Measurement of Gain, Group Index, Group Velocity Dispersion, and Linewidth Enhancement Factor of an InGaN Multiple Quantum-Well Laser Diode

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***Abstract*—Gain, group index, group velocity dispersion (GVD), temperature variation of refractive index, and linewidth enhancement factor of an $In_{0.15}Ga_{0.85}N/In_{0.02}Ga_{0.98}N$ multiple quantum-well blue laser diode was measured using the Fourier transform method as a function of wavelength from 400 to 410 nm. At the lasing wavelength (403.5 nm), the group index is 3.4, the GVD $(dn_g/d\lambda)$ is $-37\ \mu m^{-1}$, the temperature variation of refractive index dn/dT is $1.3 \times 10^{-4}\ K^{-1}$, and the linewidth enhancement factor is 5.6.**

***Index Terms*—Fourier transform (FT) method, group velocity dispersion (GVD), InGaN laser diode, linewidth enhancement factor.**

I. Introduction

THE MEASUREMENT of gain (absorption) spectra is an important material characterization tool for the development of semiconductor lasers, semiconductor optical amplifiers, and other waveguide devices. A number of different methods have been proposed to determine the net gain spectrum from the transmission spectra or spontaneous emission spectra. The Hakki–Paoli (HP) method [1], [2] uses the peak to valley ratios of individual Fabry–Pérot resonances to calculate the net gain spectrum. However, the HP method is sensitive to the instrument resolution bandwidth and may underestimate the gain if the resolution of the measurement system is not enough to resolve the peak and valley of the emission spectrum accurately. Recently, the Fourier transform (FT) method was proposed to calculate the gain spectrum [3]–[6] and refractive index [4] from the emission spectrum. The advantage of the FT method is that it allows an instrument response correction if the instrument response can be measured [5]. Since the FT method can measure gain and refractive index simultaneously, it can be used to measure other important parameters such as group index, group velocity dispersion (GVD), temperature variation of refractive index, and linewidth enhancement factor. In this letter, we will demonstrate the used of the FT method to measure the group index, group index dispersion, temperature variation of refractive index, and linewidth enhancement factor of a commercial $In_{0.15}Ga_{0.85}N/In_{0.02}Ga_{0.98}N$ multiple quantum-well (MQW) blue laser diode.

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II. Calculation of Group Index and GVD

We refer to the calculation of the gain-reflectivity product (b) and the round trip phase (ϕ) from the spontaneous emission spectrum in [4] and [5], and focus on how to calculate the net modal gain (g), group index (n_g), GVD, and linewidth enhancement factor (α). The gain-reflectivity product (b) and the round trip phase (ϕ) are given by [4]

$$b = \sqrt{R_1 \cdot R_2} \cdot \exp(g \cdot L) \tag{1}$$

$$\phi = 4 \cdot \pi \cdot \beta \cdot n \cdot L - \phi_0 \tag{2}$$

where R_1 and R_2 are the two facet reflectivities, g is the net modal gain, L is the cavity length, $\beta = 1/\lambda$ is the wavenumber, n is the effective refractive index, and ϕ_0 is an unknown phase constant [4]. From the gain-reflectivity product (b), the net modal gain can be calculated as

$$g = \frac{1}{L}\ln(b) - \frac{1}{2 \cdot L}\ln(R_1 \cdot R_2). \tag{3}$$

The refractive index (n) cannot be calculated directly from (2), because the value of ϕ_0 is unknown, unless ϕ_0 can be determined by using one known index within the measure spectra range [4]. However, without knowing the value of ϕ_0, some important parameters can still be calculated from (2). For example, the first derivative of (2) can be used to calculate the group index (n_g) as

$$n_g = n + \beta \cdot \frac{dn}{d\beta} = \frac{1}{4 \cdot \pi \cdot L} \cdot \frac{d\phi}{d\beta} \tag{4}$$

and the second derivative of (2) can be used to calculate the GVD as

$$\text{GVD} \equiv \frac{dn_g}{d\lambda} = \frac{-\beta^2}{4 \cdot \pi \cdot L} \cdot \frac{d^2\phi}{d\beta^2}. \tag{5}$$

III. Calculation of Linewidth Enhancement Factor

If a series of spontaneous emission spectra can be measured under several different injection current (I) levels and the step of the current level change are kept small enough that the induced Fabry–Pérot mode shift is smaller than one mode spacing, then the linewidth enhancement factor can be calculated with the following procedure.

First, the gain (g) and round trip phase (ϕ) at different injection current levels are calculated as shown in Section II. The next step is to calculate the derivative of the gain with respect to the current (dg/dI) and the derivative of the round trip phase with respect to the current $(d\phi/dI)$ from the results of first step. The derivative of the index with respect to the current (dn/dI) is related to $d\phi/dI$ by

$$\frac{dn}{dI} = \frac{1}{4 \cdot \pi \cdot \beta \cdot L} \cdot \frac{d\phi}{dI}. \tag{6}$$

Although the facet reflectivity does change as the current injection levels change due to the carrier-induced refractive index change, dg/dI is dominated by the change of the first term in (3). Because the carrier-induced refractive index is very small, the carrier-induced reflectivity change is also very small, unless the facet reflectivity is very low (antireflection-coated facets). So dg/dI can be calculated by neglecting the carrier-induced reflectivity change as

$$\frac{dg}{dI} = \frac{1}{L} \cdot \frac{d\ln(b)}{dI}. \tag{7}$$

The linewidth enhancement factor (α) can then be calculated as [7]

$$\alpha = -\frac{4 \cdot \pi}{\lambda} \cdot \frac{dn}{dg} = -\frac{4 \cdot \pi}{\lambda} \cdot \frac{\frac{dn}{dI}}{\frac{dg}{dI}}. \tag{8}$$

From (6), (7), and (8)

$$\alpha = -\frac{\frac{d\phi}{dI}}{\frac{d\ln(b)}{dI}}. \tag{9}$$

It is interesting to point out that α can be calculated without knowing the cavity length.

IV. Calculation of Temperature Variation of Refractive Index

If a series of spontaneous emission spectra can be measured under several different temperatures (T) at a fixed injection current level, then the temperature variation of the refractive index can be calculated as shown in (10). The step of the temperature change should also be kept small enough that the temperature-induced Fabry–Pérot mode shift is smaller than one mode spacing

$$\frac{dn}{dT} + n \cdot \alpha_{\text{thermal}} = \frac{1}{4 \cdot \pi \cdot \beta \cdot L} \cdot \frac{d\phi}{dT}. \tag{10}$$

The second term on the left-hand side of (10) is due the thermal expansion of the cavity length.

V. Experiment Results

The transverse-electric polarized spontaneous emission spectrum from a $In_{0.15}Ga_{0.85}N/In_{0.02}Ga_{0.98}N$ MQW blue laser diode was collected using a high-resolution grating spectrometer (SPEX, 0.5-m focal length, 1200 lines/mm, 10-μm slit width) operated at second order (~0.02-nm resolution). The laser diode was mounted on a temperature controlled stage in order to maintain constant temperature (20 °C). All spontaneous emission spectra were measured under pulsed operation in order to avoid heating due to current injection. The lasing wavelength, threshold current, and cavity length of the blue laser diode at room temperature were 403.5 nm, 33 mA, and 670 μm, respectively. The measured wavelength range of the spontaneous emission spectrum was 395–415 nm so that the values of the emission spectrum at both ends of measured wavelength range are about the same in order to reduce the spectrum leakage when performing the FT. No window function was used in FT method. The instrument response deconvolutions were performed with a measured response function [4], [5].

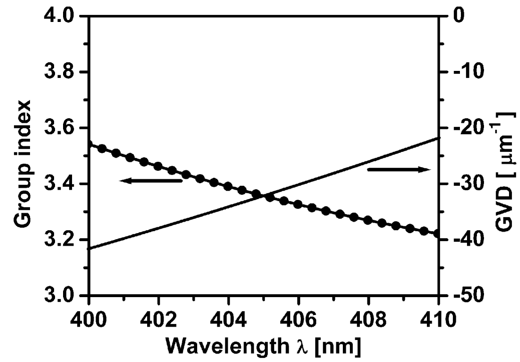

Fig. 1. Measured group index and GVD of an InGaN MQW laser diode bias at a current of 30 mA.

A. Group Index and GVD Measurement

The group index and GVD can be calculated using (4) and (5), respectively. In order to calculate the derivatives $d\phi/d\beta$ and $d^2\phi/d\beta^2$, ϕ was fitted with a third-order polynomial of β. A higher order polynomial can be used to improve the measurement accuracy if the signal to noise ratio is higher. The measurement results are shown in Fig. 1. The measured results show that the GVD of blue laser diode is very large compare with the GVD of infrared laser diode ($-0.71\ \mu m^{-1}$) [8].

B. Linewidth Enhancement Factor Measurement

A series of spontaneous emission spectra with bias current varying from 25 to 30 mA with 1-mA step were measured. The injection current change was chosen to be 1 mA so that the change of round trip phase (ϕ) is smaller than $2 \cdot \pi$ (the induced Fabry–Pérot mode shift is smaller than one mode spacing) to avoid the uncertainty of an integer multiple of $2 \cdot \pi$ in the determination of ϕ. The gain reflectivity product (b) and round trip phase (ϕ) were calculated from the measured emission spectrum. The derivative dg/dI and $d\phi/dI$ were obtained by the slope of the linear fitting of $\ln(b)/L$ and ϕ as a function of bias current. The linewidth enhancement factor (α) is shown as a function of wavelength in Fig. 2. The α parameter is larger at longer wavelengths because the change of gain with carrier density change at the long wavelength end will be smaller compared with the change of gain at the short wavelength end due to the fact that the density of states at the long wavelength end is mostly filled. Similar observations have also been reported for infrared laser diode [9].

The data in Fig. 2 was fitted with a second-order polynomial as

$$\alpha = 2.8 + 4.92(\lambda - 400) + 0.089(\lambda - 400)^2 \tag{11}$$

where the unit of λ is nanometers.

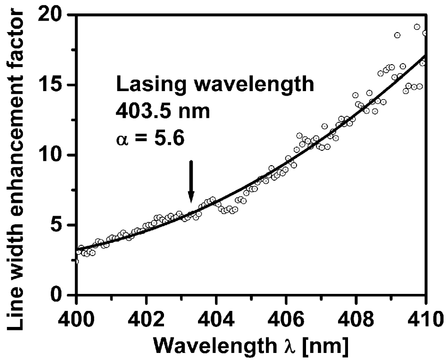

Fig. 2. Measured linewidth enhancement factor of an InGaN MQW laser diode under bias current of 25–30 mA with 1-mA step. The open circles are the measured data and the solid line is a polynomial fit to the data.

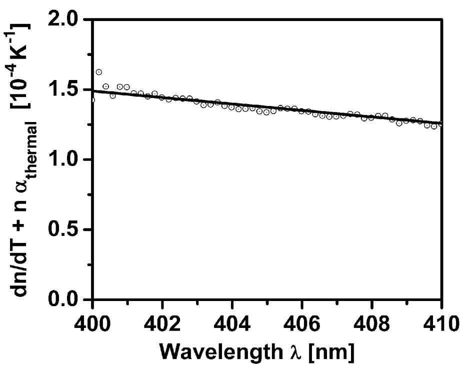

Fig. 3. Measured temperature variation of refractive index of an InGaN MQW laser diode under bias current of 25 mA and temperatures of 20.0 °C–21.5 °C. The open circles are the measured data and the solid line is a linear fit to the data.

C. Temperature Variation of Refractive Index

The calculated $dn/dT + n \cdot \alpha_{\text{thermal}}$ is shown in Fig. 3. Using the refractive index $(n = 2.65)$ and the thermal expansion coefficient $(\alpha_{\text{thermal}} = 5.59 \times 10^{-6}\ \text{K}^{-1})$ of GaN [10], we get $n \cdot \alpha_{\text{thermal}} = 1.48 \times 10^{-5}\ \text{K}^{-1}$. From Fig. 3, the value of $dn/dT + n \cdot \alpha_{\text{thermal}}$ is on the order of $10^{-4}\ \text{K}^{-1}$, so we conclude that dn/dT is much larger than $n \cdot \alpha_{\text{thermal}}$, and the value of dn/dT is estimated to be about $1.3 \times 10^{-4}\ \text{K}^{-1}$.

VI. Conclusion

We have extended the applications of the FT method from the calculation of gain spectrum to the calculation of group index, GVD, temperature variation of refractive index, and linewidth enhancement factor. We used this technique to determine the group index, GVD, temperature variation of refractive index, and linewidth enhancement factor for an InGaN MQW blue laser diode.

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