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Phase and spectral properties of optically injected semiconductor lasers

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Abstract

The main control parameters of a single mode semiconductor laser submitted to an injected external signal are the power and the frequency of the injected signal. Following their magnitude, many phenomena can be observed such as phase locking, frequency locking, frequency generation, push-pull effects, hysteresis phenomena and chaos,... We show here that the spectral signature of the slave laser enables a better understanding of the the nonlinear interaction between the two competing sources: the spontaneous emission and the external field for which spectra are equally amplified through the active medium. This amplification is then strongly dependent on their coherency. We describe the role of the injected laser as a filter and an amplifier. It follows that the laser can be used to process information in ways that are not yet completely exploited. ***To cite this article: S. Blin et al., C. R. Physique 4 (2003).***

Résumé

Signature en phase et en fréquence d'un laser à semi-conducteurs soumis à une injection optique. Les principaux paramètres de contrôle d'un laser à semi-conducteurs soumis à une injection optique sont la fréquence et la puissance du signal injecté. Suivant leurs valeurs, divers comportements peuvent être observés : accrochage en phase, en fréquence, mélange multi-ondes, tirage en fréquence, hystérésis, chaos,... Nous montrons que la caractérisation spectrale du laser esclave (injecté) permet de mieux comprendre l'interaction non linéaire entre les deux sources en compétition : l'émission spontanée et le signal externe, dont les spectres sont amplifiés sans distinction par le milieu actif. Cette amplification est par conséquent fortement dépendante de la cohérence des sources. Nous décrivons le rôle du laser injecté comme celui d'un filtre et d'un amplificateur. Nous montrons alors que le laser peut-être utilisé pour traiter le signal d'entrée de manière pas encore totalement exploitée. ***Pour citer cet article : S. Blin et al., C. R. Physique 4 (2003).***

Keywords: Optical injection; Linewidth; Semiconductor laser; Spectral transfer; Frequency locking; Phase locking; Coherency

Mots-clés : Injection optique ; Largeur de raie ; Laser à semi-conducteurs ; Transfert spectral ; Accrochage de phase ; Accrochage de fréquence ; Cohérence

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1. Introduction

The synchronisation of coupled oscillators is known as frequency locking. A famous anecdote describes such an observation by Huygens. As he was ill, he noticed that his bedroom clock synchronised to another one placed just behind the wall in another room.

In laser physics, the subject of injected lasers has been introduced by Stover in 1966 [1]. A master laser is used as a source to feed a second one called the slave laser or the injected laser. Semiconductor lasers submitted to optical injection have been widely studied since the beginning of the 1980s [2]. Different phenomena have been classified following the control parameters which are essentially the injected power P and the detuning $\Delta\nu$ between the master and slave frequencies ν_m, ν_s [2–5]. When the frequencies of both lasers are close together (detuning of the order of 10 GHz) and when the injected power is high enough ($\sim$microwatt CW), the slave laser stops working on its eigenfrequency to lock onto that of the master. For other values of the detuning or/and of the injected power, we show that depending on the gain of the slave, this locking may be partial and even may be reduced to phase locking (we will give later the definition of this notion). However this is not the only phenomenon which can be observed in this type of experiment: harmonic generation, chaos, bistability and lineshape modifications occur in injected semiconductor lasers. For instance, optical bistabilities have been observed with Distributed FeedBack (DFB) lasers emitting at 850 nm [6].

This paper presents a synthetic description of the response of a semiconductor laser fed by an external source. The purpose is to describe the synchronisation and the birth of locking phenomena. A solitary laser feeds itself on spontaneous emission, i.e., on a random source. When a (slave) laser is injected by an external laser field which is a coherent source (master laser), it can find a phase reference which is more or less strong following the relative amplitudes of both sources. Its linewidth can thus be strongly modified by the injected field [7], whose spectral density is essentially Lorentzian and fixed by the master laser. This idea is experimentally and theoretically confirmed. For a general perception, we give maps of the different phenomena appearing in the plane $(P, \Delta\nu)$. We specially describe the role of the laser as a regenerator. We show that the injected laser can be seen as an amplifier of weak (femtowatt–nanowatt range) coherent incoming radiation or used to synchronise two chaotic oscillators. In the following we will first describe the experimental results and then we will give a brief description of the theory that we are developing to understand the spectral properties of a laser.

2. Experimental set-up

Fig. 1 displays a sketch of our experiment. The wavelength is at 1.55 µm and the lasers are of the type used in optical telecommunication: semiconductor DFB multiquantum-well lasers with a side-mode suppression ratio greater than 30 dB and Fabry–Perot lasers. The master laser is a commercially available, single mode tunable extended cavity semiconductor laser

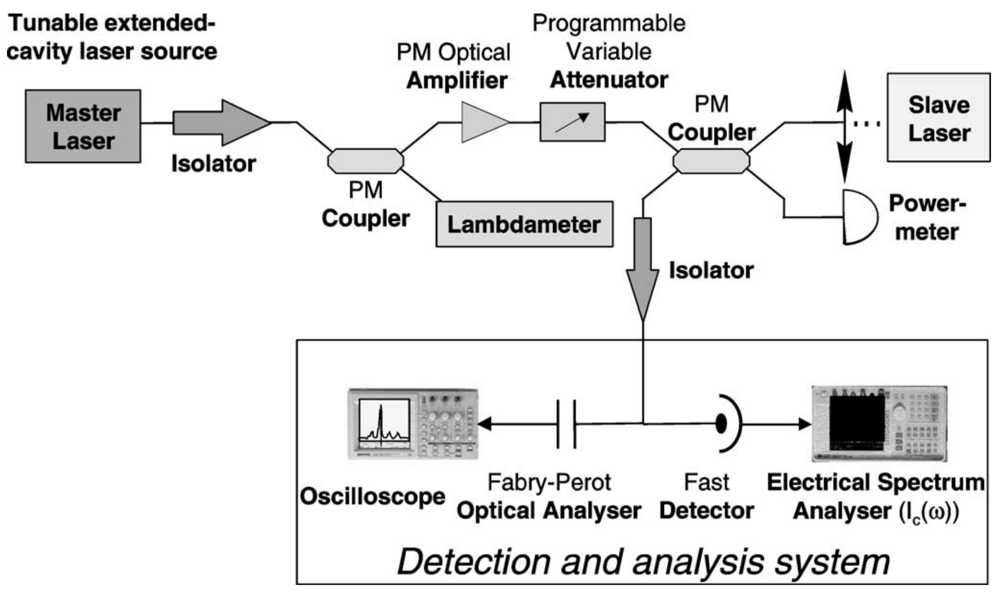

Fig. 1. Experimental set-up for the drawing of maps.

which delivers a power up to 3 mW, power which can be increased thanks to a polarisation-maintaining (PM) optical amplifier. The master may be a DFB laser if required. In that case, the master interface includes a high coefficient isolator (70 dB isolation) that ensures unidirectional coupling (injection) from the master to the slave. All components are fibred. Every angled polished fibre connection or component interface encountered on the way back to the master laser is designed for low return loss (-55 dB max.). The polarisation of the injected field has been controlled through the use of PM fibres in order to ensure a constant coupling. This mounting allows reproducible results and becomes very stable when it is properly isolated in an acoustic box.

The control parameters of interest in an injected laser experiment are the power of the injected field P_{inj} and the frequency difference, or the detuning $\Delta\nu = \nu_m - \nu_s$ between the slave (ν_s) and the master (ν_m) laser frequencies. The working point of the slave is considered here to be fixed. Experimental results are obtained either:

– by fixing the detuning and varying the injected power thanks to a programmable attenuator and a PM amplifier (+18 dBm);
– or by fixing the injected power and varying the detuning thanks to the tunable source with a precision of 1 picometre.

When the amplifier is used, we checked that it does not affect the master lineshape. The different devices of the equipment are managed by a computer which also records the data. In case of very weak injection (in the order of nanowatt, i.e., -60 dBm), the slave laser is placed far enough from a coupling lens to minimise optical feedback as shown for the slave 2 in Fig. 12. The signal can be applied on:

(1) an optical spectrum analyser (resolution bandwidth $RBW = 0.1$ nm $\equiv 12.5$ GHz@1550 nm);
(2) one of three Fabry–Perot (FP) interferometers (free spectral range $FSR = 300$ MHz, 10 GHz, 135 GHz, $Finesse = 100$);
(3) a fast detector (15 GHz bandwidth) which enables one to monitor temporal (0–5 GHz real-time, 0–15 GHz sampled) and microwave traces (0–15 GHz).

The slave and master lasers are placed into a box isolated from acoustical noise (30 dB isolation). We want to stress again, in conclusion of this section, the stability and reproducibility of this experiment thanks to the technology of optical telecommunication and especially to the use of PM fibres. Moreover the use of a PM amplifier enables to attain unprecedent optical injected power (5 dBm).

3. Experimental results

3.1. Slave laser operating close to threshold

We consider here a free slave laser operating at $1.2 I_{th}$ ($I_{th} \sim 10$ mA). Its output power is -7 dBm (200 µW). Fig. 2 shows different optical FP spectra of the injected slave when the detuning is decreased from positive values. The free slave frequency is set as the zero reference. Along with the detuning decrease, the injected photons are amplified at the expense of the spontaneous photons emitted inside the slave laser. The laser operates on two modes with very different linewidths Γ_S, Γ_M corresponding respectively to slave and master components. These lines have very different nature: one is arising from an internal spontaneous emission and the other one from a filtered external source. However the power spectral density at the slave frequency is very affected by this power transfer and progressively synchronises to the master line. The linewidth measured for the component at the free-slave frequency is decreasing to that of the master. We called this property phase-locking. Fig. 3 shows this progressive transfer which tends towards frequency locking, for which all the energy is concentrated into the master line. As a matter of fact, three regimes will characterise the injected laser:

- the seeded master light has no influence;
- the laser is bimode: both 'natural' and injected lines are amplified;
- a frequency locking occurs and the injected slave copies all properties of the master: it operates at the master frequency with the master linewidth (purity or impurity transfer).

Operation close to threshold enables to enhance the role of spontaneous emission with respect to stimulated emission. It masks the homogeneous interaction, which permits the simultaneous existence of two modes. Fig. 4 summarises the different behaviours. The locking area is not the same if the detuning is decreased or increased as indicated by the hatched area, called the bistability area. For low injected power (< -10 dBm) the locking zone is symmetric with respect to its centre which is not at the zero detuning. Contrary to what has been previously described when the detuning is decreased from the positive values (Fig. 2), an abrupt transition occurs on the left side of the locking (black) dips: at this left frontier, the system jumps suddenly from a

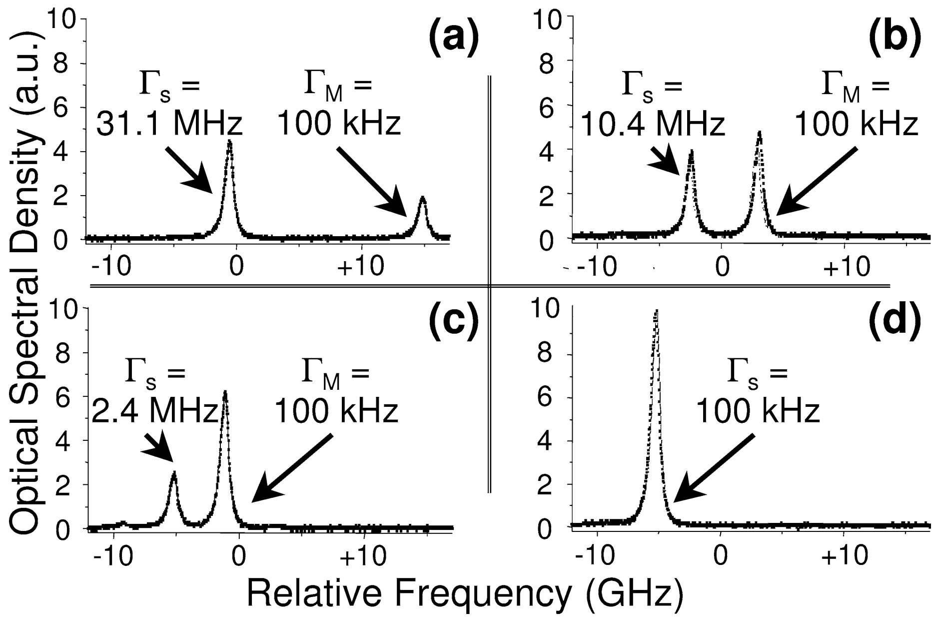

Fig. 2. Optical spectra of the injected slave laser at $I = 1.2I_{th}$. At a constant injected power (∼−20 dBm), the master frequency is decreased (one should read the figures from the top-left to the bottom-right): (a) $\Delta\nu = 15$ GHz; (b) $\Delta\nu = 3$ GHz; (c) $\Delta\nu = -1.4$ GHz; (d) $\Delta\nu = -5$ GHz. Along with this decrease, a progressive power transfer occurs from the slave line to a line at the master frequency while at the free-slave frequency the width shrinks to that of the master line (phase transfer).

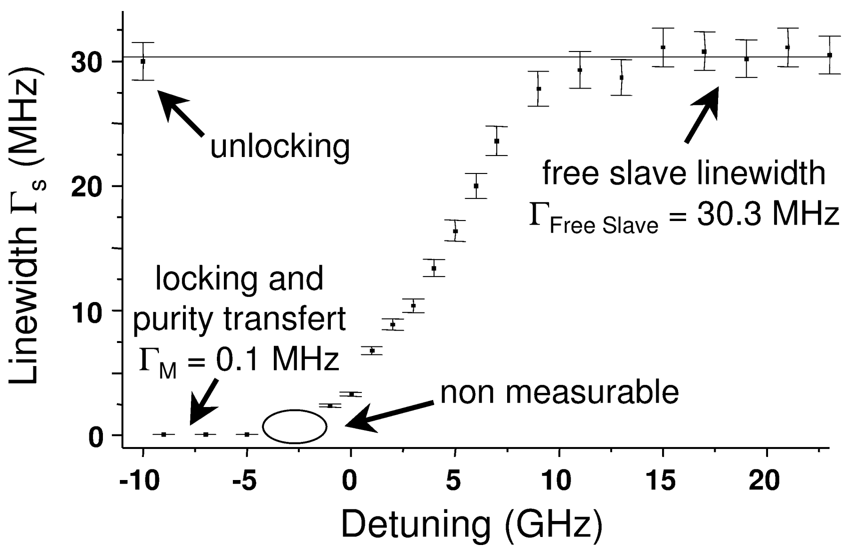

Fig. 3. Linewidth of the line at the slave frequency as a function of the detuning. Phase locking manifests itself by the progressive decreasing of the width of the line at the free-slave frequency when the detuning is decreased from the positive values. Here, the master line is around 0.1 MHz while that of the free slave is about 30 MHz. Note that the laser operating bias current is slightly above 1.2 times its threshold current.

locked state to a bimode behaviour (or the inverse depending on the sign of detuning variation). When the injected power is bigger than 3.33 dBm, the slave is always locked onto the master line: it is a permanent locking. In that case, frequency locking occurs whatever is the detuning. There are dips showing detuning for which less power is necessary to lock. They correspond to resonances of the Fabry–Perot cavity of the DFB laser as shown by the upper panel. The free spectral range of this cavity is about 150 GHz. Remark that the width of bistability areas decreases when the modes are located far from the lasing mode. The percentage gives the fraction of the total optical power inside the amplified master line: 100% correspond to frequency locking.

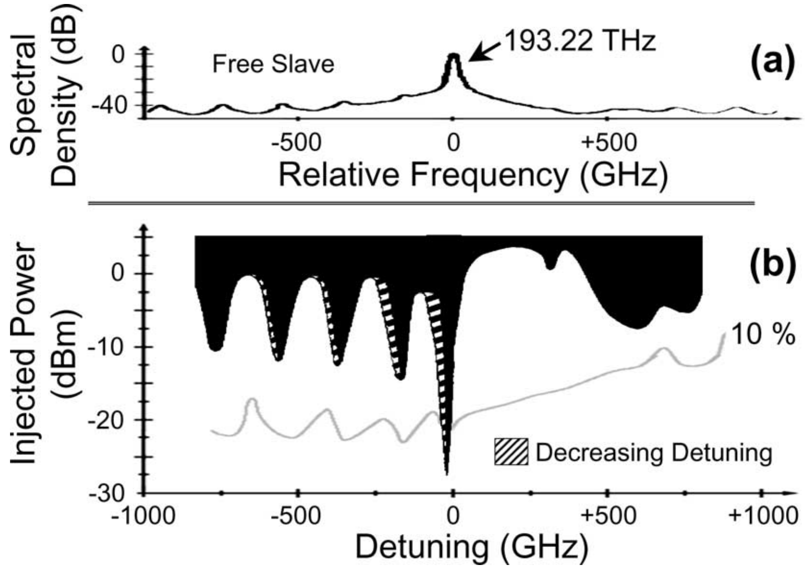

Fig. 4. Experimental map (b) showing the different regimes as a function of the detuning and the injected power expressed in dBm when the laser is operating close to threshold (the current of the slave was set at 1.2 times its threshold current). Frequency locking occurs in the black area region, bistability is in the hatched region: it represents a locking area for decreasing detuning only. The percentage (10%) indicates in the bimode regime the ratio between the power at the master frequency and the total one. The figure (a) is the optical spectrum of the free-slave DFB laser which enables to see the correspondence between the locking dips and the Fabry–Perot resonances of the free laser.

If we come back to the example of mechanical oscillators as for instance the synchronisation of two clocks and if we assume that we can tune the period of oscillation of the master pendulum, one would observe a quasiperiodic oscillation (characterised by a two-components spectrum with the two clock frequencies) before reaching the perfect synchronisation of the slave. This perfect locking will transfer the spectral properties of the master to the slave. Thus in the locking area, the slave will acquire the master linewidth. The slave linewidth can be either smaller (spectral purity transfer) or larger (spectral impurity transfer) than the free running slave's linewidth [8]. This effect is well known in the case of spectral purity transfer [9] and has been widely studied in the 1980s, in order to increase the coherence properties of semiconductor lasers for optical communications [10] or for use in spectroscopy or metrology applications. One could wonder whether locking will persist when the injected power is decreased for a zero detuning. As for the situation previously described, progressive phase-locking is observed along with a decrease of the injected power [8] as shown by Fig. 5. One should have less than 10 pW (-80 dBm) to neglect the influence of the external source. The perfect locking is reached for powers of the order of 100 nW (-40 dBm). The solid line gives the results obtained from the theory that will be described in the following. This last property showing the partial linewidth transfer for weak injection is true for most pump current points of the slave laser. The properties described in this paragraph and in the next one have been obtained with different lasers, which may have different parameter values. Note that Fig. 5 is obtained at four times the threshold current value. Unfortunately, at this pump level, properties are less simple: the bimode regime is no more present but other phenomena appear due to the nonlinear interaction. The next paragraph will describe this more complicated picture.

3.2. Slave laser operating far from threshold

Fig. 6 displays, at 4 times the threshold, a map similar to the one shown in Fig. 4 except that the injected power is varied between 5 and -50 dBm (or 3.2 and 10^{-5} mW) and the detuning from -85 to 30 GHz. The irregularity and lack of symmetry of this map are striking features for moderate and high injected power (> -20 dBm). The figure is obtained for a decrease of the detuning while the insert is given for an increase of the detuning. Regions are associated to the following different phenomena:

(1) Areas of frequency locking can be obtained for large detuning, especially for negative detunings, not only around the central zero detuning [11]. Recall that this phenomenon (see Fig. 2(d)) may be accompanied by a phase locking: when the detuning decreases from positive values, the linewidth of the slave Γ_S varies and adjusts itself to that of the master, $\Gamma_M = 100$ kHz (Fig. 2). The positive and negative detuning have very different signatures usually attributed to the phase-coupling parameter α_H of the semiconductor laser. This parameter has been introduced by Henry [12] and corresponds to

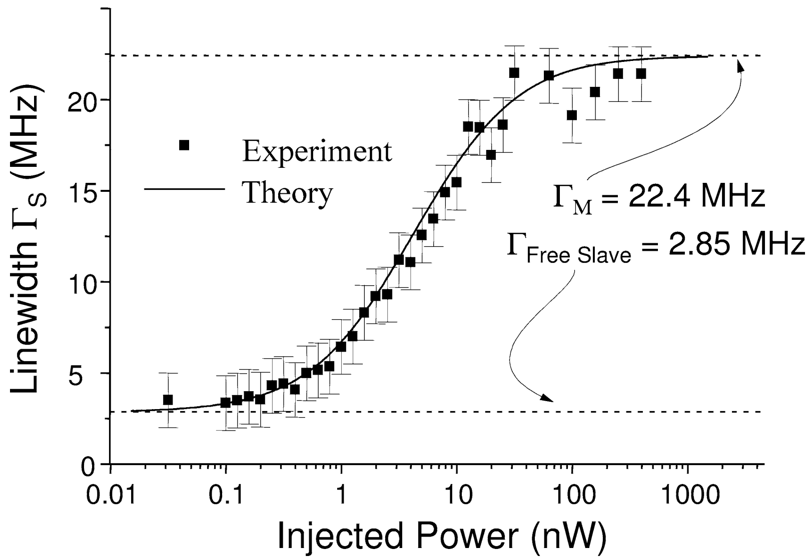

Fig. 5. Theoretical and experimental partial linewidth transfer at $I = 4I_{th}$ when the injected power is varied (the linewidth of the master laser is 22.4 MHz, and the one of the free-slave is 2.85 MHz). Experimental data points are noted by full squares.

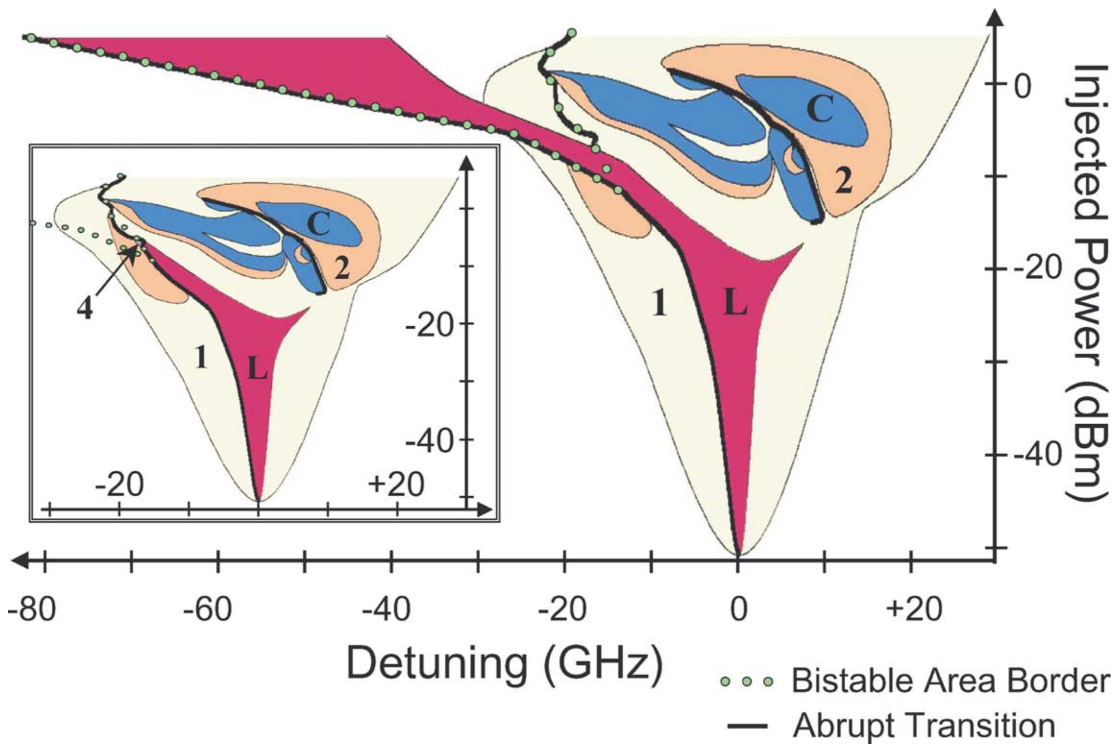

Fig. 6. Experimental map showing the regions where different phenomena can be observed when the current of the slave was set at 4 times its current threshold (its output power is equal to 5.2 dBm). The injected power varies between −50 and 5 dBm, the frequency detuning from 30 to −80 GHz. Frequency locking occurs in region **L**, frequency images in region noted **1**, period doubling in **2**, chaos in region **C**. Borders of the bistable area are represented by green dots. The insert shows the map when the detuning is increased, revealing huge bistability.

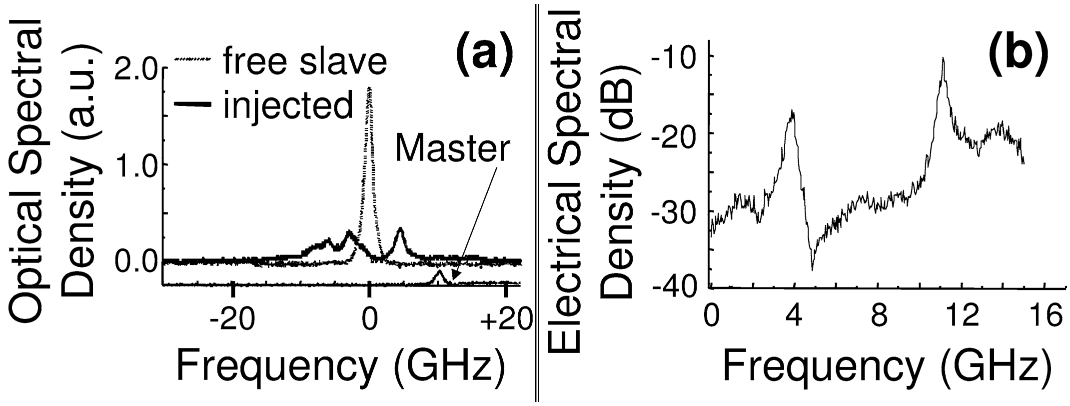

Fig. 7. Chaotic behaviour of the slave laser: generation of (a) wide optical and (b) electrical spectra.

a dissymmetry of the gain curve. It follows from the Kramers–Kronig relation that the zero dispersion is not located at the frequency of maximum gain. Above -20 dBm, for a positive detuning, the locking disappears and a hole (or plateau) of the locking area appears. It corresponds to an exaltation of the relaxation oscillation which can be used to measure α_H [13]. This process leads to multiwave mixing for which the two frequency components (master and slave) are amplified and interact. As a matter of fact, an external signal will lead to a continuous feeding of light in the band of the relaxation frequency which will tend to repeatedly destabilise the system. This simple point of view may be used to understand the birth of instability in injected systems.

(2) Before obtaining frequency locking, the wave mixing regime noted **1** generates, at the frequency $2\nu_s - \nu_m$, an 'image' of the amplified signal with respect to the frequency of the free-running slave. This 'image' is symmetric of ν_m with respect to ν_s (wave mixing). The Fabry–Perot spectrum reveals clearly this image, which shows three lines as well as the electronic spectrum shows the beating peak between the components.

(3) Period doubling can generally be observed in region noted **2**. It consists of a frequency generation located just in the middle of the lines seen in wave mixing. Period 4 can be observed too and in very particular situations period 3 may be seen [14]. Chaotic behaviour can occur in the region noted **C**. An illustration of this effect is given in Fig. 7 where a broad band could be assimilated to noise for both spectra. This map is different from the one given in [4] and obtained with lasers emitting at 850 nm where two chaotic regimes are located on the same detuning side of the injection locking region. Note that Wieczoreck et al. [15] have predicted that such regimes could appear for both positive and negative sides. As far as we know, this is the first time chaos is observed for positive detuning.

(4) Bistable domains can be observed in the vicinity of a border of a region when one of the control parameters P_{inj} or ν_m is increased and then decreased. Then a change in the laser behaviour does not occur for the same value of P_{inj} or ν_m. This hysteresis can be used to build optical memories [16]. In Fig. 6, the main drawing is given for a decreasing detuning while the insert reproduces the same map for an increasing detuning. The bistability only happens near an abrupt limit. In Fig. 6, this 'flip' regime is underlined by a bold black line, as opposed to the previously described smooth transition. An unprecedented huge bistable region is observed in Fig. 6 on the negative detuning side. This effect is surprisingly wide and has been revealed for the first time to our knowledge. The bistable area is delimited by the lines with green dots.

(5) Fig. 2 clearly shows that in the amplication process of both sources, the free-slave frequency is pushed. An increase in the injected power will also induce a pushing. This may be surprising as it is well known that optical injection leads theoretically to frequency pulling [17] by using Adler's model. However this pulling can be clearly observed for the first time at low injected power as shown in Fig. 8. The pulling and pushing effects differ by the fact that pulling is observed for an unsaturated line while the pushing is observed along with the saturation of the laser line.

(6) We have drawn the same type of map when the polarisation of the injected field is orthogonal to the slave one. However, this description is beyond the scope of this paper.

4. A generalised transfer function for the laser

Observations of the properties of light may concern the temporal dynamics in the *time domain* (chaos or mode competition) [11], the static properties in the *frequency domain* (mode spectrum, various resonances with their spectral position and linewidths). These last properties have to be linked to the statistical properties. The usual analysis gives the stability diagram [18] in terms of nonlinear analysis (linear stability analysis, Lyapunov exponents,...). In Fig. 8, it is clear that the master line

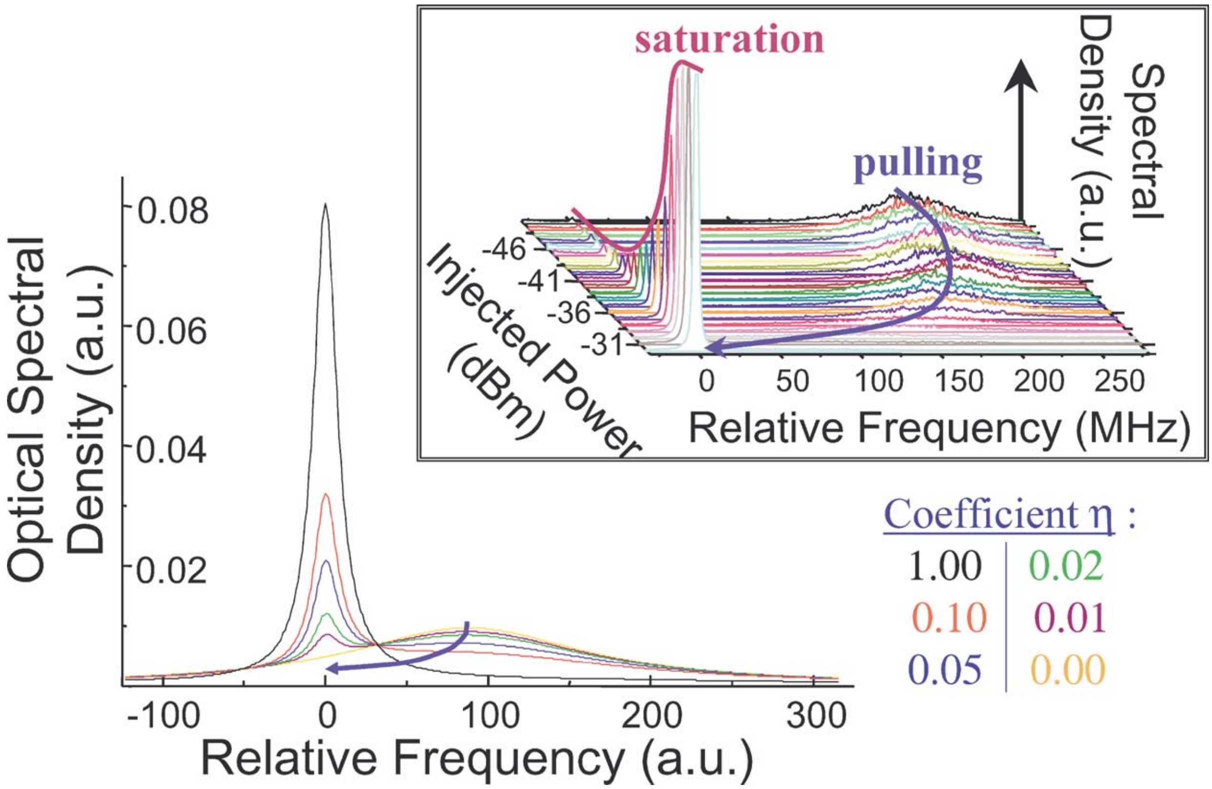

Fig. 8. Fabry–Perot Spectra obtained from theory showing the selective amplification of a coherent master line for weak injected powers (<μW) of a detuned optical injection. Frequency pulling is observed. The insert shows experimental Fabry–Perot spectra. The complete locking of the slave is defined by the saturation of the laser line. When the saturation is reached, a pushing effect takes place instead of pulling.

is amplified at the expense of the slave one which is contaminated by a phase locking (phase diffusion) and pulling. The laser receiver behaves like an amplifier and a filter. This point of view leads us to develop a transfer function applied to the laser. The traditional theory [19] which describes the linewidth is based on the Shawlow–Townes [20] formula with later refinements [21,22]. Spano et al. [23] gave an analysis of injected lasers which took into account the spontaneous emission of the master and of the slave.

Our description is based on the application of Maxwell equations together with boundary conditions on the mirrors. One easily obtains the optical Airy function which usually describes a passive Fabry–Perot interferometer. One can follow the same procedure when an internal (active) medium is included [24,8,25]. A source term is necessary to excite the laser: it originates essentially from the vacuum fluctuations which initiate the amplified spontaneous emission (ASE). From the beginning, the calculations are performed in the pure frequency domain. The laser field is considered to be the response of the system to the source provided by the amplified spontaneous emission. This method is well suited to study lasers in the permanent regime because it includes the different spectra from the beginning. The theory can be extended to injected lasers [7,25,26] or to lasers with optical feedback.

The power spectral density y_S of the slave laser is written:

$$y_S(x) = \frac{\eta y_M(x) + S_S}{\mathrm{e}^{-L+g_0/(1+Y_S)}} \frac{1}{\Gamma_S^2 + (x - x_S)^2}. \tag{1}$$

In this equation, x is the frequency normalised by the energy round-trip time ($\tau_c = 2n_g L/c$). x_S is the normalised frequency at the laser resonance. The term in the numerator is the source and the fraction is the response function. S_S represents the spectral density of the amplified spontaneous emission. S_S can be taken constant in the emission band of the laser, which can be considered narrow in comparison to the spontaneous emission (gain) band (∼4 THz). In the denominator, e^{-L} represents the losses, $\mathrm{e}^{g_0/(1+Y_S)}$ represents the gain saturated by the total intensity $Y_S = \int y_S(x)\,\mathrm{d}x/2\pi$. The source term ηy_M is the

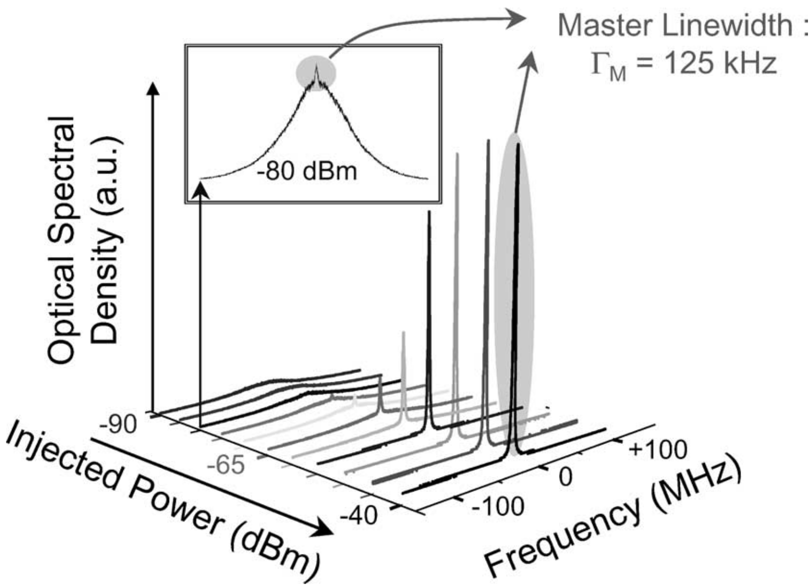

Fig. 9. Experimental Fabry–Perot Spectra obtained at zero detuning when the injected power is increased at $I = 4I_{th}$ for a master laser, which is more coherent.

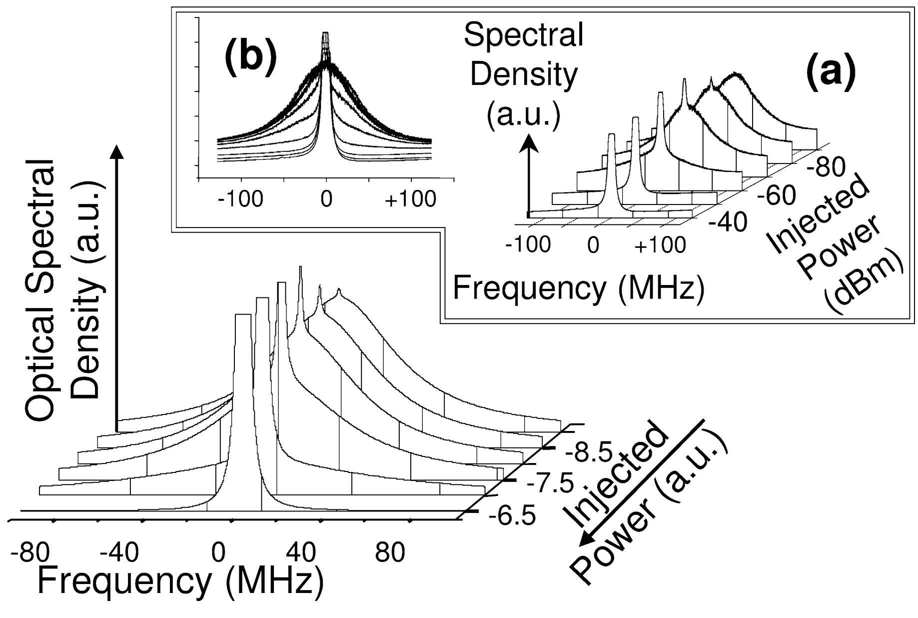

Fig. 10. Theoretical spectra at $I = 4I_{th}$ corresponding to the case of a master laser (Fig. 9), which is more coherent. Corresponding experimental traces (a) are given in the insert, (b) shows the same traces which are superimposed.

contribution of the injected signal and is taken as a Lorentzian distribution characterised by a Half Width at Half Maximum (HWHM) Γ_M (given by an explicit expression which includes losses, gain and the total intensity Y_M [7,8]). It is written:

$$y_M(x) = \frac{2\Gamma_M}{\Gamma_M^2 + (x - x_M)^2}. \tag{2}$$

The normalisation is such that $\int y_M(x)\,\mathrm{d}x/2\pi = 1$, which means that η is a measure of the injected power.

Eq. (1) is more complex than it could appear because the spectral density is dependent on its integral. Thus, integration of y_S over x gives a transcendental equation for the total intensity Y_S, which can be solved numerically. The spectrum is then

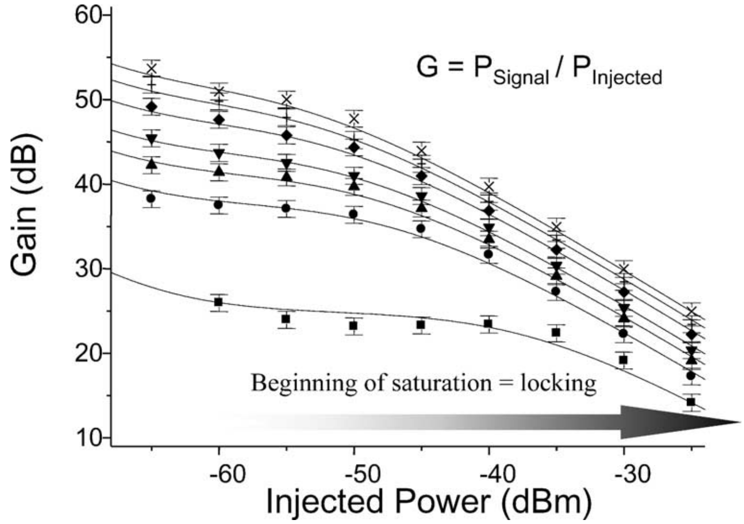

Fig. 11. Gain associated to the stimulated amplification process as a function of injected power. It is given for different values of normalised injection current $r = I/I_{th}$. ■ $r = 1.1$, $P_{\text{slave}} = -10.85$ dBm, • $r = 1.2$, $P_{\text{slave}} = -7.74$ dBm, ▲ $r = 1.3$, $P_{\text{slave}} = -5.89$ dBm, ▼ $r = 1.4$, $P_{\text{slave}} = -4.62$ dBm, ♦ $r = 1.6$, $P_{\text{slave}} = -2.76$ dBm, $+$ $r = 1.8$, $P_{\text{slave}} = -1.56$ dBm, $\times$ $r = 2$, $P_{\text{slave}} = 0$ dBm or 1 mW. Points are experimental data and solid lines are simulated gain using the generalised transfer function applied to the laser. The saturation is reached at the birth of the straight line (linear slope) and depends on the bias current.

easily calculated from Eq. (1) when the saturating intensity is known. An example of such a calculation is given in Fig. 5 for increasing weak power of injected signals. It shows a very good agreement with experiment. Another example, given in Fig. 8 at nonzero detuning, clearly shows the selective amplification and the pulling effect for weak injected powers

A complementary case to the one presented in Fig. 5 is when the master is more coherent than the slave. At weak injected powers, a selective amplification [27] of the master line, as indicated in the insert of Fig. 9, looks like what is encountered in amplifiers. When the injected power is increased, a progressive migration of energy from the master laser band to the signal band is clearly observed. In semiconductor-optical or Erbium-doped-fibre amplifiers, the gain bandwidth is a few tens of nanometres [28] while here the bandwidth at 3 dB is around the linewidth of the free-slave laser. This narrow amplification-bandwidth is the result of the laser-cavity filtering and is the price to pay for amplification of weak signal by lasers operating *above threshold*. Theoretical spectra reproduce this amplification within the laser line as it can be observed in Fig. 10. Note that these results are different from those of reference [29] where amplifiers (and not a laser running above threshold) were used to amplify 100 mW. In such amplifiers, the gain which can be reached is of the order of 30 dB while in our particular case the gain is 20 dB bigger, or about 50 dB for input signals with optical power in the range pW–100 nW. Thus if the bandwidth is small, the gain is bigger due to the cavity effect. Fig. 11 gives the theoretical and experimental gain for different bias currents. Note that this amplification is possible only before the saturation process, or in other words, when the power of the external signal is less than ~ -30 dBm. In the converse case, all the energy of the free-slave line is transferred to the master line and one can define the locking as the birth of a saturated regime. Below this regime, we show for what we believe the first time that it is possible to use a laser *above threshold* as an amplifier. The gain presented in Fig. 11 can be considered as a direct measurement of the amplification process of the stimulated emission in semiconductor lasers.

5. Seeding of chaotic spectra: synchronisation of chaos

The first chaotic synchronisation with two semiconductor lasers was realised by feeding a laser with the help of another one which was coupled to an external cavity [30]. The master laser field $E_M(t)$ interacts with its feedback image $E_M(t-\tau)$. The master output is then injected in the slave cavity and the slave field $E_S(t)$ interacts with the field $E_M(t)$. If the two lasers are identical, one directly checks that the systems are equivalent if $E_S(t) = E_M(t+\tau)$. In other words the injected laser completely synchronises with anticipation (with a time lag corresponding to the round-trip time in the external cavity). Experimental observation of anticipation has been recently observed [31]. The general idea is to inject light into a second laser with the same strength as the one used for optical feedback, in order to duplicate the first system. As the chaos is generated through optical feedback, many external cavity modes are excited and the dynamics is defined as high dimensional chaos. Mathematically, the optical field has to be initiated on a whole interval of time, so that delayed systems behave like multi-variables ones. Similar

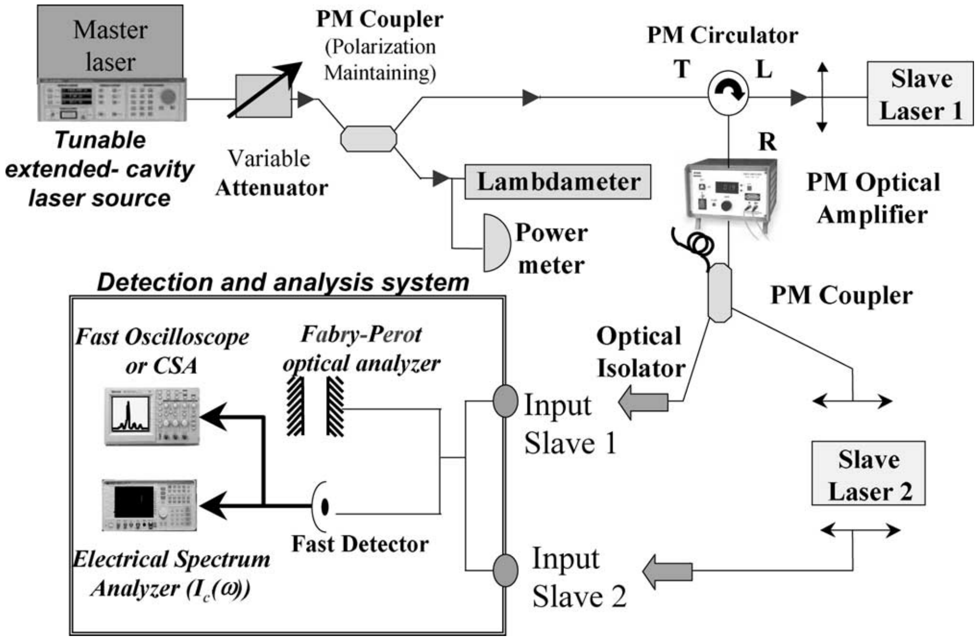

Fig. 12. Experimental set-up for chaos synchronisation.

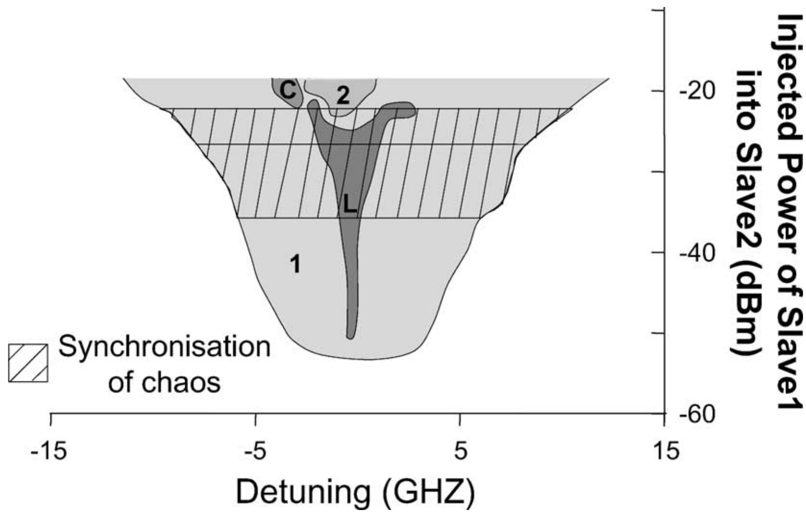

Fig. 13. Map of the slave 2. The synchronisation area of slave 2 is in hatched lines when it is seeded by a chaotic signal from slave 1. The chaos is generated by optical injection and not by optical feedback as usually done. The lower horizontal line is the limit of complete synchronisation (the precision is 1 dB). Below the middle horizontal line, the synchronisation is incomplete. The upper horizontal line gives the maximum optical power that can be injected in the slave laser 2.

experiments have been realised with fibre lasers [32]. However, more generalised chaos synchronisation can be accomplished [30] through optical injection and delayed feedback, which means that it is possible to reach synchronisation for a broad range of parameters such as injected-power level. All these experiments describe high dimensional chaos brought by a delayed system.

Here we propose a new scheme where a low dimensional chaos is produced by optical injection. A master laser feeds, through a PM circulator, a first laser (slave 1) as shown in Fig. 12. The injected power and the detuning are fixed in order to obtain chaos. Then the output of the first slave is used to feed another laser (slave 2). The aim is to analyse what are the conditions for synchronising two lasers. This scheme has many advantages:

- We can fix the operating point of the slave 1 by injecting a constant power P_1 into slave 1 with a constant detuning $\Delta\nu_1$ between the master and slave 1 frequencies. Then we vary the operating point of slave 2 by scanning the injected power P_2 into slave 2 and the detuning $\Delta\nu_2$ between the frequencies of slaves 1 and 2. It is equivalent to scanning the map injected power-detuning of the master-slave 2.
- On the other hand, we can fix the operating point of slave 2 (P_2 and $\Delta\nu_2$) and vary the operating point of slave 1 (P_1 and $\Delta\nu_1$).

This scheme enables us to make a rigourous study because we can control the main parameters of the three lasers. In an example given in Fig. 13, we give the mapping of the slave 2 for a normalised bias current of 1.5 (the mapping is different from Figs. 6, 4). We have studied the first situation for which the operating point of slave 1 is fixed and the operating point of slave 2 is varied. In Fig. 13, the dashed lines indicate where the synchronisation is effective, for different operating points of the map of the slave 2. The upper horizontal line is the maximum optical power that can be injected in slave 2. Below the middle horizontal line, the synchronisation is incomplete and not fully correlated. Under the bottom line, there is no chaos. These first results clearly show that synchronisation area exactly correspond to wave mixing zone of slave 2. These first results have encouraged us to improve the characterisation of chaos synchronisation. Complete results will be presented elsewhere. In particular, we have shown the necessity of a right spectral signature in order to get synchronisation.

6. Conclusion

We have shown that the spectral properties of the injected slave can help to describe the process of optical injection. Many phenomena such as huge bistability, wave-mixing, chaos, frequency pushing/pulling can be observed and described in the frequency domain. We have shown for what we believed the first time that a laser operating above threshold may be used as an amplifier of weak signals. This property enables us to detect at room temperature a continuous-wave signal as weak as the femtowatt [27] using heterodyne technique. We hope to lower this limit in the future. This detection of weak signal may bring new prospects in the understanding of tomography. This approach gives us the idea to realise chaos synchronisation without optical feedback as usually done. The proposed scheme of synchronisation promises its full characterisation.

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