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 $f_{\text{max}}$ in semiconductor lasers is of the most interest for high speed optical fiber communication systems. The nonlinear damping K-factor has been studied because $f_{\text{max}}$ is inversely proportional to the K-factor. The K-factor is defined as the ratio of the nonlinear gain coefficient $\xi$ 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,9,10 modulation doped multiquantum well (MQW)3 and strained layer (SL-)MQW4 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 InGaAsP wells with 1.2% compressive strain and 10 nm thick 1.28 $\mu$m InGaAsP barriers grown by a low pressure MOCVD. An SA-CM structure was employed for high frequency response measurements. 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 $\mu$m MQW DFB lasers. The bandwidth was limited by the RC constant.

![Figure 1](image-url)
The theoretical response \( R(\omega) \) is expressed as

\[
R = R_{\text{int}} \cdot R_{e}
\]

\[
R_{\text{int}} = \omega r^2 / \{(\omega^2 - \omega_0^2)^2 + \omega_0^2 \gamma^2\}
\]

\[
R_{e} = 1 / [1 + (\omega / \omega_{0C})^2] \cdot 1 / [1 + (\omega / \omega_{PN})]
\]

where \( R_{\text{int}} \) is the intrinsic frequency response; \( R_{e} \), electrical response of the diode; \( \omega r / 2\pi \), resonance frequency \( \omega_r \); and \( \gamma \), damping rate. The resonance frequency \( \omega_r \) and the damping rate \( \gamma \) 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 \( \omega_r \). The resonance frequency \( \omega_r \) is expressed as

\[
\omega_r = 1 / (2\pi) \cdot \left[ I' / (qV_a) \cdot dG / dN \cdot (I - I_{th}) \right]^{1/2}
\]

where \( I' \) 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

\[
G = G_0 \cdot \left( 1 + \ln(J/J_0) \right)
\]

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 \( \mu \)m wavelength, estimated by eq. (3), were 3580 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.

4. NONLINEAR DAMPING \( K \)-FACTOR

The \( K \)-factor is estimated from the relationship between the damping rate \( \gamma \) and the resonance frequency \( \omega_r \) as follows:

\[
\gamma = K \cdot \omega_r^2 + 1 / \tau_c
\]

where \( \tau_c \) is carrier lifetime. Damping rate \( \gamma \) for three types of SL-MQW SA-CM lasers is shown as a function of the square of \( \omega_r \) 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.
The nonlinear gain coefficient $\varepsilon$ is estimated from the following:

$$K = 4\pi^2 \left( \frac{\varepsilon}{dG/dN} + \tau_p \right) \quad (5)$$

where $\tau_p$ 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. On the other hand, the nonlinear gain coefficient $\varepsilon$, $1.5 \times 10^{-23} \text{m}^3$, 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 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 $0.13 \text{ ns}$ in the $-45 \text{ nm}$ detuned SL-MQW laser. This is the best value reported so far in $1.5 \mu \text{m}$ wavelength lasers. The intrinsic maximum bandwidth $f_{\text{max}}$ is given by

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

From substitution of the minimum K value of $0.13 \text{ ns}$ into eq. (6), we can deduce $68 \text{ GHz}$ 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 $0.13 \text{ ns}$ which corresponds to $68 \text{ GHz}$ 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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References