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.


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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, detailed measurements of its characteristics (threshold current, optical power, spectrum with and without light injection) have been performed.

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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 $\Delta f$ has been taken within the theoretical locking range ($|\Delta f| < \Delta f_L = 350MHz$) 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 $|\Delta f| = \Delta f_L$ (Fig. 3) a new spectral component close to the eigenfrequency of the laser, but slightly 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 between 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.
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 100 MHz without injection. When the slave laser is injected (τ = 15 ns), 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 (Δf = 200 MHz, 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.

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 ΔAf. Secondly, discrete jumps in the relative phase have been observed, even with |Δf| < |ΔAf|, 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 components near the laser free-running frequency.

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 <1 μm 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 keeping the conventional active layer width (W) of 1.5 μm. At the same time, this approach is thought to be very effective to provide much better temperature characteristics than our previous approach of narrow-W LDs in which the optical confinement factor is expanded by simply thinning the SCH layers while using the conventional active layer width (W) of 1.5 μm. 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 <1 μm while keeping fluctuations small). On the other hand, Γ can also be reduced by thinning the core region without using fine-stripe-pattern technology.

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