CHAOS SUPPRESSION IN VERTICAL CAVITY SURFACE EMITTING LASER DIODES

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Abstract

We studied the dynamics of Vertical Cavity Surface Emitting Lasers (VCSEL) under high frequency modulation. VCSELs can have a negative gain suppression factor and they can also exhibit self pulsation under appropriate bias conditions. When high frequency modulation is applied a variety of effects in the laser dynamical behaviour can occur, including chaos. The possibility of controlling chaos in a VCSEL laser diode, in order to use chaos control as a useful characteristic, is presented.

Laser diodes with lasing wavelength on the longer wavelength side of the gain profile and with a wavelength constraint, like DFB or VCSEL, can have a negative gain suppression factor [1]. The consequence of such negative gain suppression factor is an enhancement in the laser response to high frequency modulation, leading to self pulsation. The natural damping, that occurs when the gain suppression factor is positive is absent under proper conditions. This fact brings very important consequences to the laser diode dynamics, that can lead the laser to a chaotical regime. However, we verified that an appropriate control method can be applied to suppress the chaos.

The behaviour of the laser diode can be modeled by the rate equations:

$$\begin{aligned} \frac{d}{dt}\tau_n N &= \frac{\tau_n}{\alpha} I - \gamma\tau_n (N - N_t)(1 - \epsilon S)S - N \\ \frac{d}{dt}\tau_p S &= \Gamma\gamma\tau_p (N - N_t)(1 - \epsilon S)S - S + \Gamma\beta\frac{\tau_p}{\tau_n} N \end{aligned} \quad (1)$$

where S and N are the photon and carrier densities, τ_n and τ_p are the carrier and photon lifetimes, α is the product of the active region volume and the electronic charge, Γ is the mode confinement factor, β is the fraction of spontaneous emission entering the lasing mode, N_t is the carrier density required for transparency, γ is the optical gain coefficient, I is the injected current in the active region and ϵ is the gain suppression factor.

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In this work we study a VCSEL laser diode with the following parameters: $\alpha = 1.58 \times 10^{-35} Am^3s$, $\beta = 1.0 \times 10^{-5}$, $\gamma = 8.69 \times 10^{-13}s^{-1}m^3$, $\epsilon = -2.2 \times 10^{-23}m^3$, $\tau_p = 3.89ps$, $\tau_n = 1.49ns$, $\Gamma = 0.986$. The threshold current for the studied device is $I_{th} = 13mA$.

The effect of a negative gain suppression factor was analyzed by Bennett et. al. [1] where they have shown that, for some chosen values of $\epsilon(\epsilon < -\gamma\tau_p)$ and bias current $(I > I_{th})$, the laser diode exhibits self-pulsation with a natural frequency that depends upon the bias current value. The same authors have also investigated the laser diode dynamical behaviour when current modulation is applied. That is:

$$I = I_{dc} + I_{rf} \sin 2\pi ft \tag{2}$$

where I_{dc} is the bias current and the modulation index is given by $\frac{I_{rf}}{I_{dc}}$. The modulation leads the laser to a variety of different states in its dynamical behaviour, depending on the values of the modulation index and frequency.

Frequency locking can occur on certain situations, and for large values of I_{rf} chaotic behaviour is observed. A more detailed description of the dependence of the laser diode dynamics with the modulation amplitude is given by [1]. Figure 1 shows the atractor for the studied laser diode for a situation in which chaotic behaviour is observed. The graph on figure 2 shows the corresponding time dependent waveform for the photon density in the laser cavity. The non-periodicity of such waveform is clearly visible.

Chaotic behaviour, although in general undesirable, has some important properties like ergodicity and the presence of a very high number of unstable periodic orbits hidden (or embedded) in it. These features can be used with advantage if the “bad” feature of chaos – instability – can be eliminated. This idea has motivated the development of chaos control methods. A classical method is the OGY [2], that uses feedback to control weak perturbations in one of the system parameters.

In the situation studied here, however, the involved rates are so high that the use of any feedback method is almost impossible from the practical point of view. Therefore, we adopted a method presented by Braiman and Goldhirsch [3] in order to achieve the stabilization of an undesirable periodic orbit embedded in the chaotic attractor (Fig. 1) for the particular laser diode studied.

The Braiman and Goldhirsch method consists in adding a second alternate current to the original modulation current. The new term has small amplitude and a frequency that differs from f by a controlled ratio (Λ). The current applied to the laser diode now takes the form:

$$I = I_{dc} + I_{rf} \sin\ 2\pi ft + I_\alpha \sin 2\pi\Lambda t \tag{3}$$

There are two control parameters to be adjusted in order to attain chaos suppression. We

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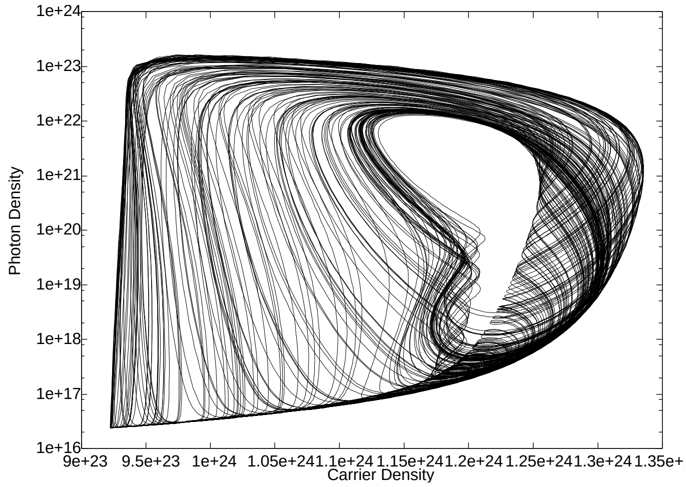

Figure 1: Chaotic attractor for a laser diode under proper bias and modulation current. See text for details.

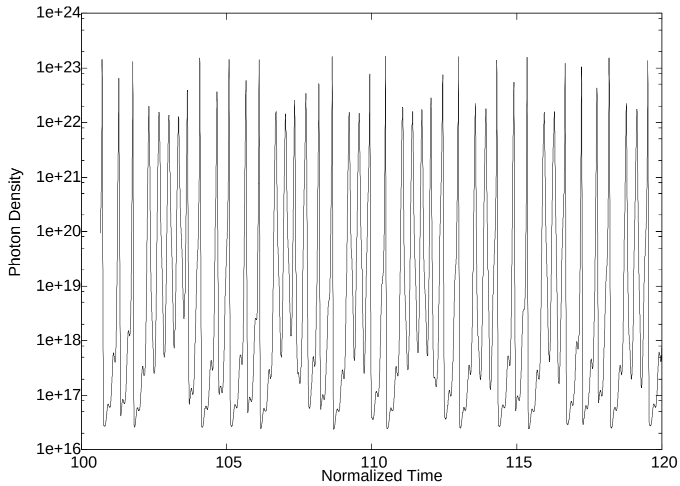

Figure 2: Photon density as a function of time for the chaotic state of the laser diode.

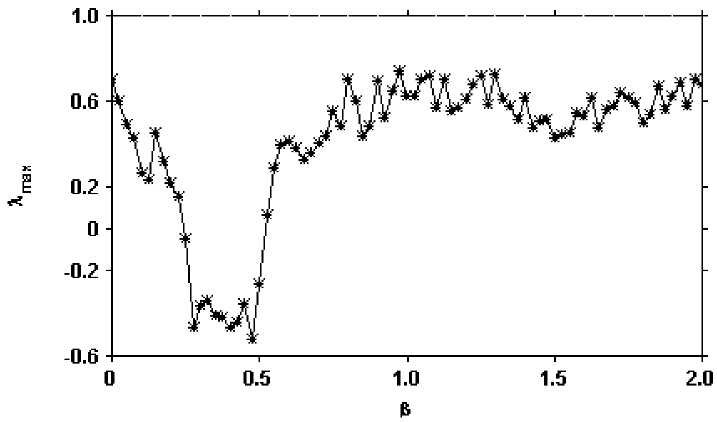

Figure 3: Maximum Lyapunov exponent for the studied system.

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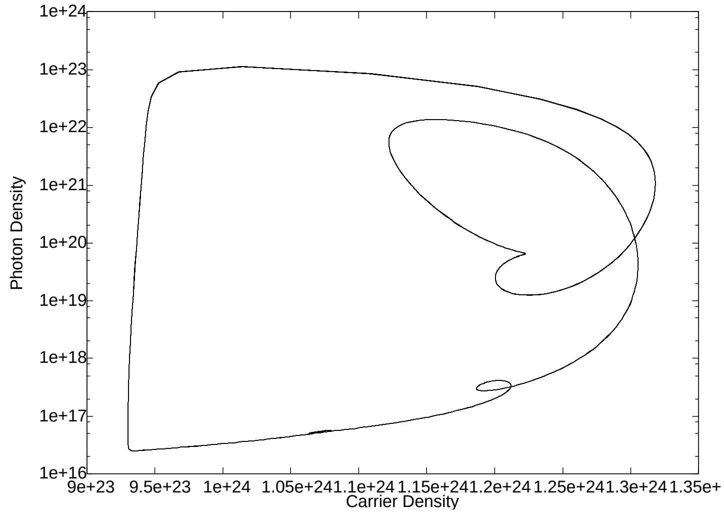

Figure 4: Stabilization of a periodic orbit for the laser diode with the given parameters.

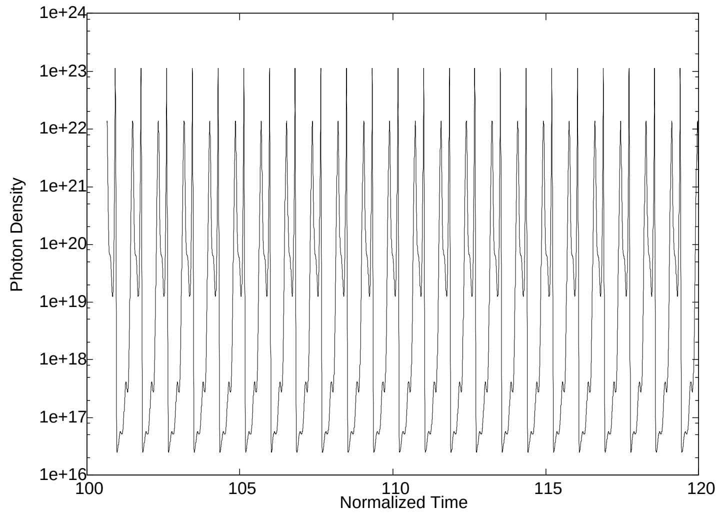

Figure 5: Photon density with chaos suppression.

investigated the control parameters values that allow the stabilization, measuring the largest Lyapunov exponent (λ_{max})[4]. The corresponding results are shown in Fig. 3.

In Fig. 3 a region with λ_{max} negative is observed and corresponds to good values (values for which chaos is suppressed) of Λ. Applying current with $\Lambda = 0.4$ results in a periodic orbit of frequency equals to $0.2 \times f$. The orbit stabilized in this manner is shown in Fig. 4, while Fig 5 shows the corresponding photon density as a function of time for this orbit. It can be seen from that figure that the laser nows exhibits a periodic and well behaved waveform for the emitted light, a fact that confirms the suppression of all chaotic behaviour. Morever, the suppression is achieved with an extra small modulation signal, compatible with an electronic control system.

By varying slightly the value of I_α or Λ it is possible to lead the system to a complete different periodic orbit. This issue can be used for coding information directly using the laser diode dynamics. Although it seems very interesting, there is an aspect that must be remarked: since we are using current modulation, frequency chirping is certainly present [5]. In this case, specifically, the chirp may cause difficulties because the modulation index related to chaotic motion is large and the broadened laser spectral bandwidth may became inadequate for optical communication.

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