Noise effects in injection locked laser simulation: Phase jumps and associated spectral components

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Indexing terms: Semiconductor junction lasers, Laser noise

Some clarifying simulation results concerning the effect of noise on injection locking are presented and analysed. A new spectral component near the eigenfrequency, associated with discrete phase jumps, is observed on the injected laser spectrum. This phenomenon, not appreciable if the noise is not taken into account, has also been observed in recent experimental works, with very similar reported results.

Introduction: When light from an external source is injected into a laser oscillating above threshold, the injected radiation competes with the spontaneous emission of the laser for being amplified. If the optical frequency of the injected light is close to the eigenfrequency of the unperturbed laser, the laser will adjust its frequency and coherence properties to those of the injected light. This phenomenon is known as 'injection locking' [1].

In recent years, considerable attention has been paid to injection locking in semiconductor lasers, owing to the great variety of its applications in long range, high speed optical communication systems and coherent transmission systems. Among the most interesting applications are: the suppression of mode partition noise; linewidth reduction of the free-running slave laser; direct optical frequency conversion by four wave mixing (FWM); and generation and amplification of optical FM and PM signals. In all these applications, the noise properties of the locked lasers are of vital importance. Particularly, in those applications that make use of the locking condition, such as FSK and PSK modulation, their operation bandwidths are limited by the time it takes to lock; this significantly depends on noise. Even in 'steady-state' applications, the relative phase between both lasers fluctuates owing to the spontaneous emission noise, and so there is a certain probability at which the locked lasers will momentarily unlock [2].

In this Letter we present and analyse some clarifying simulation results concerning determinate aspects related to the effect of noise on injection locking. Specifically, we have analysed its effect on the spectrum in the locking condition, as well as on the relative phase between both laser signals. To this end, a new semiconductor injection locked laser modelling technique that includes this important effect of noise, both from the injected laser and from the external source, has been implemented. This modelling technique is based on a description of the coherent rate equations in terms of a functional block diagram that can be analysed using a suitable computer simulation program.

Rate equations for the injected laser in the presence of noise: In a semiclassical analysis of the laser, the noise caused by spontaneous emission and carrier generation and recombination is included in the rate equations by adding appropriate Langevin driving terms. External light injection is added to these equations and, afterwards, the slowly varying amplitudes approximation is applied. Also, in order to enter them into a computer simulation program, the noise sources are discretised, giving the following set of modified equations [3]:

$$\frac{dS(t)}{dt} = \left[g(n) - \frac{1}{\tau_p}\right] S(t) + R + 2k_c\sqrt{S(t)}E_{inj}(t)\cos(\phi_{ML}(t) - \phi_0(t)) + \sqrt{\frac{2S(t_i)R}{\Delta t}}\, x_e \quad (1)$$

$$\frac{d\phi_0(t)}{dt} = \frac{1}{2}\alpha\frac{dg}{dn}(n - n_{th}) - (\omega_{ML} - \omega_N(n_{th})) + k_c\frac{E_{inj}(t)}{\sqrt{S}(t)} sen(\phi_{ML}(t) - \phi_0(t)) + \frac{1}{S(t)}\sqrt{\frac{S(t_i)}{2\Delta t}}R x_\phi \quad (2)$$

$$\frac{dn}{dt} = \frac{I}{e} - \frac{n}{\tau_s} - g(n)S(t) - \sqrt{\frac{2S(t_i)R}{\Delta t}}x_e + \sqrt{\frac{2n(t_i)}{\tau_s\Delta t}}\, x_n \quad (3)$$

where S denotes the number of photons within the slave laser cavity and E_{inj} is the normalised electric field corresponding to the externally injected photons, with k_c the coupling coefficient. $\omega_N(n)$ and $g(n)$ are the angular resonance frequency and the medium gain, respectively, both depending on the carrier number n. $\Phi_0(t)$ and $\Phi_{ML}(t)$ are the phases of the slave and master laser fields, respectively. R is the spontaneous emission rate, x_e, x_Φ and x_n represent Gaussian random variables with zero mean and unity variance, and Δt is the time slot used in the numerical integration method.

Model description: The laser model implementation, also presented here, is based on a description of the set of equations above in terms of a signal flow graph. So the equivalent block diagram can be directly analysed with the computer program SIMULINK, an extension of MATLAB for Windows that provides a set of specific tools for dynamic system simulation. This program offers a wide variety of functional blocks (integrators, function and subsystem definition, generation of random number sequences) that can be joined in a proper manner to define the dynamic behaviour of the laser. These facilities, as well as the immediacy in obtaining the results, make this model very user friendly.

The model allows the simulation of the effect of noise, both from the slave and from the master laser. To obtain the time domain behaviour of the latter, first the injected field term must be set to zero in the general model, and then the obtained results are used as an input in the slave laser simulation.

Analysis of results: The semiconductor laser chosen for the simulation was the Hitachi HLP1400. As this laser is often referenced, we disposed not only of the values of its parameters but also of detailed measurements of its characteristics (threshold current, optical power, spectrum with and without light injection). This has made it possible to make interesting comparisons which prove the validity of the results presented.

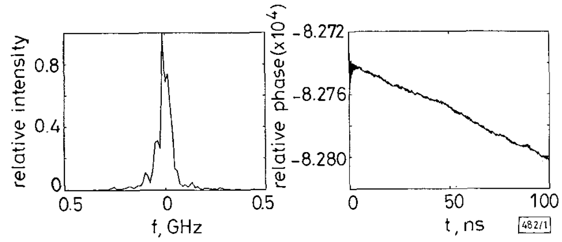

Fig. 1 *Obtained spectrum and relative phase for a detuning of Δf = 100 MHz without injection*

Fig. 1 shows the optical spectrum of the unperturbed laser, operating at a current of 65mA (zero in the frequency axis corresponds to the eigenfrequency of the unperturbed laser). The remaining figures correspond to the optical spectrum of the laser upon injection for the same value of current. The level of injection is –50dB, and the detuning Δf has been taken within the theoretical locking range ($|\Delta f| < \Delta f_L \simeq 350$MHz) but has been increased progressively from figure to figure. With $|\Delta f| \ll \Delta f_L$ (Fig. 2) the laser oscillates at the injected signal frequency and almost copies its coherence properties. As far as $|\Delta f|$ approaches $|\Delta f_L|$ (Fig. 3) a new spectral component close to the eigenfrequency of the laser, but sligthly shifted towards the injected frequency, appears and becomes more important. This phenomenon, not appreciable if the noise is not taken into account, has been observed in recent experimental works, with very similar reported results [4].

Another interesting difference between the analysis of injection locking in the presence of noise and the deterministic analysis, is its relationship to the definition of the locking range. In the deterministic analysis, it is shown that the lasers lock together if $|\Delta f/\Delta f_L| \leq 1$. In this case, the lasers remain locked as long as the above condition is maintained and the difference beetween their phases is held constant. However, the relative phase between the lasers fluctuates owing to the spontaneous emission noise and so there is a certain probability at which the locked lasers will momentarily unlock.

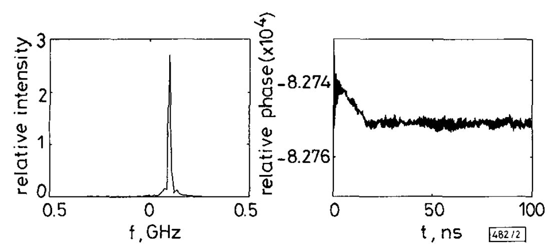

Fig. 2 *Obtained spectrum and relative phase for a detuning of Δf = 100MHz upon injection*

This fact has been made clear in several simulations. Fig. 1 shows the time domain behaviour of the phase difference between the master laser and the slave for a detuning of 100MHz without injection. When the slave laser is injected (t = 15ns), it adjusts its frequency to that of the master, and their relative phase becomes almost constant (Fig. 2). However, for a detuning closer to Δf_L (Δf = 200MHz, Fig. 3) this condition is no longer true and the phase jumps 2π. Moreover, the larger the value of Δf, the higher the number of jumps.

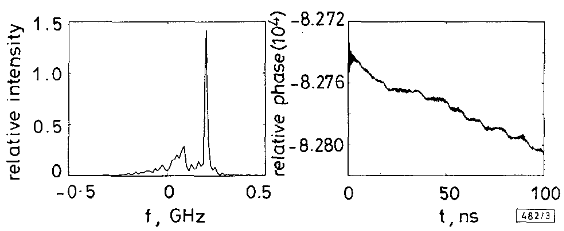

Fig. 3 *Obtained spectrum and relative phase for a detuning of Δf = 200 MHz upon injection*

This phenomenon, observed recently by other researchers [2], leads to the need to 'redefine' the locking range conditions as those for which the relative phase is held almost constant for a fixed mean time. Furthermore, there appears to be a correlation between the number of phase jumps and the amount of spectral components near the laser free-running frequency.

Conclusions: Using a specially developed model of an injected laser, including the noise, firstly it has been possible to illustrate and analyse an additional component in the laser spectrum, close to the eigenfrequency, which appears when the detuning Δf approaches the locking range Δf_L. Secondly, discrete jumps in the relative phase have been observed, even with $|\Delta f| < |\Delta f_L|$, which can be interpreted as momentary lock losses owing to the spontaneous emission effect. Moreover, both phenomena referred to clearly seem to be correlated. This is now being investigated at depth, in order to quantify the correlation. Finally, the obtained results are in good agreement with recently published experimental works, clearly supporting the validity of this study.

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Uniformly beam expanded 1.3µm laser diodes with thin separate confinement heterostructure layers for high coupling efficiency and good temperature characteristic

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Low-loss-fibre-coupling 1.3µm laser diodes with excellent temperature characteristics were fabricated by employing thin (20nm) separate confinement heterostructure layers. Fabricated LDs with an active layer width of 1.5µm show singlemode-fibre coupling loss of 2.6dB, threshold current I_{th} of 16.4 (51.0) mA and high efficiency of 0.5 (0.3) W/A at 25 (85) °C, respectively.

Introduction: One of the most important requirements for the implementation of fibre-in-the-loop and fibre-to-the-home is the availability of low-cost semiconductor laser diodes (LDs). LDs with low-loss fibre coupling without using a lens and with excellent temperature characteristics are required to reduce the cost of alignment and eliminate the need for a temperature controller.

To meet the above requirements, it is essential to enlarge the spotsize of the light without sacrificing temperature characteristics too much. From the viewpoint of fabrication, uniformly beam expanded LDs in which the optical confinement factor Γ is reduced by decreasing the index difference between the core and cladding with a multilayer structure [1] or by reducing the cross-section of the core region which consist of multiquantum-well (MQW) active layers and separate confinement structure (SCH) layers [2] are very attractive. This is because no additional fabrication processes are required. In a previous paper [2], we showed that low-loss-fibre-coupling LDs could be built by narrowing the core region composed of conventional layer thicknesses and adopting a larger bandgap material for MQW barriers and SCH layers. The latter simultaneously improves the temperature characteristics owing to increased carrier confinement. However, this requires the formation of a somewhat fine stripe pattern (a width of <1µm while keeping fluctuations small). On the other hand, Γ can also be reduced by thinning the core region without using fine-stripe-pattern technology.

In this Letter we propose low-cost and low-loss-fibre-coupling LDs in which the spot size inside the whole laser cavity is expanded by simply thinning the SCH layers while using the conventional active layer width (W) of 1.5µm. At the same time, this approach is thought to be very effective to provide much better temperature characteristics than our previous approach of narrowing W.

It has been reported that maximum operating temperature increases with increasing well number [3], or in other words, as the volume of the gain region is increased. Since Γ is reduced by thinning the SCH layers while maintaining an active layer width as wide as 1.5µm and thick 7-well MQW layers in the present approach, the volume of the MQW (gain) region is large compared with that of narrow-W-type LDs. In addition, the main reason for the degradation of current 1.3µm LDs at high temperature is considered to be owing to the recombination of carriers that spill over from the MQW region into the SCH layers [4]. Therefore, we expected that using thin SCH layers would reduce the amount of recombination current in the SCH region, because the volume of SCH layers is small.

The fabricated LDs have a fibre-coupling loss of 2.6dB even at a W of 1.5µm, and excellent temperature characteristics.

Design of large spot-size LDs: The laser spot-size enlargement was achieved by reducing Γ by means of thinning the SCH layers. The core region consists of an MQW active layer with 5.4nm-thick wells of 1.2% compressively strained InGaAsP and 10nm-thick 1.10µm InGaAsP barriers surrounded by 1.09µm-InGaAsP SCH layers. We employed seven wells because a sufficient well number is important in obtaining high temperature operation [3].