Studying Laser Diode Dynamics with Optical Feedback from 20cm Free Space External Resonator

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Abstract

In this experimental study, which was carried out in photonics laboratory at Strathclyde University, UK, dynamics of a multi-Quantum well semiconductor active medium laser, was studied. This is in order to study its emission stability and pulse shape development under the influence of strong optical feedback level with different deriving currents, in the free space transmission medium. An external stable resonator was constructed by inserting high reflectivity dielectric mirror outside the laser output, 20 cm apart from it, which is an extra-large external cavity. Controlling the reflected back optical power was done by using a non-polarized (50:50) beam splitter. The external resonator supported by focusing (plano-convex) lens in order to make it stable. Laser translated from stable emission when it was solitary, to quasi-static, and low fluctuated, behaves, to be coherence collapse. This is due to the strong (50%) level of optical feedback.

Keywords: Semiconductor Laser, External Cavity, Optical Feedback, Low Frequency Fluctuations, Coherence Collapse, Chaos.

Theoretical Part

Due to phase - amplitude coupling, semiconductor lasers (SLs) are very weak to optical feedback (OF), and instabilities are typically occurring. In many applications, such as fiber coupling, a non-negligible amount of feedback is produced nearly inevitably. Hence, the understanding of SLs under the influence of OF is of great importance from a point of view of applications. Depending on the feedback strength, i.e., on the amount of light that is reflected back into the laser cavity, different types of behaviour are known to occur. Below certain feedback strength, the emission of the SL can be stabilized and the line width can be narrowed. If the strength of the feedback exceeds a certain level, the semiconductor can be destabilized and a variety of interesting dynamical behaviours can be observed [1].

The low and moderate OFB level could be interpreted by the lang-Kobayashi rate equations model. In this limit of validity modal two simplifications are assumed, the 1st is that the spatial extension of the semiconductor can be neglected to be assuming only single longitudinal mode operation, and the 2nd is that delay time for light reflected in the external mirror and back to the laser is represented by $\tau = {}^{2L}/_{C}$ where L is the EC length, and C is the speed of light in vacuum. Duarte and Solari avoid the two above considerations, and described the diode medium in its full special extension, by allowing to longitudinal multimode operating. On the other hand, they considered the strong feedback level, which was not considered by the first modal [2]. This modal is also works in short as well as long external cavities. Monochromatic solutions for the laser in a double cavity can be found by the following electric field equation:

$$E_j(x,t) = e^{-iwt} \times \left[A_j e^{ik_j x} + B_j e^{ik_j x}\right] \qquad . \; . \; . \quad (1)$$

Where the subscript j indicates the region: $j = 0$ for the vacuum and $j = 1$ for the active media.

The output mirror of the laser and the external source of reflection, which is in the simplest case a mirror, constitute the so called external cavity (EC). Modes that are resonant in this cavity are called external cavity modes (ECMs). The (equidistant) frequency spacing of these modes is called external cavity frequency (ECF).

There is a general discrimination between different EC lengths, i.e., between long and short external ECs. Short ECs are characterized by a mode spacing of the ECMs, that is larger than the relaxation oscillation frequencies (ROFs) of the laser without feedback. Most of investigations so far have been restricted to the case of a long cavity. It is a typical issue of this regime that the occurring dynamics are qualitatively independent of small variations of the feedback phase, i.e., the phase with which the reflected light enters back into the laser cavity. Remainder of this section, the present study will be mainly focussed on the latter regime.

In recent years, secure communication systems based on chaotic dynamics have an increasingly interest in electronics, optoelectronics and optics. SL have been widely used for the studying of optical chaotic (chaos) dynamics. Such lasers are rendered chaotic through optical and opto-electronical (OE) feedback. OF in SLs is performed by re-injecting laser emission in free space EC or via optical fiber by a ring-cavity geometries, while OEF can be carried out only by re-injecting a detected optical power to the laser itself [1]. The stability of SLs subject to external injection of OF has been analysed by different authors in the last two decades [3].

For increasing strengths of feedback or for injection, the laser undergoes a route from stability to the so called Coherence Collapse (CC) phenomena [4, 5], showing a rich variety of nonlinear dynamic regimes, such as *un-damped* relaxation oscillation (RO), *chaos*, *bridges* of periodic solutions, and *low-frequency fluctuations* (LFFs).

One of the most intensely studied phenomena in the case of a long cavity is the so-called LFF, which is closely related with the CC phenomena), was observed first by Risch *et al.*,

manifest themselves as sudden dropouts followed by continuous, slow recoveries in the output power of a SL with feedback, at constant current. The term `low-frequency' is hinting to the fact that the frequency of these fluctuations is slow compared to the characteristic time scales of the SL material and the round-trip time of the light in the EC. LFFs are typically observed in the vicinity of the solitary laser threshold [6, 7].
The LFF have often been modelled using the *Lang-Kobayashi* (LK) equations, which describe the coupled dynamics the carrier density and of a single mode laser that is subjected to delay optical feedback from an external mirror [6, 8, 9].

The effects of OF on the operating characteristics of a SL depend on several parameters. These include the level of the feedback in comparison to the SL output power, the relative phase of this feedback, the length of the EC, and the injection current of the SL. SL operated with feedback have found applications in a number of areas due to the improvement that the feedback can lead to in many of the operating characteristics of the solitary laser. OF of appropriate level has been found to increase the *side mode suppression*, narrow the line width, and provide enhanced tuneability and frequency stability; relative to that of the solitary laser. A source for coherent optical communication systems (particularly for heterodyne detection and wavelength division multiplexing) and spectroscopic applications is required to be single frequency, narrow line width, and continuously tuneable over a wide range of wavelengths [10]. There are many spectroscopic techniques for which SL with feedback are ideal sources. For the laser induced cooling and trapping of atoms and the manipulation of atomic beams narrow line width low-power stable tuneable sources are required. For these reasons, diode laser with feedback systems are used extensively in many areas of research, communications, and industry [11].

The optical feedback properties of laser diodes have been sometimes classified into III regimes, this is according to the so called "feedback parameter" (C) which might have one of three values, $\mathrm{C}\begin{Bmatrix}<\\=\\>\end{Bmatrix}1$, depending on the equation:

$$\mathrm{C}=\sqrt{\mathrm{f_{ext}}}\frac{2|\mathrm{C_e}|\tau_{\mathrm{ext}}}{\tau_{\mathrm{L}}}\sqrt{1+\alpha^2}$$

where $f_{ext}=\frac{reflected\ power}{emitted\ power}$ is the feedback fraction, $C_e=(1-R)/(2\sqrt{R})$ with $|C_e|$ is the coupling coefficient from the laser to the external cavity for FP laser with facet reflectivity R or for DFB lasers, α is the linwidth enhancement factor, τ_{ext} is the roundtrip delay time and τ_{L} is the roundtrip delay time for solitary laser [12].

There has been a great deal of interesting into the properties of SL in regimes $I-IV$. These regimes encompass the low-feedback properties of SL and the CC state of operation. Few studies have been performed on the properties of SLs with strong OF, which is considered to occur when the external feedback reflectivity is comparable with or greater than the SL facet reflectivity. For the low-feedback regimes of operation the standard LK rate equations have been found to describe adequately the behaviour of the SL. Thus, to describe the behaviour of SLs subject to arbitrary levels of OF, an iterative travelling wave model (TWM) based on the original research of *Sporleder* was developed. An iterative TWM of a SL subject to strong OF, in which a SL is coupled to an external mirror producing strong OF. The SL is operating as an EC laser in which the dominant cavity is defined by the mirrors with reflectivity r_1, and r_3. A reference plane is defined just inside the laser facet. If τ_{ext} is the EC round-trip delay, and T is the laser internal round-trip time and the laser is AR coated ($r_2 << r_3$), then only a single external-cavity round trip need be considered; otherwise, multiple reflections around the EC must be taken into account.

In their series of papers, starting with [10] then [13, 14 and 15] Duarte and Solari presented an important modal that describes the laser with OF in a doubly cavity configuration for arbitrary values of EC mirror reflectivity. This model consists of a set of nonlinear differential equations with time delayed boundary conditions.

The external optical feedback is then naturally included as a consequence of the boundary conditions, fixed by the external mirror and by the laser facets. The boundary condition for the fields at $z = 0$ (the position at which the diode device ended and EC space started, i.e. semiconductor-vacuum interface) depends on the effective reflection and transmission coefficients of that diode facet and on the reflection coefficient of the external mirror, denoted here by r_3. It is assumed that r_3 is frequency independent and the EC is filled with a homogeneous, linear medium [16]. Moreover, the semiconductor medium is described in its full special extension, here allowing for multi-longitudinal-mode operation. Therefore, they avoid the assumption of single mode-operation and they overcome the inclusion of the external mirror as a perturbative term in the solitary laser rate-equations [17, 18].

The doubly cavity system consists of solitary semiconductor laser cavity and the second one is the external such that: ($L \gg \ell$) delimited by the external mirror of power reflectivity$R$. Such a general approach allows for determining the limits of LK equations [19, 20, 21]. Thus, the basic solutions of a laser subject to OF are known as ECMs, which correspond to constant intensity of the laser at a frequency that is selected by the EC. In other words, ECMs are due to the fact that the light makes one round trip outside the laser [22].

Experimental Part

The experimental set up is given in figure 1. Laser optical power that is directed output the device was incident on a *plano-convex* lens. That lens situated experimentally in a specific distance, such that focusing the laser spot light exactly on the output mirror. That mirror mounted in a 20 cm distance from the laser output face. Between the lens and the external mirror, a non-polarized beam splitter existed, its function was to split the laser power into two parts. One goes to the external mirror and the other is going to the transmission (detection) arm. When the experiment running, one has to try rotate the mirror vertically and observe the *DC* level in a simple *DSO*, only when this level jamb with the mirror rotation, it has been successfully the re-injected light interacted within the internal laser cavity. In this circumstance the experiment will start, and the data could carry out.

Our experiment was based on a laser of internal cavity type: Distributed Feedback (*DFB*). This lasers device is the standard specifications of “*ThorLabs* Co.”, and its model is: $ML725B11F$. The laser is an *InGaAsP* diode, emitting light beam around $1310nm$, with CW operation and peck power $P_o = 10\,mW$. This type is well suited for light source in long-distance digital transmission systems. It has a homogeneous grating (*AR/HR* facet coating) structure, wide temperature range operation($-40\ to\ 85^oC$), low threshold current (typical $6mA$), high speed response (typical $0.1nsec$), and flat window cap.

A $3D$ adjustable laser mountain is used for both laser and its collimating lens in order to beam collimating flexibility. Air, as a nearly free space medium, is considered in transmission and feeding backs to the laser output. Optics that is used are: A laser beam collimating/focusing; antireflected coated (ARC) *plano-convex* lens, *non-polarized* (NP) beam splitter, different highly reflectivity (R) plane mirrors, Fresnel Reflectance from 1-10% at 45°, “10B20-01NC.2”, (*Newport*) Ultrafast Laser Beam Sampler (BS) and different focusing lenses (*FL*) in signal detection part.

With respect to analysing the laser signal, all the following devices were used. Which are all connected to the laboratory desktop PC, via a *GPIB* cable network connection, where the program of *Labveiw* is installed to it.

The typical photon lifetime in the cavity ranged from few ps to few tenths of ps, while the relaxation oscillations are of the order of GHz. Thus the SLs are very fast dynamically. Fast time response is the basic requirements of the SLs monitoring equipment. The typical bandwidth for the detection system dealing with SLs ranges from 1 MHz up to tenth of GHz.

GaAs photodetectors (model: *ThorLabs PDA255*), are used for the detection, which was ideal for applications that require high speed, high sensitivity, and clean responses. Tektronix *TDS6124C*, 4 channels digital storage oscilloscope (*DSO*) 12GHz of bandwidth. Optical spectrum analyzer (*EOSA*), was also used for lower resolution optical frequencies analysing.

The experiment works optically, which includes: lenses, mirrors, non-polarizing beam splitters. Beam splitters have been used either for the detection part of the set-up, or as part of the external cavity (EC). In the EC, a high reflectivity dielectric mirror, which provides a reflectivity R $> 99.5\%$, and lower reflectivity dielectric mirror, also a lower R metal mirrors for the detection focusing alignment.

In order to laser temperature stabilization, a Peltier cell with its heat sinking, for temperature stabilization is used, with a penalty of $\mp 0.2^{o}C$ temperature fluctuation. In order to optimize thermal contact with the Peltier cell, a thermal paste has been used. A thermometer is used for laser temperature screening during the running.

Results and Discussion

DFB is attractive kind of lasers which is more important in laser feedback experiments. The internal (self) feedback necessary for the lasing action is distributed along the cavity length using a grating etched so that the thickness of the active layer varies periodically along the cavity length. The grating rejects a little light over each period of the grating until there is no light at the back of the grating. Since the light is being rejected by grating the rejected light is always in the correct phase no matter from which portion of the grating it was rejected. DFB lasers have a periodic, spatially-modulated gain, with strong selectivity for the wavelength that matches the period of the gain modulation and lase in the same single longitudinal mode from threshold up to the maximum operating power. The sensitivity of a semiconductor laser to external OFB depends on the stored energy in the cavity and the coupling of the laser mode to the external field. Thus, to compare the feedback sensitivities of edge emitted lasers such as DFBs, an optical feedback parameter k is used.

We set the laser device and the optics and the detection as shown in figure (1). In order to insure that the laser operation is nearly the same threshold and power specifications as given in its data sheet, we test it experimentally. Two beams from the three shown in figure (1) were blocked. The only one that still emitting is the detection arm. The Laser operating temperature during the 1st (solitary) and the 2nd (operating with feedback) was chosen to be: 14.5Co. Laser measured threshold current (at solitary running) was 4.03mA, and its maximum output measured optical power was 10.28mW at 30mA. This is after including the reduction of power due to NBS power dividing, and the loss, so it is a 3R class Laser.

After opening the two blocked beams, it needs to focusing the laser beam onto the external mirror, 20cm apart from the laser. The power DC level was used to ensure the reinjected light alignment.

Results show a 4.6% threshold reduction in current due to the feedback, which means a 21.90% increase in optical output power, figure (2). In this operating, laser device, as a semiconductor active medium, worked under the effect of SEED (Self Electro-optic Effect Device). This means that this laser started stimulated emission while the injected current still within the level for spontaneous emission, that is under the effect of optical feedback.

The observations for the laser dynamics were started from near above threshold, to maximum current, for random increased levels. Figure (3) shows laser dynamics with feedback at injection current 5.38mA, in which, the frequency trace indicates three main lasing modes, 0.7, 1.4 and 2.14 GHz, while the relaxation oscillation is 7.9GHz. In the next level trace, figure (4), at current 7.10mA, the lasing modes become two, and the relaxation oscillation extended to be larger than 10GHz. In fact, in all the observations, the relaxation oscillation increased linearly with the current.

Observations to results, give no distinguished lasing single mode, instead, the laser had in some current levels a double lasing modes, figures (4, and 7) and in others triple modes, figure (3 and 5) and they haven't exact lasing mode in figure (6). The OFB ratio during the experiment was constant, which was 50% of laser output power, this is due to 50:50 NPS. But its amount (the portion that reinjecting the semiconductor active medium) differs from current level to another level. From literatures, feedback ratio of 50% is large enough to make the laser under the effect of coherence collapse phenomena, which is observed in figure (6). Under this effect, there will be no distinguishable lasing mode, and the pulse will be chaos. The different between the noise (that existed in conjugate of any laser operation) and the chaos effect is that the later amplitude is higher than that in the former. From the other hand one can test the laser output as a data. It should be satisfying the so called strange attractor. Also, from the observation to the same figure, one cannot find any periodicity for the time domain signal.

Furthermore, in SEEDs, semiconductor device under optical feedback may obey rich dynamics, such as bi-stability and Bifurcation, the later makes the laser instable, and its emission will be translating between two or more states.

With respect to laser output pulse shape, results show broadening in line shape for all running levels, figure (9). Statistics for all operating current levels give a polynomial fitting between FWHM and current figure (10). That’s to say, laser line shape proportional nonlinearly with deriving current.

Conclusions

Creating a 20cm external cavity for a semiconductor laser makes it instable in emission. Strong feedback (50%) makes the laser signal broadened, and the lasing mode became note single, but function to laser deriving current level. One can employ this technique to develop the laser emission according to the application. Three parameters are most commonly used to quantify the feedback level, which are feedback rate F, feedback level $k^2$and the effective power reflectivity for the external mirror, R_{ext}. For that coupling between laser chip and its EC modes insurance, TR should be optimized to be maximum in order to laser running with perfect alignment.

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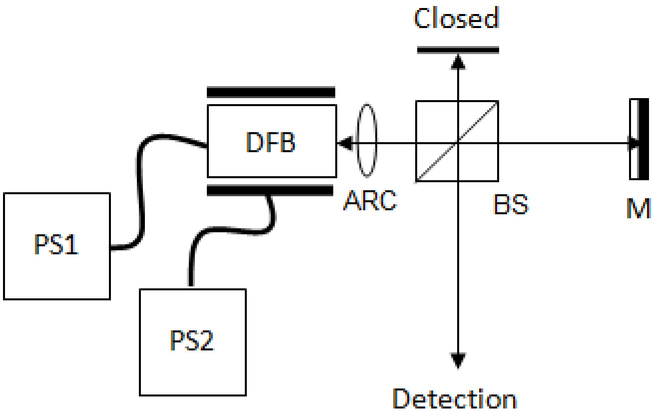
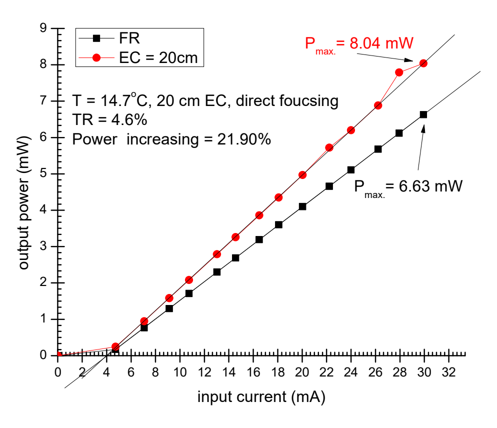
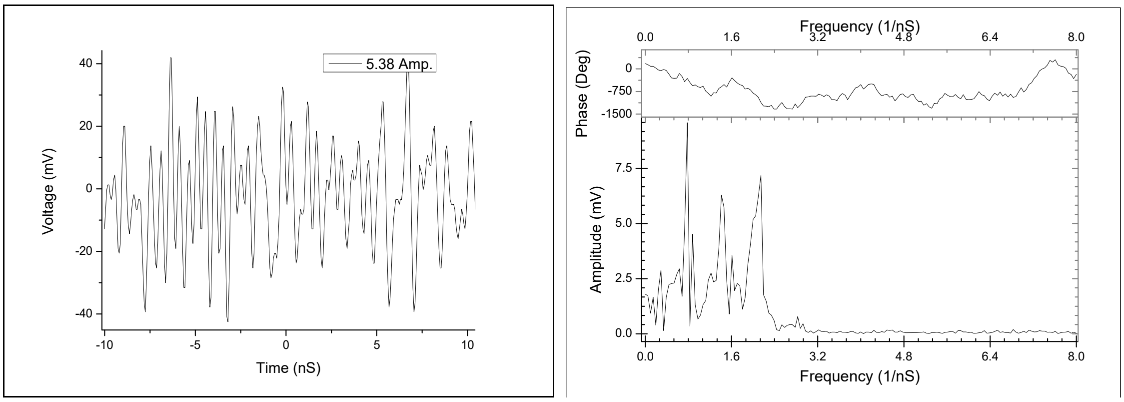
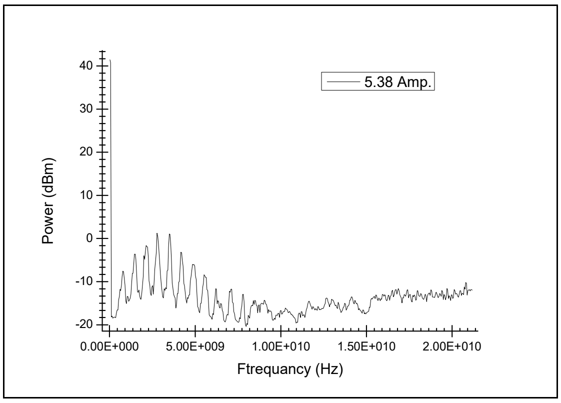


Figure(1): Experimental set up
PS1: 1st power supply, for the laser device, PS2: 2nd power supply, for the heat sinc, ARC: anti-reflected coated convex lens, BS: 50:50 beam splitter



Figure(2): Threshold reduction with the effect of optical feedback by 20 cm external cavity
Red: Laser running with optical feedback, Black: Laser free running.





Figure(3) laser dynamics with feedback at injection current 5.38mA. Upper left: time space, upper right: FFT, and lower: radio frequency

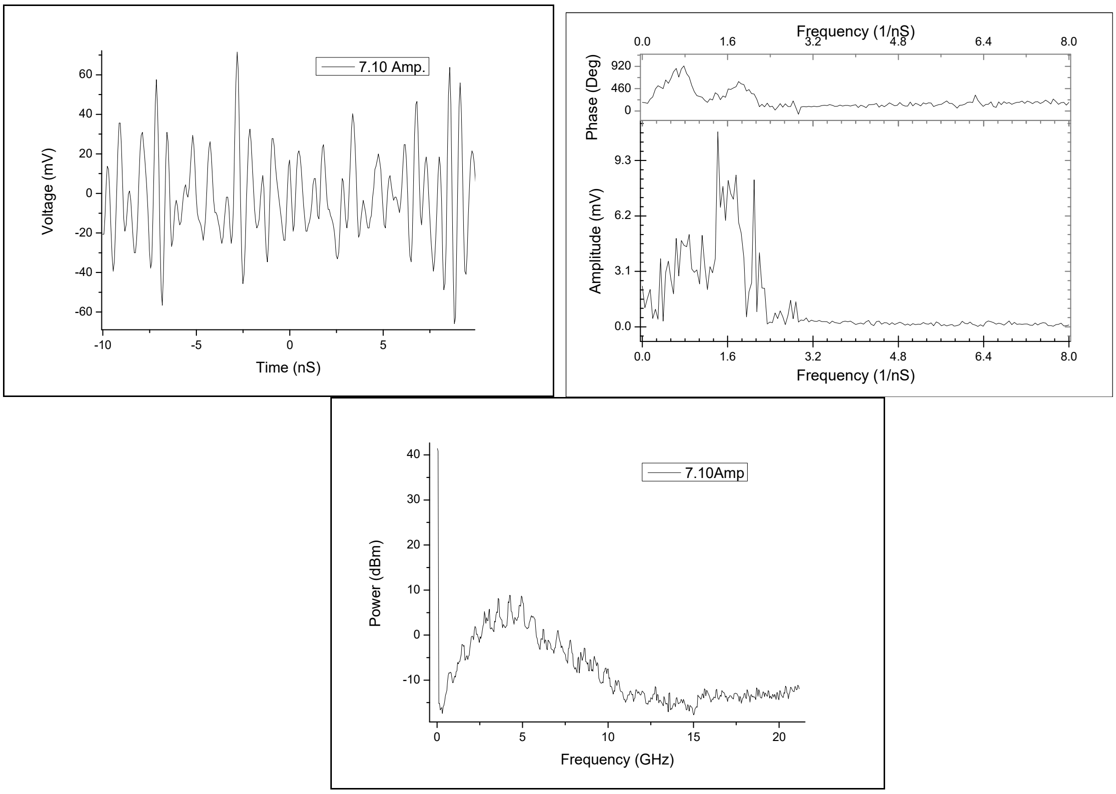
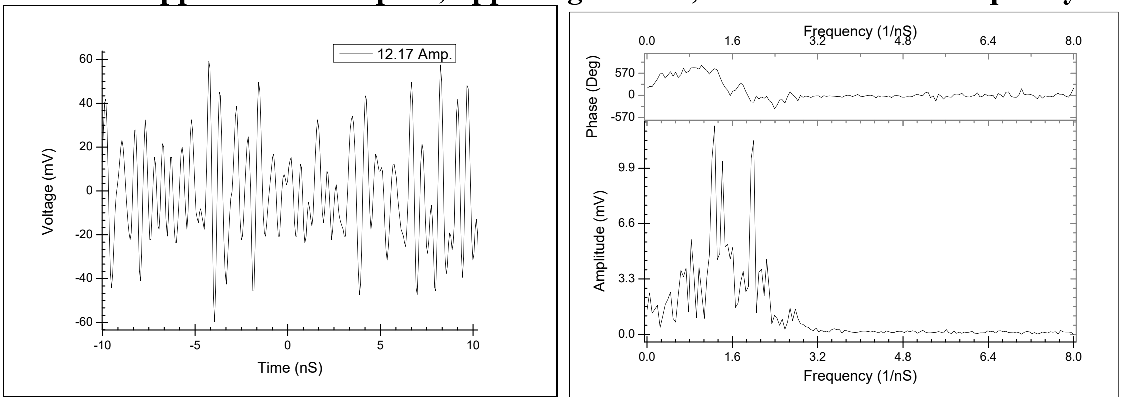
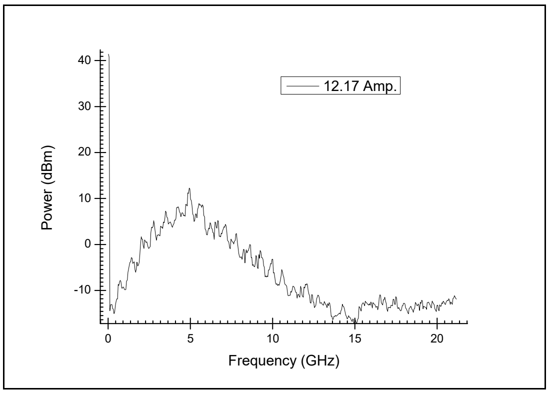
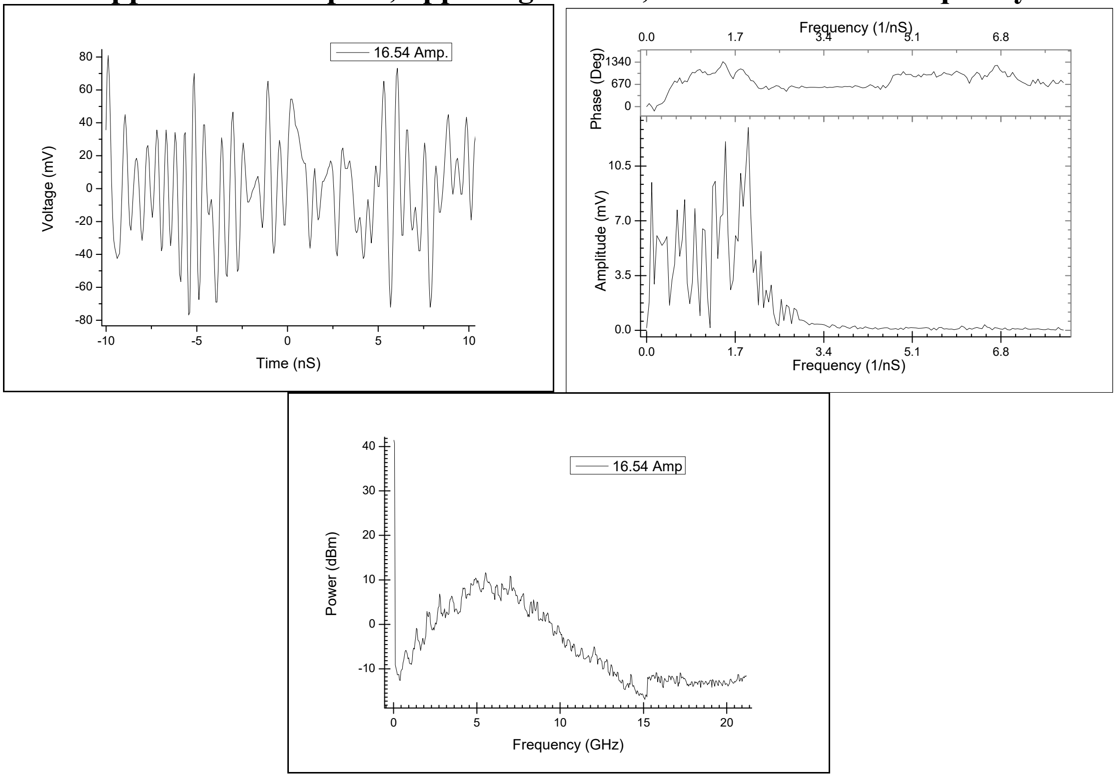


Figure (4) laser dynamics with feedback at injection current 7.10mA. Upper left: time space, upper right: FFT, and lower: radio frequency

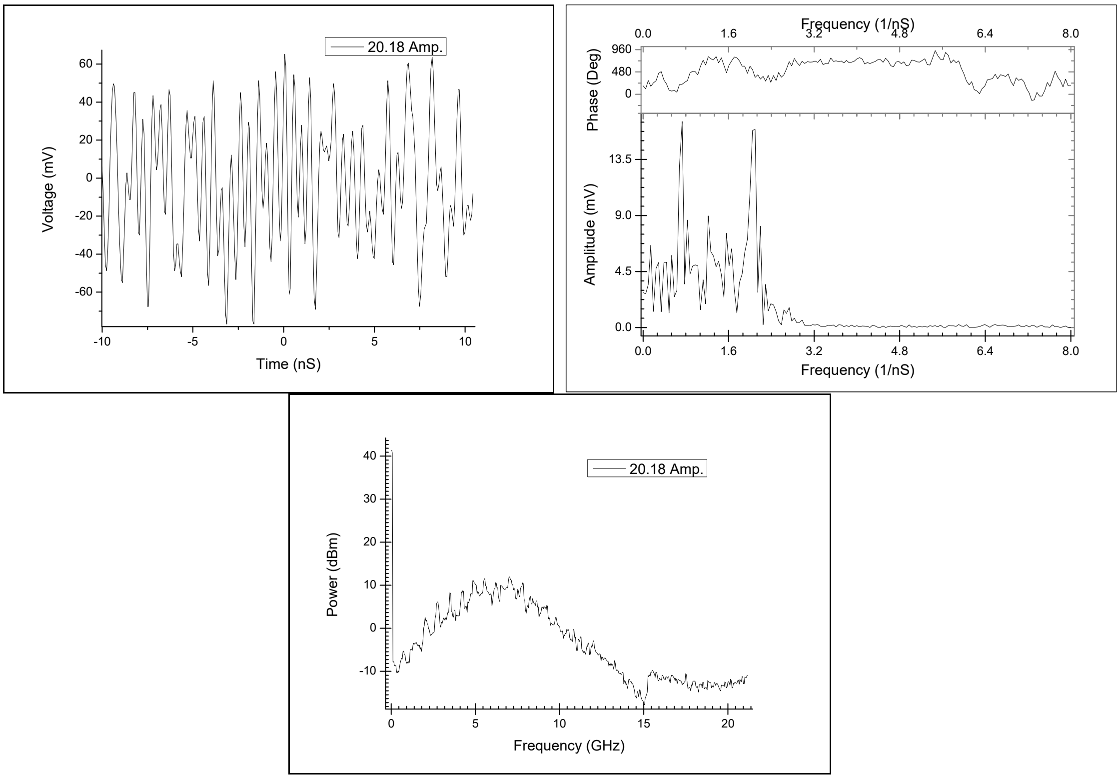




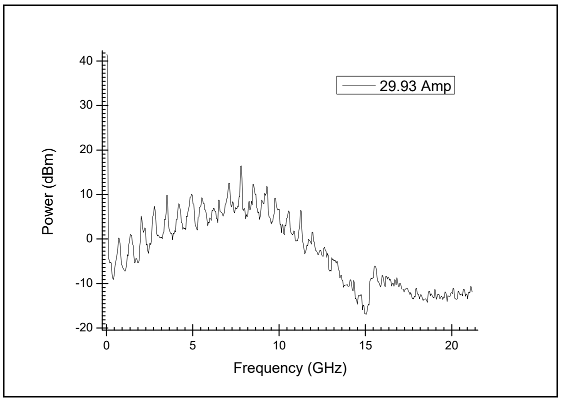
Figure(5): laser dynamics with feedback at injection current 12.17mA. Upper left: time space, upper right: FFT, and lower: radio frequency



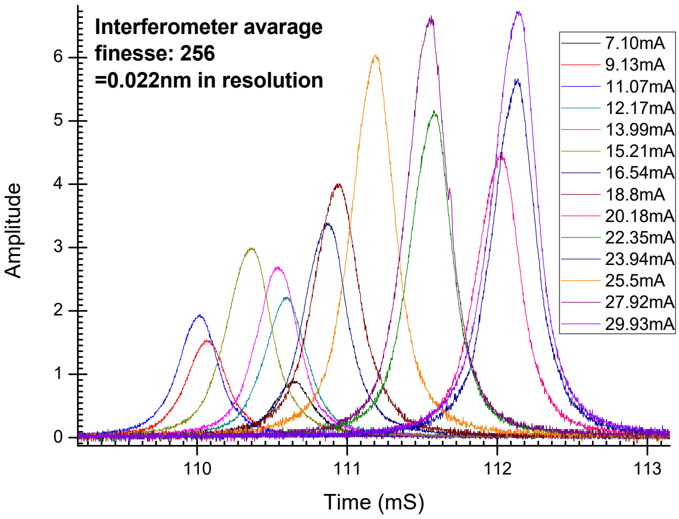
Figure(6) laser dynamics with feedback at injection current 16.54mA. Upper left: time space, upper right: FFT, and lower: radio frequency



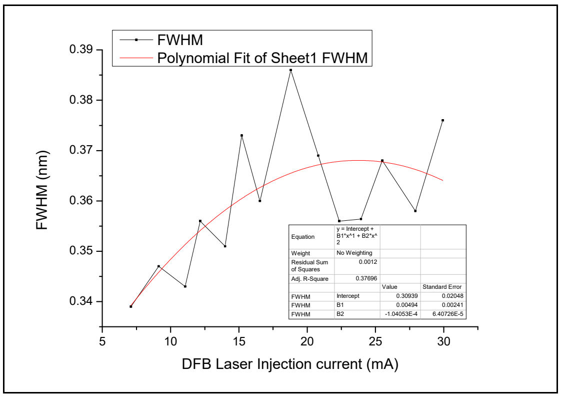
Figure(7) laser dynamics with feedback at injection current 20.18mA. Upper left: time space, upper right: FFT, and lower: radio frequency



Figure(8) Observed laser radio frequency with feedback at injection current 29.93mA.



Figure(9) Mode shift and pulse shape modifications with increasing injection current for the laser emission with 20cm external cavity.



Equation	y = Intercept + B1*x^1 + B2*x^2		
Weight	No Weighting		
Residual Sum of Squares	0.0012		
Adj. R-Square	0.37696		
		Value	Standard Error
FWHM	Intercept	0.30939	0.02048
FWHM	B1	0.00494	0.00241
FWHM	B2	-1.04053E-4	6.40726E-5

Figure(10) FWHM shift with injection current – Polynomial fitted.

دراسة ديناميكية الليزر مع التغذية العكسية الضوئية بوساطة مرنان خارجي في الفراغ بطول 20سم

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الخلاصة

في هذه الدراسة العملية التي اجريت في احد مختبرات مجموعة الفوتونيات في جامعة ستراثكلايد في المملكة المتحدة تمت دراسة ديناميكة الليزر ذات الوسط الفعال شبه الموصل من نوع بئر الجهد المتعدد. وذلك لغرض دراسة مدى استقرارية الانبعاث الليزري وتطورات عرض النبضة بتأثير تسليط تغذية ضوئية عكسية شديدة ومستويات تشغيل مختلفة في الفراغ كوسط ناقل للتغذية العكسية. تم ترتيب مرنان خارجي مستقر بتركيب مراة شديدة الانعكاسية على مسافة 20سم من الليزر. اذ تصنف هذه المسافة على انها مرنان خارجي من النوع الكبير. تم اختيار نسبة القدرة المعاد ادخالها لليزر من خلال نوع نسبة الفصل للفاصل الضوئي غير المستقطب المستخدم في التجربة والبالغة (50%). تمت عملية تركيز الاشعة الصادرة من الليزر باستعمال عدسة لامه-مستوية بهدف الحصول على مرنان مستقر. تحت هذه الظروف انتقل الانبعاث الليزري من حالة الانبعاث التلقائي للحالة المعزولة لليزر الى حالة الانبعاث المحفز في المنطقة نفسها بتاثير التغذية العكسية. وانتقل الانبعاث الليزري من حالة الاستقرار الى حالة اللااستقراريه بتأثير ظاهرة التشعب التي اودت الى حالة انهيار التشاكه ومن ثم الفوضى المسيطر عليها، كل ذلك بتأثير التغذية الضوئية العكسية.

الكلمات المفتاحية: ليزر شبة الموصل، تجويف خارجي، تغذية عكسية ضوئية، تقلبات التردد الواطيء، انهيار التشاكه، الفوضى.