Interfacing Maxim Laser Drivers with Laser Diodes

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I. Overview

Interfacing laser driver circuits with commercially available laser diodes at high data rates can be a complicated and frustrating task. This application note is intended to briefly address this topic with the goal of providing a useful reference for optical system designers that will simplify this process as much as possible.

The three major pieces of the laser interface puzzle include (1) the output circuit of the laser driver, (2) the electrical characteristics of the laser diode, and (3) the interface between them (which is usually implemented using a printed circuit board). In this application note, the characteristics of the laser diode and laser driver will first be discussed individually, and then they will be brought together in a discussion of the printed circuit board interface. An optimization section is also included that illustrates possible solutions to a number of common interface problems.

Although this application note is intended to be general in nature, specific examples will focus on Maxim's 2.5 Gbps telecommunication laser drivers such as the MAX3867 and the MAX3869.

II. Laser Diode Characteristics

In general, coherent optical output can only be generated and maintained in a semiconductor laser diode when the laser current is above its threshold value. For fast switching operation, it is a common practice to bias the laser diode slightly above the threshold to avoid turn-on and turn-off delay. The laser optical output depends on the driving current amplitude and the current-to-light conversion efficiency or slope efficiency of the laser diode. Both the threshold current and the slope efficiency are strongly related to laser structure, fabrication process, fabrication materials, and operating temperature.
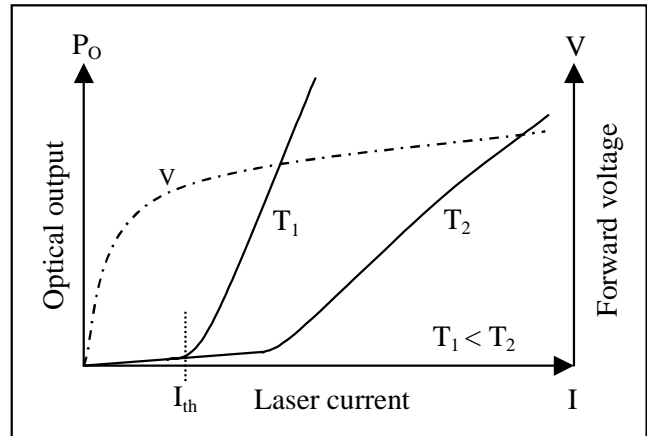

Figure 1. Laser current, forward voltage, and optical output

Figure 1 represents the voltage-current characteristic and the optical output-drive current relationship of a typical laser diode.

As the temperature increases, the threshold current (I_{th}) goes up in an amount exponentially proportional to the working temperature (T), which can be estimated by

$$I_{th}(T) = I_0 + K_I \cdot e^{\frac{T}{T_I}} \qquad (1)$$

where I_0, K_I, and T_I are laser-specific constants. Example constants for a DFB laser are $I_0 = 1.8\text{mA}$, $K_I = 3.85\text{mA}$, and $T_I = 40°C$.

The laser slope efficiency (S) is the ratio of the optical output power (in milliwatts) to the input current (in milliamperes). Increases in temperature cause the slope efficiency to decrease. The following equation provides a good estimation of the slope efficiency as a function of temperature:

$$S(T) = S_0 - K_S \cdot e^{\frac{T}{T_S}} \qquad (2)$$

For the same DFB example laser as above, the characteristic temperature, T_S, is close to 40°C and the

other two laser constants are $S_0 = 0.485mW/mA$ and $K_S = 0.033mW/mA$.

The relationship between the laser operating voltage (forward voltage, V) and the laser current (I) can be modeled by the diode voltage-current characteristic

$$I \approx I_S \cdot e^{\frac{V}{\eta \cdot V_T}} \tag{3}$$

where I_S is the diode saturation current, V_T is the thermal voltage, and η is a fabrication constant. When the laser diode is driven close to and above threshold, the voltage-current relationship is approximately linear, as shown in Figure 1.

A simplified model of a laser diode is shown in Figure 2. In this figure, the DC-offset voltage, V_{BG}, is associated with the bandgap voltage of the laser diode and R_L represents the dynamic resistance of the diode. When driving the laser above threshold, the optical output of the laser diode, P_0 (shown in Figure 2), can be estimated by
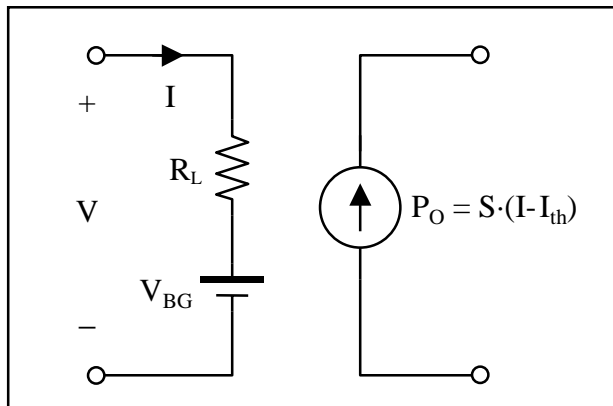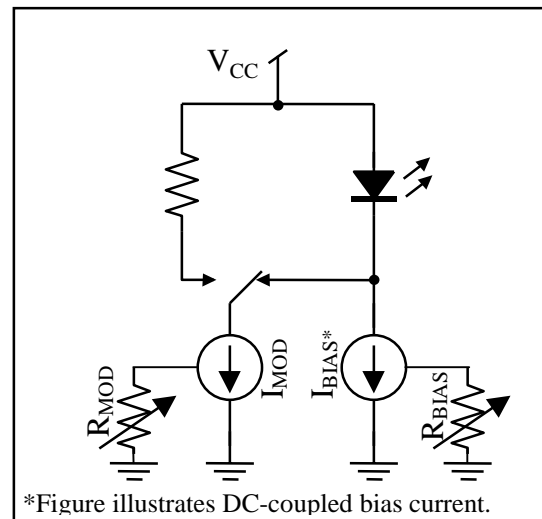
$$P_0 = S \cdot (I - I_{th}) \tag{4}$$

Figure 2. Simplified laser diode equivalent circuit

It is important to note that parasitic elements (i.e., bonding wire inductance) should be considered when modeling a packaged laser.
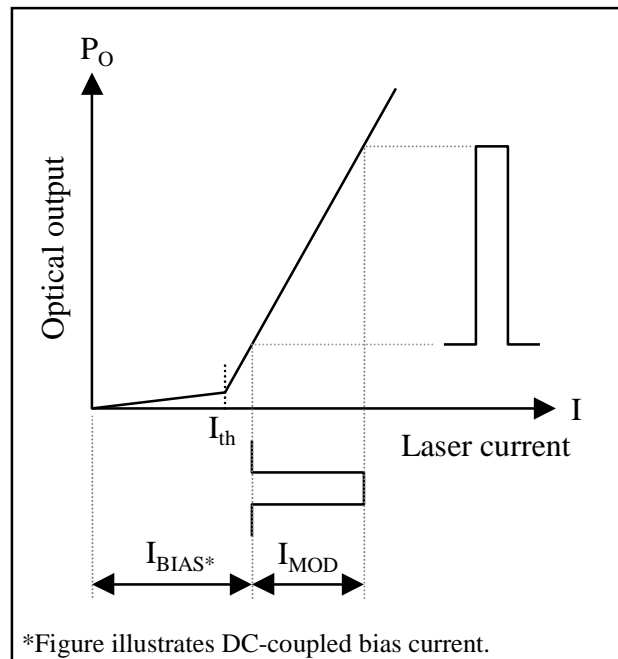
III. Laser Driver Output Structure

The primary function of a laser driver is to provide appropriate currents for bias and modulation of the laser diode (Figure 3). The bias is a constant current

(a) Functional diagram

(b) Input-output characteristics

Figure 3. Laser driver functionality

that pushes the laser diode operating range beyond its threshold value and into the linear region. Modulation is an alternating current that is switched on and off in synchronization with the input voltage waveform. Ideally, the bias current should track the changes in threshold current and the modulation current should track the changes in slope efficiency.

Laser drivers such as the MAX3867 and the MAX3869 are designed to drive common-anode laser diodes. The bias current can be set between a minimum value (typically 1-5mA) and the maximum value (typically 60-100mA) by using an external resistor.

It is important to maintain a constant impedance at the cathode of the laser diode such that the load on the high-speed output circuit versus frequency will remain stable. An unstable load on the output circuit can cause reflections, ringing, etc., that will degrade the quality of the optical waveform. The shunt capacitance associated with the biasing current source results in an impedance (Z_{BIAS}) that is a function of frequency. In order to minimize the effect of this impedance variation, an external isolation inductor (or ferrite bead) is generally connected between the cathode of the laser diode and the bias circuit. This inductor has no effect on the DC bias current but appears as a high impedance to the modulation current.

The magnitude of the modulation current is determined by external resistor R_{MOD} (Figure 4). This resistor controls a current source associated with the differential output stage. The laser driver outputs are connected to the collectors of the output stage transistors. In most cases, pullup components used with the open-collector outputs (resistors or inductors) are external to the laser driver (pullup considerations are discussed in the PC Board Interface section).
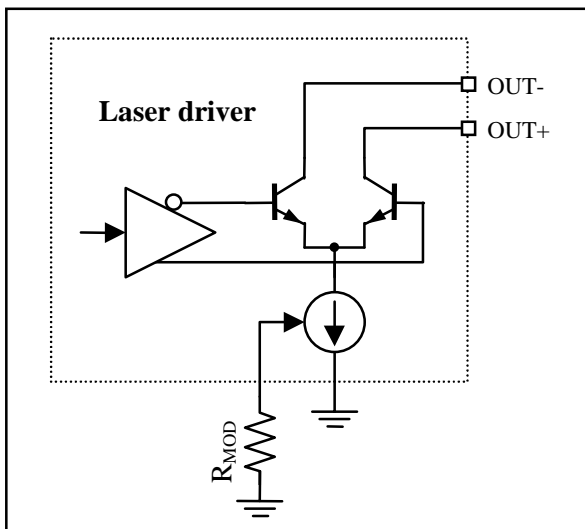

Figure 4. Typical Maxim laser driver
modulation output structure

IV. The PC Board Interface

Today's optical communication systems require improvement in operating speed, transmission distance, and power consumption. Implementation of these improvements calls for faster edge speeds, increased modulation current, and lower supply voltages. Therefore, the design of the laser driver and the corresponding interface to the laser diode are important issues for high-speed fiber optic communications design.

A. Headroom Issues with DC-Coupling

DC-coupling between the driver and the laser provides a simple and straightforward interface solution, as illustrated in Figure 5. But when the power-supply voltage is decreased to +3.3V, the headroom for the driver may not be enough to enable fast switching. ("Headroom" refers to the difference between the V_{CC} supply voltage and the sum of the individual voltage drops along a single circuit path.) Headroom calculations for circuits that contain a laser diode must include voltage drops due to the laser itself, as well as the transient voltage drop resulting from the parasitic inductance of the laser package and the voltage drop across the damping resistor, R_D.
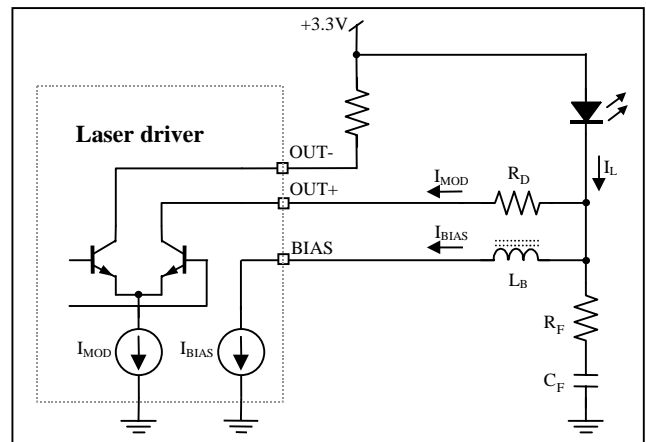

Figure 5. DC-coupled interface circuit

Typical long-wavelength Fabry-Perot-style laser diodes require forward-bias voltages on the order of 1.2V to 1.8V. This forward-bias requirement is the sum of the bandgap voltage and the voltage drop across the equivalent series resistance of the laser diode (see Figure 2). The equivalent series resistance of this type of laser is typically 4 ohms to 6 ohms.

The transient voltage drop is due to fast switching currents across the parasitic inductance associated with the laser package. Its magnitude can be loosely approximated by $V_L = L \, \Delta i / \Delta t$. If we assume a typical laser package has a parasitic inductance of about 1.5nH, a maximum modulation current of 60mA, and a 20% to 80% rise/fall time of 80ps (for 2.5Gbps), then we can calculate an approximate value for V_L. (Note that Δi during the 20% to 80% rise time is approximately 60% of the total modulation current or $0.6 \times 60mA = 36mA$.) Using the above assumed values, $V_L \approx (1.5nH)(36mA/80ps) = 0.68V$.

For an example headroom calculation (for the DC-coupled interface of Figure 5), consider a packaged laser diode with a maximum forward voltage V_F (= $V_{BG} + IR_L$ in Figure 2) of 1.6V. We will also assume a package parasitic inductance of 1.5nH, and a 60mA modulation current with 20% to 80% edge-speed of 80ps, resulting in $V_L = 0.68V$ (see preceding paragraph). Finally, we must include the voltage drop across the series damping resistor R_D, which is $I_{MOD}R_D = 1.2V$ (assuming $R_D = 20\Omega$). The resulting voltage at the driver output pin can be as low as $V_{LOW} = V_{CC} - 1.2V - 0.68V - 1.6V = V_{CC} - 3.48V$, making 3.3V operation very difficult.

B. AC-Coupling

The headroom problem described above can be improved by AC-coupling the driver to the laser diode. This is accomplished by adding a series capacitor, C_D, and pullup inductors, L_P, as shown in Figure 6.
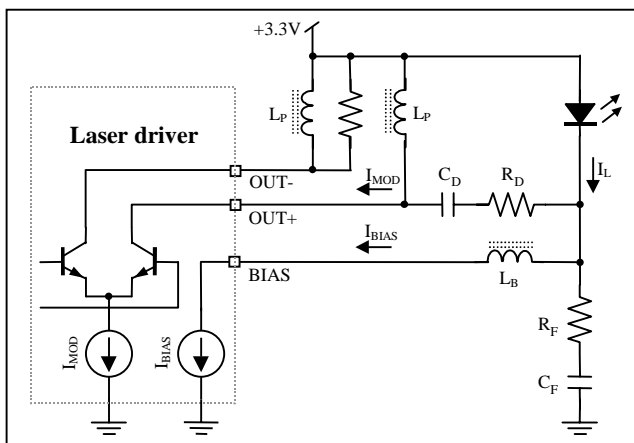

Figure 6. AC-coupled interface circuit

AC-coupling voltage drops are as follows: (1) The AC voltage drop across the laser diode is only a function of the voltage drop across its equivalent series resistance (not the bandgap), which is equal to the modulation current times the equivalent series resistance; (2) the transient voltage drop due to parasitic inductance remains unchanged from the DC example; and (3) the voltage drop across the series damping resistor, R_D, is equal to one-half the modulation current times R_D.

The last point in the preceding paragraph (voltage drop across R_D) can be understood by considering the current through the AC-coupling capacitor, C_D, and the currents at the circuit node that includes the cathode of the laser diode (see Figures 6 and 7). The current through C_D must have an average value of zero and a total peak-to-peak current swing of I_{MOD}. To satisfy these conditions, one-half of I_{MOD} must flow into C_D (from the laser) during an optical high output and one-half of I_{MOD} must flow out of C_D (toward the laser) during an optical low output. The current through the laser, I_L, is then equal to the sum of the currents flowing out of the circuit node at the cathode of the laser diode. This means that during an optical high output $I_L = I_{BIAS} + I_{MOD}/2$ and during an optical low output $I_L = I_{BIAS} - I_{MOD}/2$. The difference between I_L during an optical high output and I_L during an optical low output is then $(I_{BIAS} + I_{MOD}/2) - (I_{BIAS} - I_{MOD}/2) = I_{MOD}$.
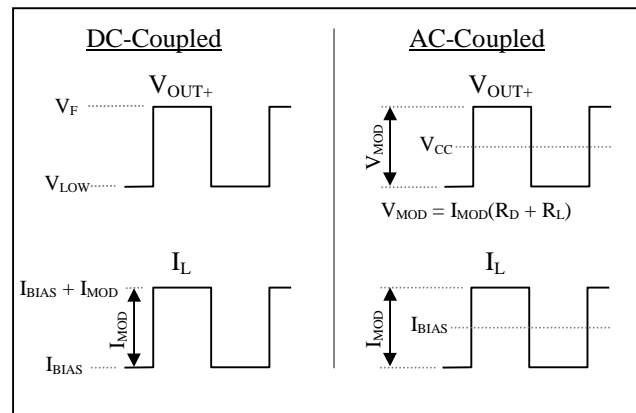

Figure 7. Output voltage (V_{OUT+}) and laser current (I_L) for DC- and AC-coupled interface circuits

The example headroom calculation for the DC-coupled interface can now be modified using the AC-coupled changes. For the AC-coupled case, we assume the equivalent series resistance of the laser is 5Ω, and the resulting headroom calculation is $V_{LOW} =$

$V_{CC} - (60mA)(5\Omega) - 0.68V - (60mA/2)(20\Omega) = V_{CC} - 1.58V$. For $V_{CC} = 3.3V$, this leaves 1.72V of headroom for the driver, which enables fast current switching in the driver output stage.

The disadvantage of the AC-coupling approach is that additional discrete components are required. These additional components include a coupling capacitor and pullup inductors or resistors for driver transistor biasing (as shown in Figure 6). Because these components are in the high–speed signal path, they can cause signal distortion. For this reason, the use of good high-frequency PC board layout techniques is critical (this subject is addressed in more detail later).

The AC-coupling capacitor will introduce a low-frequency cutoff, which can impact the pattern-dependent jitter performance of the system. To reduce the pattern-dependent jitter caused by long strings of consecutive identical bits, the value of the AC-coupling capacitor should be as large as possible. Designs that include Maxim's 2.5Gbps laser drivers generally use an AC-coupling capacitance value between 0.056μF and 0.1μF.

The pullup inductor or resistor is required in AC-coupled laser interfaces in order to keep the output driver transistor biased properly. (Small ferrite beads are generally used for the inductive pullup.) The disadvantages of using a resistor (versus an inductor) in this application are as follows: (1) A resistive pullup (R_{pullup}) creates a current divider with the rest of the laser circuit, taking part of the modulation current from the laser. This does not happen with an inductor. (2) Inductive pullups increase the headroom by allowing the average voltage at the output to be V_{CC} (as in Figure 7) instead of $V_{CC} - (I_{MOD}/2)R_{pullup}$, as would occur with a resistive pullup.

C. Interfacing a Laser to a Driver

The specifics of the interconnection between the driver and the laser diode depend on the separation distance. If this distance is smaller than a couple of millimeters (for 2.5Gbps), transmission lines are unnecessary and the priority is to reduce the parasitic elements as much as possible. The inductive load caused by the lead and bond wire inductance of the laser package may need a compensating RC shunt network (see Figure 6), consisting of a resistor (R_F) and a capacitor (C_F). The purpose of the RC shunt

network is to cancel out the parasitic inductance, thereby maintaining a constant load impedance, which results in a reduction of overshoot and ringing. The series damping resistor (R_D) serves the dual purpose of damping reflections (that cause output distortion) and creating a stable load. Load stability is improved because the load presented by the laser can vary by ±20% or more from the nominal value of approximately 5Ω ($\pm1\Omega/5\Omega \approx \pm20\%$), whereas the combined load presented by the laser and R_D varies by only ±4% ($\pm1\Omega/25\Omega \approx \pm4\%$). For the packaged MAX3867 and MAX3869, initial values for these components, assuming a coaxial-style packaged laser, are $R_D = 20\Omega$, $R_F = 75\Omega$, and $C_F = 3pF$. Because package inductance varies for different lasers, the component values for the shunt network may need to be adjusted for optimum operation. Also, it is important to note that the bias inductor is connected directly to the cathode of the laser (rather than the other end of R_D) so that R_D will not cause headroom problems in the bias stage of the driver.

When the interconnection distance becomes greater than a couple of millimeters, an impedance-controlled transmission line is required to interface the laser to the driver (Figure 9). Figure 8 represents the cross section of a microstrip line, which is commonly used in printed circuit boards. The characteristic impedance, Z_0, is estimated by

$$Z_0 \approx \frac{87}{\sqrt{\varepsilon_r + 1.41}} \cdot \ln\left(\frac{5.98 \cdot H}{0.8 \cdot W + T}\right) \qquad (5)$$

where W is the width of the top conductor, T is the thickness of the top conductor, H is the thickness of the dielectric, and ε_r is the dielectric constant. For a 25Ω microstrip line built on conventional FR4 material ($\varepsilon_r = 4.7$) with a height (H) of 356μm, a line width of approximately 1.3mm results.
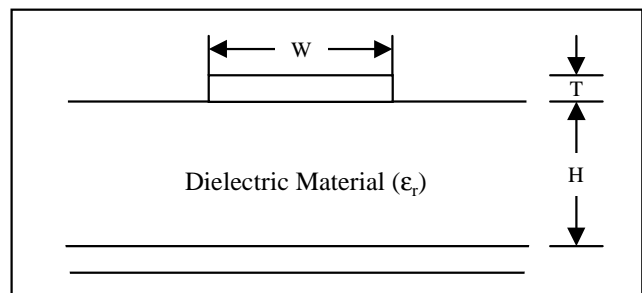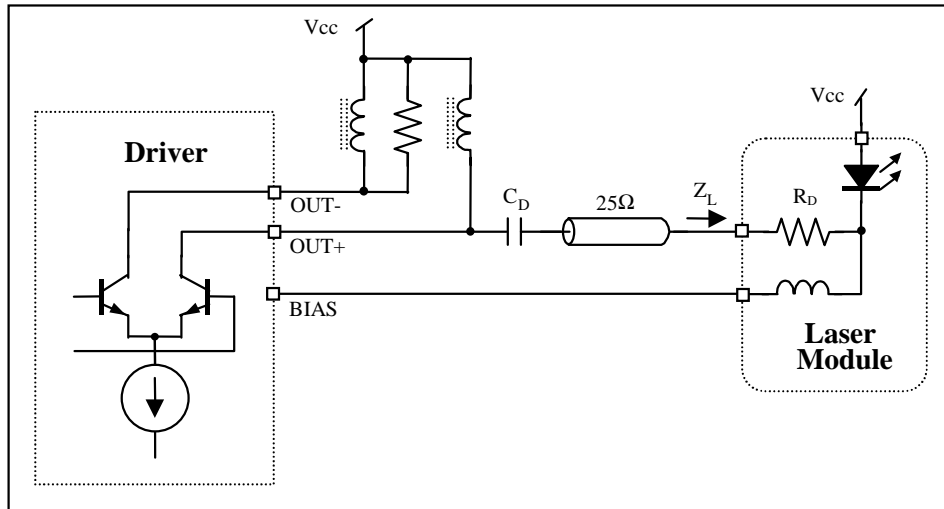

Figure 8. Cross section of microstrip line

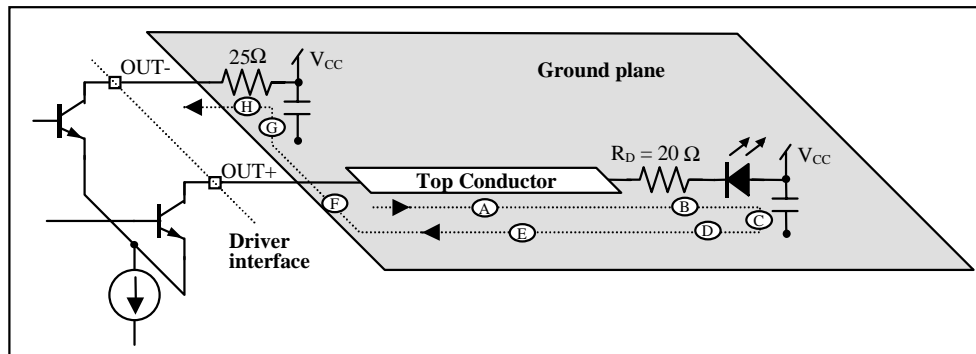*Figure 9. Interfacing a driver to a laser module with transmission line*

Figure 10. High-frequency signal path between a driver and a laser diode

D. Additional Board Design Considerations

For high-speed differential drivers, it is important to maintain a balance between the loads on the two outputs. The loads must be balanced in both the magnitude and the phase of the load impedances (Figure 9). To maintain balanced load impedance, each output is set up to drive an equivalent 25Ω load; the positive output drives a transmission line terminated on the load end to V_{CC} through a matching resistor/laser diode (a 25Ω combined load), and the negative output of the driver is connected to V_{CC} through a 25Ω resistor. Decoupling capacitors provide AC shorts from the laser anode to ground and from the 25Ω resistor on the negative output to ground.

The high-frequency path can be divided into several portions (refer to Figure 10): Portion A is from the driver positive output through the top conductor of the transmission line to the termination resistor; portion B is the termination resistor and the laser diode; portion C is the decoupling capacitor to ground; portion D is from the decoupling capacitor ground contact to the transmission line image; portion E is the transmission line image on the ground plane; portion F is from the transmission line image to the ground contact of the DC-coupling capacitor at the negative output; portion G is the decoupling capacitor at the negative output; and portion H is the resistor at the negative output.

Because the high-frequency return path includes the ground plane, it is important to provide good decoupling from V_{CC} to ground at both the positive output and the negative output. The decoupling at the positive output (C) ensures a return current (along the transmission line image) for proper transmission line operation, and the decoupling at the negative output (G) enables a current return to the negative output. It is always a good practice to use physically small capacitors for high-frequency performance in these decoupling elements. It is also important to maintain an uninterrupted ground connection between these two capacitors (D, E, F).

It is desirable to keep portions B, D, F, and H (which are not transmission lines) as short as possible to reduce the propagation delay between the two driver outputs. This is because the propagation delay can be translated into unbalanced phase termination between the outputs of the differential pair. One way to improve this situation is to select physically small termination resistors in order to keep the ground

contact of the decoupling capacitors as close to the transmission line as possible. It is also necessary to minimize the length of the nontransmission line portion of the printed circuit board at the driver output pins.

V. Troubleshooting

Experience has shown that, despite the most careful design of the interface between the laser driver and the laser diode, the optical output is generally less than optimum when the system is powered up initially. This leads to the need for troubleshooting (or at least minor adjustments) of the interface in almost all cases. This section is intended to give the engineer quick solutions to the most common interface problems.

The following optimization guidelines are based on the visual output of an oscilloscope connected via an optical-to-electrical (O/E) converter to the output of the laser diode. The input to the laser driver is assumed to be a pseudo-random bit stream (PRBS). The oscilloscope output can be displayed as a waveform (when the oscilloscope is triggered by a pattern clock) or as an eye diagram (when the oscilloscope is triggered by the bit clock).

The following are descriptions of eight common laser interface problems, along with waveform illustrations, a list of possible causes, and suggestions for possible solutions. Refer to the interface circuit shown in Figure 11 for all troubleshooting examples.
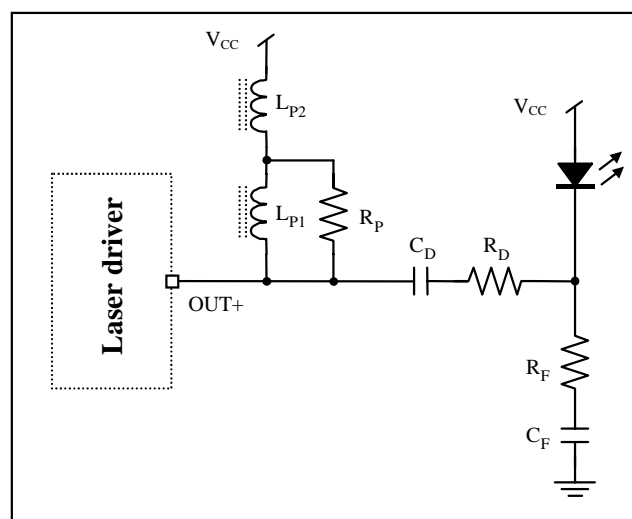

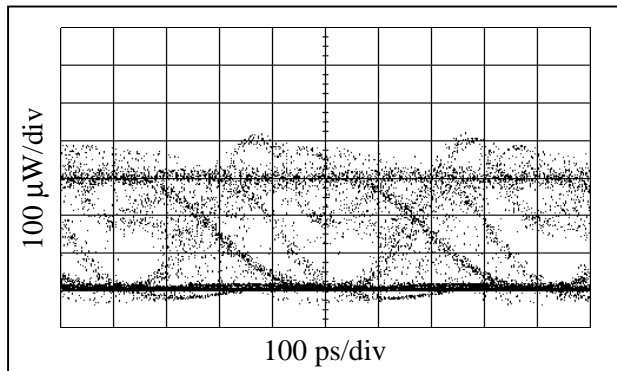Figure 11. Interface circuit

A. Waveform Compression (Figure 12)

Figure 12. Eye diagram showing waveform compression

Problem Description: No clearly distinguishable eye diagram. Dark horizontal line at the lower extreme of displayed eye diagram. Decreasing the bias current can compress the top of the displayed waveform to move down on the oscilloscope display, but the bottom of the waveform is stationary.

Possible Causes: Bias current is set too low. The digital zero level is below the threshold of the laser.

Potential Solutions: Increase the laser bias current until the bottom of the waveform begins to move up on the oscilloscope display (indicating that the digital zero level has been raised above the laser threshold). The eye diagram should become clearly distinguishable as the bias current is increased.
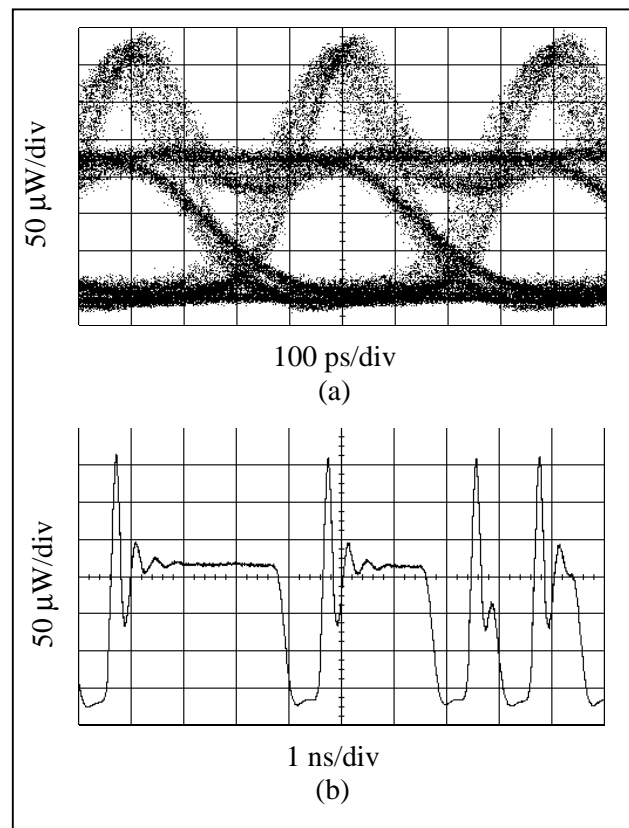
B. Relaxation Oscillation (Figure 13)

Figure 13. Relaxation oscillation
(a) Eye diagram, (b) Waveform

Problem Description: Large overshoot evident in displayed waveform. Dark horizontal line at the lower extreme of displayed eye diagram. Decreasing the bias current can cause the digital one level to move down on the display, while the overshoot remains constant or even increases in amplitude. The bottom of the waveform (the digital zero level) remains stationary as the bias current is decreased.

Possible Causes: Bias current is set too low. The digital zero level is below the threshold of the laser. Extra time is required to switch the laser from below threshold to a high level, causing a delayed rising edge. The delay in switching results in an increased buildup in potential that causes the laser to overshoot the digital one level once the threshold is overcome (known as "relaxation oscillation").

Potential Solutions: Increase the laser bias current until the bottom of the waveform begins to move up on the oscilloscope display (indicating that the digital

zero level has been raised above the laser threshold). The overshoot should decrease significantly as the digital zero level is increased past the threshold value.
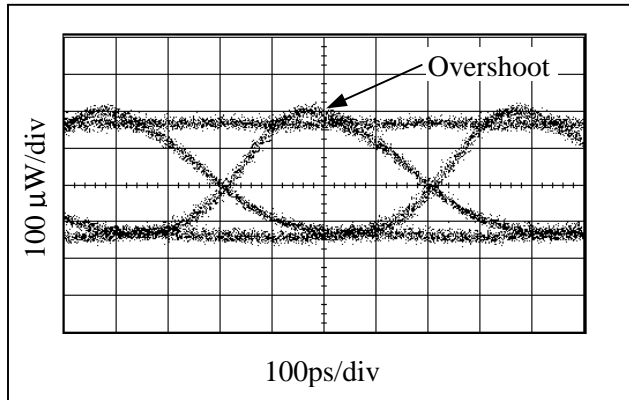
C. Overshoot (Figure 14)

Figure 14. Eye diagram showing overshoot

Problem Description: The rising edge of the waveform overshoots the digital one level. The relative amplitude of the overshoot remains almost constant as the bias and modulation currents are adjusted. No noticeable ringing is evident.

Possible Causes: (a) Rising edges too fast; (b) ferrite beads (used as pullups) have excessively high Q factor.

Potential Solutions: (a) Insert a low-pass filter with a frequency cutoff at 75% of the data rate. This will slow the rising and falling edges and decrease the overshoot. (b) Decrease the value of the resistor in parallel with the ferrite bead (R_P in Figure 11) to damp out the Q. (c) Adjust the value of the series damping resistor (R_D in Figure 11).
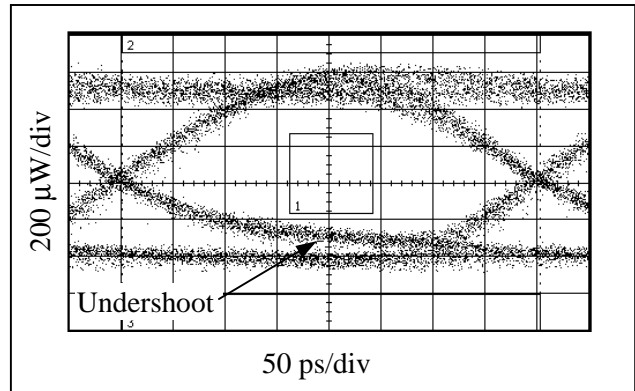
D. Undershoot (Figure 15)

Figure 15. Eye diagram showing undershoot

Problem Description: Rising and/or falling edges do not reach high or low level within the first half of the unit interval.

Possible Causes: Overdamped output circuit. In Figure 15, the undershoot was caused by a 0.5pF capacitor that was placed between OUT+ and OUT- (this was done to damp out some ringing).

Potential Solutions: (a) Reduce capacitance between OUT+ and OUT-, if possible. (b) Reduce load capacitance on OUT+. (c) Reduce the value of the series damping resistor (R_D in Figure 11).
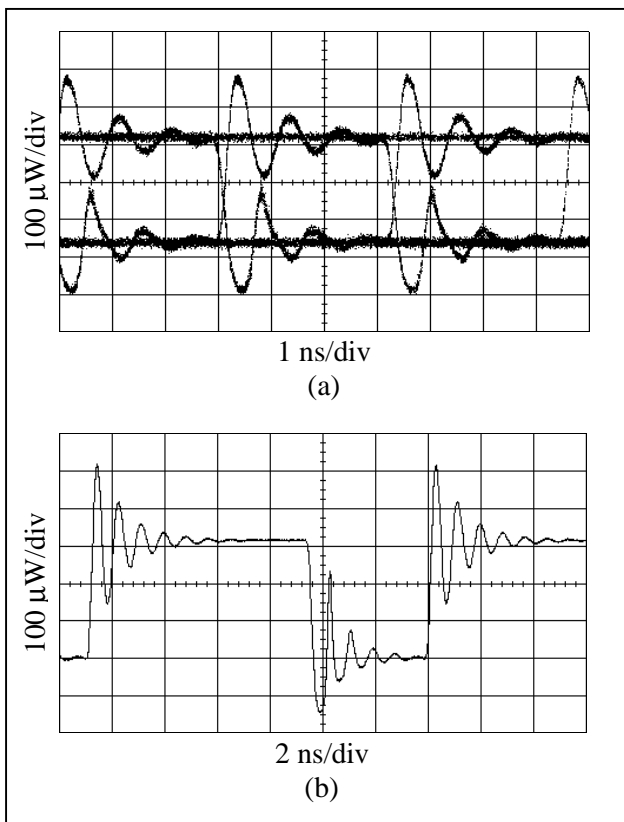
E. Ringing (Figure 16)

Figure 16. Ringing on (a) Eye diagram,
(b) Conventional waveform

Problem Description: Rising and/or falling edges exhibit ringing relative to the correct levels in a damped oscillation pattern.

Possible Causes: Impedance discontinuities, excessive inductance in the circuit, resonance effects of circuit components. In Figure 16, the ringing was caused by removing the resistor in parallel with the ferrite bead (R_P in Figure 11).

Potential Solutions: (a) Eliminate impedance discontinuities as much as possible. (b) Reduce parasitic inductance by decreasing the lead length on the laser diode as much as possible. (c) Decrease the value of the resistor in parallel with the ferrite bead (R_P in Figure 11). (d) The values of R_F and C_F (see Figure 11) can be adjusted to compensate for parasitics of the laser package.
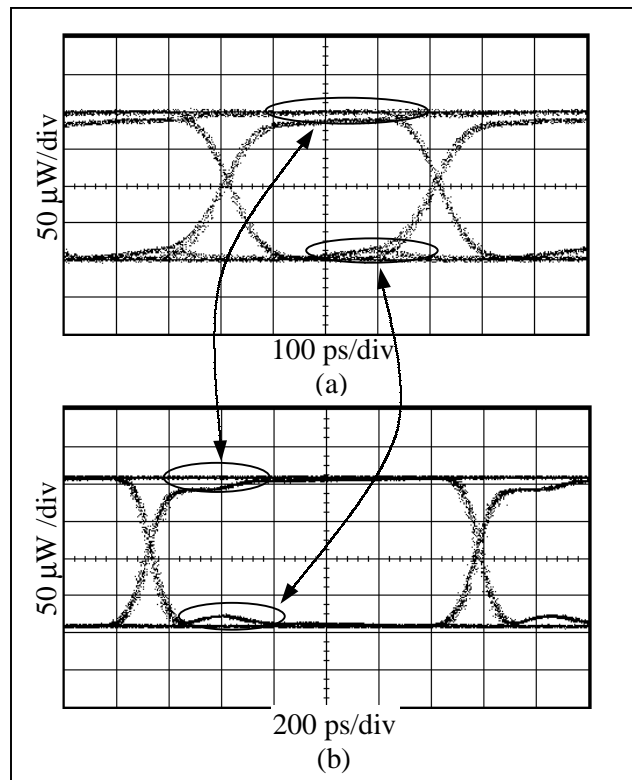
F. Reflections (Figure 17)

Figure 17. Eye diagrams showing reflections at
(a) 2.5 Gbps, (b) 800Mbps

Problem Description: Reflections due to transmission-line impedance discontinuities can appear as overshoot, undershoot, ringing, or other distortions to the eye diagram. One way to verify that the problem is the result of reflections is to decrease the bit rate in order to expand the time scale on the oscilloscope, as in Figure 17.

Possible Causes: Impedance discontinuities in the interface circuit.

Potential Solutions: (a) Make sure that the distance between the laser driver and the laser diode is as short as possible. (b) Ensure proper controlled-impedance techniques are used in PC board layout. (c) Use a time-domain reflectometer (TDR) to help identify locations of impedance discontinuities; then improve the PC board layout. (d) Adjust values of compensation network components (R_F and C_F in Figure 11) in order to obtain a better impedance match at the load end of the transmission line.

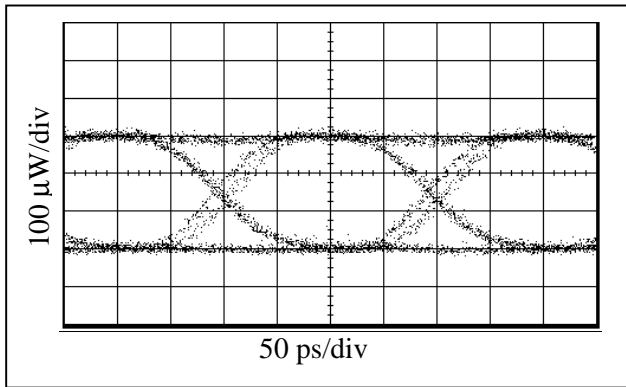### G. Double Line Pattern on Eye Diagram (Pattern Dependent Jitter) (Figure 18)

Figure 18. Eye Diagram Showing Double Line Pattern

Problem Description: Portions of the eye diagram separate into two distinct lines. The double line effect may vary when the input data pattern is changed.

Possible Causes: Pattern Dependent Jitter (PDJ) results from wide variations in the number of consecutive bits contained in NRZ data streams working against the available bandwidth. There are a number of conditions that can cause this effect.

The distortions in Figure 18 were caused by increasing the modulation current until the output transistor began to saturate, limiting its high-speed switching capabilities. The decreased switching speed limits the bandwidth during the rising edge.

The location of the lower -3dB cutoff frequency is important, and must be set to pass the low frequencies associated with long consecutive bit streams (Figure 19) in order to eliminate PDJ.

PDJ can also be present due to insufficient high-frequency bandwidth (Figure 20). If the amplifiers are not fast enough to allow for complete transitions during single-bit patterns, or if the amplifier does not allow adequate settling time, high-frequency PDJ can result.
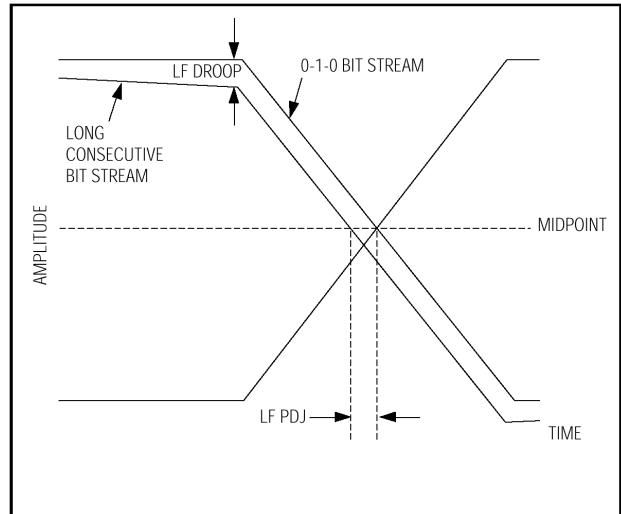

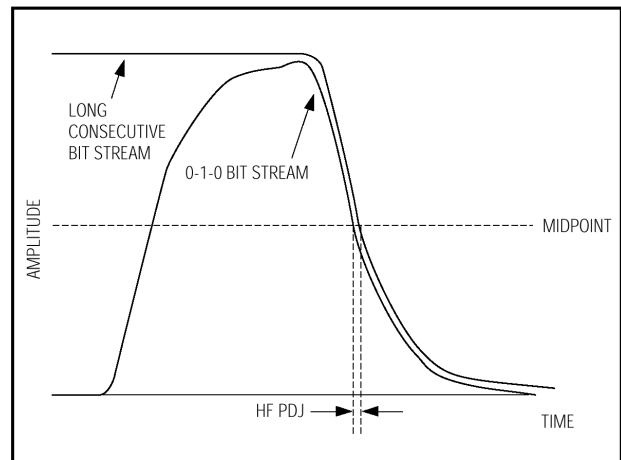Figure 19. Pattern-Dependent Jitter Due to Low-Frequency Cutoff

Figure 20. Pattern-Dependent Jitter Due to High-Frequency Rolloff

Potential Solutions: (a) Increase the value of the AC coupling capacitor (C_D in Figure 11). (b) Increase the value of the series damping resistor (R_D in Figure 11). (c) Increase V_{CC}. (d) Decrease the modulation current.
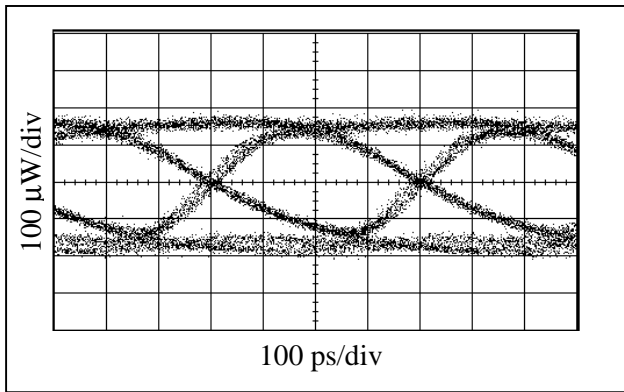
H. Asymmetrical Eye Diagram (Figure 21)

Figure 21. Asymmetrical Eye Diagram

Figure 22. Pulse-Width Distortion

Problem Description: Rise time may be significantly different from fall time (as in Figure 21) and/or the zero crossings of the eye diagram may be shifted above or below the midpoint (pulse-width distortion or PWD).

Possible Causes: Asymmetrical rise and fall times may be caused by differences in the current paths during the rise and fall times. (This happens because each path may present unique charging/discharging characteristics.) PWD results when the midpoint crossing of a 0–1 transition and a 1–0 transition do not occur at the same level due to DC offsets (Figure 22). Unequal rising and falling edge speeds and DC offsets both contribute to asymmetrical eye diagrams.
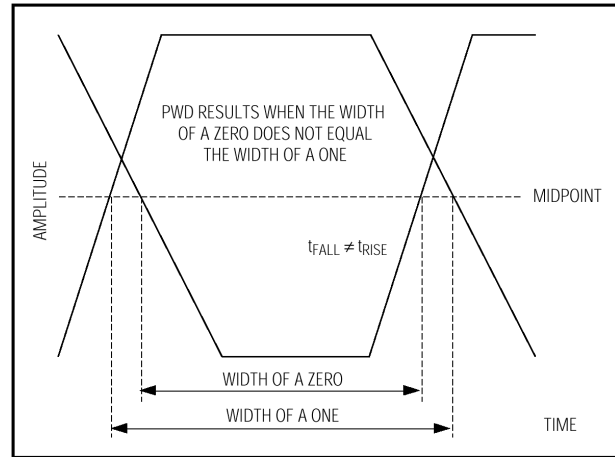
Potential Solutions: (a) Eliminate distortions inherent in input datastream (one way to do this is to clock and latch input data), (b) Use a laser with equal rise and fall times, (c) Adjust values of damping resistors (R_P and R_D in Figure 11), (d) Slow the faster edge down by using a low-pass filter with frequency cutoff at 75% of the data rate.