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Citation: Applied Physics Letters **80**, 1 (2002); doi: 10.1063/1.1428774
View online: http://dx.doi.org/10.1063/1.1428774
View Table of Contents: http://scitation.aip.org/content/aip/journal/apl/80/1?ver=pdfcov
Published by the AIP Publishing

APPLIED PHYSICS LETTERS VOLUME 80, NUMBER 1 7 JANUARY 2002

# Measurement of true spontaneous emission spectra from the facet of diode laser structures

G. M. Lewis, P. M. Smowton, J. D. Thomson, H. D. Summers, and P. Blood[a)]
*Department of Physics and Astronomy, Cardiff University, P. O. Box 913, Cardiff, CF24 3YB, United Kingdom*

(Received 23 July 2001; accepted for publication 17 October 2001)

Measurement of the spontaneous emission and gain spectra provides a complete characterization of a semiconductor gain medium, however, this requires the observation of emission in two directions to avoid amplification of the spontaneous emission spectrum. We show that both the gain spectrum and the true spontaneous emission spectrum can be obtained from amplified spontaneous emission (ASE) spectra measured from the end of a segmented-contact device. The spontaneous emission spectra agree with spectra measured through a top contact window. If the carrier populations are fully inverted at low photon energy, it is possible to convert the ASE-derived spontaneous emission into real units. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1428774]

The true, unamplified spontaneous emission spectrum emitted under high injection conditions has long been used to gain insight into the behavior of semiconductor laser structures.[1–3] This spectrum reveals the energy distribution of injected carriers and the area under the spectrum provides a measure of the intrinsic radiative current. To determine the spontaneous emission spectrum directly, a geometry must be used which avoids amplification or absorption of the emission by observation through a top-contact window,[2] through the substrate (if transparent to the emission), or through the side of a narrow buried heterostructure or mesa device.[1] If it is justified to assume that at high injection the carriers take up thermal Fermi–Dirac energy distributions, and if the quasi Fermi level separation can be measured, then it is possible to transform the emission spectrum to a gain spectrum and determine the intrinsic gain-current relation.[1,2] However, this process is critically dependent upon the accuracy of the Fermi level measurement and the transformation may be modified by broadening processes.[4] It is often preferred to measure optical gain by more direct methods based on analysis of the amplified spontaneous emission (ASE) emerging from the end of the device, for example by measurement of the amplitude of the longitudinal modes[5] or by a single-pass stripe length method.[6,7] A complete characterization of the semiconductor gain medium therefore requires a combination of techniques for measurement of spontaneous emission and for measurement of optical gain. This has been done using end and window emission spectra[8] or by fabricating a segmented contact structure for a single-pass gain measurement with a window in the top-contact stripe for observation of spontaneous emission.[9]

These approaches require the fabrication of a complex structure[9] and observation of emission from the device in two different directions.[8,9] Furthermore, the gain and spontaneous emission spectra are obtained from observations of different regions of the sample. In this letter, we show that the gain and true spontaneous emission spectrum can be obtained by analysis of single-pass ASE spectra measured from the facet of a segmented-contact device for two stripe lengths. We confirm the validity of the process by a comparison of the derived spontaneous emission spectrum with that observed through a top-contact window. We show that the derived spontaneous emission can be expressed in real units if the carrier populations are fully inverted at low photon energy.

The experiments were carried out on a 50 $\mu$m-wide, stripe-geometry laser structure consisting of a 68 Å wide compressively strained $Ga_{0.41}In_{0.59}P$ quantum well within an $(Al_{0.5}Ga_{0.5})_{0.51}In_{0.49}P$ waveguide core and $(Al_{0.7}Ga_{0.3})_{0.51}In_{0.49}P$ cladding. A 10° angled facet was provided by misorientation from the (100) axis towards the (111A) direction of the substrate which, together with a 900 $\mu$m-long passive section at the rear of the device, inhibited round-trip amplification. Two electrically isolated contact segments were produced by etching through the top gold contact and the GaAs capping layer so that ASE could be measured from the end of the device from active lengths of 300 $\mu$m ($L$) and 600 $\mu$m ($2L$) as shown in Fig. 1. A 4 $\mu$m×4 $\mu$m window was etched in the top contact of each

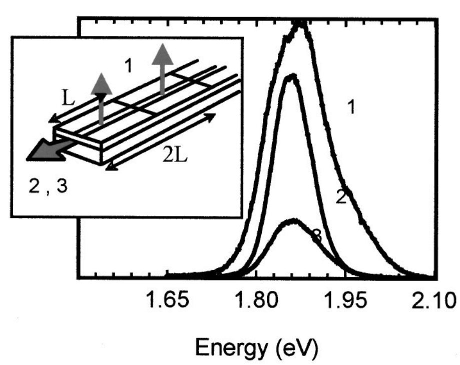


FIG. 1. Inset illustrates the segmented contact device with a window in the top contact for direct observation of the unamplified spontaneous emission spectrum. Spectra are shown for (1) the true spontaneous emission observed through the window, and amplified spontaneous emission spectra observed from the facet for lengths $2L$ (2) and $L$ (3). Spectra (2) and (3) are in the same arbitrary units, but are not on the same scale as (1). All spectra were measured at the same current density.

a)Electronic mail: bloodp@cf.ac.uk



 

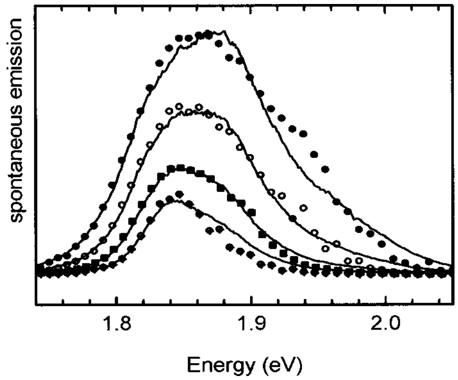


FIG. 2. Comparison of the true spontaneous emission measured through the top window (lines) and the spontaneous emission spectrum obtained from the ASE spectrum (symbols) on a linear scale. To facilitate the comparison, the scale for the spontaneous emission derived from the ASE has been chosen such that its peak value matches that of the window emission.

segment for measurement of the true spontaneous emission spectrum. Measurements were done at room temperature and low duty cycle of 0.03%.

The ASE intensity $I(l)$ from the end of a pumped stripe of length $l$ originating from point-source spontaneous emission spectra $I_{\mathrm{spon}}$ distributed uniformly along the stripe is[7]

$$I(l)=\frac{I_{\mathrm{spon}}\{\exp[(G-\alpha_i)l]-1\}}{G-\alpha_i}, \tag{1}$$

where $(G-\alpha_i)$ is the net modal gain. Equation (1) can be fitted to data for $I(l)$ for a range of pumped lengths,[10] however it is possible to extract $I_{\mathrm{spon}}$ and $G$ from measurements on only two lengths using simple expressions. If the contact segments are of equal length and we denote the ASE from the two stripe lengths $l=L$ and $l=2L$ as $I=I_L$ and $I=I_{2L}$, respectively, then we can derive the net modal gain as[7]

$$G-\alpha_i=\frac{1}{L}\ln\left[\frac{I_{2L}}{I_L}-1\right], \tag{2}$$

and the true spontaneous emission spectrum as

$$I_{\mathrm{spon}}=\frac{1}{L}\ln\left[\frac{I_{2L}}{I_L}-1\right]\frac{I_L^2}{(I_{2L}-2I_L)}. \tag{3}$$

In this analysis, $I_{\mathrm{spon}}$ is that part of the spontaneous emission which is coupled into the modes for which the ASE is observed from the facet and formally it has units of rate per unit energy interval per unit width observed emitted into a given mode. The gain is obtained in absolute units (number per unit length) whereas the *measured* spontaneous emission [Eq. (3)] is in the arbitrary units of $I_L$, $I_{2L}$ divided by length. Equations (2) and (3) show that the gain and spontaneous emission spectra can both be obtained from measurements of the end emission for two stripe lengths $I_L$ and $I_{2L}$.

The spectra in Fig. 1 show examples of the primary observations. The true spontaneous emission spectrum (curve "1") was measured through the top window and ASE spectra for the two pumped lengths ("2" $I_{2L}$ and "3" $I_L$) were measured from the end facet, for the same injection current for transverse electric (TE) polarization corresponding to the window emission. The true spontaneous emission spectra, $I_{\mathrm{spon}}$ were obtained from pairs of ASE spectra using Eq. (3), and in Fig. 2 the results (dots) are compared with measurements through a single top-contact window (lines) for a range of drive currents. Both sets of spectra are in different arbitrary units and the scale for the spontaneous emission derived from the ASE has been chosen such that its peak value matches that of the window emission to facilitate comparison. Agreement is generally good confirming the use of Eq. (3) to obtain the spontaneous emission spectrum from the ASE emitted from the end of the device.

The ratio of the local gain, $g$, to the TE polarized emission rate, $R_{\mathrm{spon}}$ (in real units), at any photon energy, $E_{h\nu}$, can be written[9]

$$\left(\frac{g}{R_{\mathrm{spon}}}\right)=\frac{3\pi^2\hbar^3c^2}{2n^2E_{h\nu}^2}P_F \tag{4}$$

The inversion factor $P_F$ depends solely on the occupation probabilities for the initial and final states of the transition, $f_i$ and $f_f$, respectively,

$$P_F=\frac{f_i-f_f}{f_i(1-f_f)}. \tag{5}$$

The occupation probabilities in Eq. (5) are not predetermined, however, for the particular case of Fermi–Dirac distributions, Eq. (5) becomes[9]

$$P_F=\left[1-\exp\left(\frac{E_{h\nu}-\Delta E_f}{kT}\right)\right], \tag{6}$$

where $\Delta E_f$ is the Fermi level separation.

Using data for $G$ obtained from ASE data by Eq. (2), we obtained the modal loss $\alpha_i$ from the asymptotic value of net gain at low photon energy[7] giving $\alpha_i=10\pm 2\ \mathrm{cm}^{-1}$. Using data for $I_{\mathrm{spon}}$ obtained from ASE data via Eq. (3), we calculated values for $P_F$ from the ratio of measured $G$ and $I_{\mathrm{spon}}$

$$P_F=\frac{1}{C}\frac{1}{\Gamma}\left(\frac{2E_{h\nu}^2n^2}{3\pi^2\hbar^3c^2}\right)\left[\frac{G}{I_{\mathrm{spon}}}\right]. \tag{7}$$

The modal gain measured experimentally is related to the local gain in Eq. (4) by the relation $G=\Gamma g$ where $\Gamma$ is the optical confinement factor which was calculated for the structure. $C$ is a scaling factor which takes account of the arbitrary units of $I_{\mathrm{spon}}$ and the coupling into the guided mode

$$R_{\mathrm{spon}}=CI_{\mathrm{spon}}, \tag{8}$$

and was chosen such that the experimental data for $P_F$ is unity at low photon energy corresponding to complete inversion of the population ($f_i=1$ and $f_f=0$). The results in Fig. 3 show that the form of the experimental data for $P_F$ corresponds to that predicted for thermal Fermi–Dirac distributions (lines). The quasi-Fermi level separation used in the calculation of $P_F$ was determined for each of the gain curves as the photon energy at the transparency point. The scatter at low photon energy arises from scatter in the data for net gain which is derived from the ratio of low-level light signals [Eq. (2)]. The experimental data used in Fig. 3 has been derived entirely from end-emitted spectra. Once the factor $C$ is known it can be used to convert the spontaneous emission spectra obtained from the end emission into real units.

Using this factor, the area under the spectrum in Fig. 2 for the highest current gives a TE spontaneous emission current of 510 $\mathrm{A\,cm}^{-2}$. Verified calculations[10,11] show that at this gain the transverse magnetic (TM) current is 0.27 of the

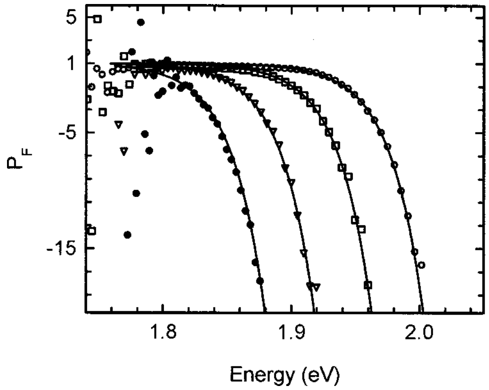


FIG. 3. Inversion function $P_F$ obtained from the ratio of $G$ and $I_{spon}$ determined from experimental ASE spectra (symbols). The scaling factor $C$ was chosen such that $P_F$ is unity at low photon energy. The lines show values of $P_F$ calculated for a Fermi–Dirac distribution.

TE current for this structure so the total radiative current is 650 A cm$^{-2}$. The drive current density is 1875 A cm$^{-2}$, derived for a pumped width of 80 $\mu$m due to current spreading, obtained by observation of the facet. This implies an overall quantum efficiency, due to non-radiative recombination and carrier leakage, of 35%.

As explained, $C$ has been determined assuming that the carrier distributions are fully inverted at low photon energies [Eq. (5)], however this does not require that the distributions are thermal at all energies. The fact that the experimental data for $P_F$ is constant at low energy is a good indication that full inversion has been achieved, irrespective of the form of $P_F$ at higher energies. It is also possible to determine the scaling factor by converting the spontaneous emission to gain using the thermodynamic relationship then adjusting $C$ to obtain agreement with the gain measured directly,[1,2] however, this requires that the distributions are thermal at all energies across the spectrum.

We have shown that it is possible to obtain both the gain spectrum and the true spontaneous emission spectrum from single-pass measurements of ASE spectra measured from the end of a segmented-contact device. The spontaneous emission spectra agree with spectra measured through a top-contact window. These data derived from the ASE spectra can be used to study the energy distributions of the carriers and if the carrier populations are fully inverted at low photon energy it is possible to convert the measured spontaneous emission spectra into real units. In effect, the method corrects for the amplification of the spontaneous emission which occurs as the light travels along the waveguide. The emission and gain are measured from the same volume of the device and the device processing is much simpler. We note also that the method described can also be used to determine the spontaneous emission spectrum for TM polarized light by observation of TM ASE spectra.

The authors thank Scott Corzine for stimulating discussion on this topic. One of the authors (G.M.L.) acknowledges the financial support of the UK EPSRC for a CASE award in conjunction with IQE plc.

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