# Measurement of Facet Reflectivity Through Reflection Gain in Fabry–PÉrot Laser Diode

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# Measurement of Facet Reflectivity Through Reflection Gain in Fabry–Pérot Laser Diode

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***Abstract*—We propose a simple and useful method to measure the facet reflectivity in a Fabry–Pérot laser diode (LD). The new measurement method does not require information on LD parameters such as threshold current or optical spectrum. The measurement is based on a simple formula that describes the relationship of facet reflectivity and reflection gain with launching the probe beam of a narrow spectral width.**

***Index Terms*—Fabry–Pérot laser diode (F-P LD), facet reflectivity, reflection gain.**

## I. INTRODUCTION

THE FACET reflectivity of semiconductor active devices has been of great interest in optimizing the laser diodes (LDs), optical amplifiers, and superluminescent diode (SLD), which are key components in the optical communication system [1]. Hence, it is most important to accurately measure the facet reflectivity. The measurement methods of the facet reflectivity have well been reported in much of the literature, which are typically based on the threshold current and optical spectrum at the semiconductor active devices. Agrawal *et al.* suggested the measurement method by comparison of power emitted in both facets of the Fabry–Pérot laser diode (F-P LD) [2]. Kaminow *et al.* proposed the more accurate method, which utilizes the spectrum of SLD at the driving current corresponding to the threshold current before antireflection (AR) coating [3]. Merritt *et al.* measured the wavelength dependence of facet reflectivity in semiconductor traveling wave amplifiers by using the optical spectra before coating and after coating of one facet [4]. Wang reported another measurement method by using the resonance effect between the flat fiber end and the F-P LD [5]. Most of the previous work requires the threshold current or optical spectra before AR coating in order to measure the facet reflectivity.

In this letter, we present a simple and useful measurement method, which can accurately measure the facet reflectivity of F-P LD without prior knowledge of optical parameters before AR coating. When obtaining the facet reflectivity, we measure the optical power of reflected beam with launching the probe beam of the narrow spectral width, which is based on a simple formula describing the relationship of the facet reflectivity and the reflection gain. Also it is necessary to measure the coupling efficiency between F-P LD and single-mode fiber (SMF) because the facet reflectivity cannot be determined without the coupling efficiency. Basically, the coupling efficiency cannot be discriminated in the facet reflectivity when measuring the optical power of the reflected beam. The coupling efficiency can be accurately measured by the ratio of optical power between before and after packaging of the F-P LD.

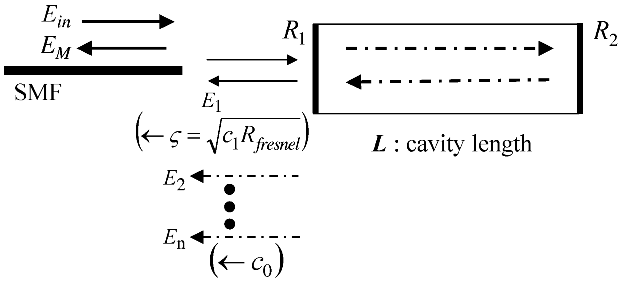

Fig. 1. Simplified model for structure of the pigtailed semiconductor LD.

## II. THEORY

Fig. 1 represents the simplified model for the structure of the pigtailed semiconductor LD, which consists of an optical SMF and an F-P LD with the cavity length of $L$ and facet reflectivity of $R_1$ and $R_2$. $E_{\text{in}}$ and $E_M$ are the electric fields of the optical input probe beam and the total reflected beam from the F-P LD, respectively. $E_M$ is the summation of the consecutive reflected beams ($E_n, n = 1, 2, \ldots$) from the front and back facets of the F-P LD. When the input probe beam from the SMF launches into the F-P LD, a reflection takes place at the front facet of the F-P LD by the Fresnel reflection and then this reflected beam will couple back to the fiber with the coupling efficiency of $c_1$. $c_0$ indicates the coupling efficiency of the light from F-P LD into the SMF, which is fundamentally resulted from the overlap integral between the transverse mode spots of F-P LD and SMF. Accordingly, the optical power ratio reflected from the semiconductor interface can be represented by $\varsigma^2 = c_1 \times R_{\text{fresnel}}$, where $R_{\text{fresnel}}$ is the Fresnel reflectivity at the front facet of F-P LD. And adding the optical waves returned into the SMF to get the total reflected waves $E_M$, we can express

$$\begin{aligned} E_M &= \sum_{n=1}^{\infty} \sqrt{c_n} E_n \\ &= \sqrt{c_1} E_1 + \sqrt{c_0} E_2 + \sqrt{c_0} E_3 + \ldots \end{aligned}$$

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$$\begin{aligned}
&= -\sqrt{c_1 R_{\text{fresnel}}}E_{\text{in}} \\
&\quad + \sqrt{c_0}\sqrt{1-R_1}\sqrt{R_2}\sqrt{1-R_1}\sqrt{c_0}\exp(-j2\beta L)G_s E_{\text{in}} \\
&\quad + \sqrt{c_0}\sqrt{1-R_1}\sqrt{R_2}\sqrt{1-R_1}\sqrt{c_0}\exp(-2j\beta L)G_s \\
&\quad \cdot \sqrt{R_1 R_2}\exp(-2j\beta L)G_s E_{\text{in}} + \dots \\
&= -\varsigma E_{\text{in}} + c_0(1-R_1)\sqrt{R_2}\exp(-j2\beta L)G_s \\
&\quad \cdot \left\{1+\sqrt{R_1 R_2}\exp(-2j\beta L)G_s + \dots\right\}E_{\text{in}} \qquad (1)
\end{aligned}$$

where $\beta$ is the longitudinal propagation constant and $G_s$ is the single-pass gain in the cavity of F-P LD. From (1), we can obtain the reflection gain as the optical power ratio of the total reflected beam to the input probe beam, as shown in (2) at the bottom of the page, where $\gamma = \varsigma/c_0$. Since the $\sin(\beta L)$ becomes "1" at the valley of the F-P LD longitudinal modes, (2) can be simplified into

$$\frac{P_{M,v}}{P_{\text{in},v}} = \left(\frac{\varsigma + \eta(\lambda_v)\left(c_0(1-R_1)+\varsigma\sqrt{R_1}\right)/\sqrt{R_1}}{1+\eta(\lambda_v)}\right)^2 \qquad (3)$$

where $P_{M,v}$ and $P_{\text{in},v}$ are the optical powers of the total reflected beam and the input probe beam at the valley wavelength of $\lambda_v$, respectively, and $\eta(\lambda_v) \equiv G_s\sqrt{R_1 R_2}$. When the F-P LD is turned OFF, the gain of $G_s$ becomes zero due to the large absorption of the active region so that $\eta(\lambda_v) \approx 0$ in (3). If $P_{M,v}^{\text{off}}$ is defined as the $P_{M,v}$ in the case of F-P LD turned OFF, then $P_{M,v}^{\text{off}}/P_{\text{in},v} \approx \varsigma^2$. As the F-P LD is turned ON and OFF, the refractive index of the active region is changed in the range of $\Delta n \approx 0.05$. It gives only 2% measurement uncertainty which can be ignored. The following relationship between the front reflectivity $R_1$ and the reflected optical power is obtained

$$c_0\frac{1-R_1}{\sqrt{R_1}} = \frac{1+\eta(\lambda_v)}{\eta(\lambda_v)}\frac{\sqrt{P_{M,v}}-\sqrt{P_{M,v}^{\text{off}}}}{\sqrt{P_{\text{in},v}}}. \qquad (4)$$

The gain-reflectance product term, $\eta(\lambda_v)(= G_s\sqrt{R_1 R_2})$, can be obtained experimentally by the several methods [6]–[9]. In this letter, we adopt the Hakki–Paoli (H-P) method [6] since it has been known as the easy and accurate method for a long time, although the gain-reflectance product by the H-P method can be sensitive to the resolution of the measurement system [7]. The peak power ($P_{\text{FP}}^{\text{peak}}$) and the valley power ($P_{\text{FP}}^{\text{valley}}$) of each F-P mode are needed to obtain the facet reflectivity through the relation of $\eta(\lambda_v) = (\sqrt{P_{\text{FP}}^{\text{peak}}} - \sqrt{P_{\text{FP}}^{\text{valley}}})/(\sqrt{P_{\text{FP}}^{\text{peak}}} + \sqrt{P_{\text{FP}}^{\text{valley}}})$. From (4), we can obtain the wavelength dependence of the facet reflectivity without any information of the as-cleaved F-P LD.

At the envelope center of F-P LD spectrum $\eta(\lambda_v)$ becomes "1" under the driving condition above the threshold current. If $P_{M,v}^{\text{center}}$ is defined as the $P_{M,v}$ at the envelop center, (4) can be simplified into the equation

$$c_0\frac{1-R_1}{\sqrt{R_1}} = 2\frac{\sqrt{P_{M,v}^{\text{center}}}-\sqrt{P_{M,v}^{\text{off}}}}{\sqrt{P_{\text{in},v}}}. \qquad (5)$$

Since the simplified formula of (5) does not require the peak and valley powers of the F-P mode, the measurement accuracy can be improved around the center of spectrum in the F-P LD. It has been reported that the peak and valley power of the F-P mode can be slightly influenced by the finite resolution of the spectrometer [10]. With high-quality AR coating, since $P_{M,v}^{\text{center}} \gg P_{M,v}^{\text{off}}$ and $R_1 \ll 1$, (5) can be much more simplified into the equation of

$$\frac{c_0^2}{R_1} \approx 4\frac{P_{M,v}^{\text{center}}}{P_{\text{in},v}} = 4G_{\max} \qquad (6)$$

where $G_{\max}$ indicates the maximum reflection gain, which can be observed around the valley of F-P modes of spectrum center under the strong lasing condition. As depicted in (6), since the facet reflectivity is proportional to the square of coupling efficiency, it is important to accurately measure the coupling efficiency. On the contrary, (6) is applicable to calculate the maximum reflection gain at the valley of F-P mode of envelope center if the coupling efficiency and front-facet reflectivity are given. For example, if the coupling efficiency of $c_0$ is ~40%, $G_{\max}$ becomes $\sim -9.0$ dB for $R_1 = 0.32$ (32%) before AR coating and ~6.0 dB for $R_1 = 0.01$ (1.0%) after AR coating, respectively.

## III. EXPERIMENTAL RESULTS

We employ the pigtailed F-P LD with coupling efficiency of ~40% and utilize the tunable LD as a probe beam with the narrow spectral width, as shown in Fig. 2. The reflectivity of F-P LD depends on the incident beam's polarization, e.g., transverse electric (TE) and transverse magnetic, due to the different confinement factor of the waveguide mode in the active medium [11]. Since the TE-polarization only contributes to the F-P LD lasing, the facet reflectivity measured in this letter is for the TE-polarization. Hence, the probe beam's polarization is adjusted into TE by the polarization controller (PC), where the optical power of the reflected beam is maximized. We measure three optical parameters in (4): 1) optical power of probe beam, $P_{\text{in}}$, 2) optical power of reflected beam when F-P LD is OFF, $P_{M,v}^{\text{off}}$, and 3) optical power of reflected beam when F-P LD is ON, $P_{M,v}$. The light produced by the laser can affect on the measurement accuracy. However, since $P_{M,v}$ is much larger than the spontaneous-emission power at the valley of F-P LD modes

$$\begin{aligned}
\frac{P_M}{P_{\text{in}}} &= \frac{|E_M|^2}{|E_{\text{in}}|^2} \\
&= c_0^2\frac{\left(\gamma - G_s\sqrt{R_2}(1-R_1+\gamma\sqrt{R_1})\right)^2 + 4\gamma G_s\sqrt{R_2}(1-R_1+\gamma\sqrt{R_1})\sin^2(\beta L)}{(1-G_s\sqrt{R_1 R_2})^2 + 4G_s\sqrt{R_1 R_2}\sin^2(\beta L)} \qquad (2)
\end{aligned}$$

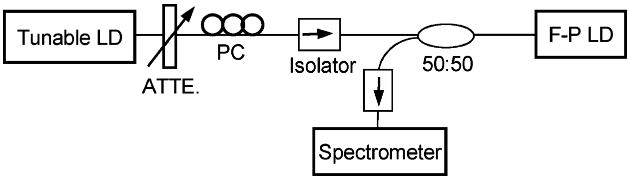

Fig. 2. Measurement setup of facet reflectivity in F-P LD.

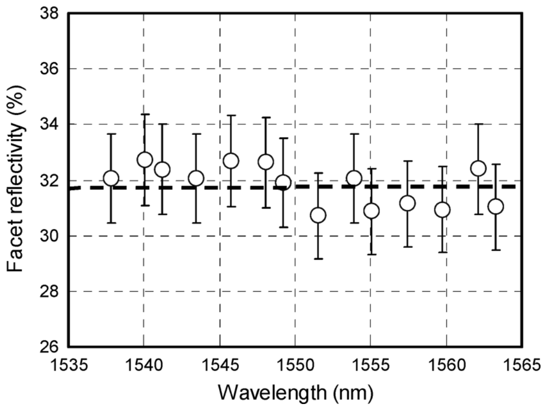

Fig. 3. Wavelength-dependence of facet reflectivity in the uncoated F-P LD.

when the optical power of probe beam is high enough, the light produced by the laser can be negligible ($<1\%$) on the measurement accuracy of facet reflectivity.

Fig. 3 shows the wavelength dependence of facet reflectivity in the uncoated F-P LD when the optical power of the probe beam is about $-25$ dBm. The measured facet reflectivity is $31.8 \pm 1.0\%$ over the wavelength range of 25 nm, which is well matched with the known value of 32% [11]. The measured values are slightly changed by the instrumental effects on spectrum measurement [10] and fluctuated by the polarization-dependence of spectrometer.

Fig. 4 illustrates the wavelength dependence of facet reflectivity in the F-P LD with AR coating of the single layer. The measured front facet reflectivity is $1.33\% \pm 0.08\%$ over the wavelength range of 25 nm. The solid line indicates the fitting result of the measured facet reflectivity. The facet reflectivity is proportional to the wavelength with the variation of about $0.16\%$ over the wavelength range of 25 nm. In the case of AR coating by the single layer of $\mathrm{SiO}_x$, the facet reflectivity normally has the wavelength dependence. Also we can find that the minimum reflectivity by AR coating of the single layer is positioned at a shorter wavelength.

## IV. SUMMARY

In this work, we have proposed the simple and useful method for the accurate measurement of facet reflectivity in the F-P LD with the coupling efficiency given. Two F-P LD samples were used to demonstrate the proposed scheme. The measured front facet reflectivity values for the uncoated and AR-coated F-P LDs are $31.8\% \pm 1.0\%$ and $1.33\% \pm 0.08\%$, respectively. The proposed method can be applied to both the F-P LD chip state and the pigtailed F-P LD, where there is no need to measure any parameters on the F-P LD before AR coating. The measurement results have been based on a formula having the relation of facet reflectivity and reflection gain, which is very capable of designing the semiconductor active devices such as F-P LDs, optical amplifiers, and SLD.

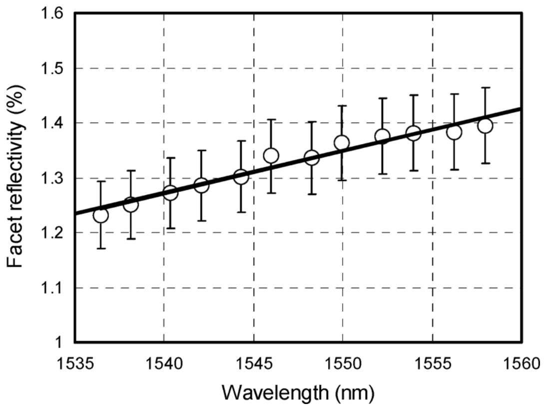

Fig. 4. Wavelength-dependence of facet reflectivity in the F-P LD with AR coating of the single layer.

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