Improving the Switching Performance of a Wavelength-Tunable Laser Transmitter Using a Simple and Effective Driver Circuit

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***Abstract*—We report a simple and effective method to reduce the switching time of a semiconductor tunable laser. We perform simulation and experiment to investigate the limitation in achieving fast switching. A low output-impedance driver is used to effectively reduce the settling time of the diode current of the laser tuning section.**

***Index Terms*—Driver circuits, laser tuning, semiconductor lasers.**

I. INTRODUCTION

FAST wavelength-tunable lasers have shown many useful applications in packet-switched wavelength-division-multiplexed systems [1]–[8]. In such systems, the switching time of the tunable laser is a critical parameter that limits the minimum guard time between adjacent packets and, therefore, the transport efficiency of the system. For data packets with lengths of microseconds duration, nanosecond-scale switching time is desired. For a grating-assisted codirectional coupler with rear sampled reflector (GCSR) laser, the switching time depends on the carrier response of the tuning sections, which is affected by the driver circuit and the electrical characteristic of the tunable laser. To speed up the switching process, overshoot–undershoot pulses were added at the rising and falling edges of the driving-current signals to effectively reduce the switching time of the tunable laser [3], [7]. The amplitude and the time duration of the overshoot–undershoot pulses should be carefully adjusted to achieve optimum switching performance. Such an overdriving technique was used in a fast-tunable transmitter with a programmable logic device to store the overshoot–undershoot values [3], switching between six wavelengths was successfully demonstrated. However, the optimum overshoot–undershoot parameters depend on the particular combinations of the channels, a complete optimization of the switching parameters for all channel combinations would become complicated and time consuming. For example, a 32-channel tunable laser would require the adjustment of 992 overshoot–undershoot parameters.

In this letter, we study the switching characteristic of a GCSR laser. We present a simple voltage-driver circuit that can effectively reduce the switching times for all channel combinations without the need for per-channel adjustment. The tunable laser transmitter can switch between 992 channel combinations in under 45 ns [9], compared to 80-ns maximum switching time using the same GCSR tunable laser driven by conventional current drivers. The average switching time is improved from 36 to 18 ns. Note that these results were obtained with a frequency accuracy of ±10 GHz under switching conditions, while the frequency accuracies in previous experiments were not reported. This scheme adds no additional components compared to conventional current drivers. The proposed driver circuit would significantly simplify the process in laser module calibration.

In the following sections, we first model an electrical circuit of the laser tuning sections, then we determine the values of the elements in the circuits by dc and microwave S_{11} measurements. By simulation, we find that slow switching is related to the equivalent high impedance of the tuning sections when they are switched to low-current values. We propose the use of a voltage driver having a low output-impedance to reduce the equivalent resistance–capacitance (RC) time constant of the tuning section when it is connected with the voltage driver. The improvement is clearly shown by simulation and experimental results.

II. PARAMETER EXTRACTION OF LASER TUNING SECTIONS

The GCSR laser is a semiconductor laser with three tuning sections: coupler, phase, and reflector. Injecting currents into the tuning sections change the refractive index and, therefore, the output wavelength. The circuit model of the tuning sections of the GCSR laser can be created with certain modifications from a classic laser model [10], as shown in Fig. 1. The modified model does not contain stimulated photon generation since the bandgap of the tuning section is wider than that of the active section. Once the stimulated emission is neglected, the spontaneous emission has no impact on electrical parameter extraction based on the model in [10]. C_p, L_p, and R_p are the parasitic capacitance, inductance, and resistance of the package, respectively. $R_{\rm sub}$ is the resistance of the substrate, C_s is the effective shunt capacitance associated with the insulator layer of the chip. R_s is the resistance in series with the diode junction, which contains the effect of substrate resistance. D is the junction diode of the switching section. The model parameters can be extracted from a combined dc and ac measurement.

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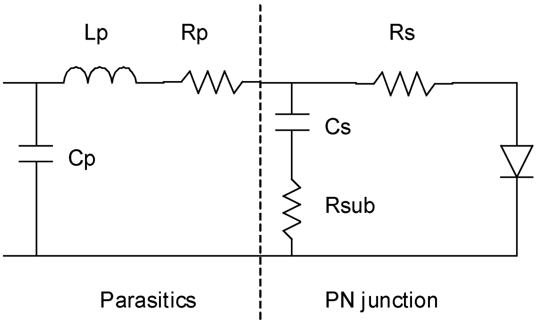


Fig. 1. Circuit model of tuning section of the GCSR laser.

TABLE I
FITTED PARAMETERS FOR THE REFLECTOR SECTION

Parameters	Reflector biased at 10 mA
I_s(A)	1.79×10^{-5}
θ	4.47
R_p (ohm)	0.1
R_s(ohm)	0.1
R_{sub}(ohm)	1.0
C_p(pF)	4.58
C_s(pF)	355
L_p(nH)	21.4

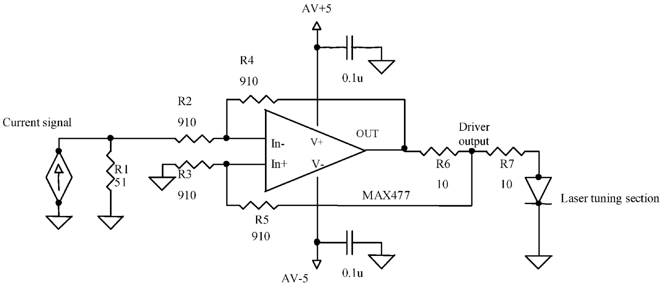


Fig. 2.Conventional current driver circuit for the laser tuning section. The laser tuning section contains the circuitory of Fig. 1.

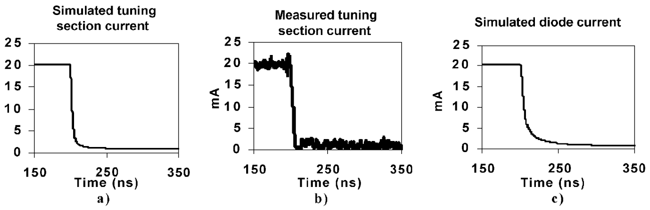


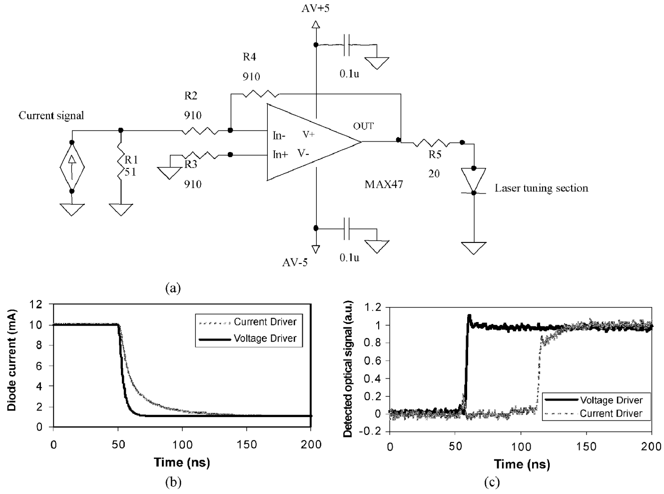
Fig. 3. (a) Simulated injected current into the reflector. (b) Measured reflector current. (c) Simulated junction diode current.

First we perform a current–voltage (I–V) dc measurement to characterize D and obtain the values of R_p and R_s. All capacitors and inductors in Fig. 1 have no effect in this dc measurement. The I–V characteristic of D is given by $I = I_s \exp((qV_j/\theta kT) - 1)$, where V_j is the junction voltage of the diode, I_s the saturation current, θ the emission coefficient, k the Boltzmann's constant, and T the temperature in K. The I–V relation of the tuning section, therefore, satisfies $V = I(R_p + R_s) + (\theta kT/q)[\ln(I/I_s) + 1]$, where V is the port voltage. Note that the I–V measurement provides the result of $R_p + R_s$; the value of R_p can be obtained by performing ohm measurement. Other dc parameters are obtained by fitting the theoretical model with the experimental data. Second, the rest of the circuit parameters can be extracted from a microwave S-parameter measurement. S_{11} is a reflection parameter commonly used in microwave techniques to probe the electrical properties of a device. The device impedance Z is related to the measured reflection factor S_{11} by $Z = Z_0((1+S_{11})/(1-S_{11}))$, where Z_0 is the characteristic impedance of the transmission line between the network analyzer and the device under the test. The RF parameters are extracted by fitting the complex impedance of the tuning-section circuit model with the impedance converted from the S_{11} measurement. The frequency range of interest we use in the parameter fitting is from 30 kHz to 400 MHz, which is sufficient for the driver circuit bandwidth. The microwave signal power from the network analyzer is −40 dBm to avoid nonlinear distortion. We performed the measurement for the reflector section, since the switching dynamics is mostly limited by this section due to its largest area among three tuning sections. Furthermore, the required tuning current for the reflector section covers a wide range including low current values for some channels [9], which cause longer switching time due to the equivalent high impedance of the tuning section. In contrast, the change of tuning currents for the coupler and phase sections is small relative to that for the reflector section, and we find driver optimization for the reflector section is the deterministic factor in achieving fast switching. Table I summarizes the results of the fits for the reflector section.

III. SIMULATION AND EXPERIMENT

Using the extracted circuit parameters, we create a tuning-section macro model that is compatible with commonly used circuit simulation software. We first study the switching performance of the tuning section driven by a conventional current driver. The driver circuitry is a current amplifier using a wide-band operational amplifier from Maxim (MAX477), as shown in Fig. 2. Under the condition that $R_2 = R_3 = R_4 = R_5 \gg R_1$ and R_6, the current gain of the amplifier is approximately given by $G = R_1/R_6$. The step signal response time of the circuit itself, with a resistor as the load, is ~10 ns.

We use a current step as the stimulus source, as if it were from a current-output digital-to-analog converter. An experiment was carried out to compare with the simulation result. In the experiment, the voltage drop on the resistor R_7 between the driver circuit and the tuning section were measured. The current sent to the tuning section is determined by the voltage drop across this 10-Ω resistor. Fig. 3(a) and (b) shows the simulated and measured currents through the tuning section, respectively, when a 20- to 1-mA current step is applied to the reflector. The noise on the measured curve mostly comes from the oscilloscope. However, the refractive index change of the reflector section of a GCSR laser is determined by the effective current through the junction diode (D in Fig. 1) rather than the current out of the driver. Simulation allows the investigation of the internal dynamics of the tuning section that would be hard to realize by experimental means. The simulation shows the current through the diode junction is much slower than the driver current, the settling time of the current to reach 99% of the stable value is 97 ns for the junction diode as shown in Fig. 3(c), compared to



(a)

(b)

(c)

Fig. 4. (a) Proposed voltage-driver circuit. (b) The current through the junction diode of the tuning section using a current driver, and a voltage driver, respectively. (c) The optical switching performance measurements.

35 ns for the tuning section in Fig. 3(a). This is because the parasitics and the chip insulator-layer capacitance C_s distort the driving current before it is injected into the junction diode. Based on the simulation as well as the experimental verification in [9], we find that the long switching time is mostly related to the equivalent high impedance of the tuning section diode when it is switched to low current. Therefore, the diode current settling time can be decreased by using a low output-impedance driver so that the RC time constant can be effectively reduced. In Fig. 4(a), we show a proposed voltage-driver circuit. Note that the driver output voltage and the tuning section input current are no longer linearly related. Previously, voltage driver was used to reduce the temperature effects on vertical-cavity surface-emitting laser arrays (VCSELs) under constant operation condition [11]. Here we take advantage of the low output-impedance of the voltage driver to reduce parasitic effects when the laser is under switching condition. Fig. 4(b) shows the simulated currents through the diode junction of the reflector section, when the current driver and the voltage driver are used, respectively. In this particular case, we use a 10- to 1-mA current step to investigate the performance of the tuning section. This stimulus covers the range of the driver currents for the reflector [9], thus, it is of particular interest for studying the switching performance of the tuning section. Based on the simulation, we find that the switching dynamics are primarily limited by C_s, the equivalent resistance of the junction diode, and the driver output impedance. Clearly the diode current settling time is reduced using the voltage driver due to its low output impedance of 2 Ω, compared to $\sim$2 K $\cdot$ Ω output impedance of the current driver. We also perform an experiment to compare the optical switching times by using current driver and voltage driver, respectively. We apply a current step from 10 to 1 mA to the reflector section, while keeping the currents of the coupler and phase sections constant. We use an optical filter with a 0.2-nm bandwidth to detect the switched signal at 1548.5 nm. Note that the settling time of the diode current correlates with the switching time of the tunable laser, which is counted between the start of the current step and the detected signal after the optical filter reaches 80% of its stable value. Fig. 4(c) clearly shows that the switching time of the optical signal is reduced from 65 to 6 ns, where the current step starts at 50 ns. We use this technique in the works reported in [9]. In those works, by using voltage drivers for the three tuning sections, the average value of the optical switching time reduces to 18 ns, compared to 36 ns in the case of using current drivers. The maximum switching time is reduced from 80 to 45 ns.

IV. CONCLUSION

We study the switching performance of a GCSR laser. We first extract the internal-circuit parameters of the tuning section of the laser by dc and microwave S-parameter measurements. Based on simulation, we find that the slow switching times for some channels are associated with the equivalent high impedance of the laser tuning section under low driving-current condition, which results in long settling time due to the large RC time constant. A low output-impedance driver is used to effectively reduce the switching time, and an experimental result of optical switching is provided. Experimental data are in good agreement with simulation results. A separate measurement shows that the average switching time is reduced from 36 to 18 ns for 992 switching combinations by using the proposed simple voltage-driver circuit.

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