的线宽约为 200 kHz。

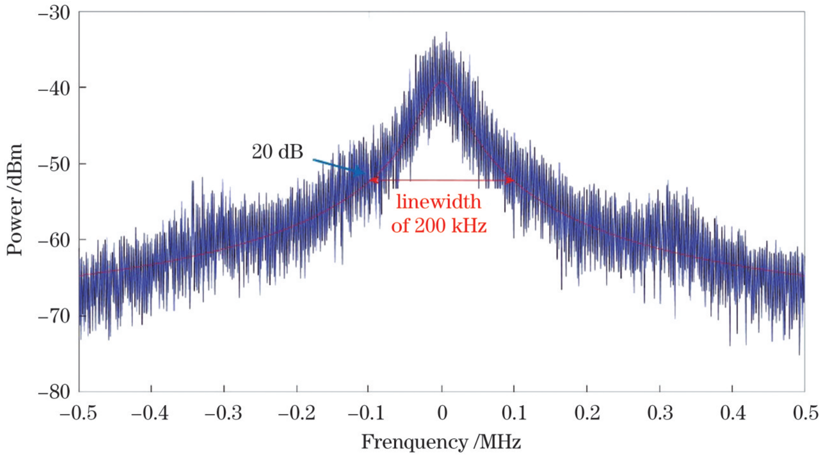

图 3　基于 20 km 长光纤的线宽测试结果

Fig. 3　Linewidth test result based on 20 km long fiber

测试激光器连续调谐范围时，使用温控系统将激光器的整体光路温度控制为恒定，并通过稳压源直接控制电阻 R 的电流以改变外腔反馈相位。我们使用信号发生器产生的三角波对激光电流和 PZT 进行同步扫描，使得激光芯片与扫频的光腔始终保持在自注入锁定状态，之后使用自己搭建的 1 m 长的马赫-曾德尔光纤干涉仪进行测试，干涉仪的自由光谱范围（FSR）约为 200 MHz。如图 4 所示，扫描重复频率控制在 0.1 kHz，最终测得激光器的连续调谐范围为 25 GHz，此时激光从光纤中输出的功率在 0.03～21.00 mW 范

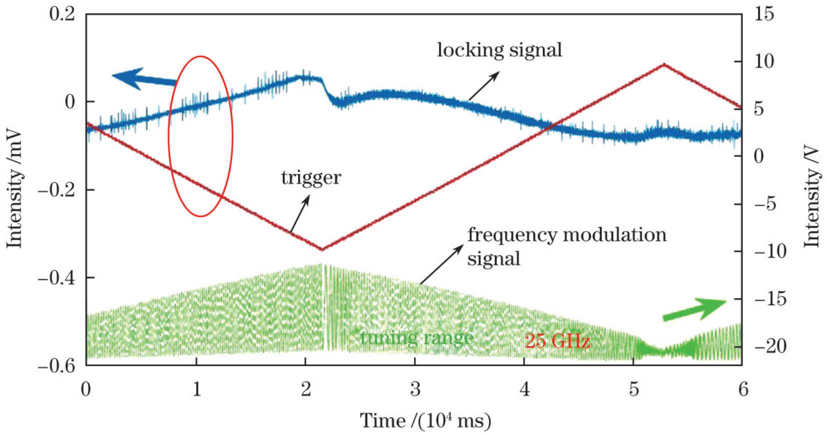

图 4　基于马赫-曾德尔干涉仪的连续调频范围的测试图

Fig. 4　Test diagram of continuous frequency modulation range based on Mach-Zehnder interferometer

围内。提高重复频率，同步调节其他参数，连续调频范围虽然有所减小，但重复频率达到 100 kHz 时，连续调频范围仍能达到 10 GHz。

本文制作了基于 FP 短光腔的外腔窄线宽激光器，3 dB 线宽约为 10 kHz。通过对 FP 光腔腔长和 DFB 激光电流的同步扫描，外腔激光器在动态调谐过程中始终保持自注入锁定状态，从而实现了 0.1 kHz 低重复频率下超过 25 GHz 的无跳模连续调谐的窄线宽激光输出。在高重复频率状态下，该激光器仍能实现超过 10 GHz 的连续调频。若要进一步增大外腔窄线宽激光的连续调频范围，需要设计更紧凑的反馈光路，减小波长调谐过程中反馈相位的变化，以保证自注入锁定状态不发生跳模。同时也需要设计控制电路，更好地实现 DFB 波长和光腔的协同调制。此外，如果采用半导体放大器 SOA 饱和输出，可以解决 DFB 芯片输出功率由于电流扫描而变化较大的问题。

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Continuously Tunable Narrow Linewidth External-Cavity Semiconductor Lasers

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Abstract

Objective　The advancement of continuously tunable, miniaturized, narrow-linewidth external-cavity semiconductor lasers holds a key position in applications such as continuous-wave LIDAR and quantum technologies. By coupling a distributed feedback (DFB) laser with a short Fabry-Perot (FP) cavity and using piezoelectric ceramics (PZT) for cavity length modulation, a miniaturized tunable laser system operating at a wavelength of 1550 nm is realized. Experimental validation using a Mach-Zehnder interferometer (differential fiber length of 1 m) reveals a mode-hop-free tuning range exceeding 10 GHz. The frequency tuning ranges of 25.0, 21.6, 18.0, and 10.0 GHz are demonstrated at the repetition rates of 0.1, 1.0, 10.0, and 100.0 kHz, respectively. Additionally, utilizing the self-delayed heterodyne technique, the laser exhibits a 3 dB linewidth approaching 10 kHz. Forthcoming endeavors would aim to achieve a broader tuning range with a narrower linewidth by optimizing the optical pathway and modifying the cavity mirror reflectivity.

Methods This study introduces a meticulously designed butterfly encapsulated laser module with dimensions of 20.8 mm× 12.7 mm× 8.9 mm. The configuration leverages a dual-output 1550 nm DFB laser diode that is controlled in terms of both current and temperature via an in-house circuit system. A schematic of the laser architecture is shown in Fig. 1. The optical resonator is formed by a planar mirror (M1) and concave mirror (M2), with M2 affixed to the PZT. This fosters cavity length modulation. Emissions from the DFB diode undergo meticulous collimation via a silicon lens and propagate within the cavity. Subsequently, these leak out of the cavity and are fed back into the diode. This results in a self-injection-locked state. The feedback phase is controlled using a heating resistor placed on top of a silicon lens.

Results and Discussions Linewidth evaluations are conducted using a 20 km fiber-based self-delayed heterodyne measurement system. The spectral characterizations reveal a 20 dB linewidth close to 200 kHz, as shown in Fig. 3. The corresponding self-injection frequency-locking signal is shown in Fig. 2. To demonstrate the continuous-tuning capabilities of the laser, we use a function generator with two output channels to apply two triangular modulation signals to the PZT and the current of the diode with the same phase. Both feedback phase and amplitudes of the two modulation signals are optimized to extend the continuous tuning to the extent feasible. Using a fiber Mach-Zehnder interferometer with a differential length of 1 m, we measure a continuous tuning range of 25 GHz at a repetition frequency of 0.1 kHz. This is shown in Fig. 4. An increase of the repetition frequency to 100 kHz still permits continuous tuning exceeding 10 GHz.

Conclusions We successfully develop a wide-range continuously tunable narrow-linewidth external cavity semiconductor laser. By scanning the DFB laser current, synchronizing the phase control, and manipulating the PZT to alter the effective cavity length, the external cavity laser consistently maintains its self-injection lock during dynamic tuning. This results in a continuous tuning range of 25 GHz and linewidth of 10 kHz at a low repetition frequency of 0.1 kHz. In scenarios with higher repetition frequencies, the laser achieves continuous tuning beyond 10 GHz. Future plans would involve the design of a more compact feedback optical path and optimization of the control circuitry to achieve a wider continuous tuning range.

Key words lasers; continuous frequency modulation; Fabry-Perot external-cavity semiconductor laser; self-injection locking