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Wide spectra characteristics of gain and carrier-induced refractive index change from measured amplified spontaneous emission spectra

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Based on our derived analytical equation directly relating small signal gain (SSG) with amplified spontaneous emission (ASE) of traveling-wave semiconductor optical amplifier (TWA), SSG spectra in an extended wavelength range from 1460 to 1660 nm are directly calculated from experimentally measured ASE spectra. Subsequently, carrier-induced refractive index changes for various injection currents are obtained with the same spectral range. We demonstrate the availability of our characterizing method by the determination of wide spectra characteristics from a bulk TWA with angled facets.

Keywords: traveling-wave semiconductor optical amplifier, wide spectra characteristics, small signal gain, carrier-induced refractive index change.

1. Introduction

Wide spectra characteristics of gain and carrier-induced refractive index change are very important parameters affecting the application of traveling-wave semiconductor optical amplifier (TWA) [1, 2]. Small signal gain (SSG) spectra of TWA are usually obtained from the ratio of amplified signal power to the input signal power for one by one wavelength at different injection currents. This conventional measurement method is not only tedious but also restricted by the wavelength range of external laser source. Amplified spontaneous emission (ASE) spectra are good and convenient information sources of these parameters. HAKKI and PAOLI [3] introduced a method, which detects the amplitude of ripple superposed on ASE to deduce the gain of semiconductor laser. CHANG *et al.* [4] further deduced more parameters of semiconductor laser by using Hakki–Paoli method and the Fabry–Perot mode shifts with injection current. In TWA, owing to the significant reduction in facet reflectivity, especially with the usage of a tilted waveguide, very small inexplicit ripple on ASE spectra invalidates the above methods. FU *et al.* [5] proposed a technique in which ASE spectra are used to obtain the gain spectra of semiconductor laser in an extended energy range. But it is not applicable to TWA, as it relies on Hakki–Paoli method to obtain some key parameters: quasi-Fermi level separation, single-pass ASE intensity and gain coefficient.

In this paper, we firstly establish the direct relationship between SSG spectra and the overall shapes of ASE spectra of TWA. Then based on the relationship, we deduce the extended SSG spectra from measured ASE spectra, which are easier to extend in a wider wavelength range. Followed the above result, carrier-induced refractive index changes are calculated with the same spectral range. The applicability of this method is demonstrated by the determination of wide spectra characteristics from a bulk TWA with angled facets.

2. Spectra extension method

A rigorous analysis of the relationship between small signal gain G_s and ASE intensity I_a of TWA is as follows.

To a TWA, facet reflectivity $R = 0$ is assumed. In this case small signal gain G_s is given by [6]

$$G_s = \exp\left(g_{\mathrm{net}} L\right), \tag{1}$$

$$g_{\mathrm{net}} = g_m - \alpha_i = \Gamma g - \alpha_i \tag{2}$$

where g_{net} is the net modal gain coefficient, g_m is the modal gain coefficient, g is the material gain coefficient, Γ is the optical confinement factor, α_i is the intrinsic loss coefficient, L is the cavity length of TWA.

ASE intensity I_a is connected with g_{net} by [7]

$$I_a = \frac{SI_s}{g_{\mathrm{net}}}\left[\exp\left(g_{\mathrm{net}} L\right) - 1\right] \tag{3}$$

where S is the cross-sectional area of the excited volume, I_s is the spontaneous emission intensity per unit volume.

Owing to the fundamental relationship between stimulated and spontaneous emission rates, the modal gain coefficient $g_m = \Gamma g$ can be determined from the spontaneous emission using [8]

$$g_m = C_p \frac{I_s}{E^3}\left[1 - \exp\left(\frac{E - \Delta E_f}{kT}\right)\right] \tag{4}$$

where energy $E = hc/\lambda$ (h is Planck constant, c is the speed of light in free space and λ is the corresponding wavelength), C_p is a fitting constant which accounts for the fact that only relative values of I_s can be determined experimentally, k is the Boltzmann constant, T is the temperature, and ΔE_f is the quasi-Fermi level separation.

By combining Eqs. (1)–(4) and eliminating I_s, the following equation, which is directly relating I_a with G_s, is obtained:

$$\frac{\lambda^3 I_a}{h^3 c^3}\left[1 - \exp\left(\frac{hc - \lambda\Delta E_f}{\lambda kT}\right)\right] = C_k\left[1 + \frac{\alpha_i L}{\ln(G_s)}\right]\left(G_s - 1\right) \tag{5}$$

where $C_k = S/C_p$.

Equation (5) is the key for realizing spectra extension, which to the best of our knowledge has never been derived previously for TWA. In the right hand side of Eq. (5), G_s can be taken as a known function of λ within a relatively narrow wavelength range, which has been directly measured. On the left hand side of Eq. (5), I_a can be directly measured in a wider wavelength range than that of G_s. ΔE_f depends upon the junction voltage. An estimate of this voltage can be obtained from the applied voltage of measured device by subtracting the series voltage drop [9]. The series resistance is obtained from the slope of the current-voltage curve. The parameters C_k and intrinsic loss coefficient-length product $\alpha_i L$ can be obtained by a curve fitting method developed by Fu *et al.* [5] in a relatively narrow wavelength range. In the curve fitting procedure, ΔE_f can also be recalibrated to obtain more precise values. Based on the known parameters, we can numerically calculate G_s through I_a in an extended wavelength range as wide as measured ASE spectra. After obtaining the G_s over a wide wavelength range, carrier-induced refractive index changes are deduced with the same spectral range.

3. Experiment results

The device under test is an Opto Speed 1550CRI TWA, which is a bulk InGaAsP/InP structure grown by metal organic chemical vapor deposition (MOCVD). The device has low polarization dependence and low ripple. The 3 dB saturation output power is 6 dBm. Low ripple is obtained by tilting the amplifier optical waveguide by 12° in respect to the amplifier facets and by application of double layer dielectric anti-reflection coatings. The thermal effects which would have resulted in a red shift of the bandgap energy have been removed by using a Peltier element and a 10 kΩ thermistor for device temperature stabilization at 20°C. The ASE spectra I_a taken from one facet of the TWA were recorded by an Agilent 86140B optical spectrum analyzer. The detected ASE spectra over a wide wavelength range of 200 nm at different injection currents are shown in Fig. 1, from which we can see that ASE peaks clearly shift toward shorter wavelengths with an increase in injection currents. This is due to the band-filling effect induced by the increase in injection carrier density.

In order to obtain a wide spectrum continuous wave signal source, an EXFO FLS-2600B tunable laser source was used together with a velocity tunable diode laser.

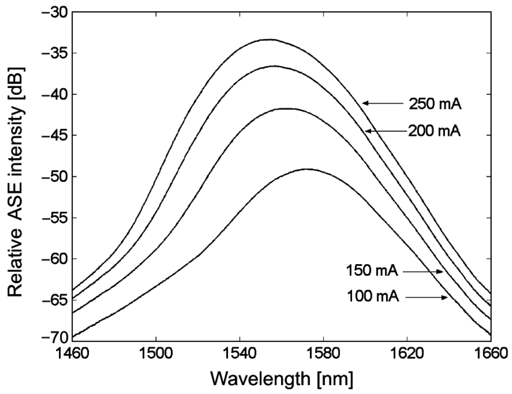

Fig. 1. Detected ASE spectra. From highest to lowest, the bias currents are: 250, 200, 150, and 100 mA.

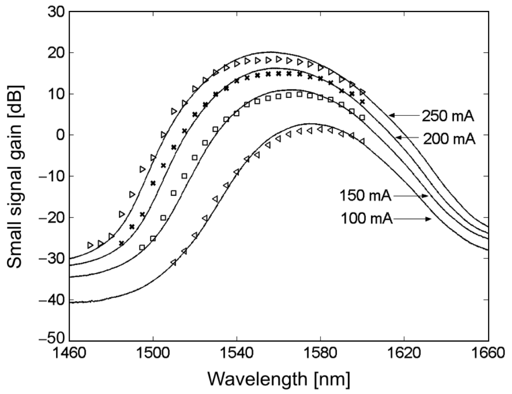

Fig. 2. Comparison between the directly measured SSG values (symbols) and the extended SSG spectra (solid lines) calculated from measured ASE spectra. From highest to lowest, the bias currents (ΔE_f) are 250 mA (0.8441 eV), 200 mA (0.8378 eV), 150 mA (0.8312 eV) and 100 mA (0.8226 eV).

The input signal power was set at –25 dBm, which means that the signal gains were measured under the unsaturated condition. The directly measured SSG values at different injection currents are shown in Fig. 2 (symbols). The ASE spectra in Fig. 1 were used to deduce extended SSG spectra by utilizing the above spectra extension method. The extended SSG spectra over a wavelength range of 200 nm at different injection currents are also shown in Fig. 2 (solid lines). As a whole, the SSG curves calculated from measured ASE spectra coincide with the directly measured SSG values very well.

Through Eq. (1), the product $g_{\text{net}}L$ spectra were deduced from spectra G_s, as is shown in Fig. 3. We choose $g_{\text{net}}L$ curve at 100 mA as a reference and subtract it from all subsequent ones. From the differences $g_{\text{net}}L$ at different injection currents, the

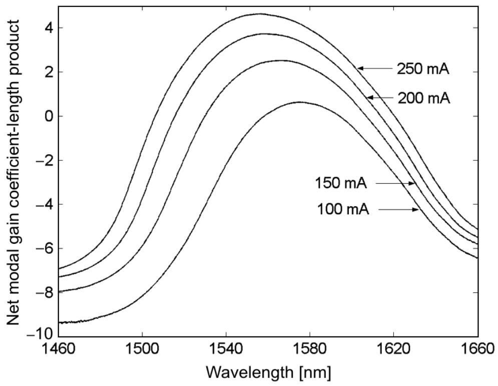

Fig. 3. Net modal gain coefficient-length product. From highest to lowest, the bias currents are: 250, 200, 150, and 100 mA.

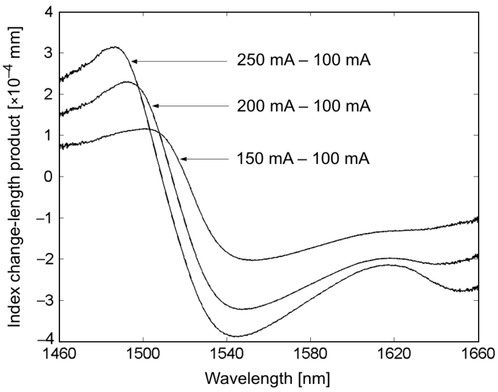

Fig. 4. Refractive index change-length product. The obvious undulations on both ends of wavelength range are not due to the residual Fabry–Perot effects, but are originated from the calculation accumulation of the noise on ASE spectra due to the limited sensitivity of optical spectrum analyzer.

carrier-induced refractive index change-length products ΔnL resulting from injection above 100 mA are computed using Kramers–Kronig transformation [10]

$$\Delta nL(E) = -\frac{\hbar c}{\pi} P \int_0^{\infty} \frac{\Delta g_{\mathrm{net}} L(E') - \Delta g_{\mathrm{net}} L(E)}{E'^2 - E^2} \mathrm{d}E' \tag{6}$$

where P indicates taking the principle value of the integral, $\hbar$ is reduced Planck constant and c is the speed of light. The numerical results of ΔnL spectra are shown in Fig. 4. As expected, the ΔnL increases with increasing injection currents for short wavelength side, and decreases for long wavelength side under the same conditions [11].

4. Conclusions

Analytical equation directly relating SSG with ASE of TWA has been presented. Based on the relationship, we have used a bulk TWA with angled facets to demonstrate our characterizing method, which is used to directly obtain the wide spectra characteristics of TWA. The SSG spectra in an extended wavelength range of 200 nm have been obtained from measured ASE spectra. Furthermore, carrier-induced refractive index changes have been deduced with the same spectral range.

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