CW Technique for Measurement of Linewidth Enhancement Factor: Application to 735-nm Tensile-Strained GaAsP Quantum-Well Lasers

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***Abstract*—We present a procedure for determining the linewidth enhancement factor (α parameter) in semiconductor lasers under continuous-wave (CW) operation. It is based on the measurement of the amplified spontaneous emission spectra, with a proper correction of thermal effects. The method is applied to 735-nm tensile strained GaAsP–AlGaAs quantum-well lasers and it is validated by comparing CW results, after correcting thermal effects, with pulsed measurements. The results show a low value of the α parameter attributed to the tensile strain.**

***Index Terms*—GaAsP, linewidth enhancement factor, quantum-well (QW) laser, semiconductor lasers.**

I. INTRODUCTION

THE LINEWIDTH enhancement factor or α parameter [1], [2] relates the variations of the real and imaginary parts of refractive index with the carrier concentration in semiconductor lasers. It is an important parameter for the continuous-wave (CW) and dynamic performance, affecting spectral linewidth, frequency chirping [2], [3], and beam filamentation [4]. The α parameter is usually determined from the amplified spontaneous emission (ASE) spectra [2], with the advantage of providing also the gain and index spectra, although other measurement techniques have been proposed [2], [5]. Most of previous α parameter measurements using ASE spectra were performed under pulsed conditions to avoid thermal effects [3], [6]. Zhao *et al.* [7] proposed a technique based on the correction of thermal effects in CW measurements, taking advantage of a better signal-to-noise ratio than in pulsed conditions. However, their correction procedure does not properly account for the difference between thermal effects below and above threshold, as it is clarified in this work, introducing, hence, a systematic error in the measured α parameter. In a previous work, Stubkjaer *et al.* [8] corrected thermal effects in CW measurements of α parameter, while some years later Bogatov *et al.* [9] proposed an improved correction procedure, although they did not verify its validity.

High-power laser diodes for the spectral region between 710 and 790 nm are becoming of increasing interest due to a range of applications in medicine, e.g., photodynamic therapy, spectroscopy, and solid state laser pumping. Tensile-strained GaAsP quantum well (QW) embedded in AlGaAs laser devices emitting at 735 nm have demonstrated reliable high-power operation up to 2 W [10], together with long-term reliability. However, as far as we know, the value of the α parameter for tensile-strained GaAsP QW lasers emitting has not been previously characterized.

In this letter, we propose a procedure to correct thermal effects in CW measurements of the modal index change and α parameter from ASE spectra. The method is applied to 735-nm GaAsP–AlGaAs QW lasers.

II. MEASUREMENT TECHNIQUE AND CORRECTION PROCEDURE

The α parameter is calculated from the modal index and gain variations with current, making use of [3]

$$\alpha = -\frac{4\pi}{\lambda}\frac{\delta\tilde{n}}{\delta g} = -\frac{4\pi}{\lambda}\frac{\frac{\delta\tilde{n}}{\delta I}}{\frac{\delta g}{\delta I}} \tag{1}$$

where λ is the wavelength, $\tilde{n}$ the modal index, g the modal gain, and I the injected current. The gain and index changes in (1) should be caused by changes in the carrier density and not by temperature variations.

Gain can be extracted from ASE spectra using different procedures [11]–[13]. Index change can be extracted from the wavelength shift of the Fabry–Pérot peaks when changing the injected current $\delta\tilde{n} = (\tilde{n}/\lambda)\delta\lambda$, where $\tilde{n}$ is determined experimentally from the fringe separation. However, in CW operation, the as-measured modal index change $\delta\tilde{n}_M$ consists of the addition of variations caused by carriers $\delta\tilde{n}_N$ and by temperature change $\delta\tilde{n}_T$; therefore

$$\frac{\delta\tilde{n}_M}{\delta I} = \frac{\delta\tilde{n}_N}{\delta I} + \frac{\delta\tilde{n}_T}{\delta I} = \frac{\partial\tilde{n}}{\partial N}\frac{\delta N}{\delta I} + \frac{\partial\tilde{n}}{\partial T}\frac{\delta T}{\delta I} \tag{2}$$

where N is the carrier density and T is the active region temperature. Temperature variations can be estimated from the dissipated electrical power W_{dis} and the thermal resistance R_T

$$\delta T = R_T \delta W_{\mathrm{dis}}. \tag{3}$$

The dissipated electrical power is given by

$$W_{\mathrm{dis}} = \begin{cases} VI, & I \le I_{\mathrm{Th}} \\ VI - P_{\mathrm{opt}}, & I > I_{\mathrm{Th}} \end{cases} \tag{4}$$

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where V is the applied voltage and P_{opt} is output optical power. Using (2) and (3), the modal index change due to carrier variations can be expressed as a function of the measured index change, the dissipated power, and the index variation due to thermal effects

$$\frac{\delta\tilde{n}_N}{\delta I} = \frac{\delta\tilde{n}_M}{\delta I} - \frac{\partial\tilde{n}}{\partial T}R_T\frac{\delta W_{\text{dis}}}{\delta I} = \frac{\delta\tilde{n}_M}{\delta I} - \frac{\partial\tilde{n}}{\partial W_{\text{dis}}}\frac{\delta W_{\text{dis}}}{\delta I} \quad (5)$$

where $\partial\tilde{n}/\partial W_{\text{dis}} = R_T\,\partial\tilde{n}/\partial T$. In the method proposed here, we measure in CW operation the output spectra as a function of the bias current both below and above threshold, together with the optical power–current–voltage (P–I–V) characteristic. Then we proceed in the following steps. 1) Gain is extracted from the ASE fringes as a function of wavelength and current using any of the previously cited methods. 2) $\partial\tilde{n}/\partial W_{\text{dis}}$ is determined from the above threshold wavelength shift of the Fabry–Pérot peaks and the measured P–I–V characteristic making use of (4) and (5). Since $\delta\tilde{n}_N/\delta I$ is negligible above threshold due to carrier clamping, the measured $\delta\tilde{n}_M/\delta I$ in (5) is only caused by thermal effects. 3) the below threshold index change $\delta\tilde{n}_N$ is calculated using expression (5) from the as-measured index change, the calculated $\partial\tilde{n}/\partial W_{\text{dis}}$, and the dissipated electrical power. 4) The α parameter is calculated from $\delta g/\delta I$ and $\delta\tilde{n}_N/\delta I$ using (1).

Our procedure is similar to that proposed by Zhao *et al.* [7] but with an important difference: They calculated $\delta\tilde{n}_N/\delta I$ using (2) to correct for thermal effects, but they considered an identical value for $\delta\tilde{n}_T/\delta I$ above and below threshold, neglecting the important fraction of the injected power transformed into optical power and not contributing to device heating. The junction heating below threshold was underestimated and consequently also the modal index change and the α parameter. The CW method proposed by Bogatov *et al.* [9] corrects thermal effects by assuming a constant applied voltage, introducing a systematic error specially relevant in the case of laser structures with high series resistance.

III. Experimental

The α parameter of GaAsP–AlGaAs laser structures emitting near 735 nm was determined using the above described CW method. The laser structure has been described with detail in [10], and only main features are repeated here. The active region consists of a 9-nm-thick GaAsP QW embedded in AlGaAs waveguide and cladding layers. Ridge waveguide structured devices mounted p-side up were used for the measurements. The cavity length and ridge width were 1000 and 3 μm, respectively, and the facets were uncoated. Measurements were performed at 25 °C. Pulsed measurements (400 ns, 1%) were also performed for validation purposes, using a 8112A Hewlett-Packard pulse generator as pulse source and a current probe to determine the pulse amplitude.

The experimental configuration consists of a 0.75-m grating monochromator with a charged-coupled device camera for detection (used in CW and pulsed measurements). A two lenses optical system was used to collimate and focus the beam onto the monochromator slit, and a polarizer selected the transverse-magnetic component of the ASE spectra.

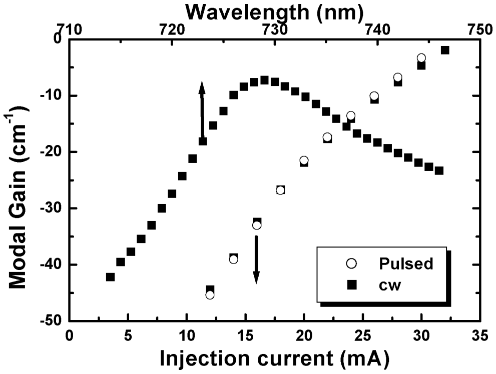

Fig. 1. Peak modal gain in CW and pulsed conditions versus current at 728 nm, and gain spectra at $I = 28$ mA in CW operation at $T = 25$ °C.

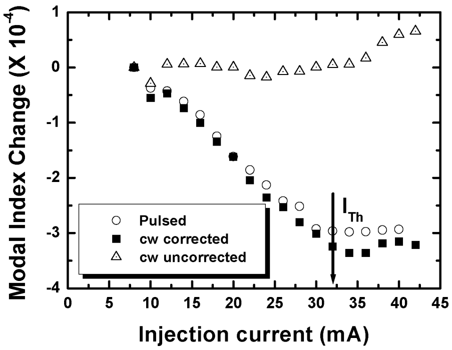

Fig. 2. Modal index change at 728 nm versus current in pulsed operation and CW at $T = 25$ °C before and after correcting thermal effects.

Gain spectra were extracted from the measured ASE using the Hakki–Paoli method [11] after correcting for the limited monochromator spectral resolution by means of an iterative procedure described in [14]. The wavelength shift of the Fabry–Pérot peaks was accurately determined by fitting each experimental ASE peak to a Lorentzian curve [14] and averaging the shifts of around 15 consecutive peaks (1 nm) to reduce random errors.

IV. Results and Discussion

Fig. 1 compares the measured gain in CW and pulsed conditions at a wavelength close to the gain maximum (728 nm), together with an example of the measured gain spectra. The measured maximum gain at threshold is close to 0 cm^{-1}, indicating a good correction of the monochromator spectral resolution. No important differences between CW and pulsed conditions are appreciated in the gain, indicating that the CW device heating is not affecting the modal gain.

Fig. 2 compares the modal index change measured in pulsed conditions with CW results after correcting thermal effects with the previously described procedure. Very good agreement can be observed. The uncorrected modal index change is also shown in Fig. 2 to illustrate the importance of the thermal component (positive index change), which is compensating the carrier-induced component (negative index change). The value of the modal effective index $\tilde{n}$ was around 3.9, showing slight variations with the injected current and wavelength.

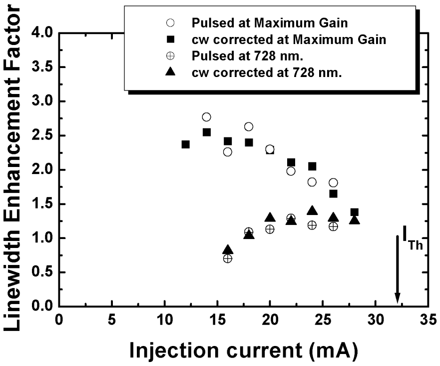

Fig. 3. Linewidth enhancement factor at 728 nm, and at the wavelength of maximum gain, measured in CW and under pulsed operation at $T = 25$ °C.

The resulting value of the α parameter at the gain maximum and at the lasing wavelength of the particular device under study (728 nm) is shown in Fig. 3, as a function of the injected current, in pulsed and CW conditions. Good agreement is observed in both cases, validating the correction procedure. The α parameter at the gain maximum decreases with the injection level, whereas, it increases at constant wavelength. The former is due to the stronger reduction of differential index compared to that of differential gain at the gain maximum, whereas, the latter is mainly caused by gain saturation at constant wavelength.

The low values of the α parameter at the gain maximum (between 1.5 and 2.5) are attributed to the tensile strain in the QW, as it has been previously reported both theoretically [15], [16] and experimentally [17] in 1550-nm InGaAs–InGaAsP QWs. These low values are consistent with the reduced tendency to filamentation observed in high-power lasers fabricated in this material system [10].

V. CONCLUSION

We have proposed a procedure for determining the modal index change and linewidth enhancement factor of semiconductor lasers by measuring in CW conditions and properly correcting thermal effects, with the advantage of an increased measurement range than in pulsed conditions. The procedure has been applied to tensile strained GaAsP QW lasers emitting near 735 nm. These devices show a low value of the α parameter at the gain maximum, attributed to the tensile strain, which makes them a suitable candidate for high-power applications.

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