Determination of Nonlinear Gain Coefficient of Semiconductor Lasers from above Threshold Spontaneous Emission Measurement

F. Girardin, G.-H. Duan, C. Chabran, P. Gallion, M. Blez, and M. Allovon

Abstract— **The measurement of spontaneous emission power above threshold has shown a nearly linear increase with biasing current in a 1.55-μm InGaAs/InGaAlAs multiple quantum-well laser. Based on this measurement, we propose a novel experimental method to determine the nonlinear gain coefficient. The obtained value is 1.2×10^{-17} cm^3 for the laser used. This value corresponds reasonably to that obtained by chirp-to-modulated-power ratio method, confirming the validity of this new measurement method.**

I. Introduction

It is well known that the carrier density in semiconductor lasers is not rigorously clamped above threshold due to nonlinear gain and spontaneous emission coupled to the lasing mode. The effect of nonlinear gain is usually dominant. One important manifestation of this non-clamping is the low-frequency red-shift of wavelength in direct current modulated semiconductor lasers, through a carrier density dependent refractive index change [1]. Consequently, the measurement of the chirp-to-modulated-power ratio (CPR) has been used to determine the nonlinear gain coefficient [2], [3]. Another more direct manifestation is the measurement of spontaneously emitted power with increasing bias current above threshold, as it is proportional to the square of the carrier density. Such a measurement has been previously reported by Larcourse *et al.* on 1.3-μm [4] and by Joindot *et al.* on 1.5-μm InGaAsP lasers [5], showing effectively an increasing spontaneous emission power with injection current. By combining this measurement with that of the external quantum efficiency, they have derived the intervalence band absorption (IVBA) coefficient [4], [5]. In this letter we report the determination of the nonlinear gain coefficient from the measurement of spontaneous emission above threshold and compare the result with that obtained from the measurement of CPR.

II. Device and Measurement Setup

The laser under test is a Fabry–Perot 1.55-μm unstrained multiple quantum-well laser made of six 9.4-nm wide GaInAs wells and InGaAlAs barriers [6]. The laser exhibits a single-mode spectrum, with a side-mode-suppression-ratio higher than 20 dB at dc condition. A transparent window with a width of 80 μm has been realized on the n-side electrode along the cavity length. The laser chip is mounted with this side up in order to collect spontaneous emission power.

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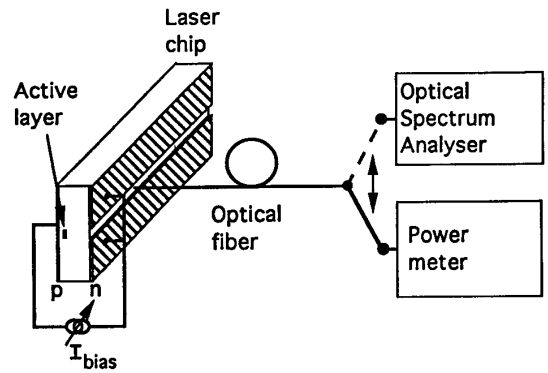

Fig. 1. Schematic diagram of the experimental set up.

The measurement setup is presented in Fig. 1, in which the laser is biased with a dc current. Light emitted through the n-side aperture is collected by a single-mode lensed fiber, which can be connected alternately to an optical spectrum analyzer or a power-meter. The collected light contains spontaneous emission as well as position-dependent scattered stimulated emission due to defects in the laser structure. It is therefore important in our measurement to resolve spontaneous emission from stimulated emission. This is achieved by choosing a point at which the received stimulated emission is negligible. The resolved spontaneous emission power received by the power-meter, P_{sp}, is given by

$$P_{sp} = \eta B N^2 \tag{1}$$

where B is the radiative recombination coefficient, N the carrier density and η is proportional to the ratio between collected and emitted spontaneous light, which depends only on geometrical parameters, but not on injection current. We assumed that the active layer is thin enough to neglect the transverse amplified spontaneous emission process. Thus any change in carrier density can be detected through the measurement of spontaneous emission power in our setup.

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III. Theoretical Analysis

For Fabry–Perot cavity lasers with uniform photon density and carrier density along the cavity length, the classical rate equations can be used. They are written as [7]:

$$\frac{dS}{dt} = v_g(g - \alpha_t)S \tag{2}$$

$$\frac{dN}{dt} = \frac{I}{eV} - R(N) - v_g g S \tag{3}$$

where S is the photon density, v_g is the group velocity, g the modal gain, α_t the total losses including mirror losses, internal losses and IVBA, e the electron charge, V the volume of the active layer, and I the injection current. The recombination term is given by $R(N) = AN + BN^2 + CN^3$, where A is the surface and defects recombination coefficient and C the Auger recombination coefficient. For GaAs materials with very high carrier density, an effective Auger coefficient should be used to include population of the L valley of the conduction band [8]. The spontaneous emission has not been taken into account in (2) because its effect is here negligible. By including the material's nonlinear gain, the modal gain is written as:

$$g = \frac{\Gamma g_d(N - N_0)}{1 + \epsilon S} \tag{4}$$

where Γ is the confinement factor, g_d the differential gain, N_0 is the carrier density at transparency, and ϵ the nonlinear gain coefficient. The total losses are expressed by:

$$\alpha_t = \alpha_d(N - N_0) + \alpha_0 \tag{5}$$

where α_d represents the differential losses due to IVBA, and α_0 the total losses at transparency.

Let us consider the static case in which we have $d/dt = 0$. By combining (2)–(5), the static carrier density above threshold is given by:

$$N = N_{\text{th}} + \epsilon S \frac{\alpha_0}{\hat{g}_d}\left(1 + \frac{\alpha_d}{\hat{g}_d}\right), \qquad I \geq I_{\text{th}} \tag{6a}$$

$$N_{\text{th}} = N_0 + \frac{\alpha_0}{\hat{g}_d} \tag{6b}$$

where N_{th} is the carrier density at threshold and $\hat{g}_d$ the net differential gain given by $\Gamma g_d - \alpha_d$. According to (6a) and (6b), it is clear that the carrier density increase above threshold is due to the nonlinear gain represented by ϵS. The effect of IVBA is to accelerate this increase and to give a more important threshold carrier density. But in any case, IVBA itself is not the origin of the carrier density increase above threshold, as long as it is considered to be independent of photon density.

For an injection current much smaller than the threshold current the main term in recombination rate $R(N)$ is the radiative recombination BN^2. In this case, we obtain from (1) and (3) by setting $S = 0$:

$$\left.\frac{dP_{\text{sp}}}{dI}\right|_{I \ll I_{\text{th}}} = \frac{\eta}{eV}. \tag{7}$$

Above threshold the derivative of the received power can be obtained by using (1), (3), and (6a):

$$\left.\frac{dP_{\text{sp}}}{dI}\right|_{I > I_{\text{th}}} = \epsilon\eta \frac{2BN_{\text{th}}\alpha_0(1 + \alpha_0/\hat{g}_d)}{eV\hat{g}_d v_g \Gamma g_d(Nth - Nth_0)}. \tag{8}$$

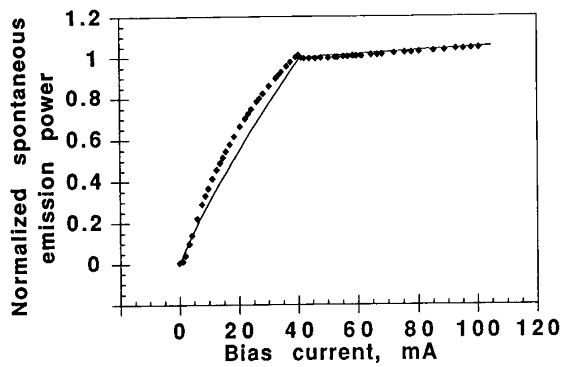

Fig. 2. Measured (♦) and calculated (—) spontaneous emission power relative to threshold spontaneous emission as a function of injection current.

Here the second order term of ϵ has been neglected. Thus this derivative is directly proportional to the nonlinear gain coefficient ϵ. As the coefficient η can be obtained from (7), the nonlinear gain coefficient ϵ is thus derived from (7) and (8):

$$\epsilon = \rho \frac{\Gamma g_d(Nth - Nth_0)\hat{g}_d v_g}{2BN_{\text{th}}\alpha_0(1 + \alpha_0/\hat{g}_d)}$$

$$\text{with} \qquad \rho = \frac{\left.\frac{dP_{\text{sp}}}{dI}\right|_{I > I_{\text{th}}}}{\left.\frac{dP_{\text{sp}}}{dI}\right|_{I \ll I_{\text{th}}}}. \tag{9}$$

Therefore, the measurement of spontaneous emission power variation with injection current, together with the knowledge of some laser parameters, allows the determination of the nonlinear gain coefficient. This is the main new theoretical result of the present letter.

IV. Results

The measured variation of spontaneous emission with injection current up to 100 mA is plotted in Fig. 2 for the laser used. One can easily distinguish two regimes: below and above threshold. A sublinear variation is observed below threshold while a nearly linear one is exhibited above threshold with a slop much smaller than that in the below threshold regime.

As the variation of spontaneous emission is only affected by recombination coefficients below threshold, this variation can be used to derive recombination coefficients B and C by using (1) and (3). We determine losses and net differential gain with the Hakki and Paoli method [9]. The values of parameters are presented in Table I. Using (9) and the values in Table I, the value of ϵ obtained by our new method is 1.2×10^{-17} cm^3.

Using these values, the spontaneous emission power is calculated as a function of injection current using (1)–(3). The result is shown in the solid line in Fig. 2. A good agreement between measured and calculated results has been found, which confirms the validity of our model. In order to check further the validity of this new method, the nonlinear gain coefficient ϵ is also measured by using the CPR method [2]. The value obtained in this experiment is in the range: $1.0 \pm 0.3 \times 10^{-17}$ cm^3; which corresponds reasonably to that obtained by our new method. Furthermore, the measured value

TABLE I
VALUES OF PARAMETERS FOR THE LASER USED

Symbol	Value	Unit
A^*	1×10^7	s^{-1}
B	2×10^{-10}	$cm^3.s^{-1}$
C	5×10^{-29}	$cm^6.s^{-1}$
$\Gamma g_d - \alpha_d$	7×10^{-17}	cm^2
α_0	105	cm^{-1}
N_0^*	1×10^{18}	cm^{-3}
V	1.2×10^{-10}	cm^3
ϵ	1.2×10^{-17}	cm^3

*Parameter value found in literature.

of ϵ is in the range given by previous measurements and calculations [10].

V. CONCLUSION

We have proposed a novel experimental method to determine the value of the nonlinear gain coefficient of semiconductor lasers from the measurement of spontaneous emission power above threshold. This method is very interesting, in the sense that the measurement is made in dc injection conditions while in other methods, it is usually necessary to modulate the carrier density. The measured nonlinear gain coefficient for a multiple quantum-wells laser is 1.2×10^{-17} cm^3, corresponding reasonably to that found with CPR measurement.

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