Application Note:

HFAN-02.6.0

Rev. 4; 12/08

Reducing Noise and Wander in Low-Speed (<622Mbps) Optical Transmitters

maxim integrated™

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1 Introduction

Designing an optical module that operates at multi-gigabit data rates (2.7Gbps) can be challenging. Careful attention to inductance, impedance and parasitic capacitance is necessary for good high-speed operation. Operating at low data rates (<622Mbps) presents other challenges due to output biasing, droop and wander. These effects can be especially difficult in SONET applications that operate with long runs of consecutive identical digits (CIDs).

This application note will discuss common causes of vertical eye closure in low speed (<622Mbps) optical transmitters. Design suggestion and tests will be provided to help diagnose the transmitter. Methods will also be provided to improve the performance.

The application note will focus primarily on the MAX3735A and MAX3646 as these devices are commonly used in multi-rate (155Mbps to 2.7Gbps) and low data rate (≤ 622Mbps) applications.

2 Verifying the Test System

Before trying to debug an issue with any optical module it is important to verify that the system is not the source of the perceived problem. In many cases the decreased performance is due to the test setup and / or connections to the test setup. Common sources of vertical eye closure of an eye diagram that are caused by the test system include:

1. O/E Converter Noise / Excessive Bandwidth
2. Insufficient bandwidth of the O/E Converter or Scope
3. O/E Converter Input Power / Gain
4. Dirty Fiber Connections

2.1 O/E Converter Noise / Excessive Bandwidth

When preparing a test system, ensure that the noise output of the optical to electrical (O/E) converter being used is low compared to the noise levels you are trying to measure. In many cases this can be done be selecting a converter with an appropriate bandwidth. If the bandwidth if very high (>10x the data rate) you may have excessive noise at the converter output due to the internal noise of the converter. However, even a converter with the appropriate bandwidth may have excessive noise depending on its design. A simple way to verify if the noise of the converter is low enough is to disconnect the optical input and measure the noise output without any input signal.

2.2 Insufficient Bandwidth of the O/E Converter or Scope

Insufficient bandwidth of the O/E converter or of the scope channel to which it is connected can also cause vertical eye closure. When putting a system together ensure that the O/E bandwidth is at least 0.75x the data rate (e.g. 117MHz when operating at 155Mbps) and that the scope and electrical interconnects have a bandwidth of at least 1 to 2x the data rate.

2.3 O/E Converter Input Power / Gain

Assuming that a low-noise O/E converter with the appropriate bandwidth is selected, one must still ensure that the optical input power applied to the converter is within the proper operating range. Operating with too much power into the converter can cause eye closure and distortion as well as potentially damage the converter. Operating with a very small input signal will cause the eye diagram to appear noisy due to the relative amplitude of the signal to the noise of the converter/system when viewed on an oscilloscope.

In the same regard, the output of the optical to electrical converter should be matched to the input range of the oscilloscope head. Depending on the gain of the converter, a low noise amplifier (in the case of not enough gain) or an attenuator (in the case of too much gain) may be needed to obtain an appropriate signal level at the oscilloscope input.

2.4 Fiber Connections

As with any optical system, the fibers and connectors should be cleaned before taking any measurements. The connections should be free of dust, residue and moisture. Verify that the proper type of fiber (Multi-mode or Single-Mode) is used. By using multi-mode fiber in place of single-mode fiber additional optical modal distortion / noise may occur. If single-mode fiber is used where multi-mode fiber should be used then the optical signal at the O/E converter may be much less than expected causing the eye to appear "noisy" as previously mentioned.

3 Baseline Wander

Baseline wander is the most common cause of eye closure in multi-rate or low data rate optical modules that operate with SONET patterns. The SONET patterns have long runs of consecutive identical digits (CIDs). The transition density of the data will also vary over time. These two effects lead to very low frequency content in the data pattern. For proper operation, the system must be able to pass this low frequency content.

To ensure that the system is able to pass the low frequency content of the pattern with minimal attenuation, the low frequency cut-off of the transmitter must be lower than the low-frequency content of the pattern. Please see references 1. and 2. for additional information on baseline wander.

The low frequency cut-off of a transmitter will be affected by the value of the capacitors used at the input, the automatic power control loop and the AC-coupling (if any) used in the interface between the laser driver and the laser. Given the large gain and limiting nature of the MAX3735A and the MAX3646 laser drivers, 0.22uF to 0.47uF capacitors are generally sufficient for 155Mbps operation when using SONET type patterns. However the low frequency cut-off that can be generated by the choice of output structure or the APC loop can be more challenging to set properly.

3.1 Baseline Wander (Output Structure)

The MAX3735A[3.] and MAX3646[4.] laser drivers provide an output that can be DC coupled to a laser using a +3.3V supply[5.]. Since this type of output does not introduce a low-frequency cut-off point it is ideal for low-frequency applications such as 155Mbps operation using SONET patterns. However, some systems require more modulation current than what can be obtained with a DC – coupled interface. In these cases AC-coupling is required.

Multi-rate transmitter modules will also often employ AC-coupled outputs so that the laser can be driven differentially to obtain the best possible performance at multi-gigabit operation. These outputs however will often have a low-frequency cut-off that is too high for proper operation at low data rates. The cut-off point can be lowered but will often require large value (and physical size) capacitors and inductors which may be difficult to place in a space constrained SFP module[6.].

A simple test to verify if the output is being affected by baseline wander is to change the test pattern from one with a lot of low-frequency content to one that has little low-frequency content, and examine the change in the output. The 2^{23}-1 PRBS for example has a large amount of low-frequency content similar to that found in SONET patterns and is therefore a good pattern to use when testing these types of optical modules. In comparison, the 2^{7}-1 PRBS pattern has very little low frequency content.

As an example, an optical module with an AC-coupled output being operated at 155Mbps with a 2^{23}-1 PRBS pattern is shown in Figure 1. This module design does not employ large inductors or capacitors; therefore, the low frequency cut-off of the output network is fairly high. As a result, there is a fair amount of eye closure in the diagram.

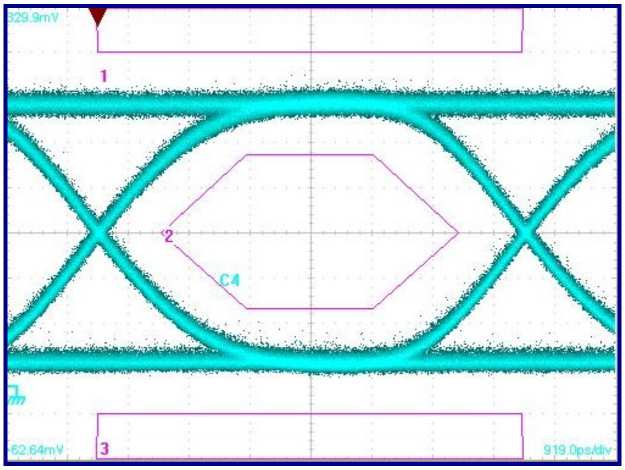

Figure 1. OC-3 (Filtered), 2^{23}-1 PRBS

By changing the pattern to a 2^7-1 PRBS, a much improved eye diagram can be seen (Figure 2). Please note that the amplitude of eye closure in the diagram of Figure 1 is similar on the one and zero level. There is also an increased level of jitter in the eye diagram. These affects are typical for modules that have a baseline wander related eye closure. However, the peak wander of a PRBS is not the same in the positive and negative direction which may lead to a difference in the speckle pattern seen in the eye diagram depending on the polarity of the PRBS sequence.

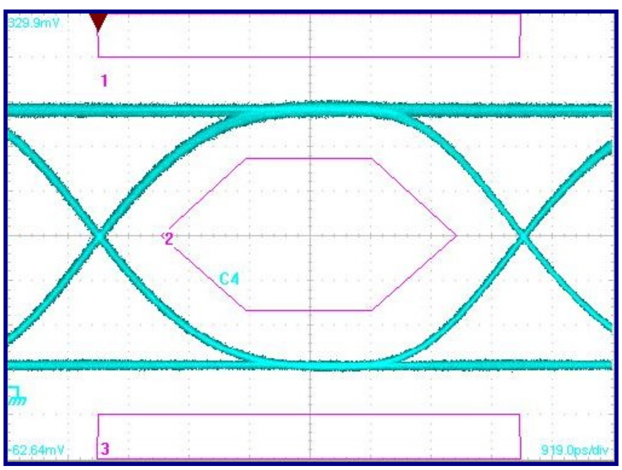

Figure 2. OC-3 (Filtered), 2^7-1 PRBS

It is often difficult to determine if the wander is due to the APC loop, the low frequency cut-off of the output structure or both. In cases where an AC-coupled output is used, a simple circuit simulator should be used to determine the low-frequency cut-off and determine what values should be used to improve the performance (by lowering the low-frequency cut-off point) if needed. As a general rule of thumb the cut-off point should be less than 10kHz for a SONET type module operating at 155Mbps.

3.2 Baseline Wander (APC Loop)

The automatic power control loop (APC loop) of a laser driver also introduces a low-frequency cut-off in the data signal path. If the loop capacitors (Capc and Cmd) are not chosen correctly for low-data rate applications, increased eye closure due to baseline wander may occur. The affect is very similar to that of an AC-coupled output. For a full discussion on these affects please refer to reference 7. .

If the cut-off point of the APC loop is affecting the response it can also be readily seen by changing the pattern and viewing the change in eye closure and jitter. In order to further isolate this as a possible cause, a simple experiment is to measure the eye closure (Figure 3), then increase the Capc capacitor by 4x or 10x and re-measure (Figure 4). If there was a dramatic change in the response similar to that seen in Figure 3 and Figure 4, the loop capacitor values should be adjusted for proper operation. Even if there is no dramatic difference when applying this experiment, the capacitor values should be verified using reference 7. (for the MAX3735A and MAX3646) as a guide to ensure that the other parameters related to the APC loop such as turn-on time, stability, etc are set correctly.

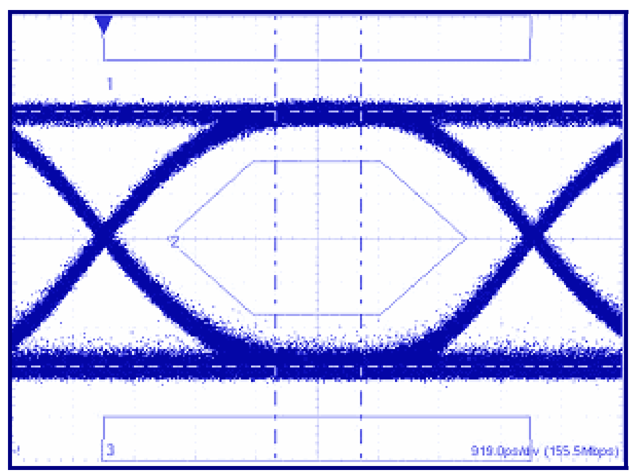

Figure 3. Optical eye – OC-3, 2^{23}-1 PRBS, C_{APC} = 0.01μF

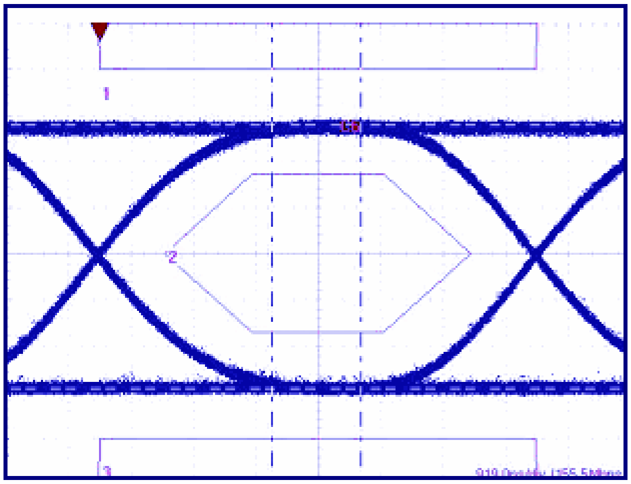

Figure 4. Optical eye – OC-3, 2^{23}-1 PRBS, C_{APC} = 0.1μF

4 Mis-Match of the Laser Driver Differential Output

A second and more subtle cause of vertical eye closure in low speed transmitters can be due to mis-match of the laser driver output. The MAX3735A and the MAX3646 use a differential pair for driving the laser. There are several different methods for connecting the laser to the driver. In general, DC-coupled output networks will have more mis-match than AC-coupled output networks since each of the outputs is biased near VCC when the output is AC-coupled.

Using a conventional single-ended DC-coupled drive network as an example (Figure 5), the laser cathode is connected through a series resistor to the driver's OUT+ pin. The OUT- pin of the driver is then connected to VCC through a resistor.

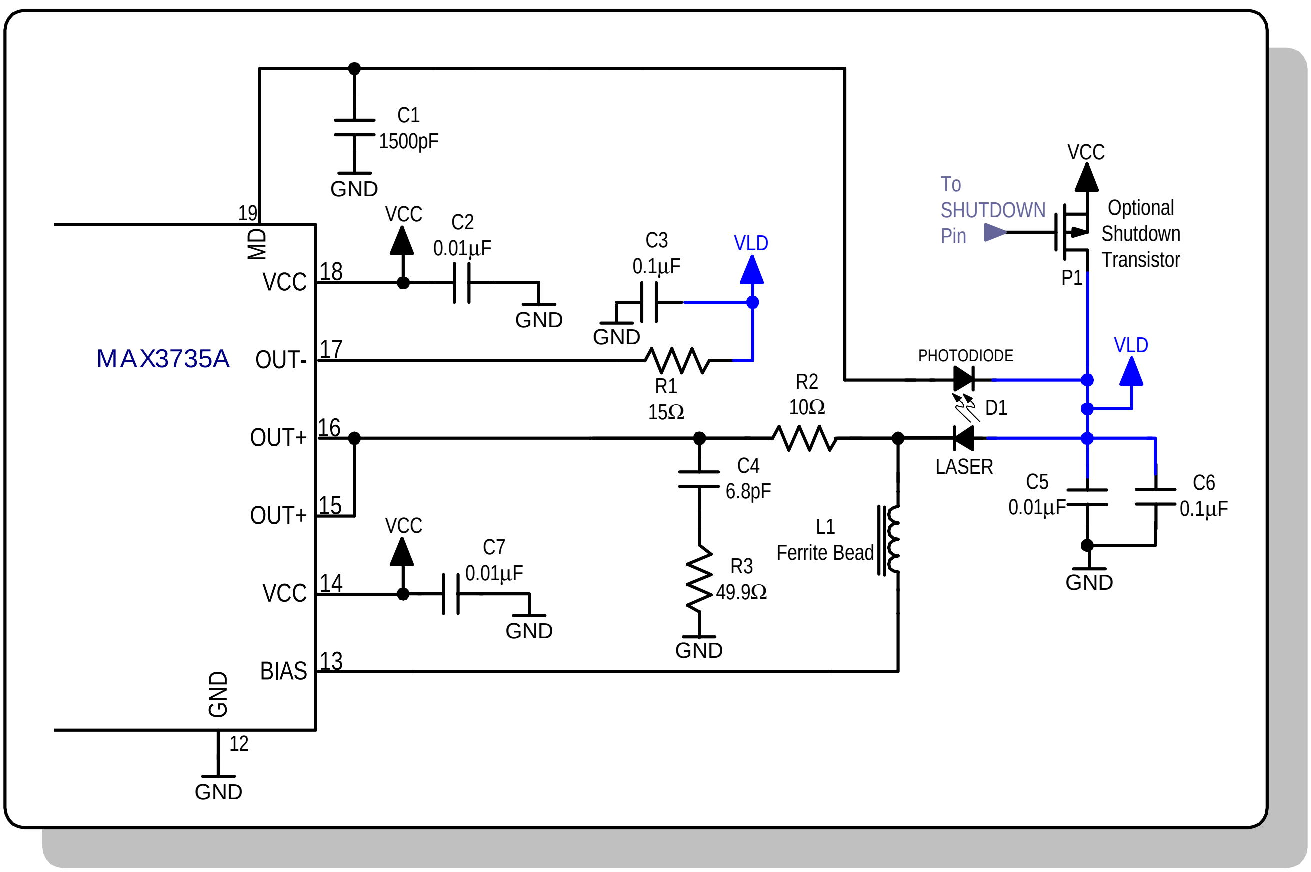

Figure 5. Typical DC-coupled laser interface

Neglecting the affects of inductance, the voltage at OUT+ when it is sinking current will be:

V_{OUT+} (V) = VCC (V) – VF_{LD} (V) – 10(Ω)*I_{MOD} (A)

(Where VF_{LD} is the forward voltage drop of the laser at a current of I_{MOD}).

When OUT- is sinking current, its voltage will be:

V_{OUT-} (V) = VCC (V) – 15(Ω)*I_{MOD} (A)

Putting typical values of I_{MOD} = 30mA, VCC = 3.3V and VF_{LD} = 1.4V into these equations we see that the voltage at OUT+ will be approximately 1.6V and the voltage at OUT- will be approximately 2.85V. This difference in voltage caused primarily by the forward voltage drop of the laser can lead to mis-match of the driver output, which in turn leads to vertical eye closure when operating at low data rates that have long CIDS. The reason why this mismatch leads to eye closure at low data rates is beyond the scope of this application note but its affects are illustrated in the eye diagram shown in Figure 6.

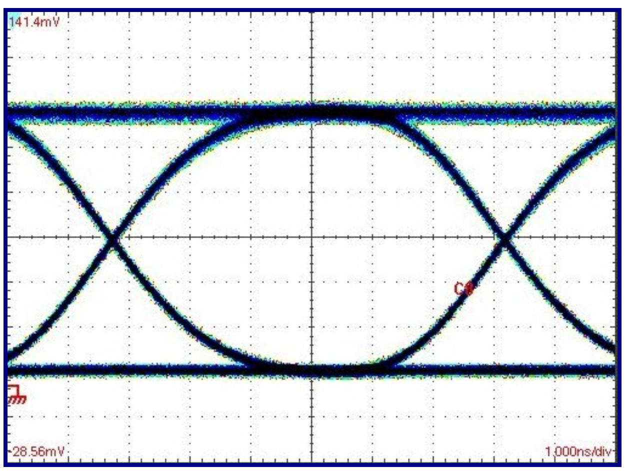

Figure 6. OC-3 (Filtered), 2^{23}-1 PRBS, Standard Configuration

As with eye closure due to baseline wander (low-frequency cut-off point set too high), changing the pattern to a long PRBS sequence such as a 2^{23}-1 will cause increased eye closure. A characteristic of mis-match induced eye closure that helps to distinguish it from a wander problem is that the eye will appear slightly "noisier" on the one level than on the zero level. The "noise" for this case is actually due to a slow increase of the modulation current over a long period of time which can be seen using a very low frequency repeating 1010 pattern (Figure 7, 20ns/div). When viewed as an eye diagram using a PRBS test pattern this slow ramp up will look like noise (Figure 6).

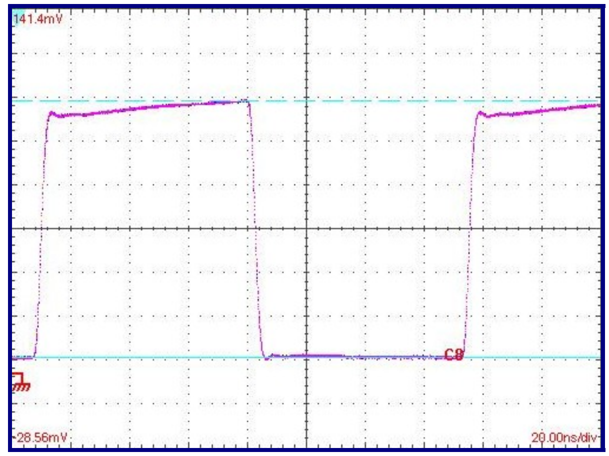

Figure 7. 1010 Repeating Pattern, 20ns/div, Standard Configuration

A second simple test that can be performed to help determine if the eye closure is due to a mis-match such as this is to view the output while slowly varying the VCC level between 3.0V and 3.6V. Assuming the driver does not run out of voltage headroom (V_{OUT+} > 0.6V) the eye quality will improve as the VCC voltage decreases (Figure 8). In other words the "noise" on the one level will increase as VCC increases.

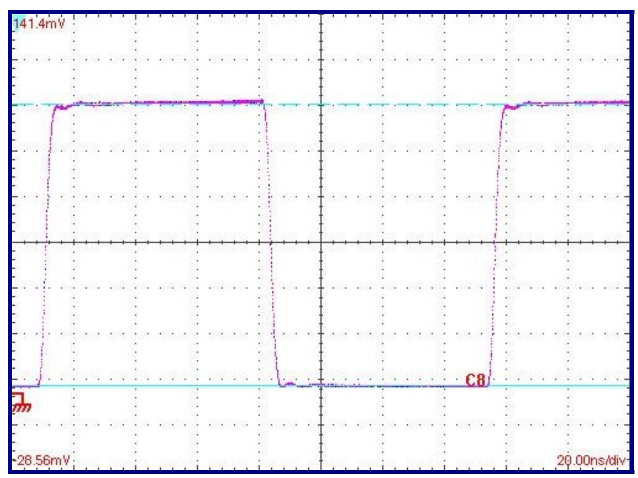

Figure 8. 1010 Repeating Pattern, 20ns/div, Voltage at VCC is lowered.

Any method that helps to lower the voltage on OUT- and/or increase the voltage on OUT+ when each is sinking current will improve the eye quality. For example: OUT- could be terminated to a voltage lower than VCC using a resistor network, a larger resistor value could be used on the OUT- pin and a smaller resistor value on the OUT+ pin, or a small, fast switching diode could be placed in series with a resistor connecting OUT- to VCC. In any of these cases it is important to ensure that the instantaneous voltage at OUT- and OUT+ does not decrease below the devices limit for these pins (approximately 0.6V for the MAX3735A and the MAX3646). Using a diode in series with OUT-, the improved results as seen in Figure 9 were obtained.

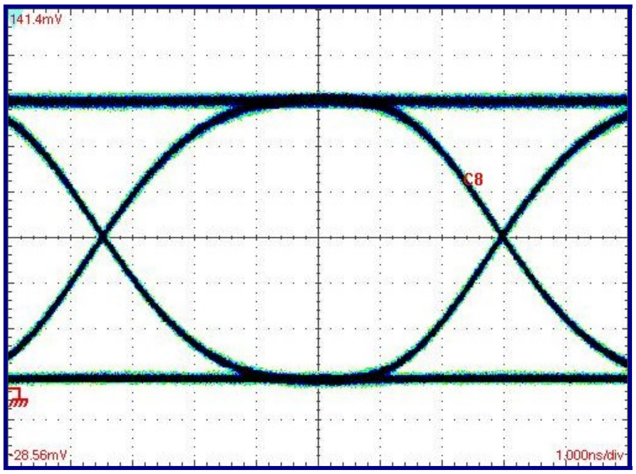

Figure 9. OC-3 (Filtered), 2^{23}-1 PRBS, Using a Diode to Lower the Voltage on OUT-

5 Insufficient Decoupling

The MAX3735A and MAX3646 laser drivers are designed to drive common anode lasers. In the standard configuration the cathode of the laser connects to a collector (OUT+) of a differential pair inside the laser driver through a series resistor. The anode of the laser then connects to VCC. In order to obtain acceptable high-speed and low-speed operation, it is critical to provide sufficient decoupling to the laser anode given the large currents that can be switched (up to 85mA) and the very fast transition rates of the switching current. If there is excessive voltage droop of the laser anode node there will be decreased eye opening and potentially increased jitter if the instantaneous voltage of the OUT+ pin drops below 0.6V.

Given that the output of the laser driver is a differential output, the OUT- should also terminate to a node that is well bypassed and when possible to the same node as the laser anode (VLD, Figure 5). Doing this will reduce noise on VCC and provide a cleaner optical output signal.

When designing a low frequency application, it is important to remember that the switching rate of the laser driver will be very fast regardless of the operating data rate or the input transition time. The decoupling should therefore be determined with a typical transition time of approximately 50ps (20% to 80%) in mind for the drivers mentioned. In low frequency applications it is also important that the decoupling capacitance will provide minimal voltage droop during long CID sequences that can occur in SONET applications.

6 Back Reflection Oscillations

Although back reflection oscillations are not related to only low-data rate applications, they can have affect on the vertical eye closure. The optical output of a laser diode can enter a state of oscillation when a reflection enters the lasing cavity. The mechanism which causes this oscillation is beyond the scope of this application note but it is sufficient for our purposes to state that they exist and are caused by optical reflections. In general, DFB lasers are more susceptible to back reflections than other types of lasers but the oscillations can occur in FP lasers as well.

In many cases, one or more optical isolators are built into the laser assembly to ensure reflections do not enter into the lasing cavity. The frequency of the oscillation is related to the geometry, construction, bias level and temperature of the laser but in general will be > 1GHz for an edge emitting laser diode used in fiber communications. When these oscillations occur, the filtered output eye diagram will appear noisy. The noise can be predominately on the one level, the zero level or balanced between the one and zero level depending on the laser and its parameters / operating conditions.

If the bandwidth of the O/E is not high enough to capture the oscillation, the eye diagram will simply appear slightly noisier due to the attenuation of the oscillation caused by limited O/E bandwidth. As an example, the eye diagram shown in Figure 10 is of an OC-48 optical eye diagram. As seen in Figure 10, there is a decreased vertical eye opening due to noise. The bandwidth of the O/E converter in this case is 2.3GHz.

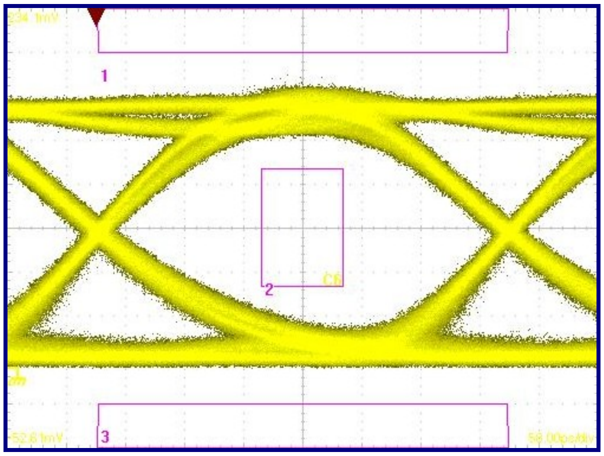

Figure 10. OC-48 (Filtered), 2^{23}-1 PRBS

The same eye diagram when viewed with an O/E converter with 11GHz of bandwidth is shown in Figure 11. Using a 1010 pattern the oscillation is more apparent (note that this can only be seen when the oscillation is correlated to the data which is not always the case) as seen in Figure 12.

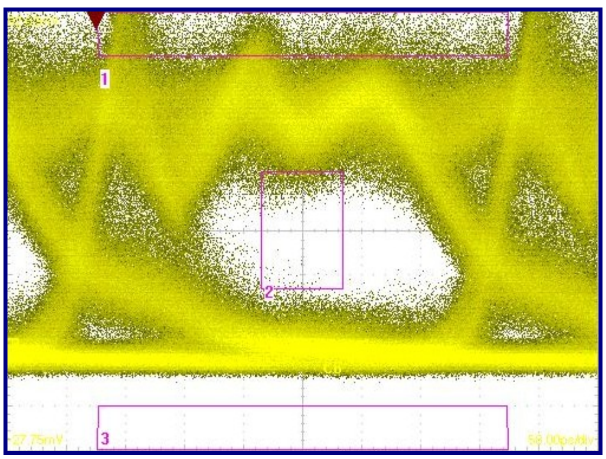

Figure 11. OC-48 (Un-Filtered), 2^{23}-1 PRBS, Optical Oscillations can be seen

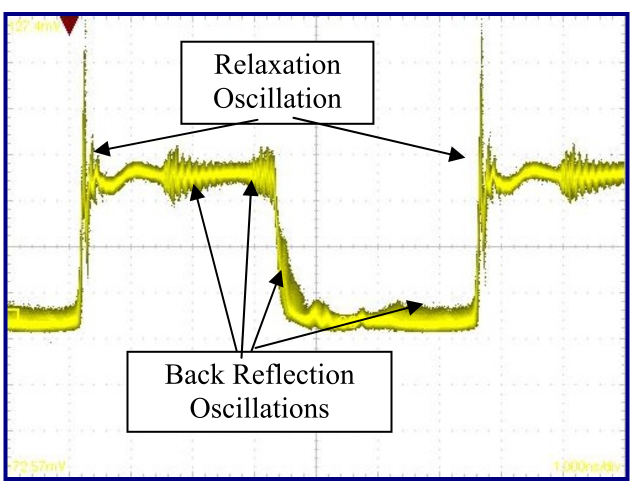

Figure 12. 1010 Pattern View of Relaxation Oscillation (1ns/div)

The following parameters can be varied to check for back reflection oscillations:

1. View the output on a high bandwidth O/E converter and check for excessive noise.

2. Change the bias level and temperature of the laser, the properties of a back reflection oscillation will vary with laser bias level and temperature.

3. Adjust the spacing between the fiber and the laser. As the fiber is pulled away from the laser the oscillations relative to the signal level should reduce. This can be seen in Figure 13.

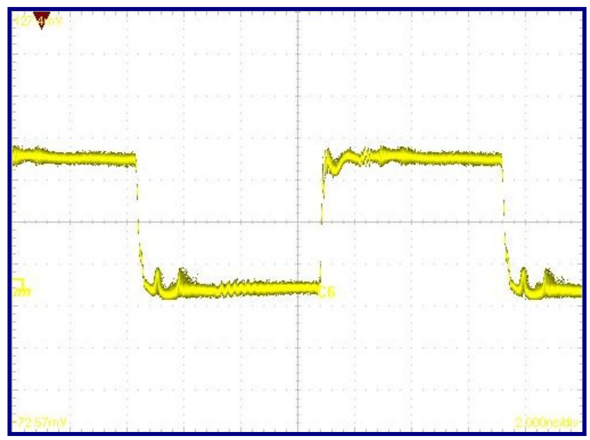

Figure 13. Change in Fiber Alignment / Position

To correct for this type of vertical eye closure:

1. Verify that all the optical connections are clean and free of moisture.

2. Verify that the proper fibers are used and that APC fiber ends are used if required by the system.

3. Use a laser with a better built in optical isolator or an external optical isolator between the laser and the location where the optical reflection occurs.

7 Additional Resources / Conclusions

There are many possible causes of vertical eye closure in optical transmitters. This application note illustrated several common causes such as: The System Configuration, Baseline Wander, Mis-Match on the Differential Pair, Insufficient Decoupling and Back Reflection Oscillations. Please contact the maxim fiber applications group for additional assistance if needed in determining the cause of vertical eye closure and/or improving the performance: https://support.maxim-ic.com/

References:

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2. Technical Article: "Spectral Content of NRZ Test Patterns" – HFTA-11.0, Maxim Integrated Products, January 2005.

3. Data Sheet: "MAX3735/MAX3735A: 2.7Gbps, Low Power SFP Laser Driver." - Maxim Integrated Products, May 2003.

4. Data Sheet: "MAX3646: 155Mbps to 622Mbps SFP Laser Driver with Extinction Ratio Control." - Maxim Integrated Products, July 2004.

5. Application Note: "MAX3735A Laser Driver Output Configurations, Part 1: DC-Coupled Optimization Techniques" – HFDN-26.0, Maxim Integrated Products, June 2003.

6. Application Note: "MAX3735A Laser Driver Output Configurations, Part 3: Differential Drive" – HFDN-26.2, Maxim Integrated Products, September 2003.

7. Application Note: "Choosing the APC Loop Capacitors Used with MAX3735/MAX3735A SFP Module Designs" – HFDN-23.0, Maxim Integrated Products, September 2002.