Broad-Area Diode Lasers With Plane-Mirror and Phase-Conjugate Feedback

J. S. Lawrence and D. M. Kane

***Abstract*—The output state of a broad-area diode (BAD) laser with phase conjugate feedback (PCF) from $\mathrm{Rh:BaTiO_3}$ crystal is compared to the same diode laser with conventional optical feedback from a plane mirror. A number of distinct output states, including low frequency fluctuations, are observed for each feedback type. Stable single spectral mode output is achieved with phase conjugate feedback above an injection current dependent critical level (∼20%). Conventional optical feedback from a plane mirror does not induce single-mode output at any feedback level.**

***Index Terms*—Diode lasers, low frequency fluctuations, optical feedback, phase conjugate feedback (PCF), semiconductor laser instabilities.**

I. Introduction

The SUBJECT of semiconductor diode lasers with phase conjugate feedback (PCF) has recently attracted considerable attention. Research has focused on two specific areas. First, such a system is an example of an optical nonlinear dynamic system that displays various dynamic behaviors, including optical chaos. Such behavior for narrow-waveguide (single-mode) diode lasers subject to PCF and its difference from narrow-waveguide diode lasers subject to conventional optical feedback (COF) has been experimentally investigated [1], [2] and theoretically modeled by a number of groups (e.g., [3]). Second, PCF is increasingly used with broad-area diode (BAD) lasers and laser diode arrays for improvement in spatial and spectral characteristics (which are typically poor in these devices when free-running), and for coupling and injection with other diode laser sources. There is little experimental knowledge of the dynamic states induced in BAD lasers by PCF or COF, nor comparison to the induced states in narrow-waveguide diode lasers, in the research literature.

Various methods have been proposed and used to improve the spatial and spectral output of BAD lasers. These include the use of optical feedback [4]–[10], optical injection [11], PCF [12], [13], and phase conjugate injection [14], [15]. Injection with a narrow linewidth single-frequency source has been shown to generate single-frequency and single spatial-mode operation [11]. Single-frequency operation has been demonstrated with frequency selective feedback, from either a refractive index grating [5], [6] or a plane mirror with an intracavity etalon [4], [9]. Phase conjugation has been used with BAD lasers primarily for coupling, typically using double pumped phase conjugate mirrors for injection locking of a BAD laser by a single-mode diode laser [14], [15]. PCF has also been used to generate either single spatial-mode or single spectral —mode output from a broad-area laser [12], [13].

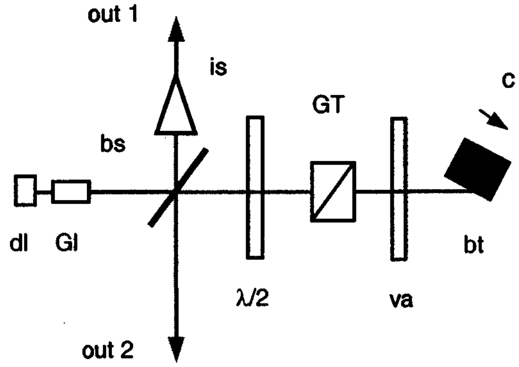

Fig. 1. Experimental arrangement for PCF. dl: diode laser; Gl: GRIN rod lens; bs: beamsplitter; $\lambda/2$: half-wave plate; GT: Glan–Talyor prism; va: variable attenuator; bt: barium titanate crystal; c: crystal c axis; is: optical isolator; out 1: monitored output power; out 2: reflected power (conjugate efficiency).

In the current work, the BAD laser with conventional optical feedback is examined and compared to the case of PCF. In particular, the optical frequency spectrum (at resolutions of the longitudinal mode spacing of the BAD laser and the external cavity mode spacing), the intensity noise spectrum, and the output power as a function of time are observed as the level of feedback is increased. It is found that the BAD laser with COF does not operate on a single frequency for any value of the feedback, but operates on a distinct multimode state indicative of coherence collapse for moderate feedback or a low frequency fluctuation (LFF)-type state for strong feedback. The same diode laser with PCF can be forced to operate on a single spectral mode of the BAD laser, provided the feedback is strong enough. The transition points between unstable and stable operating regimes are also examined as a function of injection current, and compared to previous observations with narrow-waveguide diode lasers [2].

II. Experiment

Fig. 1 shows the experimental apparatus for PCF. The diode laser is a block–mounted 200-mW, 800-nm BAD laser giving a single output beam (Sony 302B). The output is collimated with a gradient index (GRIN) rod lens. An intracavity beamsplitter is used to provide beams to monitor the output and feedback powers and to pass to diagnostic equipment. These beams are collimated, i.e., far field, and the results of monitoring do not depend on the distance at which the diagnostic equipment is placed, provided that appropriate optical isolators are used to

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Manuscript received March 21, 2001; revised July 9, 2001. This work was supported in part by the Australian Research Council and Macquarie University. The work of J. S. Lawrence was supported by a Macquarie University Postgraduate Research Award.

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Publisher Item Identifier S 0733-8724(02)00377-8.

prevent any feedback into the diode laser system. A variable attenuator is used near the system feedback element (plane mirror or phase conjugate reflector) to control the amount of feedback. The external cavity length is ~300 mm (500 MHz), which corresponds to the long cavity limit for the systems [16]. Phase conjugation is achieved with a rhodium-doped (1300 ppm) barium titanate crystal (56 mm × 62 mm × 82 mm) in a self-pumped internal reflection geometry.

In order to achieve an efficient phase conjugate generation, the diode laser must be polarized in a direction perpendicular to the crystal c axis. Additionally, the spatial coherence of the laser output must be as high as possible in this direction. Because the output of the BAD laser is highly divergent and shows low spatial coherence in the horizontal direction, the diode laser is mounted on its side. The half-wave plate is used to rotate the polarization to coincide with the highest spatial coherence and the largest crystal dimensions with respect to the c axis (i.e., horizontal).

The maximum phase conjugate efficiency (reflectance) achieved in this way is ~10–25% dependent on the injection current (pump power). This is lower than the 50% efficiency achieved with the same crystal pumped by a low-power (50 mW) 850 nm narrow-waveguide device (STC LT50-03U) [2]. This indicates the importance of the spatial and spectral properties of the probe beam for efficient phase conjugation in this type of internal reflection mirror. The higher efficiencies achieved with the narrow-waveguide device occur due to either the narrow spectral linewidth, the higher quality spatial mode, the higher lasing wavelength, or a combination of these factors. The return beam on the BAD facet has a physical size larger than the emitted near field and, therefore, no modes of the broad-area laser are preferentially pumped by the PCF, nor are zig zag modes excited.

For COF, the barium titanate crystal is replaced by a plane mirror ($R_{\text{mirror}} = 0.90$) that is focused by an intracavity convex lens of focal length ~100 mm onto the diode-laser front facet. Again, the size of the feedback spot on the BAD facet is larger than the near field of the emission, as for PCF, although a lens is used to compensate for return-beam divergence. It is the case that all modes of the BAD are pumped by the feedback field. If additional lenses were used, it would be possible to reduce the feedback field to a size smaller than the near-field emission on the BAD facet [17], with the likelihood that additional patterns of output characteristics would emerge due to preferential pumping of some spatial modes compared to others. The coupling efficiency between the diode laser and the feedback field has been estimated from the dependence of the threshold injection current and the output slope efficiency on the external feedback fraction, f_{ext} (ratio of the feedback field in font of the collimating optic to the diode laser output), as described in [18]. Maximum coupling efficiency of 0.50 is achieved with the PCF, compared to 0.12 for COF. The coupling efficiency is also reduced compared to that achievable with a narrow-waveguide laser diode [2].

For both PCF and COF, the feedback element is placed at a distance consistent with the long cavity limit [16]. In the case of PCF, shorter cavities cannot be investigated using the current geometry because it uses a number of bulk optical elements, each requiring several centimeters of cavity length for setup. It is expected that the optical spectra would evolve differently in the short-cavity limit, as has been demonstrated previously for conventional optical feedback in narrow-waveguide laser diodes [16]. In the long-cavity limit, the results are qualitatively similar for all cavity lengths [16], and this has been observed to be the case for both COF and PCF in the current experiments.

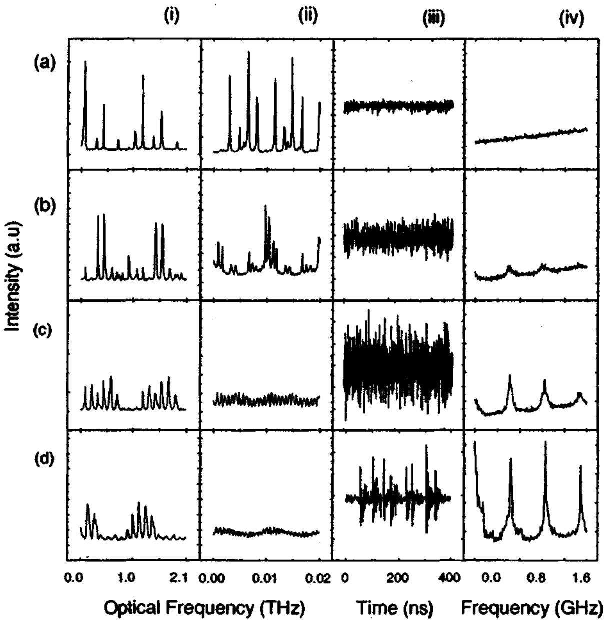

Fig. 2. Diode laser output for COF: output optical frequency spectrum at (i) longitudinal mode resolution and (ii) external cavity mode resolution, (iii) output power versus time, (iv) and intensity noise spectrum. Diode laser injection current is 240 mA (1.6 I_{th}). (a) Solitary diode laser with no feedback. (b) Solitary diode laser with external feedback fraction 0.001. (c) Solitary diode laser with external feedback fraction 0.10. (d) Solitary diode laser with external feedback fraction 0.9.

The output optical-frequency spectrum is recorded with a 1000-GHz and 10-GHz free spectral range (FSR) Fabry–Pérot interferometer to resolve optical spectral features at the frequency scales of the longitudinal mode spacing for the BAD and the external cavity. A photodiode with a bandwidth of 3 GHz is connected to a radio frequency spectrum analyzer (Tektronix 2754P) for observation of the intensity noise spectrum. A 2-GHz digital phosphor oscilloscope (TDS 7491D) is used for monitoring the output power versus time.

III. RESULTS AND DISCUSSION

The output optical frequency spectrum [at resolutions of the longitudinal mode spacing of the solitary diode laser (165 GHz) and the external cavity mode spacing (500 MHz)], the output power versus time, and the intensity noise spectrum, are shown for various feedback levels for the broad-area diode laser with COF in Fig. 2, and with PCF in Fig. 3. The two systems show significant differences in their output.

The solitary broad-area diode laser with no feedback [Fig. 2(a)] operates on a number of longitudinal modes simultaneously, and has a complex mode structure on a scale of the order of the external-cavity mode frequency. The intensity noise is low (<-80 dBm) over the frequency interval

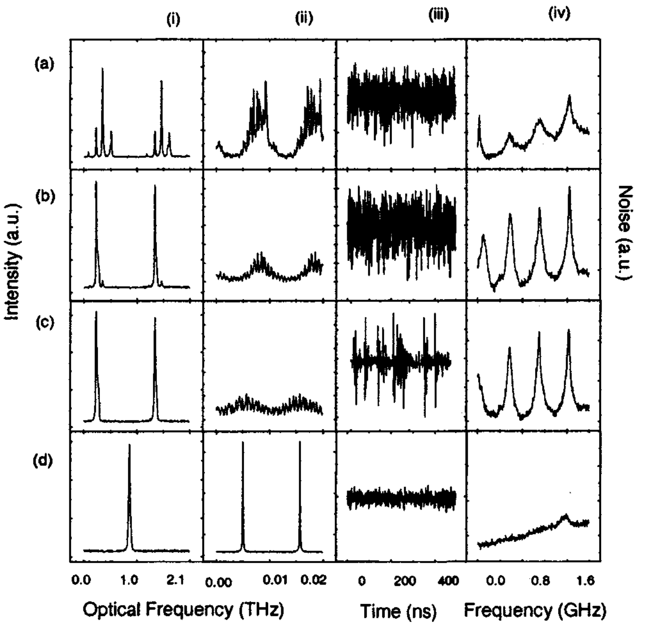

Fig. 3. Diode laser output for PCF: output optical frequency spectrum at (i) longitudinal mode resolution and (ii) external cavity mode resolution, (iii) output power versus time, and (iv) intensity noise spectrum. External feedback fractions are (a) 0.001, (b) 0.10, (c) 0.18, and (d) 0.22. Diode laser injection current is 240 mA (1.6 I_{th}).

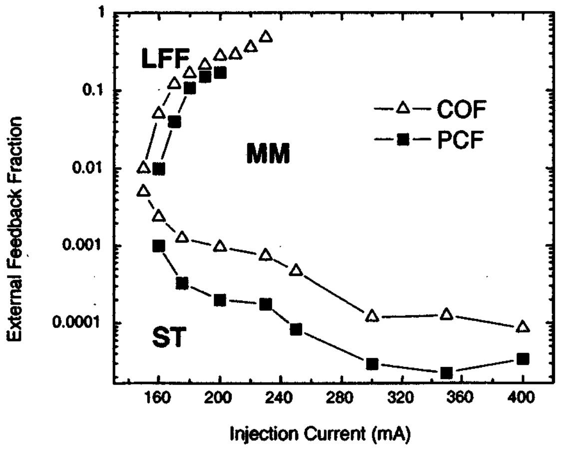

Fig. 4. Output state in parameter space of injection current and external feedback fraction for PCF and COF. LFF: low-frequency fluctuations [as in Figs. 2(d) and 3(c)]; MM: multimode unstable [Figs. 2(c); 3(a) and (b)]; ST: stable low noise state [Fig. 2(b)]. The regime of stable single-mode oscillation for PCF [Fig. 3(d)] is not shown, due to scale factors. It is only observed for low currents (<240 mA) at feedback fractions between ~0.22 and the maximum achievable (0.25 at 200 mA).

investigated (100 MHz–2 GHz) because the output power is quite stable (fluctuations $< 0.1\%$). The introduction of low levels of COF [Fig. 2(b)] has the effect of increasing the fluctuations in output power and introducing oscillation on multiple external-cavity mode frequencies. As the feedback is increased further [Fig. 2(c)], there is an abrupt transition into a very noisy state, with high intensity noise peaks at multiples of the external cavity modes and a broad-band optical spectrum at both the frequency scales studied. For very strong feedback, a state is observed [Fig. 2(d)] that shows intermittent power dropouts and recoveries on a time scale of several hundred nanoseconds, which are characteristic of the LFF state observed in narrow-waveguide diode lasers with optical feedback [19].

The output is not single-mode at either the scale of the external cavity modes or the laser diode modes, with the highest levels of optical feedback used ($f_{\mathrm{ext}} = 0.95$). This differs from the operation of narrow-waveguide diode lasers that typically operate on a stable single mode for very strong feedback (regime V). Usually, to achieve this feedback regime, the diode-laser front facet is antireflection-coated to several percent. The BAD laser used here has an approximately 10% reflectance on the front facet. It is unclear whether a lower reflectance coating would enable single-mode output in this device with COF. Other research has indicated that the frequency selectivity provided from an intracavity etalon is necessary in order to generate single-mode output from a BAD laser with plane-mirror feedback [9].

For low levels of PCF, the optical frequency spectra, the output power versus time, and the intensity noise spectra of the system are similar to the COF case. Moderate feedback [Fig. 3(a)] results in similar noise and temporal properties to the COF case, but with a reduced number of longitudinal modes lasing. Increasing the PCF further results in lasing on a single longitudinal mode with multiple external cavity modes [Fig. 3(b)] and an LFF-type state [Fig. 3(c)]. Above the LFF region, a state of low-noise single-mode oscillation is observed [Fig. 3(d)]. These results indicate the necessity to observe various output characteristics to determine accurately the output state. Predominantly single-mode output at the longitudinal mode resolution (as previously reported in [12]) can represent dramatically different dynamic states.

A map of the output state in the parameter space of injection current and feedback level is shown in Fig. 4 for COF compared to PCF. The broad-area laser is observed to show a transition from an output power that is stable in time to an output power that is unstable in time, with an increase in feedback, analogous to a similar transition from regime III→IV observed in narrow-waveguide devices [2]. In contrast to the narrow-waveguide device, the optical spectrum of the broad-area laser in regime III is multimode, not single mode. However, there is a clear transition from this multimode state to a new multimode state with a near-Gaussian mode envelope when the transition to unstable output power occurs. This is analogous to the single-mode-to-multimode (with near-Gaussian mode envelope) transition seen in narrow-waveguide devices [2].

The transition into the unstable state occurs for low external feedback fractions ($f_{\mathrm{ex}} < 0.0002$) at injection currents above ~300 mA (2 I_{th}^{dl}). As the injection current is decreased, the external feedback fraction required to cause the instability rapidly increases. This dependence of the transition points on the injection current is opposite to that observed for the regime III→IV transition for narrow-waveguide devices, in which the transition point occurs at higher feedback levels as the current is increased. However, similarity with the narrow-waveguide case is seen in that the transition into instability in the broad-area device with COF occurs at higher feedback fractions than for PCF. Additionally, these transitions occur at similar values of the internal feedback fraction (defined as the external feedback fraction multiplied by the coupling efficiency). This indicates that the transitions are driven by the same mechanisms within the

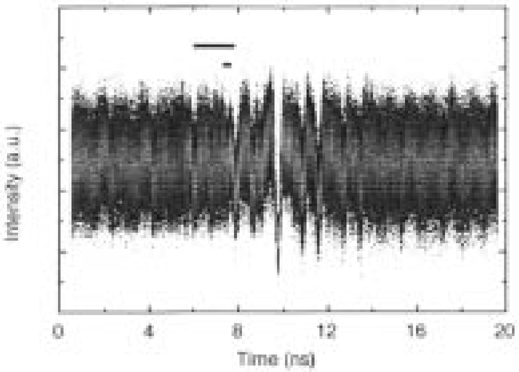

Fig. 5. Digital phosphor oscilloscope trace for COF system in multimode unstable state. Injection current 240 mA, external feedback fraction 0.40. The solid lines represent the external cavity frequency (500 MHz) and the relaxation oscillation frequency (2.5 GHz).

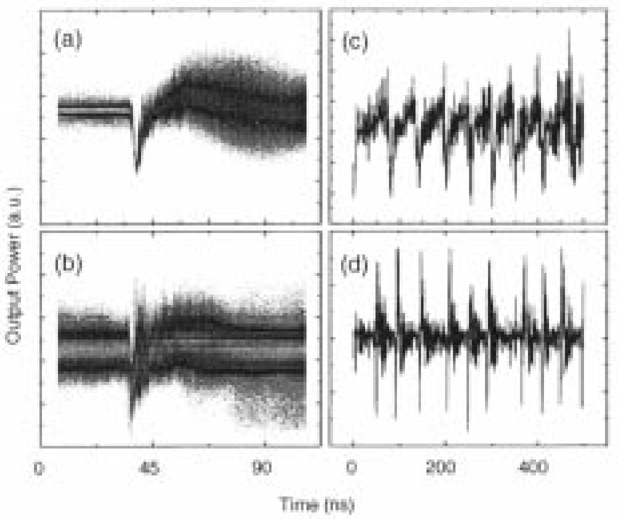

Fig. 6. DPO traces for COF (a) in LFF state with injection current 170 mA and (b) in LFF state with injection current 240 mA. Output power versus time (c) with longer time-scale output power with injection current 170 mA and (d) with longer time-scale output power with injection current 240 mA. Feedback fraction is 0.80 for all figures.

diode laser for both COF and PCF, although they are different for different diode laser types. It reinforces the result that the principal advantage of using PCF is the improved coupling efficiency for the case of a slow response phase conjugator.

The time traces shown in Figs. 5 and 6 do not show observable repetition in the output power. Operating the digital phosphor oscilloscope (DPO) in DPO mode allows some of the underlying dynamics to be observed and reduces the effect of the output noise. In DPO mode, sampling is combined with real time to generate a three-dimensional (3-D) plot of output power, average output power, and time. An example of the COF system operating in the unstable regime is shown in Fig. 5. It is expected for narrow-waveguide devices that the output of such a state is chaotic in time. The pattern observed in the case of the BAD laser is not periodic but shows some structure. Evidence of frequency components at the external-cavity mode spacing and the relaxation oscillation frequency, depicted by the two lines in the figure, are observable. Similar properties are observed for the PCF system. No apparent differences are observed between the unstable states in both PCF and COF for the broad-area laser. A more complete analysis of the time series (such as estimations of the correlation dimension or Lyapunov exponents) is required to determine the exact dynamic state (i.e., chaotic, quasiperiodic) within this regime and whether there are differences between the two different types of feedback.

The LFF states observed for both COF and PCF broad-area laser systems have similar characteristics and are consistent with observations of LFF in narrow-waveguide diode lasers. The LFF region occurs here at the strong feedback boundary, although it has been observed both at this boundary [2], [20] and at the weak-feedback regime III→IV boundary [21] for narrow-waveguide lasers.

The operating parameters determine the exact characteristics of the LFF state, which can have quite a different appearance on longer time scales. Fig. 6(a) and (b) shows DPO traces of a single fluctuation event at two different injection currents for the broad-area diode laser with COF. The output power versus time on a longer time scale is shown in Fig. 6(c) and (d). For low currents, a power dropout followed by a resonant recovery (at a combination of the external cavity and relaxation oscillation frequencies) manifests itself as the typical LFF output shown [19], [20]. For higher injection currents, the higher relaxation oscillation frequency drives the recovery (after a dropout event) much quicker and with an amplitude much higher than the steady state laser power. This results in an output power spiking behavior when observed on longer time scales, yet it is clearly still an LFF state, as evidenced by the single fluctuation event. This demonstrates further that the LFF state can have a variety of appearances when observed on different time scales, because on a much faster (subnanoseconds) scale, the LFF state is known to consist of an irregular train of intensity pulses within the envelope of a dropout event [22].

The mechanisms responsible for the differences between the feedback behavior for the BAD laser reported here and earlier work on narrow-waveguide lasers probably arise because the broad-area laser inherently supports multiple spectral and spatial modes. The increased spectral mode content arises because different modes access different spatial and spectral regions of the gain. This leads to the possibility of mode competition being a complex mixture of spatial and spectral gain nonlinearities. Little theoretical modeling of BAD lasers subject to feedback has been reported. The BAD laser has been assumed to be single-mode without feedback in [10] so that the model is no different than the single-mode rate equation analysis applied to narrow-waveguide devices. A comprehensive study of the lateral modes of broad-area lasers and how they can be modified with feedback from an external cavity [12] is a good starting point for a realistic treatment of the spatial modes. Such a treatment would need to be combined with a multispectral-mode model for the dynamics of a laser diode with optical feedback (e.g., [23], [24]) to give a model capable of describing the experimental studies that have been completed. This represents a significant theoretical challenge yet to be met.

The main difference between the PCF and COF characteristics in the broad-area diode laser observed here is due to the enhanced spatial mode matching into the diode-laser cavity for the phase conjugate reflection (which leads to more power being coupled into the laser cavity). Additionally, the PCF is expected to be phase matched to the diode-laser output, although the slow response of the phase conjugate reflector used in these experiments may affect the phase matching. Theory predicts, and experiments have verified, that these differences lead to contrasting behavior in narrow-waveguide diode lasers operated with PCF and COF [1], [2], [25]. As the broad-area diode laser supports multiple spatial modes the spatial mode matching of the PCF should be all the more important for the broad-area laser, as is evidenced by the failure to observe single-frequency operation with high levels of COF, and the achievement of single-frequency operation with PCF. It has also been shown that this is single-frequency with respect to the external-cavity mode frequency, which was not demonstrated in, for example, [12]. The effects of spatial conditioning of the feedback field, particularly to sizes less than the near-field emission pattern; the near- and far-field emission of the BAD system; and linking these to the dynamical output state are important subjects for future study.

IV. CONCLUSION

Many authors have reported that operating a BAD laser with PCF can force the laser to operate on a single frequency. The current work has shown, however, that although single-mode operation can be attained at the scale of the diode laser longitudinal mode resolution, this is only accompanied by low-noise single-mode oscillation on the external cavity modes if the phase conjugate efficiency is above a certain threshold value. PCF in a broad-area laser generates dynamically unstable operation (similar to that observed with narrow-waveguide devices in regime IV) or low frequency fluctuations at some feedback levels.

The comparison of the transitions into instability between the two systems (COF and PCF) shows that, for low feedback levels, the systems behave similarly for comparable feedback levels corrected for the differences in coupling efficiencies between the two systems. The largest differences between the two systems occur at higher feedback levels. The output within the unstable regime (for moderate feedback levels) shows similar temporal characteristics, but the PCF system lases on fewer longitudinal modes. The PCF system can also lase on a single longitudinal mode with multiple external-cavity modes, or on a single external-cavity mode. The differences in the feedback characteristics observed between the broad-area diode laser used here and a narrow-waveguide device examined previously have also been described.

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J. S. Lawrence, photograph and biography not available at the time of publication.

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