第 29 卷 第 11 期
2008 年 11 月

半 导 体 学 报
JOURNAL OF SEMICONDUCTORS

Vol.29 No.11
Nov.,2008

Intensity Noise Suppression of an FP Laser by External Injection Locking*

Ren Min†, Han Wei, Xie Liang, Chen Wei, Zhang Yan, Ju Yu, Zhang Hongguang, Zhang Banghong, and Zhu Ninghua

(*State Key Laboratory of Integrated Optoelectronics, Institute of Semiconductors, Chinese Academy of Sciences, Beijing* 100083, *China*)

Abstract: The optimal intensity noise suppression of a Fabry-Perot (FP) laser is experimentally acquired by relatively strong external optical injection locking technology. The maximum suppression is up to 9dB around the relaxation oscillation peak of the free running FP laser. We demonstrate how the injection light power and detuning frequency influence the intensity noise suppression effects. Additionally, the relationship between the optimal suppression range and the stable locking range is experimentally studied: both ranges enlarge as the injection light power increases, but the stable locking range permits larger detuning frequency at identical injection light power.

Key words: intensity noise suppression; FP laser; external injection locking
EEACC: 4320J; 4330
CLC number: TN365 **Document code**: A **Article ID**: 0253-4177(2008)11-2192-05

1 Introduction

Optical injection locking technology has attracted extensive attention. The emission characteristics of a semiconductor laser could be affected by external light injection. In the light injection system, the external light from one semiconductor laser (the master laser) is injected to the cavity of another semiconductor laser (the slave laser). Various applications of this technology have been exploited, including the attainment of optical frequency convention by four-wave mixing technology[1], the generation of microwave signals[2~4], and the realization of single-longitude mode under modulation[5]. It was also employed to enhance the 3dB bandwidth and hence increase the direct-modulation speed of semiconductor lasers[6], to reduce frequency chirping in intensity modulated communication systems[7], and to reduce nonlinear distortion in semiconductor lasers[8].

For application of a semiconductor laser, noise is an important limiting factor in analog or digital communication systems. It impairs the transmission quality of the lasers. For a typical Fabry-Perot (FP) laser, the most serious noise is laser intensity noise, which reduces signal-to-noise ratio and increases bit error rate. Operating conditions, such as bias level and modulation frequency, that directly affect the noise level, external feedback or reflection into the laser will also affect this noise[9,10,11].

Yabre *et al*. developed a model to plot the relative noise intensity spectrum based on the rate equations in which Langevin noise forces were incorporated[11]. They theoretically illustrated how the noise characteristics were influenced by strong external light injection and indicated that relative noise intensity could be significantly reduced over a large frequency range if a low-noise master laser was employed.

In this paper, we experimentally demonstrate that the noise intensity of the slave laser can be not merely reduced, but completely eliminated or optimally suppressed under relatively strong light injection of a low-noise tunable laser. Up to 9dB noise intensity suppression is observed. Furthermore, the relationship between the optimal suppression state and the stable locked state is studied experimentally. Different ranges of these two states are plotted.

2 Experimental setup

A simplified schematic of the experimental setup is shown in Fig. 1. The master laser used is a tunable laser (Agilent 8164A). Its minimal tunable step is 0.001nm. The slave laser is an FP laser, biased by a current source with a temperature stabilized controller, and its threshold current is 12.5mA. The light from the master laser is injected into the slave laser through a circulator. A polarization controller is used to maintain the polarization state of the injecting light, and a variable attenuator is used to adjust the

* Project supported by the National Natural Science Foundation of China (Nos. 60510173, 60536010, 60506006, 60606019, 60777029) and the State Key Development Program for Basic Research of China (Nos. 2006CB604902, 2006CB302806, 2006DFA11880)

† Corresponding author. Email: renmin@semi.ac.cn

Received 12 June 2008, revised manuscript received 14 July 2008

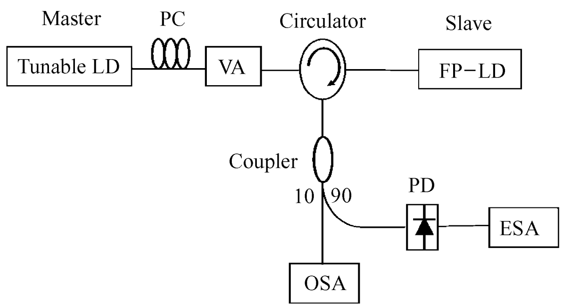

Fig. 1　Experimental setup　PC: polarizing controller; VA: variable attenuator; PD: photodetector; OSA: optical spectrum analyzer; ESA: electrical spectrum analyzer

light power injected to the slave laser. The emission light from the cavity of the slave laser is split by a 10 ∶ 90 coupler. 10% of the output light power is monitored by an optical spectrum analyzer (Agilent 8334) with a resolution bandwidth of 0.001nm, while 90% of the light power is received by a photodetector, and then monitored by an electrical spectrum analyzer (Advantest R3182).

3　Results and discussion

The light receiver in our experiment consists of a photodetector and an ESA. The total noise N_T at the output receiver results from three fundamental contributions: the laser intensity noise N_L from spontaneous light emission; the thermal noise N_{th} from the electronics; and the shot noise N_S.

The value of laser intensity noise is found from Eq. (1) by subtracting the values of the shot noise and the thermal noise from the total noise.

$$N_L = N_T - N_S - N_{th} \tag{1}$$

Based on the intrinsic electric characteristics of the receivers at the end of the system, there exists basic system noise on the electric spectrum even when no light signal is detected. This basic system noise indicates the minimal noise level that the receivers can effectively detect, and only the noise power above this level can be identified. The basic noise level is centered at −147dBm/Hz, with a fluctuation of 3dBm/Hz from 0 to 20GHz, as shown in Fig. 3(b). The basic noise spectrum remains constant in our experiment. According to the typical value at room temperature, the level of the thermal noise is −174dBm/Hz; the shot noise results from quantum characteristics of photons arriving at the receiver and related detection statistics, and its typical power is −168dBm/Hz at a photocurrent of 1mA. Both N_{th} and N_S are more than 20dB down from the basic system noise limit. Therefore, the detected noise N_T in our experiment can be considered as the laser intensity noise N_L.

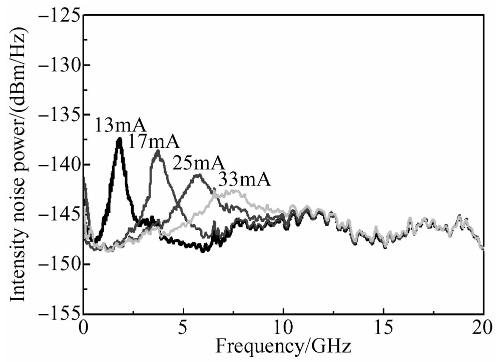

Fig. 2　Intensity noise and relaxation resonance peak vary with laser bias level

The threshold current I_{th} of the FP laser is 12.5mA. Above I_{th}, the output of the FP laser is detected by the receivers, and its intensity noise can be monitored by the ESA, as shown in Fig. 2. The dominant noise feature of the intensity noise is the intensity-noise peak at the relaxation resonance point. The relaxation oscillation frequency increases with the bias current, while the noise intensity power is damped. When the bias current is above 40mA, no obvious peaks can be observed.

Keeping the bias current of the free running FP laser (slave laser) at 17mA, its dominant mode wavelength is 1549.236nm. Its relaxation oscillation peak on the intensity noise spectrum is at 3.7GHz, up to −138.34dBm/Hz. Adjusting the output wavelength of the master laser to 1549.3nm (detuning frequency $\Delta\nu = -8$GHz), and the injection light power level at 2dBm, the optical spectrum under this condition is shown in Fig. 3(a). The slave laser is stably locked: the dominate mode wavelength of the slave laser (1549.236nm) is driven to the wavelength of the master laser (1549.3nm). At the same time, the power of other longitude modes decreases more than 20dB. Keeping the injection power at 2dBm, the total output light power from the FP laser under the optimal injection locking condition is shown in the top right corner of Fig. 3(a). When the bias current increases to above 73mA, the output power of the optimally locked FP laser is saturated to the maximal level of 3.5dBm.

The characteristics of the intensity noise are monitored by the ESA, as shown in Fig. 3(b). Compared with the intensity noise of the free running FP laser, the relaxation oscillation peak at 3.7GHz is greatly suppressed under the relatively strong external light injection; we call it the optimal suppression state. The peak power becomes −147.14dBm/Hz, up to 9dB below the free running state. The intensity noise spectrum of the stable injection locked FP laser is similar with the basic system noise.

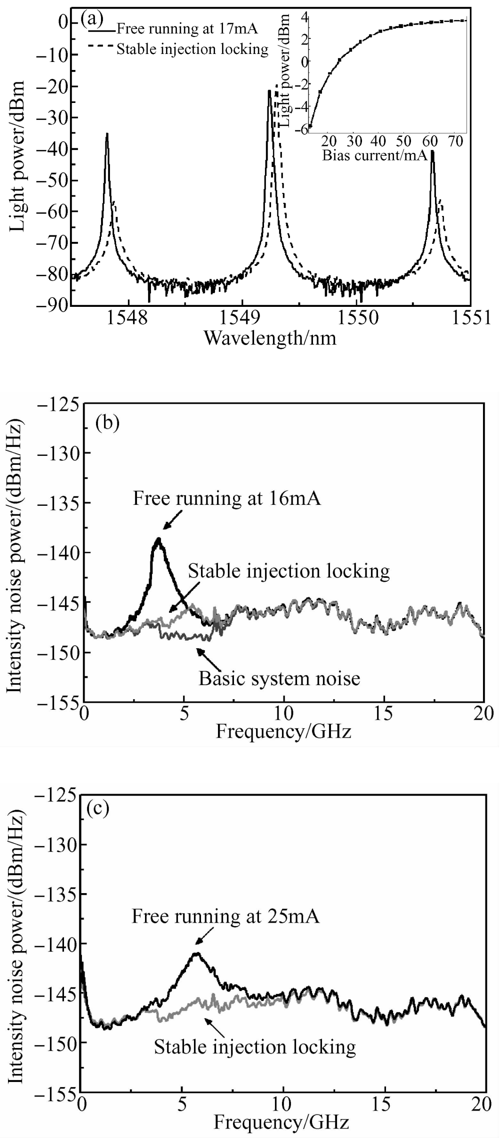

Fig. 3 Comparison between free running state and optimal noise suppression state

The noise suppression can be acquired over a wide frequency range. Changing the bias current of the slave laser from 13 to 40mA, optimal suppression states can be observed if the detuning frequency is properly selected. Figure 3 (c) shows the noise spectrum of the injected FP laser when it is operated at 25mA. A noise suppression of 5dB is acquired under the injection power level of 2dBm.

As previous works indicated, the laser intensity noise is a function of the optical power injected into the slave laser and the detuning[10,11]. Similarly, these two parameters determine whether or not the slave laser is stably locked. During our experiment, with the results monitored by OSA and ESA, we found that when the optimal noise suppression is acquired, the slave laser definitely lies in the stable locking state. However, further study reveals that the optimal suppression range is not the same as the stable locking

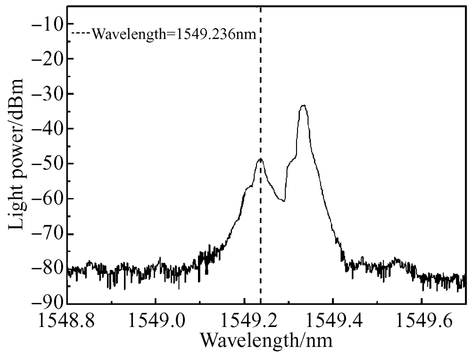

Fig. 4 Unstable locking state ($\Delta\nu = -14.75$GHz)

range, and the latter permits larger detuning frequency.

The influence that the injection light imposes on the slave laser is a complex nonlinear process. If the detuning is outside the stable locking range, or if the injection power is not enough for effective locking, the slave laser is not stably locked. In order to compare the permissible detuning range at different injected light powers, the critical optical spectrum has to be identified. Figure 4 shows the unstable locking state of the slave laser at the injection wavelength of 1549.355nm with light power level of 2dBm. The dashed line is wavelength = 1549.236nm, the wavelength when the FP laser is free running at 17mA. When the detuning is too large for the master laser to drive the slave laser's wavelength to its own wavelength, the wavelength of 1549.236nm begins to appear on the wavelength spectrum. As a result, there exist two wavelengths on the optical spectrum, and the slave laser is not considered to be stably locked under this condition. The permissible detuning frequency range for stable locking is from −14.5 to −4.75GHz, under the injection light power level of 2dBm.

Keeping the bias current of the slave laser at 17mA and adjusting the injection light level from −4 to 9dBm, the critical detuning frequency values are recorded for both the stably locked range and the optimal suppression range, and the result is shown in Fig. 5. The optimal suppression range is defined by the shadow. Upper boundary 1 is the upper limit of this range, and lower boundary 1 is the lower limit. Within this range, regardless of the injection light power, there is almost no difference for the suppression effect, and it is the same as that shown in Fig. 3(b). The stable locking range is enclosed by boundary 2. Upper boundary 2 is the upper limit of permissible detuning, and lower boundary 1 is the lower limit of permissible detuning at certain injection light powers. The stable locking state permits larger detuning frequency $\Delta\nu$ at identical injection light power. In fact,

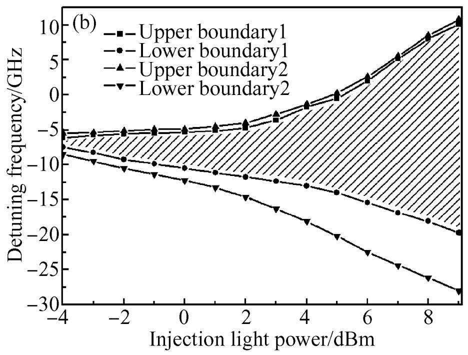

Fig. 5　Curves of the stable locking range and optimal suppressing range vary with the injection light power

when optimal relaxation oscillation peak suppression is observed from the noise spectrum, the slave laser is definitely stably locked to the wavelength of the master laser.

As the injection light power increases, the permissible detuning ranges of both states enlarge towards the positive and negative detuning frequency. There is a gap between lower boundary 1 and 2, which also enlarges when the injection power increases. When the injection power is 9dBm, the permissible maximum negative detuning for the optimal noise suppression state and stable locking state are －20 and －28GHz, respectively, which means a difference of 8GHz exists. On the other hand, the difference of upper limits between two states is negligible for any injection power.

However, an FP laser subjected to optical injection may show various behaviors. A four-wave mixing regime occurs when the detuning frequency is chosen too far from the locking range. Under this situation, a complex electric spectrum is observed: the intensity noise at the resonant peak could be enhanced, and new beating noise appears at other frequency points (Curve *a*, Fig. 6). When the detuning frequency is further increased, the master laser has little influence on the slave laser. Under this condition, the noise spectrum is almost the same as the free running state of the slave laser (Curve *b*, Fig. 6). Adjusting the slave laser a 17mA bias and the detuning frequency to

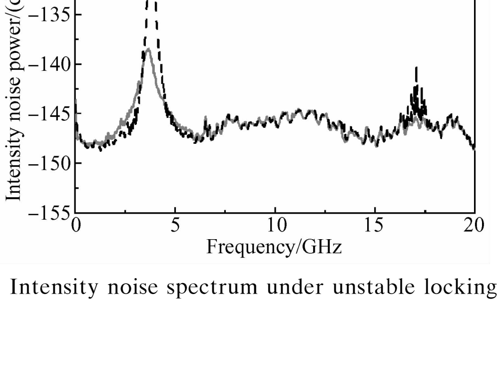

Fig. 6　Intensity noise spectrum under unstable locking states

－8GHz (the same as the parameters set in Fig. 3(b)), and reducing the injection light power continuously to under －12dBm, no optimal noise suppression can be acquired. As a result, in order to acquire optimal intensity noise suppression, suitable detuning frequency and relatively strong injection light power are both necessary.

4　Conclusion

We have experimentally investigated the intensity noise suppression of an FP laser under relatively strong optical injection with a simple schematic of the experimental setup. The relaxation oscillation peak on the electric spectrum can be greatly suppressed if the detuning frequency and injection power is properly selected. Compared with the noise spectrum of the free running slave laser biased at 17mA, a suppression level up to 9dB at the relaxation oscillation frequency is acquired when the detuning frequency is －8GHz and the injection power is 2dBm, while no additional noise is added at other frequency points. Furthermore, the optimal suppression needs two conditions: suitable detuning and relatively strong injection power. A set of critical detuning frequency values for optimal noise suppression and stable locking is measured at different injection power levels from －4 to 9dBm. A comparison between the stable locking range and the optimal suppression range was given: the optimal noise suppression phenomena occurs at part of the stable locking range; the latter permits larger detuning frequency at identical injection light power; as injection light power increases, both ranges enlarge, but the gap between their lower limits also grows.

Because the intensity noise of the slave laser can be greatly suppressed by external optical injection, the laser is expected to have better performance in analog or digital communication systems.

References

[1] Li L, Petermann K. Small-signal analysis of optical-frequency conversion in an injection-locked semiconductor laser. IEEE J Quantum Electron, 1984, 30: 43
[2] Goldberg L, Taylor H F, Weller J F, et al. Microwave signal generation with injection-locked laser diodes. Electron Lett, 1983, 19(13): 491
[3] Chan S C, Liu J M. Tunable narrow-linewidth photonic microwave generation using semiconductor laser dynamics. IEEE J Sel Top Quantum Electron, 2004, 10(5): 1025
[4] Chan S C, Liu J M. Frequency modulation on single sideband using controlled dynamics of an optically injected semiconductor laser. IEEE J Quantum Electron, 2006, 42: 699
[5] Kobayashi S, Kimura T. Injection locking in AlGaAs semiconductor lasers. IEEE J Quantum Electron, 1981, QE-17: 681
[6] Yabre G. Effect of relatively strong light injection on the chirp-to

power ratio and the 3dB bandwidth of directly modulated semiconductor lasers. J Lightwave Technol,1996,14:2367
[7] Olsson N A,Temkin H,Logan R A. Chip free transmission over 82.5km of single mode fibers at 2Gbit/s with injection locked DFB semiconductor lasers. IEEE J Lightwave Technol,1985,LT-3:63
[8] Yabre G,Le Bihan J. Reduction of nonlinear distortion in directly modulated semiconductor lasers by coherent light injection. IEEE J Quantum Electron,1997,33:1132
[9] Fujiwara M,Kubota K,Lang R. Low-frequency intensity fluctuation in laser diodes with external optical feedback. Appl Phys Lett,1981,38(4):217
[10] Spano P,Piazzolla S,Tamburrini M. Frequency and intensity noise in injection-locked semiconductor lasers theory and experiments. IEEE J Quantum Electron,1986,QE-22(3):427
[11] Yabre G,deWaardt H,van den Boom H P A,et al. Noise characteristics of single-mode semiconductor lasers under external light injection. IEEE J Quantum Electron,2000,36(3):385

外注入锁定对FP激光器强度噪声的抑制*

任 民† 韩 威 谢 亮 陈 伟 张 艳 鞠 昱 张红广 张邦宏 祝宁华

(中国科学院半导体研究所 集成光电子学国家重点实验室，北京 100083)

摘要： 采用较强的外注入光锁定FP激光器，获得了理想的强度噪声抑制效果.在自由运转的FP激光器的弛豫振荡峰处，最大噪声抑制强度可达9dB. 研究了注入光功率和频率失谐对于强度噪声抑制效果的影响.此外，通过实验研究了理想噪声抑制范围与激光器稳定锁定范围之间的关系：它们都随着注入光功率的增加而增大；但在相同的注入光功率下，稳定锁定范围允许更大的频率失谐.

关键词： 强度噪声抑制；FP激光器；外注入锁定
EEACC： 4320J；4330
中图分类号： TN365 **文献标识码：** A **文章编号：** 0253-4177(2008)11-2192-05

* 国家自然科学基金(批准号：60510173，60536010，60506006，60606019，60777029)及国家重点基础研究发展规划(批准号：2006CB604902，2006CB302806，2006DFA11880)资助项目

† 通信作者. Email：renmin@semi.ac.cn

2008-06-12收到，2008-07-14定稿