Femtosecond dynamics in semiconductor lasers: Dark pulse formation

M. Kauer[a)] and J. R. A. Cleaver
Cavendish Laboratory, University of Cambridge, Cambridge CB3 0HE, United Kingdom

J. J. Baumberg[b)] and A. P. Heberle
Hitachi Cambridge Laboratory, Madingley Road, Cambridge CB3 0HE, United Kingdom

(Received 30 December 1997; accepted for publication 3 February 1998)

We track the dynamic response of GaAs quantum-well semiconductor diode lasers after injection of a femtosecond pulse, using ultrafast upconversion. The continuous-wave emission shows gain dynamics and relaxation oscillations on timescales of 1–100 ps. The recirculating femtosecond pulse evolves into an ultrafast ''dark pulse'' in the wake of subpicosecond oscillations. © *1998 American Institute of Physics.* [S0003-6951(98)02713-2]

The dynamic behavior of semiconductor lasers and amplifiers reveals fundamental information about the electron and photon systems and their interplay on a range of timescales, which is of importance for application of these devices in optoelectronic communication systems. Pump–probe measurements in both semiconductor optical amplifiers (SOAs) and laser diodes (LDs) indicate that, in addition to interband and refilling processes occurring on a picosecond timescale, intraband processes such as carrier–carrier and carrier–phonon interactions must be considered on the femtosecond timescale.[1] Nonlinear effects such as carrier heating, spectral-hole burning, and two-photon absorption lead to gain saturation[1] and self-phase modulation which determine the propagation of femtosecond optical pulses in SOAs.[2]

In semiconductor lasers, carrier injection by optical pulses high above the band gap has been used to extract parameters critical to the modulation bandwidth of devices, thus avoiding the parasitics associated with electrical modulation techniques.[3–5] Propagation of optical pulses centered on the lasing wavelength of LDs, however, has so far been used only to determine group-velocity dispersion.[6]

Here, we report high-dynamic-range femtosecond experiments on continuous-wave (cw) semiconductor laser diodes. The recirculating pulses produced by injecting a single resonant femtosecond optical pulse are resolved, as well as the cw emission dynamics of the laser. In contrast to SOAs, where an optical pulse travels through the medium only once, a single pulse incident on a LD produces a sequence of pulses emitted due to partial reflection at the front and rear facets. Thus the evolution of ultrafast pulses can be tracked at different points along long interaction lengths. We identify a new regime in which interactions between the pulsed and cw light within the cavity leads to an oscillatory ''dark pulse'' at long times.

The measurements use the 120 fs [autocorrelation full width at half maximum (FWHM)] output of a mode-locked Ti:sapphire laser (82 MHz pulse repetition rate), split into a weak excitation ($<30\ \mu$W) and a strong gating pulse (Fig. 1, inset). The excitation pulse is coupled into the front facet of a semiconductor laser diode under cw bias. The output is collected by a microscope objective and cross correlated with the time-delayed gating pulse in a nonlinear crystal. The upconverted signal is detected by a photomultiplier. All measurements were performed with pulse energies comparable to the cw energy stored in the cavity ($\sim$300 fJ) and with TE-polarized pulses.

We used unpackaged edge-emitting quantum-well (QW) semiconductor LDs. The active region consists of three undoped 7 nm $Al_{0.1}Ga_{0.9}As$ QWs separated by two 5 nm $Al_{0.3}Ga_{0.7}As$ barrier layers. The single-mode lasers have a 5 μm wide ridge waveguide with uncoated facets and are cleaved to a length of 400 μm. The lasing wavelength is 773 nm, with a threshold current of $I_{th}=45$ mA. Details of the device structure and fabrication process can be found in Refs. 7 and 8.

Figure 1 shows the time-resolved output of the laser for a bias current of $I_{\rm bias}=1.4I_{th}$. The input pulse centered on the lasing wavelength is amplified as it propagates in the cavity and is partially reflected at the front and rear facets of the diode. This gives rise to the observed pulse train with a separation corresponding to the cavity roundtrip time of 10.55 ps. The high dynamic range makes it possible to observe more than 100 roundtrips of the circulating pulse, equivalent to an otherwise impractical path length of several centimeters. The input pulse disturbs the equilibrium between the cw photon density ($P_{\rm cw}$) and the carrier density at

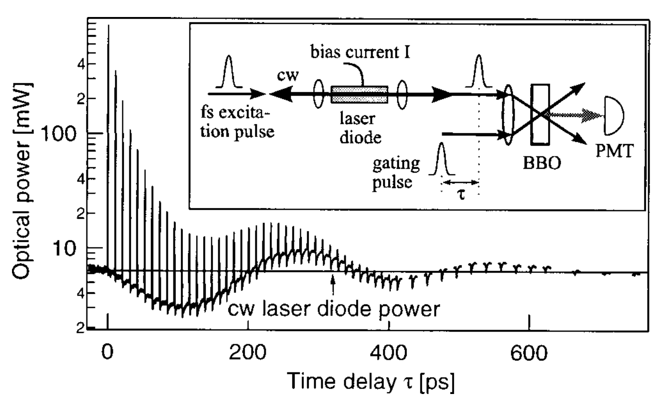

FIG. 1. Output pulse train produced by a single 85 fs pulse ($\lambda=773$ nm, $P=25\ \mu$W) incident on the laser diode at $I_{\rm bias}=1.4I_{th}=65$ mA. Every second pulse is shown after 410 ps, every fourth after 620 ps. Inset: Experimental scheme (BBO=β-barium–borate nonlinear crystal, PMT =photomultiplier).

[a)]Electronic mail: mk225@cam.ac.uk
[b)]Electronic mail: baumberg@phy.cam.ac.uk

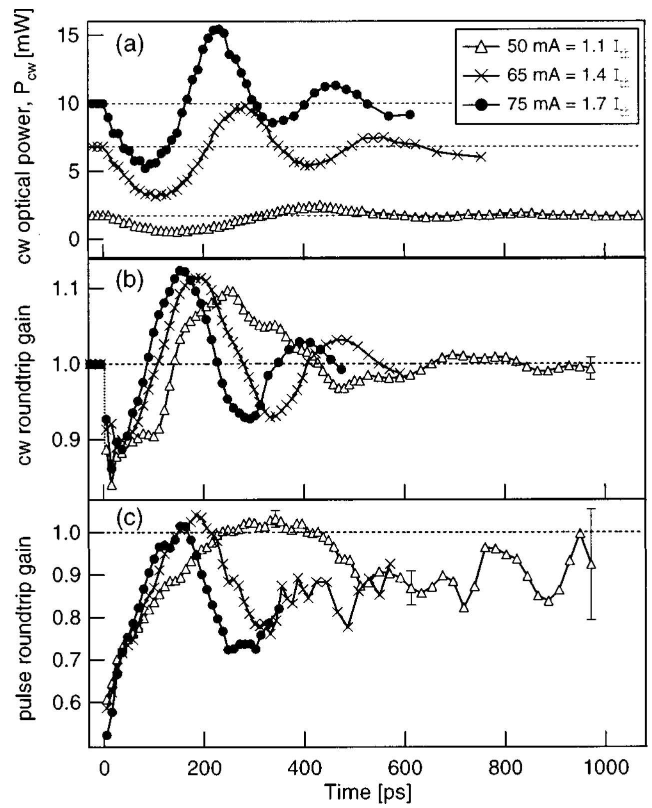

FIG. 2. (a) Laser diode cw emission at times midway between the pulses for different bias currents. (b) and (c) Roundtrip gain vs time of cw emission and pulses for different bias currents.

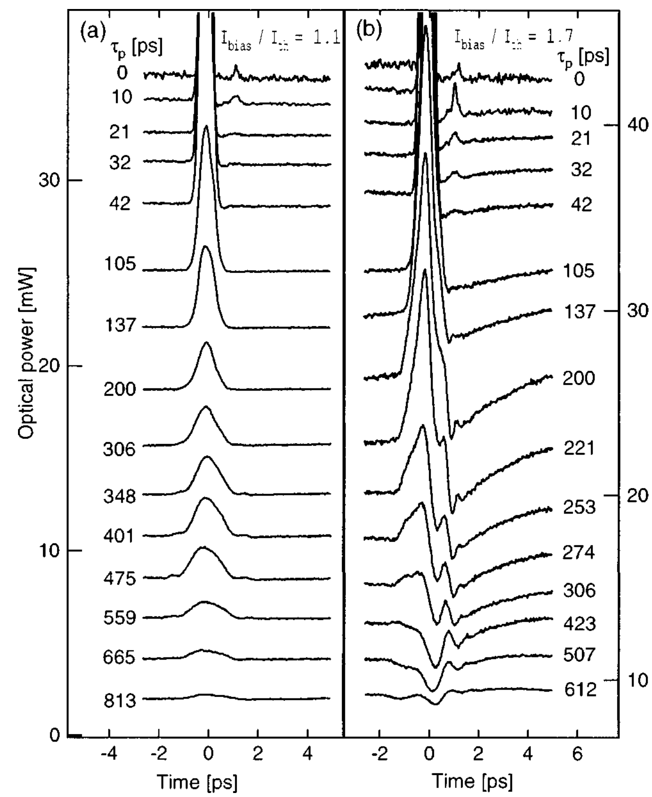

FIG. 3. Evolution of output pulses after multiple passes for (a) 50 mA and (b) 75 mA laser diode bias current. The same conditions as Fig. 1, τ_p refers to the pulse center. The pulses have been shifted by multiples of the cavity roundtrip time (10.55 ps) and offset vertically.

the lasing wavelength ($N_{\rm cw}$), initiating relaxation oscillations in the cw intensity. They form the slowest electronic response with a period of several hundred picoseconds for the coupled ($N_{\rm cw}, P_{\rm cw}$) system and a damping time of $\sim$500 ps. The relaxation oscillations in the cw emission shown in Fig. 2(a) do not exactly follow a damped sinusoid[5] since the perturbation caused by the input pulse is strong and continues beyond the initial injection.

As a consequence of group-velocity dispersion, the circulating pulse broadens as it propagates in the cavity. The broadening (and hence the group velocity dispersion) is independent of the bias current. Therefore, it can be concluded that the femtosecond pulse spectrum lies fully inside the gain spectrum.

Figures 2(b) and 2(c) directly compare the roundtrip gain for the cw emission and the femtosecond pulses. The femtosecond (cw) roundtrip gain is defined as the ratio of the pulse area of successive output pulses (ratio of cw intensity midway between pulses). The cw gain drops at zero time delay, then recovers to unity through relaxation oscillations; these become faster for larger values of the bias current. The pulse roundtrip gain, however, shows clearly different behavior. For the first few passes it is much smaller than the cw gain, then increases rapidly and also oscillates. The reduced gain experienced by the femtosecond pulse (vs $P_{\rm cw}$) is attributed to a combination of carrier heating and two-photon absorption (TPA)[1] and appears in pump–probe experiments on the same sample.

Surprisingly, the circulating pulse survives fewer roundtrips as the bias current is increased above threshold. This is due to fast transients in the laser output which occur in addition to relaxation oscillations. The output pulses and cw background have been enlarged in Fig. 3 to show these fast transients more clearly. It illustrates that the recirculating pulse is interacting in a much more complex way with the laser diode than simply causing relaxation oscillations by disturbing the equilibrium electron and photon populations.

While the cw power begins to decrease due to the onset of relaxation oscillations, it drops in further sudden steps after the passage of each successive pulse for the first few passes. This subpicosecond drop increases with increasing bias current and contains a nondecaying component. Several physical mechanisms induced by the femtosecond pulse may contribute to a drop in gain (and hence $N_{\rm cw}$). First, the pulse reduces the carrier density by stimulated emission. In this case, the following cw emission will be reduced until the gain recovers by current injection on nanosecond timescales. As shown in pump–probe experiments,[1] nonlinearities such as carrier heating and TPA can also lead to a gain reduction. These may be responsible for the $\sim$1 ps partial recovery of the drop in cw emission and the afterpulse seen at 1.5 ps (possibly an artifact). However the recovery of these excited carrier distributions is too quick to account for the observed long-lasting component.

A new timescale enters when the current is increased. In Fig. 3(a) at $I_{\rm bias}$–I_{th} the pulses retain their original shape, apart from broadening, until they vanish. As the bias current is increased, pulse and cw emission can no longer be treated separately, but instead start to influence each other strongly. This is seen in Fig. 1 for $I_{\rm bias}\sim 1.4 I_{th}$ and becomes more pronounced as the current is increased to $\sim 1.7 I_{th}$ [Fig. 3(b)].

As soon as the femtosecond pulse stops reducing N_{cw} (within 50 ps), the instantaneous drop in the cw emission starts to evolve and becomes progressively deeper and shorter lived. After a few hundred picoseconds, oscillatory behavior starts to develop which subsequently takes over. The dark pulse in the background cw emission continues to propagate for hundreds of picoseconds after the original ''bright pulse'' has died away.

One explanation for the observed behavior would be provided by recovery of gain depletion. As the circulating pulse becomes weaker, the instantaneous reduction in gain which it causes can recover within a few picoseconds. This could produce the ~ 3 ps exponential trailing edge in the wake of the dark pulse. However this does not explain why the drop in gain becomes much larger after more roundtrips of the attenuating pulse, nor would this account for the appearance of oscillations within the dark pulse itself. We tentatively suggest an alternative explanation based on coherent coupling between intracavity pulsed and cw fields. Nonlinear pulse shaping was observed previously in single-pass SOAs for intensities several orders of magnitude larger, leading mainly to stretching of the pulse.[9] In contrast in the present LDs, the oscillations would arise from destructive interference between the background bright cw field and the collapsing fs pulse. Oscillations are indeed seen at lower currents [Fig. 3(a) after 300 ps], though more weakly, as expected from intensity-dependent cross-phase modulation. We note that the time at which the oscillations appear is close to the time at which the pulse gain recovers to unity, suggesting this might be causing a pulse instability[10] which would be absent in SOAs.

An equivalent discussion in the spectral domain implicates four-wave mixing (FWM) between the original lasing mode and several nearby longitudinal modes excited by the femtosecond input pulse. Ongoing theoretical work, aimed at clarifying which of the above models is correct, is based on the distinction between *incoherent* (carrier) and *coherent* (FWM) interactions. If the dark pulse is caused by gain depletion, modeling of the photon intensity in a single mode and the carrier density are sufficient. In contrast, coherent mixing of several longitudinal modes requires modeling of the amplitude and phase of the electric field propagating in the cavity. Further experiments to spectrally resolve the upconverted emission are planned to clarify the dynamics.

In conclusion, we have studied the dynamics of femtosecond optical pulses in semiconductor lasers and their interaction with the cw lasing. Both pulse and cw emission could be monitored simultaneously due to the large dynamic range, allowing access to both N_{cw} and P_{cw} on fs–ns timescales. The transient pulse gain is smaller than the cw gain due to two-photon absorption. Relaxation oscillations at long times coexist with ultrafast dark pulses in the cw laser emission, long after the injected pulse has died away. We suggest coherent mixing of several longitudinal cavity modes is enhanced by the long interaction length available.

The authors thank Dr. M. Okai and his colleagues at HCRL for provision of the laser devices and appreciate critical comments from Jeremy Allam. M. Kauer acknowledges financial support from the Erich Müller Foundation and EPSRC.

[1] K. L. Hall, G. Lenz, A. M. Darwish, and E. P. Ippen, Opt. Commun. **111**, 589 (1994), and references therein.
[2] M. Y. Hong, Y. H. Chang, A. Dienes, J. P. Heritage, P. J. Delfyett, S. Dijaili, and F. G. Patterson, IEEE J. Sel. Top. Quantum Electron. **2**, 523 (1996).
[3] H. Schneider, J. D. Ralston, E. P. O'Reilly, S. Weisser, and E. C. Larkins, Appl. Phys. Lett. **65**, 661 (1994).
[4] D. H. Sutter, H. Schneider, S. Weisser, J. D. Ralston, and E. C. Larkins, Appl. Phys. Lett. **67**, 1809 (1995).
[5] T. Hessler, S. Haacke, J. L. Pleumeekers, P. E. Selbmann, M. A. Dupertuis, B. Deveaud, R. A. Taylor, P. Doussière, M. Bachmann, T. Ducellier, and J. Y. Emery, Quantum Semiclassic. Opt. **9**, 675 (1997).
[6] K. L. Hall, G. Lenz, and E. P. Ippen, J. Lightwave Technol. **10**, 616 (1992).
[7] S. Nakatsuka, S. Yamashita, K. Uchida, and T. Kajimura, Jpn. J. Appl. Phys., Part 1 **30**, 493 (1991).
[8] S. Yamashita, S. Nakatsuka, K. Uchida, T. Kawano, and T. Kajimura, IEEE J. Quantum Electron. **27**, 1544 (1991).
[9] R. A. Indik, R. Binder, M. Mlejnek, J. V. Moloney, S. Hughes, A. Knorr, and S. W. Koch, Phys. Rev. A **53**, 3614 (1996).
[10] J. P. van der Ziel, J. L. Merz, and T. L. Paoli, J. Appl. Phys. **50**, 4620 (1979).