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FRUSTRATED INSTABILITIES AND CHAOS IN SEMICONDUCTOR LASER AMPLIFIERS

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Non-linear dynamics of a semiconductor laser amplifier (SLA), subjected to an external input radiation are investigated experimentally by generating self-sustained pulsation (SSP). Frustrated instabilities in a SLA are demonstrated for the first time. Co-existence of multiple wavelengths satisfying the cavity resonance of the SLA is thought to be the main reason behind the appearance of frustrated instabilities. The results are found to be in line with published theoretical predictions.

Key words: Semiconductor laser amplifiers, SSP, Chaos, Frustrated instabilities, Coherence collapse

1. INTRODUCTION

Semiconductor laser amplifiers have been studied extensively due to their potential use in future optical communication systems and optoelectronic integrated circuits (OEICs) [1-2]. However, when a pre-biased SLA is subjected to external optical signals (as in optical communication systems and in OEICs), local carrier density within the active layer of SLA decreases while the refractive index increases accordingly. This results in non-linear behaviour of the device. The non-linear phenomena in a SLA (Fabry-Perot or travelling-wave) may introduce periodic pulsation (or self-sustained pulsation (SSP)), sub-harmonic generation, period doubling, period quadrupling and period tripling; all leading to chaos as a result of time dependant instabilities within the gain medium [3-6]. Chaotic dynamics and SSP have gained considerable importance due to the following reasons:

1. Non-linearities in amplifiers introduce additional cross talk and noise [7] which are the main obstacles to the application of semiconductor lasers in ultra-high frequency regime. They are undesirable in optical communication systems and in OEICs and therefore must be eliminated.
2. Non-linear behaviour and chaotic dynamics of laser based optical systems are the subject of intensive theoretical and experimental investigations because a better understanding of non-linear dynamics allows us to avoid these non-linearities and chaos [8].
3. It has potential applications in the fields of encrypted, synchronised, secure and high speed communication [9-10], linewidth enhancement [11] and ultra-fast and short pulse generating systems [12].

Normally, in a semiconductor laser based system, nonlinearities are not expected due to the fast intraband relaxation rate, but can be achieved by introducing some external effects, such as;

(a) Modulation of the pumping currents [13-14].
(b) Feedback by an external cavity [15].
(c) Injection of external optical signals [16].

In all three approaches, the essential requirement is the existence of two frequencies [17], which characterise the non-linear dynamics of the device. Individually, they assume only one degree of freedom. However, if a source laser and a SLA are coupled to each other, then the injection of the input signal can generate considerable amount of non-linearity in an optical system. Here, the last technique has been used to investigate the nonlinear dynamics of a SLA.

2. DEVICE SPECIFICATIONS AND EXPERIMENTAL SET-UP

In order to investigate the chaotic dynamics of a SLA, anti-reflection (AR) coated 2.5µm wide stripe geometry ridge waveguide GaAs device was used as a SLA. Facet reflectivities of SLA were intentionally left as 4% to achieve delay feedback within the device.The involvement of multiple frequency components with different time delays can help to analyse the mixed mode dynamics of a semiconductor laser based system [18]. In fact, this can help in establishing a clear understanding of chaotic dynamics of SLA based systems. A GaAs laser diode (LD) with the active layer thickness of 0.15 µm was used as the source laser. This laser diode had a peak emission wavelength of around 0.86 µm and a threshold current of 40 mA. Both devices (LD and SLA) were made essentially from the same material and had the same structural parameters except the facet reflectivities. Both devices were mounted on separate heat sinks and a multi-channel temperature controller was used to control the temperature of both devices individually by the help of temperature sensors and Peltier cooling elements (which were placed within the heat sinks). Heat sinks were mounted on two separate bases, which had four direction of movement (i.e. *x*, *y*, *z* and angular movement). Also, both devices were operated under pulse conditions to avoid any overheating in order to achieve more reliable results. The width of current pulses was kept constant at 200ns and 300ns for the source laser and SLA respectively with a repetition frequency of 10 kHz. This proportion between the pulse width and pulse repetition frequency was sufficient to isolate the transient temperature effects caused by one pulse by other pulses. Two BPX 65 PIN photodiodes along with the optical lens system were used to measure different characteristics of the device being investigated. The source laser and SLA were used in master-slave configuration. The source laser and SLA were aligned using a free-space alignment technique [19]. Optical output from the SLA was monitored using a monochromator (SPEX-1000), a spectrum analyser and a fast oscilloscope. All the results were either plotted using a sample & hold oscilloscope and an X-Y plotter or were recorded using Polaroid camera. Figure 1 shows the schematic of experimental set-up used during this work.

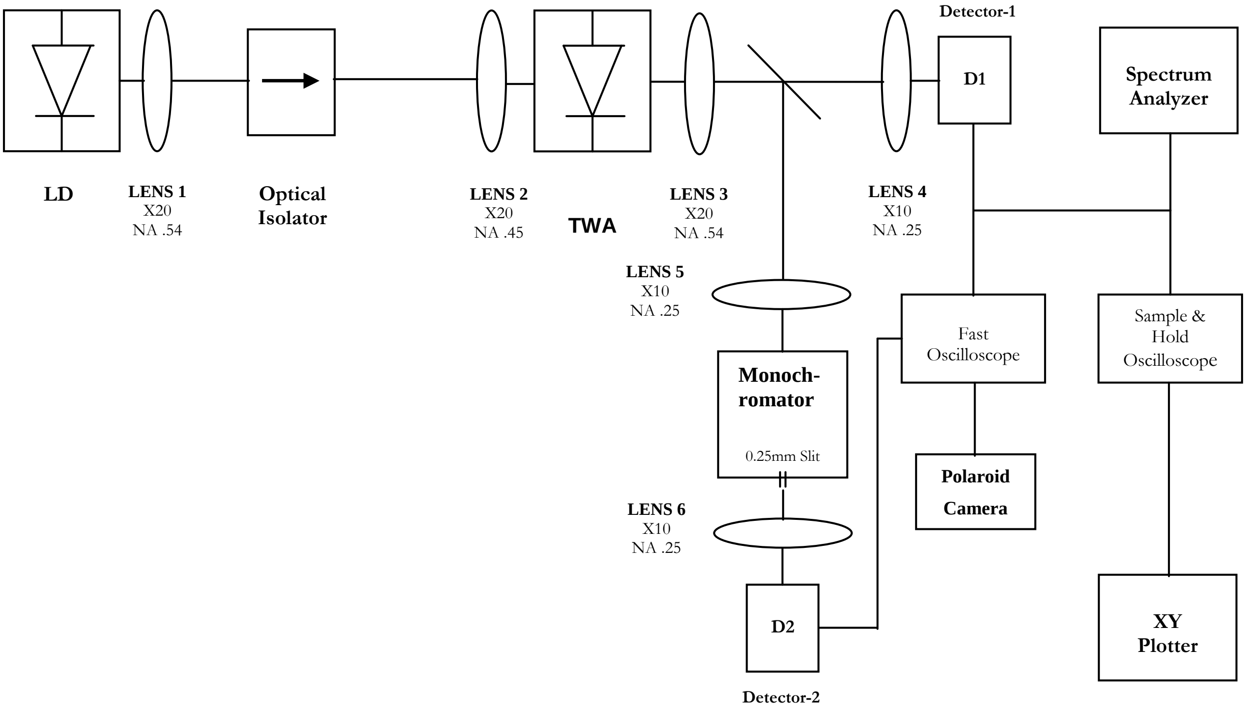

Figure 1. Experimental set-up used for the demonstration of frustrated instabilities.

3. EXPERIMENTAL RESULTS

After aligning the source laser and SLA, the gain of injected signals was maximised by changing the temperature of both devices. Once the maximum gain was achieved, light-current (I-L) characteristics from the output facet of SLA were measured with;

(a) No external optical input and no optical feedback to SLA.

(b) No external optical input but with the maximum optical feedback from the source laser to the SLA.

(c) External optical input and the maximum optical feedback to the SLA from the source laser.

(Note: The optical isolator was removed for b & c above in order to have maximum optical feedback and optical input coupled in to the SLA).

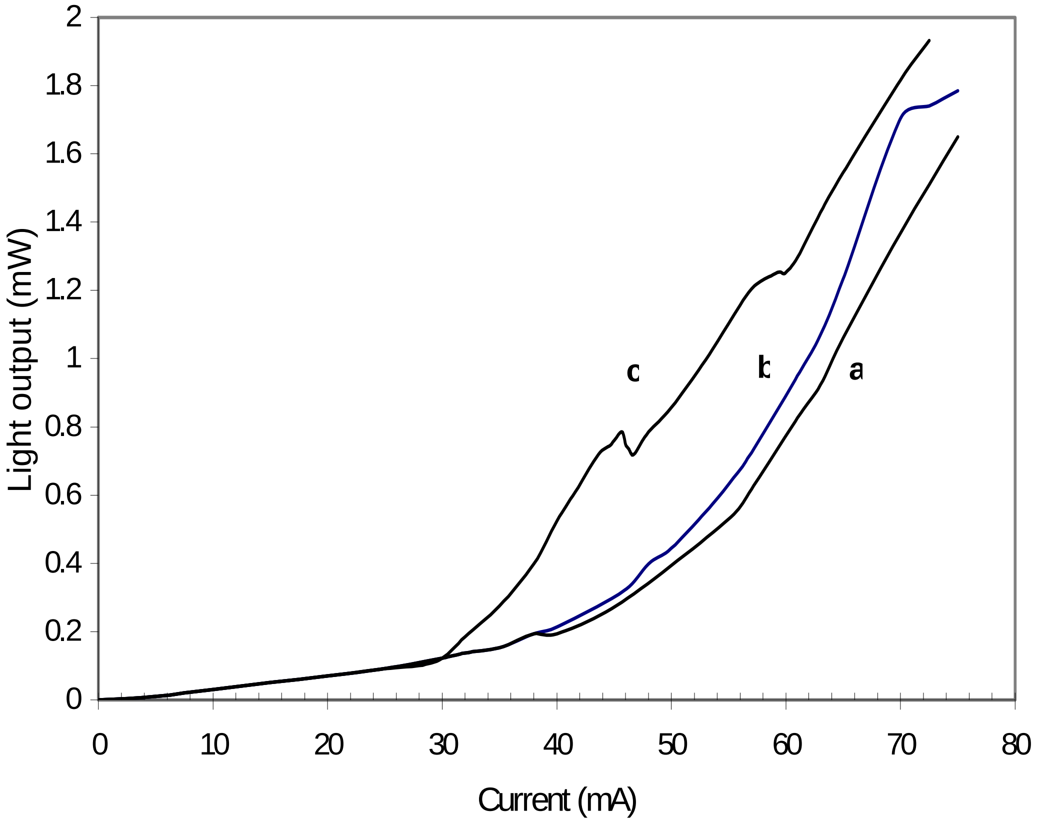

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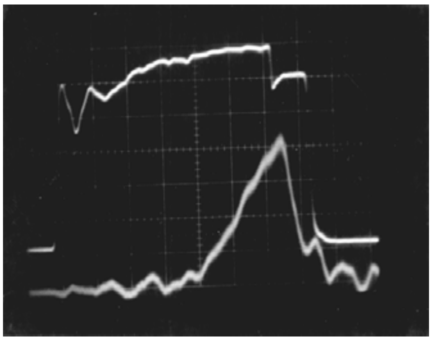
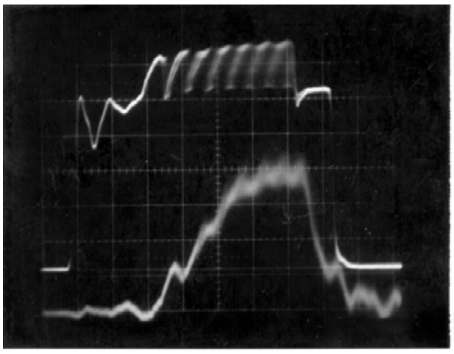
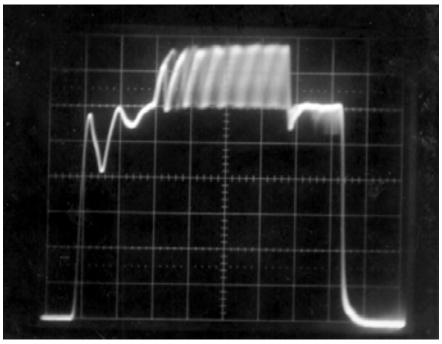
Figure 2. I-L characteristics of SLA with; (a) no external input and no feedback; (b) no external input and maximum optical feedback; and (c) external input and maximum optical feedback.



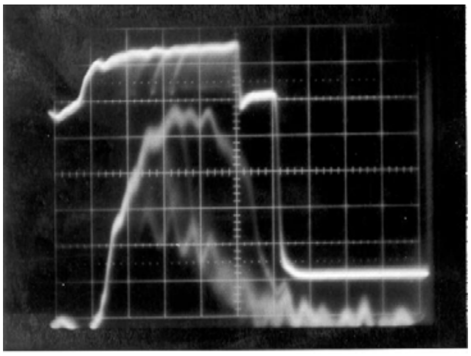
I_{LD} = 67 mA and I_{SLA} = 45 mA, *m* = 4.75
a



I_{LD} = 80 mA and I_{SLA} = 45 mA, *m* = 8.25
b



I_{LD} = 85 mA and I_{SLA} = 45 mA, *m* = 9.75
c



I_{LD} = 91 mA and I_{SLA} = 45 mA, *m* = 12.75
d

Figure 3. Observation of non-linearities as a function of modulation index. Vertical scale = 100 mV/div. and horizontal scale = 50 ns/div.

Figure 2 shows the results obtained under the above mentioned conditions. It is clear from Fig. 2 that the injection of external optical signals and multiple optical feedbacks between the source laser and SLA introduces nonlinearity in the shape of kinks in I-L characteristic of the SLA, however, these kinks are more prominent in curve ‘c’.

Once the unstable regions in I-L characteristics (in the shape of kinks) were spotted, the next step was to obtain periodic pulsation in order to look at the chaotic dynamics of the system because it is now well establish that the route to chaos is through periodicity. By continuously varying the drive currents, temperature and position of both devices, a train of periodic pulsation was obtained at 85mA and 45mA of LD and SLA biasing currents respectively. After achieving SSP, the bias current of the SLA was kept constant at 45mA, but the source laser biasing current was reduced to 67mA which corresponds to modulation index, m of 4.75 (no pulsation value). Figure 3(a) shows the results (upper traces in fig.3 (i.e. fig. 3a, 3b, 3c and 3d) show the output of the detector-1 and lower traces in figure 3 show the output of the monochromator through detector-2)). When the source laser drive current increased to 80mA ($m = 8.25$), the output of the detector-1 shows a periodic pulsation and the output of the monochromator is slightly noisy but generally smooth (see fig. 3(b)). At a slightly higher value of the source laser biasing current (i.e. 85mA and $m = 9.75$), the output of the detector-1 on time scale shows the increase in the amplitude of pulsation (as shown in fig. 3(c)). It can be seen from Fig. 3(c) that at the end of the train of pulsation, the periodic pulsation becomes chaotic. The output of the monochromator is not shown in fig. 3(c) because it did not change from its previous position except that it was shifted slightly towards left due to a shift in the gain curve because of increase in the source laser drive current. At 91mA (corresponding to $m = 12.75$), the train of pulsation almost vanishes and taken over by chaos as shown in upper trace of figure 3(d). The lower trace of fig. 3(d) shows double waveform due to the inability of the gain medium in selecting a single stable oscillating mode as different modes are satisfying the resonant frequency of the gain medium at the same time. However, the one component is dominating the other, which results in the frustration of the other because of competition between the two stable solutions (as a result of the injection of external optical signals and multiple optical feedback components with different time delays within the SLA’s cavity). This is indeed a very clear evidence of existence of frustrated instability in a SLA which occurs at very high value of modulation index. Ikeda and Mizuno [20], Otsuka & Yumoto [21] and Shore [22] have predicted this regime. Carpintero and Lamela [23] in their study have indicated the coexistence of period tripling and chaos at nearly the same value of modulation index which was previously overlooked in experimental studies (for example see ref. 5) and it was rather interpreted as periodic behaviour due to domination of one solution over other (i.e. the same scenario, which is responsible for frustrated instabilities). We believe this happened due to the frustration effect within a cavity which has mixed up the two possible solutions.

4. CONCLUSIONS

Using non-linearities induced by the injection of external signals and multiple feedbacks within the SLA’s cavity, a train of periodic pulsation, which eventually leads to chaos, was obtained. The periodicity of the pulsation suggests that the observed effects are real oscillations and are not due to noise. Although the existence of frustrated instabilities has been predicted by several researchers, it has, as yet, received a very little attention from researchers. There has never been any reported work (theoretical or experimental) on frustrated instabilities in semiconductor laser based systems. In this paper, the existence of frustrated instabilities in a SLA has been shown for the first time. However, more theoretical and experimental investigations are needed to investigate this unique phenomenon.

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