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# Measurement of Carrier Lifetime and Linewidth Enhancement Factor for 1.5- $\mu\text{m}$ Ridge-Waveguide Laser Amplifier

N. Storkfelt, B. Mikkelsen, D. S. Olesen, M. Yamaguchi, and K. E. Stubkjaer

**Abstract**—Semiconductor optical amplifiers are used for investigation of the effective carrier lifetime and the linewidth enhancement factor. Contrary to semiconductor lasers semiconductor optical amplifiers allow measurement at high levels of injected carrier density. The carrier lifetime and the linewidth enhancement factor are measured with a simple dynamic self-heterodyne method. Carrier lifetimes of 750 ps at the threshold current for the SOA without antireflection coating and 200 ps at high injection have been found. The linewidth enhancement factor is measured to be between 4 and 17 which fits with a simple empirical expression.

## INTRODUCTION

THE EFFECTIVE carrier lifetime  $\tau_e$  and the linewidth enhancement factor  $\alpha$  are two important key parameters for semiconductor lasers and semiconductor optical amplifiers (SOA) as reported in many publications, e.g., [1]–[3]. Several measurement techniques have been proposed [4]–[6]. Here we present a method for measuring the  $\alpha$  factor and the carrier lifetime by use of a SOA. The measurements are based on a small-signal modulation of the SOA and has the advantage of being simple and since it is a dynamic measurement technique thermal effects are reduced. Furthermore, the use of traveling-wave amplifiers allows measurement of the two parameters under high carrier injection contrary to measurements on semiconductor lasers for which the carrier density is clamped at low levels.

## $\alpha$ FACTOR

The measurements of the  $\alpha$  factor are based on a small-signal modulation of the carrier density of the amplifier obtained by modulation of the bias current. Since the gain and the refractive index is dependent on the carrier density, a modulation of the carrier density will generate amplitude-

modulation (AM) and frequency-modulation (FM) of a given amplified signal. As will be shown below, the ratio between the FM and AM indices determines the  $\alpha$ -factor.

From a small-signal analysis, which is based on a traveling-wave model similar to the one proposed by Adams *et al.* [7] but with a more detailed recombination model [8], the modulation amplitude  $\delta N$  of the carrier density for a given amplitude  $\delta I$  of the modulation current is given by [3]

$$\delta N = \frac{\delta I}{eV} \frac{\tau_e}{\sqrt{1 + (\omega_m \tau_e)^2}} \quad (1)$$

where  $e$  is the electron charge,  $V$  is the volume of the active region,  $\omega_m$  is the modulation angular frequency, and  $\tau_e$  is the effective carrier lifetime which will be accurately defined in the following section.

As mentioned above the carrier density modulation generates AM and FM. From the small-signal analysis it can be shown that the AM-index  $m$  is given by:  $m = \frac{1}{2} L \Gamma \frac{dg}{dN} \cdot \delta N$

and the FM-index  $\beta$  by:  $\beta = \frac{\omega}{c} L \Gamma \frac{dn}{dN} \cdot \delta N$ .  $\Gamma$  is the optical confinement factor,  $c$  is the light velocity in vacuum, and  $L$  is the length of the active region. The  $\alpha$  factor is then directly calculated from the ratio of the measured indexes [6]:

$$\alpha = -2k \frac{dn/dN}{dg/dN} = -2 \frac{\omega}{c} \frac{dn/dN}{dg/dN} = -\frac{\beta}{m} \quad (2)$$

When the effective carrier lifetime is known it is also possible to derive  $dg/dN$  and  $dn/dN$  from the measured AM- and FM-indexes.

The setup for measuring the  $\alpha$  factor is identical with that in Fig. 1 without laser no. 2. An external cavity laser is used as a signal source and a part of the signal is amplitude- and frequency-modulated by the amplifier. The modulated output signal from the amplifier is then detected with a selfheterodyne technique which uses the frequency-shifted signal from the acoustooptic modulator as reference signal. In order to reduce the influence of the amplified spontaneous emission on the AM index the amplified signal passes through a grating filter. A lightwave analyzer displays the selfheterodyned beat spectrum from which the AM- and FM-indexes are deter-

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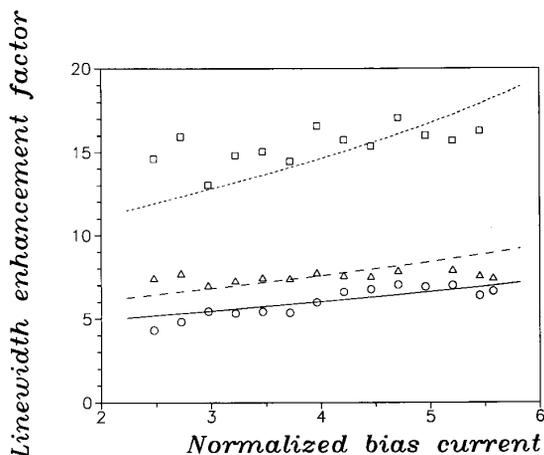


Fig. 2. Linewidth enhancement factor versus normalized bias current for wavelengths  $\lambda = 1500$  nm ( $\circ$ ),  $1510$  nm ( $\Delta$ ) and  $1530$  nm ( $\square$ ). Solid and dashed curves are calculated assuming  $dn/dN$  to be constant with bias current and dependent on wavelength.  $dn/dN$  values of  $2.21 \times 10^{-26} \text{ m}^3$ ,  $2.52 \times 10^{-26} \text{ m}^3$ , and  $3.03 \times 10^{-26} \text{ m}^3$  were used at the three wavelengths, respectively.  $dg/dN$  is obtained from (4) with  $g_N = 2.9 \times 10^{-20} \text{ m}^2$ ,  $N_0 = 0.90 \times 10^{24} \text{ m}^{-3}$  and  $\gamma_\lambda = 4.6 \times 10^{18} \text{ m}^{-3}$ .

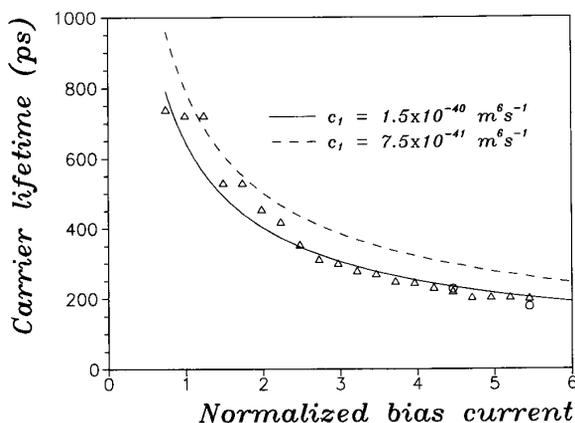


Fig. 3. Effective carrier lifetime versus normalized bias current. The measured results shown are obtained with current modulation ( $\Delta$ ) and with optical modulation ( $\circ$ ). The solid and the dashed curve represents the calculated differential carrier lifetime using our fitted Auger recombination constant and previously reported Auger constant. The other recombination constants are given in the text.

bination constant  $c_1$  is two to three times higher than the usually reported values, e.g., [13], but is lower than the  $3.2 \times 10^{-40} \text{ m}^6 \text{ s}^{-1}$  reported in [14]. Naturally our predicted recombination coefficients are sensitive to measurement uncertainties which in our case are estimated to 10%. Measurement uncertainties of  $\pm 10\%$  can change the Auger constant by  $\pm 0.4 \times 10^{-40} \text{ m}^6 \text{ s}^{-1}$  while the other recombination parameters would be almost constant. To clarify the discrepancies in reported Auger recombination constants further studies will have to be conducted.

#### CONCLUSION

The effective carrier lifetime  $\tau_e$  has been measured as function of bias current using two measurement methods.

The measured  $\tau_e$  is in agreement with a simple model for the recombination rate and values between 200 and 750 ps have been found. The AM- and FM-indexes have been measured with a self-heterodyne technique and used to determine the  $\alpha$  factors. The measured  $\alpha$  factors at a normalized bias of 2.5 and at a wavelength 25 nm below the gain peak are approximately 4 and values as high as 17 has been found at a normalized bias current of 5 and at a wavelength 18 nm above the gain peak. For low injection current, the measured  $\alpha$  factors at the gain peak agree well with previously reported values for semiconductor lasers [10]. In conclusion, characterization of laser amplifiers is a convenient way to determine material parameters.

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