Large-signal dynamics of an ultrafast semiconductor laser at digital modulation rates approaching 10 Gbit/s

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(Received 1 March 1985; accepted for publication 7 May 1985)

High-fidelity pseudorandom digital modulation at 8.2 Gbit/s of an ultrahigh speed semiconductor laser is demonstrated. Studies using simple but representative pulse patterns at 10 Gbit/s give insights into the maximum digital modulation rate attainable from a given laser, as well as relations between large-signal digital performance and small-signal analog response.

Significant progress has been made recently in the development of very high speed semiconductor lasers with direct modulation bandwidths in excess of 10 GHz.[1] One of the most common criteria for characterizing the speed of various semiconductor lasers is the corner frequency (defined, as in standard network theory, the resonance frequency or the -3 dB frequency in case a resonance is absent) under small-signal modulation. This type of characterization applies well to analog or microwave modulation but does not provide sufficient information as to the behavior of the laser under large-signal digital modulation. Results from the former are, however, often good indicators of the latter. Some qualitative conclusions drawn from previous studies[2] are that biasing the laser above threshold reduces relaxation oscillation, which tends to be weaker in lasers with a small resonance in the small-signal response. Recently, analytic results were derived which relate the large-signal performance (turn on/of time, overshoot, ringing) to small-signal parameters.[3] This letter reports on experimental studies of large-signal digital modulation at high bit rates ($\rightarrow$ 10 GHz) of an ultrafast GaAlAs laser.

The laser employed in this study was of the window buried heterostructure type described previously.[4] The small-signal modulation response (Fig. 1) shows a comparatively strong resonance peak at low optical levels, which disappears at higher power levels, typical of semiconductor lasers in general. Digital modulation with true pseudorandom pulses at rates beyond 2 Gbit/s is hampered by the lack of commercial generators. A quasirandom bit pattern is generated in our experiment using the arrangement where the output from a step-recovery diode is split and combined a number of times with suitable delays in between. One bit pattern generated is 101101001011010 at a rate of 8.2 Gbit/s, as shown in the top display of Fig. 2. The amplitude of the digital pulses is approximately 0.5 V (into 50 Ω), which would under ideal conditions produce a swing of $\sim$4 mW in the laser output. The response of the laser to the pseudorandom pulse pattern is shown in the lower two displays in Fig. 2 under two bias conditions. In the middle display the laser is biased considerably above threshold and the modulation depth is 60%, while in the bottom display the laser is biased closer to threshold, with the "off" level below 0.5 mW. The former is a faithful replica of the current drive and is therefore highly satisfactory, while the latter is obviously not.

While the type of simulation described above serves to illustrate the usefulness of the device under digital modulation, a better understanding of the large-signal dynamics of the laser can be gained by observing the response of the laser to simple but representative digital patterns. If the bit patterns have, when averaged over a few clock periods, a 50%

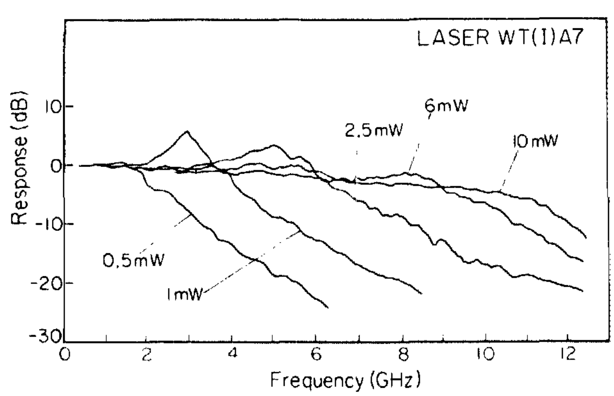

FIG. 1. Small-signal microwave modulation response of a window buried heterostructure laser.

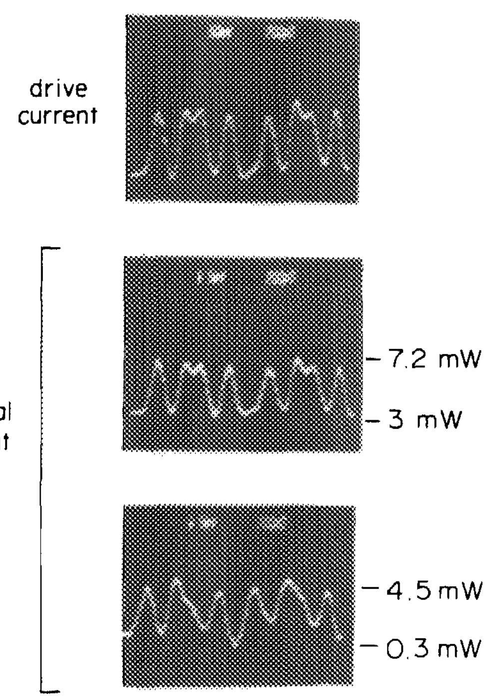

FIG. 2. Drive pulses (top) and the laser response under two different bias conditions.

duty cycle, then the laser can be regarded as being biased midway between the "on" and "off" levels and being modulated by an rf signal superimposed on the bias. The performance of the laser can then be predicted by the small-signal microwave modulation response of the laser biased at that particular level. The "small-signal" regime can include modulation depths as high as 60–70%.[5] However, the interesting cases are those when the bit pattern contains a long string of 0's or 1's. (Very long strings of 0's and 1's are usually avoided in digital systems using schemes such as Manchester Coding, since such unfortunate patterns can cause timing problems at the receiver or do other mischiefs.) The patterns that we chose to study are (a) two 0's of various spacings within a long string of 1's and (b) the complement of the above. The amplitude of the drive pulses is fixed, but the optical power level at which the 1's (or 0's) occur is varied.

The digital patterns at the rate of 10 Gbit/s are generated in the way described above. The complementary patterns are generated using a picosecond pulse inverter. The pulses are coupled into the laser using a microwave bias *T*. Since the double pulses occur at a low duty cycle, the dc bias applied to the laser is basically the 0/1 level in the case of positive/negative-going pulses. A pattern of ...010... in the midst of a long string of 1's is shown at the top left corner of Fig. 3(a).

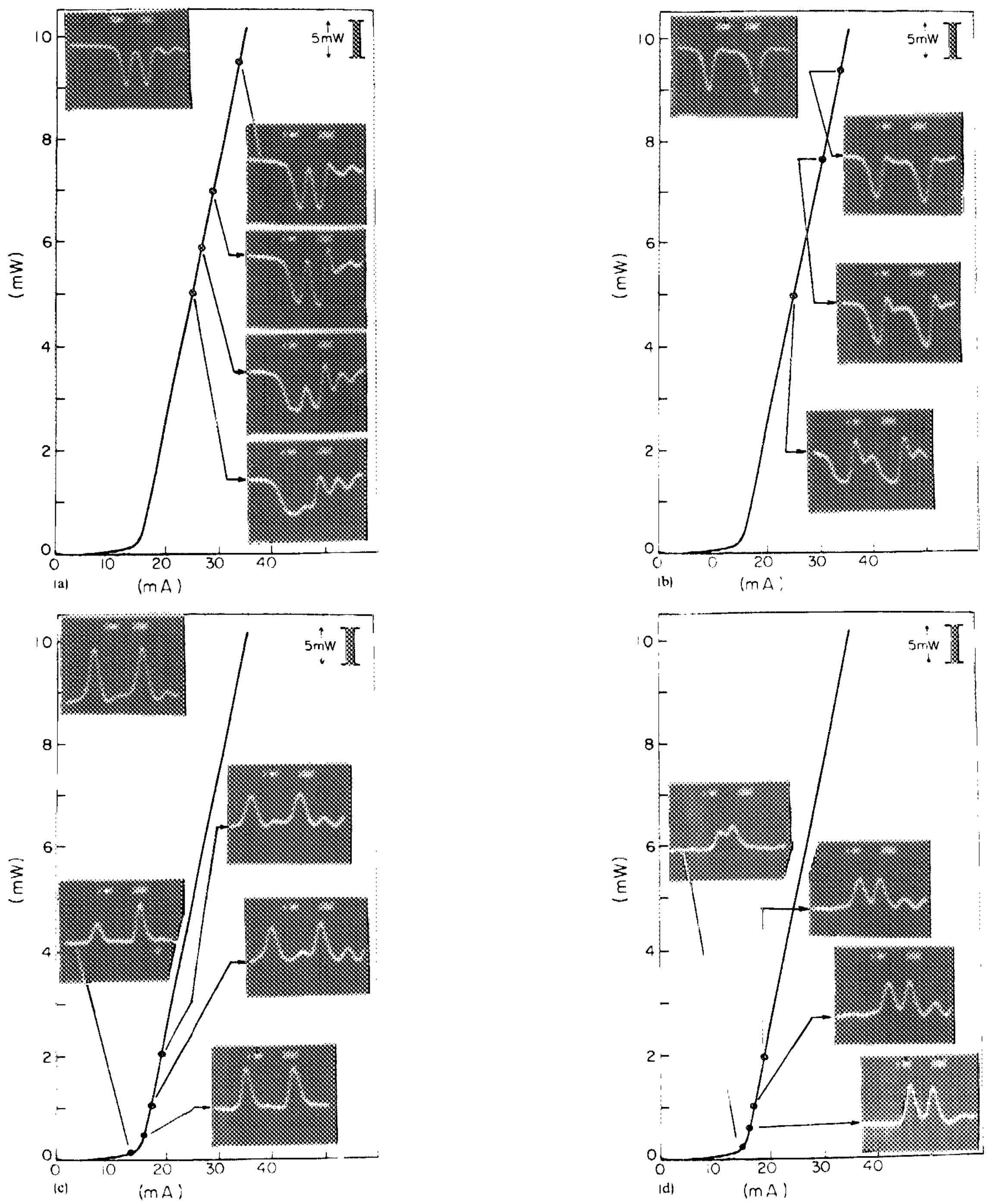

FIG. 3. Response of the laser to drive pulse patterns, shown on the top left hand corner of the figures [except in (d) which is just an inversion of (a)], at various bias conditions. (a) ...010... in the midst of 1's; (b) ...01110... in the midst of 1's; (c) ...10001... in the midst of 0's; (d) ...101... in the midst of 0's.

The response of the laser, whose light-current characteristic is also shown in the figure, is shown in the scope displays in this figure, at various bias levels (the levels of 1). The vertical scale of the displays in terms of optical power is shown at the top right-hand corner of the figure, and the time scale is 100 ps/div for all displays. It is apparent that as the 0 level approaches threshold, the laser responds sluggishly towards a 1 pulse, accompained by heavy relaxation oscillation. This occurs when the 0 level goes below ~ 1 mW.

The case of a ...01110... in the midst of a long string of 1's is shown in Fig. 3(b). As in the previous case, the laser responds faithfully when biased at 9.5 mW, with relaxation oscillation increasing when biased at lower levels.

The case of ...10001... in the midst of a long string of 0's is shown in Fig. 3(c). The optical response is faithful when the bias (i.e., 0 level) level is at 2 mW or above. When the 0 level is lowered to 1 mW, significant relaxation oscillation occurs when going from 1 to 0. This can be understood from the analog response characteristic, Fig. 1, which shows that the laser has a comparatively large resonance in the neighborhood of 1 mW. When the 0 level is lowered further, there comes a point ($\sim 1/2$ mW) when a clean response is observed without any ringing [bottom display, Fig. 3(c)]. The response is, however, nonlinear since the detailed shape of the input drive is not reproduced as in the previous cases. This operating condition is ideal for single-pulse modulation but is less than favorable when going one encounters a transition from 0 to a string of 1's, as shown in Figs. 3(a) and 3(b). When one further lowers the 0 level below lasing threshold, there is a large disparity in the amplitude of the two 1's. This is the well known pattern effect which arises from residual charge storage in the laser.[6]

The complement of the above, ...101... in a long string of 0, is shown in Fig. 3(d). The general trend at different bias levels follows those of Fig. 3(c). Notice that there also exists a bias level (at $\sim 1/2$ mW) at which the response appears to be ideal, but which, as pointed out in the last section, becomes less satisfactory when going from 0 to a string of 1's.

It appears from the above measurements that to obtain the highest digital modulation rate from a given laser with minimum transient effects, one should have (a) the 1 level at a high optical power (presumably at the maximum rated power of the device) and (b) the 0 level at the lowest optical power at which the small-signal response ceases to exhibit a prominent resonance. The former maximizes the transition speed while the latter minimizes relaxation oscillation during the high to low transition. The example shown in Fig. 2 is based on this format. The digital modulation rate attainable in this format is basically that of the small-signal corner frequency of the laser when biased midway between the high and low levels. If one assumes a maximally flat small-signal response (i.e., $Q = 0.7$), the transition time, as measured from the application of the current step to the maximum of the optical output (with a 4% overshoot) is $0.56 f_r$, where f_r is the corner frequency. For $f_r = 10$ GHz as in this study, the transition time is 56 ps. The transition times of the drive current pulses as shown in Fig. 3 are approximately 70 ps, and to the best as one can tell the transition times of the laser are the same as those of the drive pulses.

The optimal digital scheme described above necessitates a less than 100% extinction ratio. For the type of laser described in this letter, the suppression of the small-signal resonance usually occurs at 2 mW, which should be chosen as the 0 level. The 1 level can be as high as 20–30 mW, since the catastrophic damage level of these lasers lies beyond 100 mW. The extinction ratio can thus be as high as 90%. The extinction ratio in our simulation (Fig. 2) is limited by the amplitude of the current pulses available. A low extinction ratio will incur penalties in the signal/noise ratio in very long distant transmission (beyond 100 km), but such penalties are minimal in shorter links, such as in computer communications where the data-shuffling speed is of primary concern. The experiments in this letter show quite convincingly that recently developed high-speed lasers with a small-signal bandwidth of 10 GHz/s can indeed be used for large-signal digital transmission at 10 Gbit/s.

This work is supported by Defence Advanced Research Project Agency and Naval Research Laboratory.

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