OPTOELECTRONICS LETTERS Vol. 1 No. 1, 15 July 2005

Characteristics measurement of gain and refractive index of traveling-wave semiconductor optical amplifier*

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(Received 6 June 2005)

A novel method to measure the gain and refractive index characteristics of traveling-wave semiconductor optical amplifier(TMA) is presented. In-out fiber ends of TWA are used to construct an external cavity resonator to produce big ripple on amplified spontaneous emission(ASE) spectrum. By this means, Hakki-Paoli method is adopted to obtain the gain spectra of TWA over a wide spectral range. From measured longitudinal mode spacing and peak wavelength shift due to increased bias current, we further calculate the effective refractive index and the refractive index change. Special feature of refractive index change above lasing threshold is revealed and explained.

CLC number: TN248.1 **Document code:** A **Article ID:** 1673-1095(2005)01-0046-03

Traveling-wave semiconductor optical amplifier (TWA) is a rather attractive device in future optical transmission and switching systems. It is particularly in the latter field[1], which is the way for achieving all-optical networks. Some of the important parameters affecting the performance of TWA include gain and refractive index etc. Amplified spontaneous emission (ASE) spectra are good information sources to extract these parameters. Hakki-Paoli[2] introduced a method, which detects the amplitude of ripple superposed on ASE to deduce gain of semiconductor laser. In TWA, owing to the significant reduction in facet reflectivity and especially the usage with a tilted waveguide, very small inexplicit ripple on ASE spectra invalidates the Hakki-Paoli method.

In this letter we present a novel method, by which Hakki-Paoli method can still be used to characterize TWA. The method is realized by the external cavity resonator constructed by in-out tapered fiber ends of TWA. By this technique, over a wide wavelength range, gain spectra are obtained by Hakki-Paoli method. The refractive index profile and the refractive index change with increased bias current are measured from the longitudinal mode spacing and peak wavelength shifts in ASE spectrum. Remarkable characteristic in the change of refractive index above lasing threshold is revealed and explained. The applicability of the method is demonstrated by the determination of the performance characteristics of a TWA with tensile-strained-barrier multiple-quantum-well active layer.

A TWA sample, which is fabricated with MOCVD epitaxy equipment, has been used in the measurement. Its active layer is composed of the matched quantum wells and the tensile strained quantum barriers based on quaternary material $In_{1-x}Ga_xAs_{1-y}P_y$. Its length is 500 μm, the width is 2.0 μm, and the height is 0.09 μm. This device is of low polarization dependence. Owing to antireflection coating, its facet reflectivity is on the order of 10^{-4}. A temperature controller makes the device temperature stabilize at 20 ℃.

Light is coupled to and from the TWA by use of tapered single mode optical fibers. In the experiment, antireflection (AR) coating is not used to the ends of the optical fibers. So the fiber ends cause big reflection, whose reflectivity is on the order of 10^{-2}. Then the tapered ends of in-out fibers construct an external cavity resonator as shown in Fig. 1, resulting in big ripple on ASE spectrum, by which Hakki-Paoli method can be used to characterize TWA. The Fabry-Perot resonance caused by TWA facets can be ignored, because facet reflectivity is small enough compared with that of tapered fiber ends. The distance between fiber end and facet of TWA is very small compared with the length of the TWA, so we can regard the cavity length of TWA as the length of external resonator constructed by in-out tapered fiber ends. When the location between the fiber end and the TWA facet on both sides is fixed and the reflectivity of the fiber end has been accurately measured, the effective reflectivity of external cavity resonator can be obtained. Then the Hakki-Paoli method can be used to characterize TWA.

The ASE spectra I_a taken from one facet of the TWA through tapered fiber are recorded by an Agilent 86140B optical spectrum analyzer. The detected ASE spectra over a wide wavelength range at different injection currents are shown in Fig. 2. Because of the resonance caused by fiber ends, TWA is at lasing state when injec-

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* Supported by Chinese "973" Project foundation under Grant No. G2000036605 and the Science and Technology Foundation of Wuhan City, China.

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tion current is great than 93 mA. ASE maximal peak clearly shifts toward shorter wavelength (blue-shift) with an increase in injection currents up to 90 mA. But when injection current changes from 90 mA to 110 mA, ASE maximal peak has a slight shift toward longer wavelength (red-shift).

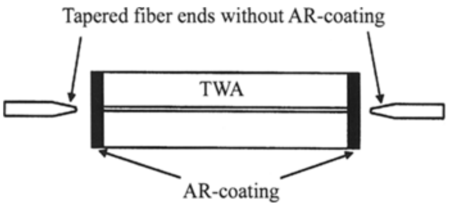

Fig. 1 Schematic illustration of the external cavity resonator constructed by the tapered ends of in-out fibers

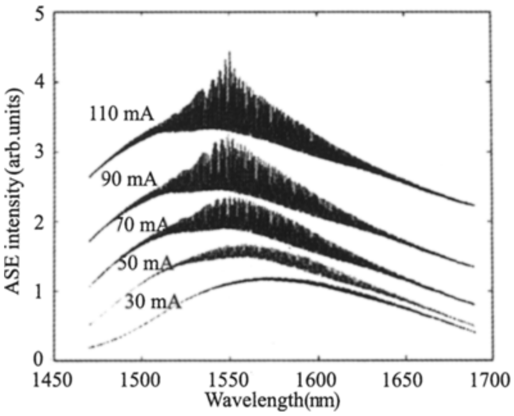

Fig. 2 Measured ASE spectra for five bias current levels. The ASE spectra are displaced to ease viewing

A small portion of the ASE spectra in Fig. 2 at injection currents of 50 mA and 70 mA is enlarged in Fig. 3, which exhibits an increase of ripple amplitude as well as the shift of peak wavelengths with an increase of injection currents. This phenomenon is just what we will use in following calculations.

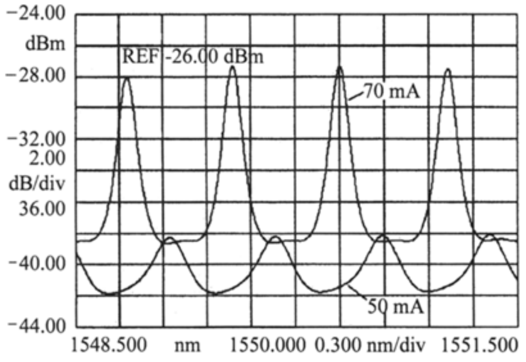

Fig. 3 An expanded region of Fig. 2 at two currents, $I=50$ mA and 70 mA, showing an increase of ripple amplitude and the shift of peak wavelengths in the presence of a larger injection current

The optical gain spectra, plotted in Fig. 4, are calculated from ASE spectra based on the Hakki-Paoli method[2]. We first eliminate the influence caused by the overall shape of ASE spectrum by averaging each two consecutive peaks intensities $(I_i^+ + I_{i+1}^+)/2$, then divide by the intermediate valley intensity I_i^-, thereby obtain the depth of modulation in the following form:

$$r_i = \frac{I_i^+ + I_{i+1}^+}{2I_i^-} \tag{1}$$

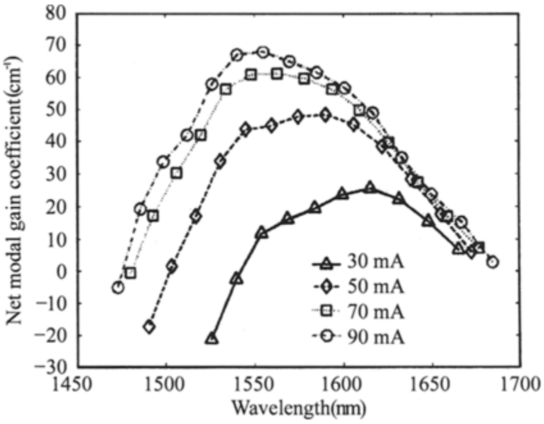

Fig. 4 The optical gain spectra calculated from ASE spectra based on the Hakki-Paoli method

Then the net modal gain coefficient $g_{\text{net}} = \Gamma_g - \alpha_i$ is extracted from the following relation:

$$g_{\text{net}} = \frac{1}{L}\ln\left(\frac{r_i^{1/2}-1}{r_i^{1/2}+1}\right) + \frac{1}{L}ln\,\frac{1}{R} \tag{2}$$

where 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 and R is the effective reflectivity of tapered fiber ends.

Effective refractive index n_{eff}, which lies on the refractive index of the material and its wavelength-dependence as well as the waveguide structure of TWA, can be determined by the longitudinal mode spacing $\Delta\lambda_m$ at a wavelength λ and the cavity length L[3]:

$$n_{\text{eff}} = \frac{\lambda^2}{2L\Delta\lambda_m} \tag{3}$$

The obtained effective refractive indexes are shown in Fig. 5. We can see that the effective refractive indexes tend to decrease with increasing wavelength. The calculated value of n_{eff} is accordance with the effective refractive index $n=3.23$ given by Magari[4] etc.

The peak wavelength of each mode in the ASE spectrum is a function of effective refractive index. In reverse, the change in effective refractive index Δn_{eff} with respect to the change in current can be obtained from the measured peak wavelength shift $\Delta\lambda_s$ with respect to the increase of injected current[5]:

$$\Delta n_{\mathrm{eff}} = \frac{\lambda}{2L}\frac{\Delta\lambda_s}{\Delta\lambda_m} \tag{4}$$

The obtained changes in effective refractive index are plotted in Fig. 6, which shows that Δn_{eff} is weak dependent on wavelength. A special feature should be noticed from Fig. 6, i. e. n_{eff} first decreases with an increase of injection current up to 90 mA, and it then slightly increases when injection current increases from 90 mA to 110 mA. The special phenomenon is arising from the sum of carrier-induced index change and thermal-induced index change.

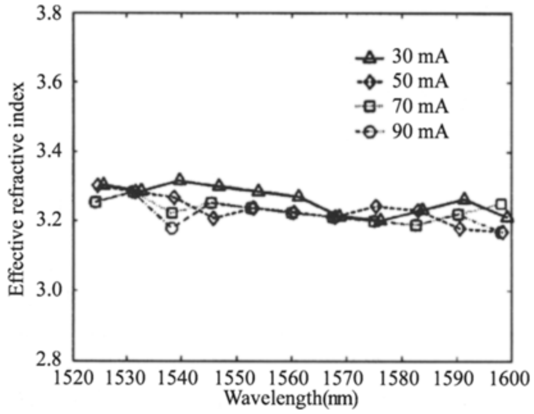

Fig. 5 Effective refractive index calculated from mode spacing

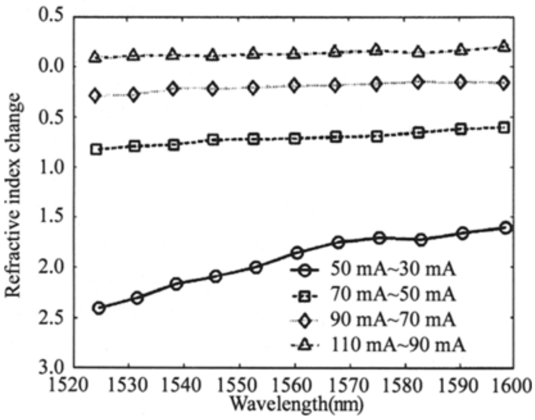

Fig. 6 The changes in effective refractive index with 20 mA intervals

First, carrier density increases with the increase in injection currents up to lasing threshold, which produces a negative Δn_{eff}[6]. Second, although a temperature controller is used to stabilize the TWA temperature, there is still a temperature gradient between device surface and active layer. The thermal effects arising from the current injection will make the temperature of active layer increase. As a result, band gap decreases, which makes a positive Δn_{eff}.

Carrier-induced negative Δn_{eff} is obviously dominant when injection current is below 90 mA. But the magnitude of the negative Δn_{eff} gradually decreases with the increasing of injection current because of the elevated temperature of active layer and the increasing stimulated recombination that prevents the carrier density to increase. When injection current increases from 90 mA to 110 mA (above lasing threshold value), stimulated recombination uses up all additional carrier injection above threshold. Carrier density clamps at threshold. Then, thermal-induced positive Δn_{eff} is appreciably dominant, yielding the increase of n_{eff}.

External cavity resonator constructed by in-out tapered fiber ends without AR-coating is used to produce big ripple imposed on ASE, by which over a wide spectral range Hakki-Paoli method has been used to obtain the gain spectra of TWA with tensile-strained-barrier multiple-quantum-well structure. Measured longitudinal mode spacing and peak wavelength shift have been used to further obtain effective refractive index and refractive index change with increased bias current. Noticeable phenomenon is that the effective refractive index firstly decreases with an increase of injection current up to lasing threshold. It then slightly increases when the injection current is above the threshold. We explained the above characteristic as the synthetical effects of carrier-induced refractive index decreasing and thermal-induced refractive index increasing.

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