Research Article Vol. 26, No. 14 | 9 Jul 2018 | OPTICS EXPRESS 17927

Optics EXPRESS

Experimental investigation of broad area quantum cascade lasers under external feedback

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Abstract: Mode creation and temporal response of broad-area quantum cascade lasers (BA-QCL) placed within an external feedback cavity are described in this publication. The critical feedback parameter becomes the mirror angle relative to the BA-QCL facet. With judicious angle choices, a plethora of curious modes can be created, each with their particular threshold and slope efficiency. These range from a nearly single far-field intensity peak to highly multimode emission similar to their diode counterparts. Dynamics are strongly dominated by transverse mode competition ranging for less than 20MHz to greater than 100MHz. When the mirror is parallel to the facet, higher frequency external cavity oscillations become undamped.

OCIS codes: (140.3070) Infrared and far-infrared lasers; (140.5965) Semiconductor lasers, quantum cascade; (190.3100) Instabilities and chaos

References and links

1. N. Yu, L. Diehl, E. Cubukcu, D. Bour, S. Corzine, G. Höfler, A. K. Wojcik, K. B. Crozier, A. Belyanin, and F. Capasso, "Coherent Coupling of Multiple Transverse Modes in Quantum Cascade Lasers," Phys. Rev. Lett. **102**(1), 013901 (2009).
2. A. K. Wojcik, N. Yu, L. Diehl, F. Capasso, and A. Belyanin, "Nonlinear coupling of transverse modes in quantum cascade lasers," Opt. Eng. **49**(11), 111114 (2010).
3. Y. Bai, S. Slivken, S. R. Darvish, A. Haddadi, B. Gokden, and M. Razeghi, "High power broad area quantum cascade lasers," Appl. Phys. Lett. **95**(22), 221104 (2009).
4. N. Stelmakh, "Harnessing Multimode Broad-Area Laser-Diode Emission Into a Single-Lobe Diffraction-Limited Spot," IEEE Photonics Technol. Lett. **19**(18), 1392–1394 (2007).
5. J. W. Nicholson, J. M. Fini, X. Liu, A. M. DeSantolo, P. S. Westbrook, R. S. Windeler, E. Monberg, F. DiMarcello, C. Headley, and D. J. DiGiovanni, "Single-frequency pulse amplification in a higher-order mode fiber amplifier with fundamental-mode output," in *Conference on Lasers and Electro-Optics (CLEO)* (2013), paper CW3M.3.
6. G. C. Dente and M. L. Tilton, "Class of resonator for slab waveguide lasers," Appl. Opt. **53**(11), 2384–2389 (2014).
7. D. J. Bossert, J. R. Marciante, and M. W. Wright, "Feedback effects in tapered broad area semiconductor lasers and amplifiers," IEEE Photonics Technol. Lett. **7**(5), 470–472 (1995).
8. J. R. Marciante and G. P. Agrawal, "Lateral spatial effects of feedback in gain-guided and broad-area semiconductor lasers," IEEE J. Quantum Electron. **32**(9), 1630–1635 (1996).
9. S. K. Mandre, I. Fischer, and W. Elsässer, "Spatiotemporal emission dynamics of a broad-area semiconductor laser in an external cavity: stabilization and feedback-induced instabilities," Opt. Commun. **244**(1-6), 355–365 (2005).
10. T. Tachikawa, S. Takimoto, R. Shogenji, and J. Ohtsubo, "Dynamics of Broad-Area Semiconductor Lasers with Short Optical Feedback," IEEE J. Quantum Electron. **46**(2), 140–149 (2010).
11. M. Chi and P. M. Petersen, "Dynamics of a broad-area diode laser with lateral-mode-selected long-cavity feedback," J. Appl. Phys. **116**(10), 103101 (2014).
12. S. Ferré, L. Jumpertz, M. Carras, R. Ferreira, and F. Grillot, "Beam shaping in high-power broad-area quantum cascade lasers using optical feedback," Sci. Rep. **7**, 44284 (2017).
13. R. Lang and K. Kobayashi, "External optical feedback effects on semiconductor injection laser properties," IEEE J. Quantum Electron. **16**(3), 347–355 (1980).

#324986 https://doi.org/10.1364/OE.26.017927
Journal © 2018 Received 27 Feb 2018; revised 11 Apr 2018; accepted 13 Apr 2018; published 27 Jun 2018

14. L. Jumpertz, F. Michel, R. Pawlus, W. Elsässer, K. Schires, M. Carras, and F. Grillot, "Measurements of the linewidth enhancement factor of mid-infrared quantum cascade lasers by different optical feedback techniques," AIP Adv. **6**(1), 015212 (2016).
15. N. Stelmakh, M. Vasilyev, F. Toor, and C. Gmachl, "Degenerate and nondegenerate lateral-mode patterns in quantum cascade lasers," Appl. Phys. Lett. **94**(1), 013501 (2009).
16. R. Kaspi, S. Luong, T. Bate, C. Lu, T. C. Newell, and C. Yang, "Distributed loss method to suppress high order modes in broad area quantum cascade lasers," Appl. Phys. Lett. **111**(20), 201109 (2017).
17. M. Kinzer, Q. Yang, S. Hugger, B. Stefan, M. Brunner, F. Fuchs, and J. Wagner, "Diffraction-Limited Infrared-Imaging of the Near-Field Intensity Emitted by Quantum-Cascade Lasers," IEEE J Quant. Electron. **48**(5), 696–702 (2012).
18. G. C. Dente, "Low Confinement Factors for Suppressed Filaments in Semiconductor Lasers," IEEE J Quant. Electron. **37**(12), 1650–1653 (2001).
19. L. Jumpertz, K. Schires, M. Carras, M. Sciamanna, and F. Grillot, "Chaotic light at mid-infrared wavelength," Light Sci. Appl. **5**(6), e16088 (2016).
20. D. W. Sukow, J. R. Gardner, and D. J. Gauthier, "Statistics of power-dropout events in semiconductor lasers with time-delayed optical feedback," Phys. Rev. A **56**(5), R3370–R3373 (1997).
21. Private conversations with Prof. A. Lyakh at the University of Central Florida and independently Prof. F. Grillot's group at Telecomm ParisTech. Both groups have observed drop outs in free-running single transverse mode QCLs.

1. Introduction

Multi-transverse mode quantum cascade lasers exhibit curious behavior such as the coherent locking of low order modes [1,2] and for wider striped broad-area quantum cascade lasers (BA-QCLs) a dual lobed "bat-ear" far-field pattern as would be produced by a single yet high order transverse mode [3]. This latter single transverse mode characteristic suggests the savory possibility of converting the high order mode into the fundamental mode in similar manner to diode lasers [4], optical fiber amplifiers [5] and slab-waveguides [6]. Another option, which is initiated in this paper, is using external cavity feedback in an attempt to select a particular transverse mode and also to probe their dynamics. In the event BA-QCLs can be coerced into a fundamental mode operation, they should achieve higher power and brightness operation than single-mode QCLs.

Shifting attention to the dynamics of feedback driven broad area semiconductor lasers, experimental papers on diode lasers have been published with a non-exhaustive list from 1995 to 2014 explored in Refs [7–11]. Yet BA-QCLs have not been intensively investigated, with exception being Ref [12], and they pose a largely unexplored area. Building a theory based on the single-mode (both transverse and longitudinal) Lang-Kobayashi feedback model [13] is particularly difficult. Feedback will influence each mode differently and additionally modes are coupled due to the χ_3 nonlinearity [1]. In the QCL laser rate equations note that there is a picosecond gain recovery in the active region, a linewidth enhancement factor theoretically as low as 0 but experimentally measured as low as 1.3 [14], a carrier lifetime to photon lifetime ratio approximately 1 and etching the laser sidewalls entirely through the active region to prevent excessive current spreading. In light of these traits, a reasonable mode approximation considers the BA-QCL as having "box modes", [15] which is to say that the electric field can be taken simply as the sine and $\cos(M\pi x/w)$ where w is the stripe width and M is an integer mode number. A more accurate determination of the modes and their propagation constants can be obtained by noting that the commonly used wet etching process leaves an angle to the sidewall dependent upon the etch depth. In the facet plane the area can be more trapezoidal than rectangular. As an aside, this sidewall can be modified so as to completely disrupt higher order modes [16].

Motivated by their novelty, we probe a BA-QCL placed in an external cavity arrangement using a partially reflective feedback mirror. The interest is to determine if the beam can be controlled or steered and if their dynamical behavior follows a similar path as their single mode counterparts.

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2. Experimental arrangement

The QCL of interest is a 40μm wide emitter, 3mm long, λ = 4.7μm and is HR-coated on the back facet and as-cleaved on the other. The free running laser threshold is 1.74A, and at 3.5A the peak pulse power as measured at the facet is over 4.5W peak power under 500ns pulses, 0.5% duty cycle and 15°C heat sink. Figure 1 is a schematic of the external cavity (ECL) experimental arrangement. The ECL is bounded by the QCL and rotatable partially reflective mirror (PR). The mirror, a CaF window coated with a thin germanium layer for a reflectivity near 67%, is rotated about an axis perpendicular to the laser's junction plane, i.e. out of the plane of this paper. The ECL was as short as 0.96cm but most of the experimental measurements were made with longer lengths. The other components consist of a f = 1.87mm collimating lens (CL), pellicle beam splitter with low reflectivity at 4.7μm (BS), a midinfrared polarizer to vary the feedback intensity (P), f = 200mm focusing lens (FL), integrating sphere and detector (PM), an amplified Mercury-Cadmium-Telluride (MCT) detector, mirrors (M) and Spectral Products DK240 monochromater. From Fig. 1, note that the power is monitored from a sampling of the total emitted light and is less than the facet power described above for the free running case.

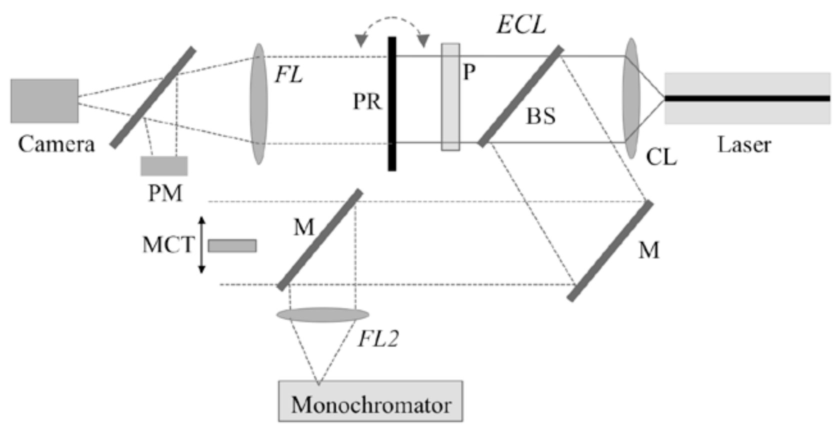

Fig. 1. Schematic of the experimental arrangement.

Near-field images at the facet are obtained using the technique described in Ref [17]. with the CL and FL lens pair relaying the image to a Xenics Onca 3369 InSb camera. From the images, examined QCLs show a dominant mode of M = 9 in their free running state but other transverse modes are also oscillating, see Fig. 2(a). No clear evidence of filamentation is observed. This observation is consistent with its low linewidth enhancement factor since filament formation gain is proportional to $\sqrt{\alpha^2+1}-1$ [18]. As an empirical observation, our internal studies of 100μm wide emitters suggest that the primary high order mode, whatever its particular mode number may be, is even more dominant for wider cavities than narrow ones.

Fast oscillations are taken using the MCT detector coupled to a 7GHz bandwidth Tektronix TDS7704 Oscilloscope recorded at a 200ps digitization rate. The 3dB bandwidth of the MCT amplifier is about 1GHz which means that when the ECL is short, round-trip oscillations of frequency c/2nL aren't well resolved. The detector is placed a couple of meters from the cavity on a linear translation stage and is swept across the beam to reveal mode competition. The MCT detector was also placed at the output of the monochromator to temporally resolve longitudinal mode pulsations.

Initial cavity alignment is facilitated by viewing the live facet image with the camera as the collimating lens and also the feedback mirror is adjusted. Coupling light into the cavity is

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quite easy to accomplish, and it is immediately observed by a changing of the near-field intensity pattern, see Fig. 2. Fine tuning of the alignment is determined by monitoring the output power near threshold with the integrating sphere. The key parameter is that the mirror is rotated to create different cavity modes, thus steering the beam or inciting various dynamical effects. The coupling factor is not known; rather the reduction in threshold current, $\Delta I = (I-I_{th})/I_{th}$, from the free running case is measured.

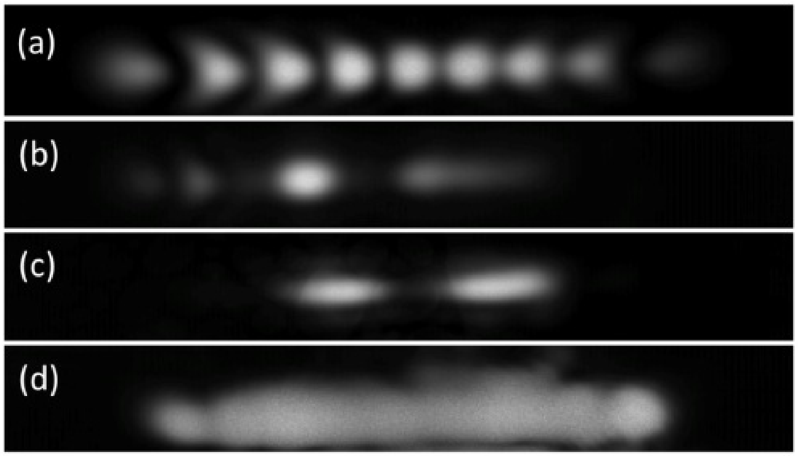

Fig. 2. Facet images of 40um QCL, (a) Free-running case with M = 9, (b) Feedback case with a dominant single peak, (c) Feedback case with two symmetric oval peaks, (d) fuzzy image indicative of a strongly multimode beam.

3. Experimental Results

3.1 Mode coercion

Figure 2 presents four facet images obtained as the mirror is rotated. Here the external cavity length is 15cm. The images show the case of (a) no feedback, (b) feedback that resulted in most of the fluence within a single peak (c) feedback creating a curious dual lobed mode and (d) feedback exciting of a large number of modes creating a fuzzy image. In Fig. 2(a), a principal M = 9 mode is observed although the intensity of each antinode varies and the furthest to the right is quite dim. In the far-field, two peaks are observed at angles ± 33° as anticipated ($sin\theta = \lambda M / 2w$) but other lesser peaks are also observed. Figures 2(b-d) show some of the ECL modes that can be generated via mirror rotation. Figure 2(b) shows a principal intensity peak that propagates into the far-field remaining as a single dominant energy peak. This is not the true fundamental mode as a number of lesser peaks are observed. Figure 2(c) shows a very distinct dual lobed pattern with very little intensity elsewhere. In both Figs. 2(b) and 2(c) the laser fluence is much higher at the distinct intensity peaks and as a negative consequence one anticipates that facet failure to be more likely due to the large fluence in a limited spot. Contrast these with 2(d) that shows a large number of modes are oscillating. This latter image is similar to that which is typically observed in a diode laser. With mirror rotation, a diverse collection of images can be discovered ranging from a single near field lobe to blurry figures. We note that most of these modes appear time-averaged stable, i.e. no obvious changes in the near-field profile, with respect to the injection current up to $I = 2.5I_{th}$.

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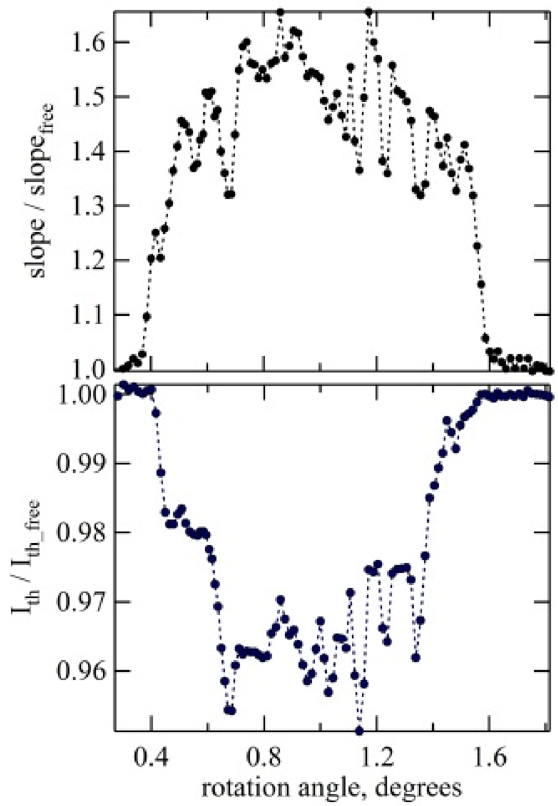

Fig. 3. The slope efficiency and threshold current relative to the free-running case when the mirror angle is varied. Dots are measured points. (a) slope efficiency and (b) threshold.

The threshold current, I, along with slope efficiency is mapped over the mirror rotation angle and displayed in Fig. 3. Both slope efficiency, Fig. 3(a), and threshold current, Fig. 3(b), are scaled relative to the free running case. Hence a value of 1 indicates no effect from feedback. Both plots show a curious kind of structure over a 1.2-degree window where feedback is effective. Over this range complex internal-external cavity modes are created and destroyed in addition to the two shown in Fig. 2. As one would expect, the threshold current is always less than the free running case with the lowest value being 95% of the free running threshold current. Yet it also shows fluctuations within the window. Concurrently the slope efficiency varies, and in the best case it is over 1.6x superior to the free running case. Zones of high slope efficiency do not necessarily correspond to a low threshold current. Modes identified by strong near field intensity peaks, such as Fig. 2(b & c), exhibit a low threshold current. The modal gain is very high. But, energy is not efficiently extracted from electric field nulls within the cavity. Thus, the slope efficiency is weaker. At other angles, near field laser facet pictures show images indicative of a large number of oscillating modes, see Fig. 2(d). Each mode possesses its characteristic threshold current, and the net laser threshold current, which is measured, becomes soft. That is to say, the light-current curve at threshold curves up gently rather than showing a distinct kink as would a single mode laser. Fortunately, these modes successfully extract energy from the entire cavity resulting in superior slope efficiency. When free running BA-QCLs oscillate on only a few transverse modes as often observed in the literature, the above novel result suggests that their electrical to optical efficiency can be improved merely by destabilizing the dominant mode.

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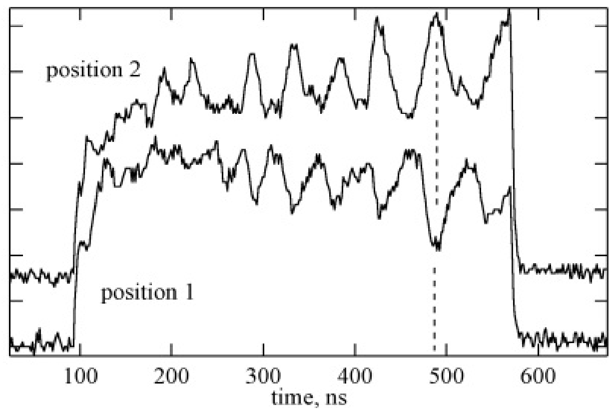

Fig. 4. Time series taken at two different positions in the beam front. The oscillations are out of phase showing mode competition.

3.2 Dynamical behavior

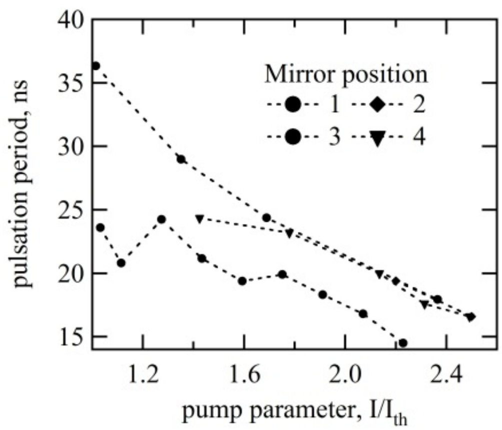

Fig. 5. Mode competition oscillations are injection current dependent and similar regardless of the feedback mirror angle. Each plot represents a different mirror angle.

The traditional ECL examination tests their dynamical response to feedback and injection [19], and we follow that track here. Yet in contrast to the anticipated performance, the temporal behavior that commands immediate attention are strong oscillations due to transverse mode competition. As a simple way to observe this, the MCT detector is positioned 2.4m downstream from the cavity and translated along the face of the beam. One particular case is shown in Fig. 4 that shows two time series recorded at different points. For Fig. 4, the ECL is 10.6cm long, although similar results are observed for other cavity lengths. The plots are shifted vertically in the graph to aid the reader. In this particular case, the net effect is a mode switching so that an intensity peak at one position is accompanied by a trough at a second position, see the vertical dotted line at t = 486ns. These pulsations are almost completely replicated from pulse to pulse with an average period of 56ns. More generally the oscillation periods range from longer than 67ns (15MHz) to less than 10ns (100MHz). The frequency increases with the injection current, see Fig. 5, and there is no clear correlation to the ECL length. The frequency and amplitude do depend on the feedback mirror angle ranging from strong slow fluctuations to faster but lower amplitude oscillations. A 2-dimensional map of the oscillation frequency as a function of mirror angle is shown in Fig. 6. This map was created by extracting the frequency peaks from the oscilloscope's Fast-Fourier

Transform function versus the mirror angle at a fixed injection current of 1.12 I_{th}. The strength of the frequency is gray-scale coded on the graph. Similar to Fig. 3 above, there is a kind of structure that arises from the different modes that are created. In cases, no oscillations are observed.

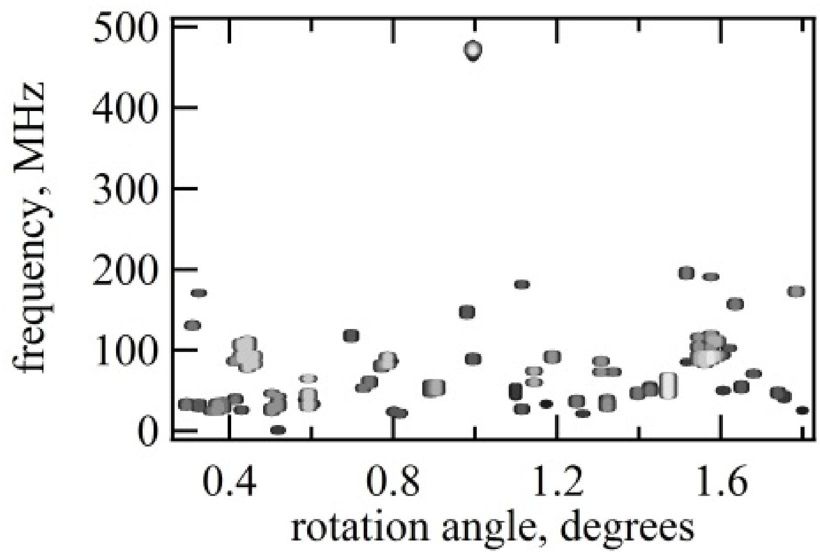

Fig. 6. A two-dimensional plot of the observed oscillation frequencies plotted versus the mirror angle. The strength of the oscillations is gray-scale colored with lighter colors signifying a stronger signal. External cavity oscillations at 430MHz are only observed when the mirror is aligned parallel to the QCL facets.

When the mirror becomes parallel with the BA-QCL facets, the high frequency oscillations corresponding to a traditional ECL are observed. These are designated as an on-axis mode. Such oscillations are only found with careful adjustment of the feedback mirror. In Fig. 6, at an angle near 1.06°, a strong signal in the FFT is observed around 420MHz and with the MCT detector positioned near the center of the beam. This FFT also shows a slight very broad signature centered near 840MHz, which corresponds to the round trip time of the cavity arrangement. Figure 7 displays a time series of these oscillations. The time series is very regular repeating from pulse to pulse. This regularity and frequency signal suggests that the dynamical system has undergone a Hopf bifurcation from steady state to a limit cycle. This would be consisted with experimental observations published in Ref [19]. However, here the bifurcation process was not observed experimentally. Instead, the high frequency oscillations are observed at threshold. As the current injection increases the amplitude of ECL oscillations become damped and ultimately are extinguished near 1.6 I_{th}. This is in marked contrast to Lang-Kobayashi models of single transverse mode QCLs that show ongoing bifurcations and sometimes chaotic states.

In addition to current injection, the feedback ratio into the cavity can be adjusted by rotating the polarizer. The results are very similar to changing the injection current. We note that concurrent with the on-axis mode, other modes continue to oscillate. Coupling of the feedback into these modes can be substantially weaker than the on-axis mode. Consequently, they may not undergo a bifurcation and at high injection levels simply dominate the sum of the laser emission.

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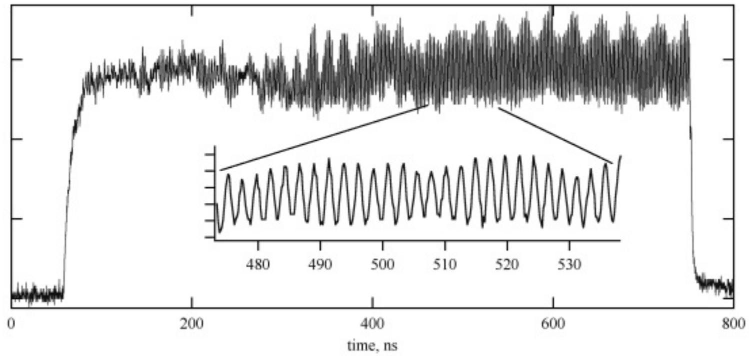

Fig. 7. Quasi-periodic behavior when high frequency external cavity oscillations exist concurrently with lower frequency mode competition.

Two other interesting yet rare phenomena are shown in Fig. 8(a) and (b). Figure 8(a) hints of the existence of low frequency fluctuations (LFFs), which were also observed in Ref [19]. The two arrows in Fig. 8(a) point to such events. Unfortunately, this state proved elusive to reproduce. A statistical analysis of the events for comparison with that performed by Sukow et al. [20] was insufficient. Whereas LFFs are normally a near-threshold phenomena, this occurs well above I_{th}. Figure 8(b) shows a very strong power dropout, see the region between the arrows. Again the current is well above $I_{th.}$ There is a sudden switch to another state unrelated to the mode oscillations seen above. In contrast to the phenomena observed above, the occurrence of such drop-outs is irregular. These kind of dropouts have also been observed in single-transverse mode lasers [21], and in this single-mode case it is possible that energy is switching from the fundamental mode to the second order mode. An investigation focused on the dropouts is ongoing.

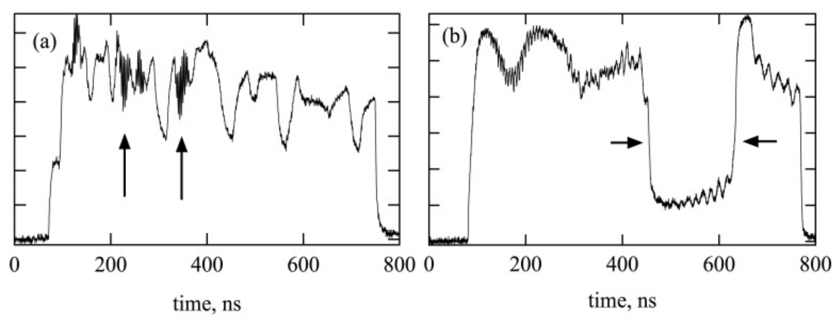

Fig. 8. Rare cases in which (a) the time series shows similarities to low-frequency oscillations and (b) sudden power dropouts lasting nearly 180ns.

4. Summary

Summarizing, we have observed that BA-QCLs subject to external cavity feedback can be coerced into a plethora of curious hybrid ECL Fabry-Perot transverse modes ranging from a nearly single far-field peak to a broad beam reminiscent of diode lasers. These new modes possess their own threshold and slope efficiency depending upon their unique modal gain and electrical field. Experiments suggest that the lucrative prospect that BA-QCL efficiency can be improved by exciting numerous modes to uniformly fill the gain-volume. One can thus envision configuring a BA-QCL for single mode operation with strong far-field propagation or efficient yet highly multimode operation for near-field pumping of a solid-state media or illumination.

The temporal behavior of ECL BA-QCLs is strongly dominated by mode competition with observed frequencies from less than 20MHz to over 100MHz depending on the mode and injection current. These slow time scales suggest localized temperature fluctuations as a possible cause. Figure 2 shows that strong intensity peaks exist in the broad-area cavity adjacent to null regions. Thermal diffusion from one region to the adjacent sufficiently perturbs the refractive index and in turn destabilizes the modes so that new hot spots are being generated. The QCL is operated in pulse mode operation, which clearly leads to device heating during the pulse.

High frequency ECL oscillations are observed when the feedback mirror is parallel to the QCL facets. These ECL temporal oscillations arise with threshold then become damped at higher injection currents. While we did not observe bifurcation processes or chaotic dynamics, such phenomena may reveal themselves under yet undiscovered conditions. In a rare case, we did observe phenomena reminiscent of LFFs. This lack of rich dynamics is likely attributed to the low linewidth enhancement factor and time scales. Furthermore, oscillating transverse modes with weak feedback coupling may dominate the total lasing intensity.

We have also observed sudden power dropouts within the pulse that are unrelated to the oscillatory mode competition. Such dropouts, with time durations of approximately 200ns, have also been seen in single-mode QCLs not placed within an external cavity. This is likely a mode switching but needs additional examination.

A theoretical BA-QCL model based on the Lang-Kobayashi (LK) equation may be composed. However, analysis will be complicated due to the number of modes, their coupling, e.g. χ_3 nonlinearity and gain sharing among the mode, and the feedback coupling that is mode dependent. One should also include the inevitable temperature rise within the active region. Still, the complexity both in theory and experimental analysis creates a stimulating challenge.

Funding

TCN would like to thank the Air Force Office of Scientific Research (AFOSR).

Acknowledgements

The authors thank L. Jumpertz for helpful assistance with preliminary experimental work.