Bandwidth extension by trade-off of electrical and optical gain in a transistor laser: Three-terminal control

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We present data and describe analytically the "trade-off" between collector current gain and the differential optical gain of a heterojunction bipolar transistor laser (TL). The electrical-optical gain relationship shows that a reduction in the transistor current gain is accompanied by an increase in the differential optical gain of the TL and, as a consequence, results in a larger optical modulation bandwidth. Third-terminal electrical control can be used to enhance the optical bandwidth of a TL beyond the "gain-clamped" cutoff limitation of the carrier-photon (population) resonance characteristic of a diode laser. © *2009 American Institute of Physics*. [DOI: 10.1063/1.3068489]

The transistor laser (TL),[1,2] operating simultaneously as a transistor and a laser, provides both a high impedance output with current gain, $\beta(=I_C/I_B)$, at the base-collector junction and laser emission from stimulated base electron-hole recombination. It exhibits and gives access uniquely to two forms of gain: electrical and optical. In the present work the "trade-off" between collector current gain and the differential optical gain in a quantum-well base heterojunction bipolar TL is studied and shown to make possible, because of the gain trade-off, improved optical bandwidth. This is possible only with a three-port electrical-optical active device, which in the case of the TL, is a consequence of the photon-carrier interaction occurring in conjunction with emitter-to-collector carrier transport in competition with base recombination. The nature of the photon-carrier interaction and gain trade-off in a TL can be described analytically by modifying and extending the Statz–deMars coupled photon-carrier rate equations.[3–5] Based on the calculated gain trade-off and third terminal device control, significant improvement in the optical modulation bandwidth of the TL is achieved.[6]

The devices studied in this paper are *n-p-n* heterojunction bipolar transistors (n-InGaP/p-GaAs+InGaAs quantum well (QW)/n-GaAs) similar to those employed in Refs. 4–7. The TLs used for this study have a cleave-to-cleave emitter-base cavity length of 200 μm. The p-type base region contains an active InGaAs QW with width of $L_z \approx 120$ Å. The recombination outside the QW (p-GaAs) is negligible compared to the recombination in the QW region. By considering the continuity condition applied to the base population number at the QW active region (N in Fig. 1) and the cavity photon population number N_P, we obtain for the Statz–deMars rate equation,[3–5]

$$\frac{dN}{dt} = \frac{I_E}{q} - \frac{I_C}{q} - \frac{N}{\tau_{B,\text{spon}}} - \Gamma v_g g N_P, \tag{1}$$

where I_E and I_C are the emitter and collector currents, $\tau_{B,\text{spon}}$ is the effective spontaneous carrier lifetime, v_g is the photon group velocity, g is the laser optical gain, and the optical confinement factor $\Gamma = V_{\text{active}}/V_{\text{opt}}$. V_{opt} is the effective optical mode volume and V_{active} is the effective volume of the active QW region. To simplify the analysis, only a single laser mode is considered; hence, higher order effects such as the transition in operation to the first excited state are ignored.[7,8] Equation (1) for $dN/dt=0$ is written in differential form and for the optical gain gives the expression

$$\Gamma g' = \left(\frac{1}{\tau_B} - \frac{1}{\tau_{B,\text{spon}}} - \Gamma v_g g \eta_i\right)\frac{V_{\text{active}}}{v_g N_P}, \tag{2}$$

where $g' = \partial g/\partial n$ is typically defined in terms of carrier density at the active volume (QW) with $n=N/V_{\text{active}}$. To arrive at Eq. (2), the following substitutions have been used: the quantum efficiency is $\eta_i = \partial N_P/\partial N$ and the effective recombination current is $\delta I_E - \delta I_C = q\delta N/\tau_B$, where τ_B is the effective carrier lifetime including the effects of both stimulated and spontaneous recombinations. From transistor charge analysis[5] τ_B is related to the carrier transit time from emitter-to-QW, $\tau_{t,2}$, and to the tilted emitter-to-collector base population by the relation $1/\tau_B = 1/\tau_{\text{bulk}} + \kappa/\tau_{t,2}$, where $\kappa = Q_2/(Q_1+Q_2)$ defines the proportion of injected carriers transported to the QW and τ_{bulk} is the recombination lifetime of carriers in the region outside the QW. Q_1 and Q_2 are the carrier populations that transport carriers to the reverse-biased base-collector junction and to the QW, respectively (Fig. 1). Since the recombination radiation emission outside the QW may be considered negligible (i.e., $\tau_{\text{bulk}} \gg \tau_{t,1}, \tau_{t,2}$), the fraction κ is related to the current gain, $\beta = I_C/I_B$, of the

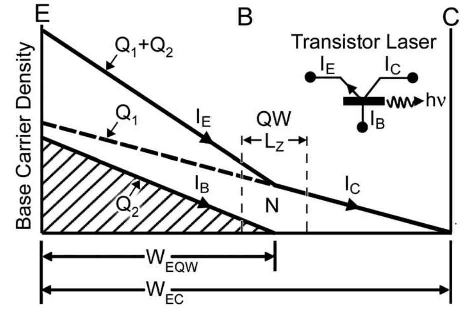

FIG. 1. Charge analysis of the base minority carrier density of a TL illustrating the continuity condition applied to the minority carrier population number at the base QW active region. The arrows I_E, I_B, and I_C denote the flow of minority carriers (electrons).

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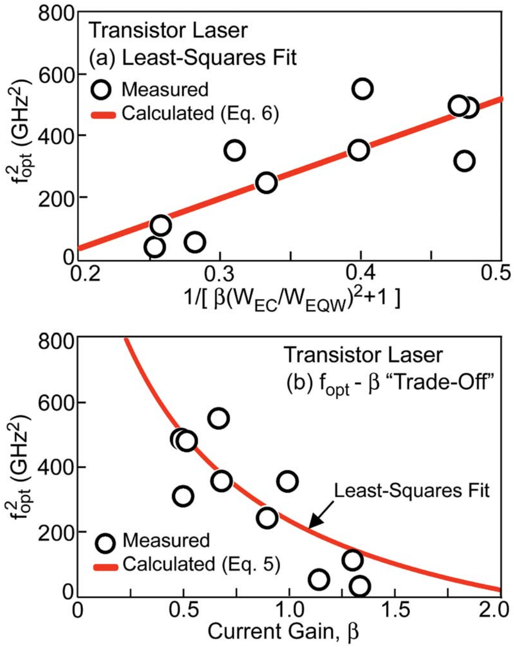

FIG. 2. (Color online) Plot of f_{opt}^2 vs β of the TL in Ref. 6. To obtain the data points (β, f_{opt}^2), the bias conditions (I_B, V_{CE}) are varied with the BC junction ($V_{\text{CB}}>0$) in usual reverse bias. The least-squares fit to Eq. (6) (solid line) yields the values $(1.32/2\pi)^2\,\Gamma/\tau_{t,2}\tau_p=1.6\times10^3$ GHz^2 and $\tau_{t,2}(1/\tau_{B,\text{spon}}+\Gamma v_g g\,\eta_i)=0.17$ (unitless).

TL by noting that $I_C=Q_1/\tau_{t,1}$ and $I_B=Q_2/\tau_{t,2}$. The transit times are given by $\tau_{t,1}=W_{\text{EC}}^2/2D$ and $\tau_{t,2}=W_{\text{EQW}}^2/2D$, where W_{EC} is the emitter-to-collector distance and W_{EQW} is the emitter-to-QW distance. For $D=26$ cm^2/s, $W_{\text{EC}}=880$ Å and $W_{\text{EQW}}=590$ Å, $\tau_{t,1}=1.5$ ps and $\tau_{t,2}=0.67$ ps. We obtain

$$\kappa \approx \frac{1}{\beta(W_{\text{EC}}/W_{\text{EQW}})^2+1} \tag{3}$$

and

$$\frac{1}{\tau_B} \approx \left[\frac{1}{\beta(W_{\text{EC}}/W_{\text{EQW}})^2+1}\right]\frac{1}{\tau_{t,2}}. \tag{4}$$

To obtain values of the differential optical gain, $\Gamma g'$, the *L-I* relation $v_g\alpha_m N_P=\eta_{\text{ext}}(I_B-I_{\text{TH}})/q$ is substituted into Eq. (2) to express N_P in terms of quantities that may be obtained experimentally. The factor α_m is the distributed mirror loss, I_{TH} is the threshold base current, and η_{ext} is the external quantum efficiency. With these substitutions, Eq. (2) becomes

$$\Gamma g' \approx \left[\frac{1}{\beta(W_{\text{EC}}/W_{\text{EQW}})^2+1} - \tau_{t,2}\left(\frac{1}{\tau_{B,\text{spon}}}+\Gamma v_g g\,\eta_i\right)\right] \times \frac{q\alpha_m V_{\text{active}}}{\eta_{\text{ext}}(I_B-I_{\text{TH}})\tau_{t,2}}. \tag{5}$$

Equation (5) exhibits the gain trade-off relation where a reduction in β accompanies an increase in the differential optical gain, $\Gamma g'$. By substituting the expression for the optical modulation bandwidth at -3 dB, $f_{\text{opt}} \approx (1.32/2\pi)\sqrt{\Gamma v_g g' N_P/\tau_p V_{\text{opt}}}$,[8] we may express Eq. (5) in a form convenient to use to extract the values of the numerical constants $\Gamma/\tau_{t,2}\tau_p$ and $\tau_{t,2}(1/\tau_{B,\text{spon}}+\Gamma v_g g\,\eta_i)$ from the experimental data. This yields

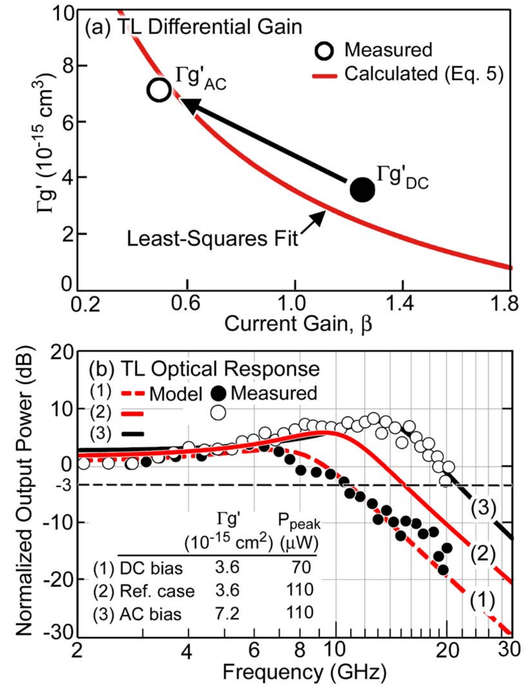

FIG. 3. (Color online) (a) Plot of the calculated differential optical gain vs current gain of a TL (see Ref. 6) using Eq. (5) and the experimental values $\alpha_m=59$ cm^{-1}, $I_{\text{TH}}=19$ mA, $\eta_{\text{ext}}=16\%$, $V_{\text{active}}=6.7\times10^{-12}$ cm^3 (emitter width of ≈ 3 μm), and steady-state conditions with $I_B=40$ mA, and $V_{\text{CE}}=1.5$ V. (b) TL measured optical response (see Ref. 6) and the corresponding calculated response for (1) the dc bias case of no auxiliary ac bias signal, (2) the reference ac bias case assuming in the model no gain trade-off, and (3) the ac bias case of the differential optical gain enhanced with auxiliary biasing and gain trade-off.

$$f_{\text{opt}}^2 \approx \left(\frac{1.32}{2\pi}\right)^2\left[\frac{1}{\beta(W_{\text{EC}}/W_{\text{EQW}})^2+1} - \tau_{t,2}\left(\frac{1}{\tau_{B,\text{spon}}}+\Gamma v_g g\,\eta_i\right)\right]\frac{\Gamma}{\tau_{t,2}\tau_p}. \tag{6}$$

The data for optical bandwidth f_{opt} of interest here are obtained by direct modulation of a TL as in Ref. 6. The TL is operated in its normal active mode, i.e., with its base-collector junction in reverse bias. The gain β, in general, varies as a function of bias I_B and V_{CE} and is obtained directly from the collector *I-V* characteristics (Ref. 6). A straight line, linear least-squares fit to the measured data, f_{opt}^2 versus $1/[\beta(W_{\text{EC}}/W_{\text{EQW}})^2+1]$, yields the values for the constants in Eq. (6) [Fig. 2(a)]. The plot of f_{opt}^2 versus β in Fig. 2(b) using the constants obtained from the least-squares fitting is consistent with the measured data. Some deviations are expected due to the simplifying assumptions made in arriving at Eqs. (2)–(4), and device limitations such as lateral resistance and loss and nonlinear effects that are not accounted for. Equation (6) implies that a TL system (of a given layer structure and design) with a larger intrinsic current gain β would inherently have more "room to trade" for improvement in the optical bandwidth.

Using the values of the constants obtained from Fig. 2, we calculate and plot in Fig. 3(a) the differential gain $\Gamma g'$ versus the current gain β. In the same figure, we plot experimental results showing that f_{opt} is improved from 10.5 to 22 GHz by using an external low-frequency auxiliary base-biasing signal.[6] In the case of auxiliary biasing, the gain β decreased from 1.3 to 0.5, conveniently making possible trade-off in electrical and optical gains. In the earlier work of Ref. 6, $\Gamma g'$ is obtained by the alternative procedure of fitting the measured frequency response over a range of microwave frequencies (2–20 GHz) to the expression $H(\omega)/(1+jf/f_{3\ \mathrm{dB}})$, where $H(\omega)$ is the intrinsic laser response given by the solution of the coupled photon-carrier rate equation.[3–5] The 3 dB pole, $f_{3\ \mathrm{dB}}$, is determined by the parasitic base emitter and base-collector junction charging time [Fig. 3(b)].[6] The differential optical gains obtained are $\Gamma g'_{\mathrm{ac}}=7.2\times10^{-15}\ \mathrm{cm}^2$ with and $\Gamma g'_{\mathrm{dc}}=3.6\times10^{-15}\ \mathrm{cm}^2$ without the effect of the auxiliary bias signal [curve 1 in Fig. 3(b)].[6] The response assuming no gain trade off in the model (i.e., the "gain-clamped," β and $\Gamma g'$ fixed during laser operation) is plotted as curve 2 in Fig. 3(b). Curve (2) based on the usual theoretical treatment of carrier-photon laser dynamics, where the bandwidth is enhanced by a higher photon density but the differential optical gain is fixed ("clamped"), does not explain the observations. The experimental observations[6] agree well only if we use the "gain trade-off" model [curve 3 in Fig. 3(b)] described here leading to Eq. (5). Note that since we are dealing with a TL and a tilted emitter-to-collector carrier population, no photon-carrier resonance is apparent.

Concluding, we show that in the three-terminal TL the current gain β may be "traded" for improvement in the differential optical gain and consequently in the optical bandwidth. Unique to the TL, i.e., trade-off of one gain for another [Eq. (5)], a reduction in the electrical gain β complements and yields an increase in the differential optical gain $\Gamma g'$. The two gains, electrical and optical, are coupled. This can be confirmed using an external low-frequency auxiliary base signal to reduce the gain β, thus increasing the base recombination, the photon density, and enhancing the optical bandwidth. Note that gain trade-off is much more convenient to increase the cavity photon population than optical methods such as Q-switching. The TL capability to trade-off current gain for optical gain and bandwidth provides an opportunity for greater design flexibility in optoelectronics and, in addition, circumvents (with a tilted dynamic emitter-to-collector carrier population) the bandwidth limitations of a "gain-clamped" carrier-population photon-density resonance.

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