Dual Modulation of Semiconductor Lasers

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I. 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 demostrated in a different context. In DBR lasers for coherent optical communications, it is posible 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 demostrated 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 demostrated[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 the 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 [$(I\&g)$[3] and $(I\&\tau_{ph})$[4] schmes] 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 suppresing 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 80Gbit/sec. Moreover, we shall demostrate that dual modulation allows to maintain a *linear* relationship between $I(t)$ and the output optical power $P(t)$ in a wide band of frequencies.

II. 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:

$$\frac{dn}{dt}=J-gS-Bn^2 \tag{1a}$$

$$\frac{dS}{dt}=S(\Gamma g-\tau_{ph}^{-1})+\beta\Gamma Bn^2 \tag{1b}$$

where $J=I/eV_a$ is the electron flux per unit volume V_a 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, $B=(n\tau_{sp})^{-1}$ is the bimolecular radiative coefficient, and $\tau_{sp}(n)$ the radiative recombination lifetime of carriers.

It is evident from system (1) that a high frequency modulation of any one of its parameters, J, Γ, g, τ_{ph}, β 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 parameters. In the next section we discuss the posibility of suppressing δn with a dual modulation of J and one of the other three parameters g, Γ, or τ_{ph}.

1.Elimination of relaxation oscillations.

Let us neglect by β in the system (1) and consider the possibility of eliminating the relaxation oscillations by keeping n as a constant ($n=n_{th}$, $dn/dt=0$). System (1) will be of the form:

$$0 = J-J_{th} - gS \quad (2a), \qquad \frac{dS}{dt} = S\,(\,\Gamma g-\frac{1}{\tau_{ph}}) \quad (2b).$$

where $J_{th}= Bn^2_{th}$ and the n_{th} is the pinned carrier concentration.
System (2) establishes a *linear* relationship between S and J for any kind of dual modulation. Consider first the dual g & J modulation. We shall suppose here T_e to be the only independent parameter (other than J). In this case Eq.(2b) esteblishes a linear relationship between S and J.
Solution of (2b) is then of the form:

$$S=\int_0^t G(t-t')e^{-t'/\tau_{ph0}}dt'=e^{-t/\tau_{ph0}}\int_0^t G(t')e^{t'/\tau_{ph0}}dt' \tag{3}$$

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

$$g[\Omega,n_{th},T_e(t),S]=\frac{J(t)-J_{th}}{S} \tag{4}$$

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, but in these cases linear relation between S and J will follow from Eq.(2a), due to keeping gain as a constant $g=g_0$: $S=(J-J_{th})/g_0$ (5).
For fulfilling (5) one has to maintain proper relation between current J and second factor (Γ or τ_{ph}) of the dual modulation, which follows from Eq. (2b),

$$\frac{\Gamma}{\Gamma_0} = 1 + \tau_{ph0}\,\frac{d\,\ln(J-J_{th})}{dt}\,, \qquad \frac{\tau_{ph0}}{\tau_{ph}} = 1 - \tau_{ph0}\,\frac{d\,\ln(J-J_{th})}{dt} \tag{6}$$

Let us now consider a small-signal response of the laser to a dual modulation, say, of ($J\&g$) type, under the condition $dn/dt=0$. For signals $J(t)=J_0+\delta J\, e^{i\omega t}$, $g=g_0+\delta g e^{i\omega t}$ equation (3) yields the following response function δS and required relation between the dual inputs δg & δJ:

$$\delta S=\frac{\delta J}{g_0\,(1+i\omega\tau_{ph0})} \quad (7a), \qquad \frac{\delta g}{g_0}=\frac{i\omega\tau_{ph0}\,\delta J}{(1+i\omega\tau_{ph0})} \quad (7b).$$

For dual modulation of the types ($JI\&\Gamma$, $J\&\tau_{ph}$) we obtain frequency-independent laser response δS and $\delta\Gamma/\Gamma$ (or $\delta\tau_{ph}/\tau_{ph}$) ratio increasing proportionally to ω:

$$\delta S=\frac{\delta J}{g_0} \quad (7c), \qquad \frac{\delta\Gamma}{\Gamma_0}=\frac{i\omega\tau_{ph0}\,\delta J}{S_0\,g_0} \quad (7d).$$

Figure 1 shows a comparison of the laser response functions for different modulation schemes. (Laser parameters: $V_a=250\mu m \times 1\mu m \times 7$ QW:7nm, $\Gamma_0=0.075$, $g'_n=5\cdot 10^{-16}$ cm^2, $I_{th}=10$mA, $\eta=40\%$ have also been used in all calculations below.) It is evident that the dual $J\&g$ modulation response (curve 4) has a substantially larger 3dB bandwidth. It shows no electron-photon resonance peak and at high frequencies the response drops only as $1/\omega$. We remark that the "target condition" (7b) is practically frequency-independient for $\omega\tau_{ph}>1$ and that the relative magnitude of the required dual modulation input ($\delta g/g_0$, etc.) is inversely proportional to S_0.

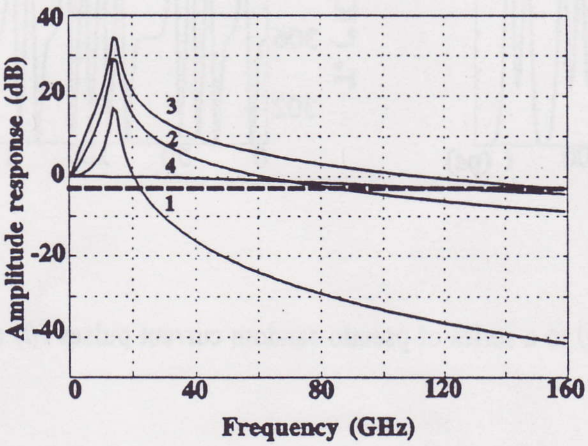

Figure 1. Small-signal laser response.

1- conventional δI modulation,
2- single modulation δg,
3- single modulation $\delta\Gamma$ (or $\delta\tau_{ph}$),
4- dual modulation by $\delta I\&\delta g$
---- - -3dB line

2. *High frequency digital information coding*

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

$$J(t)=J_0+J_A\sum_{n=0}^{\infty}\delta_n e^{(t-nT)^2/2\Delta t^2} \qquad (8)$$

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)

$$S(t)=S_0+S_1\frac{\Delta t}{\tau_{ph0}}e^{\Delta t^2/2\tau_{ph0}^2}\sum_{n=0}^{\infty}\left\{e^{(nT-t)/\tau_{ph0}}\times\left[\Phi\left(\frac{nT+\Delta t^2/\tau_{ph0}}{\Delta t\sqrt{2}}\right)+\Phi\left(\frac{t-(nT+\Delta t^2/\tau_{ph0})}{\Delta t\sqrt{2}}\right)\right]\right\} \qquad (9)$$

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

Figure 2 shows a pseudo-random train of coding pulses (8) at the repetition rate of 80 Gbit/s together with the laser response (9) as well as the 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. Note that the required amplitude δg increases with decreasing P_0.

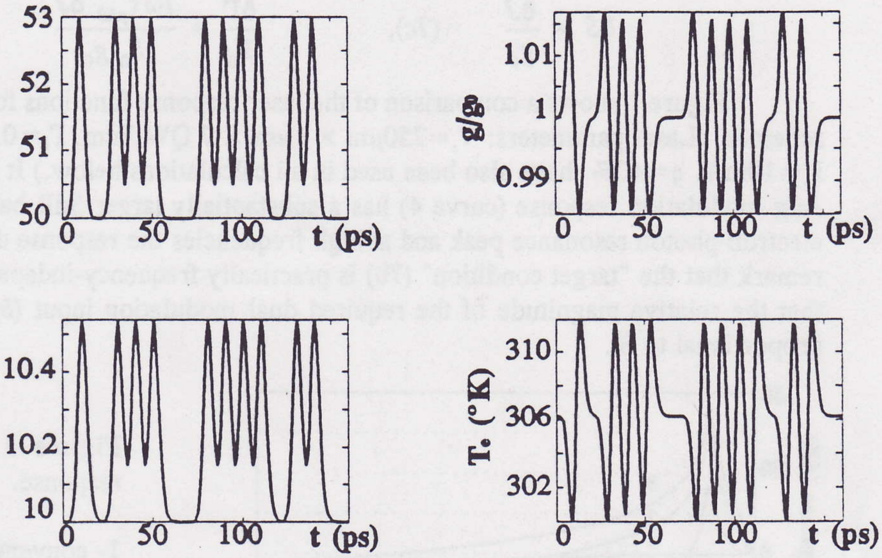

Figure 2. Laser response *P(t)* to a series of pseudo-random current pulses *I(t)* at coding rate of 80 Gbit/s.

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