tudinal mode behaviors of mode-stabilized $Al_xGa_{1-x}As$ injection lasers," *J. Appl. Phys.*, vol. 49, pp. 4644-4648, Sept. 1978.
[66] H. Olesen, E. Nicolaisen, and M. Danielsen, "Quantitative experimental results on modal distortion and comparison with theory based on AM-FM conversion," in *Proc. 6th Eur. Conf. Opt. Commun.*, York, England, Sept. 1980, pp. 84-87.
[67] K. Petermann, "Nonlinear distortions due to fibre connectors," in *Proc. 6th Eur. Conf. Opt. Commun.*, York, England, Sept. 1980, pp. 80-83.
[68] H. G. Unger, "Optical pulse distortion in glass fibres at the wavelength of minimum dispersion," *Arch. Elektr. Übertr.*, vol. 31, pp. 518-520, Dec. 1977.
[69] K. Furuya, M. Miyamoto, and Y. Suematsu, "Bandwidth of single mode optical fibers," *Trans. IECE Japan*, vol. E 62, pp. 305-310, May 1979.
[70] F. P. Kapron, "Baseband response function of monomode fibers," in *Proc. Top. Meet. Opt. Fiber Commun.*, Washington, DC, Mar. 6-8, 1979, p. 104, paper ThC5.
[71] D. Marcuse, "Pulse distortion in single-mode fibers," *Appl. Opt.*, vol. 19, pp. 1653-1660, May 15, 1980.
[72] S. C. Rashleigh and R. Ulrich, "Polarization mode dispersion in single-mode fibers," *Opt. Lett.*, vol. 3, pp. 60-62, Aug. 1978.
[73] W. A. Gambling, H. Matsumura, and C. M. Ragdale, "Joint loss in single-mode fibres," *Electron. Lett.*, vol. 14, pp. 491-493, July 20, 1978.
[74] K. Petermann, "Nonlinear transmission behaviour of a single-mode fibre transmission line due to polarization coupling," *J. Opt. Commun.*, vol. 2, pp. 59-64, June 15, 1981.
[75] K. Petermann, "Transmission characteristics of a single-mode fibre transmission line with polarization coupling," in *Proc. 7th Eur. Conf. Opt. Commun.*, Copenhagen, Denmark, Sept. 1981, paper 3.2.

Klaus Petermann (M'76) was born in Mannheim, Germany, on October 2, 1951. He received the Dipl.Ing. degree in 1974 and the Dr. Ing. degree in 1976, both in electrical engineering from the Technische Universität, Braunschweig, Germany.

From 1974 to 1976 he was a Research Associate at the Institut für Hochfrequenztechnik, Technische Universität, Braunschweig, where he worked on optical waveguide theory. Since 1977 he has been with AEG-Telefunken Forschungsinstitut, Ulm, Germany, where he is engaged in research work on semiconductor lasers and optical fibers.

Dr. Petermann is a member of the Nachrichtentechnische Gesellschaft in the Verein Deutscher Elektrotechniker (VDE).

Günther Arnold was born in Jena, Germany, on April 7, 1932. He received the Dipl.Phys. degree in physics from the University of Jena, Germany, in 1958, and the Dr.rer.nat. degree from the University of Ulm, Germany, in 1976.

From 1958 to 1960 he was responsible for the spectroscopy laboratory at Light & Co., Colnbrook, England. From 1960 to 1964 he was a member of the Max Planck Institut für Spektroskopie, Göttingen, Germany, and worked on reaction kinetics and molecular spectroscopy. In 1965 he joined the Research Institut of AEG-Telefunken, Ulm, Germany. After structural research work on UV-sensitive films for optical data storage, he joined the optical communication group in 1973 and is engaged in research work on semiconductor laser properties.

Spectral Characteristics of Semiconductor Lasers with Optical Feedback

LEW GOLDBERG, HENRY F. TAYLOR, SENIOR MEMBER, IEEE, ANTHONY DANDRIDGE, JOSEPH F. WELLER, AND RONALD O. MILES, MEMBER, IEEE

***Abstract*—Optical feedback-induced changes in the output spectra of several GaAlAs lasers operating at 0.83 μm are described. The feedback radiation obtained from a mirror 60 cm away from the laser is controlled in intensity and phase. Spectral line narrowing or broadening is observed in each laser depending on the feedback conditions. Minimum linewidths observed with feedback are less than 100 kHz. Improved wavelength stability is also obtained with optical feedback resulting in 15 dB less phase noise. An analytical model for the three-mirror cavity is developed to explain these observations.**

I. Introduction

THE spectral characteristics of single-mode semiconductor lasers are important in determining the performance of optical fiber transmission systems and optical fiber sensors. Narrow spectral linewidth and low frequency wavelength stability are particularly vital in optical heterodyne communication systems [1] and interferometric fiber sensors with a large pathlength difference [2], [3].

Changes in the spectral characteristics of a single-mode laser occur when a portion of the laser output is fed back into the laser cavity after reflection from an external mirror, grating, or a fiber end. Feedback-induced effects previously observed are linewidth broadening [4], [5], line narrowing [6], [7], and reduction of low frequency wavelength fluctuations [8]. As shown in Fig. 1, the external reflector extends the normal laser cavity. The resulting cavity is composed of three mirrors; these include the two end facets of the semiconductor laser separated by a distance l, and the external reflecting surface that is a distance L from the laser diode. The reflectivity of the end facets on the laser are R_0 and R_1, respectively, and the external reflector has a reflectivity r.

Here we report the theoretical and experimental results on the effect of feedback on laser diode emission characteristics. Formulas for predicting the presence of external cavity modes and for feedback-induced line narrowing and phase noise

Manuscript received November 12, 1981; revised December 9, 1981. This work was supported by DARPA and Naval Electronics Systems Command.

The authors are with the Naval Research Laboratory, Washington, DC 20375.

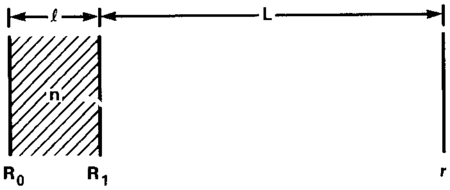


Fig. 1. Schematic representation of laser diode with external optical feedback.

reduction are derived. Experimental results on the spectral characteristics of several single-mode lasers emitting near 0.83 μm are also reported and compared with predictions.

II. Theory

A simple analysis of the three-mirror cavity of Fig. 1 is useful in explaining many of our observations on feedback, including the presence of strong external cavity mode spectra, longitudinal mode instability, line narrowing, and phase noise reduction. It is assumed that $r << R_1$, so the external cavity can be regarded as a wavelength-dependent perturbation in the round-trip phase shift θ for the primary cavity, and the effective reflectivity of the adjacent facet. The amplitude A of the wave reflected from the facet of reflectivity R_1 is

$$A = \sqrt{R_1} + (1 - R_1)\sqrt{r}\, e^{i\theta_1} \tag{1}$$

where $\theta_1 = 4\pi L/\lambda$, λ is the free-space wavelength, and the incident wave has an amplitude equal to unity. It follows from this expression and the assumption of small r that the primary cavity phase shift can be written

$$\theta = \theta_2 + \frac{(1 - R_1)\sqrt{r}}{\sqrt{R_1}} \sin \theta_1. \tag{2}$$

With $\theta_2 = 4\pi nl/\lambda$, we rewrite (2) as

$$\theta = \frac{4\pi nl}{\lambda} + \frac{(1 - R_1)\sqrt{r}}{\sqrt{R_1}} \sin\left(\frac{4\pi L}{\lambda}\right). \tag{3}$$

This equation will be used extensively in our treatment of feedback effects in laser diodes.

External Cavity Modes

In the absence of feedback, the modes of the Fabry–Perot laser cavity must satisfy the relation

$$\theta = 2\pi I, \quad I \text{ integer}. \tag{4}$$

We consider a single-mode laser characterized by the integer I_0 with a lasing wavelength $\lambda_0 = 2nl/I_0$. For small deviations in λ from λ_0, θ is a linearly decreasing function of λ given by

$$\theta = 2I_0\pi - \frac{4\pi nl(\lambda - \lambda_0)}{\lambda_0^2}. \tag{5}$$

When feedback is present, the mode of the three mirror cavity must still satisfy (4) but θ is no longer a linear function of λ. This is illustrated by plots of θ as a function of λ for increasing levels of feedback in Fig. 2. For sufficiently small r [Fig. 2(a) and (b)], only one mode is present, but at the highest feedback level [Fig. 2(c)], (3) is satisfied for multiple values of λ. Note, however, that changing the phase of the feedback, e.g., by varying L by a fraction of a wavelength, is equivalent to translating the ripple in the curves diagonally along the line corresponding to $r = 0$. Thus, altering the phase $\theta_1(\lambda_0)$ by π rads at constant feedback causes a change from single-mode operation [Fig. 2(b)] to the multimode case [Fig. 2(d)]. In general, if r is less than some value r_a, then $\theta(\lambda)$ will decrease monotonically and the laser will remain single-mode regardless of the phase of the feedback. For larger feedback values, $\theta(\lambda)$ is no longer monotonically decreasing and the laser will exhibit multiple external cavity modes for at least some range of phase of the feedback. Finally, for r greater than a second value r_b for which a minimum in $\theta(\lambda)$ is lower than the next two subsequent maxima, as in Fig. 2(c), the laser will be multimode regardless of the phase of the feedback. These three regimes of operation are summarized in Table I.

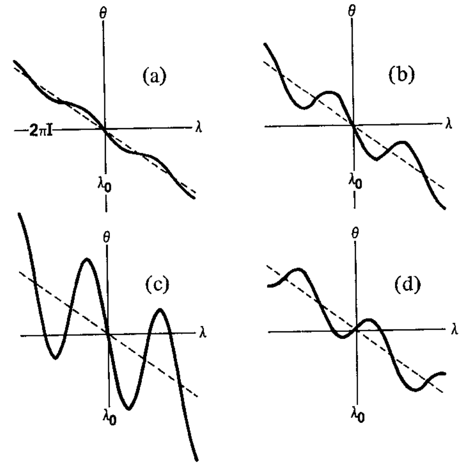


Fig. 2. Wavelength dependence of round-trip phase shift in primary cavity plotted for different levels of feedback: (a) low feedback, single-mode operation; (b) moderate feedback, single-mode operation; (c) high feedback, multiple external cavity mode operation. In (d), the feedback level is the same as (b), but the phase in the external cavity is shifted by π rads to give multimode operation. In (a)–(d) the dashed curve corresponds to no feedback ($r = 0$).

Expressions for the values r_a and r_b will now be derived. First, for multiple cavity modes to exist the condition $d\theta/d\lambda = 0$ must be satisfied for some value of λ. Differentiating (3) yields the condition

$$\cos\left(\frac{4\pi L}{\lambda}\right) = -\frac{nl}{L}\frac{\sqrt{R_1}}{\sqrt{r}(1 - R_1)}. \tag{6}$$

The smallest value of r for which this condition is satisfied is r_a. This value, which occurs for $\cos(4\pi L/\lambda) = -1$, is given by

$$r_a = \frac{(nl)^2 R_1}{L^2(1 - R_1)^2}. \tag{7}$$

The conditions which determine r_b are that $\theta(\lambda_+) = \theta(\lambda_-)$ and $(d\theta/d\lambda)_{\lambda_+} = (d\theta/d\lambda)_{\lambda_-} = 0$ for some λ_+ and λ_-, with $\lambda_+ > \lambda_-$. Without loss of generality, we assume that $\theta(\lambda_0) = 2\pi I$, as in Fig. 2(c). The first condition will then be satisfied if $\theta(\lambda_+) = \theta(\lambda_0)$. From (2), the first condition is satisfied for

$$4\pi nl\left(\frac{1}{\lambda_+} - \frac{1}{\lambda_0}\right) + \frac{(1 - R_1)\sqrt{r_b}}{\sqrt{R_1}} \sin\left(\frac{4\pi L}{\lambda_+}\right) = 0. \tag{8}$$

After differentiating (3) with respect to λ, the second condition requires that

$$\frac{4\pi nl}{\lambda_+^2} + \frac{4\pi L}{\lambda_+^2}\frac{(1 - R_1)\sqrt{r_b}}{\sqrt{R_1}} \cos\left(\frac{4\pi L}{\lambda_+}\right) = 0 \tag{9}$$

which is approximately correct if $\theta(\lambda_+)$ is the first maximum in

TABLE I
CAVITY MODE REFLECTANCE REGIMES

	Number of modes in a longitudinal mode group
$r < r_a$	1
$r_a < r < r_b$	1 or 3, depending on phase of feedback
$r > r_b$	3 or more

$\theta(\lambda)$ for λ greater than λ_0. As a trial solution, we assume that $\sin(4\pi L/\lambda_+) = -1$. This implies that $4\pi L(1/\lambda_+ - 1/\lambda_0) = -3\pi/2$. Substituting these results into (8) yields

$$r_b = \left(\frac{3\pi}{2}\right)^2 \frac{(nl)^2 R_1}{L^2(1-R_1)^2}. \tag{10}$$

The more accurate result, which requires the simultaneous solution of (8) and (9), is

$$r_b = 1.047 \left(\frac{3\pi}{2}\right)^2 \frac{(nl)^2 R_1}{L^2(1-R_1)^2}. \tag{11}$$

Laser Line Narrowing

In treating laser line narrowing due to feedback, we consider first a resonator pumped internally from an energy source (in this case, spontaneous emission) of spectral power density P_{λ_0}. The spectral power density P_λ in the resonator is given by

$$P_\lambda = \frac{P_{\lambda_0}}{1 + R_0 R_1 G^2 - 2\sqrt{R_0 R_1}\, G \cos\theta} \tag{12}$$

where R_0 and R_1 are the mirror reflectivities, G is the single-pass cavity gain, and θ is the round-trip phase shift in the cavity given by (3) [9]. Greatest line narrowing is obtained when $|d\theta/d\lambda|$ is a maximum. Differentiating (3) gives us

$$\frac{d\theta}{d\lambda} = -t_0 \left[1 + \gamma \cos\left(\frac{4\pi L}{\lambda}\right)\right] \tag{13}$$

with

$$t_0 = \frac{4\pi nl}{\lambda^2} \tag{14}$$

$$\gamma = \frac{(1-R_1)\sqrt{r}L}{\sqrt{R_1}\, nl}. \tag{15}$$

The narrowest line is obtained by adjusting the length of the external cavity to give $\theta_1 = 2\pi J$, J integer, so that $\cos\theta_1 = 1$. Since the resonance condition requires that $\theta = 2\pi I$, I integer, then θ_2 must also satisfy such a condition, i.e., $\theta_2 = 2\pi K$, K integer. It is also evident from (3) that under these conditions, the effective facet reflectivity, is a maximum so the laser is at a stable operating point. It follows from (13) that dependence of θ on $\Delta\lambda$ for small $\Delta\lambda$ is given by

$$\theta = 2I_0\pi - t_0(1+\gamma)\Delta\lambda \tag{16}$$

with

$$\Delta\lambda = \lambda - \lambda_0$$

where λ_0 corresponds to the center of the lasing spectrum without feedback, and with feedback when the external cavity length is adjusted for the narrowest line.

The dependence of effective facet reflectivity R_1' will vary periodically with wavelength as illustrated in Fig. 3. This variation, which should also be taken into account in computing the linewidth, is calculated from (1), with $R_1' = |A|^2$, to be

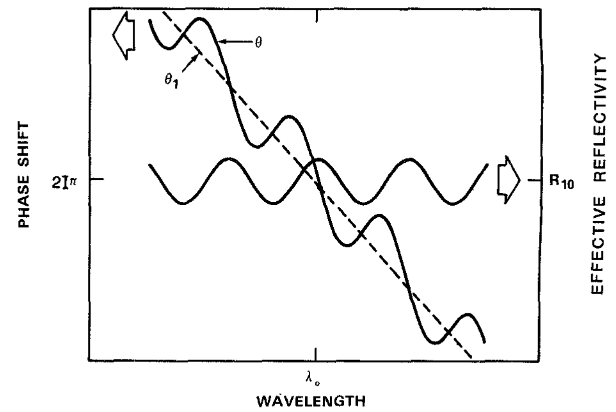


Fig. 3. Round-trip phase shift and reflectivity plotted as a function of wavelength. The dashed wave corresponding to the phase shift for $r = 0$ is included for comparison.

$$R_1' = R_1 + r(1-R_1)^2 + 2\sqrt{R_1 r}(1-R_1)\cos\theta_1.$$

For the conditions on θ_1 and θ_2 indicated above, this can be written

$$R_1' = R_{10} - \sqrt{R_1 r}(1-R_1)\theta_1^2$$

with $R_{10} = R_1 + (1-R_1)^2 r + 2\sqrt{R_1 r}(1-R_1)$. In terms of $\Delta\lambda$, this can be written

$$R_1' \simeq R_{10}[1 - \mu(\Delta\lambda)^2] \tag{17}$$

with

$$\mu = \frac{\sqrt{r}}{\sqrt{R_1}}(1-R_1)\left(\frac{t_0 L}{nl}\right)^2$$

and it is assumed that $R_{10} \sim R_1$.

These results can now be used to determine the dependence of of linewidth on feedback. If we define

$$\delta = 1 - \sqrt{R_0 R_1'}\, G$$

it follows from (17) that

$$\delta \simeq \delta_0 + \tfrac{1}{2}\mu(\Delta\lambda)^2$$

where

$$\delta_0 = 1 - \sqrt{R_0 R_{10}}\, G.$$

Recalling the assumption that $|\theta - 2I\pi| << 1$, then

$$\cos\theta \simeq 1 - \frac{(\theta - 2I_0\pi)^2}{2}$$

or, from (16),

$$\cos\theta \simeq 1 - \left[\frac{t_0(1+\gamma)\Delta\lambda}{2}\right]^2.$$

Substituting those results into (12) gives the result

$$\frac{P_\lambda}{P_{\lambda_0}} = \left\{1 + \left[1 - \delta_0 - \frac{\mu}{2}(\Delta\lambda)^2\right]^2 - 2\left[1 - \delta_0 - \frac{1}{2}\mu(\Delta\lambda)^2\right]\left[1 - \frac{(1+\gamma)^2(t_0\Delta\lambda)^2}{2}\right]\right\}^{-1}.$$

Keeping terms to second order in δ_0 and $\Delta\lambda$ yields

$$\frac{P_\lambda}{P_{\lambda_0}} = \frac{1}{\delta_0^2 + (1+\gamma)^2 t_0(\Delta\lambda)^2}. \tag{18}$$

This gives the familiar Lorentzian shape for the lasing line. However, in order for the total power in the lasing mode to remain constant as the feedback level is increased, the gain in the cavity must increase to compensate for the line narrowing. We take this into account by writing

$$\delta_0 = C\delta_0'$$

where δ_0' is the value of δ_0 in the absence of feedback, and the value of C is feedback-dependent. We then write the total power P as an integral of the power density over wavelength given by

$$P = P_{\lambda_0} \int_{-\infty}^{\infty} \frac{d(\Delta\lambda)}{C^2\delta_0'^2 + (1+\gamma)^2 t_0^2(\Delta\lambda)^2}$$

which yields

$$P = \frac{\pi P_{\lambda_0}}{\delta_0' C t_0 (1+\gamma)}.$$

The requirement for constant total power in the mode implies that $C = (1+\gamma)^{-1}$, so (18) becomes

$$\frac{P_\lambda}{P_{\lambda_0}} = \frac{(1+\gamma)^2}{\delta_0'^2 + (1+\gamma)^4 t_0^2(\Delta\lambda)^2}.$$

It follows from this expression that the full spectral width to half maximum power points $(\Delta\lambda)_{1/2}$ is given by

$$(\Delta\lambda)_{1/2} = \frac{\delta_0'}{(1+\gamma)^2 t_0}.$$

In terms of the linewidth for no feedback $\Delta\lambda_0$

$$\Delta\lambda_{1/2} = \frac{\Delta\lambda_0}{(1+\gamma)^2} \tag{19}$$

with γ given by (15).

Frequency or Phase Noise Reduction

Frequency stability of the laser is also improved by feedback. We assume that the frequency fluctuations $\Delta\nu$ arise from a change in the refractive index-length product $\Delta(nl)$. From (3) it follows that

$$\Delta\theta = \frac{4\pi\Delta(nl)}{\lambda} - \left[\frac{4\pi}{\lambda^2}(nl) + \frac{(1-R_1)\sqrt{r}L}{\sqrt{R_1}}\right]\Delta\lambda. \tag{20}$$

But the lasing mode must satisfy the condition that θ equals an integral multiple of 2π rads. Thus, in (20) $\Delta\theta = 0$. Using this result and the relation for γ in (15), we find that

$$\Delta\lambda = \frac{\lambda\Delta(nl)}{nl[1+\gamma]}.$$

Letting $\Delta\nu_0$ equal the frequency change in the absence of feedback, and noting that $\Delta\nu = -(c/\lambda^2)\Delta\lambda$, we find that

$$\Delta\nu = \frac{\Delta\nu_0}{(1+\gamma)} \tag{21}$$

with

$$\Delta\nu_0 = -\frac{\Delta(nl)c}{\lambda_0 nl}.$$

III. Experimental

In the experiments described here, the linewidth and other spectral characteristics of several Hitachi HLP 1400 channeled substrate planar (CSP) lasers and a HLP 3400 buried heterostructure (BH) laser are measured as a function of optical feedback into the laser cavity. Fig. 4 gives a schematic representation of the laser with feedback and the measuring apparatus. Controlled optical feedback is provided by an external cavity consisting of the laser (LD), a collimating microscope lens, a beam splitter (BS1), a variable neutral density filter (ND1), a focusing microscope lens, and a mirror (M) mounted on a piezoelectric transducer stage. The separation L between the feedback mirror and the laser diode is 60 cm. The intensity of light fed back into the laser is changed with the variable neutral density filter, while its phase is controlled by the voltage applied to the piezoelectric transducer.

The equivalent reflectivity of the external feedback cavity is taken as

$$r = T^2 r'$$

where T is the one-way transmission of the external cavity and r' is the reflectivity of the mirror M. The value of T was measured as the ratio between power incident on M and the total power output from a single laser facet.

Two techniques are used to measure the spectral characteristics of the laser diode operating with or without feedback. Over large frequency ranges a scanning Fabry–Perot interferometer (FPI) examines the optical radiation exiting one facet of the laser diode. The FPI is isolated from the laser by a quarter-wave plate (QW)-polarizer (P) combination and a neutral density filter (ND2). Two different mirror separations on the FPI are employed to give free spectral ranges of either 1.7 GHz or 1200 GHz. The best resolution obtained with the FPI is approximately 30 MHz.

In order to measure smaller linewidths, a delayed self-heterodyne technique [10] is used to examine a portion of the beam exiting the other facet of the laser. The linewidth measuring portion of the experimental setup (inside the dashed lines in Fig. 4) is isolated from the laser diode by a Faraday isolator that rejects reflected light of all polarizations. Collimated light from the laser is divided by a beam splitter (BS2), then coupled into two arms of a single-mode fiber interferometer. Reflections from the fiber ends are minimized by inserting index-matching fluid between a fiber end and a tilted glass slide. Light coupled into the short interferometer arm is frequency shifted by an acoustooptic cell (AO) operating at 90 MHz. The long interferometer arm provides a 4 μs time delay corresponding to approximately 100 kHz frequency resolution of the linewidth measurement. After the optical signals from the two interferometer arms are combined using a single-mode fiber coupler [11] (FC), they are mixed by an avalanche photodiode (APD). The beat signal centered at 90 MHz is displayed on a spectrum analyzer. The FWHM linewidth of a Lorentzian laser emission line is taken

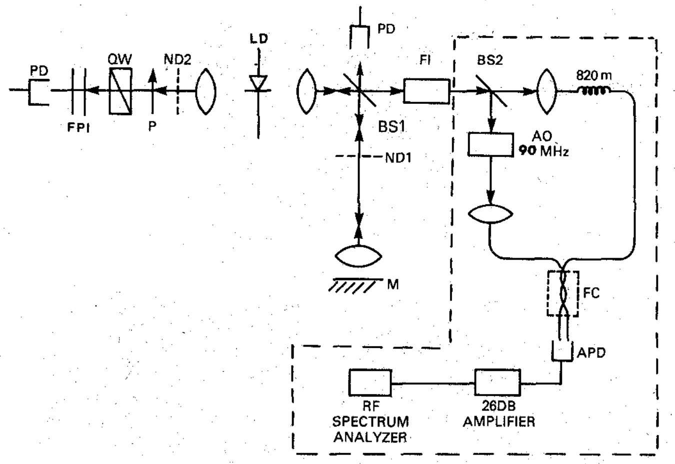


Fig. 4. Experimental arrangement for observing emission spectra of lasers with optical feedback. The delayed self-heterodyne system is within dashed lines. PD–photodetector, FPI–Fabry-Perot interferometer, QW–quarter waveplate, ND–neutral density filter, LD–laser diode, BS–beam splitter, M–mirror, FI–Faraday isolator, AO–acoustooptic Bragg cell, FC–single-mode fiber coupler.

as one half the spectral width of the beat signal observed on the spectrum analyzer display.

IV. Results

Feedback-induced changes in the laser emission spectra are pictorially outlined in Fig. 5. In the free-running state (i.e., no feedback), the lasers tested emitted in one of the laser cavity longitudinal modes (LM), as shown in Fig. 5(a). The frequency separation of the LM's, given by $c/2nl$, is approximately 130 GHz for the four lasers used in the measurements. The free-running laser emission linewidth is 17 ± 3 MHz at $I/I_{th} = 1.1$–1.3 for the lasers tested.

In the presence of optical feedback, several peaks corresponding to the longitudinal modes of the external cavity, appear in the laser emission spectrum shown in Fig. 5(b). These external cavity modes (XCM's) have a frequency separation given by $c/2L$, or 250 MHz for an external cavity length of $L = 60$ cm. At low feedback levels, the emission spectrum consists of a single dominant XCM surrounded by a few modes of much smaller intensity [Fig. 5(b)]. The spectral linewidth of the dominant XCM decreases with increasing feedback so that it becomes much narrower than the free-running laser emission. At high feedback levels, the emission spectrum is composed of several XCM groups as shown in Fig. 5(c), and is no longer truly single-mode. The center wavelength of each of the groups corresponds to a longitudinal mode of the free-running laser. Each XCM group consists of many external cavity modes of comparable power.

Experimental data illustrating the effects depicted in Fig. 5 are given in the next three figures for three spectral resolution levels. Fig. 6 shows the low resolution spectra measured with the FPI at 1200 GHz free spectral range for four feedback levels: $r = 0$ in Fig. 6(a); $r = 1.9 \times 10^{-4}$ in Fig. 6(b); $r = 4.2 \times 10^{-4}$ in Fig. 6(c); and $r = 2.9 \times 10^{-3}$ in Fig. 6(d). Medium resolution spectra with a FPI free spectral range of 1.7 GHz are given in Fig. 7 at the same feedback levels. Fig. 8 shows high-spectral-resolution measurements made with the fiber interferometer. In that case the peaks correspond to

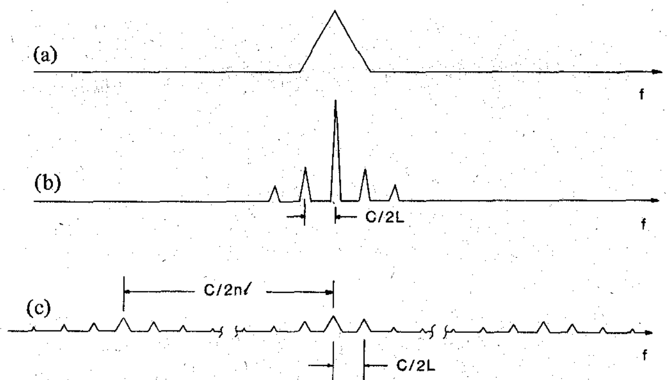


Fig. 5. Pictorial representation of emission spectra of laser operating with: (a) no feedback, (b) low feedback power, (c) high feedback power.

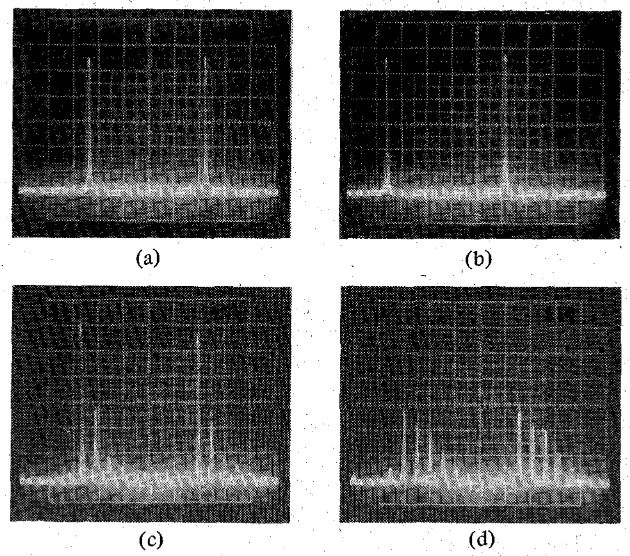


Fig. 6. FPI scans of emission spectra of laser CSP 7287 operating with feedback of: (a) $r = 0$, (b) $r = 1.9 \times 10^{-4}$, (c) $r = 4.2 \times 10^{-4}$, (d) $r = 2.9 \times 10^{-3}$, $I/I_{th} = 1.1$. The FPI free spectral range is 1200 GHz and two spectral orders appear in each case. Several XCM groups, each represented by a narrow peak and spaced by 130 GHz appear in (c) and (d).

XCM beat frequencies of 0 MHz, 250 MHz, 500 MHz, $\cdots$ shifted by the ± 90 MHz Bragg cell frequency. A summary of experimental results illustrated in those figures is contained in Table II.

Some other aspects of the feedback-induced changes in the emission spectra of several lasers are discussed below.

External Cavity Modes

The spectral purity of the emission of lasers operating in the low feedback regime depends, in part, on the relative strength of the XCM's adjacent to the dominant mode. We define M as the ratio of the optical power emitted in the dominant XCM to that in one of the adjacent modes. Fig. 9 shows the measured dependence of M on the feedback r, for two CSP lasers. The measurement is made using an FPI. Before each measurement of M is made, the feedback phase θ is adjusted to maximize the dominant mode height. A sufficient change in phase induces the laser emission to hop from one XCM to an

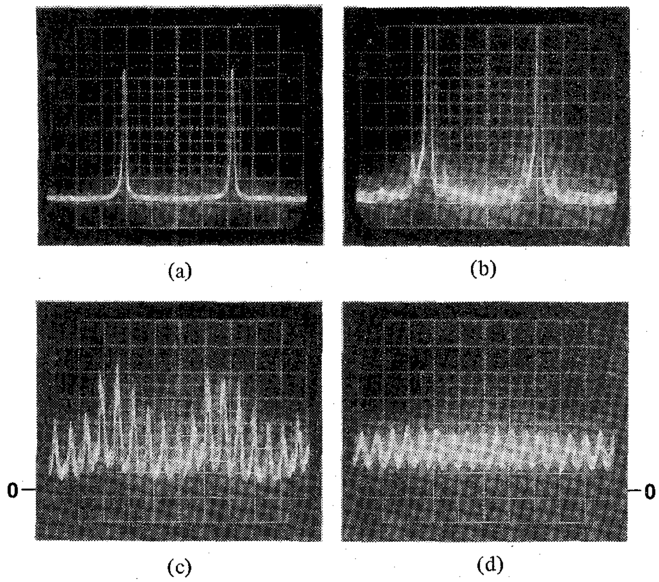


Fig. 7. FPI scans of emission spectra of laser CSP 7287. The free spectral range is 1.7 GHz, and two FPI spectral orders appear in each case. Laser operating conditions in (a)–(d) are the same as in Fig. 6 (a)–(d). External cavity modes appear in (b), (c), (d). In (b) only the bottom section of the central peak is visible, $M = 40$. FPI mirror spacing is such that laser cavity modes (LM's) overlapped on the display.

adjacent one (similar mode hopping also occurs when the laser temperature shifts due to changes in the ambient conditions or the laser current). Note that for laser CSP 7287, M gradually decreases with increasing feedback from 80 at 6.5×10^{-7} to 35 at 2.5×10^{-3}. This change is mainly due to a gradual increase in the height of the side modes, with the dominant mode height remaining relatively constant. An abrupt transition from primarily a single XCM emission to a multimode one ($M < 10$) occurs when the feedback exceeds a critical level $r_b \cong 3 \times 10^{-4}$ (r_b defined in Section II). In the multi-XCM region of operation the emission also occurs in several XCM groups 130 GHz apart. Emission spectra of a laser operating in this feedback region are shown in Figs. 5, 6, and 7(c) and (d). For feedback levels approaching but less than r_b, laser emission is single or multimode depending on the feedback phase θ. As r gets closer to r_b, the range of θ for which single-mode operation is possible becomes smaller until it is zero at $r \cong r_b$. Frequency instability of the laser, in the form of random hopping between XCM's within a single XCM group and between several XCM groups, is observed for feedback levels in the single to multimode transition region, $3 \times 10^{-4} < r < 5 \times 10^{-4}$. Two other lasers, another CSP and a buried heterostructure, exhibit similar behavior.

On the other hand, the magnitude of M for laser CSP 6189 shown in Fig. 9 exhibits a more gradual change with feedback than did the other lasers tested. For feedback levels, $r < 2.0 \times 10^{-5}$, the change in M is primarily due to an increase in the height of the side modes, with the height of the dominant mode remaining constant. For $r > 2.0 \times 10^{-5}$ the height of the two XCM's adjacent to the dominant mode remains relatively constant while the height of the dominant mode decreases with increasing feedback. This decrease is accompanied by an increase of optical power in the cavity modes which are

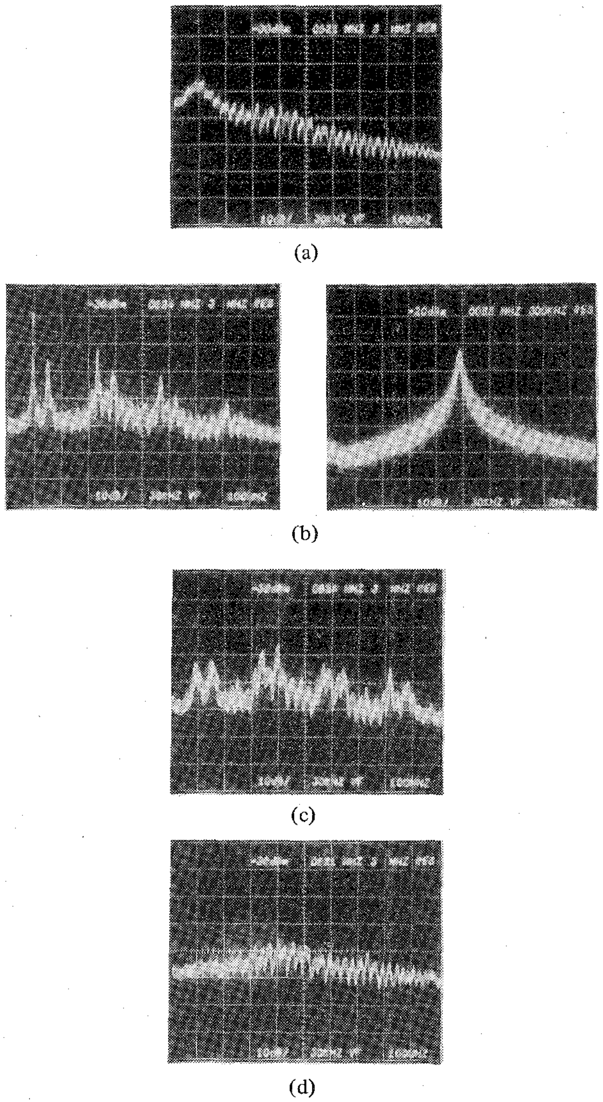


Fig. 8. Spectrum analyzer display of the self-heterodyne beat signal. The laser is CSP 7287 and operating conditions in (a)–(d) are the same as in Fig. 6(a)–(d). Dispersion in 100 MHz/div except in right half of (b) where it is 2 MHz/div. The dominant XCM is represented by a narrow peak at 90 MHz in the left half of (b). An expanded display of the peak is shown in the right half of (b).

TABLE II
SUMMARY OF OBSERVED LASER SPECTRA AT VARIOUS FEEDBACK LEVELS

r	low resolution (Fig. 6)	medium resolution (Fig. 7)	high resolution (Fig. 8)
0	Single LM	No XCMs	Spectral width of central peak = 17 MHz
1.9×10^{-4}	Single LM	Weak XCMs	Spectral width of central peak = .1 MHz
4.2×10^{-4}	Several LMs	Strong XCMs	Multiple XCM beat spectra
2.9×10^{-3}	Several LMs	Strong XCMs, spectrally broadened	Multiple XCM beat spectra

separated in frequency by 500, 750, 1000 MHz $\cdots$ from the dominant mode; line broadening of the dominant XCM also occurs as will be discussed later.

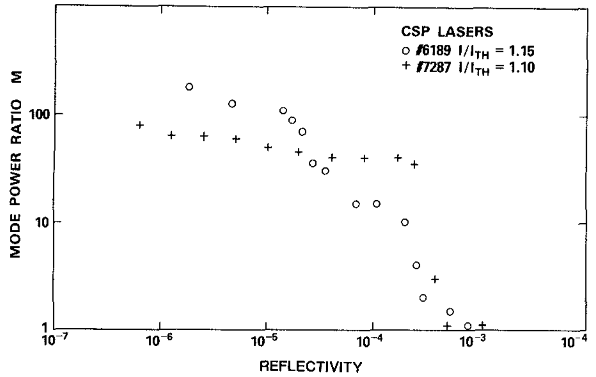


Fig. 9. Ratio M between power in the dominant mode and the adjacent XCM.

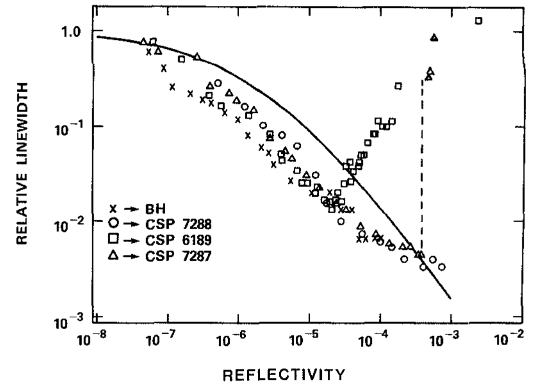


Fig. 10. Linewidths of the dominant XCM normalized by the free-running laser linewidths. The vertical dashed line corresponds to the abrupt transition where laser 7287 goes from single to multimode operation.

Line Narrowing

In the feedback region of single-mode operation ($M > 10$), the spectral linewidth of the laser emission can be considered to be equivalent to the linewidth of the dominant mode. This linewidth, measured with the heterodyne technique, is found to undergo significant narrowing with increasing feedback, as shown in Fig. 10. The solid line in Fig. 10 is a theoretical plot given by (19) of the linewidth dependency on optical feedback from an external source. Measured data are normalized to the free-running laser linewidth. In all cases, the feedback phase θ is adjusted to obtain a minimum width of the beat signal displayed on the spectrum analyzer. However, it should be noted that for low values of feedback, corresponding to Fig. 2(a), it is also possible by appropriate choice of θ to induce emission linewidth which is broader than that of a free running laser.

Spectrum analyzer displays of the beat signal generated by a free-running and line-narrowed laser are shown in Fig. 7(a) and (b). Minimum linewidths in all lasers except the CSP 6189 are obtained at maximum feedback levels at which it is still possible (by adjusting θ) to obtain single-mode emission. Laser CSP 6189 exhibits minimum linewidth at feedback level $r = 2 \times 10^{-5}$, with a further increase of feedback intensity resulting in spectral broadening of the dominant mode. The minimum linewidth measured with feedback in the lasers tested is 100 kHz with the exception of CSP 6189 for which it is 300 kHz.

Line Broadening

Feedback-induced broadening of the total laser diode emission is observed to result from two phenomena, broadening of the individual XCM's and broadening of XCM groups. In two of the CSP lasers and the BH laser, for $r > r_b$, the emission spectra abruptly change from a dominant single-mode that is 100 kHz wide to many XCM's that are each 5-10 MHz in width. The linewidth continues to broaden once beyond this transition. Such behavior is shown in Fig. 10 by the vertical dashed line for one of the CSP lasers; another CSP laser indicated in Fig. 10 showed a similar but more gradual increase. For all lasers with sufficient feedback, the spectral width of each external cavity mode becomes comparable to the mode spacing of 250 MHz. The spectra of the individual external cavity modes within a single XCM group then coalesce together as shown in Fig. 7(d) where the onset of this condition can be recognized. Thus, each XCM group takes on a smooth envelope representing the convoluted spectrum of the individual external cavity modes.

The FWHM linewidth of the convoluted spectrum of an individual XCM group also broadens with increasing optical feedback. For the feedback region of multimode operation, the distribution of optical power among the many external cavity modes within an individual XCM group becomes more uniform with increasing feedback. This effect can be seen in the FPI scan in Fig. 7(d). As a result, the envelope of the convoluted spectrum of each XCM group broadens with increasing feedback. The spectral linewidth (FWHM) of a single convoluted XCM group as a function of feedback is shown in Fig. 11. Only data for the BH laser are shown, but similar behavior for the CSP lasers is also observed. The line broadening data in Fig. 11 is consistent with that reported elsewhere [4].

Frequency Instability

The wavelength instability (also referred to as phase noise) exhibited by lasers is measured using a FPI in a nonscanning mode of operation [8]. The Fabry-Perot mirror separation is adjusted such that the FPI transmission [as shown in Fig. 12(a)] is held at approximately 70 percent of the resonance peak maximum. In this condition wavelength fluctuations of the laser source are observed as relatively large fluctuations in the FPI transmission intensity. These intensity fluctuations are analyzed by monitoring the FPI photodetector output with a low-frequency spectrum analyzer.

Fabry-Perot transmission intensity fluctuations caused by wavelength instability of laser CSP 7287 are shown in Fig. 12(a). The upper trace is taken with no feedback while the lower trace is taken with a feedback of $r = 4 \times 10^{-5}$. The FPI free spectral range is 8.8 GHz and the finesse is 50; the photodetector output voltage at maximum FPI transmission is 8 mV corresponding to a frequency fluctuation of approximately 200 MHz. The two traces in Fig. 12(a) indicate that a significant reduction in the laser wavelength instability occurs when feedback is introduced. Low frequency intensity fluctuations present in the lower trace of Fig. 12(a) are partially caused by random time-dependent changes in the FPI mirror separation and in the external cavity length. These are caused by thermal

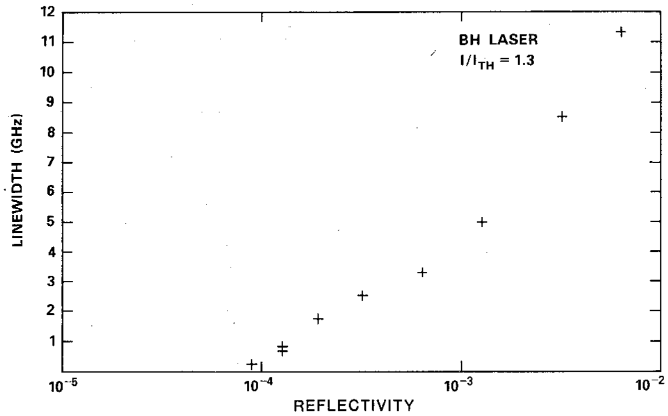


Fig. 11. Spectral width of a single convoluted XCM group as a function of feedback in a buried heterostructure laser.

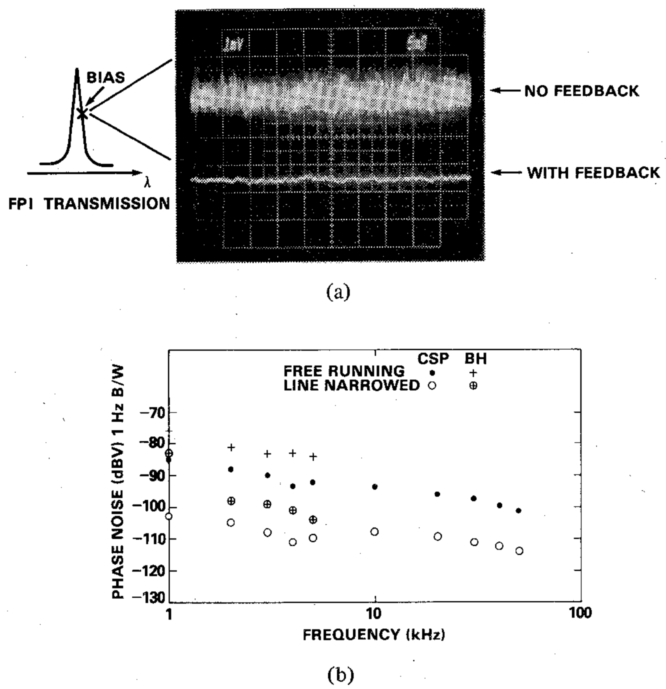


Fig. 12. Effect of feedback on low frequency wavelength instability (phase noise): (a) FPI transmission intensity of the emission of laser CSP 7287 operating without feedback (upper trace) and with feedback of $r = 4 \times 10^{-5}$ (lower trace), (b) phase noise for free running and line narrowed BH and CSP 7288 lasers ($r = 1 \times 10^{-5}$), 1 Hz bandwidth.

and acoustic disturbances in the vicinity of the experimental setup.

The noise spectra of the transmitted FPI signal is shown for two laser diodes in Fig. 12(b) for a 1 Hz bandwidth. The data are normalized relative to a 1 V dc photodetector output. Both lasers exhibit a 15 dB reduction in the low frequency wavelength instability of phase noise when a feedback of 1×10^{-5} is introduced. In the BH laser case, the noise reduction might be somewhat larger, as the noise measurement at the signal levels employed became limited by the noise floor of the spectrum analyzer. The predicted reduction is $20 \log (\Delta\nu)/(\Delta\nu)_0$, with $\Delta\nu$ given by (21). For $R_1 = 0.35$, $nl = 1.1$ mm, and $L = 60$ cm, the predicted reduction is 9.2 dB.

V. Discussion

The analytical results developed in Section II provide a convenient basis for discussing the observed external cavity mode effects and stability of the laser in the presence of feedback. It is predicted that only one mode will be present for small feedback ($r < r_a$), while multiple external cavity modes are predicted at large feedback levels ($r > r_b$). At intermediate levels of feedback ($r_a < r < r_b$), the model predicts that single-mode behavior can be obtained by adjusting the phase of the feedback, but that multiple XCM's will exist over some range of feedback phase. Values for these critical reflectivities are calculated to be $r_a = 2.8 \times 10^{-6}$ and $r_b = 6.5 \times 10^{-5}$ in our experiments, using (7) and (11) with $nl = 1.1$ mm, $L = 60$ cm, and $R_1 = 0.35$.

Actually, evidence for low-intensity external cavity modes is obtained in the heterodyne experiment for external reflectivity values much lower than r_a, as illustrated in Fig. 8. We believe that these weak XCM's are associated maxima in the reflectance versus wavelength curves. Even though θ does not equal an integral multiple of 2π rads for these weak modes, the peaks in reflectivity can give rise to increases in the spectral density which appear as beat signals in the spectrum analyzer display and additional peaks in the FPI scans.

At much higher feedback levels, strong XCM's and multiple LM's are observed regardless of the phase of the feedback. This behavior is first seen at feedback levels varying from 5×10^{-5} to 5×10^{-4} in the lasers we studied. The lower of these values is slightly less than the calculated value of r_b. The appearance of multiple LM's in the Fabry-Perot spectra results initially from longitudinal mode hopping, which is probably induced by fluctuations in carrier density and refractive index due to the beating of the XCM's in the laser cavity. At higher feedback levels, the multiple LM spectra are temporally stable.

These data appear to support the presumption that the achievable line narrowing is limited by the appearance of strong XCM's at high feedback levels. If we assume that r_b represents the maximum feedback for line narrowing, it follows from (11), (15), and (19) that the minimum spectral width is

$$(\Delta\lambda)_{1/2} = \Delta\lambda_0 \left[1 + \sqrt{1.047}\,(3\pi/2)\right]^{-2}$$

or $(\Delta\lambda)_{1/2} = 0.0295\ \Delta\lambda_0$. This is in fact close to the maximum narrowing achieved in some lasers, but as indicated in Fig. 10, considerably greater reduction was obtained in other lasers. In the latter case, the XCM's remain weak at feedback levels well above the calculated value of r_b.

A similar calculation based on the appearance of multiple XCM's can also be used to predict the maximum frequency noise reductions. From (21) and the observation that the electrical noise power due to optical frequency fluctuations is proportional of $(\Delta\nu)^2$, it follows that the frequency fluctuation noise is reduced by the same factor as the spectral width. A maximum reduction in frequency noise, occurring at $r = r_b$, by a factor of 0.0295, or 15.3 dB, is thus predicted. This value is quite close to the noise reduction achieved experimentally.

The measured feedback induced spectral changes exhibited by each of the four lasers described show considerable variation. Two of the lasers, CSP 7288 and CSP 7287, exhibited greater linewidth reduction and greater values of r_b than the other two lasers tested. This might be related to the fact that the two lasers were new when the measurements were begun, while CSP 6189 and BH have been previously operated. In addition to the four lasers already described, several more lasers fabricated by different manufacturers and with different structures were also tested. Minimum linewidths in these were observed in some cases to be insensitive to feedback, and in others, to exhibit much less linewidth reduction than shown in Fig. 10.

As indicated in Fig. 10, substantial line-narrowing effects are obtained with small amounts of reflectivity. An alternative configuration to decrease the linewidth using spatially distributed feedback is an optical fiber. Feedback from a fiber can come from reflections off the end faces, fused joints, or Rayleigh backscattering in the fiber [12]. With only 50 m of single-mode fiber, line narrowing of a CSP laser from a free-running width of 20 MHz to less than 100 kHz has been obtained by butt-coupling a single-mode fiber to the laser and using only the Rayleigh backscattering [13]. Due to the random nature of the backscattering and thermal fluctuations affecting the fiber's refractive index, the line narrowing of the laser is not in this case accompanied by improved frequency stability.

VI. Conclusion

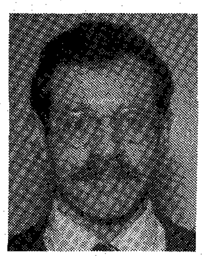
The effects of optical feedback on the spectral characteristics of GaAlAs laser diodes have been determined both theoretically and experimentally. A three mirror resonator pumped internally from an energy source has been analyzed. Using this model, line narrowing, phase noise reduction, multimode operation, and other spectral effects can be predicted. Experimental results on several lasers of two structures are generally in good agreement with the model. These effects can be expected when reflections from a coupling lens, fiber ends, or other reflecting surfaces in an optical system reenter the laser cavity.

Acknowledgment

The authors wish to thank C. A. Villarruel for the fiber couplers and fiber coil used in the self-heterodyne measurement and M. E. Gingerich for technical support throughout the study.

References

[1] Y. Yamamoto and T. Kimura, "Coherent optical fiber transmission systems," *IEEE J. Quantum Electron.*, vol. QE-17, pp. 919–933, June 1981.
[2] A. Dandridge and A. B. Tveten, "Phase noise of single-mode diode lasers in interferometer systems," *Appl. Phys. Lett.*, vol. 39, pp. 530–532, Oct. 1981.
[3] K. Petermann and E. Weidel, "Semiconductor laser noise in an interferometer system," *IEEE J. Quantum Electron.*, vol. QE-17, pp. 1251–1256, July 1981.
[4] R. O. Miles, A. Dandridge, A. B. Tveten, H. F. Taylor, and T. G. Giallorenzi, "Feedback induced line broadening in CW channel-substrate planar laser," *Appl. Phys. Lett.*, vol. 37, pp. 990–992, Dec. 1980.
[5] A. Olsson and C. Tang, "Coherent optical interference effects in external-cavity semiconductor lasers," *IEEE J. Quantum Electron.*, vol. QE-17, pp. 1320–1323, Aug. 1981.
[6] S. Saito and Y. Yamamoto, "Direct observation of Lorentzian lineshape of semiconductor laser and linewidth reduction with external grating feedback," *Electron. Lett.*, vol. 17, pp. 325–327, Apr. 1981.
[7] O. Nilsson, S. Saito, and Y. Yamamoto, "Oscillation frequency, linewidth reduction and frequency modulation characteristics for a diode laser with external grating feedback," *Electron. Lett.*, vol. 17, pp. 589–591, Aug. 1981.
[8] L. Goldberg, A. Dandridge, R. O. Miles, T. G. Giallorenzi, and J. F. Weller, "Noise characteristics in line-narrowed semiconductor lasers with optical feedback," *Electron. Lett.*, vol. 17, pp. 677–678, Sept. 1981.
[9] V. N. Smiley, "An active interference filter as an optical maser amplifier," *Proc. IEEE*, vol. 51, pp. 120–124, Jan. 1963.
[10] T. Okoshi, K. Kikuchi, and A. Yakayama, "Novel method for high resolution measurement of laser output spectrum," *Electron. Lett.*, vol. 16, pp. 630–631, July 1981.
[11] C. A. Villarruel and R. P. Moeller, "Fused single mode fibre access couplers," *Electron. Lett.*, vol. 17, pp. 243–24, Mar. 1981.
[12] E. Brinkmeyer, "Backscattering in single-mode fibres," *Electron. Lett.*, vol. 16, pp. 329–330, Apr. 1980.
[13] L. Goldberg, H. F. Taylor, and J. F. Weller, to be published.



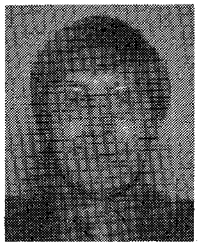
Lew Goldberg was born on July 27, 1950, in Minsk, U.S.S.R. He received the B.S. degree in electrical engineering from Tufts University, Medford, MA, in 1973, the M.S. degree from Carnegie-Mellon University, Pittsburgh, PA, and the Ph.D. degree in applied physics from the University of California, San Diego, in 1979.

His doctoral thesis research was conducted in the area of integrated optics and semiconductor devices. Since 1980 he has been with the Naval Research Laboratory, Washington, DC, working on semiconductor laser properties and high-speed integrated optical modulators.

Dr. Goldberg is a member of the Optical Society of America and the American Physical Society.

Henry F. Taylor (SM'78) received the Ph.D. degree in physics from Rice University, Houston, TX.

He worked for the Naval Electronics Laboratory Center, San Diego, CA, for ten years, and at Rockwell International Science Center, Thousand Oaks, CA, for two years before joining the Naval Research Laboratory, Washington DC, in 1980, where he now heads the Optical Techniques Branch. He is the author of about 90 journal articles and conference presentations and holds 11 U.S. patents in the area of fiber optics and guided wave optics. He received the NELC Annual Award for Achievement in Science in May 1974 and the American Society of Naval Engineers' Solberg Award for Applied Research in 1975. His present interests include fiber optic signal processing and noise effects in diode lasers.



Anthony Dandridge was born in Kent, England, on November 11, 1951. He received the B.Sc. and Ph.D. degrees in physics from the Sir John Cass School of Science and Technology, City of London Polytechnic, England.

His postgraduate and postdoctoral research work included flow birefringence and light scattering studies of short chain polymers. In 1979 he was a Lecturer in Physics at the University of Kent, Canterbury, England. Since 1980 he has been associated with Georgetown University, Washington, DC, John Carroll University, Cleveland, OH, and the Naval Research Laboratory, Washington, DC. His research work covers fiber optic sensor systems and the noise and spectral characteristics of semiconductor lasers.

Dr. Dandridge is a Fellow of the Royal Astronomical Society.

Joseph F. Weller was born in Louisville, KY in 1939. He received the B.S. degree in physics from Xavier University, Cincinnati, OH, in 1960, and the M.S. and Ph.D. degrees in physics from American University, Washington, DC, in 1968 and 1972, respectively.

He joined the Naval Research Laboratory, Washington, DC, in 1960 where he began work on radiation damage on semiconductor devices. Since then he has been active in areas of quantum electronics and ultrasonics. His research interests have included rare earth spectroscopy in glasses, glass lasers, nonlinear optics, and optical interactions with surface acoustic waves. He is presently Head of the Optical Hybrid Devices Section of the Optical Techniques Branch. His current research interests include properties of laser diodes and optical interactions in microwave and millimeter wave devices.

Dr. Weller is a member of the American Physical Society.

Ronald O. Miles (S'66–M'77) was born in Salt Lake City, UT, on November 25, 1940. He received the B.S. degree in electrical engineering in 1967, and the M.S. and Ph.D. degrees in 1973 and 1978, respectively, all from the University of Utah, Salt Lake City.

While at the University of Utah he was a Teaching Assistant and Research Assistant in the Microwave Device and Physical Electronics Laboratory, where his primary interest has been in CO_2 laser plasma diagnostics and CO_2 waveguide lasers. In 1974 he was a Consultant on preliminary design of a gas dynamic laser for a laser-driven ionization process for applications in MHD power-generating systems for the Department of Mechanical Engineering, University of Utah. From 1975 to 1976 he was a Consultant on laser applications in development of new processes for preventive denistry for the Department of Mechanical Engineering, University of Utah. His research interests include hollow-core distributed-feedback waveguide lasers. Since 1978 he has been with the Naval Research Laboratory, Washington, DC, where his research is on noise in semiconductor lasers and laser fiber sensor systems.

Dr. Miles is a member of the American Physical Society, the Optical Society of America, and Sigma Xi.

Noise in an AlGaAs Semiconductor Laser Amplifier

TAKAAKI MUKAI AND YOSHIHISA YAMAMOTO, MEMBER, IEEE

***Abstract*—The noise characteristics in a Fabry-Perot (FP) cavity type semiconductor laser amplifier, biased at just below its oscillation threshold current, have been studied theoretically and experimentally. Quantum mechanical multimode rate equations containing a Langevin shot noise source and an input signal term were numerically solved for an exponential band-tail model with no *k*-selection rule. Noise power calculated using this rate equation was compared with a simpler photon statistic master equation method. The experimental results on noise power for an AlGaAs laser amplifier are in reasonable agreement with the two different theoretical predictions. Dominant noise powers in a semiconductor laser amplifier are beat noise powers between signal and spontaneous emission, and between spontaneous emission components. Noise characteristics in a Fabry-Perot cavity type laser amplifier can be improved both by the reduction of the facet mirror reflectivities and by use of an asymmetric cavity configuration with low-input and high-output mirror reflectivities. Two beat noise powers are expressed in simple analytic form by introducing an equivalent noise bandwidth and an excess noise coefficient as figures of merit in an optical amplifier.**

Manuscript received September 1, 1981; revised December 7, 1981.

The authors are with the Musashino Electrical Communication Laboratory, Nippon Telegraph and Telephone Public Corporation, Tokyo, Japan.

I. Introduction

APPLICATIONS of semiconductor laser amplifiers have been studied, both to a PCM-IM direct detection optical transmission system [1], and a coherent optical fiber transmission system [2]. Experimental results with signal gain [3], [4], link gain [5], frequency bandwidth [4], saturation output power [4], and preamplifier performance for a 100 Mbit/s PCM-IM signal [6], [7] of a Fabry-Perot (FP) cavity type AlGaAs laser amplifier have been reported. These works indicate that an FP cavity type semiconductor laser amplifier is promising as an optical linear repeater in these systems.

The noise characteristics of a semiconductor laser amplifier are indispensable in estimating the *S/N* performance of optical direct amplification transmission systems. Amplitude noise in semiconductor lasers was originally measured by Armstrong and Smith, using a Hanbury Brawn-Twiss experiment [8]. Paoli *et al.* measured the resonance peak of AM noise [9]. Recently, Jäckel *et al.* measured the quantum-noise-limited intensity fluctuation in a transverse-mode-stabilized CSP laser [10], and reported that the noise behavior of a CSP laser agrees

0018-9480/82/0400-0410$00.75 © 1982 IEEE