Measurement of Cavity Loss and Quasi-Fermi-Level Separation for Fabry-Pérot Semiconductor Lasers*

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Abstract: A fitting process is used to measure the cavity loss and the quasi-Fermi-level separation for Fabry-Pérot semiconductor lasers. From the amplified spontaneous emission (ASE) spectrum, the gain spectrum and single-pass ASE obtained by the Cassidy method are applied in the fitting process. For a 1550nm quantum well InGaAsP ridge waveguide laser, the cavity loss of about ~ $24\mathrm{cm}^{-1}$ is obtained.

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1 Introduction

The cavity loss (α) of semiconductor lasers is an important parameter that influences many aspects of device operation such as external quantum efficiency and threshold carrier density. The conventional techniques[1,2] for determining the cavity loss are all based on the simple relationship connecting net gain, modal gain, and cavity loss in the laser, is given by

$$g = g_m - \alpha \quad (1)$$

where g is the net gain, g_m is the modal gain, α is the cavity loss. From Eq. (1), it is clear that g is equal to the cavity loss if the modal gain is zero. Thus, we can determine the value of the cavity loss through finding the net gain at these points. But the below-bandgap measurements are difficult because of the low intensity of amplified spontaneaus emission (ASE) in this region.

Recently Fu *et al*.[3] proposed a new technique by a fitting process method. In this method, the cavity loss and the quasi-Fermi-level separation can be determined through the fitting process method as the formula below,

$$p(E) \equiv \frac{P_1}{E^2}\left[1-\exp\left(\frac{E-\Delta E_f}{kT}\right)\right] = C_0 + C_1\left(1+\frac{\alpha}{g}\right)\left(e^{gL}-1\right) \equiv q(E) \quad (2)$$

where E is the photon energy, P_1 is the single-pass amplified spontaneous emission (SASE) intensity, C_0 and C_1 is proportionality constant, L is the cavity length, ΔE_f is the quasi-Fermi-level separation, k is the Boltzmann constant, and T is the temperature. In this method, P_1 and g are obtained by the Hakki-Paoli method[4], then by using linear relationship of function $p(E)$ and $q(E)$ defined in Eq. (2), a self-

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consistent correction in determining the quasi-Fermi-level separation and the cavity loss is obtained. Detailed process for the fitting process will be given later in this paper.

In this article, through using the Cassidy method[5], we develop a simple modification for this fitting process for measuring the cavity loss and the quasi-Fermi-level separation. The single-pass ASE spectrum including the two-directional emission waves is considered in our fitting process.

2 Measurement technique

The amplified spontaneous intensity I_{ASE} emitted from a facet of a Fabry-Pérot (FP) semiconductor laser can be expressed as[6],

$$I_{ASE} = (1-R)\left[\frac{BI_s}{g}\right]\frac{(e^{gL}-1)(1+b)}{1-2b\cos\theta+b^2} \quad (3)$$

where R is the reflectivity of both facets of the laser, I_s is the spontaneous emission rate per unit volume, L is the cavity length, B is a constant, and $b = Re^{gL}$, θ is the phase of the longitudinal mode. We can obtain the gain spectrum from the adjacent maxima P^+ and minima P^- of I_{ASE} at $\theta = 0$ and π by the Hakki-Paoli method. And under the Hakki-Paoli method, the single-pass amplified spontaneous intensity I_{SASE} can be obtained by

$$I_{SASE} = P^+P^-\{1/2[(P^+)^{1/2}+(P^-)^{1/2}]\}^{-2} \quad (4)$$

which can be reduced to

$$I_{SASE} = B\frac{I_s}{g}(e^{gL}-1)(1-R)(1+Re^{gL}) \quad (5)$$

However, the Hakki-Paoli method is sensitive to the resolution of the measurement system, and the maximum value P^+ is usually underestimated, especially as lasers approaching threshold.

To improve the accuracy of the measured gain spectrum, Cassidy proposed a gain measurement technique based on the minimum value P^- and the integrated intensity over one mode I_{ave}, which can be obtained by integrating Eq.(3) from $\theta = -\pi$ to π:

$$I_{ave} = \frac{BI_s(e^{gL}-1)(1-R)}{g(1-Re^{gL})} \quad (6)$$

The gain spectrum can be measured by the Cassidy method:

$$g_m = \frac{1}{L}\left[\ln\left[\frac{r-1}{r+1}\right]-\ln R\right] \quad (7)$$

where r is the ratio of the integration of mode intensity I_{ave} to the minimum P^- of the ASE spectrum. From Eqs.(5) and (6), we have

$$I_{SASE} = I_{ave}(1-(Re^{gL})^2) \quad (8)$$

which is based on the integrated mode intensity and is also called as Cassidy method in this article. Using the relationship between the net gain and the mode gain Eq.(1) and Einstein's relationship, we can obtain the following relationship between the net gain and the spontaneous emission rate

$$g(E) = C\frac{I_s}{E^2}\left[1-\exp\left(\frac{E-\Delta E_f}{kT}\right)\right]-\alpha \quad (9)$$

where E is the photon energy, C is a proportionality constant, ΔE_f is the quasi-Fermi-level separation, k is the Boltzmann constant, and T is the temperature. The cavity loss α is assumed to be weakly dependent on energy. Combining Eqs.(5) and (9) and eliminating I_s, we can obtain the following formula

$$p(E) \equiv \frac{I_{SASE}}{E^2}\left[1-\exp\left[\frac{E-\Delta E_f}{kT}\right]\right] = C_2\left(1+\frac{\alpha}{g}\right)(e^{gL}-1)(1-R)(1+Re^{gL}) \equiv q(E) \quad (10)$$

where C_2 is a constant in determining the quasi-Fermi-level separation and the cavity loss can be determined by a self-consistent correlation using the linear relationship of function $p(E)$ and $q(E)$ defined in Eq.(10).

3 Measurement results

The FP cavity semiconductor laser used in our experiment was a quantum-well InGaAsP ridge waveguide laser designed by Ref.[7]. The cavity length of the laser was 250μm, threshold current was 8mA at room temperature, the calculated facets reflectivity was $R = 0.32$. The amplified spontaneous emission of the laser biased at 5mA was measured by an Agilent 86142B optical spectrum analyzer (OSA) with the resolution of 0.06nm, and was plotted in Fig. 1.

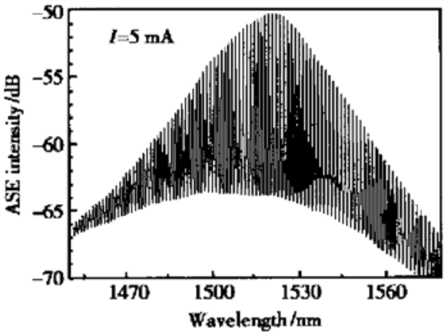

Fig. 1　Measured amplified spontaneous emission spectra below lasing threshold showing minimum and maximum due to the Fabry-Pérot cavity modulation of the emission intensity

From the ASE spectrum, we can directly obtain the SASE intensity I_{SASE} by the Hakki-Paoli method from Eq. (4). By the Cassidy method, we need to obtain the gain spectrum firstly and then calculate I_{SASE} from Eq. (8). Figure 2 shows the gain spectrum obtained by the Cassidy method from Eq. (7) at the injection current of 4, 5, 6, and 7 mA. We can find that the mode gain value in the long wavelength region is nearly identical at different currents, which indicate

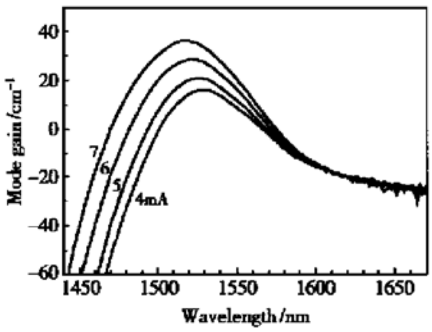

Fig. 2　Measured mode gain spectra at injection current of 4, 5, 6, and 7mA by the Cassidy method

that the cavity loss is not influenced by the injection current. Figure 3 shows the SASE spectra obtained by the Cassidy method from Eq. (8) as the solid and dash lines and by the Hakki-Paoli method as the opened and solid circles, respectively, at the OSA resolution to be 0.06 and 0.2nm. The results show that the two spectra obtained by the Cassidy method have very little difference, however, the difference between the two spectra obtained by the Hakki-Paoli method is distinct. And the SASE spectrum obtained by the Cassidy method at the resolution of 0.2nm is almost in coincidence with that obtained by the Hakki-Paoli method at the resolution of 0.06nm. So the Cassidy method is superior to the Hakki-Paoli method in the case with the OSA has a low resolution.

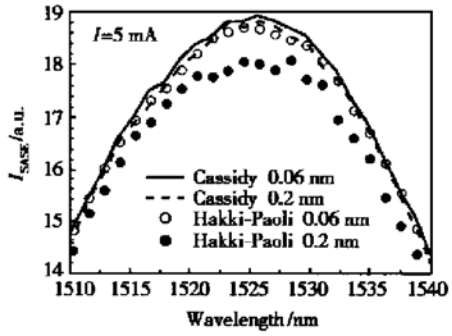

Fig. 3　Comparison between the SASE spectra calculated by the Hakki-Paoli method and the Cassidy method The resolution of the optical spectrum analyzer is taken to be 0.06 and 0.2nm.

Based on the gain spectrum obtained by the Cassidy method, we can determine the value of α from the gain spectrum at well below the bandgap[2] by a curve fitting in the long wavelength range of the gain spectrum and is named as below bandgap in Table 1. And the ΔE_f can also be determined roughly through the gain spectra where the net gain is equal to the cavity loss[8]. Using α and ΔE_f obtained from the gain spectra as the initial values, we adjust the values of α, ΔE_f, and the constant C_2 to fit the linear relationship of function $p(E)$ and $q(E)$. The relations between $p(E)$ and $q(E)$ are plotted in Fig. 4 for different α and ΔE_f.

If the used ΔE_f is not chosen properly, the increasing part and decreasing part around the maximum of $p(E)$ and $q(E)$ will not coincide together as one straight line, even an error is less than 1meV as shown in the dashed line in Fig. 4. And if the assumed absorption α is not chosen properly, the relation of $p(E)$ and $q(E)$ will not go through the original point as shown in the two solid lines in Fig. 4. The results show that the linear fitting between $p(E)$ and $q(E)$

is sensitive to the values of α and ΔE_f, so the cavity loss and the quasi-Fermi-level separation with good accuracy can be obtained from the linear fitting process. The obtained cavity loss and the quasi-Fermi-level separation are listed in Table 1, where the cavity losses of below bandgap and transparency point are obtained from the measured gain spectrum in the long wavelength side and the photon energy of ΔE_f, respectively. We find that the cavity losses obtained by three methods agree very well, and they increase a little with the increase of the injection current.

Table 1 Measured cavity loss and quasi-Fermi-level separation

Injection current /mA	ΔE_f/eV	α/cm^{-1}		
		Fitting process	Below-bandgap	Transparency-point
4	0.8337	−23.0	−22.6	−22.7
5	0.8394	−23.3	−23.7	−23.2
6	0.8444	−23.9	−24.4	−24.8
7	0.8517	−24.1	−24.5	−26.9

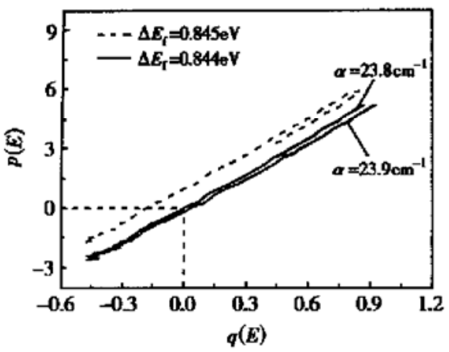

Fig. 4 Linear relationship between function $p(E)$ and $q(E)$ The dashed line with the same α represents a deviation from by a small error of 1meV, and the two solid lines show the difference of the linear relationship between function $p(E)$ and $q(E)$ under the condition, varying in α but ΔE_f equivalent.

4 Conclusion

The cavity loss and the quasi-Fermi-level separation are measured by the Cassidy method through a fitting process technique. The obtained cavity loss agrees very well with that determined from the gain spectrum in the photon energy much less than the bandgap energy and in the photon energy of ΔE_f. A cavity loss of ~ 24cm^{-1} is obtained for a 1550 nm ridge-waveguide quantum well laser.

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FP 腔半导体激光器的腔内损耗和准费米能级差的测量*

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摘要: 利用一种拟合方法测量 FP 腔半导体激光器的腔内损耗和准费米能级差. 从放大的自发发射谱, 利用 Cassidy 方法得到用于拟合过程的增益谱和单程放大的自发发射谱. 利用上述方法, 测出的 1550nm InGaAsP 量子阱脊型波导结构激光器的腔内损耗大约为 $24cm^{-1}$.

关键词: 半导体激光器; 测量技术; 腔内损耗
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