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PHASE LOCKING QUANTUM CASCADE LASERS

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9 Jan 2019

Final Report

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14. ABSTRACT

Talbot external cavity is one of the methods of passive phase-locking linear arrays of laser emitters. Feedback is accomplished in the former using a flat mirror while a lens is necessary for the latter. Each emitter couples with every other emitter and hence these are known generically as global coupling methods. Quantum Cascade Lasers (QCLs) are a particularly good system to investigate these types of phase-locking. QCL arrays with their fast time scales, low frequency detunings and small linewidth enhancement factor are posited to lock stably and with good coherency. The long-term vision is to develop a system for mid- and infrared directed energy.

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Quantum cascade lasers, Talbot cavity, coherent coupling

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1.0 SUMMARY

Laboratory Principal Investigator: Dr. Timothy Newell

AFRL Program Manager: Dr. Andy Lu

Air Force Office of Scientific Research (AFOSR) Program Officer: Dr. Gernot Pomrenke, AFOSR

Statement of Objectives

- Investigation of passive coherent phase-locking in external cavity quantum cascade laser (QCLs) arrays via the following primary tasks.
  - Task 1. Experimental approach to Talbot cavity phase-locking.
  - Task 2. Study of dynamical behavior with broad-area QCLs (BA-QCLs).

Applications:

- Protection of aircraft from electro-optic/infrared (EO/IR) threats where compact laser sources are required.

Mode creation and temporal response of broad-area quantum cascade lasers (BA-QCL) placed within an external feedback cavity are described in this report. 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 20 MegaHertz (MHz) to greater than 100MHz. These slow time scales suggest localized temperature fluctuations as a possible cause.

High frequency oscillations are observed when the feedback mirror is parallel to the QCL facets. These 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 low frequency fluctuations (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 (nano-second), have also been seen in single-mode QCLs not placed within an external cavity. This is likely a mode switching but needs additional examination.

2.0 INTRODUCTION

Arising from their intersubband electron transitions and also the specialized material processing procedures, QCLs display surprisingly different temporal dynamics and transverse mode characteristics than their diode laser semiconductor counterparts. One of the objective of this project is to explore into some of this uncharted territory to understand if and how QCL arrays can be coherently phase-locked in a Talbot cavity. The intent is to pursue feedback effects leading to phase-locking in mid- and infrared (IR) QCL. The motivation to continue the investigation stems from the ongoing need for infrared countermeasures (IRCM), illumination, tracking, gas sensing, medical diagnosis and weather agnostic free-space communications. Additionally, fundamental research into feedback dynamics remains limited. Theoretical routes from temporal stability to possible chaotic oscillations are not completely confirmed by experiment.

The Talbot effect was predicted in 1836 [1] when it was mathematically shown that an infinite linear array of point light sources reproduce their image after freely propagating a distance, (Talbot distance/length) $z_t = 2a^2/\lambda$ here *a*' is the emitter spacing. The concept of phase-locking an array of lasers implies placing a planar feedback mirror at a distance of $z_t/2$, $z_t/4$ or other multiples of z_t so that lasers are re-imaged upon themselves. (Positioning the mirror at some multiple of z_t recreates the image but each emitter will be phase shifted accordingly.) It is a global coupling type of arrangement in which the coherent state is a supermode of the array. A body of experimental literature was produced in the late 1980s and 1990s using diode lasers that was modestly successful in that coherency was demonstrated [2-4]. Some of these and also theoretical treatments originated with Air Force funding [5,6] and hence the principal motivation was geared to a direct diode high energy laser. Talbot arrays would never achieve this level of performance and were mostly abandoned. In contrast, mid- and IR laser requirements remain sedate, ~10s W, so that a coherently locked small QCL array has a realistic possibility of system implementation.

An order parameter (r(t)) i.e. an estimate of the coherence between the lasers can be defined by

$$r(t) = \frac{1}{N}\frac{< \left|\sum_{n=1}^{N} E_n(t)^2\right| >}{< \sum_{n=1}^{N} |E_n(t)^2| >} \tag{1}$$

where $E_n(t)$ (Electric field of n_{th} laser) is the field from each laser in the array. The order parameter (r(t)) is inversely proportional to the beam quality as it can be determined from the near field and far field data and can be considered as an interference term of several fields. For equal phases, r converges towards the unity while for anti-phase or random phases it leads to 0. This is the same effect in the far field except the overall envelope is the Fourier transform hence on the axis one either gets $r \rightarrow 1$ for equal phases or $r \rightarrow 0$ for random anti-phase. In general, we would like to monitor the time development of the r(t) in time to identify any possible global bifurcations. The r(t) will suffer greatly when emitter '*n*' is detuned in frequency from a selected reference laser, say emitter 1. This has a chance to occur for uneven pumping or variations in the material structure. But the greatest threat is when cleaves creating the two facets are not parallel, which leads to differing length emitters. Fortunately, the zinc-blende crystal structure strongly motivates the cleaved facet surfaces to not be so. That being said, bad cleaves certainly occur. Fortunately the bar is not a total loss. One re-cleaves to a shorter cavity length, at least 0.5mm shorter. The possible detuning must be modeled theoretically and validated experimentally.

Figure 1 shows a cartoon of the Talbot concept and photograph of the initial experiment. A multi-emitter 4.7μm QCL bar is the source. Its back facet has a highly reflective coating (HR) and a modest anti-reflective coating is deposited on the front facet so that emission only occurs into the cavity. The bar is temperature controlled using a jet impingement cooling system designed by Teledyne Scientific, Inc. specifically for high thermal impedance QCLs. The cooler work was funded through internal AFRL (Air Force Research Laboratory) funds along with support from the High Energy Laser - Joint Technology Office (HEL-JTO). Within the cavity a cylindrical fast-axis collimating lens is placed. Such lenses are readily available for visible and near-IR wavelengths. Currently only simple optical elements are available in the IR. To rectify this limitation and ideally enhance the commercial market, the principle investigator (PI) created an AFRL Small-Business Technology Transfer Program (STTR) to develop low cost chalcogenide optics, including fast axis collimating lenses. Positioning of the lens yields 5-degrees of freedom (two translation and three rotation) for proper collimation of the beam array. The Talbot resonator is completed by a partially reflecting mirror. Here, a transparent window was coated in a metal evaporator with a layer of Germanium to create a 67% reflective mirror. Its positioning adds two rotational degrees of freedom for alignment. Fine alignment of the key optics is accomplished with picomotor actuators (Newport.com) since even the pressure of the fingertip on a micrometer can be sufficient to disturb the positioning. In the figure in addition to the external cavity components, there is a *f*=50mm cylindrical lens that is used to image the slow axis of the beam onto two IR-cameras and detectors not shown in the photograph.

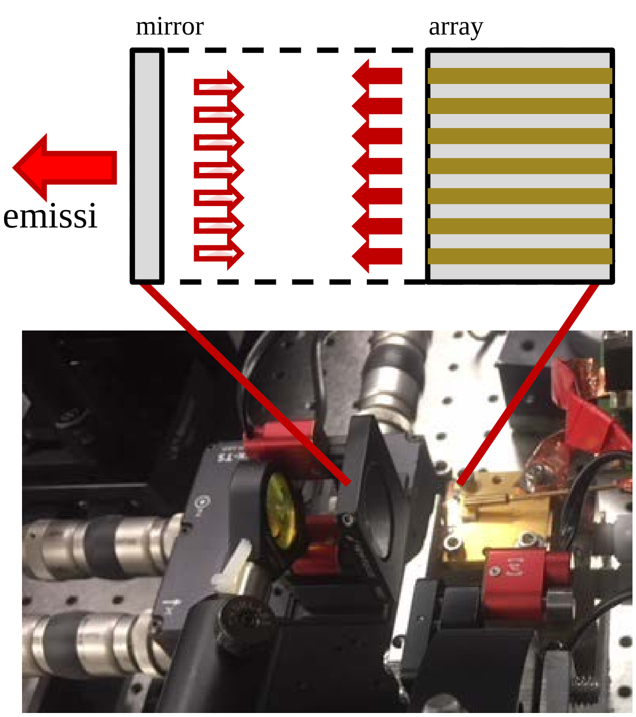

Figure 1. The upper cartoon of the Talbot cavity is shown in the experimental arrangement

3.0 TECHNICAL APPROACH

In this work the cavity was driven by small arrays (3 to 5 emitters) of single transverse mode QCL. The preliminary results were quixotic. Tantalizing images of a coherent state for 5 emitters could be observed. But usually the lasers simply operated as independent free-running Fabry-Perot emitters. That is to say, on infrequent occasions the cavity began to lock but coupling was too inefficient to fully realize a coherent state. This can be explained with two primary causes. First, an array of only a few emitters suffers large side losses since the outer elements freely expanding beam does not effectively join in the global coupling. This obvious fact was known yet the severity to experimental success was not. Consequently, the original study of locking as a function of array elements proved to be unfruitful. This is exacerbated by the need for high quality antireflective coatings (AR) in the midinfrared. Our AR coatings, based on silicon dioxide (SiO2) and germanium, should be good but spectrally narrow. The wide gain of the QCL simply means that the QCL will shift to a Fabry-Perot line away from the AR minima, i.e. the maximum net gain mode. Hence superior coatings are being pursued.

Passive phase-locking from global coupling such as Talbot or Self-Fourier type of cavities is at heart a feedback problem. As a prelude to array work, we investigated broad area QCLs with external feedback. This was driven by curiosity in observing some of the underlying dynamics and issues with external cavities. A secondary pragmatic reason was that the required fast axis collimating lens was in development under the above mentioned STTR program. While the beam is allowed to freely propagate parallel to the array, the beam perpendicular to the array, i.e. the fast axis of the QCL, must be collimated.

Key results from the feedback investigation are describe. The setup is quite similar to that shown in Figure 1 except that only a single 40μm wide stripe emitter is powered and a short focal length round lens partially collimates the beam. The control parameter is the external mirror that is rotated to sweep the feedback across the facet observing the response. Feedback light couples back into the laser cavity but at an angle and thus the transverse modes are affected. One of the curiosities not totally understood of the QCL is that broad area QCLs do not oscillate in a strongly multimode state as diodes do but rather as if a single yet higher order mode dominates. In this case the higher order mode is the 9^{th} and the electric field at the facet can be described by $\cos(M\pi x/w)$ where M=9 and w=40μm. Figure 2 presents four facet images obtained as the mirror is rotated. The external cavity length is 15cm. The images show the case of (a) no feedback, (b) feedback that resulted in most of the power within a single peak (c) feedback creating a curious dual lobed mode and (d) feedback exciting a large number of modes creating a fuzzy image. In Figure 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 $\pm 33^{o}$ as anticipated ($\sin\theta = \lambda M/2w$) but other lesser peaks are also observed. Figures 2(b-d) show some of the external cavity laser (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 Figures 2(b) and 2(c) the laser intensity 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 intensity 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 $I = 2.5I_{th}$ (laser threshold current). The threshold current, I, along with slope efficiency is mapped over the mirror rotation angle and displayed in Figure 3. Both slope efficiency, Figure 3(a), and threshold current, Figure 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 Figure 2. As one would expect, the threshold current is always superior to the free running case depending 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.

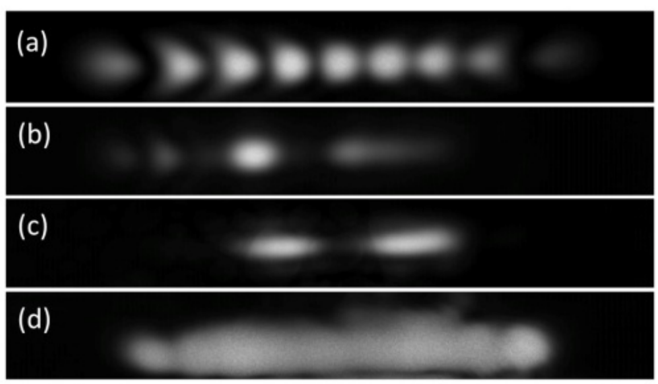

Figure 2. Facet images of 40um QCL, (a) Free-running case with M=9, (b) Feedback case with a dominant single peak, (c) Feedback case with two symmetric oval peaks, (d) fuzzy image indicative of a strongly multimode beam

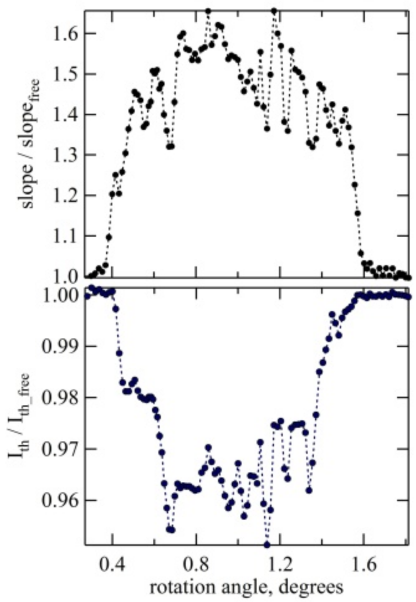

Figure 3. The slope efficiency and threshold current relative to the free-running case when the mirror angle is varied. Dots are measured points. (a) slope efficiency and (b) threshold

Zones of high slope efficiency do not necessarily correspond to a low threshold current. Modes identified by strong near field intensity peaks, such as Figure 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 Figure 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. With respect to the phase-locking question, the observations suggest that the external cavity can be made temporally stable.

4.0 RESULTS AND DISCUSSION

The traditional ECL examination tests their dynamical response to feedback and injection [7], 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 Mercury Cadmium Telluride (MCT) detector is positioned 2.4m downstream from the cavity and translated along the face of the beam. One particular case is shown in Figure 4 that shows two time series recorded at different points. For Figure 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 Figure 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 Figure 6. This map was created by extracting the frequency peaks from the oscilloscope's Fast-Fourier Transform (FFT) function versus the mirror angle at a fixed injection current of 1.12 Ith. The strength of the frequency is gray-scale coded on the graph. Similar to Figure 3 above, there is a kind of structure that arises from the different modes that are created. In cases, no oscillations are observed.

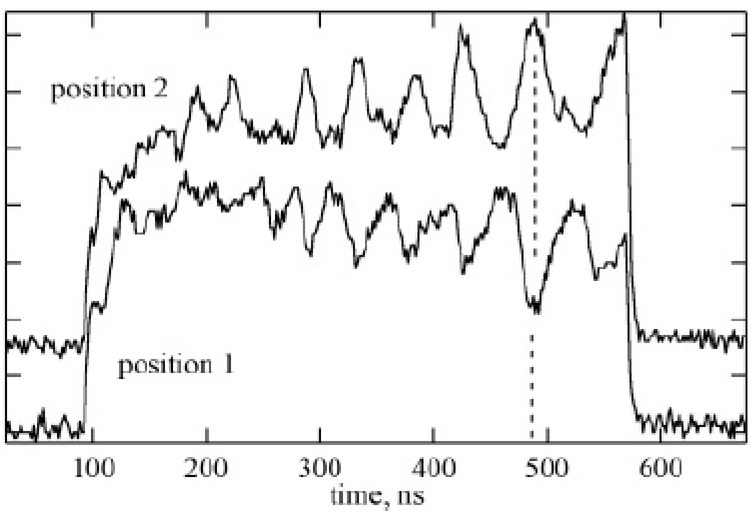

Figure 4. Time series taken at two different positions in the beam front. The oscillations are out of phase showing mode competition

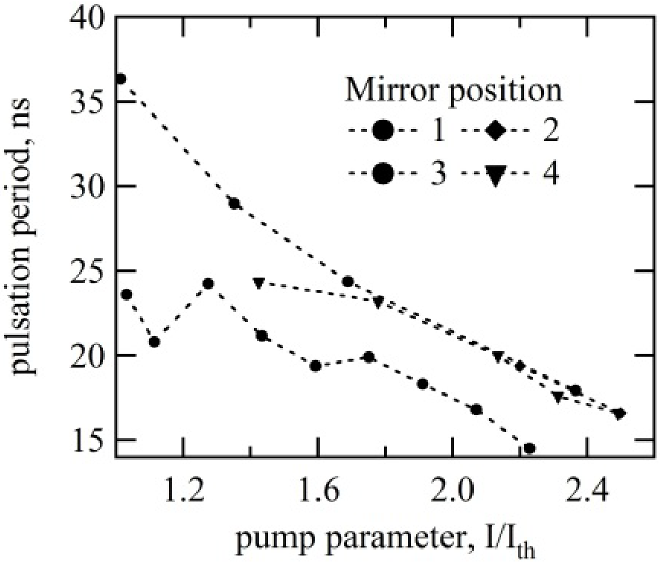

Figure 5. Mode competition oscillations are injection current dependent and similar regardless of the feedback mirror angle. Each plot represents a different mirror angle

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 Figure 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 Reference [7]. 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 Ith. This is in marked contrast to Lang-Kobayashi (LK) models of single transverse mode QCLs that show ongoing bifurcations and sometimes chaotic states.

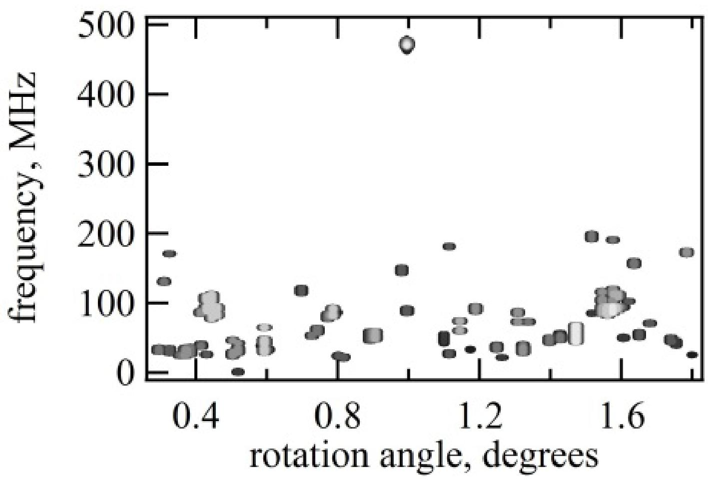

Figure 6. A two-dimensional plot of the observed oscillation frequencies plotted versus the mirror angle. The strength of the oscillations is gray-scale colored with lighter colors signifying a stronger signal. External cavity oscillations at 430MHz are only observed when the mirror is aligned parallel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

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.

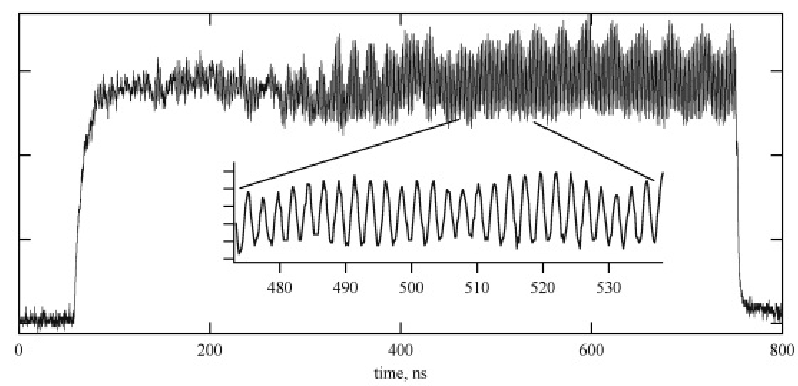

Figure 7. Quasi-periodic behavior when high frequency external cavity oscillations exist concurrently with lower frequency mode competition

Two other interesting yet rare phenomena are shown in Figure 8(a) and (b). Figure88(a) hints of the existence of LFFs, which were also observed in Reference [7].[The two arrows in Figure 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. [8] was insufficient. Whereas LFFs are normally a near-threshold phenomena, this occurs well above Ith. Figure 8(b) shows a very strong power dropout, see the region between the arrows. Again the current is well above Ith. 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 [9], 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.

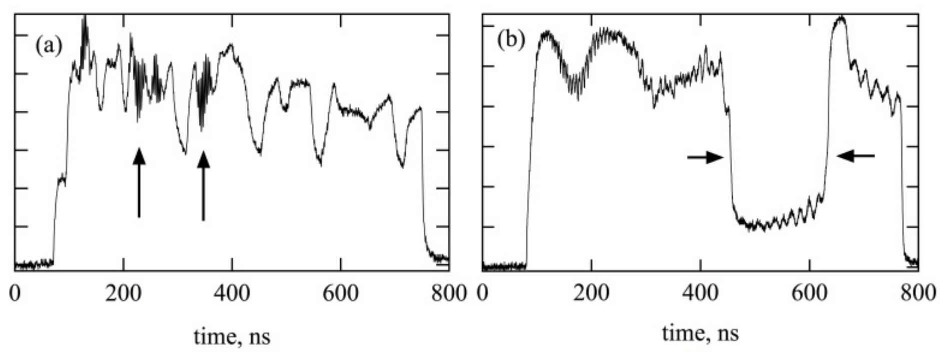

Figure 8. Rare cases in which (a) the time series shows similarities to low-frequency oscillations and (b) sudden power dropouts lasting nearly 180ns

5.0 CONCLUSIONS

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. $\chi 3$ 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.

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[9] 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.

SYMBOLS, ABBREVIATIONS, AND ACRONYMS

AFOSR	Air Force Office of Scientific Research
AFRL	Air Force Research Laboratory
AR	Antireflective coatings
BA-QCLs	Broad-area quantum cascade lasers
ECL	External cavity laser
$E_n(t)$	Electric field of n_{th} laser
EO/IR	Electro-optic/infrared
FFT	Fast-Fourier Transform
IRCM	Infrared countermeasures
HEL-JTO	High Energy Laser-Joint Technology Office
HR	Highly reflective coating
IR	Infrared
IRCM	Infrared counter Measure
I_{th}	Laser threshold current
LFFs	Low frequency fluctuations
LK	Lang-Kobayashi
MCT	Mercury cadmium telluride
MHz	MegaHertz
mm	millimeter
ns	nano-second
PI	Principle investigator
QCLs	Quantum cascade lasers
$r(t)$	Order parameter
STTR	Small Business Technology Transfer
SiO_2	Silicon dioxide
μm	Micrometer
z_t	Talbot distance/length

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