Dual Modulation of Semiconductor Lasers

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Abstract

Large signal analysis of dual modulation of semiconductor lasers (by a simultaneous high-frequency control of the pumping current I and an additional intrinsic parameter) shows that the method allows suppressing the relaxation oscillations for an arbitrary shape of the pumping current signal $I(t)$. Because of that, the rate of information coding can be enhanced to about 80 Gbit/sec. Moreover, we demonstrate that dual modulation allows to maintain a *linear* relationship between $I(t)$ and the output optical power in a wide frequency band.

Introduction

We discuss a new method for modulating output radiation of semiconductor lasers. The key idea is to control the laser with an additional high-frequency input signal, varied simultaneously with the pumping current I. The additional signal can be any one of the several physical parameters influencing the optical wave in a laser cavity, such as the gain g, the confinement factor Γ, the photon lifetime τ_{ph}, the wavelength λ, etc. Although controlling such parameters may not be as technologically straightforward and natural as modulating the pumping current, we shall argue below that it is certainly worth the trouble and may even be indispensable for certain important goals in optical communications.

Dual laser modulation with a parameter X varied together with I will be referred to as the $(I \,\&\, X)$ dual modulation scheme. Technical feasibility of several such schemes is not in doubt, since most of the required elements have been demonstrated in a different context. In DBR lasers for coherent optical communications, it is possible to vary the optical path in the cavity simultaneously with the pumping current, thus implementing the $(I \,\&\, \lambda)$ dual scheme. Feasibility of the $(I \,\&\, \tau_{ph})$ scheme follows from the recently demonstrated electro-optic control of DBR mirror reflectivity in surface-emitting microcavity lasers.[1] Similar electro-optic control can be used for the implementation of the $(I \,\&\, \Gamma)$ scheme in edge-emitting lasers. High-frequency modulation of the modal gain has been demonstrated[2] in a four-terminal laser structure of special design, where the lateral distribution of carriers in a cross-section of the cavity can be rapidly shifted relative to the optical wave intensity profile. An attractive and, in our opinion, quite feasible approach to implementing the $(I \,\&\, g)$ dual scheme is to control an effective temperature T_e of carriers in the laser active region. This can be done in a variety of ways, e.g., by heating the carriers by a lateral electric field, or by making use of the power that electrons or holes, injected from a wide-gap cladding layer, bring into the carrier ensemble in a narrow-gap active layer.

Previously, we considered two special cases [$(I \,\&\, g)$ scheme[3] and $(I \,\&\, \tau_{ph})$ scheme[4]] and showed by a small-signal analysis that dual modulation allows to eliminate relaxation oscillations, enhance the modulation frequency, and achieve pure AM or pure FM modulation regimes of the laser output radiation. In this work we dispense with the assumption of a small-signal linear system and present a large-signal analysis of dual modulation in general. We show that it allows suppressing the relaxation oscillations for an arbitrary shape of the pumping current signal $I(t)$. Because of that, the rate of information coding can be enhanced to about 80 Gbit/sec. Moreover, we shall demonstrate that dual modulation allows to maintain a *linear* relationship between $I(t)$ and the output optical power $P(t)$ in a wide band of modulation frequencies.

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Large Signal Analysis of Dual Modulation

We shall describe the laser by a standard system of rate equations for the carrier density n and the photon density S in the active layer:

$$\frac{\mathrm{d}n}{\mathrm{d}t} = J - gS - B\,n^2 \;; \tag{1a}$$

$$\frac{\mathrm{d}S}{\mathrm{d}t} = S\,(\Gamma g - \tau_{\mathrm{ph}}^{-1}) + \beta\,\Gamma\,B\,n^2 \;, \tag{1b}$$

where $J \equiv I/eV_{\mathrm{act}}$ is the electron flux per unit volume V_{act} of the active layer, g the optical gain in the active layer, Γ the confinement factor for the radiation intensity, β the spontaneous emission factor, τ_{ph} the photon lifetime in the cavity, $B = (n\,\tau_{\mathrm{sp}})^{-1}$ is the bimolecular radiative coefficient, and $\tau_{\mathrm{sp}}(n)$ the radiative recombination lifetime of carriers.

It is evident from system (1) that a high frequency modulation of any one of its parameters,* J, g, Γ, or τ_{ph}, is accompanied by a variation of both S and n. It is also evident that in a conventional laser modulation by pumping current alone, variations δn, accompanying any high-frequency modulation δS, are of parasitic nature. The outcome is not so obvious when the laser is influenced by simultaneously varying *two* of the above parameters. In the next section we discuss the possibility of suppressing δn with a dual modulation of J and one of the other three parameters g, Γ, or τ_{ph}.

Elimination of relaxation oscillations

Consider first the situation where simultaneously with the pumping current (and independently of it) we can vary the optical gain g. In general, g depends on several parameters, $g = g\,(\Omega\,,n\,,T_{\mathrm{e}}\,,S\,)$, where Ω is the optical frequency.** We shall consider T_{e} to be the only independent parameter (other than J). Let us re-write Eqs. (1) under the condition $\mathrm{d}n/\mathrm{d}t = 0$:

$$0 = J - J_{\mathrm{th}} - gS \;; \tag{2a}$$

$$\frac{\mathrm{d}S}{\mathrm{d}t} = \Gamma\,(J - J_{\mathrm{th}}) - \tau_{\mathrm{ph}}^{-1}\,S \;, \tag{2b}$$

where $J_{\mathrm{th}} \equiv B\,n_{\mathrm{th}}^2$ and n_{th} is the pinned carrier concentration. For the sake of simplicity, we have neglected the spontaneous emission term in (2), since typically $\beta \approx 10^{-4}$. Equation (2b) establishes a *linear* relationship between S and J of the form

$$S = \int_0^t G\,(t - t')\,\mathrm{e}^{-t'/\tau_{\mathrm{ph}}}\,\mathrm{d}t' = \mathrm{e}^{-t/\tau_{\mathrm{ph}}} \int_0^t G\,(t')\,\mathrm{e}^{t'/\tau_{\mathrm{ph}}}\,\mathrm{d}t' \;, \tag{3}$$

where $G\,(t) \equiv \Gamma\,[\,J\,(t) - J_{\mathrm{th}}\,]$. Linearity of the $S\,[\,J\,(t)\,]$ relationship is of great value for optical communication systems. However, in order for this property to hold, we must satisfy Eq. (2a) with the help of a simultaneous variation of T_{e}, viz.

$$g\,[\,\Omega\,,n_{\mathrm{th}}\,,T_{\mathrm{e}}\,(t)\,,S\,] = \frac{J\,(t) - J_{\mathrm{th}}}{S} \;. \tag{4}$$

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* We shall not be concerned here with the possibility of varying β, which may be of interest only in the context of future microcavity lasers having $\beta \to 1$.

** In a single-mode microresonator, Ω may vary in a wide range, influenced by variations in the refractive index (due to varying n and T_{e}) and in the phase of the mirror reflection.[4]

Having solved Eq. (4) for the time dependence $T_e\ (t)$, we can determine the required heating power signal from an appropriate energy balance equation.

Similar effect of relaxation oscillation suppression, resulting in a linear relationship between the optical power signal and the pumping current, can be obtained by varying Γ (or τ_{ph}) rather than g. Since the gain is now constant, $g\ (n_{th}) = g_0$, in these cases linearity of the relation between S and J follows directly from Eq. (2a),

$$S = \frac{J - J_{th}}{g_0}\ . \tag{5}$$

In order to fulfil Eq. (5) one needs to maintain the following relationship between the current J and the second controlled parameter of dual modulation, (Γ or τ_{ph}):

$$\frac{\Gamma}{\Gamma_0} = 1 + \tau_{ph}^{(0)}\ \frac{d \ln (J - J_{th})}{dt}\ ; \qquad \frac{\tau_{ph}^{(0)}}{\tau_{ph}} = 1 - \tau_{ph}^{(0)}\ \frac{d \ln (J - J_{th})}{dt}\ . \tag{6}$$

Let us now consider a small-signal response of the laser to a dual modulation, under the condition $dn/dt = 0$. For signals of the $(J\ \&\ g)$ type,

$$J\,(t) = J_0 + \delta J\ e^{i\omega t}\ ; \tag{7a}$$

$$g\,(t) = g_0 + \delta g\ e^{i\omega t}\ , \tag{7b}$$

equation (3) yields the following response function:

$$\delta S = \frac{\delta J}{g_0\ (1 + i\ \omega\ \tau_{ph})}\ , \tag{8a}$$

while the required relation between the dual inputs δg and δJ is of the form

$$\delta g = \frac{i\ \omega\ \tau_{ph}}{1 + i\ \omega\ \tau_{ph}}\ \frac{\delta J}{S_0}\ . \tag{8b}$$

We remark that the "target condition" (8b) is practically frequency-independent for $\omega\ \tau_{ph} > 1$ and that the magnitude of the required dual modulation input is inversely proportional to S_0.

For a dual modulation of the type $(J\ \&\ \Gamma)$ or $(J\ \&\ \tau_{ph})$ we obtain a frequency-independent response

$$\delta S = \frac{\delta J}{g_0}\ , \tag{9a}$$

while the required ratio $\delta\Gamma/\Gamma_0$, (or $\delta\ \tau_{ph} / \tau_{ph}^{(0)}$) increases with the frequency:

$$\frac{\delta\Gamma}{\Gamma_0} = \frac{i\ \omega\ \tau_{ph}^{(0)}\ \delta J}{S_0\ g_0}\ . \tag{9b}$$

We see that the relative magnitude of the required dual modulation input ($\delta\Gamma/\Gamma_0$ or $\delta\ \tau_{ph} / \tau_{ph}^{(0)}$) is again inversely proportional to S_0.

Figure 1 shows a comparison of the laser response functions for different modulation schemes. It is evident that the dual modulation response (curve 4) has a substantially larger 3 dB bandwidth. It shows no electron-photon resonance peak and at high frequencies the response drops only as $1/\omega$.

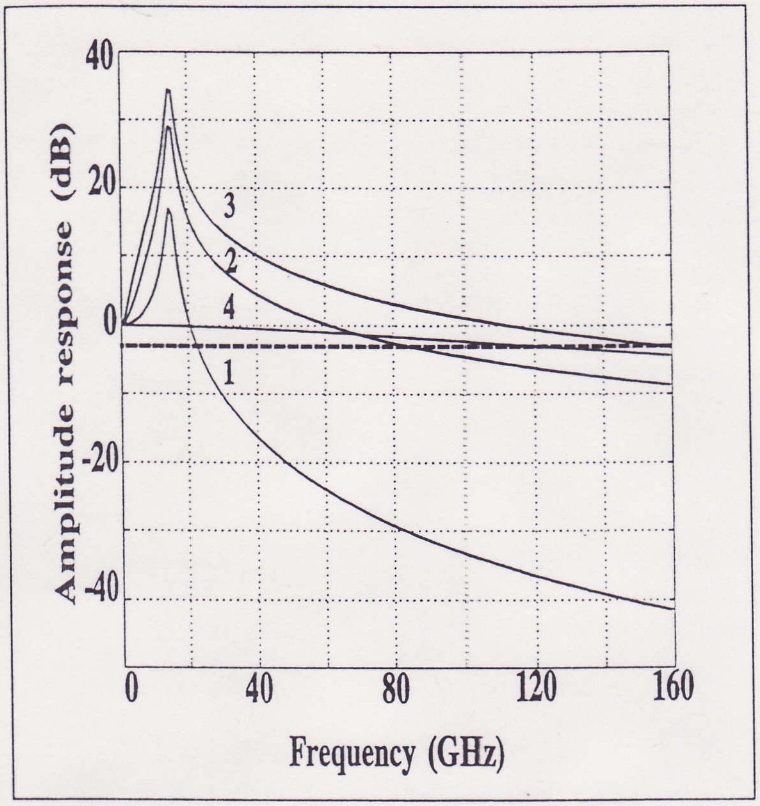

Figure 1. Small-signal laser response.
1: conventional δI modulation,
2: single modulation δg,
3: single modulation $\delta\Gamma$ (or $\delta\,\tau_{ph}$),
4: Dual modulation by δI & δg (equivalently, δI & $\delta\Gamma$ or δI & $\delta\,\tau_{ph}$).
Broken fat line indicates $-$ 3 dB level.
Laser parameters:
250 μm $\times$ 1 μm $\times$ 7 QW : 70 Å,
$\Gamma_0 = 0.075$, $g'_n = 5 \times 10^{-16}$ cm^2,
$I_{th} = 10$ mA, $\eta = 40$ %.

High frequency digital information coding

Let the signal to be coded consist of a series of Gaussian pulses of the form

$$J(t) = J_0 + J_A \sum_{n=0}^{\infty} \delta_n \, e^{-(t - nT)^2/2\Delta t^2} , \tag{10}$$

where J_A is the pulse amplitude, Δt its halfwidth, $\delta_n = (0, 1)$ is the code, and $T = 1/f$ is the period (f being the pulse repetition rate). Assuming that the pulse train begins at $t > 0$, we find from Eq. (3)

$$S(t) = S_0 + S_1 \frac{\Delta t}{\tau_{ph}} e^{\Delta t^2/2\tau_{ph}^2} \sum_{n=0}^{\infty} e^{(nT - t)/\tau_{ph}}$$
$$\times \left[\Phi\left[\frac{nT + \Delta t^2/\tau_{ph}}{\Delta t\sqrt{2}} \right] + \Phi\left[\frac{t - (nT + \Delta t^2/\tau_{ph})}{\Delta t\sqrt{2}} \right] \right], \tag{11}$$

where $S_0 \equiv (J - J_{th})/g_0$, $S_1 \equiv J_A \delta_n / g_0$, and Φ is the error integral [$\Phi(x) \to 1$ for $x \gtrsim 1$, $\Phi(-x) = -\Phi(x)$], The sum of two Φ's in the square brackets decreases with n much faster than $\exp(-nT/\tau_{ph})$, so the overall sum converges very rapidly.

Figure 2 shows a pseudo-random train of coding pulses (10) together with the laser response $P(t) = \eta\, S\, \hbar\Omega\, V_{act}/g\,\tau_{ph}$, as well as the variation of gain $g(t)$ and carrier temperature $T_e(t)$ targeted to maintain a constant carrier concentration $n = n_{th}$. The required amplitude δg increases with decreasing S_0.

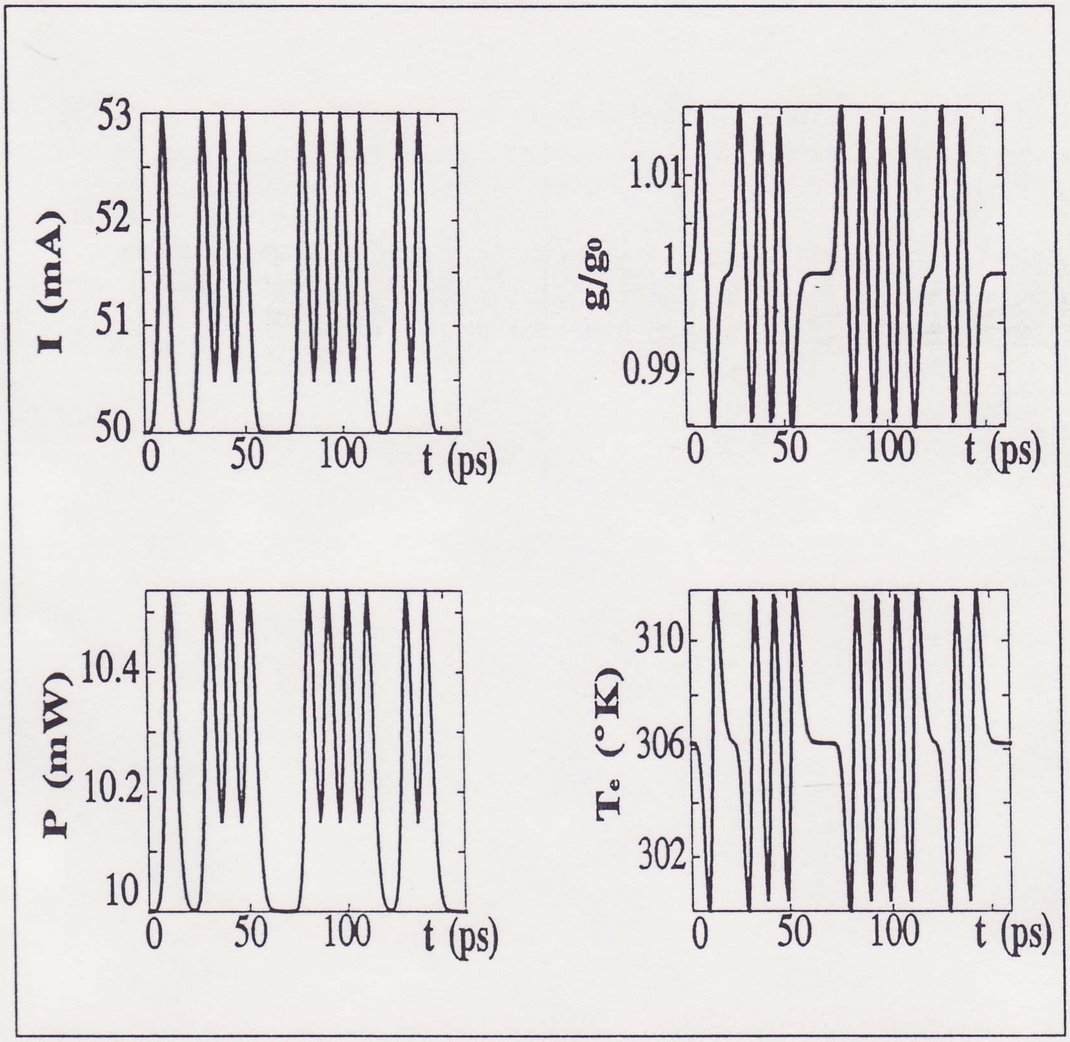

Figure 2. Laser response P (t) to a series of pseudo-random current pulses $I(t)$, at a coding rate of 80 Gbit/sec, accompanied by a dual variation of gain $g(t)$, targeted to maintain a constant carrier concentration. The figure also shows the carrier temperature variation $T_e(t)$ which provides the required gain variation. Laser parameters as in Fig. 1.

Conclusion

We have presented a large-signal analysis of the dual laser modulation method and demonstrated that this method allows digital coding at bit rates as high as 10^{11} Gb/s. In our illustrative example we assumed that the dual control is achieved by using a carrier heating scheme, although it is clear that other dual schemes can also be used.

On first glance, the carrier heating scheme appears rather power consuming but really it is not so bad. For example, in InGaAs where the energy relaxation time is rather long, $\tau_\varepsilon \gtrsim 1$ ps, the power required to heat carriers by 1° K is only $\lesssim 1.4 \cdot 10^{-11}$ W/carrier. In a laser with the active layer dimensions of $250 \times 1 \times 0.1\ \mu m^3$ and carrier concentration $n = p = 10^{18}\ cm^{-3}$, the required heating power is about 0.7 mW/K. Inasmuch as variation of T_e by several degrees is sufficient (as shown above) for many applications, the necessary additional power may be as low as 10 mW.

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