LIMITATIONS ON SWITCHING SPEED IN WIDEBAND SEMICONDUCTOR LASERS

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ABSTRACT

An experimental and theoretical study of large-signal switching transients in directly modulated semiconductor lasers is reported. The main parameters affecting high-speed switching are identified and device-dependent limitations on modulation at multi-gigabit per second data rates are described.

INTRODUCTION

Improved understanding of the modulation dynamics of high-speed semiconductor lasers has led to impressive developments in wideband modulation performance [1], [2]. Bandwidths as high as 16 GHz at room temperature have been reported [2], with even higher figures being acheivable at lower temperatures. It is usual to characterize the modulation performance of high-speed lasers using small-signal (linear) frequency response measurements. This method is attractive, due to its relative simplicity, and is directly relevant to analog modulation applications. However, small-signal measurements do not give a complete picture of the laser's modulation behaviour. If the laser is to be used in gigabit per second pulse code modulation (PCM) applications, then the *large-signal* (nonlinear) modulation response also is important, [3], [4]. Large-signal switching delays, overshoot, and ringing all affect the maximum achievable transmission bit-rate and must be considered if device-dependent limitations on high speed operation are to be understood.

This paper reports an experimental and theoretical study of switching transients in directly modulated semiconductor lasers. The main circuit and device parameters affecting switching delays, rise- and fall-times, overshoot, and ringing are identified, and limitations on modulation at multi-gigabit per second rates are determined. Simple theoretical expressions for the large-signal switching transients, based on knowledge of the small-signal response of the laser, show good agreement with measured data. The large-signal transients, particularly the fall time at turn-off, impose limitations on the maximum achievable modulation bit rate. It follows that the maximum achievable bit-rate of a semiconductor laser under large-signal modulation is much less than can be obtained from a strictly linear system with the same bandwidth.

MEASUREMENTS

Fig. 1 shows the general form of a single pulse from a high-speed electrical drive signal and the resulting optical pulse waveform. The electrical drive pulse (upper curve) has an off-level current of I_{off} and an on-level current of I_{on}. The off-level current is usually set to be slightly above the threshold current (I_{th}) as shown. The 10% to 90% rise-time and the 90% to 10% fall-time of the electrical pulse are t_{re} and t_{fe}, respectively. The off-level and on-level optical power levels of the optical pulse (lower curve in Fig. 1) are P_{off} and P_{on}, respectively, and the peak power, due to overshoot, is P_p. The 10% to 90% optical rise-time is t_r and the 90% to 10% fall-time is t_f. The optical rise-time t_r can be quite small (~ 15ps in the laser used here), but there is also a significant delay t_{d1} between the leading edge of the electrical pulse and the resulting optical pulse. The corresponding turn-off delay is t_{d2}. (See Fig. 1 for the precise definitions of t_{d1} and t_{d2}.)

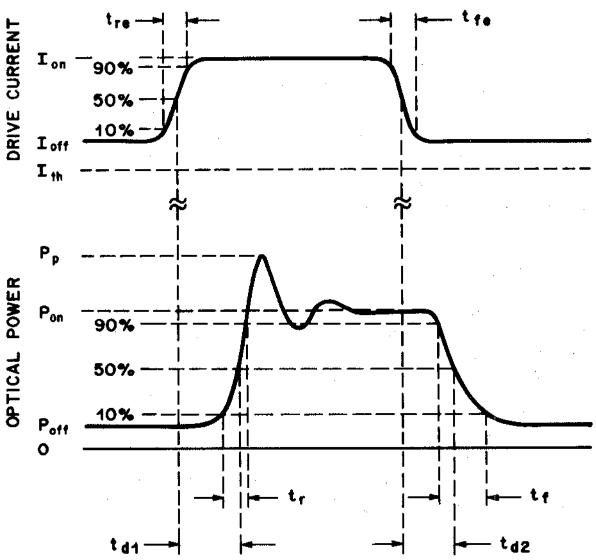

Fig. 1: Electrical drive pulse waveform (upper curve) and large-signal laser response (lower curve).

Measurements of switching transients have been carried out using the experimental setup shown in Fig. 2. A high-speed photoconducting microstrip switch on an InGaAs substrate [5] provides a fast transition-time ($t_{re} = t_{fe} \approx 22$ ps) electrical step function to the laser under test. Both turn-on and turn-off transients can be obtained by appropriate selection of the switch bias polarity. The optical output transient waveforms from the laser are measured by optical upconversion sampling in a nonlinear $LiIO_3$ crystal. The sampling source is a mode-locked dye laser, which provides ultra-short (0.5 ps) pulses synchronized to the switch [6]. The upconverted signal is detected using a photomultiplier tube (PMT) and a phase-sensitive lock-in amplifier, and the temporal characteristics of the laser response are

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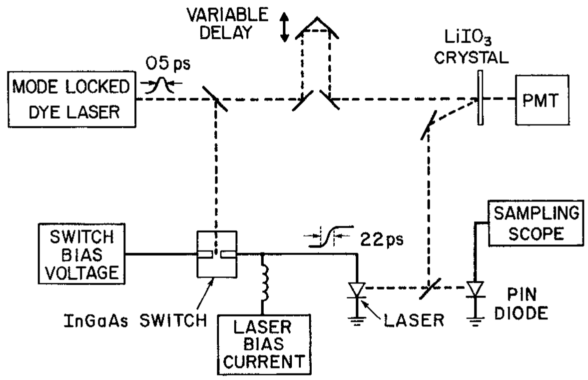

Fig. 2: Experimental setup.

determined by scanning a variable delay line in the path of the sampling pulses. The resolution of this detection system is approximately 0.5 ps, which enables the optical waveforms to be resolved completely. In comparison, the resolution of the fastest available pin photodiode [7] and sampling oscilloscope (Tektronix 7S11-7T11) is ~ 25 ps, which would give unacceptable measurement errors in the fast turn-on transitions [6].

(a) Turn on

Fig. 3 shows the measured optical rise time t_r and turn-on delay t_{d1} of a constricted mesa laser [2] as a function of the off-level current I_{off} for a drive pulse amplitude of magnitude $\Delta I = I_{on} - I_{off} = 75$ mA. For I_{off} less than the threshold current (30 mA), the delay t_{d1} is relatively large and is a strong function of I_{off}, while the rise-time is quite small (~15 ps). Above threshold the delay decreases slowly, while the rise-time is almost constant. The broken curves in Fig. 3 are calculated from expressions which have been obtained by analytical solution of the laser rate equations [8]:

$$t_{d1} = \frac{0.23}{f_r}\left[\ln\frac{P_{on}}{2P_{off}}\right]^{1/2} \qquad (1)$$

and

$$t_r = \frac{0.15}{f_r} \qquad (2)$$

where f_r is the small-signal relaxation oscillation resonance frequency[8] of the laser when biased at the on-level current I_{on}.

The calculated values of t_{d1} and t_r in Fig. 3 were obtained from (1) and (2) using data from an independent small-signal measurement of the resonance frequency f_r which employed a pin photodiode and microwave network analyzer. The resonance frequency f_r varied from 4 GHz at a bias current of 40 mA to 8 GHz at 100 mA. Agreement between the measured and calculated curves in Fig. 2 is reasonable. It is therefore possible to estimate the large-signal response characteristics using data taken from the measured small-signal response only.

The theoretical expressions (1) and (2) confirm that t_r is almost constant above threshold, due to the insensitivity of f_r (~8 GHz) to I_{on} over the range of I_{on} values used here. On the

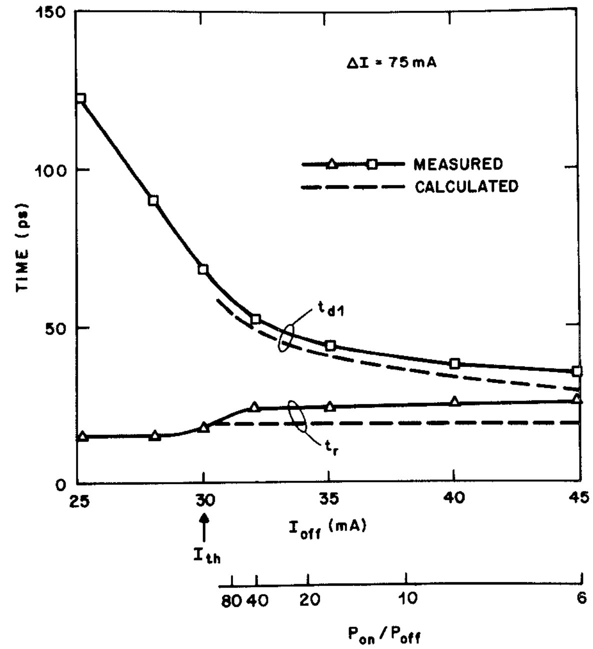

Fig. 3: Optical rise time and turn-on delay against off-level current for a 75 mA pulse height.

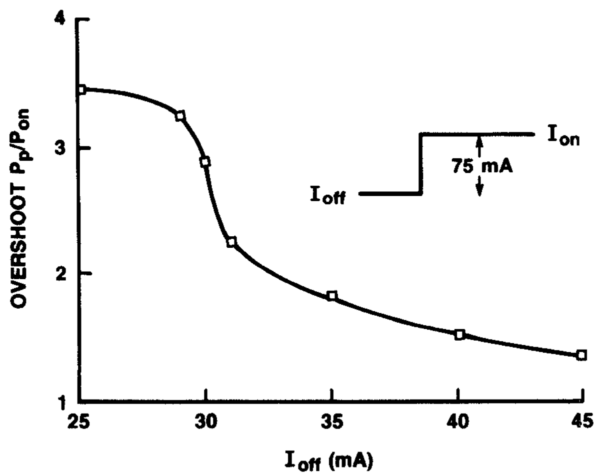

Fig. 4: Overshoot against off-level current.

other hand, t_{d1} decreases significantly as I_{off} is increased above threshold, due to the on/off ratio term P_{on}/P_{off} in (1). Fig. 4 shows the measured overshoot P_p/P_{on} against I_{off} for the same 75 mA current step. The overshoot is large below threshold, but decreases rapidly as I_{off} increases above threshold. The overshoot characteristic is of particular interest in long haul systems since frequency chirp of the optical carrier is directly associated with fast transitions in output power, and this leads to a potential degradation in system performance due to the effects of fiber dispersion [8].

It can be seen from Figs. 3 and 4 that the turn-on delay and overshoot are both reduced as the off-level current I_{off} is increased above threshold. This suggests that in systems applications it would be desirable to adjust the bias to a value well above threshold. However, increasing I_{off} tends to decrease the on/off ratio P_{on}/P_{off} which, in turn, causes a receiver sensitivity penalty.

(b) Turn off

Fig. 5 shows the measured and calculated optical fall-time t_f and turn-off delay t_{d2} as a function of I_{on} for I_{off} fixed at 32 mA (2 mA above threshold). The theoretical data is based on simple expressions which have been obtained by solution of the rate equations. These expressions are

$$t_{d2} = \frac{0.22}{f_r} \tag{3}$$

and

$$t_f = \frac{0.39}{f_r} \tag{4}$$

Note that the turn-off transition time t_f is significantly larger than the turn-off delay t_{d2}. This transition time is also larger than the rise time t_r, and will become the major speed limitation in high bit rate applications, particularly if there is significant parasitic capacitance shunting the device [8]. A linear network with a strongly damped low-pass transfer function has transition times which are approximately 65% of t_{d2} [9]. Thus the maximum bit rate of the semiconductor laser under large signal conditions is approximately 65% of what could be obtained in a linear system with the same small-signal bandwidth.

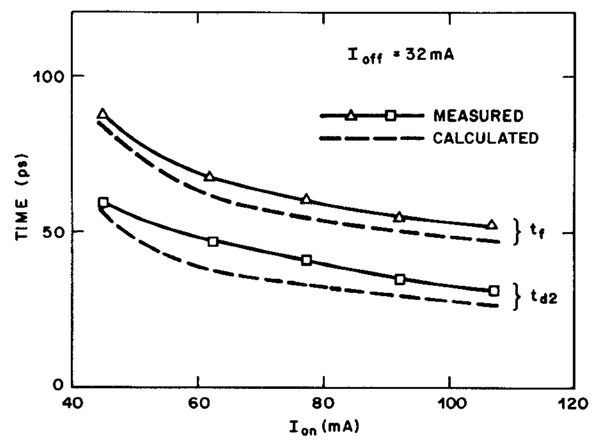

Fig. 5: Optical fall time and turn-off delay against on-level current for an off-level current of 32 mA.

CONCLUSIONS

High-resolution measurements of large-signal switching transients in high-speed InGaAsP lasers have been demonstrated. Switching delays, transition times, and overshoot have been measured as functions of bias conditions, and simple analytical expressions have been presented which enable the delay times and transition times to be estimated from small-signal data. The turn-off transition time is a major limitation on switching speed.

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