Spatial Feedback Effects in Narrow-Stripe Index-Guided Semiconductor Lasers

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Abstract— We demonstrate experimentally that spatial effects of feedback are important in determining the operating characteristics of index-guided semiconductor lasers. It is in fact the inflexibility of the index-guided mode that makes the laser susceptible to small misalignments of the external cavity, which can induce power variations of nearly 40% of the solitary laser power with feedback levels of less than 2% (-17 dB). With a simple model, we calculate the modification of the feedback wavefront as a function of the external cavity length and show that the power variations are induced through changes in the cavity loss brought on by the interference of the feedback field with the field reflected off the laser facet. By experimental comparison to a partly gain-guided laser, we conclude that these large-scale variations will be significantly reduced or absent in purely gain-guided lasers.

Index Terms— Beam profile, Gaussian beams, optical alignment, optical beams, optical communication, optical feedback, optical waveguides, semiconductor lasers.

I. INTRODUCTION

OPTICAL feedback is a practical problem in most applications of semiconductor lasers. The laser light is typically focused onto some target, e.g., an optical fiber or a rotating disk, which reflects the light, some of which gets back into the laser. The optical feedback produced by reflecting surfaces has many detrimental effects that have been extensively studied in the spectral domain: at low levels, feedback can introduce linewidth broadening [1], while at higher levels, the behavior of the laser is dominated by coherence collapse, a chaotic regime where the laser linewidth can broaden up to 25 GHz [2]–[4]. Spectral effects of optical feedback have been studied using single- and multilongitudinal-mode models [4], [5], and methods of controlling detrimental effects appearing in the spectral domain have been discussed [5], [6].

Recently, attention has focused on the effects of feedback on the spatial mode of the laser. An experimental study of feedback effects in tapered broad-area semiconductor lasers shows that the lateral mode of such lasers can be drastically altered, resulting in severe degradation of the far-field image with a significantly reduced power in the central lobe [7]. A recent theoretical study proposes that feedback can be used to provide a nearly single-lobed far field in gain-guided devices that typically exhibit twin-lobed far fields, and that in broad-area lasers, feedback can introduce a spatial modulation of the lateral field that increases the tendency for filamentation [8], a phenomenon through which the optical beam breaks up into a filamentary structure [9].

Given the interesting spatial effects occurring due to feedback in broad-area lasers, it is appropriate to ask whether spatial effects are important for narrow-stripe devices. Previous work on narrow-stripe devices has given no attention to the spatial mode of the laser, reasoning that the narrow width of the waveguide would prevent any spatial effects from occurring. The study we present here shows that, contrary to this widely held belief, the spatial effects of feedback play an important role in determining the operating characteristics of the laser. In particular, we investigate index-guided, narrow-stripe lasers, commonly used in a multitude of applications including optical communications and optical data storage. Our experimental results show that although the index guiding predetermines the lateral mode for a narrow active region, spatial modification of the beam in the external feedback cavity can have drastic effects on the performance of the laser.

II. EXPERIMENT WITH INDEX-GUIDED LASER

The experimental arrangement used is shown in Fig. 1. For the study, two semiconductor lasers were selected: a Hitachi HLP1400 and a ROHM #RLD-78MA. Both lasers operate near 780 nm and have about the same stripe width of $\sim$4 μm. The Hitachi laser is an index-guided device with a flat lateral phase profile. The ROHM laser has a weak, built-in, index step sufficient enough to retain a single-lobed far field while still inducing an astigmatism of nearly 20 μm, yielding a diverging field within the laser. Both lasers were operated continuously at a current level 1.5 times their respective threshold values. The external cavity was approximately 27 cm long, consisting of collimating optics, a beam splitter, a chopper, and a cateye-configuration reflector to provide the feedback. For the ROHM laser, a cylindrical lens was employed to remove the lateral astigmatism so collimation could be achieved in both transverse and lateral directions; a small attenuator was used with the Hitachi laser to keep the feedback levels the same for both lasers. A small part of the beam was sampled from the beam splitter and used to monitor either the lateral profiles with a photodiode array, or the laser output with a photodetector. Since both lasers exhibited small power fluctuations on a slow time scale, a chopper was used to directly compare the feedback measurements to those of the solitary (feedback free) laser. The feedback mirror allowed
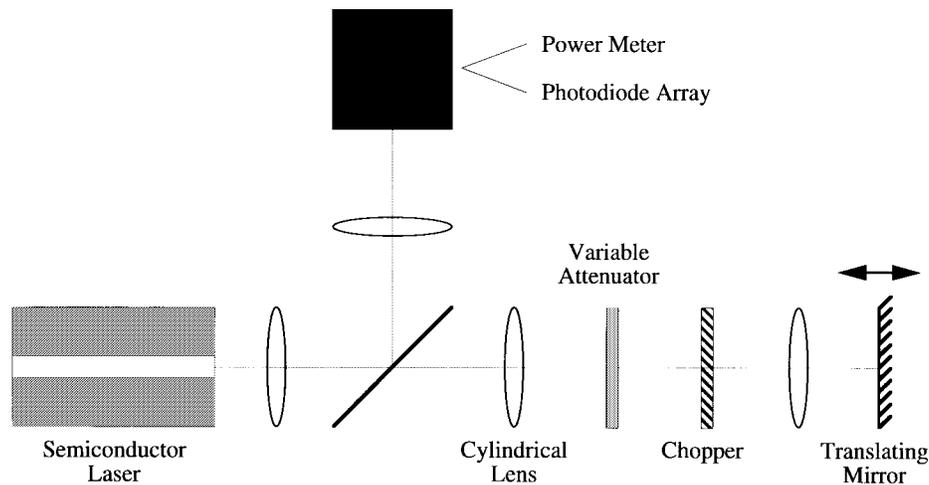
Fig. 1.   Experimental arrangement used to study the spatial effects of feedback in narrow-stripe semiconductor lasers. The cylindrical lens was used only with the astigmatic ROHM laser. The photodiode array was used to measure near- and far-field profiles, while the photodetector measured the laser output power.

simultaneous translation on a gross scale ($\sim$13-μm steps) as well as on a fine scale (subwavelength) with a piezoelectric positioner. Assuming a 10% mode coupling factor, the laser was exposed to -17.6 dB (1.7%) of feedback with this external-cavity configuration. This feedback level is high enough to operate in the coupled-cavity regime.

Initially, the near- and far-field profiles of the Hitachi laser were examined under feedback, while varying the position of the feedback mirror. No qualitative deviation from the solitary laser profiles was observed, unlike the results found in [7]; narrow-stripe devices do not have the lateral-mode flexibility found in broad-area lasers. However, surprisingly large variations in the output power of the laser were observed when the feedback mirror was moved over a 12-mm range. Fig. 2(a) displays the relative change in output power from its solitary value against the displacement of the feedback mirror Δz from its perfect-focus position; positive values of the defocus Δz represent an increase in cavity length. As a function of this defocus, the laser power exhibits oscillations of varying amplitude and period primarily on the positive defocus side of a broad pedestal. The maximum peak-to-peak variation measured was nearly 72% of the solitary laser power. Fig. 2(b) shows the same measurement with an additional attenuation in the cavity, such that the feedback level has been reduced to -29.6 dB (0.11%). Upon comparison with Fig 2(a), the qualitative behavior is nearly identical, except for the reduction in peak-to-peak variations and range of defocus. No changes were observed in the mode profiles or output power when Δz was varied on a subwavelength scale.

However, the oscillatory nature of the large-scale variations in Fig. 2 indicates a phase effect. Under feedback, the action of the lenses is to re-image the near field on the facet of the laser. However, as the external cavity length is varied, this image will be longitudinally displaced or defocused with respect to the laser facet. This means that the feedback field entering the facet will be either converging (if the near-field image is displaced within the laser) or diverging (if the near-field image is displaced outside the laser). Since the intracavity laser mode reflecting off the facet remains planar, these two wavefronts
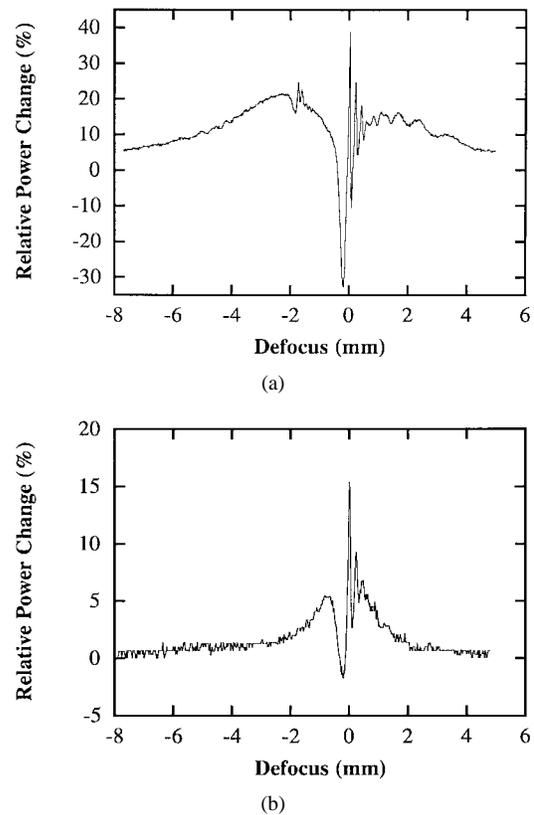
Fig. 2.   Experimentally measured laser power as a function of defocus of the feedback mirror for the index-guided Hitachi laser with a feedback level of (a) -17.6 dB (1.7%) and (b) -29.6 dB (0.11%). In both cases, the power changes are represented as a percent deviation from the solitary laser power.

combine such that there is little or no phase difference in their central portions, and a larger phase difference in the wings due to the curvature of the feedback field. As the defocus Δz is varied, the imaging of the near field changes, as does the curvature of the feedback wavefront. This will vary the levels of constructive and destructive interference between the two fields, causing the oscillations shown in Fig. 2. The parameter Δz not only modifies the curvature of the feedback wavefront, but the amplitude and width of the field as well. This beam

spreading creates the broad pedestal that the oscillations rest upon.

III. THEORETICAL ANALYSIS

To verify the intuitive picture described above, we present a simple model consisting of geometrical imaging, Gaussian beam propagation, and a rate-equation analysis. We introduce the modification of the laser power through an effective facet reflectivity calculated by

$$r_{\text{eff}} = \frac{\dfrac{1}{2w}\displaystyle\int_{-w}^{w} dx [r_f E_L(x) + r_{FB} E_{FB}(x)] E_L^*(x)}{\dfrac{1}{2w}\displaystyle\int_{-w}^{w} dx |E_L(x)|^2} \qquad (1)$$

where $2w$ is the width of the integration region (chosen to be finite because of the finite gain region), E_L and E_{FB} are the laser and feedback fields, respectively, r_f is the facet reflection coefficient, and $r_{FB} = \exp(i\phi_{FB})(1 - r_f^2)\sqrt{\eta R_{FB}}$. Here, η is the power mode coupling efficiency, R_{FB} is the feedback reflectivity representing the fraction of output power returned to the laser facet, and $\phi_{FB} = \omega\tau$ is the (longitudinal) feedback phase which depends on the central frequency of the laser ω and the external cavity round trip time τ. Equation (1) is a measure of the effective feedback and contains the interference between the laser and feedback wavefronts as well as the coupling of this combined field back into the laser.

The effective reflectivity from (1) is incorporated into the laser rate equations through the cavity loss as

$$\alpha_{\text{cav}} = \alpha_{\text{int}} - \frac{1}{2L} \ln(|r_f|^2 |r_{\text{eff}}|^2) \qquad (2)$$

where α_{int} is internal loss and L is the laser cavity length. Assuming that the modal gain varies linearly with the carrier density as $g_m = \Gamma a(N - N_0)$ and equating gain to loss yield the threshold carrier density as $N_{\text{th}} = N_0 + \alpha_{\text{cav}}/(a\Gamma)$, where N_0 is the transparency value of the carrier density, a is the gain coefficient, and Γ is the confinement factor. From the carrier-density rate equation [10], we obtain the output power P in the presence of feedback (normalized to the solitary laser power $\overline{P}$):

$$\frac{P}{\overline{P}} = \frac{\overline{\alpha}_{\text{cav}}}{\alpha_{\text{cav}}} \frac{J/qd - N_{\text{th}}/\tau}{J/qd - \overline{N}_{\text{th}}/\overline{\tau}} \qquad (3)$$

where the bars indicate values for the solitary laser ($r_{FB} = 0$). J is the injected current density, q is the electron charge, d is the active layer thickness, and $\tau = (1/\tau_{nr} + BN_{\text{th}})^{-1}$ is the carrier recombination rate which includes the nonradiative lifetime τ_{nr} and the spontaneous-emission coefficient B.

Ideally, one would like to find the exact variation of the feedback field as a function of Δz. A full spatio-temporal analysis of the beam propagation in both the laser and external cavities goes beyond the scope of this paper. Instead, we construct a simple, yet analytic, model to substantiate the intuitive picture described in Section II. The only practical way to analytically describe beam propagation is by using Gaussian beams and ABCD matrices. In reality, however, the beam in the external cavity is non-Gaussian, and accumulated

diffractive effects can become important. As a result of the Gaussian beam approximation, it turns out that the intensity profile has too strong of an effect in the integral in (1). We compensate for this artifact by replacing the Gaussian intensity profile by its peak value, thus accounting for beam spreading. The resultant integration of (1) yields

$$r_{\text{eff}} = r_f + r_{FB}\frac{1}{2w}\sqrt{\frac{i\lambda\rho_{FB}}{n}}\frac{w_L}{w_{FB}}\text{erf}\left(w\sqrt{\frac{\pi n}{i\lambda\rho_{FB}}}\right) \qquad (4)$$

where λ is the free-space wavelength of the light, n is the effective mode index inside the laser, and w_L is the spot size of the laser field E_L. The parameters w_{FB} and r_{FB} are the spot size and radius of curvature of the feedback field E_{FB}. Since most lens combinations can be analytically combined to form a single compound lens, we consider only one lens of focal length $F = (1/L_1 + 1/L_2)^{-1}$, where L_1 is the distance from the laser facet to the lens, and $L_2 + \Delta z$ is the distance from the lens to the external mirror. The parameters w_{FB} and ρ_{FB} of the feedback field can then be extracted from the resultant ABCD matrix [11] which is used to calculate the propagation of the Gaussian beam through the external cavity.

Most of the parameters used in the calculation come from the experimental setup with the exception of the feedback phase ϕ_{FB}. It is well known that subwavelength changes in the external cavity length can cause dramatic changes in the output characteristics of a semiconductor laser subject to weak (< -40 dB) optical feedback [1], [4], [12]. This is due to the fact that the feedback is not strong enough to guarantee maximum output power [12]. In the high-feedback regime, the system always reaches this maximum gain mode. Since the laser adapts itself to reach this optimum state, no longitudinal feedback phase effects will be present. Indeed, we found no such effects in our experiment, neither on the mode profiles nor the output power, suggesting coupled-cavity (high-feedback) operation. However, the curvature of the feedback field causes the feedback phase to be dependent on the defocus, which can be understood as follows. For a planar feedback field, the interference between the laser and feedback fields is maximized with no phase difference between them. However, as the feedback field becomes curved, some parts of the beam become out of phase with the intracavity field. If the phase difference between the two fields is proportional to the curvature, the destructive interference along the width of the fields will be minimized.

Using our simple model, we calculate the power variation of the laser as a function of defocus and display the results in Fig. 3. This figure is qualitatively similar to Fig 2(a) in that there exists asymmetric oscillations on a broad pedestal. Note that the period of the oscillations increases with the defocus, as seen in the experimental results. This feature is a function of the curvature of the beam. At beam focus, the curvature is zero but rapidly changes on either side of perfect focus. Eventually, the curvature becomes a maximum and then works its way back to zero in an asymptotic fashion. It is this behavior that accounts for the rapid oscillations near perfect focus with increasing period at large defocus. With such high feedback levels, one may wonder if multiple reflections should be taken in to account. With an extension
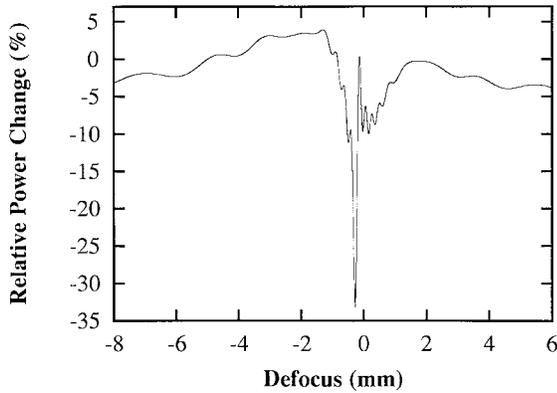
Fig. 3. Theoretically calculated laser power as a function of defocus of the feedback mirror for an index-guided laser laser with a feedback level of -17.6 dB (1.7%). The power changes are represented as a percent deviation from the solitary laser power.

Fig. 4. Experimentally measured laser power as a function of defocus of the feedback mirror for the weakly index-guided ROHM laser with a feedback level of -17.6 dB (1.7%). The power changes are represented as a percent deviation from the solitary laser power.

of the model presented, multiple round trips in the external cavity can be included. Preliminary results indicate that the secondary set of oscillations located at $\Delta z = -2$ mm in Fig 2(a) are due to multiple reflection effects.

IV. EXPERIMENT WITH WEAKLY INDEX-GUIDED LASER

Since we now understand that the physics involves the interference between the laser and fed-back fields, what effects will laser mode curvature show? To answer this question, we repeated the experiment described for the Hitachi laser on the ROHM laser, a device with enough weak index guiding to retain a single-lobed far field while still inducing an astigmatism of nearly 20 μm. This astigmatism represents a curved field within the laser, diverging as it approaches the laser facet. The results of this experiment are shown in Fig. 4. In comparison with Fig. 2(a), we notice that the oscillations occur only for relatively small values of Δz. We postulate two reasons for this behavior. The first results from the inherent curvature of the laser mode; the minimum spot size at perfect focus is no longer the near-field profile, but rather an image of the virtual source from which the near field appears to be originating [7]. Thus, the feedback field at perfect focus has the opposite curvature of the laser field [8], which means that part of the lateral extent of the fields is already out of phase at $\Delta z = 0$. The implication of this situation is that for some nonzero value of defocus, the curvature of the feedback field will match identically with the laser field. Since this phase match happens at a different value of defocus from the spot-size match at $\Delta z = 0$, the laser will experience a lower effective feedback level away from perfect focus as compared to the index-guided case, similar to the behavior shown in Fig. 2(b).

The second reason for this behavior is the flexibility offered by the gain guiding, or rather the lack of strong index guiding. While an index-guided laser offers no flexibility in its spatial mode profile, the mode of a gain-guided laser can adapt to the operating conditions. In fact, a recent theoretical study describes the use of perfect-focus feedback to flatten the mode profile, resulting in a nearly single-lobed far field for a laser which, without feedback, exhibits a twin-lobed structure [8].
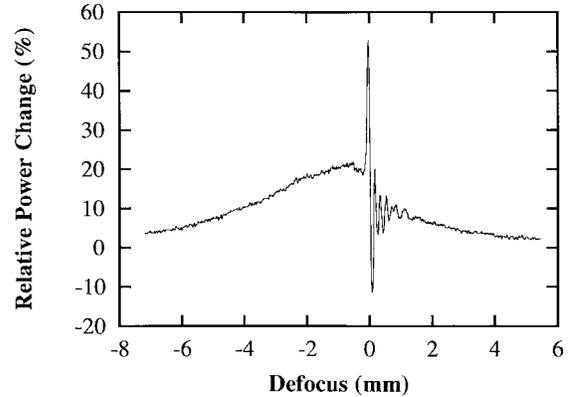
Thus, due to the flexibility in the mode profile along with the lower effective feedback level, we expect that a purely gain-guided laser will exhibit little or no oscillations as a function of defocus.

V. CONCLUSION

We have demonstrated experimentally that spatial effects of feedback are important in determining the output characteristics of index-guided semiconductor lasers. It is in fact the mode inflexibility of the index guiding that makes the laser susceptible to small misalignments of the external cavity, which can induce power variations of nearly 40% of the solitary laser power with feedback levels less than 2% (-17 dB). With a simple model, we have calculated the modification of the feedback wavefront as a function of defocusing and shown that the power variations are induced through an effective facet reflectivity brought on by the interference of the feedback field and the field reflected off the laser facet. By experimental comparison to a weakly index-guided laser, we conclude that these large-scale variations will be significantly reduced or absent for purely gain-guided lasers.

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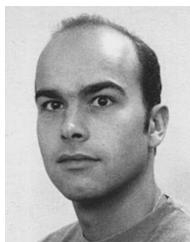
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