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A Corrugation-Pitch-Modulated Strained Multiple-Quantum-Well Distributed Feedback Laser with an Ultranarrow (3.6kHz) Spectral Linewidth

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We demonstrate that the spectral linewidth of corrugation-pitch-modulated distributed feedback (CPM-DFB) lasers can be reduced by introducing a strained multiple-quantum-well (MQW) active layer. By evaluating the relationship between subthreshold driving current and the spectrum shape and wavelength of 250-μm Fabry Perot MQW lasers with and without strain, we estimated that the introduction of 1% compressive strain results in a spectral linewidth enhancement factor of 1.8. Introducing a +1% strained MQW active layer into a CPM-DFB laser reduces the linewidth floor (residual linewidth for extrapolated infinite output power) to 2 kHz and results in a linewidth-power product of 140 kHz·mW. A strained MQW CPM-DFB lasers produced a 55-mW output with a spectral linewidth of only 3.6 kHz.

1. Introduction

Semiconductor lasers with a narrow spectral linewidth semiconductor lasers are needed for coherent transmission systems and for optical measuring systems. Spectral linewidths below 100 kHz have been produced by using a long-cavity corrugation-pitch-modulated distributed feedback (CPM-DFB) laser with a lattice-matched multiple-quantum-well (MQW) active layer (56 kHz) [1], a long-cavity distributed Bragg reflector (DBR) laser with a lattice-matched MQW active layer (85 kHz) [2], and a long-cavity DFB laser with a strained MQW active layer (70 kHz) [3]. The minimum spectral linewidth of semiconductor lasers is usually limited by the linewidth rebroadening (the increase in linewidth with increasing output power) and by the linewidth floor (the residual linewidth for infinite output power). The causes for linewidth rebroadening and the linewidth floor are not yet fully understood, but B. Tromborg *et al.* [4] have suggested that the linewidth floor may be a result of the spatial hole-burning.

Strained MQW structures and CPM structures inhibit spatial hole-burning, and this paper describes how the narrowest spectral linewidth yet reported has been achieved by introducing a strained MQW active layer into CPM-DFB lasers.

2. Principles and laser structure

As shown by the inset in Fig. 1, the CPM structure uses a slightly longer corrugation pitch in the phase-arranging region than in the other regions to obtain an effective λ/4-phase-shift. Spatial hole burning can be reduced by lengthening the phase-arranging region of the CPM structure [5].

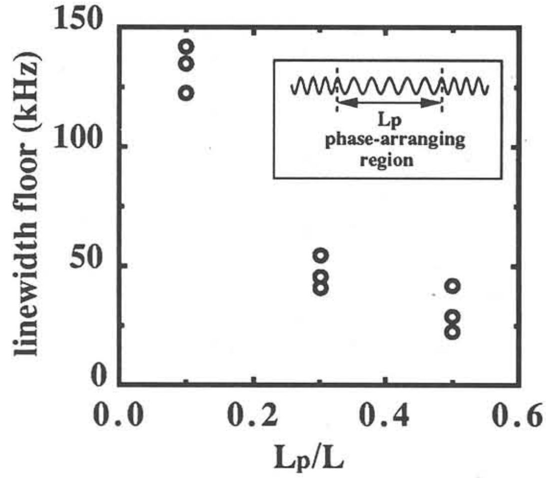

Fig. 1 Linewidth floor as a function of the phase-arranging region length Lp normalized by the cavity length L for CPM-DFB lasers with a lattice-matched MQW active layer.

The minimum spectral linewidth of CPM-DFB lasers is limited by the linewidth floor and linewidth rebroadening is not observed [1]. For CPM-DFB lasers with a lattice-matched MQW active layer, the linewidth floor is shown in Fig. 1 as a function of the phase-arranging region length L_p normalized by the cavity length L. Because less spatial hole-burning occurs when L_p/L values are larger [5], this decrease in linewidth floor with increasing L_p/L implies that the linewidth floor decreases as a result of reduced spatial hole-burning.

A larger L_p/L, however, reduces the stability of the single-mode operation [5] and narrow spectral linewidths cannot be obtained because of mode competition noise. Decreasing the value of the spectral linewidth enhancement factor, on the other hand, can inhibit the spatial hole-burning effect without interfering with the stability of single-mode oscillation [6]. The spatial hole-burning can therefore be suppressed effectively by combining the CPM structure with a smaller spectral linewidth enhancement factor in a CPM-strained MQW-DFB laser (Fig. 2).

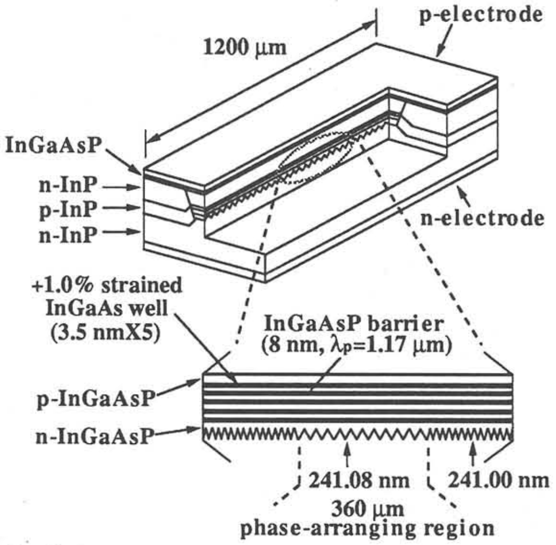

Fig. 2 Schematic structure of a corrugation-pitch-modulated strained multiple-quantum-well distributed feedback (CPM-strained MQW-DFB)laser.

To reduce the spectral linewidth enhancement factor, we introduced a +1.0% strained 5-well MQW active layer into the CPM-DFB laser. The well layer was 3.5-nm InGaAs and the barrier layer was 8.0-nm InGaAsP with its photoluminescence peak at 1.17 μm. (The well number was not optimized for narrowing the spectral linewidth). The length of the phase-arranging region for the 1200-μm-long cavity was 360 μm. The normalized coupling coefficient was 3.7 and both cavity facets were anti-reflection coated with a sputtered SiN_x thin film to reduce their reflectivity to less than 1%.

3. Results and discussion

We estimated the value of the spectral linewidth enhancement factor evaluating the relationship between subthreshold driving current and the spectrum shape and the wavelength of a 250-μm Fabry Perot laser. Plotting the spectral linewidth enhancement factor as a function of the wavelength for lattice-matched and +1.0% strained MQW Fabry Perot lasers (Fig. 3) shows that the introduction of the +1% strained MQW structure reduces the value of the spectral linewidth enhancement factor by one-half. We measured samples with strains +0.5%, +1.0%, and +1.5%, and the smallest spectral linewidth enhancement factor - 1.8 at the 1543-nm lasing wavelength - was obtained with +1% strain.

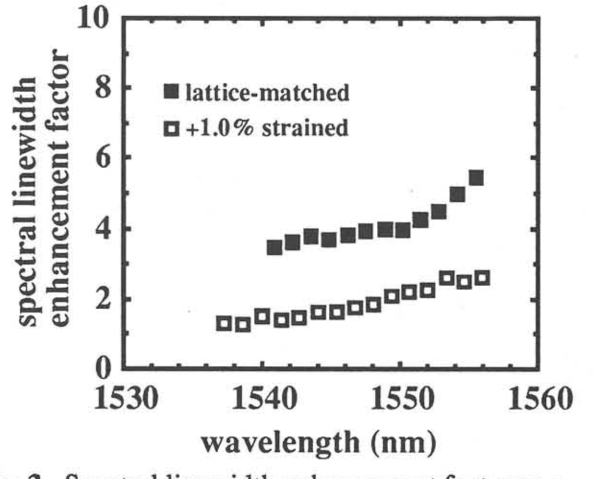

Fig. 3 Spectral linewidth enhancement factor as a function of wavelength.

The setup for the delayed self-heterodyne measurement of spectral linewidth is shown in Fig. 4. To ensure noise-free measurement of the intrinsic spectral linewidth, we used a battery as the current source and put the laser into a vacuum chamber without a temperature controller.

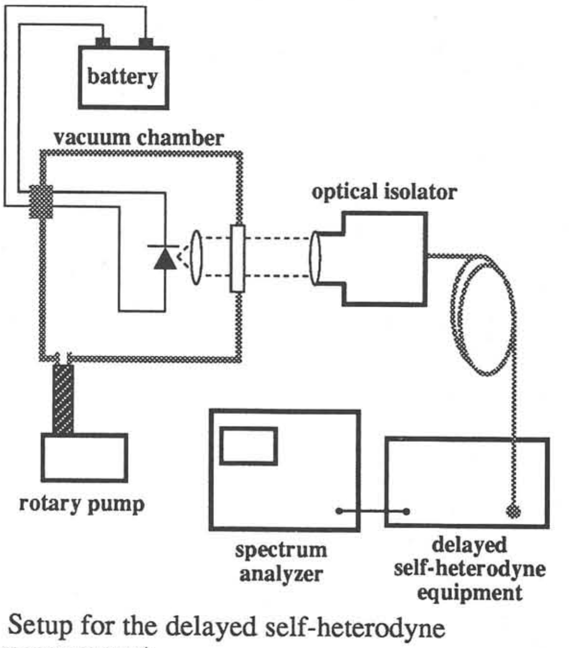

Fig. 4 Setup for the delayed self-heterodyne measurement.

The light-current characteristics of a strained MQW CPM-DFB laser are shown in Fig. 5, and the inset in this figure shows the delayed self-heterodyne lineshape obtained when the spectral linewidth was 3.6 kHz. A side mode suppression ratio better than 40 dB was obtained up to the maximum output power of 67 mW limited by the thermal effect.

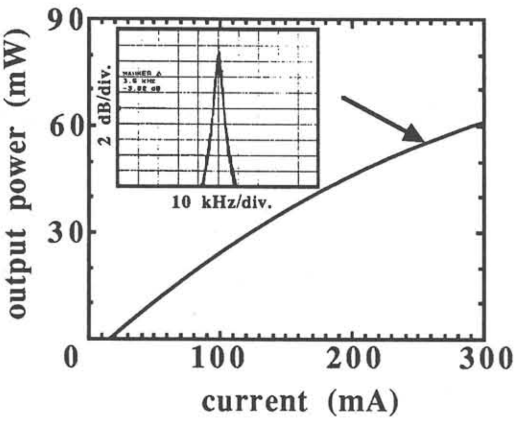

Fig. 5 Light-current characteristics and delayed self-heterodyne lineshape when the spectral linewidth is 3.6 kHz.

The delay fiber for this delayed self-heterodyne measurement was 20 km long and the minimum measurable linewidth is usually roughly estimated as $1/(2\tau_d)$ (τ_d is the delay time), which would be 5 kHz for 20-km delay fiber. The minimum measurable linewidth can be estimated more precisely, though, by using the following equation:

$$S(f) = \frac{S_0}{f^2 + (\pi S_0)^2} \times \left[1 - e^{-2\pi^2\tau_d S_0}\left\{\cos(2\pi f\tau_d) + \frac{2\pi^2 S_0}{f}\sin(2\pi f\tau_d)\right\}\right] + e^{-2\pi^2\tau_d S_0}\delta(f)$$

where S(f) is the delayed self-heterodyne lineshape, S_0[Hz^2/Hz] is the white noise, and δ(f) is the delta function (which is broadened by the video bandwidth of the spectrum analyzer). This equation yield a resolution of 2.0 kHz for the 20-km delay fiber, so we also also measured spectral linewidth by using a 40-km delay fiber (for a resolution of 1.0 kHz). The minimum spectral linewidth of a strained MQW CPM-DFB laser measured with the 40-km fiber was 3.8 kHz.

Plotting the spectral linewidth measured by using 20-km delay fiber as a function of the inverse output power (Fig. 6) shows that introducing the +1.0% strained MQW structure into the active layer reduced the linewidth from 45 kHz to 2 kHz. With the strained MQW structure, the minimum spectral linewidth of 3.6 kHz was obtained at an output power of 55 mW and the spectral linewidth was less than 40 kHz when the output power was more than 4.5 mW. The linewidth - power product for this laser was 140 kHz·mW.

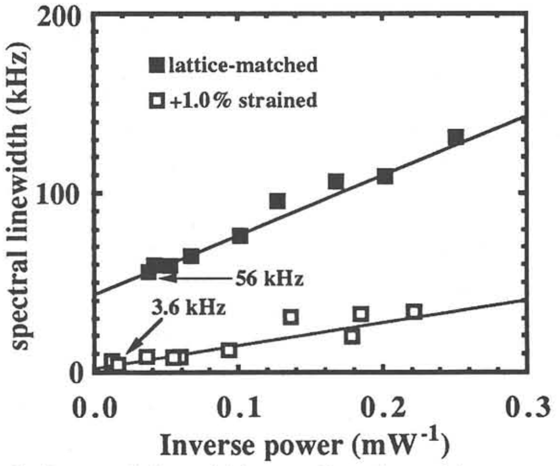

Fig. 6 Spectral linewidth as a function of inverse power.

4. Conclusion

The small spectral linewidth enhancement factor of the CPM-DFB laser decreases the linewidth floor and linewidth-power product. The minimum spectral linewidth of 3.6 kHz is limited by the linewidth floor of 2 kHz.

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