

# Determination of Internal Loss and Quasi-Fermi Level Separation From the Amplified Spontaneous Emission Spectrum of Fabry–Pérot Semiconductor Lasers

W. H. Guo, D. Byrne, Q. Y. Lu, R. Phelan, J. F. Donegan, and B. Corbett

**Abstract**—The net modal gain and the un-amplified spontaneous emission (ASE) coupled into the laser waveguide mode are extracted from the ASE spectrum of Fabry–Pérot semiconductor lasers by the Fourier transform method with a deconvolution process. Highly accurate quasi-Fermi level separation and internal loss are then derived by a minimum search process from the relationship between the spontaneous emission and gain.

**Index Terms**—Amplified spontaneous emission (ASE), Fabry–Pérot (FP) semiconductor laser, Fourier transform (FT) method, internal loss, quasi-Fermi level separation.

## I. INTRODUCTION

AT PRESENT, the Fourier transform (FT) method has been successfully applied to extract net modal gain from the amplified spontaneous emission (ASE) spectrum of Fabry–Pérot (FP) semiconductor lasers [1]. Further work using this method to measure the linewidth enhancement factor was also carried out [2]. Compared with the well-known Hakki–Paoli method [3], the resolution bandwidth influence on the FT method can be alleviated by a deconvolution process [4]. In this letter, we extend the functionality of the FT method to extract both quasi-Fermi level separation and internal loss from the ASE spectrum. The internal loss and quasi-Fermi level separation can be derived from the relationship between the spontaneous emission and gain [5], [6]. This requires the unamplified spontaneous emission to be measured, for example, from the side of the FP laser [5], which is quite difficult in practice. The emission from the end facet of the FP laser is easy to measure but is intrinsically modulated by the FP cavity. This modulation can be easily decomposed by the FT method, which transforms the quasi-periodic spectrum into a series of separated peaks corresponding to harmonics of the optical round-trip of the cavity [1], [4], [7]. The round-trip gain can be derived from the ratio of the inverse Fourier transformed zeroth and first peaks [1], [4]. As described

below, the zeroth harmonic also contains the spontaneous emission information [6] which, however, is omitted in the standard FT method. In this letter, we use a minimum search process to extract the internal loss and quasi-Fermi level separation from the spontaneous emission and the net modal gain spectrum, both of which are obtained from the FT method. The gain extraction always needs a high resolution bandwidth, otherwise the underestimation of the gain will have a negative influence on the accuracy of the extracted internal loss and quasi-Fermi level separation. We also show that by using a deconvolution process, the gain underestimation can be reduced [4] so that the requirement for high resolution bandwidth can be eased.

## II. THEORY

The ASE spectrum of FP semiconductor lasers can be described by [8], [9]

$$I = \frac{I_{\text{sp}}(1-R)(1+b)}{1+b^2-2b\cos(2n_{\text{eff}}kL)} \quad (1)$$

where  $b = \exp(gL)R$  is the round-trip gain,  $g$  is the net modal gain;  $L$  is the cavity length;  $R$  is the power reflectivity of the end-facet;  $k = 2\pi/\lambda$  is the wavenumber in vacuum

$$I_{\text{sp}} = \frac{S[\exp(gL) - 1]}{g} \quad (2)$$

is the single pass ASE,  $S$  is related to the spontaneous emission rate  $r_{\text{sp}}$  by  $S = A\beta r_{\text{sp}}hc/\lambda$ ,  $A$  is the transverse area of the quantum wells (QWs),  $\beta$  is the ratio of the spontaneous emission coupled into the waveguide mode. The FT of the modulated ASE spectrum (1) is composed of a series of separated peaks, which correspond to harmonics of the optical round-trip of the FP cavity. Selecting the zeroth and first harmonics and taking their inverse FT, the following spectra can be obtained:

$$I_0 = \left| \int_{-n_{\text{eff}}L}^{n_{\text{eff}}L} \tilde{I}(z) \exp(ikz) dz \right| = \frac{I_{\text{sp}}(1-R)}{1-b} \quad (3)$$

$$I_1 = \left| \int_{n_{\text{eff}}L}^{3n_{\text{eff}}L} \tilde{I}(z) \exp(ikz) dz \right| = bI_0 \quad (4)$$

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where  $\sim$  above indicates a Fourier transformed quantity. The round-trip gain can consequently be calculated as  $b = I_1/I_0$  [1]. This is the fundamental aspect of the FT method for gain extraction. The net modal gain can be calculated as  $g = \log(b/R)/L$ . Combining (2) and (3) the spontaneous emission coupled into the laser waveguide mode,  $S$  in (2), is also obtained

$$S = \frac{I_0(1-b)g}{(1-R)[\exp(gL) - 1]}. \quad (5)$$

The relationship between the spontaneous emission rate and the material gain is [5]

$$g_m = \frac{\lambda^4}{8\pi c n^2} \left[ 1 - \exp\left(\frac{hc}{\lambda} - \frac{\Delta F}{k_B T}\right) \right] r_{sp} \quad (6)$$

where  $\Delta F$  is the quasi-Fermi level separation. The material gain is related to the net modal gain through  $g = \Gamma g_m - \alpha_{in}$ ,  $\alpha_{in}$  is the internal loss. Now combining the above relations we can obtain

$$g(\lambda) = C\lambda^5 S \left[ 1 - \exp\left(\frac{hc}{\lambda} - \frac{\Delta F}{k_B T}\right) \right] - \alpha_{in} \\ \equiv Cq(\lambda, \Delta F) - \alpha_{in} \quad (7)$$

where  $C = \Gamma/(8\pi c^2 n^2 h \beta A)$ . From (7), it is seen that the net modal gain  $g(\lambda)$  is a linear function of  $q(\lambda, x)$  as  $x = \Delta F$ . This point can be used to extract the quasi-Fermi level separation  $\Delta F$ . The extraction process is as follows: scanning  $x$  within a range in which  $\Delta F$  is estimated; for each value of  $x$ , linearly fitting  $[q(\lambda, x), g(\lambda)]$  and monitoring the norm of the residuals; determining  $\Delta F$  from the minimum of the norm; determining  $\alpha_{in}$  from the intercept of the linear fit with  $x = \Delta F$ . The experimentally measured spectrum is the laser ASE spectrum convoluted by the response function of the measurement system. The gain will be underestimated if the resolution bandwidth used is not high enough. However, with a deconvolution process [4], even a moderate resolution bandwidth can produce a satisfactory result. The deconvolution process yields modified equations of (3) and (4)

$$I_0 = \int_{-n_{eff}L}^{n_{eff}L} \frac{\tilde{I}(z)}{2\pi \tilde{f}^*\left(\frac{k^2}{2\pi}z\right)} \exp(ikz) dz \quad (8)$$

$$I_1 = \int_{n_{eff}L}^{3n_{eff}L} \frac{\tilde{I}(z)}{2\pi \tilde{f}^*\left(\frac{k^2}{2\pi}z\right)} \exp(ikz) dz \quad (9)$$

where  $*$  means complex conjugate,  $f(x)$  is the response function of the measurement system which can be obtained by measuring a single wavelength source with a linewidth much narrower than the designated resolution bandwidth.

### III. SIMULATION AND MEASUREMENT

To check the above scheme, we performed some numerical simulations first. An FP semiconductor laser with the active region composed of six strain-compensated QWs was simulated.

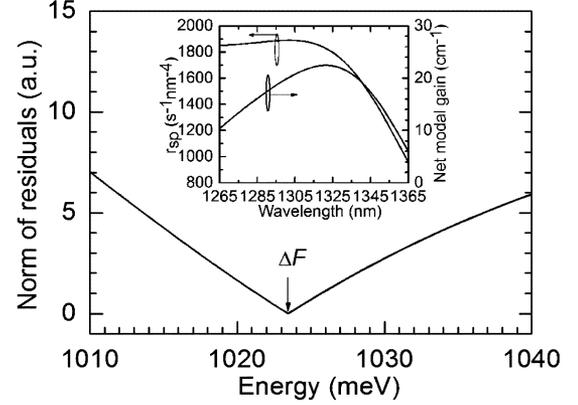


Fig. 1. Norm of residuals from linear fit versus  $x$ . Inset: spontaneous emission and net modal gain spectrum used in the simulation.

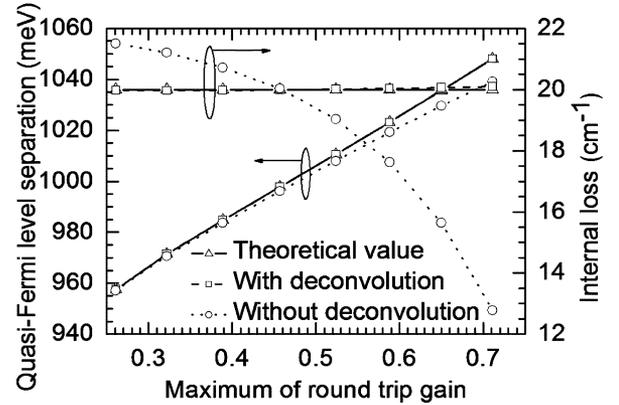


Fig. 2. Extracted quasi-Fermi separations and internal loss versus maximal round-trip gain with and without the deconvolution process. The theoretical values are also shown for comparison.

The gain and the spontaneous emission spectrum were calculated taking account of valence-band mixing and many-body effects [5]. The ASE spectrum was produced through (1) with the cavity length  $300 \mu\text{m}$  and a group index 3.61. The simulated ASE spectrum was analyzed by the FT method to extract the net modal gain and the spontaneous emission spectrum. Through the minimum search process introduced above we determined the quasi-Fermi level separation and the internal loss. In the simulation, we first set the parameters  $\Delta F = 1023.18 \text{ meV}$  and  $\alpha_{in} = 20 \text{ cm}^{-1}$ . The extracted values were  $1023.43 \text{ meV}$  and  $20.02 \text{ cm}^{-1}$ , so very high accuracy was obtained. The norm of the residuals is plotted in Fig. 1, which shows the minimum indicating the quasi-Fermi level separation  $\Delta F$ . The inset shows the spontaneous emission and the net modal gain spectrum used in the simulation, which cover a range of 100 nm around the gain peak. To show the resolution bandwidth influence, we then convoluted the simulated ASE spectrum with a triangular response function [9] which has a full-width at half-maximum (FWHM) of 0.1 nm. The carrier density in the QWs was varied and this produced different maximal round-trip gain for the FP cavity. The quasi-Fermi level separation and the internal loss were extracted with and without the deconvolution process and the results are shown in Fig. 2 versus the maximal round-trip gain. It is seen that without the deconvolution process, the quasi-Fermi

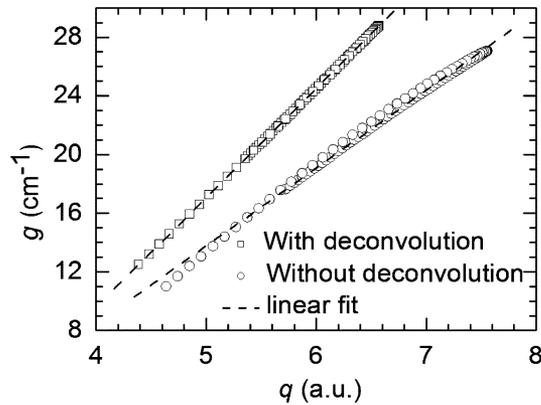


Fig. 3.  $[q(\lambda, \Delta F), g(\lambda)]$  curve obtained with and without the deconvolution process along with the linear fit.

level separation is always underestimated and the underestimation is severe for high round-trip gain situations. The internal loss is overestimated in the low round-trip gain case and underestimated in the high gain case. Overall the accuracy is better for low gain situations. However, with the deconvolution process, the extracted parameters are always obtained with high accuracy, which means that the requirement for high resolution bandwidth can be greatly eased by this process. In Fig. 3, we plot the  $[q(\lambda, \Delta F), g(\lambda)]$  curve along with the linear fit. The maximal round-trip gain in this case was 0.711. It is seen that without the deconvolution process, the final curve is nonlinear indicating that the resolution used is not high enough.

In the following, we measured a practical FP ridge waveguide laser operating around 1300 nm. A single-mode fiber with an antireflection-coated lens on its head was used to couple the ASE power into an optical spectrum analyzer (OSA) (Agilent 86140B). The laser length was measured to be 300  $\mu\text{m}$ . The laser is mounted on a heat sink and was held at a constant temperature of 20  $^{\circ}\text{C}$  using a thermoelectric cooling unit. We do not use a polarizer here because the QWs used in the laser are highly compressively strained and the TM emission can be neglected. The threshold current of the laser is about 12 mA. The nominal resolution bandwidth of the OSA was set to be 0.2 nm. The true resolution bandwidth determined from the FWHM of the OSA response function around 1300 nm is 0.176 nm which is about 23% of the longitudinal mode spacing. The ASE spectrum covering a range of about 100 nm around the gain peak was recorded and averaged over 20 times to improve the signal-to-noise ratio. The Hanning window function was multiplied to the measured spectrum to soften the intensity variation from the center to the edge, which can reduce the derived gain fluctuations at the edge of the measurement window [4]. Fig. 4 shows the internal loss and the quasi-Fermi-level separation extracted with and without the deconvolution process. It is seen that with the deconvolution process the internal loss extracted is more reliable. The value slightly increases with increasing current and almost saturates as the current comes close to threshold. As the simulation shows, insufficient resolution bandwidth results in overestimation of the internal loss in the low gain case and underestimation in the high gain case. The quasi-Fermi level separation, however, is always underestimated.

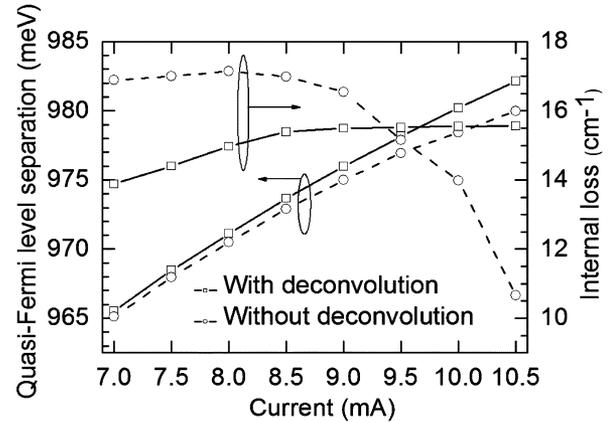


Fig. 4. Measured quasi-Fermi level separations and internal loss versus current with and without the deconvolution process.

#### IV. CONCLUSION

We propose a minimum search process to extract the internal loss and quasi-Fermi-level separation from the ASE spectrum of FP semiconductor lasers. The FT method was used to extract the net modal gain and the unamplified spontaneous emission coupled into the laser waveguide mode. By using a deconvolution process the net modal gain can be obtained almost free from the influence of the resolution bandwidth, which yields more accurate internal loss and quasi-Fermi level separations.

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