ACCURACY OF FABRY–PEROT METHOD OF SEMICONDUCTOR LASER GAIN MEASUREMENT

Indexing terms: Measurement, Semiconductor lasers

The Fabry–Perot (FP) method of semiconductor laser gain measurement, first proposed by Hakki and Paoli (1975), is widely used. It is based on the measurement of the FP resonances excited by spontaneous emission. Its validity rests on the assumption that a single mode is significant. We show, using a simplified laser model, that this assumption is valid only when the power mirror reflectivity is very small, or near the laser oscillating frequency. For example, the error is in the order of 20% when the power facet reflectivities are equal to 37% and the modal gain is unity. These results apply to both index-guided and gain-guided lasers.

Above threshold and at the oscillation frequency f_0, the single-pass power gain g of a laser equals the loss

$$g(f_0) = \alpha + L^{-1} \ln (1/R) \tag{1}$$

where α denotes the internal loss, L the laser length and R the mirror power reflectivity, in a symmetrical configuration. At optical frequencies f other than the oscillation frequency, the gain decreases approximately parabolically. It is important for the design of semiconductor lasers to be able to measure the dependence of the gain g on optical frequency f (or free-space wavelength). A simple method of semiconductor laser gain measurement has been proposed by Hakki and Paoli.[1] This method is based on the excitation of the laser FP resonances by spontaneous emission.[2] It is nowadays widely used for both index-guided[3] and gain-guided[4] lasers. Some improvement has been proposed[5] to reduce the influence of the spectrometer imperfections. In this letter we assume that the spectrometer has infinite resolution.

The theory on which the method is based assumes single-mode excitation. The purpose of this letter is to show that the field in the laser junction plane excited by spontaneous emission differs significantly from the fundamental-mode field at frequencies other than the oscillating frequency. As a result, the method should give accurate $g(f)$ curves only when the mirror reflectivity is small (e.g. $R \leq 0{\cdot}1$) and the corresponding laser gain is very large. In that case, spatial mode filtering is indeed large enough to eliminate the radiation-mode field from the junction plane. This, unfortunately, is not the case for usual mirror reflectivities ($R \simeq 0{\cdot}37$). Most authors are aware that spontaneous emission in modes other than the fundamental transverse mode may introduce errors. However, they seem to assume that this spurious radiation may be eliminated, at least in principle, by reducing the spectrometer aperture to a pin hole located at the centre of the laser active region. The numerical calculations presented here show that this is not always the case.

To calculate the spectral density of the laser spectral field intensity in the junction plane, we use a simple thin-active-slab model already used by us in Reference 6. As shown in Fig. 1, the active region is supposed to be thin enough to be represented by a reactive plane located at $x = 0$. This surface imposes the following boundary condition on the field E at $x = 0$:

$$\partial E/\partial x \Big|_{x=0} - iu_0 E = 0 \tag{2}$$

$u_0 = b_0 + ia_0$, where a_0 expresses guidance by the real part of the refractive index and b_0 is the material gain. The power gain of the guided wave is $g = 2a_0 b_0/k$, where $k = 2\pi fn/c$ and n is the refractive index of the confining layer.

In this model, the mirrors are supposed to be perfectly reflecting but the confining layers have a power loss α, so that eqn. 1 reads

$$g(f_0) = 2a_0 b_0(f_0)/k = \alpha \tag{3}$$

The distributed loss α is, however, almost equivalent to a

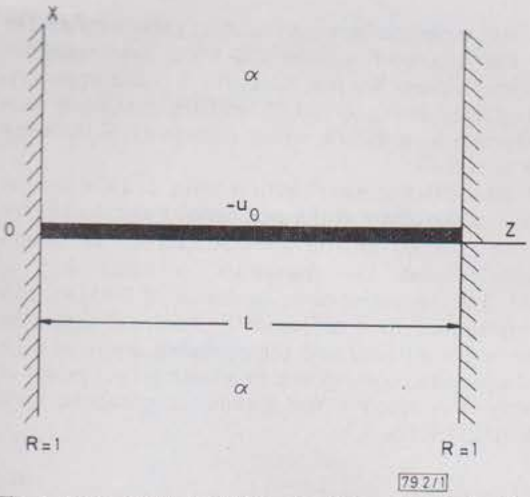

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Fig. 1 *Laser model consisting of a thin active slab with susceptance* $-u_0 = -(b_0 + ia_0)$ *in a lossy medium (of loss* α*)*

L is semiconductor laser length. Loss α is equivalent to a facet reflectivity R according to eqn. 4

mirror reflectivity R such that

$$\alpha = L^{-1} \ln (1/R) \tag{4}$$

so that it is permissible to express the distributed loss α by the equivalent R-value according to eqn. 4.

Our model enables us to treat both index-guided lasers ($b_0 \ll a_0$) and gain-guided lasers ($b_0 \gg a_0$). The distinction between these two types of wave guidance may be established by considering Petermann's K-parameter: $K = 1 + (b_0/a_0)^2$, $K \simeq 1$ for index-guided and $K \gg 1$ for gain-guided lasers.

Spontaneous emission is modelled by random currents that are uncorrelated in space. Equivalently, with the help of a Fourier series transform they correspond to currents that have the following dependence on the axial z-co-ordinate:

$$J_l(z) = \sqrt{[b_0(f)]} \sin (\pi l z/L) \tag{5}$$

where l denotes the axial mode number, and the dependence of b_0 on the optical frequency f is exhibited. An unimportant constant factor has been dropped, and a two-dimensional model is assumed.

Each of these current components J_l excites a field in the junction plane ($x = 0$) with intensity[6]

$$|E_l(0)|^2 = b_0(f)/|u_l(f) - u_0(f)|^2 \tag{6a}$$

to within a constant factor, where

$$u_l(f) = [(k + i\alpha)^2 - (\pi l/L)^2]^{1/2} \tag{6b}$$

is the x-component of the propagation vector in the lossy confining layers. Assuming that there is no phase relationship between the various axial modes, the measured field intensity $s(f)$ in the junction plane is obtained by summing $|E_l(0)|^2$ in eqn. 6 over l, in principle from $l = 0$ to ∞:

$$s(f) = \sum_{l=0}^{l=\infty} |E_l(0)|^2 \tag{7}$$

The spectral density $s(f)$ of the field intensity fluctuates quickly as a function of f. Following the definition introduced by Hakki and Paoli[1] we define

$$r_i = (p_i + p_{i+1})/2v_i \tag{8}$$

at frequency f_i, where v_i is a minimum of the $s(f)$ curve and p_i, p_{i+1} are the adjacent maximum values. From eqn. 8 we define, following eqn. 2 of Reference 1, the gain

$$g = L^{-1} \ln \{[\sqrt{(r_i)} + 1]/[\sqrt{(r_i)} - 1]\} + \alpha \tag{9}$$

which we call the 'measured' gain.

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Numerical comparison between the exact gain postulated in eqn. 3 and the 'measured' gain in eqn. 9 has been made for usual parameter values. We first select the K-value appropriate to index-guided lasers, $K = 1{\cdot}05$, and the maximum gain value appropriate to a mirror power reflectivity R (R being related to α by eqn. 4).

The medium oscillating wavelength is taken as $1\,\mu\mathrm{m}$, so that $k_0 = 2\pi\,\mu\mathrm{m}^{-1}$ at the centre of the gain curve. For example, for $R = 0{\cdot}37$ and $L = 200\,\mu\mathrm{m}$ (or $\alpha = 0{\cdot}005\,\mu\mathrm{m}^{-1}$) we obtain $a_0 = 0{\cdot}374\,\mu\mathrm{m}^{-1}$ and the maximum b value b_{0m} is $0{\cdot}0837\,\mu\mathrm{m}^{-1}$. For an active-layer thickness of $0{\cdot}05\,\mu\mathrm{m}$, this a_0-value corresponds to a difference in refractive index Δn between the active medium and the confining layers of 0·19. The b_{0m} value selected corresponds to a laser output power of approximately $P = 10\,\mathrm{mW}$. We assume a parabolic gain variation as in Reference 6:

$$b_0(f) = b_{0m}[1 - 100(k/2\pi - 1)^2] \tag{10}$$

where k is expressed in $\mu\mathrm{m}^{-1}$.

The comparison between the exact gain $g = 2a_0 b_0/k$, where $b_0(f)$ is given in eqn. 10, and the 'measured' gain calculated from eqns. 6–9, is shown in Fig. 2 for three values of R.

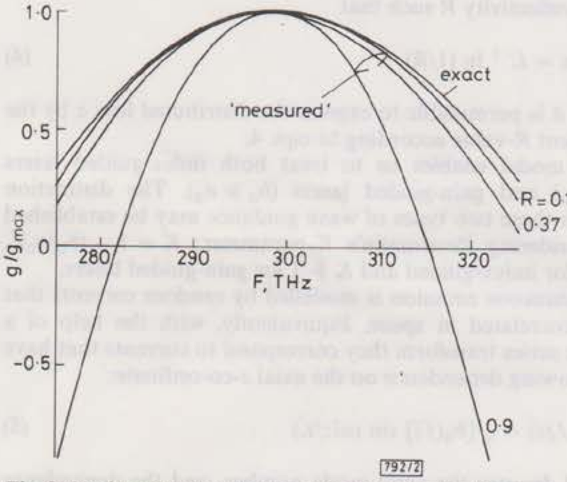

Fig. 2 *Single-pass power gain as a function of optical frequency*

Upper curve, 'exact', is postulated gain $[g(f) = 2a_0 b_0(f)/k]$.
Lower curves, 'measured', are calculated from optical field spectrum using Hakki and Paoli formula. R-parameter is equivalent mirror power reflectivity. If active layer thickness is $0{\cdot}05\,\mu\mathrm{m}$, difference in refractive index is $\Delta n = 0{\cdot}19$. Laser length is $L = 200\,\mu\mathrm{m}$ and wavelength is $1\,\mu\mathrm{m}$

The curves show that, while the Fabry–Perot method is accurate for large-gain, low-reflectivity lasers ($R \simeq 0{\cdot}1$) because of strong spatial filtering of the fundamental mode, the accuracy is poor for usual reflectivities ($R \simeq 0{\cdot}37$), and the method is inapplicable when $R \simeq 0{\cdot}9$ or larger except near the oscillating frequency. The same conclusion is found to apply to gain-guided lasers.

The accuracy of the method would be improved if a spatial mode filter were introduced between the laser and the detector. For example, in the measurements reported in Reference 7 a single-mode fibre was used which acts as a power-orthogonal mode filter. However, because the modes of a semiconductor laser, strictly speaking, are not power-orthogonal, such an external spatial mode filter is not sufficient to remove entirely the radiation mode field. Furthermore, it is unlikely that the mode selected by the fibre coincides with the laser mode.

The model that we have used in this letter should be improved to account for exact three-dimensional laser configurations. However, it seems that this model is accurate enough to estimate the errors involved in Hakki and Paoli's method of gain measurement.

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M. B. EL MASHADE
J. ARNAUD
Equipe de Microoptoélectronique de Montpellier
CNRS
34060 Montpellier Cédex, France

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