Modulation Properties of an Injection-Locked Semiconductor Laser

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***Abstract*—The modulation properties of an injection-locked semiconductor laser are investigated using the rate equation formalism. Intensity and phase modulations (IM and PM) are analyzed throughout the locking range where the locked laser is stable. The relaxation oscillation resonance in the IM and PM frequency responses can be dramatically reduced by tuning the injected power and the frequency difference between the master laser and the free-running slave laser. The power spectra under direct modulation are derived throughout the stable locking range. The spreading of the harmonics of the modulated locked laser is strongly affected by the frequency detuning, the injected power, and the injected current modulation. Measurements illustrating the theoretical results are also presented.**

I. Introduction

Several methods for modulating the phase or the frequency (PM or FM) of the output lightwave of a semiconductor laser have been reported [1], [2]. The direct phase modulation of an injection-locked semiconductor laser appears particularly promising for communication systems. The dependance of both the gain and the refractive index on the carrier density results in a combined intensity and frequency modulation of the laser output wave under direct current modulation. The change in the instantaneous frequency of the light emitted by a modulated semiconductor laser is referred to as the frequency chirping [3], [4]. With a direct detection system, the frequency chirping results in dispersion penalties for high bit-rate long distance systems. In heterodyne systems using amplitude modulation, the spurious frequency modulation requires an increase of the amplification bandwidth at the intermediate frequency, thus reducing the signal to noise ratio of the receiver [5]. In addition, spurious intensity modulation in a frequency shift keying (FSK) system gives rise to demodulation errors [6].

Injection locking is a technique using two semiconductor lasers. A fraction of the light of the first laser, the master, is launched into the second laser, the slave. The locking occurs within a certain frequency locking range defined by the injection level and the amplitude-phase coupling coefficient [7]–[9]. The amplitude-phase coupling is typical of semiconductor lasers. It is responsible for the asymmetry of the locking range, the existence of instabilities in the locking range, and the simultaneous modulation of the amplitude and phase of the optical carrier when the laser current is modulated. The injection-locking technique results in several advantages, such as the reduction in the frequency chirping [10]–[12], the linewidth reduction of the free-running slave laser [13], [14], and the suppression of partition noise [15] and mode hopping. Injection locking has also been used to perform a conversion from frequency to phase modulation [16], to study an optical phase locked loop [17], [18] and an optical FSK modulator [19], to design a multifrequency laser transmitter [20], or to investigate the injected laser in a way free from electrical bandwidth consideration [21].

The aim of this paper is to present an investigation of the modulation properties of an injection-locked semiconductor laser. In Section II, the formalism for the evaluation of the phase and intensity responses to a current excitation is developed. The approach uses the rate equations. The formalism for the derivation of the locked laser power spectrum is developed in this section also. In Section III, the modulation responses to a sinusoidal current modulation are derived. Our approach complements the previous analysis of Kobayashi and Kimura [16] by including amplitude-phase coupling, relaxation effects, and the stability considerations. Then, power spectra are evaluated in the stable locking range for various types of modulation current waveforms. Finally, the measurement system is presented, the experimental results are reported and compared to theory.

II. Theory

A. Modulation Frequency Responses

Two semiconductor laser diodes are required in order to perform an injection-locking system. One laser diode, the master laser, injects its light into the other laser diode, the slave laser. An optical isolator prevents the reverse light coupling. In the present analysis, emphasis is put on the intrinsic laser behavior through the study of its active layer and its cavity. The package parasitics, consisting generally of a bond wire inductance and a small capacitance between the input terminals and the parasitics of the semiconductor chip, which are usually modeled by a stray capacitance and a resistance for the material surrounding the active region, are not taken into account. Thermal effects are omitted also, thus the analysis is only valid for frequencies above 100 MHz.

The rate equations for a single-longitudinal-mode injection-locked semiconductor laser are expressed as [8]

$$\frac{dP}{dt} = \left(G - \frac{1}{\tau_p}\right)P + \frac{1}{L} v_g (P_i P)^{0.5} \cos\theta + R \qquad (1)$$

$$\frac{d\Phi}{dt} = (\omega_j - \omega_o) + \frac{1}{2L} v_g \left(\frac{P_i}{P}\right)^{0.5} \sin\theta \qquad (2)$$

$$\frac{dN}{dt} = -\frac{N}{\tau_e} - GP + Q. \qquad (3)$$

P is the photon number in the laser cavity and P_i is the number of injected photons. θ is the difference between the phase of the optical field of the master laser and that of the injected slave laser Φ. N stands for the carrier number in the active volume.

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R is the spontaneous emission rate, G is the gain, $1/\tau_p$ is the total cavity loss rate, τ_e represents the excited carrier lifetime, and Q is the carrier injection rate. ω_o is the stationary value of the optical frequency equal to the master frequency and ω_j represents the resonant frequency of the jth longitudinal mode of the slave laser cavity. v_g is the group velocity of light in the cavity and L is the length of the cavity.

Under a direct current modulation, the carrier injection rate is an ac component $Q_m f(t)$ together with a dc value at the bias level Q_o, that is:

$$Q(t) = Q_o + Q_m f(t) \tag{4}$$

where $f(t)$ is a normalized temporal function containing the signal to be transferred on the phase-locked optical carrier.

In order to solve (1)–(3) by linearization, a small-signal analysis is going to be used. According to Agrawal, this condition is satisfied for indexes of modulation $m = Q_m/(Q_o - Q_{\text{th}})$ less than 0.3 [22].

The steady-state values of the rate equations are obtained by setting the left members of (1)–(3) equal to zero. We call $p(t)$, $n(t)$, and $\varphi(t)$ the deviation of $P(t)$, $N(t)$, and $\Phi(t)$ from their steady-state values P, N, and Φ:

$$P(t) = P + p(t)$$

$$\Phi(t) = \Phi + \varphi(t)$$

$$N(t) = N + n(t).$$

Within a first-order approximation [23]:

$$G = G_o + G_n n + G_p p \tag{5}$$

$$\omega_j = \omega_{oj} + \frac{\alpha}{2} G_n n + \omega_p p. \tag{6}$$

G_o and ω_{oj} are the stationary values of the gain G and the frequency ω_j, respectively. $G_n = \partial G/\partial N$ is the differential gain. α is the linewidth enhancement factor, also equal to the ratio of the real part and the imaginary part of the carrier-induced change in the refractive index [24]. The value of α dramatically affects the modulation characteristics of a semiconductor laser. As the diode is directly modulated, the variation in gain results in a change in the laser frequency as shown in (6), and consequently an indirect frequency modulation. $G_p = \partial G/\partial P$ is a parameter representing spectral hole burning [23]. $\omega_p = \partial \omega_j/\partial P$ expresses a dependence of the resonant frequency on the photon number but is negligible in (6), because the gain change is nearly symmetrical about the laser line [25] and the corresponding index change, which is the Kramers Krönig transform, is nearly zero. Equations (1)–(3) are linearized and the second order terms in $p(t)$, $\varphi(t)$, and $n(t)$ are neglected. By making use of the Fourier transform $a(\omega)$:

$$a(\omega) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{+\infty} a(t) \exp(-i\omega t)\, dt \tag{7}$$

the linearized equations are solved.

In order to simplify the notations, we define:

$$A = 2P\rho \sin\theta \qquad B = G_n P$$

$$C = \frac{\rho}{2P} \sin\theta \qquad D = \rho \cos\theta$$

$$E = \frac{\alpha}{2} G_n \qquad F = G_o + G_p P$$

$$H = \frac{1}{\tau_e} + G_n P \qquad I = \frac{R}{P} - PG_p$$

$$J = \frac{G_n P}{\tau_p}$$

where $\rho = (1/2L)\, v_g (P_i/P)^{0.5}$ is the normalized injection rate.

The photon number and the optical phase, solutions of (1)–(3) in the frequency domain, are thus given by:

$$p(\omega) = Q_m \frac{[AE + BD + i\omega B]}{L(\omega)} f(\omega) = H_p(\omega) f(\omega) \tag{8}$$

and

$$\varphi(\omega) = Q_m \frac{[EI + ED - BC + i\omega E]}{L(\omega)} f(\omega) = H_\varphi(\omega) f(\omega) \tag{9}$$

where

$$L(\omega) = FAE + FBD + HID + HD^2 + HAC - \omega^2(H + 2D + I) + i\omega(FB + 2HD + HI + ID + D^2 + AC - \omega^2). \tag{10}$$

$f(\omega)$ is the Fourier transform of $f(t)$, $H_p(\omega)$ and $H_\varphi(\omega)$ are the modulation transfer functions of the locked laser for the photon number and the phase of the optical field, respectively.

Their moduli and arguments are given by

$$\text{mod}\,[H_p(\omega)] = G_n P Q_m \sqrt{\frac{\rho^2(\cos\theta + \alpha\sin\theta)^2 + \omega^2}{L(\omega) L^*(\omega)}}$$

$$\arg\,[H_p(\omega)] = \tan^{-1}\left[\frac{\omega}{\rho(\cos\theta + \alpha\sin\theta)}\right] - \tan^{-1}\left[\frac{\text{Im}\,[L(\omega)]}{\text{Re}\,[L(\omega)]}\right] \tag{12}$$

$$\text{mod}\,[H_\varphi(\omega)] = \frac{\alpha}{2} G_n Q_m \sqrt{\frac{\left[\frac{R}{P} - PG_p + \rho\left(\cos\theta - \frac{\sin\theta}{\alpha}\right)\right]^2 + \omega^2}{L(\omega) L^*(\omega)}} \tag{13}$$

$$\arg\,[H_\varphi(\omega)] = \tan^{-1}\left[\frac{\omega}{\frac{R}{P} - PG_p + \rho\left(\cos\theta - \frac{\sin\theta}{\alpha}\right)}\right] - \tan^{-1}\left[\frac{\text{Im}\,[L(\omega)]}{\text{Re}\,[L(\omega)]}\right]. \tag{14}$$

Re $[L(\omega)]$, Im $[L(\omega)]$, and $L^*(\omega)$ are the real part, the imaginary part, and the complex conjugate of $L(\omega)$, respectively. For the case of a sinusoidal current modulation $f(t) = \sin(\omega_m t)$, where ω_m is the modulation frequency, the deterministic photon number $p(t)$ and phase $\varphi(t)$ of the optical field, it is written:

$$p(t) = \text{mod}\,[H_p(\omega_m)] \sin(\omega_m t + \arg\,[H_p(\omega_m)]) \tag{15}$$

and

$$\varphi(t) = \text{mod}\,[H_\varphi(\omega_m)] \sin(\omega_m t + \arg\,[H_\varphi(\omega_m)]). \tag{16}$$

The moduli of H_p and H_φ lead to the amplitude of the modulation for the photon number and the phase of the optical field, respectively, whereas their arguments give the phase shifts to the current excitation. The amplitudes of the modulated photon number and optical phase are directly proportional to the current modulation Q_m.

Stability of the emitted mode is achieved when, after a perturbation, the laser returns to its stationary state after a nonperiodic transition or damped relaxation oscillations. In mathematical terms, the roots of the equation $L(\omega) = 0$, given by the complex frequencies $\omega = ix$ and $\omega = iy \pm z$, must be found in the upper half of the complex frequency plane. x and y represent the decay rate of the relaxation oscillations and z is the frequency of the relaxation oscillations.

They are linked together by the following equations:

$$x + 2y = H + I + 2\rho \cos\theta \tag{17}$$

$$2xy + y^2 + z^2 = J^2(1 - (I + 2\rho\cos\theta)\tau_p) + HI + 2(H + I)\rho\cos\theta + \rho^2 \tag{18}$$

$$x(y^2 + z^2) = \rho\{J^2(1 - (I + 2\rho\cos\theta)\tau_p)(\alpha\sin\theta + \cos\theta) + I(H\cos\theta + \rho) + \rho(I + H)\}. \tag{19}$$

The stability requirement must be combined with the following condition. The net gain $G - 1/\tau_p$ must be negative in order that the forced oscillation prevails over the amplification of the spontaneous emission [9]. The locking range can be expressed in terms of the phase detuning θ, which is related to a frequency detuning $\Delta\omega = \omega_{jo} - \omega_o$ through:

$$\theta = \cos^{-1}\left[\frac{\omega_{jo} - \omega_o}{\rho\sqrt{1 + \alpha^2}}\right] - \tan^{-1}\left[\frac{1}{\alpha}\right] \tag{20}$$

where ω_o is the optical frequency of the master and ω_{jo} the resonant frequency of the jth longitudinal mode for the free-running laser.

B. Power Spectra

In this section, the formalism used to evaluate the power spectrum of an injection-locked semiconductor laser is developed. In the following analysis, the intensity noise is neglected since it only leads to a slight asymmetry in the noise sidebands of the static power spectrum [26].

When the current of the slave laser is modulated, its field may be expressed by:

$$E(t) = m(t)\exp j[\omega_o t + \Phi + \varphi_n(t)] \tag{21}$$

where $\varphi_n(t)$ is the stochastic phase noise process, treated under the stationarity assumption. $m(t)$ is a complex stationary modulation process expressing

$$m(t) = E_o \exp j[\varphi_c(t) + \varphi_o] \tag{22}$$

where E_o is a constant and $\varphi_c(t)$ a complex deterministic modulation process given by:

$$E_o^2(\text{mod}\,[\exp(j\varphi_c(t))])^2 = [P + p(t)] \tag{23}$$

with appropriate normalization of the field and

$$\arg\,[\exp(j\varphi_c(t))] = \varphi(t). \tag{24}$$

φ_o represents the start phase uncertainty of the modulation process with respect to the carrier phase. φ_o is a random variable, independent on $\varphi_n(t)$, with uniform probability distribution from $-\pi$ to π. In the following analysis, the stochastic phase noise process $\varphi_n(t)$ is assumed to be independent on $m(t)$. This assumption is reasonable for lasers under small-signal modulation [27].

Thus, the autocorrelation function of the field is:

$$G_{EE}(\tau) = \langle \exp j\Delta\varphi_n(t, \tau)\rangle \exp i(\omega_o\tau) G_M(\tau) \tag{25}$$

where $\Delta\varphi_n(t, \tau) = \varphi_n(t + \tau) - \varphi_n(t)$ is the phase jitter and $G_M(\tau)$ is the autocorrelation function of the electric field modulation. For a deterministic periodic modulation function, expanded as a Fourier series with real coefficients a_n and b_n, the autocorrelation function of the electric field modulation then writes

$$\begin{aligned} G_M(\tau) = \frac{1}{T}\int_0^T &\Big\{P + \sum_{n=1}^{\infty} \text{mod}\,[H_p(\omega)]\,[a_n\cos(n\omega(t + \tau) + \arg\,[H_p(\omega)]) + b_n \sin(n\omega(t + \tau) + \arg\,[H_p(\omega)])]\Big\}^{0.5} \\ &\cdot \Big\{P + \sum_{n=1}^{\infty} \text{mod}\,[H_p(\omega)]\,[a_n\cos(n\omega(t) + \arg\,[H_p(\omega)]) + b_n\sin(n\omega(t) + \arg\,[H_p(\omega)])]\Big\}^{0.5} \\ &\cdot \exp 2i\Big\{\sum_{n=1}^{\infty}\text{mod}\,[H_\varphi(\omega)]\sin\left(\frac{n\omega\tau}{2}\right) \\ &\cdot \Big[b_n\cos\left(n\omega\left(t + \frac{\tau}{2}\right) + \arg\,[H_\varphi(\omega)]\right) \\ &- a_n\sin\left(n\omega\left(t + \frac{\tau}{2}\right) + \arg\,[H_\varphi(\omega)]\right)\Big]\Big\}\,dt \end{aligned} \tag{26}$$

where T is the modulation period.

Since the phase jitter $\Delta\varphi_n(t, \tau)$ is known to have a Gaussian distribution [28], [29] it can be easily shown [30] that

$$\langle \exp[i\Delta\varphi_n(t, \tau)]\rangle = \exp\left(-\frac{\langle\Delta\varphi_n^2(\tau)\rangle}{2}\right). \tag{27}$$

For an injection-locked semiconductor laser, the mean square phase jitter $\langle\Delta\varphi_n^2(\tau)\rangle$ is given by [31]:

$$\langle\Delta\varphi_n^2(\tau)\rangle = \frac{R_m}{2P_m}(1 + \alpha^2)\tau + \frac{1 + \alpha^2}{2k(\alpha\sin\theta + \cos\theta)}\left(\frac{R}{P} - \frac{R_m}{P_m}\right) \cdot (1 - \exp[-\tau \cdot k(\alpha\sin\theta + \cos\theta)]) \tag{28}$$

where P and P_m are the photon numbers in the cavities of the slave and the master lasers, respectively. R and R_m are the rates of spontaneous emission into the lasing mode. This expression does not take into account the dynamic phenomenon which affects the carrier density and the subsequent relaxation oscillations between the carrier density and light intensity. If these effects were to be taken into consideration, the current modulation would lead to modulation sidebands around the relaxation frequency in the same way as it happens around ω_o.

The average power spectrum is thus evaluated by

$$S(\omega) = \frac{1}{\sqrt{2\pi}}\int_{-\infty}^{+\infty} G_{EE}(\tau)\exp(-i\omega\tau)\,d\tau. \tag{29}$$

III. Results

A. Numerical Results

The values of the parameters chosen are typical for a 0.83 μm index guided CSP AlGaAs semiconductor laser. A 300 μm

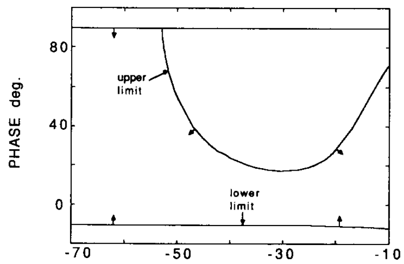


Fig. 1. Authorized phase detuning as a function of injection rate, indicated by the heads of arrows.

long laser is considered with a cavity volume of $1.2 \cdot 10^{-10}$ cm^{-3}; The linewidth enhancement factor α is equal to 5; this value comes from locking range measurements [32]. The photon lifetime is $\tau_p = n_g c^{-1}[\alpha_a + \log(1/R_m)/L]^{-1}$, where c is the free-space velocity of light, $\alpha_a = 45$ cm^{-1} is the distributed loss, $n_g = 4.3$ is the group refractive index, and $R_m = 0.31$ is the mirror reflectivity. The active region gain is given by $G = G_n(N - N_o)$ where $G_n = 5.75 \cdot 10^3$ s^{-1} is the differential gain and $N_o = 1.7 \cdot 10^8$ is the number of carriers at transparency. The spontaneous-emission rate R is related to the gain by $G \approx n_{sp}R$ where $n_{sp} = 2.6$ is the spontaneous-emission factor. The carrier recombination rate is N/τ_e where $\tau_e = 2.2 \cdot 10^{-9}$ s. A 0.1% gain suppression due to the spectral hole burning is assumed, leading to $G_p = -10^{-3}\, G/P$ [22]. The carrier injection rate Q_o corresponds to an average output power P_o of 2 mW per facet related to the intracavity photon number P by $P = 2L \cdot P_o \cdot n_g/[c \cdot h\nu \cdot \log(1/R_m)]$.

The lower and the upper limits of the stable locking range are defined as the phase detunings for which the decay rate x and y are null, respectively. Fig. 1 shows the stable locking range for the locked laser.

The IM response, in modulus and argument to the drive current, are calculated at various injection levels P_i/P for phase detunings θ within the stable locking range. For the injection level $P_i/P = -20$ dB in Fig. 2, the efficiency of the IM decreases when the lower limit of the stable locking range is neared. A flat IM response is obtained if the frequency of the master laser and that of the slave laser, which is shifted by injection, are equal, i.e., the phase detuning θ between the two laser fields is zero. At this point, the maximum output power is reached [9]. For injection levels as weak as $P_i/P = -60$ dB, the effect of the injection locking on the IM response is negligible.

The PM response, in modulus and argument to the drive current, is calculated for various injection levels P_i/P and phase detunings θ within the stable locking range. For the injection level $P_i/P = -20$ dB and a phase detuning $\theta = 0$, a flat PM response is obtained up to a frequency of 2 GHz (see Fig. 3); an improved conversion of frequency to phase modulation is obtained near the lower limit of the stable locking range at the expense of the bandwidth. The derivation of the argument of the CPR (chirp to power ratio), obtained from the ratio of the FM and IM responses, is useful in order to assess the IM degradation in a M-ary FSK system [6]. For injection levels as weak as $P_i/P = -60$ dB (see Fig. 4), the PM response is no longer flat. However, stable phase modulation can be performed for a phase detuning θ varying over a region slightly larger than $\pi/2$.

If we restrict our model to a low frequency approximation (frequencies much smaller than the inverse of the damping time

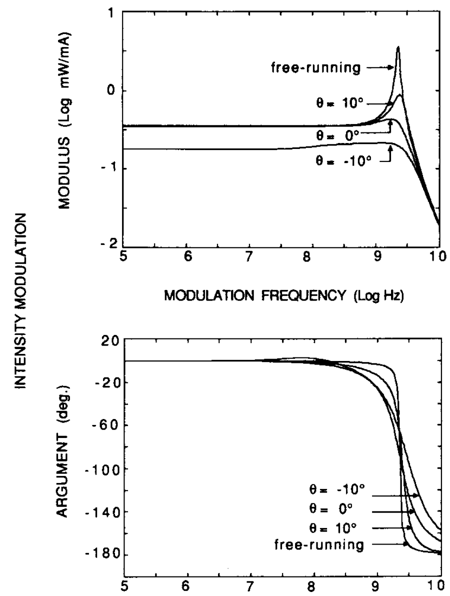


Fig. 2. Intensity modulation response in modulus (top) and argument (bottom) of an injection-locked laser for a 2 mW output power for facet and an injection level of -20 dB and for different values of the phase detuning in degree.

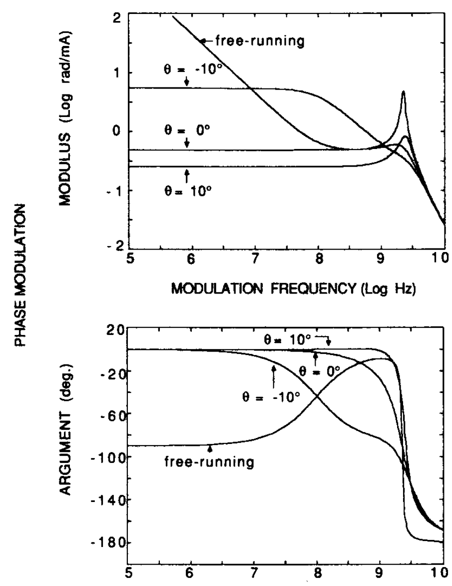


Fig. 3. Phase modulation response in modulus (top) and argument (bottom) of an injection-locked laser at a 2 mW output power per facet and an injection level of -20 dB and for different values of the phase detuning in degree.

of the relaxation oscillations) and we set the detuning between the master and slave laser phases to a given value, our results for the phase modulation response are similar to those obtained

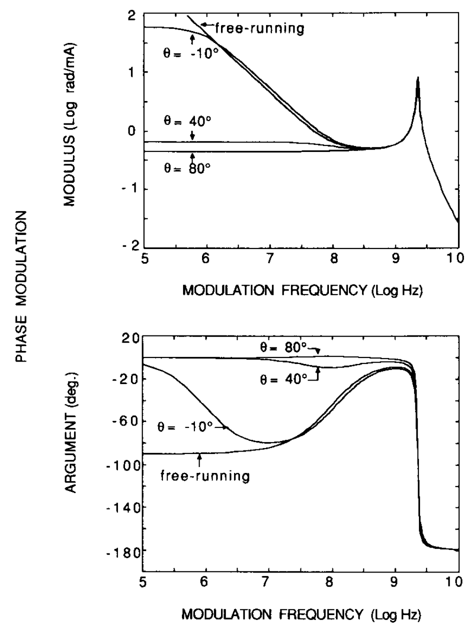


Fig. 4. Phase modulation response in modulus (top) and argument (bottom) of an injection-locked laser at a 2 mW output power per facet and an injection level of −60 dB and for different values of the phase detuning in degree.

by Kobayashi and Kimura [16]. Our results should be more accurate since their approach, using the Van Der Pol equation, was unable to predict the stability conditions, the effects of the phase detuning on the IM and PM responses and the resonances between the carriers and the intensity for the locked laser. The results obtained with the present analysis in terms of CPR are in agreement with those obtained by Piazzolla *et al.* [12].

The power spectra have been evaluated for three types of current modulations: sinusoidal, sawtooth, and square waves. In the following analysis, the amplitude of the modulation current eQ_m and the modulation frequency ω are chosen as 2 mA and 500 MHz, respectively. The power spectrum of the locked and modulated laser field is shown in Fig. 5 for three different modulation current waveforms. It is centered around the lasing frequency ω_0. The sawtooth modulation is given by

$$f(t) = \begin{cases} -1 + \dfrac{4t}{T} & t \in \left[0, \dfrac{T}{2}\right] \\ 3 - \dfrac{4t}{T} & t \in \left[\dfrac{T}{2}, T\right] \end{cases}$$

and is developed to the 50th order of the Fourier series. The square wave modulation is given by

$$f(t) = \begin{cases} -1 & t \in \left[0, \dfrac{T}{2}\right] \\ 1 & t \in \left[\dfrac{T}{2}, T\right] \end{cases}$$

and is developed to the 100th order of the Fourier series. The spreading of the harmonics of the locked laser is strongly enhanced in comparison to the sinusoidal and sawtooth modulations. The power spectrum of the free-running and modulated slave laser is shown in Fig. 6 for a sinusoidal modulation. A substantial reduction of the spreading of the harmonics is obtained with the injection-locking technique, as shown experimentally earlier [16].

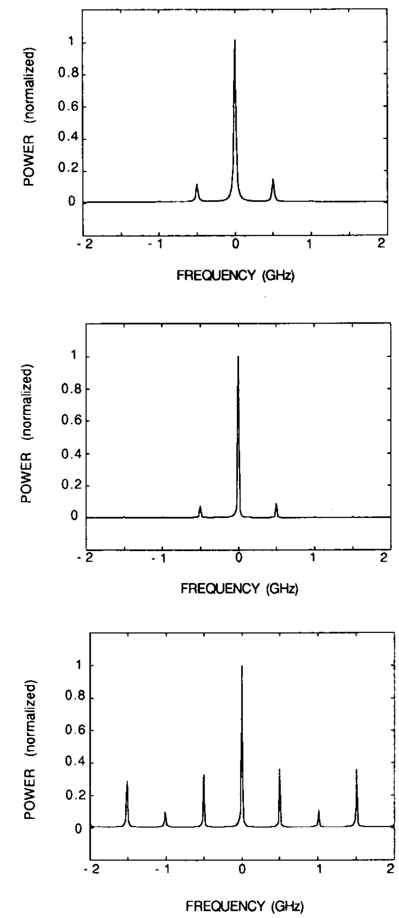


Fig. 5. Power spectra of an injection-locked laser under a direct modulation at a 2 mW output power per facet. The modulation frequency is 500 MHz, the injection level −30 dB and the phase detuning 10°. The current waveform is sinusoidal (top), sawtooth (middle), and square wave (bottom).

To summarize, the frequency response and the spreading of the harmonics of the locked laser depend on the level of injected power, the static phase detuning between the fields of the two lasers, the modulation frequency and the current modulation waveform. The locked laser has been studied within the stable locking range, whose width depends on damping mechanisms such as spectral hole burning, lateral carrier diffusion and multimode effects. Lateral carrier diffusion and multimode effects have not been modeled but they affect the response of the locked laser and are thus likely to influence the variation of the spreading of the harmonics of the locked laser in the stable locking range.

B. Experimental Results

The master and slave lasers are two CSP AlGaAs semiconductor lasers (Hitachi 1400). They have identical cavity lengths

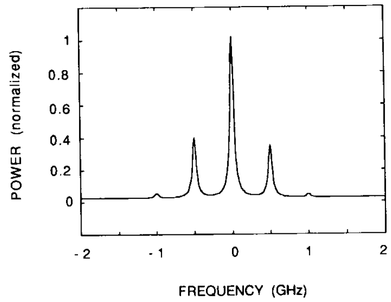


Fig. 6. Power spectra of a free-running laser under a direct modulation at a 2 mW output power per facet. The modulation frequency is 500 MHz and the current waveform sinusoidal.

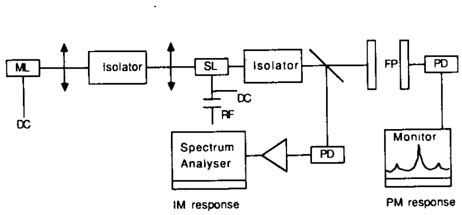


Fig. 7. Experimental setup to study the modulation properties of the injection-locked semiconductor laser. The spectrum analyser is used to measure the intensity modulation and the scanning Fabry–Perot interferometer is used to measure the phase modulation from power spectra.

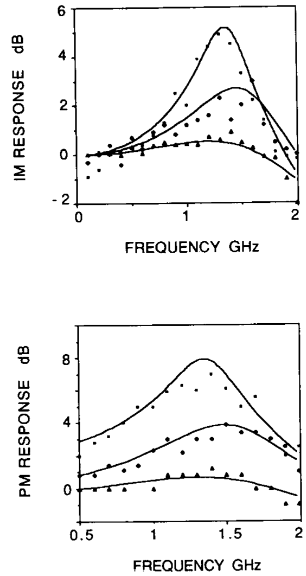


Fig. 8. Normalized intensity and phase responses to a sinusoidal small-signal modulation in dB versus frequency in an injection-locked GaAlAs laser for three different values of the injected power 11.1, 3.5, and 0.4 μW. The corresponding experimental values are represented by triangles, diamonds, and squares, respectively. The slave laser output power is 1 mW.

and emit continuously a single longitudinal mode at 830 nm. Their frequencies are stabilized by thermoelectric elements providing a 0.01K accuracy. The experimental setup is shown in Fig. 7. The master laser output is collimated with antireflection coated microlenses and injected into the slave laser. An optical isolator providing 36 dB isolation prevents reciprocal coupling.

The measurement of the injected power is performed by the coupling efficient method reported by Kobayashi and Kimura [33]. The intensity and the phase modulation indexes are obtained by the means of a spectrum analyzer and a scanning Fabry–Perot interferometer, respectively, as done by Doyle [34]. The photodetector frequency response has been calibrated using the beating of two lasers. The frequencies of emission for the slave and master lasers can be modified by acting on their temperature or their bias current. When the phase detuning reaches the lower limit of the locking range, the free-running mode vanishes, the slave laser frequency locks onto the master laser frequency and the resonance between the carrier density and the light intensity is significantly suppressed [32]. The locking can be easily checked by the scanning Fabry–Perot interferometer; when a shutter is positioned on the light path of the master laser, the power spectrum is dramatically changed. When the phase detuning is scanned to reach the upper limit of the stable locking range, the resonance is strongly enhanced. The upper limits of the stable locking range can not be characterized with the PM measurement method used as the resonance between the carrier density and the light intensity dramatically increases near this limit. The modulation sidebands cannot be resolved because of the gradual increase of the relaxation sidebands near this limit.

Fig. 8 shows the intensity and phase modulation responses of the locked laser for different values of the injected power. The output power of the slave laser is 1 mW. The lowest modulation frequency in the IM response is chosen as 100 MHz to facilitate the comparison with the theoretical results which neglect the thermal effects occurring below. On the other hand, the PM response is measured down to 500 MHz which is the lower limit of resolution of the FP interferometer. The 0 dB reference level in the IM and PM response curves is chosen as the response at 100 and 500 MHz, respectively, in the case of the highest injection level. The value of the phase detuning θ for the theoretical curves has been obtained by measuring the frequency detuning between the master laser and the free-running slave laser frequencies. The phase detuning θ may be tuned by changing slightly the bias current of the slave laser. The intensity and phase modulation responses of the locked laser for a fixed injected power in the stable locking range is shown in Fig. 9. The output power is 1 mW. The variation of the IM response through the stable locking range is described accurately by the model, but the variation of the PM response is not so important as predicted by theory.

IV. Conclusion

A detailed study of the modulation properties of an injection-locked semiconductor laser has been carried out, both theoretically and experimentally. The theory is based on three coupled rate-equations for the field amplitude and phase and carrier density of the injected laser. Theoretical results are obtained in terms of modulation response and power spectra. The effects of the phase detuning and the injection rate has been analyzed. In particular, it has been shown that flat IM and PM responses can be obtained, provided the injected power level is high. In this case the peak due to the resonance between the optical field and the carrier density is nearly suppressed. Therefore injection locking turns out to be a mean of flattening the frequency response of a semiconductor laser. Experimental evaluation of

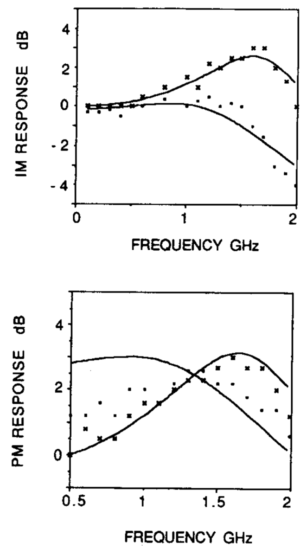


Fig. 9. Normalized intensity and phase responses to a sinusoidal small-signal modulation in dB versus frequency in an injection-locked GaAlAs laser, at the injected power of 5.9 μW for two different values of the phase detuning: $\theta = 20°$ and 5°. The corresponding experimental values are represented by crosses and squares, respectively. The slave laser output power is 1 mW.

PM and IM responses has been carried out. They are in agreement with the theory.

References

[1] J. M. Osterwalder and B. J. Rickett, "Frequency modulation of GaAlAs injection lasers at microwave frequency rates," *IEEE J. Quantum Electron.*, vol. QE-16, pp. 250–252, 1980.

[2] S. Saito, Y. Yamamoto, and T. Kimura, "Optical heterodyne detection of directly frequency modulated semiconductor laser signal," *Electron. Lett.*, vol. 16, pp. 826–827, 1980.

[3] T. L. Koch and J. E. Bowers, "Nature of wavelength chirping in directly modulated semiconductor lasers," *Electron. Lett.*, vol. 20, pp. 1038–1040, 1984.

[4] R. A. Linke, "Modulation induced transient chirping in single frequency lasers," *IEEE J. Quantum Electron.*, vol. QE-21, pp. 593–597, 1985.

[5] K. Kikuchi, T. Okoshi, and S. Tanikoshi, "Amplitude modulation of an injection-locked semiconductor laser for heterodyne-type optical communications," *Opt. Lett.*, vol. 9, pp. 99–101, 1984.

[6] D. Welford, "A rate equation analysis for the frequency chirp to modulated power ratio of a semiconductor diode laser," *IEEE J. Quantum Electron.*, vol. QE-21, pp. 1749–1751, 1985.

[7] R. Lang, "Injection-locking properties of a semiconductor laser," *IEEE J. Quantum Electron.*, vol. QE-18, pp. 976–983, 1982.

[8] P. Gallion and G. Debarge, "Influence of amplitude-phase coupling on the injection locking bandwidth of a semiconductor laser," *Electron. Lett.*, vol. 21, pp. 264–266, 1985.

[9] C. H. Henry, N. A. Olsson, and N. K. Dutta, "Locking range and stability of injection-locked 1.54 μm InGaAsP semiconductor lasers," *IEEE J. Quantum Electron.*, vol. QE-21, pp. 1152–1156, 1985.

[10] C. Lin and F. Mengel, "Reduction of frequency chirping and dynamic linewidth in high-speed directly modulated semiconductor lasers by injection locking," *Electron. Lett.*, vol. 20, pp. 1073–1075, 1984.

[11] N. Olsson, H. Temkin, R. A. Logan, L. F. Johnson, G. J. Dolan, J. P. van der Ziel, and J. C. Campbell, "Chirp-free transmission over 82.5 km of single mode fibers at 2 Gbit/s with injection-locked DFB semiconductor lasers," *J. Lightwave Technol.*, vol. LT-3, pp. 63–67, 1985.

[12] S. Piazzolla, P. Spano, and M. Tamburrini, "Small signal analysis of frequency chirping in injection-locked semiconductor lasers," *IEEE J. Quantum Electron.*, vol. QE-22, pp. 2219–2223, 1986.

[13] R. Wyatt, D. W. Smith, and K. H. Cameron, "Megahertz linewidth from 1.5 μm semiconductor laser with HeNe laser injection," *Electron. Lett.*, vol. 18, pp. 292–293, 1982.

[14] P. Gallion, H. Nakajima, G. Debarge, and C. Chabran, "Contribution of spontaneous emission to the linewidth of an injection-locked semiconductor laser," *Electron. Lett.*, vol. 21, pp. 626–628, 1985.

[15] K. Iwashita and K. Nakagawa, "Suppression of mode partition noise by laser diode light injection," *IEEE J. Quantum Electron.*, vol. QE-18, pp. 1669–1674, 1982.

[16] S. Kobayashi and T. Kimura, "Optical phase modulation in an injection-locked AlGaAs semiconductor laser," *IEEE J. Quantum Electron.*, vol. QE-18, pp. 1662–1669, 1982.

[17] K. Kikuchi, T. Okoshi, M. Nagamatsu, and N. Henmi, "Degradation of bit-error rate in coherent optical communications due to spectral spread of the transmitter and the local oscillator," *J. Lightwave Technol.*, vol. LT-2, pp. 1024–1033, 1984.

[18] B. S. Glance, "Minimum required power for carrier recovery at optical frequencies," *J. Lightwave Technol.*, vol. LT-4, pp. 249–255, 1986.

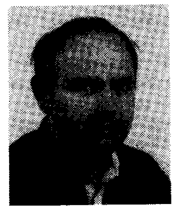
[19] P. Spano, M. Tamburrini, and S. Piazzolla, "Optical FSK modulation using injection-locked laser diodes," *J. Lightwave Technol.*, vol. 7, pp. 726–728, 1989.

[20] K. Kikuchi, C. E. Zah, and T. P. Lee, "Amplitude-modulation sideband injection locking characteristics of semiconductor lasers and their application," *J. Lightwave Technol.*, vol. 6, pp. 1821–1830, 1988.

[21] P. Gallion, G. Debarge, and C. Chabran, "Output spectrum of an unlocked optically driven semiconductor laser," *Opt. Lett.*, vol. 11, pp. 294–296, 1986.

[22] G. P. Agrawal, "Power spectrum of directly modulated single-mode semiconductor lasers: Chirp-induced fine structure," *IEEE J. Quantum Electron.*, vol. QE-21, pp. 680-686, 1985.
[23] C. H. Henry, "Theory of the phase noise and power spectrum of a single-mode injection laser," *IEEE J. Quantum Electron.*, vol. QE-19, pp. 1391-1397, 1983.
[24] —, "Theory of the linewidth of semiconductor lasers," *IEEE J. Quantum Electron.*, vol. QE-18, pp. 259-264, 1982.
[25] R. F. Kazarinov, C. H. Henry, and R. A. Logan, "Longitudinal mode self-stabilisation in semiconductor lasers," *J. Appl. Phys.*, vol. 53, pp. 4631-4644, 1982.
[26] K. Vahala, C. Harder, and A. Yariv, "Observation of relaxation resonance effects in the field spectrum of semiconductor lasers," *Appl. Phys. Lett.*, vol. 42, pp. 211-213, 1983.
[27] E. Eichen, P. Melman, and W. H. Nelson, "Intrinsic lineshape and FM response of modulated semiconductor lasers," *Electron. Lett.*, vol. 21, pp. 849-850, 1985.
[28] B. Daino, P. Spano, M. Tamburrini, and S. Piazzolla, "Phase noise and spectral line shape in semiconductor lasers," *IEEE J. Quantum Electron.*, vol. QE-19, pp. 266-270, 1983.
[29] M. Lax, "Classical noise v. noise in self sustained oscillators," *Phys. Rev.*, vol. 160, pp. 290-307, 1967.
[30] H. E. Rowe, *Signals and noise in communication systems.* Princeton, NJ: Van Nostrand, 1965.
[31] O. Lidoyne, P. Gallion, C. Chabran, and G. Debarge, "Locking range, phase noise and power spectrum of an injection-locked semiconductor laser," *IEE Proc.*, part J, vol. 137, pp. 147-159, 1990.
[32] I. Petitbon, P. Gallion, G. Debarge, and C. Chabran, "Locking bandwidth and relaxation oscillations of an injection-locked semiconductor laser," *IEEE J. Quantum Electron.*, vol. 21, pp. 148-154, 1988.
[33] S. Kobayashi and T. Kimura, "Injection locking in AlGaAs semiconductor laser," *IEEE J. Quantum Electron.*, vol. QE-17, pp. 681-689, 1981.
[34] O. Doyle, "Measuring modulus and phase of chirp/modulated power ratio," *Electron. Lett.*, vol. 23, pp. 133-134, 1987.

O. Lidoyne, photograph and biography not available at the time of publication.



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D. Erasme, photograph and biography not available at the time of publication.