Control of surface-emitting laser diodes by modulating the distributed Bragg mirror reflectivity: Small-signal analysis

E. A. Avrutin[a)]
School of Electron and Electrical Engineering, University of Bath, BA27AY, United Kingdom

V. B. Gorfinkel
Department of High Frequency Engineering, University of Kassel, D-3500, Germany

S. Luryi
AT&T Bell Laboratories, Murray Hill, New Jersey 07974

K. A. Shore
School of Electron and Electrical Engineering, University of Bath, BA27AY, United Kingdom

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Cavity-loss control of surface emitting distributed Bragg reflector lasers by electro-optic modulation of the Bragg mirror reflectivity is shown to be more efficient at high frequencies than the conventional control by current modulation. Combining both means of control offers additional possibilities, such as the elimination of relaxation oscillations and the achievement of a pure frequency-modulation regime.

Conventional methods of modulating semiconductor lasers by varying the pumping current are limited[1] to relatively low frequencies on the order of the relaxation oscillation frequency ($2\pi\omega_{\rm rel}\lesssim 10$ GHz at moderate currents). Several alternative schemes have been proposed recently. Gorfinkel and co-workers[2–5] discussed theoretically and demonstrated experimentally a direct modulation of the material gain coefficient by means of controlled heating of nonequilibrium carriers in the laser active region. Besides posing technological problems, this method is likely to dissipate a lot of power and require relatively high threshold currents. Yamamoto and Bjork proposed[6] to employ the modulation of the spontaneous emission factor β in microcavity lasers with high-quality resonators ($\beta\approx 1$). Excellent dynamical properties can in principle be achieved in this scheme, however its practical realization is likely to be difficult. The above schemes have one common feature in that they both attempt to directly affect the light intensity in a laser cavity by modulating a physical quantity other than the pumping current (which acts indirectly through the relatively slow-varying carrier density). In the present work, we discuss another scheme of this kind: Control of the photon lifetime $\tau_{\rm ph}$ in the laser cavity by a modulation of the reflectivity of the cavity mirrors.

One promising way to achieve this modulation is to use electro-optically tuned distributed Bragg reflectors (DBR) for surface-emitting microcavity lasers. Such tuned DBR have been recently realized by Blum *et al.*,[7] with the reflectance modulation as high as 12% for 1 V variation in the applied voltage. Their tunable DBR consists of alternating layers of direct and indirect materials. The mirror reflection modulation occurs due to the refractive index variation in a multiple quantum well (MQW) system built in the direct gap layers. The MQW index has been varied by more than 0.01 by an electro-optical shift of the excitonic absorption resonance. Most of our discussion below is in the context of an assumed structure similar in principle to that demonstrated in Ref. 7.

Consider the high-frequency response of the laser output power to a variation of $\tau_{\rm ph}$. For this purpose, it is adequate to use the standard system of rate equations for the carrier density n and the photon density S in the laser active layer:

$$\frac{dn}{dt}=J-Sg-\frac{n}{\tau_{sp}}, \tag{1a}$$

$$\frac{dS}{dt}=\Gamma gS-\frac{S}{\tau_{\rm ph}}+\frac{\beta n}{\tau_{sp}}, \tag{1b}$$

where $J\equiv I/eV_a$ is the electron flux per unit volume V_a of the active layer, I is the pumping current, g the optical gain in the active layer, Γ the confinement factor for the radiation intensity, and $\tau_{\rm sp}(n)$ the radiative recombination lifetime of carriers. In principle, any of the parameters of Eqs. (1) can be modulated. Thus, the pumping current modulation enters the system as a variation δJ in Eq. (1a) for the carrier density, the scheme in Ref. 6 corresponds to a variation $\delta\beta$ in Eq. (1b) for the photon density, and the carrier-heating modulation[2–5] enters both equations as a variation of gain $\delta_g=g'_T\delta T_e$ in response to variations in the carrier temperature T_e. In the present work, we assume that only the pumping current and the photon lifetime may be subject to external modulation δJ and $\delta\tau_{\rm ph}$, respectively.

Assuming harmonic small signals at a modulation frequency ω and linearizing the system (1) around a steady state in the laser generation regime, we obtain the following expression for the light intensity response:

$$\delta S=\frac{\Gamma\tau_{\rm st}^{-1}\delta J-(i\omega+\tau_d^{-1}+\tau_{\rm st}^{-1})S\delta\tau_{\rm ph}^{-1}}{i\omega\gamma-\omega^2+\omega_{\rm rel}^2}, \tag{2}$$

where the stimulated recombination time $\tau_{\rm sd}$, the dynamical carrier lifetime τ_d, the relaxation oscillation frequency $\omega_{\rm rel}$, and the damping factor γ are defined by

a)On leave from A. F. Ioffe Phys.-Tech. Institute, St. Petersburg, 194021, Russia.

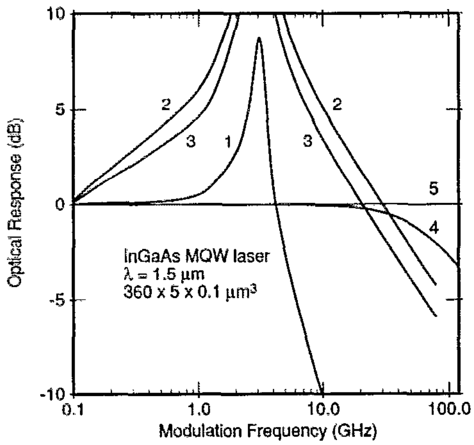

FIG. 1. Frequency dependence of the optical response $\delta S(f)/\delta S(0)$ to the variation of different parameters in a stripe MQW laser. Assumed laser parameters: Five 100 Å QWs, area 360×6 μm; steady-state values $S=3.5\times 10^{14}$ cm^{-3}, $\Gamma=0.2$, $\tau_{\rm ph}=2.5$ ps; the differential gain $g_n'=2.5\times 10^{-16}$ cm^{-2}. Curve 1: Modulation by δJ; curve 2: Modulation either by $\delta\tau_{\rm ph}$ or by $\delta\Gamma$; curve 3: Modulation by δT_e; curve 4: Dual modulation by δJ and δT_e subject to $\delta n=0$; curve 5 (flat response) corresponds to the dual modulation by δJ and $\delta\tau_{\rm ph}$ (or $\delta\Gamma$), subject to $\delta n=0$.

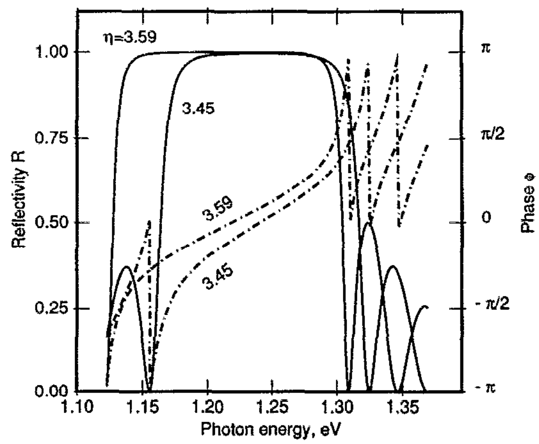

FIG. 2. Calculated amplitude and phase of the reflection coefficient in a 22-period DBR in which the lower refractive index (AlAs) in each period is fixed at $\eta_2=3.384$, while the higher index η_1 (GaAs/AlGaAs MQW) is varied. In the plateau region $\hbar\Omega\approx 1.25$ eV, the phase of reflection varies approximately linearly ($\varphi\approx 2.1\,\eta$) with the refractive index difference.

$$\tau_{\rm st}^{-1}\equiv S\frac{\partial g}{\partial n},\quad \tau_d^{-1}\equiv\frac{\partial}{\partial n}\left(\frac{n}{\tau_{sp}(n)}\right),$$

$$\omega_{\rm rel}^2\equiv\frac{1}{\tau_{\rm st}\tau_{\rm ph}}+\frac{\beta n}{S\tau_d\tau_{sp}}-\frac{\Gamma S}{\tau_d}\frac{\partial g}{\partial S}\approx\frac{1}{\tau_{\rm st}\tau_{\rm ph}},$$

$$\gamma\equiv\frac{1}{\tau_d}+\frac{1}{\tau_{\rm st}}+\frac{\beta n}{S\tau_{sp}}-\Gamma S\frac{\partial g}{\partial S}.$$

In writing down Eq. (2), we have used the steady-state relation $\tau_{sp}^{-1}-\Gamma g=\beta n/S\tau_{sp}$ and made the usual approximation neglecting $\beta\tau_d^{-1}\ll\Gamma\tau_{\rm st}^{-1}$.

The frequency dependence of the laser response to the variation of different parameters is shown in Fig. 1. For the conventional modulation by pumping current only, corresponding to setting $\delta\tau_{\rm ph}^{-1}=0$ in Eq. (2), we recover the usual response curve (curve 1, Fig. 1), which exhibits a resonant peak at $\omega_{\rm rel}$ (the electron-photon resonance) and for higher frequencies, $\omega\gg\omega_{\rm rel}$, the intensity response decays as $1/\omega^2$. In contrast, the intensity variation due to modulation of $\tau_{\rm ph}$ decays at high frequencies only as $1/\omega$ (curve 2). A similar $1/\omega$ behavior was predicted earlier[3] for the carrier-heating modulation scheme (curve 3). Moreover, it was recently shown[4] that a combined action of two independent modulation mechanisms with properly adjusted amplitudes and phases offers other significant advantages over the conventional current modulation scheme. Thus, it becomes possible to eliminate the relaxation oscillations by suppressing the high-frequency carrier density variation $\delta n=0$. The resultant flat modulation response (curve 4, Fig. 1) is advantageous for analogue and digital applications. This feature is immediately reproduced by the present model; in fact, for $\delta n=0$ there is no high-frequency roll-off at all in the modulation response (curve 5). The price paid, however, is that the relation between $\delta\tau_{\rm ph}^{-1}$ and δJ, necessary to suppress relaxation oscillations, becomes progressively more difficult to maintain at higher frequencies. This relation is of the form

$$\delta\tau_{\rm ph}^{-1}=\frac{\delta J(i\omega-\Gamma S\partial g/\partial S+\beta n/S\tau_{sp})}{S(g+S\partial g/\partial S)},\tag{3}$$

which shows that the magnitude of $\delta\tau_{\rm ph}^{-1}$ (dual to δJ so as to maintain $\delta n=0$) increases with the frequency.[8]

So far, our discussion has been fairly general. The above model describes the small-signal behavior of any laser with a cavity-loss modulation, but it does not account for the peculiarities of any specified structure. We shall now discuss the special case of a microcavity surface-emitting laser with a Bragg mirror reflectance modulated electrooptically. Consider a reflector comprising alternating layers of GaAs/AlGaAs MQW and AlAs. The electrooptic effect changes the difference η between the refractive indices η_1 of the MQW and η_2 of AlAs, thus shifting the Bragg reflectance peak. We shall assume that the two DBRs are identical and can be described by the same wave-amplitude reflection coefficient

$$r\equiv\sqrt{R}\,e^{i\varphi}.$$

Both the amplitude $R(\eta,\Omega)$ and the phase $\varphi(\eta,\Omega)$ of the DBR reflectance vary[9] under electro-optic modulation, see Fig. 2. The variation in φ leads to a dynamic change (chirp) in the lasing frequency Ω. Therefore, the radiation modulation is essentially of mixed amplitude-frequency type.

The salient feature of Fig. 2 is the existence of a relatively wide range of frequencies where the reflection amplitude does not change even as we vary the index of refraction of MQW layers. In this range there is no modulation of $\tau_{\rm ph}$ and only the phase φ is varied. At first glance, it may appear that the plateau of constant reflection (characteristic of a lossless DBR) can be used for the implementation of a pure frequency modulated (FM) regime. This is not so, however, if the refractive index in the DBR layers is the only externally controlled parameter. Indeed, the variation gain g (owing to its wavelength dependence) in the active region of the cavity itself contributes to δS and cannot be compensated in general in a one-parameter modulation scheme. Pure FM regime can be brought about only by a coherent dual modulation of the laser.

To show that this can be done, we complete our system (1) with the resonant condition

$$r^2 \exp(2ik_0 \bar{\mu} L) = 1, \tag{4}$$

where L is the microcavity length, $k_0 = \Omega/c$ is the vacuum wave number, and $\bar{\mu} = \bar{\eta} - i\bar{\alpha}/2$ is the complex refractive index for the lasing mode. Both the spectral position Ω of the lasing line (which we shall assume to correspond to the fundamental mode) and the value of $\tau_{\rm ph}$ are determined

$$\Omega = (\bar{c}/L)[\pi - \varphi(\eta,\Omega)], \tag{4a}$$

$$\tau_{\rm ph}^{-1} \equiv \bar{c}\bar{\alpha} = -(\bar{c}/L)\ln[R(\eta,\Omega)], \tag{4b}$$

where $\bar{c} \equiv c/\bar{\eta}$ is the speed of light in the medium. Estimates made from Eqs. (4) and numerical calculations[9] of the reflectance for a typical DBR structure show that even changes as small as 10^{-3} in the refractive index shift the lasing wavelength by as much as 100 Å, which is comparable to the gain spectrum width.

We are considering the situation where the independent variables are the pumping current δJ and the refractive index $\delta\eta = \delta\eta_1$ of tuned MQW layers in the DBR. Our target is that the power P of the output optical signal remains constant even as its wavelength is modulated:

$$\frac{dP}{dt} = 0, \quad \text{where } P \equiv \frac{SV_a\hbar\Omega}{\Gamma\tau_{\rm ph}}. \tag{5}$$

Let us simplify the analysis by assuming that we are operating within the plateau of constant DBR reflectance, $d\tau_{\rm ph}/dt = 0$ (as evident from Fig. 2, this is our best case anyway). Neglecting the small contribution to δP from the variation $\delta\Omega$, Eq. (1b) implies that $g = 1/\Gamma\tau_{\rm ph}$ and hence the gain must remain constant,

$$\delta g \equiv g'_n \delta n + g'_\Omega \delta\Omega = 0, \tag{6}$$

where $\delta\Omega \equiv \Omega'_n \delta n + \Omega'_\eta \delta\eta$. The variation Ω'_n results from the dependence $\bar{c}[\bar{\eta}(n)]$ and the variation Ω'_η from $\varphi(\eta)$ [see the phase equation (4a)]. The primes in Eq. (6) and below denote the partial differentiation with respect to a variable indicated by the subscript. The functional dependence of the gain is assumed in accordance with

$$g = g[\Omega(\eta,n), n, T_e, S]. \tag{7}$$

The frequency control by $\delta\eta$ is expressed by

$$\delta\Omega = \frac{g'_n \Omega'_\eta \delta\eta}{g'_n + g'_\Omega \Omega'_n}, \tag{8}$$

which implies that the overall variation $\delta\Omega$ can, in principle, be enhanced compared to $\delta\Omega_\eta \equiv \Omega'_\eta \delta\eta$, provided $g'_\Omega \Omega'_n < 0$.

The dual relationship between δJ and $\delta\eta$, required to maintain $\delta P = 0$, can be obtained from Eqs. (1a) and (5):

$$\delta J = -\frac{\delta\eta \Omega'_\eta g'_\Omega (i\omega + \tau_{sp}^{-1})}{g'_n + g'_\Omega \Omega'_n}, \tag{9}$$

where we have again neglected the contribution to δP from the variation $\delta\Omega$.

When condition (9) is fulfilled, the concentration n is no longer constant,

$$\delta n = -\frac{g'_\Omega \Omega'_\eta \delta\eta}{g'_n + g'_\Omega \Omega'_n}. \tag{10}$$

It is still possible, of course, to opt for the elimination of relaxation oscillations to achieve a high-frequency response. To this end, one must set as the target $\delta n = 0$, instead of Eq. (5). This leads to a dual relationship between $\delta\eta$ and δJ, analogous to Eq. (3). It should be borne in mind, however, that the modulation of light will then be of well-developed mixed amplitude-frequency type.

[1] K. Y. Lau and A. Yariv, Semiconductors and Semimetals **22B**, 70 (1985).

[2] V. B. Gorfinkel and I. I. Filatov, Fiz. Tech. Poluprovodn. **24**, 742 (1990) [Sov. Phys. Semicond. **24**, 466 (1990)].

[3] T. Yu. Bagaeva, I. I. Filatov, B. M. Gorbovitsky, V. B. Gorfinkel, E. Avrutin, and S. A. Gurevich, *Proc. 1991 Int. Semicond. Device Res. Symp.* (Engineering Academic Outreach, U. VA, Charlottesville, 1991), pp. 403–406.

[4] V. B. Gorfinkel and S. Luryi, Appl. Phys. Lett. **62**, 2923 (1993).

[5] S. A. Gurevich, V. B. Gorfinkel, G. E. Stengel, and I. E. Chebunina, Proceedings of the 13th International Semiconductor Laser Conference, Sept. 21–25, 1992, Japan (unpublished).

[6] Y. Yamamoto, S. Machida, and G. Bjork, Phys. Rev. A **44**, 657 (1991).

[7] O. Blum, J. E. Zucker, T. H. Chiu, M. Divino, K. L. Jones, S. N. G. Chu, and T. K. Gustafson, Appl. Phys. Lett. **59**, 2971 (1991); O. Blum, J. E. Zucker, X. Wu, K. H. Gulden, H. Sohn, T. K. Gustafson, and J. S. Smith, IEEE Photonic Technol. Lett. **5**, 695 (1993).

[8] A precisely similar situation arises in a dual modulation of a laser by the variations δJ and $\delta\Gamma$. When the relaxation oscillations are suppressed, the frequency response of $\delta S/\delta J$ becomes flat and the amplitude of the dual signal $\delta\Gamma$, required to achieve this effect, increases with ω [V. B. Gorfinkel and S. Luryi (unpublished)].

[9] Analytical expressions for $R(\eta,\Omega)$ and $\varphi(\eta,\Omega)$ can be found in the classical text by M. Born and E. Wolf, *Principles of Optics*, 6th ed. (Pergamon, Oxford, 1980), Sec. 1.6.5.