Contrasting conventional optical and phase-conjugate feedback in laser diodes

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An experimental comparison of phase conjugate feedback to conventional optical feedback in a semiconductor laser is presented, which contrasts the optical frequency spectra and power noise spectra with varying levels of feedback. These spectra are correlated with the single frequency regimes III and V and the chaotically unstable regime IV. Conventional feedback is derived from a mirror and variable neutral density filter, and the phase conjugate feedback is derived from a self-pumped rhodium doped barium titanate photorefractive crystal. Both systems show two stable, single frequency operation regions analogous to regime III and V operation separated by a single region of unstable operation analogous to regime IV. It is found that phase conjugate feedback leads to distinctive behaviors including: differences in the relative intensity noise spectra; dynamically varying output frequency spectra close to the transition from regime IV to V; systematic power transfer from one laser diode longitudinal mode to a nearest neighbor through regime IV; and a very much larger range of feedback levels leading to unstable output. The level of optical feedback leading to a transition from regime III to IV is the same for conventional optical feedback and phase conjugate feedback when the correction for the different coupling efficiencies is made. The transition from regime IV to V occurs for much higher levels of feedback when PCF is used leading to the larger range of feedback levels giving chaotic behavior with PCF. The results are discussed in the context of existing theoretical models of laser diodes with phase conjugate feedback.

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I. INTRODUCTION

Over the last twenty years, many aspects of the behavior of semiconductor diode lasers subject to conventional optical feedback (COF) have been investigated; both theoretically and experimentally. Such feedback has been found to induce a variety of effects on the laser diode's operating characteristics, such as a narrowing or broadening of the lasing linewidth, a reduction in threshold gain, and a variety of stable and unstable dynamic states [1–3]. Also, diode lasers with phase conjugate feedback (PCF) have been experimentally and theoretically examined [4–23]. Early work concentrated on obtaining narrow-linewidth, single-frequency operation using PCF [16] and identified self-frequency scanning as a feature of laser diodes with PCF derived using a ring or cat PCM (phase conjugate mirror), in common with other laser systems using these PCMs [23]. Subsequent work has continued these themes and also shown that the nonlinear system of a laser diode with PCF induces distinct dynamics [1,4–14]. Phase conjugate feedback is found to influence the intensity and frequency noise and may significantly reduce both compared to the case of COF in certain operating regimes [10,11]. The frequency spacing of the external cavity resonator modes is predicted to be half that of the COF case [4,14] if the conjugation is achieved by nondegenerate four-wave-mixing.

Phase conjugate feedback in single-mode narrow-stripe diode lasers has been found to induce a multi-mode state indicative of coherence collapse [15], to force predominantly multi-mode lasers to operate single-mode [16] or with increased side mode suppression [17], to narrow the lasing linewidth [16,18,19] (below that possible with COF [20]), and to provide frequency stabilization [18,21] and mode-locking [22]. These effects have been observed at a number of different feedback levels, dictated by the phase conjugate efficiency. The use of PCF has also been shown to provide better mode coupling for broad area diodes or laser diode arrays [24,25]. Such work is concerned with the spatial attributes of phase conjugation.

Diode lasers with COF operate in one of a number of distinct regimes of behavior dependent on the level of the feedback [3]. The regimes relevant to the study here are III, IV, and V. At the lower levels of feedback (regime III) the diode laser operates in a stable single longitudinal mode (the narrowest linewidth mode) with constant power. As the level of optical feedback is increased, the laser diode system undergoes a transition to a chaotic state, known as coherence collapse (or regime IV), which is characterized by a dramatically broadened noise spectrum and an optical spectrum which is multi-mode. The spectrum is multi-mode both on the frequency scale of the longitudinal mode spacing of the laser diode and a frequency close to the external cavity mode frequency. The route to this unstable, chaotic output state involves a series of bifurcations driven by oscillations derived from one of several possible sources, such as undamped relaxation oscillations of the diode laser, oscillations at the external cavity frequency, low frequency fluctuations, or noise [26–29]. Still further increase in the optical feedback level results in a transition to another single-mode, strong feedback regime (regime V), when a diode laser with a low reflectance or anti-reflectance coated facet facing the

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external mirror is used [2]. This regime is not expected when uncoated laser diodes are used.

A number of theoretical studies on diode lasers with PCF have shown that the spatial and temporal phase reversal induced by the PCM incites dynamic instabilities that are much richer than for COF [1,4–11]. These models describe weak to moderate levels of feedback only (one round trip of the external cavity is included). The dynamical behavior is typically explored via bifurcation diagrams and noise spectra, obtained from solutions of the Lang–Kobayashi rate equations modified for PCF, for a range of phase conjugate reflectivity and different cavity lengths. Poincare maps and attractors of the Poincare map have also been determined to give additional insight into the dynamics [9]. The general form of the rate equations, which define the photon number $P(t)$ and phase $\phi(t)$ of the electric field, and the average carrier density within the active region $N(t)$, are

$$\frac{dP(t)}{dt}=\left(G(N)-\frac{1}{\tau_p}\right)P(t)+2\kappa\sqrt{P(t)P(t-\tau)}\times\cos\phi(t)+R_{sp}+F_p(t), \tag{1}$$

$$\frac{d\phi(t)}{dt}=\Delta\omega-\frac{\alpha}{2}\left(G(N)-\frac{1}{\tau_p}\right)+\kappa\sqrt{\frac{P(t-\tau_p)}{P(t)}}\times\sin\phi(t)+F_\phi(t), \tag{2}$$

$$\frac{dN(t)}{dt}=J-\frac{N(t)}{\tau_s}-G(N)P(t)+F_N(t), \tag{3}$$

with

$$\phi(t)=\omega_0\tau+\phi(t)-\phi(t-\tau),\quad \text{for COF}, \tag{4}$$

and

$$\phi(t)=\phi_{\rm PCF}+\phi(t)+\phi(t-\tau),\quad \text{for PCF}. \tag{5}$$

$G(N)$ is the gain; τ_p is the photon lifetime: $R_{\rm sp}$ is the spontaneous emission rate: α is the linewidth enhancement factor: $\Delta\omega$ is the detuning of the pump frequency from the free running laser diode frequency (it is zero for degenerate PCF using a self-pumped phase conjugate mirror): J is the injection current density: τ_s is the carrier lifetime: τ is the external cavity round trip time: $\phi_{\rm PCF}$ is the constant phase shift due to the PCM: ω_0 is the solitary diode frequency: and $F_{P,\phi,N}(t)$ are the Langevin noise forces. There is a requirement that the dynamic change in the complex wave number is small i.e., $\Delta kl \ll 1$, with l the solitary diode length, for the Lang–Kobayashi rate equations to be valid. This condition is violated at high feedback levels. The Langevin noise terms and the effects of spontaneous emission are commonly ignored to separate the deterministic effects from the stochastic. Also, the effect of nonlinear gain suppression is commonly omitted. The coupling coefficient κ, for the case of weak feedback, is given by

$$\kappa=\frac{1-R_1}{\tau_{\rm in}}\sqrt{\frac{\eta_c R_{\rm ext}}{R_1}}, \tag{6}$$

where R_1 is the laser diode facet reflectivity: $\tau_{\rm in}$ is the laser diode internal round trip time: $R_{\rm ext}$ is the external feedback fraction (from the phase conjugate or ordinary mirror): and η_c is the coupling efficiency (less than or equal to 1) between the external feedback field and the diode laser (which has a lower value for COF than for PCF). The introduction of feedback has coupled the phase to both the photon number and carrier density, leading to the possibility of chaotic dynamics.

Period doubling, quasi-periodic, intermittency, and symmetry-lifting routes to chaos have all been observed in theoretical simulations using the rate equations for PCF. These routes, and the feedback levels at which transitions between stable and unstable/chaotic states occur, are found to be dependent on a number of system parameters. The majority of these models assume an instantaneously responding PCM with zero interaction depth. In this case, the system is stable for very low levels of PCF; and once it makes a transition to unstable output it remains unstable for all levels of PCF and the nature of the instability changes with feedback.

The assumption that the PCM responds instantaneously to the incident light fields may be valid for certain types of PCM, such as fast Kerr media or semiconductor PCMs which have a response time of the order of the carrier lifetime. Photorefractive ferroelectrics (such as $BaTiO_3$) and sillenites have a slow response to incident radiation due to low carrier mobility, and the PCM response time is slower than the round trip time. Thus κ becomes time dependent, and a fourth equation must be added to Eqs. (1)–(3), which describes the PCM dynamics. Two predictions of the effect of finite response time have been made, both for nondegenerate four wave mixing (NDFWM). Van der Graaf *et al.* predict that the finite response time tends to stabilize a laser with PCF. The low feedback stability edge is shifted upwards and the system becomes stable again at higher levels of feedback—a regime III>IV>V sequence is shown with increasing PCF [13]. Bochove has predicted that a finite response time diminishes stability at higher feedback levels [14]. The predictions of Ref. [13] are consistent with the results of the experiments using finite response time degenerate four wave mixing reported here. Second, the interaction length of the PCM is generally considered to be zero in theoretical treatments. This is a measure of the time taken for the incident beams to penetrate inside the PCM in order to generate the phase conjugate signal. Thus it may rely on factors such as the PCM size and geometry. The effect of finite interaction depth has been predicted to suppress chaotic output and remove much of the external cavity spacing dependence of the dynamics for PCF derived from NDFWM [12]. The smallest interaction length simulated was at least a factor of 5 longer than would be appropriate for the experiment reported here.

None of the theoretical treatments to date is strictly applicable to the region of strong PCF studied in the experiments. A number of methods have been used to examine the behavior of diode lasers coupled to strong COF. These are generally derived from a traveling wave description of the system, and include iterative [30] and composite-cavity approaches [31,32]. This method has yet to be applied to strong feedback in PCF systems.

In the study presented here, a comprehensive systematic experimental comparison of the same laser diode with both conventional optical feedback and PCF is presented. In particular, the evolution of the intensity noise spectrum, the optical frequency spectrum, and the output power versus time, with increasing feedback level, are observed. The level of feedback is extended well into regime V (very strong feedback) for both cases. From the spectral observations, inferences can be made about the system's high frequency dynamics. Also, critical feedback levels that result in transitions between stable and unstable regimes are compared for the two cases, for a number of different cavity lengths. The main difference between the two systems (COF and PCF) is found to occur at the IV→V transition. It is found that a state characterized by an intensity noise spectrum consisting of large broad peaks at the external cavity mode spacing and an optical spectrum consisting of the excitation of adjacent laser diode longitudinal modes is observed for PCF but not for COF. Power is transferred systematically from one mode to the other as the PCF level is increased. Also, close to the IV–V transition boundary PCF leads to a temporal evolution of the optical frequency spectrum through a number of distinct states. Low frequency fluctuations are observed for low injection currents for both COF and PCF. A very much larger range of feedback levels gives chaotic output when using PCF. The level of optical feedback leading to a transition from regime III to IV is the same for conventional optical feedback and phase conjugate feedback when the correction for the higher coupling efficiency of PCF compared to COF is made. It is the transition from regime IV to V that occurs at much higher levels of feedback when PCF is used that leads to a larger range of feedback levels giving chaotic behavior. The relative intensity noise spectra for the two types of feedback are also qualitatively different. Some of the observed characteristics are consistent with the current theoretical understanding, as is discussed later.

II. EXPERIMENT

The experimental arrangement is shown in Fig. 1. The solitary diode laser used is a quantum-well, index-guided, hi/lo reflection coated, 850 nm, 50 mW device (STC # LT50-03U); which is mounted on a heat sink and temperature controller. This type of diode laser is predominantly single-mode (with a side mode suppression of typically 20 dB) through a large range of injection currents. The output is collimated (with a Melles Griot GRIN rod lens) and feedback is generated at a distance of 50–1000 mm. Conventional optical feedback is produced by a plane mirror of 95% reflectivity. Phase conjugate feedback is obtained from an internal reflection geometry self-pumped rhodium-doped (1300 ppm) $BaTiO_3$ crystal ($5.6\,\text{mm}\times 6.2\,\text{mm}\times 8.2\,\text{mm}$). The maximum phase conjugate reflectance achieved is 50%, which is well within the strong feedback regime. The time taken for the phase conjugate mirror to become established is dependent on alignment. It is of the order of 200–300 s when close to optimum alignment. The Glan–Taylor prism is used to ensure horizontal polarization (i.e., in the same plane as the c axis of the Rh:$BaTiO_3$ crystal). For both COF and PCF an intracavity beam splitter is used to pick off some of the intracavity power to allow monitoring of the system output and phase conjugate efficiency. A variable attenuator is used to control the amount of feedback. The output is monitored with a power meter, a 10 and 1000 GHz FSR Fabry–Perot interferometer, and a fast photodiode (3 GHz) connected to a radio frequency spectrum analyzer or fast oscilloscope.

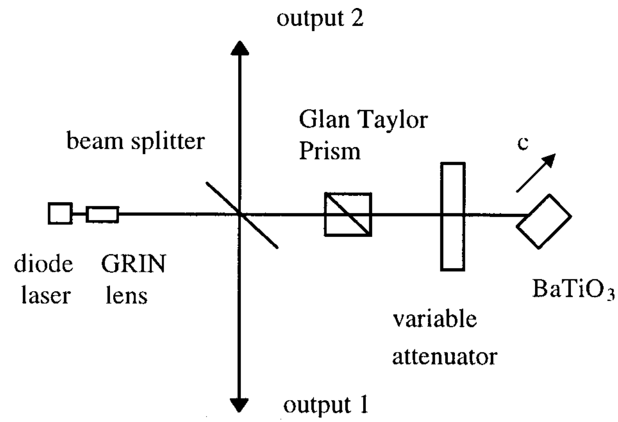

FIG. 1. Experimental setup for PCF. For COF the barium titanate crystal is replaced by a plane mirror. Output 1 is measured with a power meter, Fabry–Perot interferometer and a noise spectrum analyzer.

The feedback fraction, R_{ext}, is defined as the ratio of the emitted power from the front facet of the diode to the reflected power entering the collimating optic; i.e., the ratio of the average power at output 2 to the average power at output 1. The feedback fraction, measured by this method, does not include the coupling efficiency, η_c, which accounts for the losses through the collimating optic, reflection off the diode front facet, and any mode mismatch between the feedback light and the waveguide mode. This efficiency has been estimated, from fits to the slope efficiency, threshold and output power for different external reflectivities, to be 0.28 for COF and 0.7 for PCF [33]. To ensure the fidelity of the phase conjugate reflection image restoration experiments, similar to those in Ref. [34] have been performed.

III. RESULTS AND DISCUSSION

The evolution of the output intensity noise spectrum as a function of increasing feedback is shown for COF in Fig. 2 and PCF in Fig. 3, for two different cavity lengths in each case. In both Figs. 2 and 3, the lowest feedback level shown (spectra a) corresponds to the system operating in a stable single-mode (regime III), with low intensity noise over all frequencies. For the case of COF (Fig. 2), if the feedback level is increased, the noise spectrum undergoes a transition into a state (b) where the external cavity mode frequencies have been excited. These are spaced by 500 and 330 MHz; representing external cavity lengths of 300 (2 i) and 450 mm (2 ii), respectively. Some previous experimental and theoret-

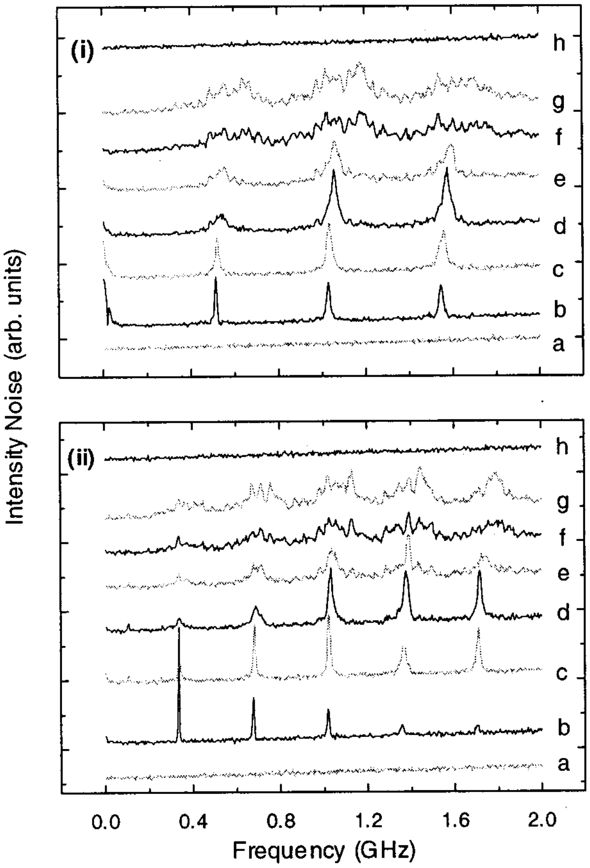

FIG. 2. Intensity noise spectra for increasing COF level. The external cavity length is 300 mm in (i) and 450 mm in (ii). The feedback fractions from a–h are 0.15%, 0.20%, 0.50%, 0.75%, 1.0%, 1.5%, 2.5%, and 5.0%, respectively. The diode laser injection current is 55 mA ($1.7 I_{th}$). All spectra are plotted on identical vertical scales that are shifted vertically for clarity.

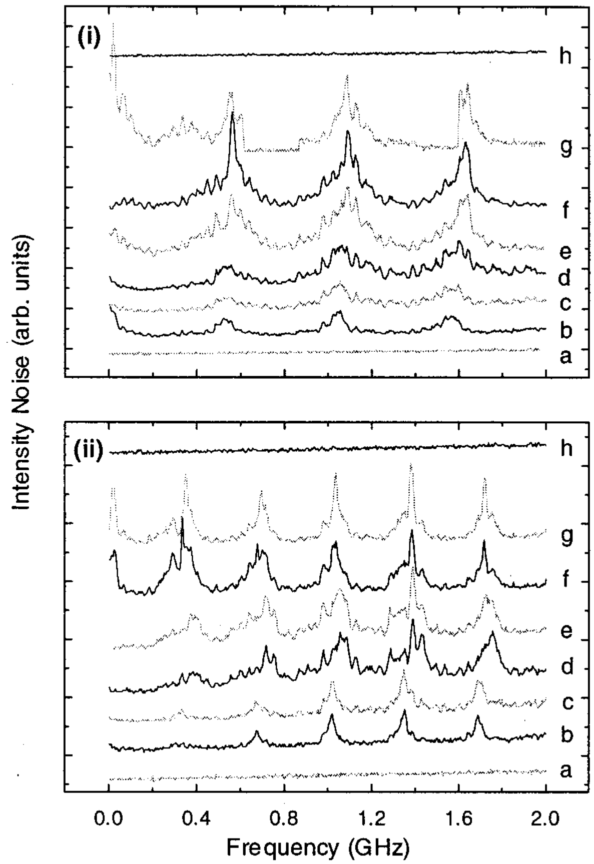

FIG. 3. Intensity noise spectra for increasing PCF level. The external cavity length is 300 mm in (i) and 450 mm in (ii). The feedback fractions from a–h are 0.04%, 0.06%, 0.15%, 0.5%, 1.0%, 5.0%, 10%, and 25%, respectively. The diode laser injection current is 55 mA ($1.7 I_{th}$). All spectra are plotted on identical vertical scales that are shifted vertically for clarity.

ical investigations [10,26–29] have shown that the initial bifurcation from steady state behavior is to a periodic state of oscillation at the relaxation oscillation frequency. This state would manifest itself as a peak in the optical frequency spectrum at the relaxation oscillation frequency. Such a peak is not observed, indicating either that the relaxation oscillation remains highly damped or that the period one behavior occurs over a finer range of feedback fractions than is resolvable in the experiments. The observed initial excitation of the external cavity mode frequencies represents an output power with a periodicity at the inverse of the external cavity frequency (2 ns). Observation of the output power versus time (with a 2 GHz oscilloscope) indicates that this initial state is not a stable periodic orbit, but is a periodic oscillation (with components at both the relaxation oscillation frequency and the external cavity frequency) that decays transiently into noise. Further investigation into such behavior will be published elsewhere.

As the feedback is further increased, the noise peaks at the external cavity mode spacing broaden and decrease in magnitude, and a number of smaller peaks of irregular spacing are observable. These spectra imply that the output power versus time has an increased number of characteristic frequencies; the smaller peaks represent harmonic and entangled frequencies of the external cavity modes, the diode laser longitudinal modes and the relaxation oscillation frequency. It is unclear at which exact feedback fraction the system is operating chaotically, although the noise spectra that appear in f and g are characteristic of chaotic output as theoretically predicted [7,9,27]. The output power versus time for these feedback levels shows some transient periodicity at the external cavity mode spacing that decays into a very noisy signal with no resolvable repetition. Further investigation of such time series is required to ascertain if chaotic behavior is being observed.

When the plane mirror is replaced with a PCM the noise spectrum evolves somewhat differently. This is shown in Fig. 3 for the same two cavity lengths. It can be seen that the resonant noise frequencies occur at the same excited mode frequencies (c/2L) as for COF for both cavity lengths; this is found to be the case for all other cavity lengths examined (50–1000 mm). The evolution of the noise spectrum (for PCF) is also common to all cavity lengths. The initial excitation of the external cavity modes that occurs at the first transition into the coherence collapse regime (spectrum b), from the low feedback regime, is similar to that for COF.

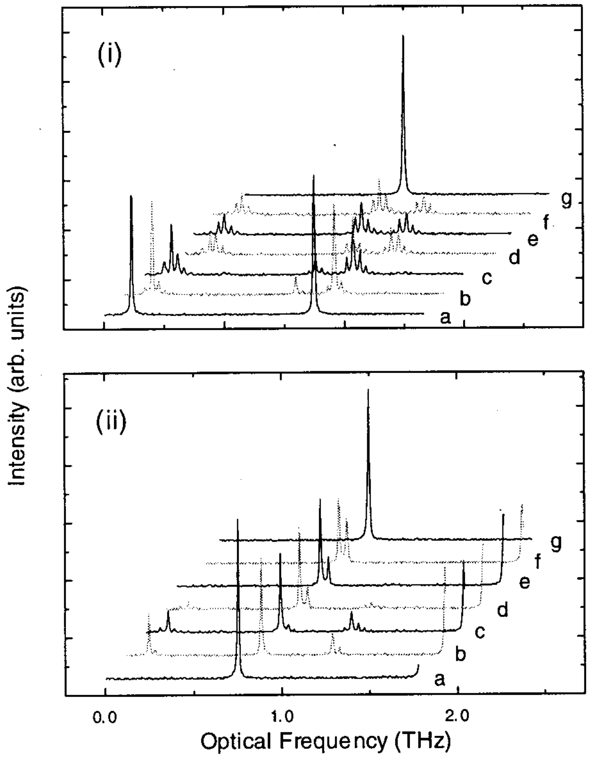

FIG. 4. Optical frequency spectra for increasing feedback level. COF is shown in (i) with feedback fractions from $a-g$ of 0.15%, 0.20%, 0.70%, 1.0%, 1.5%, 2.5%, and 5.0% respectively. PCF is shown in (ii) with feedback fractions from a–g of 0.04%, 0.06%, 0.5%, 1.0%, 5.0%, 10%, and 25%, respectively. The diode laser injection current is 55 mA ($1.7\,I_{\text{th}}$). All spectra are plotted on identical vertical scales that are shifted vertically and horizontally for clarity.

However, the external cavity mode resonances do not reach the same magnitude and are much broader. There are two possible reasons for this difference. First, it may be that the PCF system bifurcates into higher-order dynamics more quickly than the COF system and the initial bifurcations occur on a finer resolution of feedback level than experimentally observable. Second, it may be that total internal reflection geometry PCM introduces an uncertainty in the external cavity length, due to the dynamically forming grating within the crystal relying on beam fanning effects. This may cause a loss of constraint on the systems lasing frequency. Unlike the simple transition from broadband chaos into single-mode behavior, which is observed for COF, the transition into regime V (h) is preceded by a significant increase in the noise around the external cavity mode frequencies (e–g); though there is still a large number of closely spaced smaller peaks at these feedback levels. This indicates that the IV→V transition for PCF may involve a series of bifurcations from chaos into stability, through some other higher-order dynamic states.

Further difference between the two types of feedback are shown in the optical frequency spectrum. At an FSR of 1000 GHz the longitudinal modes of the laser diode spaced by 90 GHz are observable. Figure 4(i) shows the optical frequency spectra for COF with increasing feedback levels. Spectrum (a) is for a low feedback level that corresponds to stable single-mode behavior (regime III), with side mode suppression (not resolvable at the given scale) of greater than 30 dB. Increasing the feedback results in an abrupt transition to a multi-mode state (b), which corresponds to an excitation of the external cavity modes, as shown in Fig. 2. Further increase in feedback results in an increase in the number and magnitude of the laser diode longitudinal modes (c–f), until at a feedback level of 5% there is an abrupt transition to stable single-mode regime V operation (g). At low feedback levels the optical spectrum evolves similarly for the case of PCF [Fig. 4(ii) b–d]. However, at feedback levels above approximately 5% (e, f) a new state is observed. This state comprises lasing on two adjacent longitudinal modes of the laser diode, and corresponds to the noise spectra which comprises broad peaks at the external cavity mode spacing (Fig. 3 f and 3 g). Such a spectrum may represent either the system lasing simultaneously on two (adjacent) modes or rapid mode hopping between the two, similar to the regime II mode hopping state observed at very low feedback levels for COF. Although the presence of significant noise at low frequencies indicates that the system might be mode hopping, i.e., as due to mode partition noise, it has been experimentally determined that mode hopping does not occur at frequencies slower than 15 MHz. Power is systematically transferred from one of these modes to the other as the PCF is increased.

If the optical frequency is examined at a higher resolution, that of the external cavity modes (FSR 10 GHz), further differences are observed. Figure 5(i) shows the evolution with feedback power for COF. Figure 5(i) (a) shows a stable single-mode (regime III) followed by a transition into a state of excited external cavity modes in (b) and (c). With increased feedback, the output evolves into a broadband multimode spectrum indicative of chaos in (d) and (e), before switching back to stable single-mode behavior (regime V) in (f). Figure 5(ii) shows the similar evolution for PCF, although the broadband chaotic spectra [(c) and (d)] develop more rapidly and appear to have fewer features spaced by the external cavity frequency spacing than for comparable COF. In this sense the dynamics for PCF are simpler than those for COF. However, there is also a small region of feedback fractions close to the IV→V transition [Fig. 5(ii) (e)] which show a temporal evolution of the output state with fixed feedback fraction. This is shown in more detail in Fig. 6. The output is observed to switch through a number of distinct states over the time interval of 0.5–1 s. It generally starts in a chaotic multi-mode state (a), then switches to a state with excited external cavity modes (b) which increase in number (c, d) before a transition to a state of lasing on the fundamental mode with a series of side-modes (e, f) spaced by approximately 2–3 GHz. The separation between the central peak and the side-modes is found to increase linearly with the square root of the current above threshold. This indicates that this state is an excitation of the laser diode relaxation oscillation frequency, similar to that observed in collinear nondegenerate-four-wave-mixing [35] or injection locking [36] in semiconductor diode lasers. This evolution of the output state with time is due to the self-induced frequency

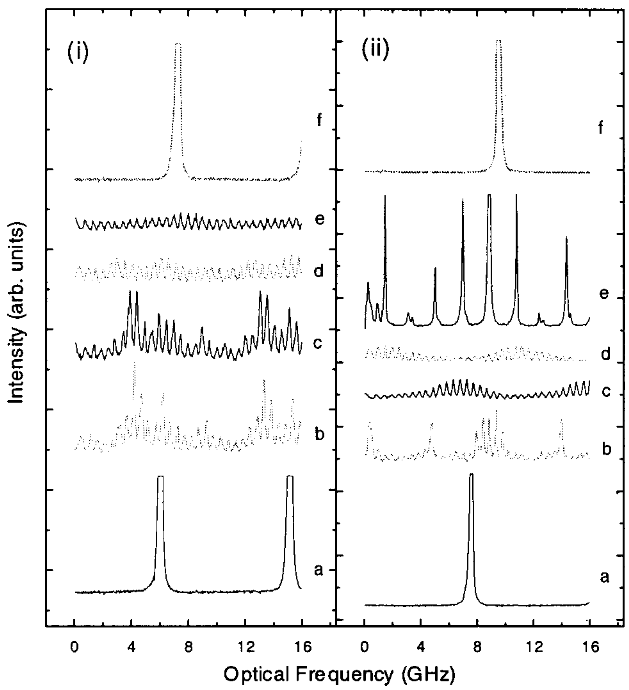

FIG. 5. Optical frequency spectra for increasing feedback level. COF is shown in (i) with feedback fractions from a–f of 0.15%, 0.20%, 0.70%, 1.5%, 2.5%, and 5.0%, respectively. PCF is shown in (ii) with feedback fraction of 0.04%, 0.06%, 0.5%, 5.0%, 22%, and 25%, respectively. The external cavity length is 300 mm. The diode laser injection current is 55 mA ($1.7\,I_{th}$). All spectra are plotted on identical vertical scales that are shifted vertically for clarity.

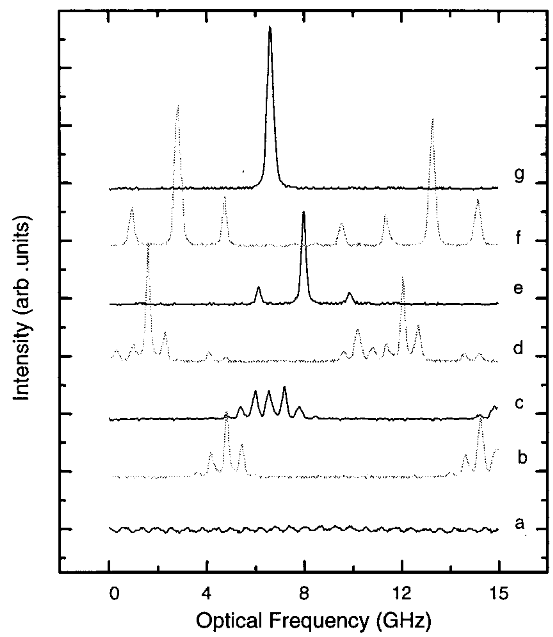

FIG. 6. Optical frequency spectra for PCF at a fixed feedback level of 22%. The output evolves over time through the sequence of distinct states shown. The diode laser injection current is 55 mA ($1.7\,I_{th}$). All spectra are plotted on identical vertical scales which are shifted vertically for clarity.

scanning of the phase conjugate feedback which occurs at these feedback fractions. Such scanning has been previously observed in a similar geometry PCM [37], although the phase conjugate signal is isolated in that case and therefore the multimode dynamics have not been observed. The range of different states occur because the feedback is now detuned from the diode's fundamental lasing frequency, and the detuning is changing over time. The relaxation oscillation may be excited when the detuning frequency is a multiple of the relaxation oscillation frequency. This self-induced frequency scanning also manifests itself on the optical frequency spectrum at the solitary diode mode resolution. The frequency is observed to scan over several hundred gigahertz in the high feedback end of regime IV.

Other differences between the two systems appear in the feedback levels at which transitions between stable and unstable output states occur. This is shown in Fig. 7. It has been previously observed that for COF the transition points, either III→IV or IV→V, are strongly dependent on external cavity length for this type of laser [38]. For long cavities (>500 mm) the transition points are constant. However, as the cavity length reduces from 200 mm, the range of feedback levels resulting in chaotic operation decreases. The feedback fraction of the III→IV transition increases and the feedback fraction of the IV→V transition is constant, until at approximately 80 mm when no coherence collapsed is observed for any level of feedback. It is, however, found that when the plane mirror is replaced by the Rh:$BaTiO_3$ PCM, the transition points remain approximately constant over the full range of experimentally investigated external cavity lengths (50–1000 mm). The III→IV transition is found to occur at a feedback fraction of approximately 0.05% and the IV→V transition occurs at approximately 20%, regardless of cavity length. It is found that the role of the PCM response time is important for this because heating the crystal, which decreases the response time [39], has been found to lower the

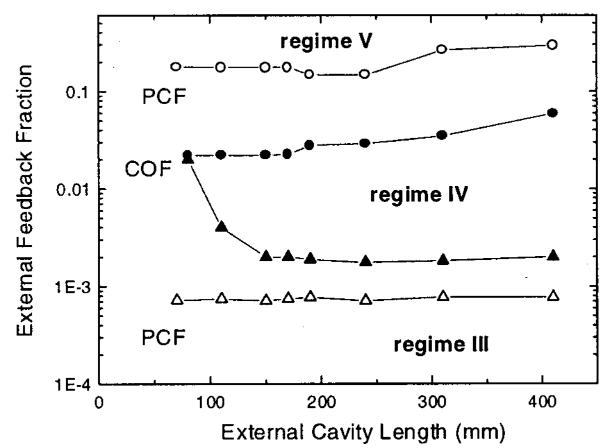

FIG. 7. The feedback fractions at which transitions between stable and unstable output states occur for PCF (open data points) and COF (solid data points) as a function of external cavity length. The points mark transitions from stable single-mode regime III into coherence collapse regime IV (triangles), and from coherence collapse regime IV into stable single-mode regime V (circles). The diode laser injection current is 55 mA ($1.7\,I_{th}$).

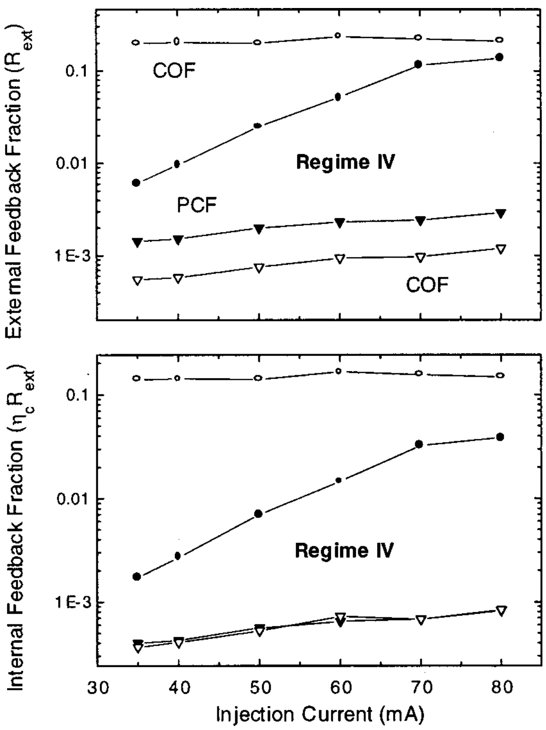

FIG. 8. (a) The feedback fractions at which transitions between stable and unstable output states occur for PCF (solid circles) and COF (open triangles) as a function of injection current. The points mark transitions from stable single-mode regime III into coherence collapse regime IV, and from coherence collapse regime IV into stable single-mode regime V. (b) The same data after it has been corrected for the different experimentally derived coupling coefficient for COF and PCF. The external cavity is 300 mm in each case.

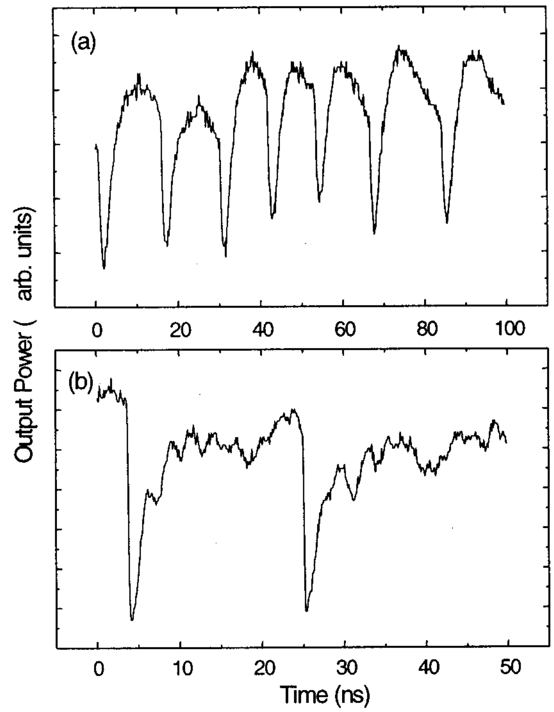

FIG. 9. Low frequency fluctuations induced by phase conjugate feedback; near the transition from coherence collapse to stable single-mode high feedback regime V. Feedback fraction is 20% in (a) and 10% in (b). Solitary diode laser injection current is 35 mA ($1.1\,I_{th}$).

IV→V transition point for shorter cavities. The transition points are shown as a function of injection current in Fig. 8(a). When the feedback fraction is corrected for the different coupling efficiencies for COF and PCF [Fig. 8(b)], it is seen that the transition from regime III to IV occurs for the same feedback levels.

At injection currents close to the solitary diode laser threshold, a low-frequency-fluctuation- (LFF) type state is observed for both COF and PCF. This is shown (for PCF) in Fig. 9. The LFF instability has been attributed as a time-inverted type II intermittency [40], characterized by intermittent breakdown events (power dropouts) followed by a return to equilibrium. The distribution of the dropout events is determined by the injection current and feedback fraction. The recovery may either be a gradual increase to the equilibrium power value [40] or a rapid power increase to a value higher than equilibrium, followed by a gradual decrease to equilibrium [41–43]. This recovery is governed by the value of the feedback fraction (this work) and/or the asymmetry of the laser diode facet reflectances [41]. The states shown in Fig. 9 both represent types of LFF behavior previously observed in COF systems [40–43]. The intensity noise spectrum for these cases shows increased noise at low frequencies, as expected. There is little apparent difference between the two LFF states (COF and PCF).

Interpreting the results in terms of existing theories is not entirely appropriate because the assumptions and approximations made in these models are not always met by the experiment which involves a PCM with finite response time and interaction length. Also, many of the new behaviors are observed close to the IV→V transition, and there is no published theoretical research on PCF for such high optical feedback levels to our knowledge. However, some qualitative agreement between existing theory and the current experiment occurs, and some useful discussion can be made. Both COF and PCF lead to a progression from a stable, single frequency regime (III) to an unstable regime (IV), and then to a second stable, single frequency regime (V) with increasing levels of feedback, either COF or PCF. This progression is expected for COF but is not expected for instantaneous PCF where the system is predicted to remain unstable once it has made the transition to instability, and it makes this transition at much lower levels of feedback compared to COF. The experimentally observed progression is consistent with the model of Van der Graaf *et al.* for a finite response time PCM [13]. This predicts that the PCF with finite response time stabilizes the system for lower levels of feedback and that a transition back to stable behavior will be seen at higher PCF levels. The fact that the experimentally determined feedback level for transitions from regime III–IV is the same for both PCF and COF, when the correction for the different coupling coefficients is made, further supports that this transition for PCF has been stabilized and is similar to COF when the response time of the PCM is slow. That there are clear differences between PCF and COF is shown by the differing spectral characteristics and the higher feedback levels for the regime IV–V transition for PCF compared to COF. This latter result is consistent with Bochove's prediction that increasing the response time of the PCM causes increased instabilities at higher levels of feedback [14]. Thus the predictions of both these models [13,14] are seen to be consistent with the experimental results, although it would be plausible to interpret these predictions as being contradictory in the absence of the results from the experiment. The effect of finite interaction depth is predicted to lead to a stabilization of the system with higher levels of PCF [12], which is inconsistent with the observations, indicating that this effect may not be significant in these experiments. The interaction length in the experiments is about a fifth of the lowest value simulated in Ref. [12] so the effect would be expected to be smaller than the results of that paper. It appears that the finite response time is dominant in determining the stability of the PCF system, though more work needs to be done to support such speculation. A difference between the length dependence of PCF and COF is predicted [8], again for a nonzero response time PCM, and a change in this PCF length dependence with response time is predicted in Ref. [12], although for NDFWM PCF.

The experiments and results reported here indicate the directions and the important parameters that need to be included for a full theoretical description of diode lasers with PCF. These are higher levels of feedback that can be described validly by the theoretical model methods reported to date, a variable time response of the phase conjugate mirror, and the possibility of an ill-defined external cavity length when a two-interaction-region PCM is used. Further experimental results are also needed for a full description of these systems. Areas of study should include repetition of the above experiments using a semiconductor phase conjugator (which will have a much faster response time), comparison with phase conjugation using nondegenerate four-wave-mixing (rather than self-pumped), and the effect of the specific type of diode laser. The observation of a temporal evolution of the output state observed near the IV–V transition for PCF is probably too complex to treat theoretically. It relies on the phenomenon of self-induced frequency scanning which is not entirely understood, is difficult to fully characterize, and occurs at strong feedback levels. All of these represent very difficult theoretical problems.

The observation of the external cavity mode spacing, c/2L, as the dominant frequency appearing in the relative intensity noise and optical spectra, for both COF and PCF, as the transition to unstable operation occurs is worthy of further discussion. Several authors have predicted that the observed dominant frequency is c/4L for PCF compared to c/2L for COF in theoretical studies [14]. These studies have been for nondegenerate four wave mixing (NDFWM) and, in turn, refer to earlier work [44] which demonstrated that there is no stable mode for a single roundtrip in the nondegenerate case. However, for the case of degenerate FWM, which is relevant for the present experiments, Ref. [44] shows that there are a large range of possible stable modes for both single and double roundtrips, with the only constraint being that the mode will have a radius of curvature that matches the radius of curvature of the real mirror of the two mirror resonator (the second mirror being the PCM). The mode that will actually lase will be the one that uses the available gain most efficiently, taking into account any real or effective aperturing arising from, for example, the spatial extent of the pump beams [44]. In the laser system studied here the ''real'' mirror is, in fact, the laser diode end facet, or indeed, the laser diode waveguide. The experimental results demonstrate that the mode that uses the gain most efficiently in this system, with both PCF and COF, is the single roundtrip mode. Some previous experiments of PCF in laser diodes [18,45] have observed c/4L modes when utilizing spectrally degenerate FWM and have taken this observation of c/4L modes as proof that phase conjugate feedback is being generated. An independent check of the phase conjugate nature of the feedback has been carried out in this study, following the method of Ref. [34]. The results of all experimental studies of PCF in laser diodes to date [18, 39, this work] suggest the c/2L modes will be seen when the PCF is both spectrally and spatially degenerate and the c/4L modes are seen when the PCF is spectrally degenerate but spatially nondegenerate and vice-versa.

IV. CONCLUSION

Phase conjugate and conventional optical feedback (PCF and COF) into a laser diode have been contrasted in a system using the same laser device. Results from any study of laser diodes with optical feedback depend on the diode and feedback used. The self-pumped phase conjugate mirror (SPPCM) used here is based on a rhodium doped $BaTiO_3$, photorefractive crystal. The SPPCM is thus characterized by slow response time, has a finite interaction depth, and the self-pumped geometry introduces an uncertainty in the external cavity length. The laser diode has the characteristics of being very nearly single mode with strong damping of the relaxation oscillation. The results show that the system with PCF displays unstable, coherence collapsed, chaotic behavior starting at optical feedback levels which are the same for COF and continuing to levels 5–50 times higher than for COF (depending on the injection current), in the long external cavity limit. This increased range of feedback levels giving unstable output for PCF is expected from theory. The route to chaos for this system using a highly damped laser diode does not appear to be undamping of the relaxation oscillations, as is commonly predicted by many theoretical treatments published to date. Excitation of external cavity modes is the first periodic output observed. Within regime IV, there is a large difference in the spectrum of the power noise for PCF compared to COF. For PCF, broad noise features about the external cavity mode frequencies appear as soon as the transition to regime IV has occurred in contrast to the narrow features that appear for COF. For PCF these features further broaden with increasing feedback, but not as much as they do for COF. The features narrow again as the feedback level approaches the IV–V transition level, whereas for COF the features remain broad until the abrupt transition to regime V occurs. Also, low-frequency noise appears as the regime V boundary is approached, which is not seen for COF.

Two new types of behavior have been seen for the case of PCF. The optical spectrum of the solitary laser modes shows a systematic transfer of power from one solitary laser mode to its nearest neighbor. Close to the IV–V transition boundary a new regime of self-frequency scanning is observed. This regime has an optical frequency spectrum which cycles in time through four distinct states: single frequency, single frequency with strong excitation of the relaxation oscillations, coherence collapsed, and multimode. These new observations and the evolution of the power noise and optical spectra are tasks for future theoretical investigation.

In the context of using PCF to obtain narrow linewidth, high spatial quality output the present study shows that slow, photorefractive crystals can give this output, but the level of feedback required to achieve strong feedback behavior are higher than for COF. The main advantage of PCF is the much higher coupling efficiency of the feedback to the laser diode. More experimental studies that derive the PCF using alternative PCMs, particularly ones with faster response times, are needed to determine the relative occurrence of stable and unstable output. Theory suggests stable output at high feedback levels may not be achievable using instantaneous PCMs. Additionally, there are new opportunities to study the detailed nature of the instabilities using the Rh:doped $BaTiO_3$ PCM and alternates that will contribute to the understanding of these complex nonlinear systems.

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[1] G. H. M. van Tartwijck and D. Lenstra, Quantum Semiclassic. Opt. **7**, 87 (1995).
[2] R. W. Tkach and A. R. Chraplyvy, J. Lightwave Technol. **LT-4**, 1655 (1986).
[3] K Petermann, IEEE J. Sel. Top. Quantum Electron. **1**, 480 (1995).
[4] A. Murakami and J. Ohtsubo, IEEE J. Quantum Electron. **QE-34**, 1979 (1998).
[5] G. P. Agrawal and J. T. Klaus, Opt. Lett. **17**, 1325 (1991).
[6] G. H. M. van Tartwijck, H. J. C. van der Linden, and D. Lenstra, Opt. Lett. **17**, 1590 (1992).
[7] G. R. Gray, D. Huang, and G. P. Agrawal, Phys. Rev. A **49**, 2096 (1994).
[8] A. Murakami, J. Ohtsubo, and Y. Liu, IEEE J. Quantum Electron. **QE-33**, 1825 (1997).
[9] B. Krauskopf, G. R. Gray, and D. Lenstra, Phys. Rev. E **58**, 7190 (1998).
[10] G. P. Agrawal and G. R. Gray, Phys. Rev. A **46**, 5890 (1992).
[11] L. N. Langley and K. A. Shore, Opt. Lett. **18**, 1432 (1993).
[12] D. H. DeTienne, G. R. Gray, G. P. Agrawal, and D. Lenstra, IEEE J. Quantum Electron. **33**, 838 (1997).
[13] W. A. van der Graaf, L. Pesquera, and D. Lentsra, Opt. Lett. **23**, 256 (1998).
[14] E. Bochove, Phys. Rev. A **55**, 3891 (1997).
[15] M. Cronin-Golomb, K. Y. Lau, and A. Yariv, Appl. Phys. Lett. **47**, 567 (1985).
[16] K. Vahala, K. Kyuma, A. Yariv, S. Kwong, M. Cronin-Golomb, and K. Lau, Appl. Phys. Lett. **49**, 1563 (1986).
[17] S. Mailhot and N. McCarthy, Can. J. Phys. **71**, 429 (1993).
[18] P. Kurz and T. Mukai, Opt. Lett. **21**, 1369 (1996).
[19] A. Shiratori and M. Obara, Appl. Phys. Lett. **69**, 1515 (1996).
[20] M. Ohtsu, I. Koashishi, and Y. Teramachi, Jpn. J. Appl. Phys. **29**, L2060 (1990).
[21] N. Cyr, M. Breton, M. Tetu, and S. Theriault, Opt. Lett. **16**, 1298 (1991).
[22] E. Miltenyi, M. O. Ziegler, M. Hoffman, J. Sacher, W. Elsasser, E. O. Gobel, and D. L. MacFarlane, Opt. Lett. **20**, 734 (1995).
[23] M. Cronin-Golomb and A. Yariv, Opt. Lett. **11**, 455 (1986).
[24] S. MacCormack and R. W. Eason, Opt. Lett. **16**, 705 (1991).
[25] M. Cronin-Golomb, A. Yariv, and I. Ury, Appl. Phys. Lett. **48**, 1240 (1986).
[26] P. Besnard, B. Meziane, and G. M. Stephan, IEEE J. Quantum Electron. **QE-29**, 1271 (1993).
[27] H. Li, J. Ye, and J. G. McInerney, IEEE J. Quantum Electron. **QE-29**, 2421 (1993).
[28] H. Olesen, J. H. Osmundsen, and B. Tromborg, IEEE J. Quantum Electron. **QE-22**, 762 (1986).
[29] J. Mork, B. Tromborg, and J. Mark, IEEE J. Quantum Electron. **QE-28**, 93 (1992).
[30] L. N. Langley, K. A. Shore, and J. Mork, Opt. Lett. **19**, 2137 (1994).
[31] D. R. Hjelme, A. R. Mickelson, and R. G. Beausoleil, IEEE J. Quantum Electron. **27**, 352 (1991).
[32] M. H. Rose, M. Lindberg, W. W. Chow, S. W. Koch, and M. Sargent, Phys. Rev. A **46**, 603 (1992).
[33] J. S. Lawrence and D. M. Kane, Electron. Lett. **36**, 535 (2000).
[34] M. Cronin-Golomb, B. Fischer, J. O. White, and A. Yariv, Appl. Phys. Lett. **42**, 919 (1983).
[35] R. Nietzke, P. Panknin, W. Elsasser, and E. O. Gobel, IEEE J. Quantum Electron. **25**, 1399 (1989).
[36] F. Mogensen, H. Olesen, and G. Jacobsen, IEEE J. Quantum Electron. **21**, 784 (1985).
[37] M. Cronin-Golomb and A. Yariv, Opt. Lett. **11**, 455 (1986).
[38] J. S. Lawrence, D. M. Kane, and P. S. Spencer, in *Technical Digest, Advanced Semiconductor Lasers and Applications 1999* (Conference Edition, OSA, Washington, 1999), pp. 49–51.

[39] T. Honda and H. Matsumoto, Opt. Commun. **91**, 390 (1992).
[40] T. Heil, I. Fischer, and W. Elsasser, Phys. Rev. A **58**, R2672 (1998).
[41] M. Pan, B. Shi, and G. R. Gray, Opt. Lett. **22**, 166 (1997).
[42] F. Tomasi, E. Cerboneschi, and E. Arimondo, IEEE J. Quantum Electron. **30**, 2277 (1994).
[43] J. Sacher, D. Baums, P. Panknin, W. Elsasser, and E. O. Gobel, Phys. Rev. A **45**, 1893 (1992).
[44] J. Auyeung, D. Fekete, D. M. Pepper, and A. Yariv, IEEE J. Quantum Electron. **15**, 1180 (1979).
[45] P. P. Vasil'ev and I. H. White, Appl. Phys. Lett. **71**, 40 (1997).