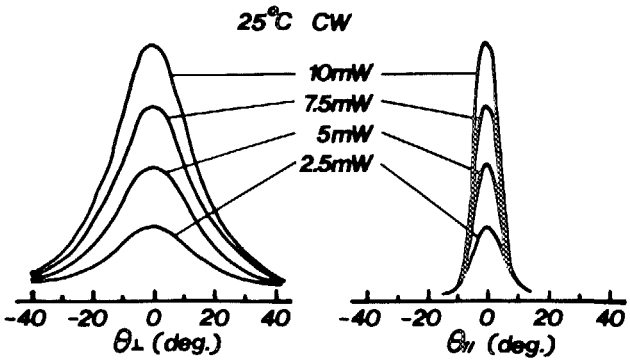

FIG. 5. Far-field patterns under fundamental transverse mode operation.

lasing spectra and the far-field patterns at several power levels under fundamental transverse mode operation. Single longitudinal mode operation is achieved above a power level of 2.5 mW, and the full angles at half-maximum of the beam divergences are 30° and 10° for the directions perpendicular to and parallel to the junction plane, respectively. All of these data were obtained without any facet coating.

In summary, a novel technique of fabricating a channeled stripe AlGaAs/GaAs laser diode emitting at 780 nm, named as melt-etched inner stripe LD, has been reported. In the present method, only two-step LPE and conventional wet chemical etching are required. The inner channeled stripe is grooved by a novel preferential melt-etching technique during crystal growth without exposure of the wafer to air; therefore, the problem of oxidization is small. The lifetime of the MEIS LD has been tested, and rapid degradation has not been observed. Detailed, preliminary results of the aging test will be reported in near future.

[1]T. Kajimura, T. Kuroda, S. Yamashita, M. Nakamura, and J. Umeda, Appl. Opt. **18**, 1812 (1979).
[2]S. Yamamoto, H. Hayashi, S. Yano, T. Sakurai, and T. Hijikata, Appl. Phys. Lett. **40**, 372 (1982).
[3]M. Wada, K. Hamada, H. Shimizu, T. Sugino, F. Tajiri, K. Itoh, G. Kano, and I. Teramoto, Appl. Phys. Lett. **42**, 853 (1983).
[4]J. J. Coleman and P. D. Dapkus, Appl. Phys. Lett. **37**, 262 (1980).

Observation of modulation speed enhancement, frequency modulation suppression, and phase noise reduction by detuned loading in a coupled-cavity semiconductor laser

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Simultaneous direct modulation response enhancement, phase noise (linewidth) reduction, and frequency modulation suppression are produced in a coupled-cavity semiconductor laser by the detuned loading mechanism.

An understanding of the modulation dynamics and quantum noise properties of semiconductor lasers will be essential in nearly all system applications of these devices. In characterizing direct modulation or noise performance of a given device, the set of important parameters to be quantified depends on the specific application. For single mode semiconductor lasers, four very important parameters will probably fall into many characterization schemes, however. For consideration of direct modulation performance, the relaxation oscillation frequency ν_R sets the useful direct modulation bandwidth of the device,[1] and the linewidth enhancement factor α determines the apportioning of modulation energy into FM and AM components (as well as the amount of chirping under digital modulation)[2]; phase noise and power noise can be specified in terms of linewidth $\Delta\nu$[3] and relative power noise (RPN). Many investigators have studied ways to control one or several of these properties. To date, however, only two techniques have proven effective for increasing device speed and reducing noise simultaneously: high power operation or operation at reduced temperatures.[1,3]

In another paper, two of us have proposed a new method for control of the above properties.[4] This method, referred to as "detuned loading," was shown in that paper to simultaneously cause enhancement of modulation speed, reduction of phase noise (linewidth), and suppression of FM modulation (chirping). (Although not discussed in that paper, we show elsewhere that reduction of RPN accompanies these improvements.[5]) The opposite situation, in which modulation speed is reduced and noise is enhanced, can also be arranged. In general, the method involves the introduction of a frequency-dependent loss mechanism in the spectral proximity of the lasing frequency and relies upon the unique physics involved in lasing action in a semiconductor (a strongly detuned gain spectrum leading to amplitude phase coupling in the lasing field). The practical implementation of this method can be accomplished in several ways, as discussed in Ref. 4. These include distributed feedback lasers

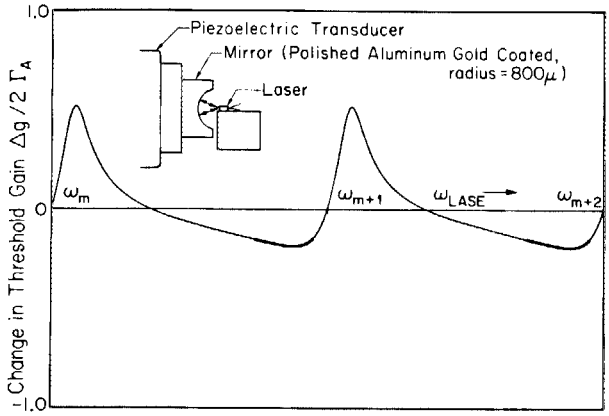

FIG. 1. Change in threshold gain caused by coupling to the passive cavity (optical gain here is in units of s^{-1} and is normalized using the active resonator free-spectral range Γ_A). Lasing action is preferred in the emboldened regions where threshold gain will be lowest, and detuned loading occurs from the slight variation of effective loss in these regions. Inset is a schematic of the coupled-cavity system used in this measurement.

and coupled-cavity lasers. In this letter, we present the first experimental observations of the detuned loading effect in semiconductor lasers. Specifically, we have observed enhancement of modulation response with simultaneous reduction of linewidth and frequency modulation resulting from application and control of detuned loading.

Our measurements employed a coupled-cavity device consisting of an active cavity loaded by a passive cavity. A schematic of this device is given in the inset of Fig. 1, and its steady-state characteristics, including mode suppression and frequency pulling characteristics, are described elsewhere.[6] The active resonator was formed by an Ortel large optical cavity buried heterostructure GaAs/GaAlAs injection laser (cavity length $\approx 300\,\mu$m), which lased in predominantly one mode and had a threshold current of 25.6 mA. The passive cavity was formed by one facet of the laser and a small gold-coated concave mirror, having an 800-μm radius of curvature. Piezoelectric micropositioners controlled the position of the mirror relative to the laser for tuning purposes.

One expects a coupled-cavity system to exhibit the detuned loading effect, since such a system has an effective cavity loss function that depends strongly on frequency. By tuning the passive cavity, the slope of this loss spectrum is varied at the lasing frequency and, hence, the amount of detuned loading is varied.[4] In practice, the strength of the effect (i.e., the steepness of the loss spectrum at the lasing frequency) is limited by mode hopping. To see this, consider Fig. 1 where we have plotted the change in the threshold gain caused by coupling to the passive cavity versus the lasing frequency (coupling parameters were taken from Ref. 6). The loss variation caused by the coupling can be seen to have a period given by the free-spectral range of the passive cavity. Lasing action is preferred in frequency ranges that correspond to antiresonances of the passive cavity (emboldened regions) since here threshold gain is lowest. When tuning the passive cavity piezoelectrically, a lasing mode will sweep through a particular emboldened region and will continue to lase until its threshold gain exeeds that of another mode. At this point, a mode hop will occur. The tuning characteristics of the coupled-cavity system were such that the passive cavity resonances could be shifted by 30–50 GHz (via piezoelectric control of the concave mirror) or nearly 25% of a passive free-spectral range before a longitudinal mode jump would occur in the system. Over this tuning range, the oscillation was single mode to better than 20 dB, and power in the lasing mode varied by no more than 20%, peaking near the middle of the tuning range.

The experimental setup used in this measurement included a high-speed silicon avalanche photodetector for measurement of the modulation response, both high- and low-resolution (7.5- and 75-GHz instrumental bandwidth) scanning Fabry–Perot etalons for measurement of linewidth and modulation, and a grating spectrum analyzer equipped with a multichannel analyzer to monitor mode suppression and modal power. Feedback effects in the system were controlled by insertion of neutral density filters.

A coupled-cavity system similar to the one described in this letter was used as a pedagogical vehicle in Ref. 4 to analyze the detuned loading effect. That analysis used a coupled mode approach to show that the net effect of passive cavity loading was to introduce new effective differential quantities into the equations of motion governing modulation and noise; i.e., the form of the equations of motion remains unchanged under coupling.

Resulting expressions for modulation corner frequency and linewidth are altered as follows under loading by the passive cavity.[4]

$$\nu_R^2 = \frac{g'_{\rm eff} P}{(2\pi)^2 \tau_{\rm eff}}, \tag{1}$$

$$\Delta\nu = \frac{S}{2PV}(1+\alpha^2)_{\rm eff}, \tag{2}$$

where the conventional unloaded expressions are simply those without the eff subscripts. In these expressions P, V, and S are the photon density, mode volume, and spontaneous emission rate into the lasing mode. g' and τ are the derivative of gain with respect to carrier density and the unpumped photon lifetime of the lasing mode. In the analysis of Ref. 4, the loading caused by a single mode of the passive resonator was considered. In the present case, several passive modes are involved in the coupling since tuning is through an antiresonance of the passive cavity. Consequently, only the qualitative predictions of Ref. 4 remain valid in the present case. In another paper, we give a more detailed analysis in which loading by all modes of the passive resonator is included in the determination of effective quantities.[5] The basic result remains unchanged, however, in that the effective quantities are functions of passive resonator tuning through the detuned loading mechanism. In this measurement, they vary as the passive resonator is tuned piezoelectrically.

In Fig. 2, we show the measured modulation response for this device taken at extremes of the tuning region for a single mode. The output powers (and, hence, the photon densities) at these points were the same (output power ≈ 1 mW). The effective photon lifetimes are also equal in the two cases, as these are endpoints of the tuning range. Therefore, from Eq. (1), the observed corner frequency variation from 1.6 to

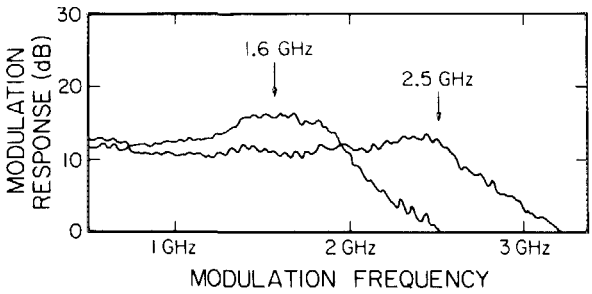

FIG. 2. Modulation response for coupled-cavity system measured at extremes of the tuning range of a particular mode. The observed variation in corner frequency is caused entirely by the detuned loading mechanism.

2.5 GHz results solely from variation of the effective differential gain with tuning, i.e., from the detuned loading effect. In this case, the net variation in g'_{eff} was roughly $2\times$. Qualitative measurements of frequency modulation were also performed at these tuning extremes by using the low-resolution Fabry–Perot to measure suppression of the optical carrier under direct modulation. These measurements showed that the FM component of modulation was smaller (i.e., the optical carrier was larger) at the tuning extreme where modulation bandwidth was enhanced.

We also measured linewidth as a function of tuning in this device to verify that $(1+\alpha^2)_{\text{eff}}$ could be controlled. These data are presented with additional modulation corner frequency data in Fig. 3. Again, the data were taken over a single tuning range at roughly 1-mW output power. It can be seen that linewidth varied from around 180 MHz at one extreme of the tuning range to below 60 MHz at the other extreme. Resolution in this measurement was limited by microphonics coupling into the system through the concave mirror mount. If we again compare results at the extremes of the tuning ranges, where photon density and photon lifetime are identical, then from Eq. (2) we conclude that $(1+\alpha^2)_{\text{eff}}$ has varied by at least $3\times$ as a result of the detuned loading effect. It is also interesting to note that, as predicted in Ref. 4, over the same tuning range for which linewidth is decreasing, modulation response is increasing. The variations in these quantities are smaller than predicted in Ref. 4, however. This is primarily the result of tuning in the antiresonant region of the passive cavity and will be discussed in greater detail elsewhere.[5]

In summary, we have presented the first experimental observation of the detuned loading effect in semiconductor lasers. The implementation of this mechanism employed

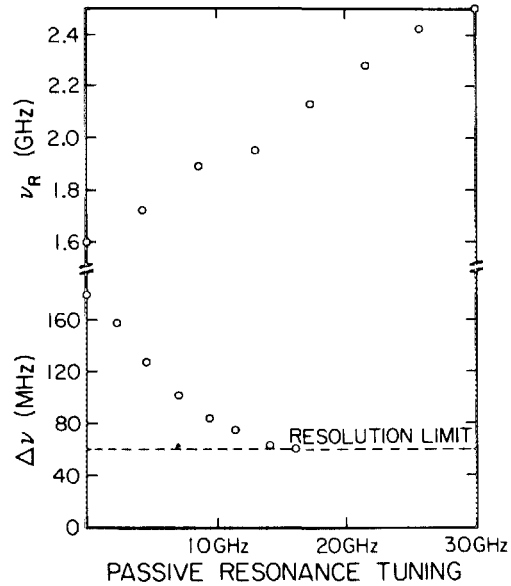

FIG. 3. Linewidth and modulation corner frequency measured vs tuning of the passive cavity resonances near the lasing frequency. The observed variations result primarily from the detuned loading mechanism.

here involved a small passive resonator coupled to an active resonator, and the variation of effective quantities with tuning of the passive resonator was inferred from modulation corner frequency and field spectrum linewidth measurements. These variations, though sizable, were limited by antiresonant tuning, as discussed earlier. We believe that much larger variations may be possible in systems that can be resonantly tuned, such as in the cleaved coupled-cavity device.[7] It is important to stress that the detuned loading mechanism is more general than the coupled-cavity context of this letter. For instance, we predict similar results in lasers having distributed feedback.[4,5]

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[1]K. Y. Lau, N. Bar Chaim, I. Ury, Ch. Harder, and A. Yariv, Appl. Phys. Lett. **43**, 1 (1983).
[2]Ch. Harder, K. Vahala, and A. Yariv, Appl. Phys. Lett. **42**, 328 (1983).
[3]M. Fleming and A. Mooradian, Appl. Phys. Lett. **38**, 511 (1981).
[4]K. Vahala and A. Yariv, Appl. Phys. Lett. **45**, 501 (1984).
[5]K. Vahala, J. Paslaski, and A. Yariv (unpublished).
[6]J. Paslaski, K. Vahala, and A. Yariv (unpublished).
[7]W. T. Tsang, N. A. Olsson, and R. A. Logan, Appl. Phys. Lett. **42**, 650 (1983).