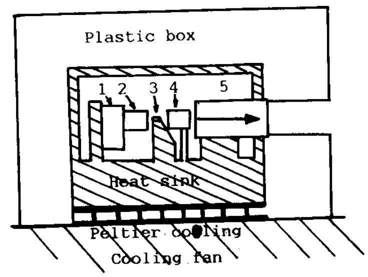
An Experimental Study on Stable Single-Frequency Semiconductor Lasers with External Cavity

HUI RONGQING, TAO SHANGPING, WU YIZUN, AND PENG HUAIDE

Abstract—**An experiment on external-cavity semiconductor laser consisting of 1.3 μm BH laser diode with AR coated facet and a 4 mm GRINROD is reported. Because of its enclosed compact structure and strong optical feedback, it provides a stable single mode, with mainside mode ratio of more than 30 dB, and is not sensitive to the environmental perturbations. No mode jumping occurred during 12 h of continuous observation. The measured linewidth is 900 kHz, which is in good agreement with the newly developed theoretical calculation.**

IN optical fiber coherent communications and single-mode fiber high-speed transmission, single-frequency semiconductor lasers with high-frequency stability and narrow spectral linewidth are required [1], [2]. By present state of laser technology, it is considered that the external-cavity semiconductor laser (ECSL) is an important and practical means [3]–[5]. It is well-known that long external cavity semiconductor lasers have the excellent property of narrow linewidth, but they are bulky and not easy to get mechanical stability for practical uses. On the other hand, if a short external cavity is used, single longitudinal mode operation can be easily obtained. Using a few hundred micrometer multimode fiber as an external cavity, the main-side mode ratio of the laser can be very high [6]–[14]; however, its linewidth reduction is not remarkable. Thus, for practical usage, further improvement is needed on the linewidth of short external cavity lasers with a compact structure. Theoretically, the problem of linewidth narrowing ratio in external cavity lasers has been treated by many authors. Their analyses were mainly limited to weak optical feedback [7], [13], [15]. Some recent papers extend the analysis to an arbitrary amount of optical feedback [8], [9]; however, the experimental verification has not yet been found. For the above end, a new experiment has been made [10] and its schematic diagram is shown in Fig. 1. In it a 4 mm (0.23 pitch) GRINROD with 0.45 NA is used as an external cavity. The front facet of this ROD is anti-reflection coated and the rear facet is coated with gold. The laser diode used here is an InGaAsP BH type. Its facet facing the GRINROD is AR coated in order to get strong optical feedback. The reflectivity of the uncoated laser facet is about 0.35. By measuring the ratio of the output optical power from two facets of the diode, we can estimate the reflectivity of the coated facet to be about 0.07. After adding the external cavity to it, the threshold current of the diode is reduced from 75 to 62 mA, as shown in Fig. 2.



1. PZT, 2. GRINROD external cavity
3. Laser diode, 4. GRINROD
5. Isolator

Fig. 1. Schematic diagram of the external-cavity semiconductor laser.

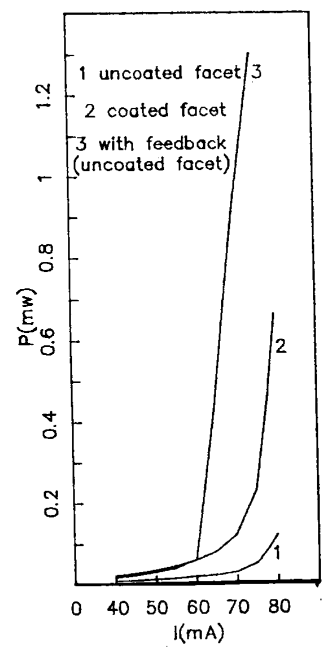


Fig. 2. *P–I* curve of the laser without (1, 2) and with (3) optical feedback.

The feedback parameter X can be estimated as follows [11]:

$$\Delta I_{th}/I_{tho} = \ln\,[1 + (1 - R_2)X/R_2]/(2\gamma l \ln R_1R_2) \qquad (1)$$

where I_{tho} is the threshold current of the solitary diode, ΔI_{th} is the change in threshold current due to external feedback, $R_1 = 0.35$ and $R_2 = 0.07$ are the facet reflectivities of the diode, γ is the effective absorption coefficient, $l = 250\ \mu m$ is the diode cavity length, $\gamma l = 0.8$ is assumed. X is the fraction of light feedback into the diode. From (1) we can estimate X in our

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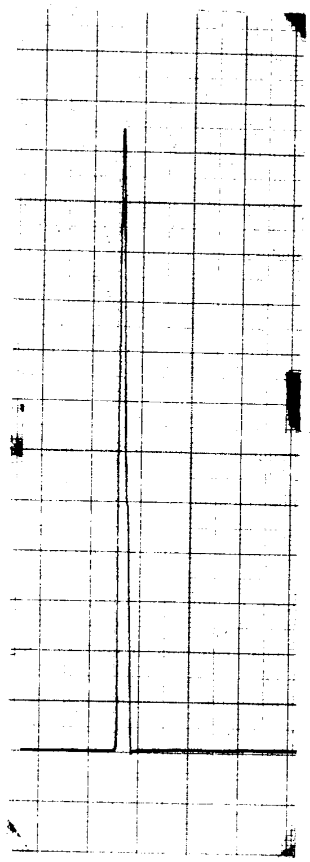
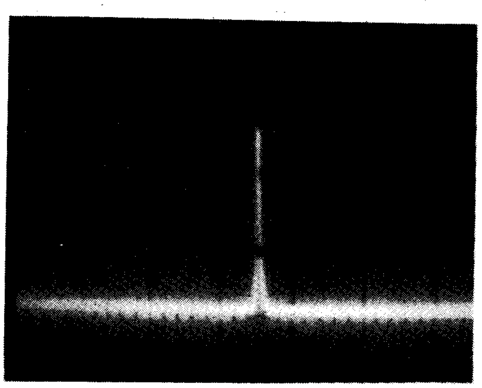


(a)



(b)

Fig. 3. (a) The spectrum measured by a monochrometer. (b) The spectrum measured by a confocal scanning FP interferometer 100 MHz/div.

configuration to be 14 percent. Obviously X is greater than the residual reflectivity of the active cavity, so it belongs to the so-called strong feedback situation. From the above parameters the linewidth reduction ratio F can be calculated by the following formula which can be used for semiconductor lasers with an arbitrary amount of optical feedback [12]:

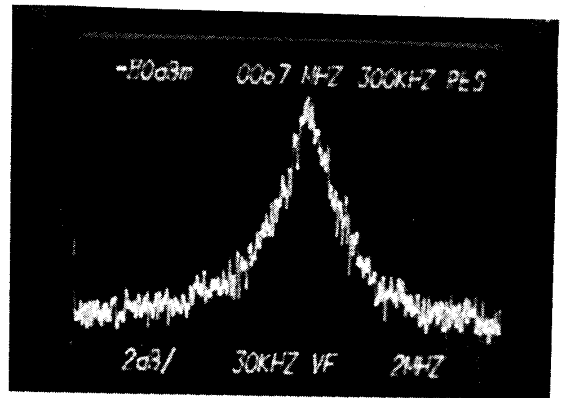


Fig. 4. The spectrum measured by a self-heterodyne system with the resolution of 15 kHz.

where τ is the roundtrip time delay in the external cavity and ω is the central frequency of the laser. $n = 3.5$ and $n_0 = 1.5$ are the refractive index of diode and GRINROD, respectively, $L = 4$ mm is the external cavity length, α is the linewidth enhancement factor, and $\alpha = 3.8$ is assumed. From (2) the linewidth reduction ratio F can be estimated approximately to be 100. The linewidth of the solitary laser diode is measured to be about 90 MHz at 1 mW of output power. Fig. 3 shows the spectrum of the laser with an operating current $I = 65$ mA and temperature $T = 30$ °C (in summer) measured by a monochrometer and a confocal scanning FP interferometer, its main-side mode ratio is larger than 30 dB and the measured linewidth is less than 12 MHz which is limited by the resolution of the interferometer. Fig. 4 shows the spectrum measured by a self-heterodyne system with the resolution of 15 kHz. The measured linewidth of this external cavity laser is about 900 kHz as shown in Fig. 4. This value verifies our calculation by using (2). If the conventional linewidth formula was used, e.g., the formula in [7] and [13], the calculated linewidth narrowing ratio of this short external cavity laser would be about 800; thus, the deviation would be obvious. The frequency change and "in phase condition" of this laser can be achieved by varying the voltage on the PZT and/or the operating current as well as the temperature. The laser chip is mounted on a Cu heat sink with a thermoelectric cooler for temperature control. In the temperature loop, the accuracy of the electric equipment for temperature control is 0.2 percent °C. In order to get high temperature stability, the heat sink of our laser is made into an enclosed structure and has a larger heat capacity, which isolates the laser from environmental perturbations. This version provides the full utilization of the temperature accuracy of the electric unit. For the mechanical stabilization, all the elements of the laser unit are fixed directly to the heat sink, not adjustable, which makes the laser immune to mechanical disturbances and temperature induced external cavity length perturbations. In more than 12 h of continuous observation, no mode jumping occurred. This result was obtained without any external active frequency stabilization.

$$F=\left\{1+\left(\frac{n_0L}{nl}\right)\frac{\sqrt{X/R_2}(1-R_2)[\sqrt{X/R_2}(1+R_2)+(1+X)\cos\omega\tau-\alpha(1-X)\sin\omega\tau}{1+X[(1+R_2)^2/R_2+X]+2\sqrt{X/R_2}(1+R_2)(1+X)\cos\omega\tau+2X\cos 2\omega\tau}\right\}^2 \tag{2}$$

In conclusion, we have succeeded in making an InGaAsP semiconductor laser with strong feedback from a GRINROD external cavity, which shows a stable single frequency operation with main-side mode ratio more than 30 dB and the linewidth of 900 kHz which verifies the newly developed theoretical prediction. Although monolithic integration of external cavity lasers is the obvious way to go, the result of this letter demonstrates that hybrid external cavity lasers with good mechanical and temperature stability can also be a good version.

Acknowledgment

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