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Extremely Low Damping K-Factor in Highly Detuned DFB Strained Layer MQW SA-CM Lasers

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Wavelength detuning effect on the high speed characteristics of strained layer multiquantum well lasers is studied. Negative wavelength detuning increases differential gain without varying the nonlinear gain coefficient. The nonlinear damping K-factor of 0.13 ns, which corresponds to a 68 GHz intrinsic bandwidth, is obtained by negative detuning of 45 nm.

1. INTRODUCTION

The intrinsic maximum bandwidth f_{max}[1] in semiconductor lasers is of the most interest for high speed optical fiber communication systems. The nonlinear damping K-factor has been studied because f_{max} is inversely proportional to the K-factor. The K-factor is defined as the ratio of the nonlinear gain coefficient ε to the differential gain dG/dN.

Recently, low K values as a consequence of the increase in the differential gain dG/dN in p-doped bulk[2], modulation doped multiquantum well (MQW)[3] and strained layer (SL-)MQW[4] InGaAsP lasers have been reported. It is known that dG/dN in bulk and MQW lasers is enhanced by negative detuning. It is, however, unknown whether dG/dN increases by detuning for SL-MQW lasers. In this paper, we demonstrate the effect of wavelength detuning on dG/dN and the K-factor in SL-MQW self-aligned constricted mesa (SA-CM) lasers. It is found that negative wavelength detuning in SL-MQW lasers increases dG/dN drastically. As a result, a low K value as small as 0.13 ns was obtained in a highly detuned distributed feedback (DFB) SL-MQW SA-CM laser.

2. DEVICE STRUCTURE AND MEASUREMENTS

The strained active layer consists of four 4 nm thick $In_{0.7}Ga_{0.3}As$ wells with 1.2 % compressive strain and 10 nm thick 1.28 μm InGaAsP barriers grown by a low pressure MOCVD. An SA-CM structure was employed for high frequency response measurement[4]. We compared the three kinds of SL-MQW lasers, that is, -45 nm, -30 nm detuned DFB, and Fabry-Perot (FP) lasers. Threshold current values ranged from 20 to 60 mA. The DFB lasers had side mode suppression ratios of more than 40 dB.

Figure 1 shows small signal frequency responses for (a) a FP and (b) a -45 nm detuned DFB SL-MQW laser. The frequency response in a detuned laser is remarkably excellent compared with that in a FP laser at the same bias. A 17 GHz 3 dB modulation bandwidth in a -45 nm detuned DFB SA-CM laser was the best value ever reported in 1.5 μm MQW DFB lasers. The bandwidth was limited by the RC constant.

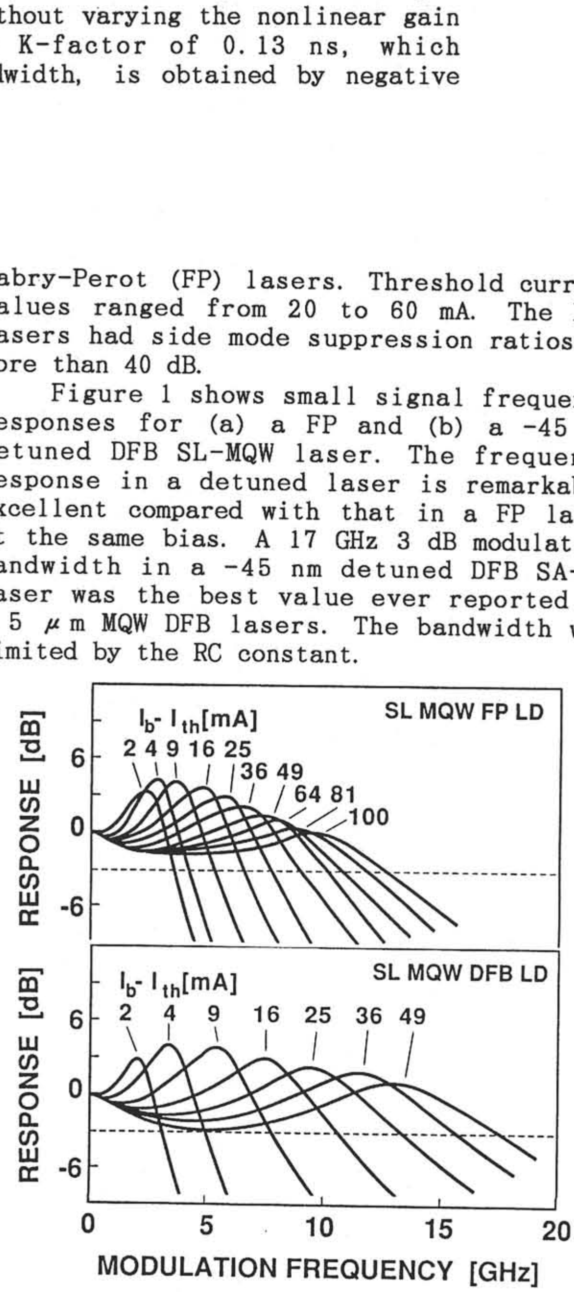

Fig. 1 Small signal frequency responses. a) FP, b) -45 nm detuned DFB laser.

The theoretical response R[1] is expressed as

$$R = R_{int} \cdot R_e \qquad (1)$$

$$R_{int} = \omega_r^4 / \{(\omega^2 - \omega_r^2)^2 + \omega^2 \gamma^2\}$$

$$R_e = 1/\{1+(\omega/\omega_{RC})^2\} \cdot 1/\{1+(\omega/\omega_{PN})\}$$

where R_{int} is the intrinsic frequency response; R_e, electrical response of the diode; $\omega_r/2\pi$, resonance frequency f_r; and γ, damping rate. The resonance frequency f_r and the damping rate γ are obtained by fitting the theoretical curve given by eq. (1) to the response data. These two parameters will be used to determine the differential gain and K-factor in the following sections.

3. DIFFERENTIAL GAIN

The wavelength detuning dependence of dG/dN in the SL-MQW lasers was investigated from both frequency responses and gain spectra.

First, the differential gain dG/dN was estimated from the bias dependence of f_r. The resonance frequency f_r is expressed as

$$f_r = 1/(2\pi) \cdot \{\Gamma/(qV_a) \cdot dG/dN \cdot (I - I_{th})\}^{1/2} \qquad (2)$$

where Γ is the confinement factor; q, electric charge element; V_a, volume of active region; I, injection current; and I_{th}, threshold current. The threshold carrier density (N_{th}) dependence of dG/dN was investigated by changing the cavity length of the three kinds of lasers. The results are shown in Fig. 2. The relationship between gain G and current density J can be approximated by the simple form[5]

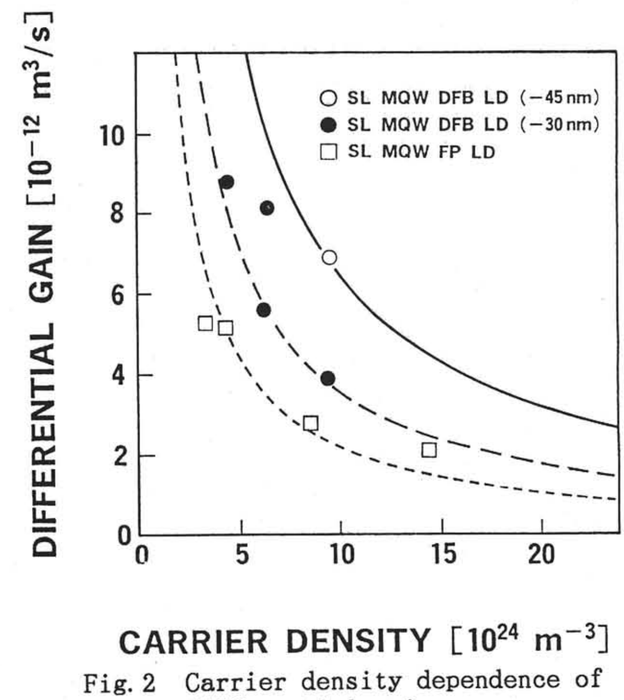

Fig. 2 Carrier density dependence of differential gain.

$$G = G_0 \cdot \{1 + \ln(J/J_0)\} \qquad (3)$$

where G_0 and J_0 are constants. The fitted curves ($dG/dN \propto N_{th}^{-1}$) in Fig. 2 were obtained by differentiation of eq. (3). Differential gain dG/dN in the -45 and -30 nm detuned DFB SL-MQW lasers were 3 and 1.5 times larger than that in the FP SL-MQW lasers at the same N_{th}, respectively. In practice, however, N_{th} tends to increase in highly detuned DFB lasers if the cavity length is the same.

Next, gain spectra in FP SL-MQW lasers were obtained from the ripple of EL spectra under threshold bias. Dependence of gain on current density for various wavelengths are presented in Fig. 3. Gain constant G_0 values per well in 1.54 and 1.57 μm wavelength, estimated by eq. (3), were 3590 and 2370 cm^{-1}, respectively. That is, 1.5 times the gain enhancement is obtained by -30 nm detuning. This is consistent with the result from the response data.

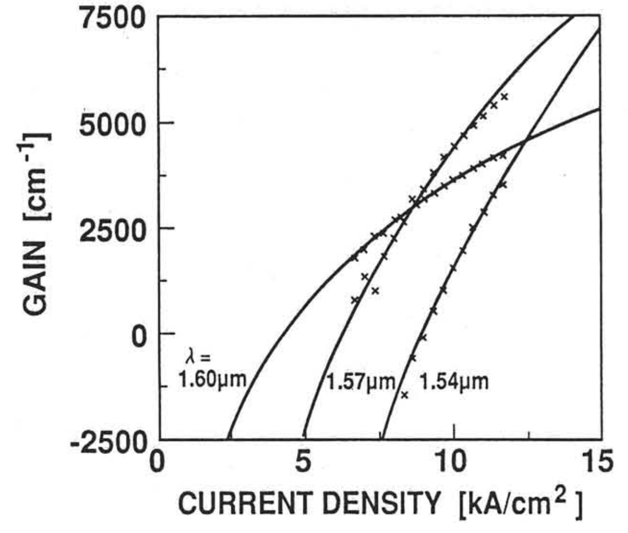

Fig. 3 Gain vs. current density for various wavelengths. Gain peak is 1.57 μm in SL-MQW FP lasers. The fitted lines are estimated by eq. (3).

4. NONLINEAR DAMPING K-FACTOR

The K-factor is estimated from the relationship between the damping rate γ and the resonance frequency f_r as follows;

$$\gamma = K \cdot f_r^2 + 1/\tau_c \qquad (4)$$

where τ_c is carrier lifetime. Damping rate γ for three types of SL-MQW SA-CM lasers is shown as a function of the square of f_r in Fig. 4. The estimated K-values were 0.13, 0.32, and 0.41 ns in the -45, -30 nm detuned DFB, and FP lasers at the same N_{th}, respectively.

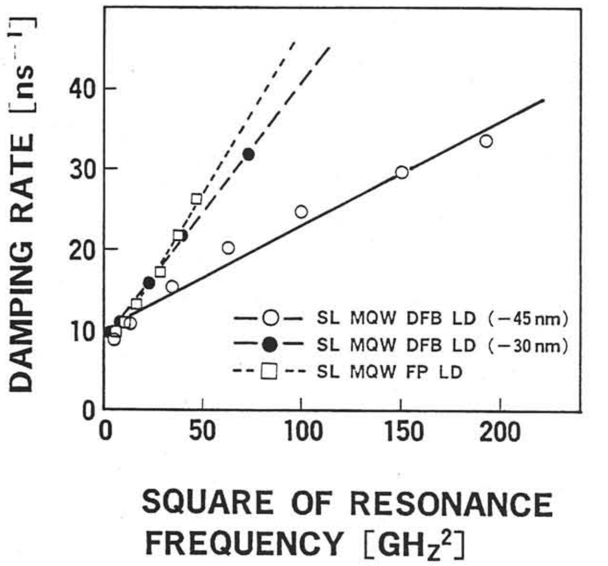

Fig. 4 Damping rate γ vs. squared resonance frequency f_r^2. K is found from the slope.

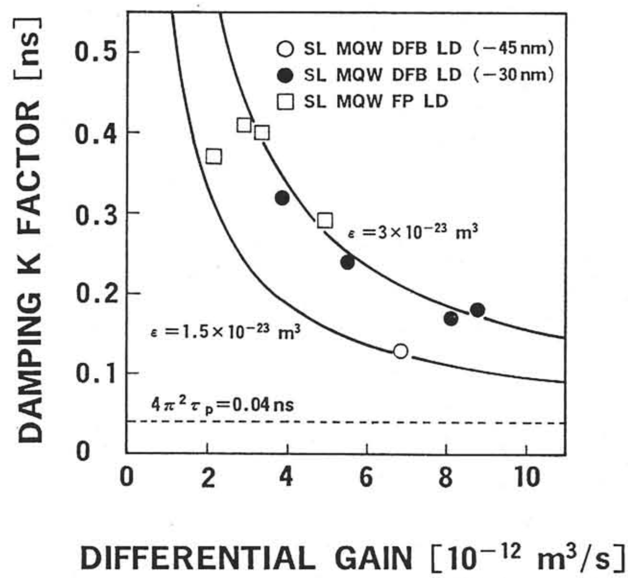

Fig. 5 The K-factor vs. differential gain. The lines are estimated by eq. (5).

The nonlinear gain coefficient ε is estimated from the followings:

$$K = 4\pi^2 \{\varepsilon/(dG/dN) + \tau_p\} \qquad (5)$$

where τ_p is photon lifetime. Figure 5 shows the relationship between K and dG/dN for three types of SL-MQW lasers. The reduction of the K-factor is mainly due to the increase in dG/dN. This phenomenon can be explained if we assume the model of spectral hole burning[6]. On the other hand, the nonlinear gain coefficient ε, $1.5\sim3\times10^{-23}$ m^3, was insensitive to the dG/dN change due to the wavelength detuning and carrier density.

The strong damping has been reported and the spatial and energetic redistribution of carriers[7] has been proposed as a physical reason for that strong damping. However, no anomalous damping was observed in the authors' experiment. The difference between these results may possibly be caused by the fact that each quantum well in our structure is in touch with a p^+-clad layer on the side wall. Therefore, the hole injection from the side may enhance the restoration of carrier distribution.

The K-factor was reduced to 0.13 ns in the -45 nm detuned SL-MQW laser. This is the best value reported so far in 1.5 μm wavelength lasers. The intrinsic maximum bandwidth f_{max} is given by

$$f_{max} = 2^{3/2}\pi / K \qquad (6)$$

From substitution of the minimum K value of 0.13 ns into eq. (6), we can deduce 68 GHz intrinsic bandwidth. By lowering the RC constant in the laser structure, further high speed modulation will be possible.

5. SUMMARY

The SL-MQW SA-CM lasers show excellent high speed characteristics. Wavelength detuning effect on differential gain is studied by both frequency responses and gain spectra measurements. Differential gain is increased by negative wavelength detuning without changing the nonlinear gain coefficient. The damping K-factor was reduced significantly to 0.13 ns which corresponds to 68 GHz intrinsic bandwidth in the highly detuned DFB SL-MQW SA-CM laser. These results strongly suggest that negative wavelength detuning in a SL-MQW SA-CM laser is a very effective means to expand frequency response.

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