Theoretical analysis of the damping effect on a transistor laser

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Abstract: The impact of carrier pulling on the modulation characteristics of a transistor laser is discussed. The results of a theoretical analysis of modulation bandwidth and damping effect show that the carrier transport effect obtained by using a transistor laser allows for a gain compression factor of about one-tenth that of a conventional laser ($0.7 \times 10^{17}$ cm$^3$), as well as for a maximum modulation bandwidth of 45 GHz.

Keywords: semiconductor laser, transistor laser, damping effect

Classification: Optoelectronics, Lasers and quantum electronics, Ultrafast optics, Silicon photonics, Planar lightwave circuits

References

1 Introduction

Because optical communication allows for substantial increases in data transmission speeds, use of systems such as fiber-to-the-home (FTTH) is on the rise. In the near future, 40–100 GbE systems will likely supplant the 1–10 GbE systems in current use [1]. Although the first generation of commercial modules for such systems utilizes laser diodes with electro-absorption modulators, the use of directly modulated lasers operating at speeds faster than 40 Gbps would represent a significant advance for this technology. In moving beyond laser diodes (LDs), transistor lasers (TLs) represent one candidate type of directly modulated, multifunctional light source that could meet the demands of operation above 40 Gbps. Previous studies have provided experimental data relating to electrical and current gain [2, 3, 4, 5, 6, 7] for TLs operating in the continuous wave (CW) mode; recently, CW operation using a 1.3-μm AlGaInAs/InP quantum well active region has also been reported [8]. Theoretical studies have also returned results including a primary analytical model that expands upon the carrier transport model [9, 10, 11, 12], an equivalent TL circuit model [11], and a large-signal analysis that clearly describes the differences in the operational mechanisms of LDs and TLs [12]. Although these reports all indicate that a larger TL modulation bandwidth could be achieved by carrier pulling in a transistor, they do not discuss the relationship between the magnitude of the carrier pulling and the modulation bandwidth.

In this paper, the carrier pulling dependence of the damping effect, which affects the maximum modulation speed needed in a high-speed TL design, is evaluated.

2 Modulation bandwidth of transistor lasers

In this Section, the impact of carrier pulling on the damping factor is assessed using small-signal analysis with a controlled degree of carrier pulling. Fig. 1 shows a structure of the TLs in our simulations. The active layer, which consists of AlGaInAs quantum wells (QWs), is located in the base layer and the both side of the active layer is covered with n/p/n/p thyristor structures as a buried hetero (BH) structure to confine the injected carriers and light.

A model of the TL used to represent the effects of carrier pulling is shown in Fig. 2. Carriers injected from the emitter ($J_E$) diffuse into the base layer, which serves as an active layer in which QWs have been set. Some of the diffused carriers are captured; these are recombined in the QWs, while the rest are diffused to the collector ($J_C$) and removed.
The small-signal response of a TL has been discussed in previous studies [9, 12]. For a common base (CB) configuration, response $\frac{\Delta S}{\Delta J_E}$ was originally described [12] using

$$\frac{\Delta S}{\Delta J_e} = \frac{\Delta S}{\cosh \left( \frac{d_B}{2L_D} \right) \Delta J_{V.S.} + q D_n \frac{L_D}{2L_D}} \left[ 2 \sinh \left( \frac{d_B}{2L_D} \right) + \frac{1}{\sinh \left( \frac{d_B}{2L_D} \right)} \right] \Delta N_{V.S.}$$

(1)

where $S$ is the photon density, $d_B$ is a base-width, $L_D$ is the diffusion length, $N_{V.S.}$ is the floating carrier density at a QW before capture or after escape from the QW, $J_{V.S.}$ is the current density at the position where $N_{V.S.}$ is measured, $q$ is the electron charge, and $D_n$ is the diffusion coefficient. For these simulations, parameters based on 1.3-$\mu$m AlGaInAs/InP quantum well lasers are used, which can be found from Ref. [12] using a coefficient of reflectivity of 0.3 for both facets. The effects of carrier pulling can then be determined by introducing a new term into Eq. (1):

$$\frac{\Delta S}{\Delta J_e} = \frac{\Delta S}{\cosh \left( \frac{d_B}{2L_D} \right) \Delta J_{V.S.} + q D_n \frac{L_D}{2L_D}} \left[ 2 \sinh \left( \frac{d_B}{2L_D} \right) + R_{col} \frac{1}{\sinh \left( \frac{d_B}{2L_D} \right)} \right] \Delta N_{V.S.}$$

(2)
where \( R_{\text{col}} \), which relates to the collector current, determines the carrier distribution rate beyond a certain energy gap at the base-collector junction. It should be noted that setting \( R_{\text{col}} = 0 \) reduces Eq. (2) to an LD response. By setting \( R_{\text{col}} = 0.02, 0.10, 0.25, 0.64, \) and 0.78, the differential base transport efficiencies \( \alpha_{\text{diff}} = \Delta J_C/\Delta J_E \) of (a) 0.07, (b) 0.26, (c) 0.47, (d) 0.64, and (e) 0.78 respectively, are obtained. In a region of low carrier pulling, such as that characterized by \( \alpha_{\text{diff}} = 0.07 \) (a), the modulation characteristics closely match that of an LD response curve, as shown in Fig. 3. Owing to slow carrier transport, the modulation responses of both the LD and the TL at (a) are strongly damped. On the other hand, a small amount of damping is observed at high carrier pulling magnitudes, such as (e), where fast carrier supply times into the QW active region lead to a band enhancement effect. In such cases, the response will be mostly limited by the relaxation oscillation (which is governed by the photon lifetime) as this is the same for both LDs and TLs. Fig. 4 shows the 3 dB modulation bandwidths of the LD and of the TL at values of \( \alpha_{\text{diff}} \) (a) to (e). By setting a required bandwidth, the necessary carrier pulling magnitude can be determined, and this magnitude can be controlled by designing an energy barrier within the base-collector junction or within the base energy gap itself. Modulation bandwidths of over 40 GHz can be obtained by using \( \alpha_{\text{diff}} \) (c) or (d). For (d), a base transport efficiency of \( \alpha_{\text{diff}} = 0.64 \) (at a current gain \( \beta_{\text{diff}} = 1.74 \)) was estimated.

### 3 Damping effect of transistor lasers

In this Section, the carrier pulling effect is shown quantitatively in a conventional format. It has been theoretically shown that the carrier transport effect can be expressed, using an equation similar to that for parasitic capacitance [13], as

\[
\left| \frac{s}{J_E} \right|^2 = \frac{A \cdot f_r^4}{\left( f_r^2 - f_r^2 \right)^2 \left( 1 + 4\pi^2 \tau_{\text{cap},E} f_r^2 \right)^2 + f_r^2 \left( \frac{\Gamma \sqrt{1 + 4\pi^2 \tau_{\text{cap},E}^2 f_r^2}}{2\pi} \right)^2} \tag{3}
\]

![Fig. 3. Small-signal responses of LD and TLs for various base transport efficiencies \( \alpha_{\text{diff}} \) at a recombination current \( I_{\text{rec}} \) of 100 mA.](image-url)
where $\tau_{\text{capE}}$ is the effective carrier capture time determined by the carrier diffusion time and the quantum capture time (which in turn is equivalent to the relaxation time from the unconfined 3D state $N_{V,S}$ to the confined 2D state, $N_{QW}$, used in previous sections [12], and $A$ is a fitting parameter. In addition to the carrier pulling effect, the damping factor $\Gamma$ is the major determinant of the reduction in sensitivity of the modulation characteristics. For large $\Gamma$, the response will be damped strongly. A total damping factor, $\Gamma_{\text{total}}$, incorporating the carrier transport effect can be expressed as a function of the effective carrier capture time as follows:

$$
\Gamma_{\text{total}} = \Gamma \sqrt{1 + 4\pi^2 \tau^2_{\text{cap,E}} f^2}
$$

Although $\Gamma$ may remain independent of the modulation frequency $f$ for a specific bias current, the total damping factor $\Gamma_{\text{total}}$ will increase with $f$. By fitting Eq. (3) to the series of simulated modulation responses shown in Fig. 3, $\tau_{\text{capE}}$ can be estimated (Table I). At $\alpha_{\text{diff}} = 0.78$, the effective carrier capture time is estimated as 2.3 ps, which is about one-fifth as long as that of the LD (11.5 ps). At $\alpha_{\text{diff}} = 0.47$, $\tau_{\text{capE}}$ is estimated to be approximately 6.0 ps. Fig. 5 illustrates the impact of the carrier transport effect on the total damping factor. For an LD at $f = 50$ GHz, the ratio of the total damping factor to the conventional damping factor, $\Gamma_{\text{total}}/\Gamma$, is approximately 5, whereas that of

![Fig. 4](image-url) 3 dB modulation bandwidths of LD and of TLs for various base transport efficiencies $\alpha_{\text{diff}}$.

![Fig. 5](image-url) Total damping factors as functions of frequency.
the TL ($\alpha_{\text{diff}} = 0.78$) remains close to 1. These results indicate that damping caused by the carrier transport effect can be removed by utilizing carrier pulling of an appropriate magnitude. In general, the maximum modulation bandwidth, $f_{\text{max}}$, of a directly modulated semiconductor laser can be given by using the so-called “$K$ factor” as follows:

$$f_{\text{max}} = \frac{2\sqrt{2\pi}}{K}$$

(5)

where

$$K = 4\pi^2 \left( \tau_p + \frac{\varepsilon_{\text{other}} + \varepsilon_{\text{trans}}}{G'} \right)$$

(6)

and $\varepsilon_{\text{trans}}$ is the gain compression factor corresponding to the carrier transport effect, whereas $\varepsilon_{\text{other}}$ corresponds to other effects, such as hole burning or carrier heating. By using the $K$ factor (or “gain compression factor”), it might be feasible to evaluate the ultimate modulation bandwidth of a TL where the damping caused by the carrier transport effect increases as a function of the modulation frequency $f$ (i.e., where $\varepsilon_{\text{trans}}$ is dependent on $f$). The estimated $K$ factor and $\varepsilon_{\text{trans}}$ used in this study (based on the calculated value of $f_{\text{max}}$) are listed in Table I. Here, a constant value of $\varepsilon_{\text{other}} = 0.5 \times 10^{17} \text{cm}^3$ is assumed. For the TL, the value of $\varepsilon_{\text{trans}}$ obtained is about one-tenth of that obtained for the LD. As discussed previously in this Section, the gain compression effect (which restricts the modulation bandwidth in conventional LDs) can be suppressed in TLs by use of a three-terminal configuration.

### 4 Conclusion

In this paper, damping caused by the carrier transport effect in a TL is described. For TLs, the base transport efficiency of the compression factor corresponding to a carrier transport effect of $0.7 \times 10^{17} \text{cm}^3$ is estimated to be 0.78, which is about one-tenth of the corresponding value in an LD. From these results, it can be seen that the TL technology is a strong candidate to be the next-generation light source.

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