

# Coherence collapse and low-frequency fluctuations in quantum-dash based lasers emitting at 1.57 $\mu\text{m}$

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**Abstract:** Optical feedback tolerance is experimentally investigated on a 600- $\mu\text{m}$ -long quantum-dash based Fabry-Pérot laser emitting at 1.57 $\mu\text{m}$ . While quantum-dashes are structurally intermediate to quantum-wells and quantum-dots, the observed behaviour is distinctly like that of a quantum-well based laser but with greater stability. Coherence collapse and low-frequency fluctuation regimes are observed and are reported here. The onset of the coherence collapse regime is experimentally determined and is found to vary from -29 dB to -21 dB external feedback level when increasing the current from twice to nine times the threshold current.

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## 1. Introduction

When subjected to intentional or inadvertent external optical feedback, the coherence and stability properties of semiconductor lasers can be greatly altered, with multiple distinct regimes identified including linewidth narrowing, mode hopping and linewidth broadening [1]. For on-off keyed telecommunications lasers, the regime of most interest is that of coherence collapse (CC) [2] where the laser intensity undergoes deep fluctuations and the laser linewidth can broaden to several 10s of gigahertz. Within the CC regime, there is a range of parameters where the laser typically displays power dropouts with a staircase recovery at a rate of tens of megahertz, far lower than any natural frequency of the system; a behaviour termed low-frequency fluctuations (LFF) [3]. CC can be induced through small, unwanted reflections in optical systems and greatly degrades communication links and therefore has been the subject of close study for some time.

The technological remedy for this susceptibility to external reflections has been to incorporate an optical isolator into transmitter laser packages. For cost sensitive metropolitan and local area networks this is a major drawback, and efforts have been made to develop lasers highly tolerant to optical feedback. Quantum-dot (QD) based semiconductor lasers offer such a possibility. Early, simple models of QD lasers predicted narrow, symmetric gain spectra [4] due to the discrete density of states. As a result, near-zero linewidth enhancement factors (LEF) were expected. They were also expected to display enhanced performance under feedback conditions compared to quantum-well based devices as a result of their comparatively low LEFs. In particular, they were expected to have a high CC threshold. In the InAs/GaAs QD system near the 1.3  $\mu\text{m}$  communications band, several experimental works have fulfilled the predictions of these early models; near-zero LEF has been reported [5] and QD devices do indeed show high resistance to feedback instabilities [6-8]. However, the LEF does not turn to be the most important factor for the enhanced resistance; instead it is found that increased relaxation oscillation damping arising from gain saturation is the feature most responsible for the extra stability [7]. In the InAs/GaAs QD system, this saturation arises from the quantized energy states of the dots and the currently achievable areal densities of QDs, on the order of  $3 \times 10^{10} \text{ cm}^{-2}$  per layer [4].

Despite the excellent performance of InAs/GaAs QD lasers near the silica fibre dispersion minimum, currently the material system cannot provide gain in the vital loss minimum band near 1.55  $\mu\text{m}$ . To address this need, InAs/InP (100) nanostructured materials have been investigated. In comparison with InAs/GaAs QD materials, it is much more difficult to grow isotropic dots in this system; rather quantum-dashes are typically obtained. These dashes

nonetheless provide high gain and low losses [9-12]. Indeed, continuous-wave (CW) room-temperature lasing operation has been demonstrated on the ground state for a cavity length as short as 200  $\mu\text{m}$ . The high gain results from the reduced quantization of the density of states in one direction, giving a structure intermediate between quantum wells and quantum dots. Broadly speaking, the quantum-dash structures reported in the literature can be classified either as dashes-in-a-barrier or dashes-in-a-well. We have previously reported on direct modulation at 10 Gbps of a dashes-in-a-well based laser emitting at 1.51  $\mu\text{m}$  up to the coherence collapse at -24-dB feedback from the system, which is nearly compliant with the 10 Gbps Ethernet standard [13].

In this work, we investigate the tolerance to optical feedback of quantum-dash based lasers realised from a dashes-in-a-barrier structure. Using two distinct experimental arrangements, we observe and investigate coherence collapse and low-frequency fluctuation regimes over a wide range of external reflector distances. The feedback level for the onset of coherence collapse,  $\gamma_{crit}$ , is experimentally determined in CW operation using both the microwave and optical spectra. The performance under optical feedback is found to be superior with respect to quantum-well devices, though the dash structure is less resistant than QD devices at 1.3  $\mu\text{m}$ . It is found that these devices are compliant with the 10 Gbps Ethernet standard for isolator-free operation.

## 2. Device

The dashes-in-a-barrier structure was grown by gas source molecular beam epitaxy on a (100) InP substrate. It consists of InAs quantum dashes enclosed within 40-nm-thick barriers and two 80-nm-thick separate confinement heterostructure (SCH) layers. Both the barriers and the SCH layers are undoped and lattice-matched quaternary  $\text{Ga}_{0.2}\text{In}_{0.8}\text{As}_{0.4}\text{P}_{0.6}$  layers ( $\lambda_g = 1.17 \mu\text{m}$ ) [11]. From this structure, a 600- $\mu\text{m}$ -long Fabry-Pérot laser was fabricated with ridge width of 1.5  $\mu\text{m}$  and cleaved facets. The device was mounted on a temperature stabilised holder. The threshold current was 13 mA at 25°C and the slope efficiency was 0.18 W/A. The linewidth enhancement factor (LEF) estimated by the FM/AM method [14], and damping factor (high-frequency modulation technique) values are reported in Fig. 1. For comparison, the typical values for the LEF and the damping factor for a 350- $\mu\text{m}$ -long strained multiple quantum well based laser are  $\sim 3$  and  $\sim 30 \cdot 10^9 \text{ rad}\cdot\text{s}^{-1}$  at 10 mW respectively.

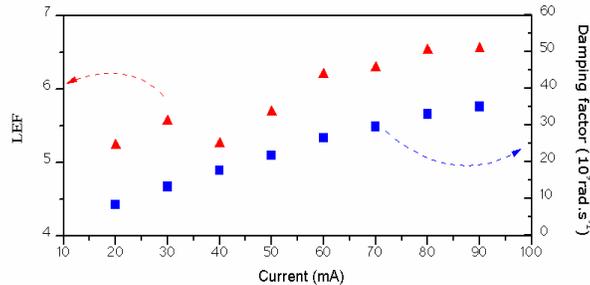


Fig. 1. Linewidth enhancement factor (LEF) and damping factor versus current.

## 3. Experimental setups and feedback level determination

The behaviour of quantum-dashes under optical feedback was assessed using the same device on both a fibre-coupled and a free-space setup, respectively described in Fig. 2 and Fig. 3. The fibre-based experiment permitted long feedback lengths, much like those found in optical systems with splice or connector reflections. The free-space setup was restricted in its feasible feedback distance, but allowed far higher feedback levels. For bulk or quantum-well lasers,  $\gamma_{crit}$  is independent of the external cavity length and so agreement between both setups would

be expected (regime IV, Fig. 8 in Ref [1]). For quantum-dot lasers this is not the case [15] and one would expect quite varied values of  $\gamma_{crit}$  depending on the length. While quantum-dash lasers are expected to be intermediate devices to the two, we find that in this respect they behave distinctly like quantum-wells.

### 3.1 Setup 1

In setup 1 (Fig. 2), light from the device under test was coupled using a lensed fibre to branch 1 of a four port 90/10 fibre coupler. The optical feedback was created with a reflector in branch 2, 90% coupled to branch 1, and its level was controlled via a variable attenuator. A polarisation controller was used to match the feedback to the emitted TE polarised light. The effect of the optical feedback was analysed in branch 3 with a 10-pm resolution optical spectrum analyser (OSA). The external cavity length was 18 m.

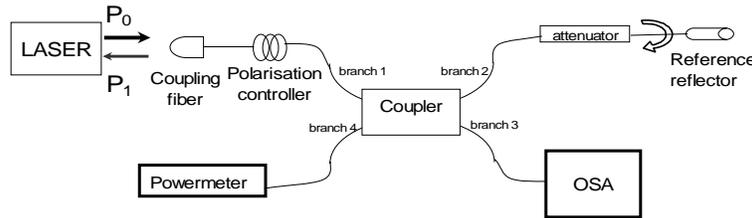


Fig. 2. Experimental setup 1. The device under test was coupled using a lensed fibre to a 90/10 single-mode power splitter. The power meter was used to estimate the feedback level and the OSA was used to determine the onset of coherence collapse.

The feedback level  $\gamma$  is defined as the ratio of the power returned to the facet  $P_1$  to the emitted power  $P_0$ ,

$$\gamma = \frac{P_1}{P_0} \quad (1)$$

and its value is determined by measuring the power in branch 4 and accounting for the coupler ratio and fibre coupling losses. A maximum feedback level of -17 dB can be achieved, depending on the coupling losses from the laser facet to the coupling fibre.

### 3.2 Setup 2

In setup 2 (Fig. 3), the device was mounted on a temperature-controlled stage that gave optical access to both facets, allowing significantly higher feedback levels than those in setup 1. The laser output from one facet was focused by a high numerical aperture (NA) aspheric lens onto a broadband mirror. The mirror angle and the beam focus were adjusted to maximise the coupling back into the laser, deduced by minimising the threshold current. The feedback level was then adjusted using a calibrated variable neutral density filter placed in the beam path. The output from the second facet was collimated through a free-space isolator and coupled to a single mode fibre isolator. The output from the fibre isolator was connected either to an OSA, an electrical spectrum analyser (ESA) or to a 6 GHz real-time oscilloscope. The OSA was used here as with setup 1, while the ESA made known the existence of external cavity modes and the oscilloscope gave details on the time series of the laser intensity.

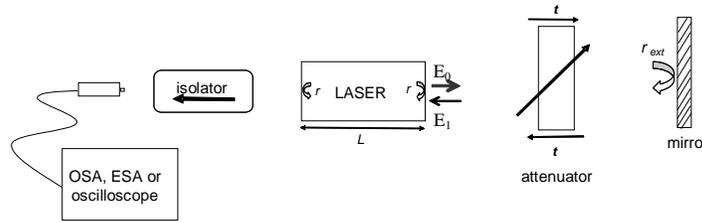


Fig. 3. Experimental setup 2. The output from one facet of the device was focused by a high NA aspheric lens onto a broadband mirror. The output from the other facet was collimated through a free-space isolator and coupled to a single mode fibre isolator connected either to an OSA, an electrical spectrum analyser (ESA) or to a 6 GHz real-time oscilloscope. The OSA, ESA and oscilloscope were used to determine the onset of the CC and LFF regimes.

The laser facet and the external mirror formed a composite reflector with an effective field reflectance  $r_{eff}$ . We find an expression for  $r_{eff}$  by assuming we have coherent, steady-state operation in the extended cavity in a manner similar to [16]. We then solve the boundary-value problem for the fields in the extended cavity to get

$$r_{eff} = r + \frac{(1-r^2) \cdot r_{ext} \cdot T \cdot \xi}{1 + r \cdot r_{ext} \cdot T} \quad (2),$$

where  $r$  is the field reflectance of both laser facets,  $r_{ext}$  is the field reflectance of the external reflector,  $T$  is the power transmittance of the variable attenuator and  $\xi$  is a geometrical coupling constant resulting from the non-perfect coupling of the light back into the cavity due to effects such as beam astigmatism. Of course, this expression is not suitable for use in a dynamical regime like that of coherence collapse since the steady state assumption fails there, but it suffices to give a threshold for entry into such regimes and so is appropriate for this work. The feedback level in this setup is given by the square of the ratio of the backward going field component  $E_1$  to the forward going field component  $E_0$  at the facet all attenuated by  $\xi^2$ . Thus the feedback strength with this setup is given by,

$$\gamma = r_{ext}^2 T^2 \xi^2 \quad (3).$$

A maximum feedback level of about -1.1 dB can be achieved.

The amplified spontaneous emission spectrum of the solitary laser was measured as a function of injection current and, using the Hakki-Paoli method [17], the gain of the solitary laser versus current was deduced.

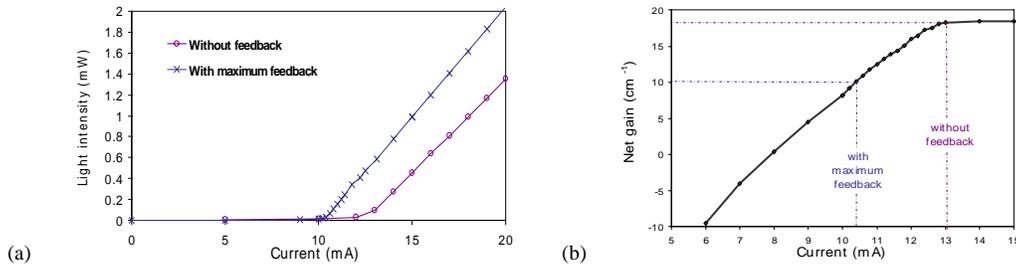


Fig. 4. (a). Light-current characteristics. (b) Net gain versus current.

On introduction of feedback the laser threshold is reduced [Fig. 4(a)]. The gain at reduced threshold can be read from Fig. 4(b) and the effective reflectance for this feedback level derived from the condition of unity round trip gain

$$r_{eff} = \frac{1}{r \cdot e^{g \cdot L}} \quad (4),$$

where  $g$  is the net modal gain at the reduced threshold and  $L$  is the laser length (600  $\mu\text{m}$ ). The logic for calculating the feedback strength proceeds as follows. First one finds the reduced threshold current. Then the gain at this current can be found from Fig. 4(b). Expression (4) can now be used to find the effective reflectance. Of course, this must also be given by expression (2) and so the geometrical factor  $\xi$  can be found. Finally one calculates the feedback strength  $\gamma$  using expression (3).

#### 4. Coherence collapse

Coherence collapse was manifested by this device in several ways: a sudden broadening of the optical spectrum [Fig. 5(a)], enhancement of the RF noise and external cavity peaks in the RF spectrum [Fig. 5(b)] and power fluctuations in the time-series [Fig. 5(c)].

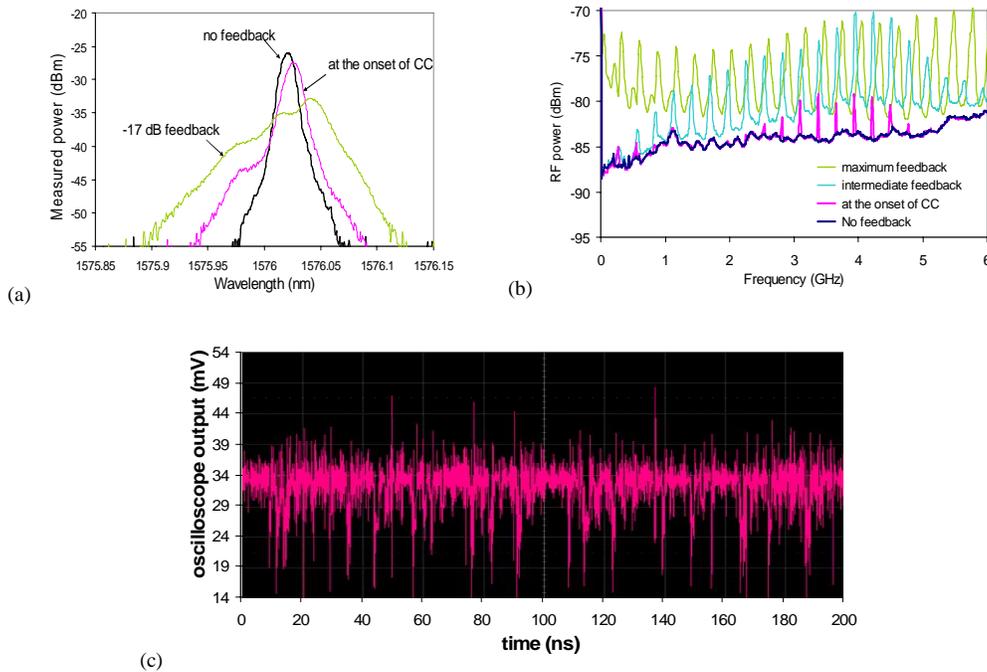


Fig. 5. (a). Optical spectrum with increasing feedback. (b) RF spectrum with increasing feedback at 30 mA. (c) Time series in the CC regime.

With both setups,  $\gamma_{crit}$ , the value of the feedback strength at the onset of coherence collapse, was determined from the sudden broadening of the optical spectrum which occurs at this critical strength [Fig. 5(a)] as this method was both reproducible and precise. This broadening results from the undamping of the relaxation oscillations. Each mode in the optical spectrum has relaxation oscillation sidebands and when the oscillations become undamped the sidebands grow in strength causing the mode to apparently broaden dramatically. Figure 6 illustrates the onset of coherence collapse determined using this criterion with both setups as a

function of the emitted power. The significantly different external cavity lengths do not affect the onset of CC. Thus, in this respect the device behaves more like a QW laser [1] than a QD laser [15].

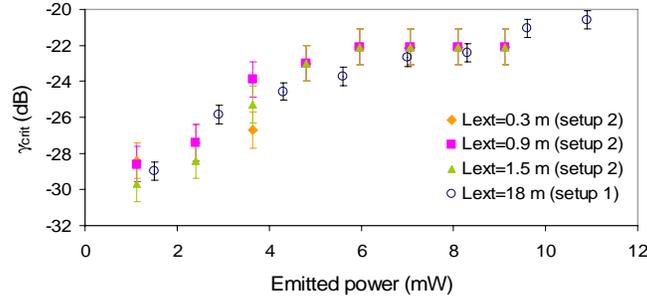


Fig. 6. Onset of coherence collapse (dB) versus emitted power determined at external cavity lengths of 0.3m, 0.9m, 1.5m (setup 2) and 18m (setup 1).

The onset of coherence collapse is found to increase with current from  $-29$  dB at 20 mA to  $-21$  dB at 90 mA. This increase in feedback stability with current injection has also been previously reported for bulk lasers [1]. In setup 2, the microwave spectrum of the laser was simultaneously observed and the onset of coherence collapse was seen to be abrupt, without the cascade of oscillations seen for QD lasers [15]. In [18] a period doubling route to chaos was observed when the ratio of the relaxation oscillation frequency and the external cavity frequency was an integer. We did not observe any such route to chaos but we did not investigate such finely tuned setups, instead focusing on generic cases.

The maximum return loss tolerance  $\Gamma_{crit}$  from the system as defined in the 10 Gbps Ethernet standard, can be deduced by using:

$$\Gamma_{crit} = \gamma_{crit} - (2 \cdot C) \quad (5),$$

where  $C$  is the coupling loss from the laser to the fibre estimated at  $\sim -5$  dB for this device. By using Eq. (5) and Fig. 6, a  $-19$  dB  $\leq \Gamma_{crit} \leq -11$  dB maximum return loss tolerance is obtained.

## 5. Low-frequency fluctuations

Using setup 2, the LFF regime was observed from near laser threshold up to about 30 mA at maximum feedback ( $-1.1$  dB). Figure 7 shows a representative time-trace near threshold where infrequent power dropouts are followed by a staircase-like recovery. Each step in the recovery corresponds to a round-trip time for the external cavity. After several steps the laser displays deep, chaotic intensity pulsations that reduce in intensity before the next dropout occurs. This behaviour has been observed for quantum-well lasers previously [19]. When increasing the current from threshold to about 30mA, the power dropouts increase in frequency until the time-trace becomes chaotic as in Fig. 5(c).

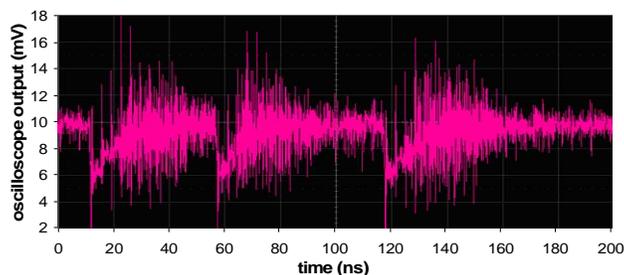


Fig. 7. Time-series in the LFF regime at -1.2 dB feedback at 19 mA. The trace shown was obtained for an external cavity length of 0.5m.

The LFF can also be observed in the RF spectrum, appearing as a broad peak at low frequencies (Fig. 8). The frequency increase of dropouts with injection current is reflected in the RF spectra.

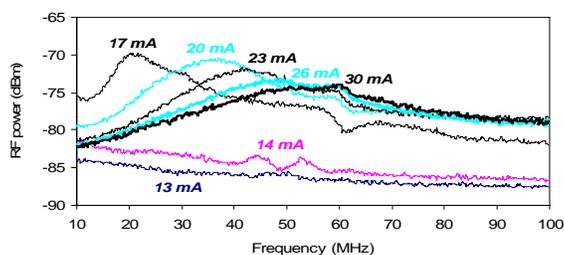


Fig. 8. RF spectrum in the LFF regime (at -1.2 dB feedback).

This is the first report to our knowledge of LFF in quantum-dash lasers and the phenomenon manifests itself essentially as with quantum-well lasers, forming another distinction from the behaviour of quantum-dot lasers.

## 6. Conclusion

In this work, quantum-dash based lasers emitting at 1.57  $\mu\text{m}$  were assessed under optical feedback and their behaviour was found to have significantly more in common with conventional bulk or quantum-well lasers than QD lasers at 1.3  $\mu\text{m}$ . Several well-known features of quantum-well feedback behaviour were observed, such as the onset of coherence collapse being independent of external reflector distance, increased stability with increased injection current and the presence of a low-frequency-fluctuation regime close to threshold, all in contrast with reported QD experiments. Just as striking, the oscillation cascade reported as a route to coherence collapse for QD lasers was completely absent. Coherence collapse was observed at higher feedback levels than for quantum-well based lasers ( $\sim -23$  dB compared to  $\sim -37$  dB at 5 mW). We demonstrated an onset of coherence collapse varying from -29 dB to -21 dB (depending on the injection current), corresponding to a maximum return loss tolerance of -19 dB / -11 dB from the system as defined in the 802.3ae 10 Gbps Ethernet standard. Thus, these devices comply with the requirement for isolator-free operation since their maximum return loss tolerance is greater than -21 dB.

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