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Signal Integrity Concerns when Modulating Laser Transmitters at Gigabit Rates

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Abstract

This manuscript will describe the challenges facing high-speed digital designers when trying to optimize optical transmitter performance. The paper begins by giving a brief overview of the evolving optical network. It will lay a foundation of semiconductor laser fundamentals, then discusses the relationship between electrical signal integrity of laser driver circuits and the resulting impact on optical performance of Distributed Feedback (DFB) and Electroabsorptive Modulated Lasers (EML's). Laser modulator package architectures utilizing flexible interconnects will be investigated to determine affect on eye diagram quality at 2.5 and 10 Gb/s. Finally, the paper will present state-of-the-art optical laser transmitter measurement techniques for 40 Gb/s Return-to-Zero (RZ) data signals.

Author Biography

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Stephen is a Senior Design Engineer in the Transmission Subsystems Group of JDS Uniphase in Melbourne, FL. He is responsible for providing technical support for the design of 2.5 Gb/s, 10Gb/s, and 40Gb/s fiber optic transmitters and receivers. Stephen's recent projects include the development of a 40 Gb/s fiber optic transponders for telecommunication applications. Stephen has over 5 years of experience in fiber optic transmitter and receiver design. Stephen received his Bachelor of Science degree in Electrical Engineer at the University of Central Florida, and his Master of Science Degree in Electrical Engineer through the Center for Research and Education in Optics and Lasers (CREOL), at the University of Central Florida.

Laurie Taira, Delphi Connection Systems

Laurie is a Senior Project Engineer in the R & D Department. Her current responsibilities include, simulation, design, and test and measurement of high density, high speed flexible circuit interconnects. She is the task leader of the electrical simulation and measurement laboratory at Delphi Connection Systems and her laboratory has received the Center of Excellence recognition from Delphi Corporate. She was previously a microwave, fiber optic and telecom compliance engineer. Laurie obtained her B.S. in Physics from U.C.L.A. and her M.S. in Physics from California State University, Long Beach.

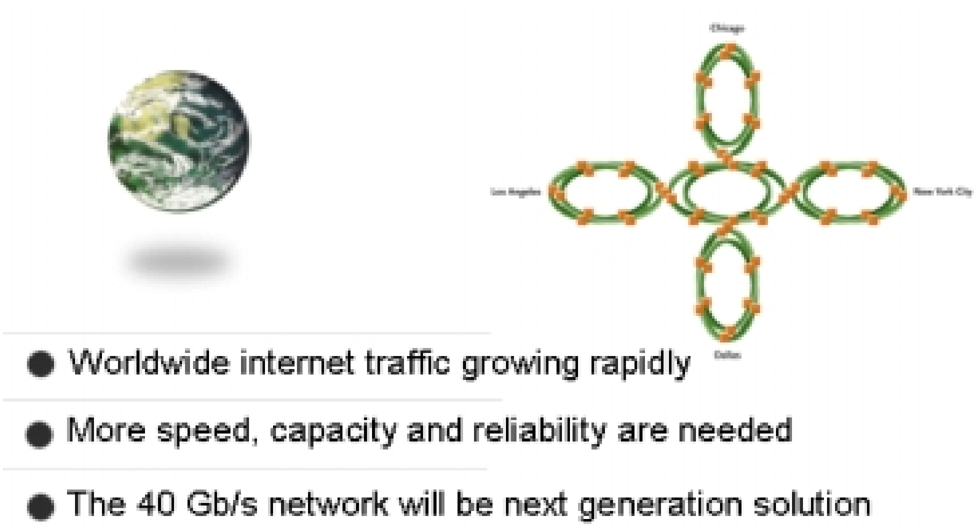
Mike Resso, Agilent Technologies

Mike is a Product Manager in the Lightwave Division of Agilent Technologies. He is responsible for technical training of Agilent field engineers, symposium lecturing and interfacing with Agilent R&D engineers to bring innovative high-bandwidth products to the 40 Gb/s marketplace. Mike's recent projects include the development of novel signal integrity measurement techniques and defining the feature set of Agilent's next generation Terahertz Optical Sampling Oscilloscope. Mike has 10 years of experience in the development of electro-optic test instrumentation and has published numerous technical papers. Mike received his Bachelor of Science degree in Electrical and Computer Engineering from University of California, Santa Barbara.

Signal Integrity Concerns when Modulating Laser Transmitters at Gigabit Rates

The Evolving Optical Network

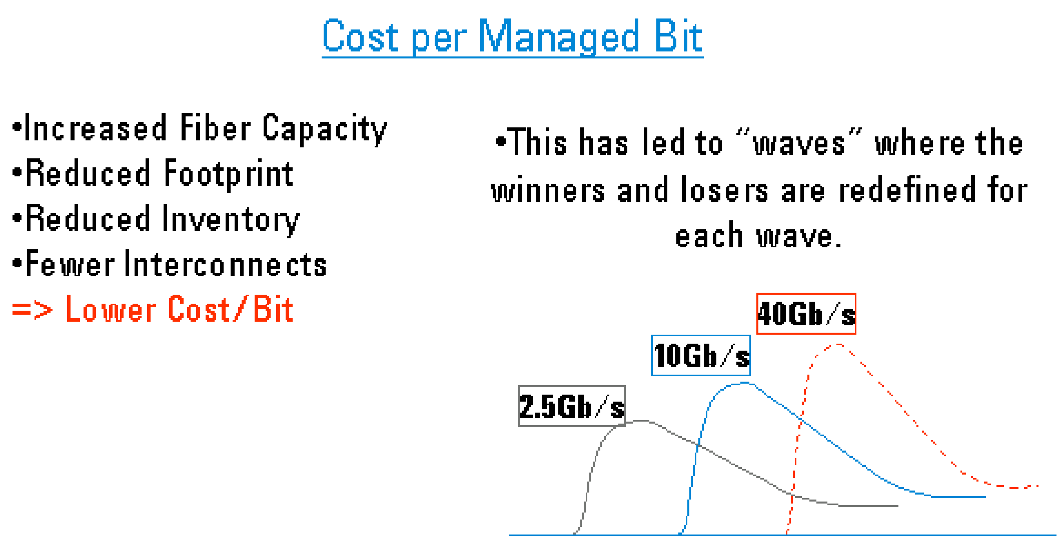
In the last 20 years optical fiber transmission networks have progressed tremendously in terms of link distance and information handling capability. Major advances in the electronic and optical technology of laser transmitters have made this possible. The single mode photonic emission from a semiconductor distributed feedback laser (DFB) can be coupled efficiently into today's single mode fiber. In addition, these lasers can be switched on and off with transition times on the order of 5-10 picoseconds to provide data rates up to 40 Gb/s. The electrical circuits required to drive the related laser modulators and multiplexers are so demanding that manufacturers are developing new material technologies to meet the challenge. Indium Phosphide (InP), Silicon Germanium (SiGe), and Gallium Arsenide (GaAs) are materials that will be needed as data rates reach 160 Gb/s in development laboratories in 2002.
The outstanding performance of semiconductor lasers has in fact provoked considerable effort to improve the capabilities of test equipment in order to fully characterize the capabilities of of these optical components. A technological breakthrough in test instrumentation is needed to expand the time domain bandwidth for all Digital Communications Analyzers for analyzing the modulation characteristics of tomorrow's optical networking laser transmitters.



Why Gigabit Rates?

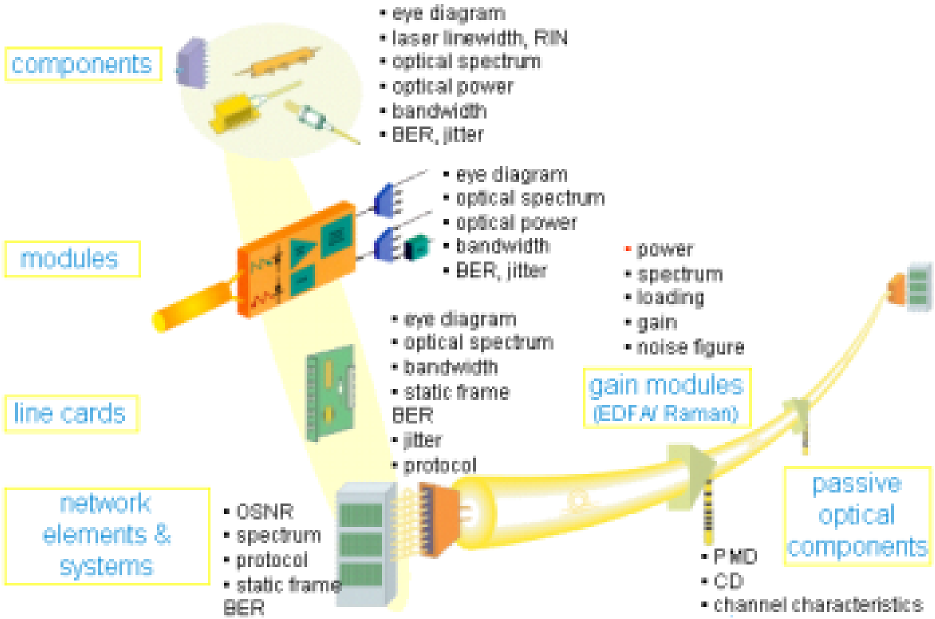
Historically, each successive wave of higher speeds has led to a lower cost per bit for network equipment. Once a new technology becomes mature, it has typically delivered 4 times the bit rate at only 2.5 times the cost. A "managed" bit includes all the indirect costs associated with data transport. Increased fiber capacity has prevented the laying of new fiber in areas where there is fiber exhaust, and has avoided the cost of additional repeater stations. Higher rates usually leads to smaller form factor equipment, smaller backplanes with shorter transmission lines, and reduced power requirements. These can be a major cost of a central office or other Point of Presence. Also, by increasing the capacity of each wavelength by a factor of four, the number of wavelengths can be reduced. This technology is called wavelength division multiplexing. Since each wavelength of data channel will need at least one spare circuit pack for that wavelength, this can reduce the inventory of spare equipment for repair by a factor of four.

These cost dynamics have lead to technology waves, where the winners and losers are redefined for each wave. We saw this happen at 2.5Gb/s, when Lucent took leadership market share in 2.5G DWDM. Then we saw the 10Gb/s wave take over 2.5Gb/s for DWDM equipment. Nortel, being the first to reliably deploy 10Gb/s took enormous market share, moving from 13% to 43% in 6 months. So, the industry expects the same thing to happen sometime with 40Gb/s, once it becomes a mature technology and delivers a true cost per bit advantage. This is why the stakes are so high, and so many investments are being made.



Laser Transmitters Used in the Optical Network

There are significant key test and measurement challenges in developing 40G components and systems. At the equipment level, there is the network terminal equipment, the Line Amplifiers, and passive optical equipment, such as Optical Multiplexers and dispersion compensators. The equipment that is in a central office, often referred to as network elements, is composed of line cards, which are composed of modules, which are composed of basic electrical and optical components. Gigabit data rates challenges today's technology, so characterizing and testing each point in the supply chain is essential. Listed besides each component are some of the critical measurements that must be made to ensure reliable products. It is from these requirements that Agilent is strategically focusing our plans for delivering the required test and measurement equipment.



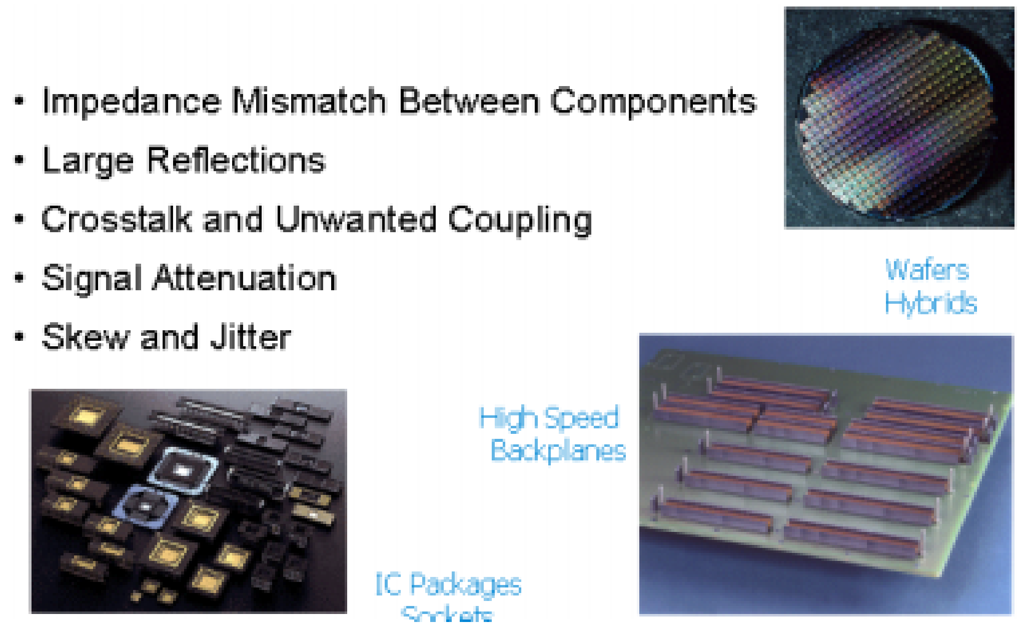
Optical Network Physical Layer Test Instrumentation

There is a fairly large suite of measurement solutions available today to address the 40 Gb/s industry. The majority of the measurements that we will focus on today is the waveform analysis section of this suite that incorporates the use of the Digital Communications Analyzer. Hopefully, we will stimulate your interest in this 40G arena such that you will be interested in learning about more 40G test equipment.

- **Measurement tools**
  - Electronic design automation (ADS, IC-CAP)
  - Waveform analysis (DCA)
  - Active optical components (DCA,LSA)
  - Raman amplifier test (OSA, TLS)
  - Passive optical components (OSA,CD,PMD)
  - BER test (BERT)

Signal Integrity Concerns

When designing high-speed digital electronics, it becomes more difficult to transmit ones and zeros as the data rates increase. This is due to the fact that high data rates usually translate into a faster risetime transition between a logic low level and a logic high level. As this risetime becomes shorter, the subsequent electrical length of a PCB trace that becomes a transmission line is much shorter. Design of transmission lines require significantly more care and rigorous understanding of underlying microwave phenomena. To enhance signal integrity of the optical network physical layer (I.e. electrical drivers of optical transmitters, router backplanes, gigabit interconnects, etc.), the designer must follow good high-speed practices. Minimizing reflections by reducing impedance mismatch between components and lowering crosstalk between adjacent electrical lines is important. These techniques will avoid problems such as signal attenuation, skew and jitter.



Fiber Optic Transmitters Technologies

Telecommunications and data networks require more bandwidth over longer distances at a lower cost. As a result, fiber optics are evolving into a diverse array of technologies that can accommodate these factors depending on the applications. For the lower cost, short distance networks, direct modulation of the current of a semiconductor laser is the best choice. There are three main types of lasers used for direct modulation: Fabry-Perot (FP) lasers, Vertical-Cavity Surface-Emitting (VCSEL) Lasers and Distributed Feedback (DFB) Lasers.

For higher quality, long distance networks, external modulation of the laser light is the preferred approach. This maintains the spectral purity of the laser light. Two main technologies compete for this space: Electro-Absorptive Modulators (EAM's) and Mach-Zehnder (MZ) Interferometers. Electro-Absorptive modulators (EAM) are constructed of semiconductor materials such as Indium Phosphide (InP). EAM's modulate the light by absorbing the optical energy when a negative voltage is applied. The main advantage of EAM's is the ability to be integrated with a DFB laser on the same die. When the EAM and DFB laser are monolithic the assembly is commonly referred to as an Electroabsorptive Modulated Laser (EML). Although EML's are an improvement over directly modulated lasers, they still have some technical disadvantages when compared to Mach-Zehnder interferometer modulators.

Designers use Lithium Niobate (LiNbO3) Mach-Zehnder Interferometer Modulators to achieve the highest quality optical transmitter. More recent technologies use Gallium Arsenide (GaAs), Indium Phosphide (InP), and polymers to create MZ modulators. Each material has technical advantages, however, LiNbO3 remains the main technology for MZ modulators. This is due to the proven reliability, low insertion loss, and broad operating wavelength range of LiNbO3. This makes this material ideal for tunable lasers and wavelength division multiplexing (WDM).

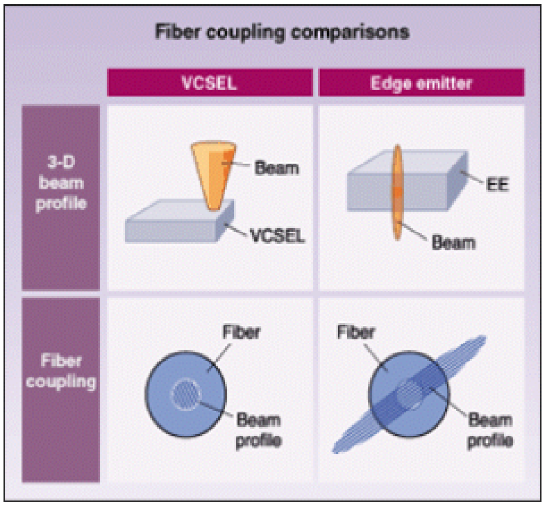
- Direct Modulation of the Laser Current ($\leq$ 10GB/s)
  - Fabry-Perot Semiconductor Lasers (FP)
  - Vertical-Cavity Surface-Emitting Lasers (VCSEL)
  - Distributed Feedback Lasers (DFB)
- External Modulation of Laser Light ($\geq$ 2.5Gb/s)
  - Electro-Absorptive Modulator (EAM)
    - Electroabsorptive Modulated Laser (EML)
  - Mach-Zehnder Interferometer Modulator(MZ)

Semiconductor Laser Comparison

Semiconductor laser technology as been advancing at ever accelerating pace. FP lasers are the simplest laser structure and have been around the longest time, forming the foundation for the more recent technologies. At 1310 and 1550 nm, FP lasers are fabricated on InP with the active laser layers made of InGaAsP. The waveguide structure of the laser is grown horizontally on the semiconductor wafer. Hence in order for the light to be emitted, there is a post process of cleaving, polishing, and thin film coating that adds cost and time to manufacturing. The lasing action is simply created by two semi-reflecting surfaces with the semiconducting material in-between setting the gain and wavelength of the laser device. Thus, there are multiple modes of light creating a picked fence type spectral wavelength map, making the effective spectral width of the laser of up to 3 nm. Due to the large spectral width of the FP laser, they cannot be used for long distances, since chromatic dispersion would limit their performance.

DFB lasers were developed next by adding a Bragg grating structure inside the laser waveguide between the reflecting surfaces of a FB laser. This isolates only on mode inside the laser making its spectral width extremely thin on the order of 5 MHz. Hence, DFB laser are used for much longer distance transmissions. DFB’s however still require the extra post-processing steps, since it is an edge-emitting laser. Furthermore, the output beam is elliptical due to the rectangular waveguide structure of the laser. In order to bring the laser cost down, much research as gone into the development of VCSEL’s. VCSEL’s are radically different structure than FP’s and DFB’s. Their laser cavity is built vertically on the semiconductor substrate during the doping and etching processes, and there is no need to dice the chips up, or to polish the output surfaces. Hence, VCSEL’s can be manufactured at a reduced cost, since their manufacturing process requires less steps. Furthermore, since the emit light from their top surface their output beam are designed to be round, making optical coupling to a fiber much more efficient and easier. VCSEL’s also have more stable output over temperature, hence they don’t require a monitor photodiode. VCSEL also have lower threshold currents, which mean they require less power. Although

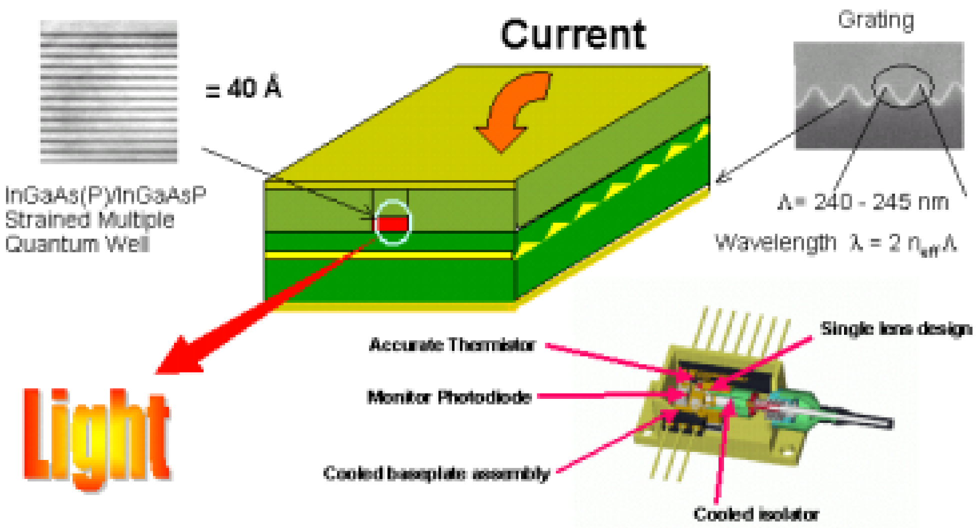
VCSEL's have advanced significantly in the last couple of years, 5MHz line widths and high power 1550 nm operation have not been demonstrated yet with VCSEL's; therefore, DFB lasers still dominate the long-range applications.



	FP	VCSEL	DFB
Common Wavelengths	1310 nm, 1550nm	850nm, 1310nm	1310 nm, 1550nm
Materials	InGaAsP / InP	GaAs, InGaAsP	InGaAsP / InP
Output Power	≤ 10 mW	≤ 5 mW	≤ 40 mW
Spectral Width	3 nm	0.05 - 0.2 nm	0.0001nm
Threshold Current @25C	5mA – 15mA	2 – 4mA	5 – 15mA
Transmission Distances (at 2.5Gb/s)	< 20 km	< 40 km	<200 km
Coupling Efficiency	30% – 50%	85% – 90 %	30% – 50%
Cost	$25-$500	$5-$100	$100-$3,000

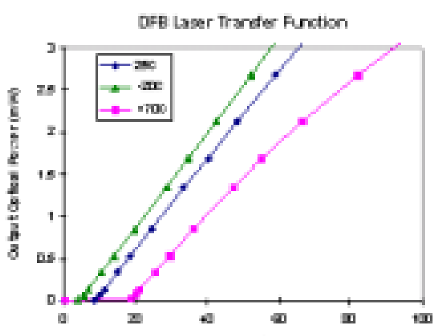
Distributed FeedBack (DFB) Laser for WDM

This slide illustrates the fundamental constructions of a Indium Gallium Arsenic Phosphate (InGaAsP) Multiple Quantum Well DFB laser used for WDM applications. The Multiple Quantum Well structure provides the gain medium for the laser cavity. The Grating structure underneath and perpendicular to the laser waveguide selects the operating wavelength. The wavelength of the laser as a linear relationship with change in temperature of approximately 0.08nm/C, thus the laser must be placed on a thermoelectric cooler, in order to maintain the correct operating wavelength over time and temperature. Thus, a thermistor is placed in thermal contact with the laser, so that it can be use in a control loop that maintains the laser at a specific operating temperature. The laser is then placed into a butterfly package for thermal heat sinking purposes. The laser light exits on both sides of the laser with a majority of the light emitting out of the front face to the lens and a small amount exiting on the back side towards the monitor photodiode. The monitor photodiode is used in a control loop that maintains the output power constant over temperature and time. The light exiting the front face goes through a lens and through an optical isolator, which keeps light reflecting back into the laser cavity and disrupting the lasing process.

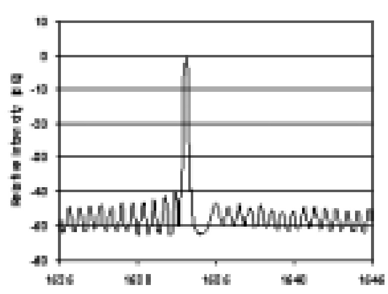


Semiconductor Laser Fundamentals

This slide illustrates the fundamental constructions of a Indium Gallium Arsenic Phosphate (InGaAsP) Multiple Quantum Well DFB laser used for WDM applications. The Multiple Quantum Well structure provides the gain medium for the laser cavity. The Grating structure underneath and perpendicular to the laser waveguide selects the operating wavelength. The wavelength of the laser as a linear relationship with change in temperature of approximately 0.08nm/C, thus the laser must be placed on a thermoelectric cooler, in order to maintain the correct operating wavelength over time and temperature. Thus, a thermistor is placed in thermal contact with the laser, so that it can be use in a control loop that maintains the laser at a specific operating temperature. The laser is then placed into a butterfly package for thermal heat sinking purposes. The laser light exits on both sides of the laser with a majority of the light emitting out of the front face to the lens and a small amount exiting on the back side towards the monitor photodiode. The monitor photodiode is used in a control loop that maintains the output power constant over temperature and time. The light exiting the front face goes through a lens and through an optical isolator, which keeps light reflecting back into the laser cavity and disrupting the lasing process.

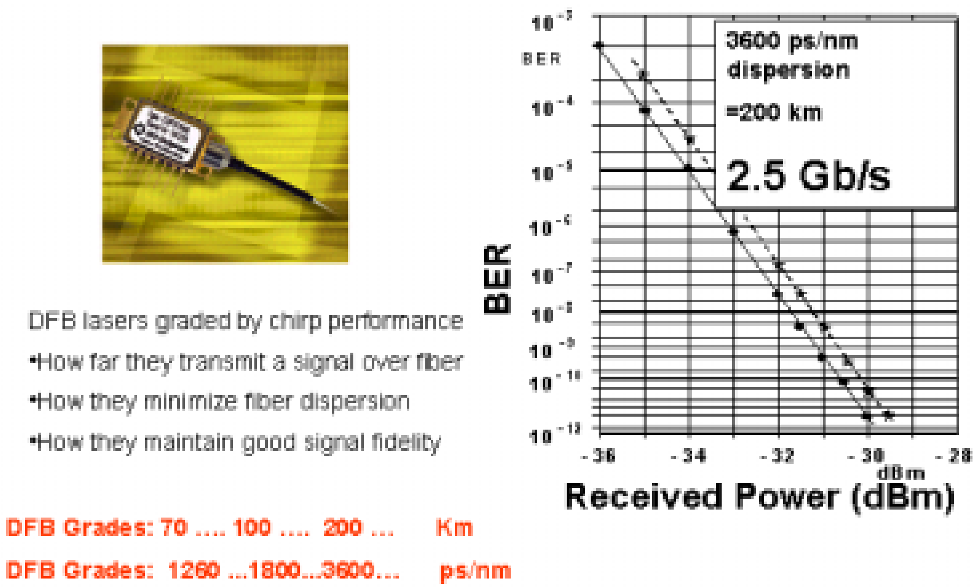


- Laser current is modulated
  - Shifts operating wavelength of the laser
  - Spectral line width of the laser broadens



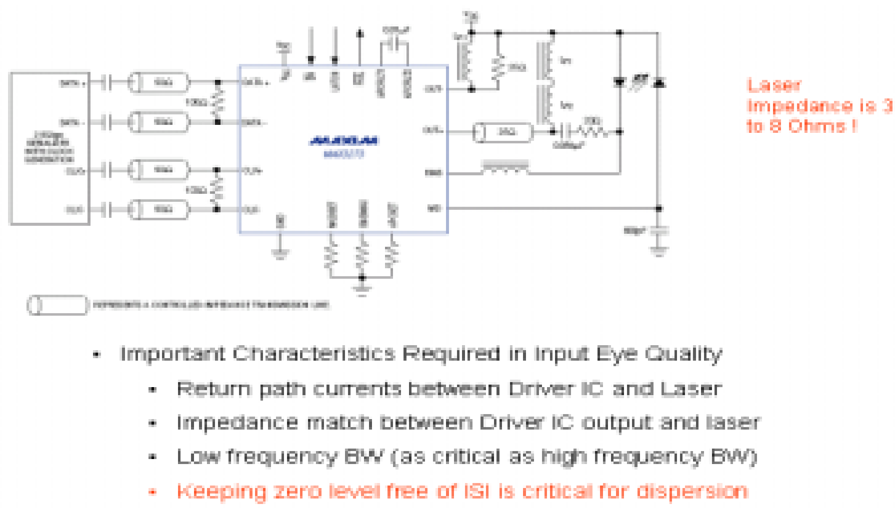
DFB Laser Chirp

In the 1550 nm range, DFB lasers are graded on the amount of chirp they produce when modulated directly. To separate the low chirp lasers from the high chirp lasers, DFB lasers are graded by the amount of dispersion that the laser can handle before there are significant errors in received signal at the end of the fiber link. Bit Error Rate (BER) curves at different lengths of fiber are used to illustrate how the fiber chromatic dispersion has caused the chirp of the DFB laser to limit the transmission distance. The common metric used is the dispersion penalty, which is the measure in dB of optical power between the back-to-back BER curve and the BER curve over some fixed fiber length. Typically, if the dispersion penalty is greater than 2dB then the DFB cannot be used for that length of fiber. The DFB laser manufactures would then specify that a laser could handle a fixed amount of dispersion in ps/nm and guarantee that it could handle this dispersion with less than a 2dB dispersion penalty.
Recent advances in DFB technologies have produced lasers with less chirp allowing them to reach distances of 200km. In the above graph, the BER curves for a 3600 ps/nm DFB laser is plotted first for the case of a the transmitter connected directly to the receiver, then with 200km of standard single mode fiber inserted between them. Standard single mode fiber has a dispersion coefficient of up to 18 ps/(nm km) in the 1550 nm range, hence the dispersion would equate to the fiber length times the dispersion coefficient.



Sample Driver Circuits for a Laser at 2.5Gb/s

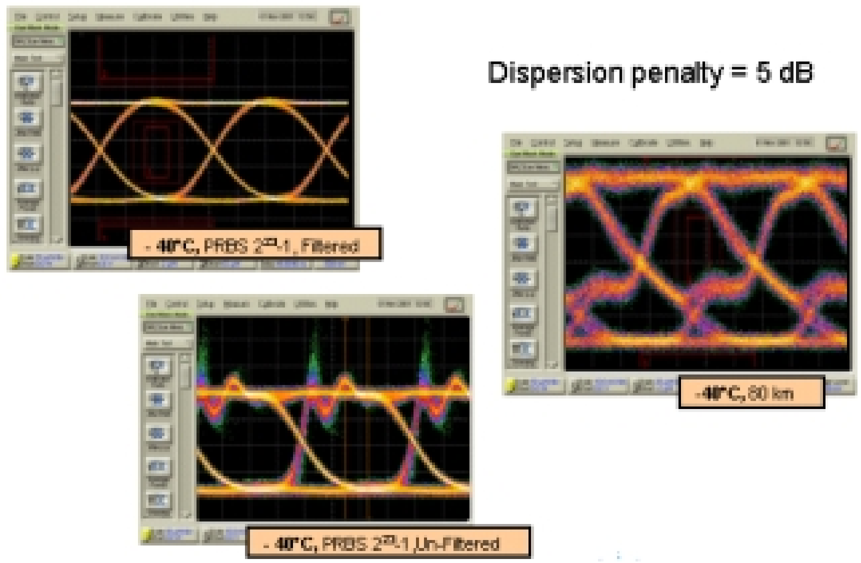
Illustrated below is a schematic of a MAXIM laser driver connected to a semiconducting laser. This IC takes the 2.5GB/s data stream and 2.5Gb.s clock and re-times the data providing a low jitter data stream to the laser. The input impedance of the drive is 50 Ohms for the input differential signals, and the output differential signals are 25 Ohms. The 25-Ohm transmission impedance is used because it is closer to the input impedance of the laser, which is between 3 and 8 ohms depending on the bias and the laser. A series 20-ohm resistor is commonly used in series as the most straightforward way to match the impedance of the laser to the driver output impedance. Ideally, the laser and the driver a very close together, but in some cases, there is significant distance between the laser and the drive circuit. This requires a controlled transmission line microstrip between the laser and the driver. It is critical that the return path for the laser, the driver and the microstrip have a common AC ground with as little resistance or inductance between them.



1550 nm DFB Performance at 2.5Gb/s

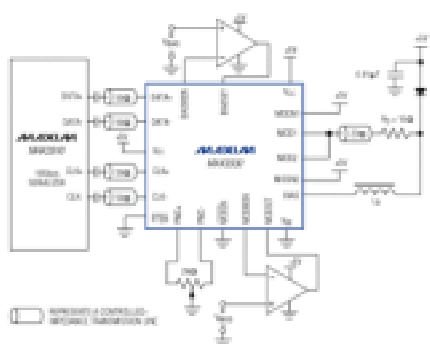
Illustrated below are three eye diagrams of an uncooled 1550 nm DFB laser. The top eye diagram is the output of the laser directly into the Agilent 86100A Digital Communications Analyzer using a plug-in with an OC-48 filter. This filter removes the laser ringing that occurs in the eye diagram. The filter is used as a standard for all extinction ratio, jitter, and eye quality measurements. This filter is a fourth order Bessel-Thompson filter that approximates the receiver bandwidth and it is used for compliance measurements. Its 3dB bandwidth is typically 75% of the data rate.

The unfiltered eye diagram can observe key parameters such as the laser relaxation frequency and magnitude. The filtered eye measurement may cover up the relaxation frequency ringing and may not properly characterize possible problems when tested in an actual link. This was true above when viewing the eye diagram after 80km of standard SMF-28 fiber. The large extinction ratio (~11dB) was causing the laser to chirp significantly during turn on which would also cause excessive ring of the laser. In this case the above-dispersed eye diagram caused a 5 dB dispersion penalty. The correct way to characterize relaxation frequency ringing is to make an unfiltered measurement.



Sample Driver Circuit for Laser at 10Gb/s

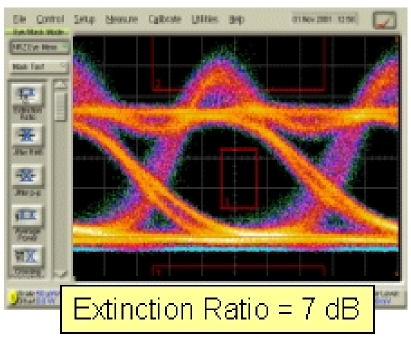
Direct modulation of laser at 10GBs as been shown to work very effectively at the 1310nm wavelength due to the zero dispersion point of standard single mode fiber. Thus, the spectral broadening of the laser at 1310 nm is not as critical as it was at 1550nm. Again as with 2.5 GB/s, return path currents between Driver IC and Laser are critical, impedance match between Driver IC output and laser is critical, and low frequency BW is just as critical as high frequency BW. However, the signal integrity is 4 time more challenging due to the parasitic and laser limitations. At the 10GHz the laser leads become inductive, and the internal bond wires to the laser chip radiate and capacitive couple to the laser case, which is typically AC ground. Hence, packaging of the lasers become challenging from an RF perspective, severely limiting the rise and fall times. Hence, industry trends have been pushing integration of the driver with the laser in a hybrid package to improve performance and yields in production.

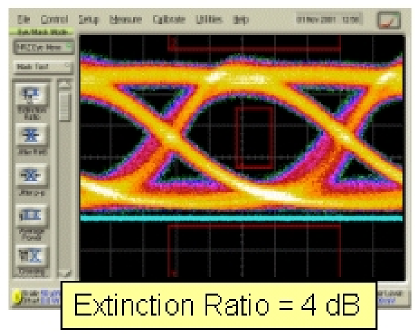


- Important Characteristics Required in Input Eye Quality
  - Return path currents between Driver IC and Laser are critical
  - Impedance match between Driver IC output and laser is critical
  - Low frequency BW is just as critical as high frequency BW

1310nm DFB Laser Performance at 10Gb/s

Operating a semi conducting lasers at 10GB/s pushes the technology to its limits squeezing every ounce of performance out of the device. Typically, biasing the laser for more output power increases the bandwidth of the laser, but at the same time requires more drive level to create the same extinction ratio. Higher bias levels means shorter life or higher power lasers. Lower bias levels means an decrease in laser relaxation oscillation frequency, along with an increase in its the magnitude of the oscillation. This sometimes occurs below 10GHz causing the ringing to dip into the middle of the eye diagram when trying to reach the required minimum 6dB extinction ratio for short fiber links (<2Km) at OC-192. This means that there is this trade between laser extinction ratio and eye quality.
More recent DFB lasers have reduced the magnitude of the relaxation oscillation and have pushed relaxation frequency past 17GHz, but still most 10Gb/s DFB lasers used today have significant ringing that can be masked by the OC-192 filter, causing interoperability problems between receivers. Since fiber optic receivers from different manufacturers use different photodiodes with different bandwidth and group delays. Receivers that work great with EML and MZ transmitters sometimes produce errors across the optical input range due to direct modulated DFB lasers, which have severe ringing in the middle of the eye diagram. The ringing passes through the receiver bandwidth and into the error detector, creating BER floors in the BER curve. In other words, the receiver always produces at least a fixed amount of errors no mater what optical input power is placed into it.



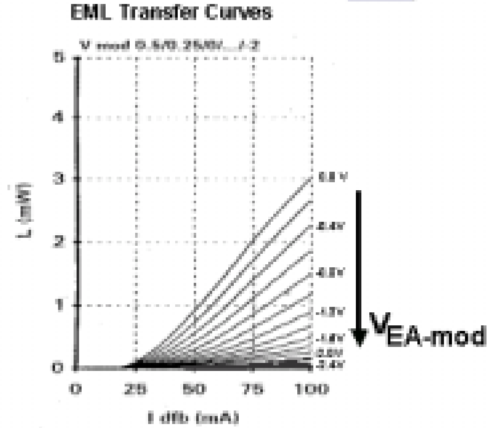


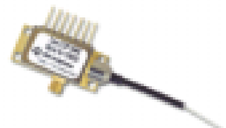
- Bandwidth Limitations
  - Bandwidth is dependent on bias current
  - Typically the bandwidth increases with bias current
- Relaxation Oscillation Frequency
  - The laser tends to ring at 10 GHz depending on bias current
  - Large extinction ratios cause more severe ringing

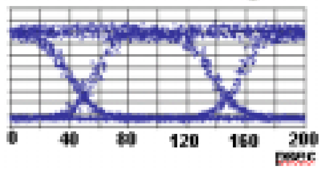
EML Laser Fundamentals

Due to the limitations of DFB lasers at 2.5Gb/s and 10Gb/s, electroabsorbtive lasers (EMLs) have become the standard laser for medium to long reach applications. At 2.5 Gb/s the transmission distance moved from 200 km maximum for directly modulated lasers to 600 km with EMLs. EMLs are fabricated together on the same die with a DFB laser, hence their transfer function is dependent upon the DFB bias current and the bias on the electroabsorbtive section. Although not as severe as direct modulation, the chirp performance of EMLs are dependent upon the bias level and the drive level of the EA section. The EA section is relatively efficient at about 5dB/V. The drive levels required for EAMs are typically around 2.5Vp-p in order to obtain extinction ratios greater than 8.2dB. EAMs also require a negative bias adjust between –0.7 and –1.8 V in order to optimize the output waveform extinction ratio and insertion loss.

- Construction
  - 20 mW DFB integrated with an EA modulator
  - EAM matched to 50-Ω through GPO connector.
- Wavelengths
  - 1310 nm and 1550 nm
- Dispersion Limitations
  - 600km at 2.5Gb/s
  - 80km at 10Gb/s (1600 ps/nm)

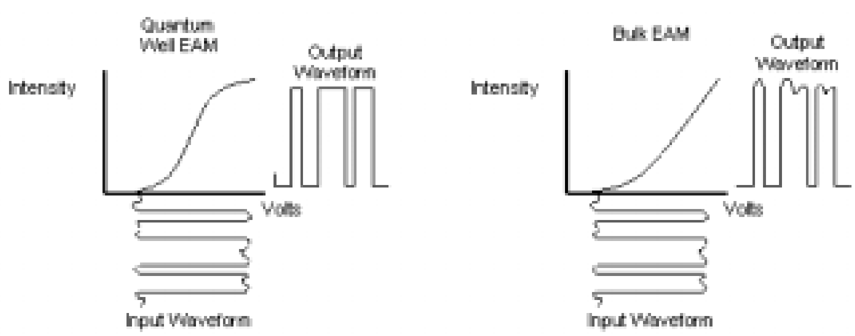






Signal Integrity Concerns with EML Lasers

There are basically two types of EAMs: bulk EAMs and quantum well EAMs. Bulk EAM work over a broader wavelength range and require slightly higher drive levels when compared to a quantum well EAMs. One advantage of some quantum well EAMs is that the one and zero levels when driven optimally have a flattened transfer functions that saturates, thus pattern dependent noise on the one and zero levels can be cleaned up. On the other hand, bulk EAMs remains linear at the one level, hence any pattern dependent noise on the one level is magnified on the optical output. However, the bulk EAM has a zero level that will flatten out without having to worry about it folding over just like the quantum well EAM. This means that with bulk EAMs the optimum eye diagram for best dispersion penalty performance has a crossing that is skewed lower than 50%. For both types of EAMs, it is critical not to over drive them or bias them positively above ground. Not only will this degrade the eye diagram, but it could eventually damage the device.



Important Characteristics Required in Input Eye Quality

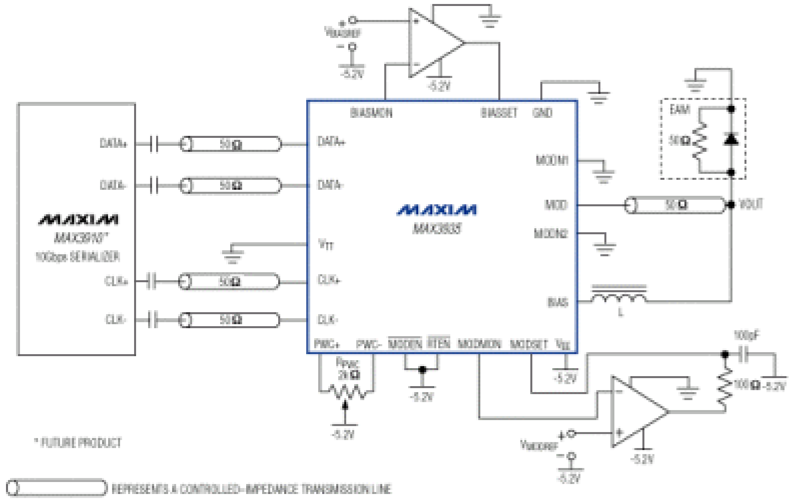
- Minimize waveform ringing on the 1 level, especially on bulk EAMs
- Changes in modulation depth and bias causes the extinction ratio, chirp, or output average power of the EML to change
- Poor matching of impedance between driver IC and EML degrades BER performance.
- Jitter and Rise times are critical for maximum dispersion penalty.

Sample Driver Circuit for EML Laser 10Gb/s

The EA modulator is essentially a photodiode that has an absorption band close to the wavelength of the laser. When the EAM is reversed biased and an electric field is created in the EAM, its absorption band is shifted to the laser wavelength. The incident photons are absorbed and an electrical current is produced. Thus, the effective impedance of the EAM is dependent upon drive and bias levels. To fix the impedance match EAM manufactures effectively use a resistive match at the input of the EA section that creates about 6dB of loss between the driver and the EAM. The parallel 50-Ohm resistor with the EAM in the above diagram is for descriptive purposes only.

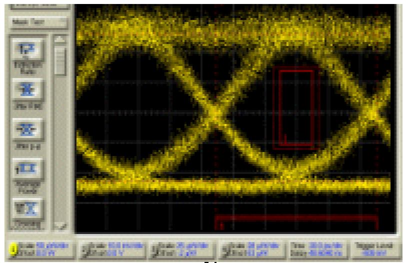
Since most EAMs at 10Gb/s and higher have coaxial RF input connectors, impedance matching between the driver, the PWB micro-strip, and the cable launch at 50 ohms are the main critical parameters. This means the bias-T that brings the negative bias to the modulator is critical and needs to be a broadband RF choke. Other IC drivers have the bias-T's internal to the IC making the RF matching easier.

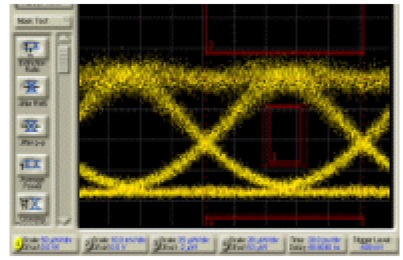
- 50 Ohm Impedance used at Driver output



EML Laser Performance at 10Gb/s

A JDS Uniphase bulk type EML was used to create the above eye diagram and to illustrate how dispersion penalty can be improved by altering the driver parameters. The top two eye diagrams show how an acceptable eye diagram in a back-to-back measurement creates a degraded eye diagram after 50 km of standard SM fiber. The resultant dispersion penalty is 4.6 dB due to chirp and poor driver parameters. The two lower eye diagrams illustrate how adjusting the EA bias and driver output parameters can improve the eye diagram quality and dispersion penalty after 50 km of fiber. By reducing the pattern dependent jitter, decreasing the rise and fall times out of the driver and by adjusting the bias of the EA section a dispersion penalty of 1.2 dB can be achieved.

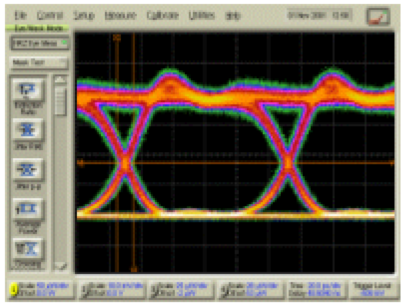


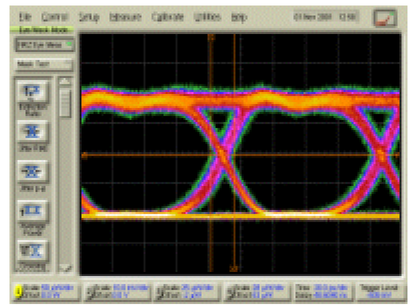


0 km eye
BER =1.2e-9 @ -18.2dBm

DP = 4.6dB

50 km eye
BER = 1.4E-9 @-13.7dBm





0 km eye
1e-9 @ -17.8dBm

DP =1.2dB

50 km eye
1E-9 @-16.6 dBm

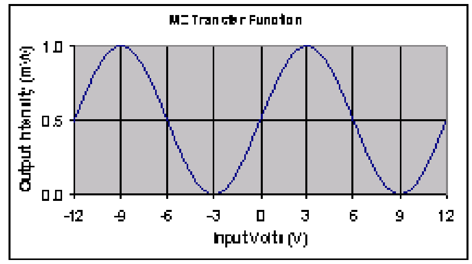
Mach-Zehnder Modulator Fundamentals

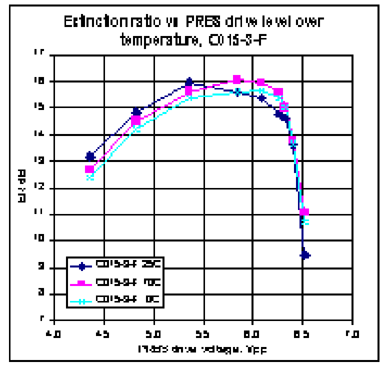
Mach-Zehnder Modulators (MZ) create the highest quality optical eye diagram. MZs modulate the light by interference, hence they have a sinusoidal transfer function that repeats itself periodically. The period of the sine transfer function is referred to as 2 Vpi. In the above transfer function plot, the Vpi voltage is 6 Volts. There transfer function is very repeatable and stable over time and temperature, if the correct bias is maintained. The only down fault of MZs is that they have a bias point that varies over time and temperature, which must be actively controlled in a closed loop. The above plots illustrate the excellent extinction ratios that can be achieved with a MZ modulator and how stable it is over temperature. The Vpi of the tested modulator is close to 6V, which means that the best extinction ratio occurs when the output sing of the driver matches the MZ Vpi at 6Vp-p. The plot also illustrates how over- driving the MZ modulator generates a very severe degradation in extinction ratio with only a slight increase above Vpi.

- Transfer Function

$$P_{out} = \frac{P_{max}}{2} + \frac{P_{max}}{2} Sin\left(\pi \frac{V_{in}}{V_{\pi}}\right)$$

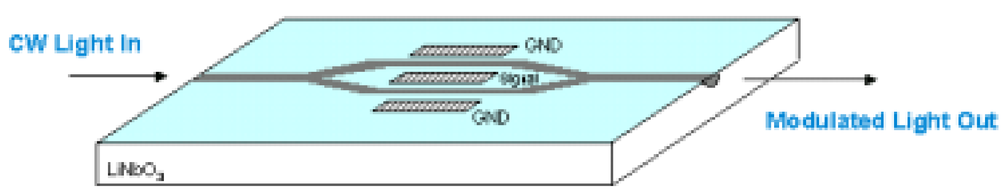
- Materials Used
  - LiNbO3, GaAs, InP, Polymers
- Chirp
  - Fixed to zero or small negative value
- Dispersion Limitations
  - Modulation Bandwidth Limited
- Wavelengths
  - 1310 nm and 1550 nm
- The RF port Vpi is stable to within 1% over a temperature of 0 to 70C.



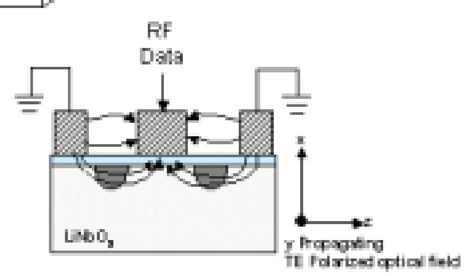


Electrode Layout for x-cut $LiNbO_3$ MZ Modulator

The X-Cut Lithium Niobate ($LiNbO_3$) modulators are commonly used due to their near zero chirp performance. The top figure illustrates how a Y-branch interferometric waveguide structure is separates the continuous-wave CW light into two separate waveguides, then recombines the waveguids together creating interference that provides the mechanism for amplitude modulation of the CW light. Lithium Niobate modulators operate by the electro-optic effect, in which the applied electric field changes the refractive index making light travel faster or slower in the two split waveguids of the Y-branch interferometer. The electro-optic is strongest along the z-axis, hence the continuous-wave (CW) laser output needs to have its electric field polarized along the z-axis of the lithium niobate crystal. By placing optical waveguides between the RF signal electrode and the ground electrodes that form the RF co-planar waveguide, a "push-pull" configuration is created that causes a symmetric E-field overlapping each optical waveguide leading to low, near-zero chirp.

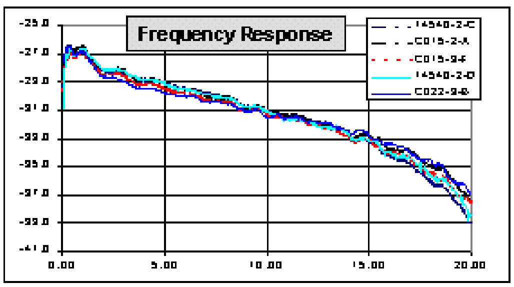


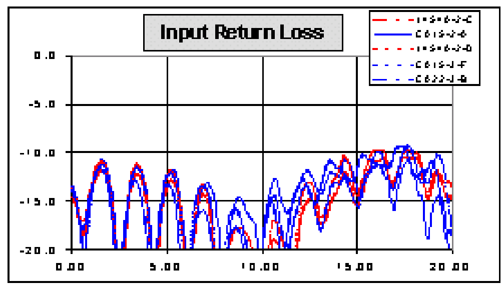
Lithium Niobate X-cut crystal orientation
- Requires the drive electrode to be placed between the optical waveguides
- Produces a symmetric E-field overlap in each optical waveguide
- Leads to low, near-zero transmitter chirp



Signal Integrity Concerns with MZ Modulators

The above frequency response curves illustrate how consistent the bandwidth is over several production units. And, the above input return loss measures the impedance mismatch reflections across the bandwidth of the device, revealing that from unit-to-unit the reflection are below –10dB out to 15GHz. This illustrate how the LiNbO3 modulator has an extremely well matched 50 Ohm termination that is very constant with drive levels. The bandwidth of the MZ is also very independent from bias levels and is very consistent from unit to unit. The sinusoidal shape of the transfer function transforms slow rise and fall time signals with noisy 1 and zero levels on the electrical input eye and produce sharper optical eye diagrams. However, cleaner electrical input eye usually means less pattern dependent jitter on the output optical eye diagrams. The one concern with having sloppy electrical eye diagrams at the input to the MZ is that the bias control loops of the MZ can be sensitive to eye quality. Hence, if the eye quality degrades over temperature (especially crossing ratio) the bias control loops of the MZ can severely distort the optical eye diagram or even become unstable.





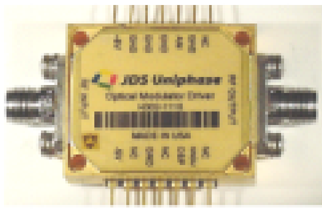
- Excellent Impedance Matching
  - Co-planar transmission waveguide on the $LiNbO_3$ crystal terminated in 50 Ohms
- Constant Bandwidth from unit-to-unit.
  - LiNbO3 modulator bandwidth maximized by phase matching the velocity of the RF wave guide with the optical wave guide.
- Important Characteristics Required in Input Eye Quality
  - Since the transfer function is sinusoidal, the eye diagram rise times, pattern dependent noise on the 1 and 0 levels are cleaned up by the modulator.

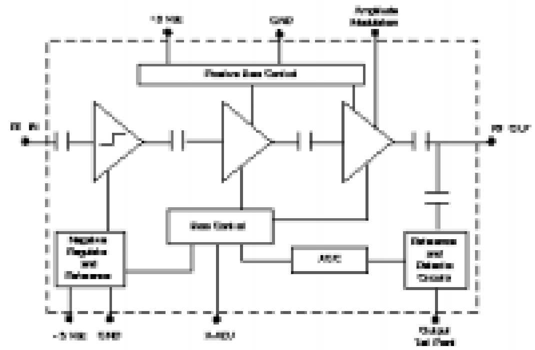
Sample Driver Circuits for MZ modulators

An ideal driver for an MZ modulator would be a limiting amplifier that compensates for different or changing input levels and maintains the same output level over temperature. The limiting amplifier would also have the additional advantage of sharpening up the input waveform from a 10Gb/s serializer. The above picture and block diagram illustrates the H302 driver amplifier designed by JDS Uniphase to provide up to 7.5Vp-p swings that is required for some LiNbO3 MZ modulators.

10Gb/s Limiting Amplifier

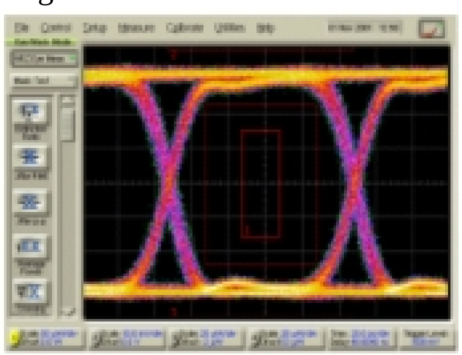
- 50 Ohm input and output impedance
- 7.5Vp-p Adjustable Output Swing
- 250mVp-p to 1.5Vp-p input levels



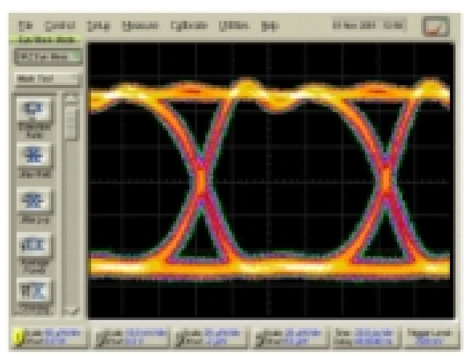


Mach-Zehnder Performance at 10Gb/s

The above eye diagrams illustrate the superb eye quality out of the hybrid MZ driver and how the JDS Uniphase MZ modulator even improves the eye diagram further by sharpening up the rise and fall times and by removing the ringing on the one level. The output level swing of the driver can be adjusted to maximize extinction ratio and rise times out of the MZ modulator. Improving rise times and pattern dependent jitter will decrease the dispersion penalty. At 10 Gb/s, an X-cut lithium niobate modulator is dispersion limited to about 60 km for less than a 1dB dispersion penalty over standard single mode fiber in the 1550nm range.



Driver Electrical Output

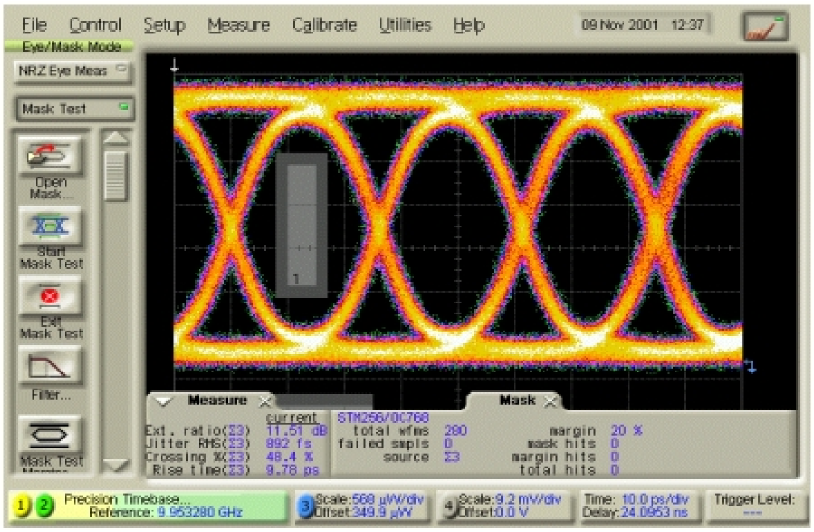


MZ Optical Output

Mach-Zehnder Performance at 40Gb/s

At 40Gb/s external modulation is the only way to achieve acceptable eye quality. This means that EAM or MZ modulators will most likely be used for all fiber optic transmitters at 40Gb/s and higher. The above eye diagram illustrates recent developments in using a JDS Uniphase X-cut LiNbO3 modulator in a fiber optic transmitter. At 40Gb/s, the X-cut lithium niobate modulator is dispersion limited to about

3.7km for less than a 1dB dispersion penalty over standard single mode fiber in the 1550nm range, assuming a dispersion coefficient of 17 ps/(nm*km). This means that the dispersion limited distance decreased by a factor of 16, with only a factor of 4 increase in bit rate when going from 10Gb/s to 40Gb/s. One can use the equation $DL < 10^5/B^2$ to determine the dispersion allowed for a specific bit rate of NRZ data, assuming zero chirp and a 1 dB dispersion penalty. D is the dispersion coefficient of the fiber in ps/(nm*km), L is the length of fiber in km and B is the bit rate in Gb/s. This illustrates how at increasing data rates the fiber dispersion becomes the significant limitation that needs to be solved.

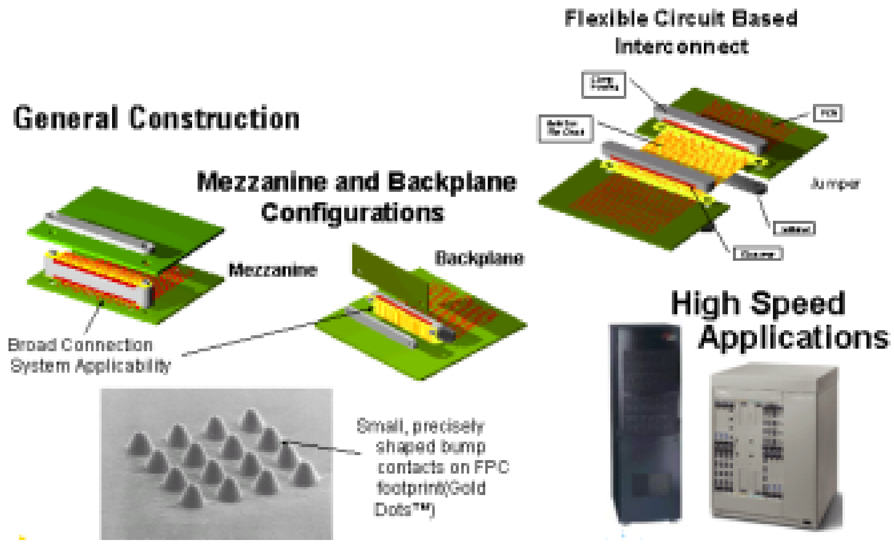


Gold Dot Interconnect Profile

Printed circuit boards are often implemented as the interconnect between the laser driver circuit and the laser diode. Considering the requirements on signal integrity characteristics and the ability to manufacture a variety of configurations, a flexible circuit interconnect offers advantages over traditional PCB's.

The Gold Dot flexible circuit has superior electrical performance in harsh environments. The small, precisely formed bump bonds provide the physical transition to the printed circuit board provides less impedance mismatch and change in contact resistance through environmental extremes. The bump bonds can either mate to printed circuit boards in an elastomer based clamping system for a temporary connection or a chip-on-dot for a permanent connection.

The flexible circuit can be manufactured in a stripline or microstrip ground configuration. Additionally, the circuit may be used as a jumper, a mezzanine or a backplane connection. Design geometries available yield configurations and footprints optimized for applications in high speed switching units, routers, mobile computers, and cell phones. Optical transmitter driver applications are a new and exciting technology that is studied in this paper.



Laser Transmitter Interconnect Solutions

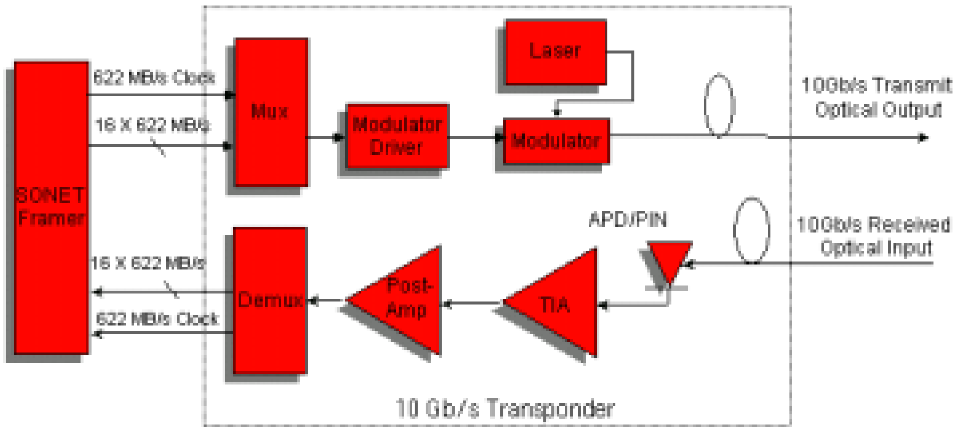
Fiber optic transmitters are commonly integrated into transponders that contains both a fiber optic transmitter and receiver. The fiber optic transponder usually contains a serializer (Mux) and de-serializer (Demux). The serializer or Mux transforms 16 channels of a lower data rate into a single channel of data at 16 times faster the the lower data rate. The de-serializer or Demux returns the 16 channels of the lower data rate from the high speed single channel, along with a recovered clock that is in phase with the incoming data stream.

The interconnect between the transponder and the SONET framer contains differential controlled impedance lines on all channels and clocks. Hence, high density, high speed interconnects with controlled impedances and equal line lengths are necessary in order not to introduce line skew and other undesirable characteristics into the optical system. At high data rates such as a 40Gb/s transponder which would have 16 channels of 2.5Gb/s, these issues become even more critical. Flexible interconnects could be an ideal way to maintain the differential controlled impedances and equal line lengths and solve other technical issues of connecting the transponder to the SONET framer.

Furthermore, there are interconnect requirements between each of the critical blocks inside the transponder. Here signal integrity is of utmost concern, especially between the optical devices and the interface IC's that drive or receive the high-speed data. Due to packaging restraints and the ever increasing desire to reduce the overall size of the transponder, flexible interconnects provide a way to solve the technical issues of connecting the high-speed components.

For example, the driver circuit interconnects not only require signal traces on high densities but they also require that these signals not to be distorted while being sent from one component to another, such as a laser driver diode to a laser. The optical eye diagram performance of the laser is dependent on the electrical characteristics of the transmitted signals between components in an laser driver circuit. High density signal lines, both single ended and differential must carry signals in excess of 2.5 Gbps.

All of these considerations must be taken into account when routing high density, high speed interconnects from one optical device to another. Though environmental conditions are not extreme, operating temperatures, often in the range of –40C to 80C are not uncommon, and may be only one of the many environmental extremes to be considered when choosing an interconnect for a fiber optic transponder.



10 Gb/s Fiber Optic Transponder Block Diagram

Interconnect Electrical Performance

A flexible circuit interconnect is able to provide single ended and differential signaling from one device or component to another. Cross talk, attenuation, and propagation delay have been measured on a host of materials and signal densities. In general, the performance of these flexible circuits can be predicted with simulation tools. The general electrical performance of a Gold Dot flexible circuit interconnect has been characterized in the time domain and frequency domain. Performance characteristics are highly dependent on material properties, flexible circuit stack-up, signal trace dimensions as well as the manufacturing process.

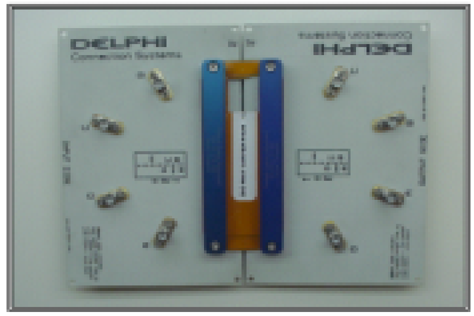
Parameter	Performance
Impedance	50 Ohms Single Ended 100 Ohms Differential
Cross Talk NEXT	<5% Single Ended <.5% Differential
Attenuation(5 GHz)	<.5dB/inch
Propagation Delay	<200 ps/inch
Data Rate	>2.5 Gbps

Proposed Interconnect for Modulating Semiconductor Laser

A Gold Dot jumper interconnect configuration was evaluated as the interconnect between the laser driver circuit and the laser diode. With the Gold Dot flexible circuit supported by two printed circuit boards, inserting this device in series with the driver circuit would quickly and effectively determine how this type of interconnect would affect the performance of the laser driver circuit. The Gold Dot flexible circuit supported on the printed circuit boards mounted with SMA’s would allow the signals to be sent and received through the Gold Dot interconnect and laser driver circuit. The elastomer backed clamping system provides the necessary pressure to the Gold Dot to the PCB pad interface. Four SMA’s mounted on each of the printed circuit boards allow four signal lines of the three hundred available signal lines in the circuit to be characterized . The desired electrical performance for the laser driver circuit was determined prior to designing the Gold Dot circuit and test boards with the key characteristics being a single ended impedance of 50 ohms and a data rate in excess of 10 Gbps.

Electrical Requirements

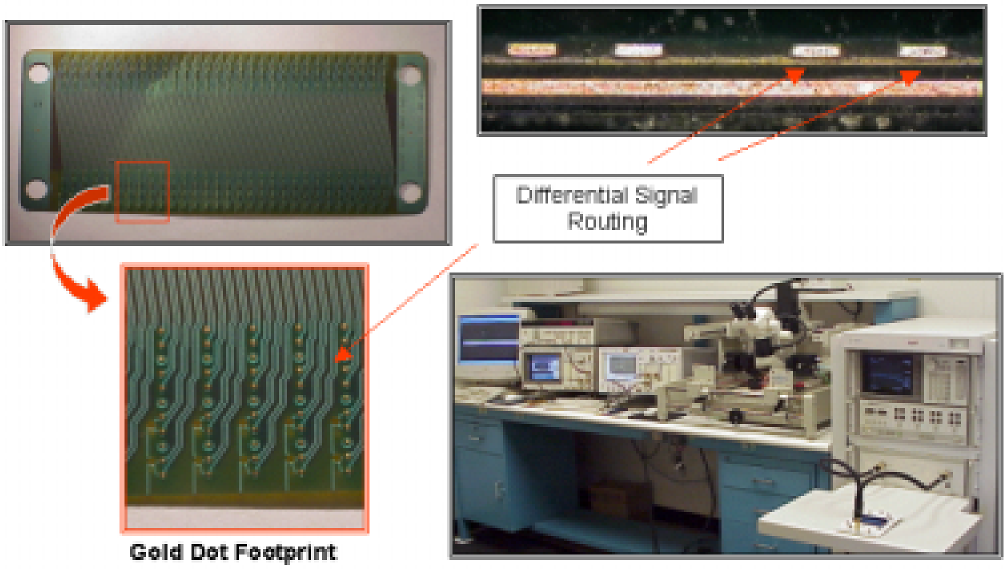
Impedance	50 Ohms
Differential Impedance	100 Ohms
NEXT	<5%
Differential NEXT	<.5%
Data Rate	> 10 Gbps
Propagation Delay	<170 ps/inch



300 Way Differential Gold Dot Jumper

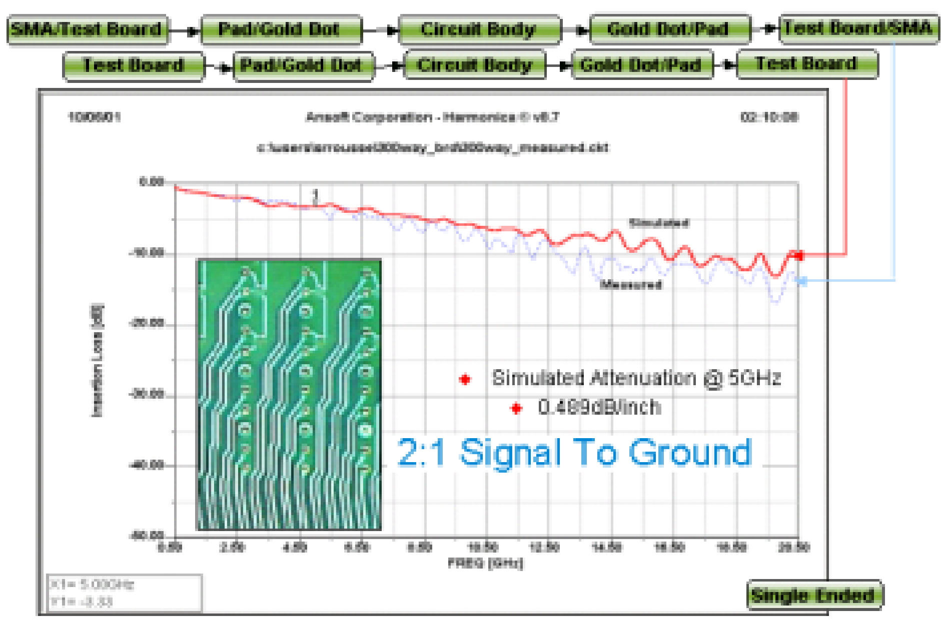
Manufacturing and Testing of Gold Dot Flexible Circuit

For controlled impedance circuits at data rates in excess of 2.5 Gbps, manufacturing tolerances on line width and spacing have a strong effect on desired electrical performance. The Gold Dot flexible circuit interconnect requires over 30 wet processes which all effect signal trace width and spacing as well as reliability in environmental extremes. Tolerances on trace width of +/-.0002 inches equate to a +/- 2.2% single ended impedance variation. With the stringent process controls in place, line widths and spacings of less than .003” are achievable well within the requirement of less than +/-10% impedance variation. Once the Gold Dot circuit is manufactured, the required performance must be confirmed in the test and measurement laboratory. Confirming signal integrity characteristics on a high density, high speed interconnect requires the measurement of time and frequency domain characteristics such as impedance, cross talk, insertion loss and return loss. Eye diagrams to confirm the data rate of are also necessary. The test equipment often includes a TDR, VNA, and a BERT. Stimuli and responses of the Gold Dot interconnect under test require a test fixture or a probe station. In this specific case, two printed circuit boards with SMA connectors provide the stimuli and responses to be launched and detected by the measurement equipment. Electrical performance is measured and a comparison to the predicted performance is made.



Electrical Test Data Insertion Loss

To predict the insertion loss of the circuit while the device was being manufactured additional simulation tools were applied. Ansoft Harmonica was able to quickly predict the insertion loss of a model composed of the Gold Dot flexible circuit and the two printed circuit boards. The SMA's on the printed circuit boards were not included in the model. The prediction of insertion loss and the actual measurement on an Agilent 8510C VNA illustrate close correlation up to approximately 10 GHz. Deviation of the measurement from the simulation can be attributed to the omission of the SMA's and vias from the simulation model.



Performance of Flexible Circuit Interconnect

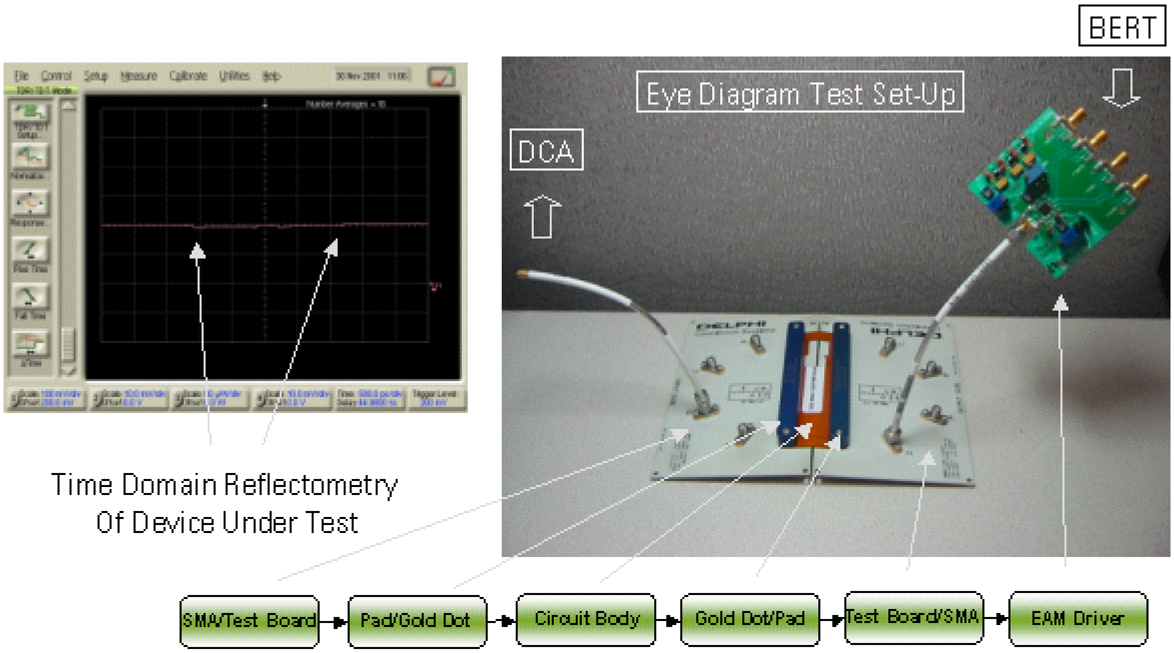
The electrical performance of the Gold Dot flexible using the printed boards as a part of the device under test was measured in both the time and frequency domain. Eye diagrams at both 2.5 and 10 Gbps were also performed while applying the OC-48 and OC-192 masks. The single ended and differential impedance were within the predetermined requirements for the laser driver circuit.

Though the measurements of attenuation and propagation delay were within the goal performance, these characteristics will be improved in the actual flexible circuit for the laser driver circuit. Adhesives of lower dielectric constant and an impedance of 50 +/- 2 ohms would allow signals of higher data rates to be sent through the Gold Dot flexible circuit interconnect. Additionally, the use of printed circuit boards and SMA's contribute to degrading the rise time of a signal and add further attenuation which would not be present in the actual Gold Dot circuit used in a packaged laser driver circuit and EML.

Parameter	Simulation	Measured	Goal
Single Ended Impedance	52.1 Ohms	53 Ohms	50 +/-10% Ohms
Differential Impedance	95.2 Ohms	98 Ohms	100 +/- 10% Ohms
Attenuation (5GHz)	<.44 dB/inch	<.44 dB/inch	<.5 dB/inch
Propagation Delay	152 ps/inch	158 ps/inch	170 ps/inch
Single Ended NEXT	<4.5%	<4.5%	<5%
Differential NEXT	<.3%	<.3%	<.5%
Data Rate	10 Gbps	10 Gbps	10 Gbps

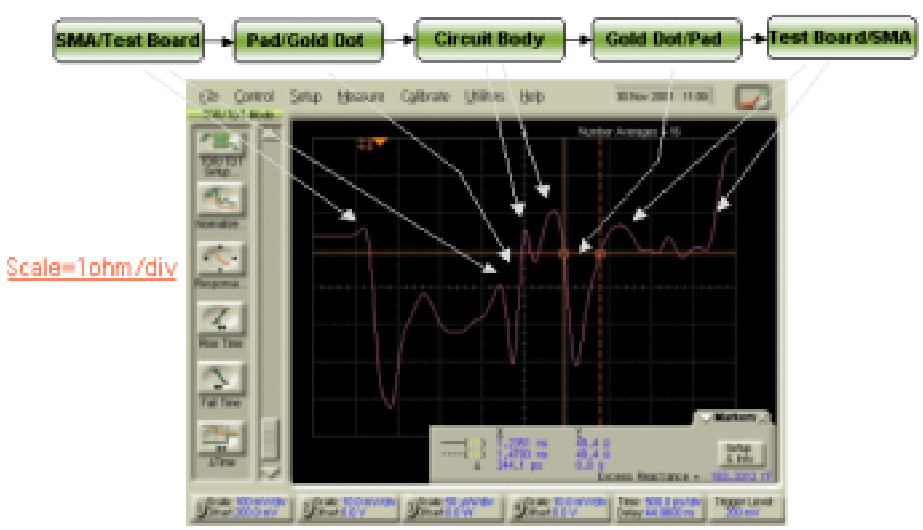
Electroabsorption Modulator Driver Test Set-Up

The test system used to analyze the eye diagrams of the test board/flex circuit is shown above. A Bit Error Rate Tester (BERT) capable of generating a 10 Gb/s Psuedo Random Binary Sequence (PRBS) was used to drive the EAM. The resultant data stream output was fed into a Digital Communications Analyzer (DCA) with a 65 GHz bandwidth electrical module. The Time Domain Reflectometry (TDR) measurements were made using a differential TDR module in the DCA as a source rather than the BERT. The TDR measurement shows a very well controlled impedance environment throughout the Device Under Test (DUT). However, this is not very interesting to analyze, so let's expand the vertical scale to exaggerate the reflections.



Time Domain Reflectometry Details

The impedance profile of the flex circuit/test board assembly can be measured by using Time Domain Reflectometry (TDR). The TDR test equipment launches a 200mV amplitude, 35 picosecond risetime step into the device under test. When this step encounters impedance discontinuities, reflections are sent back into the test equipment module. The reflection coefficient (rho) is then calculated and the impedance value is extracted. In the flex/test board assembly, the first section shows a large negative reflection indicating excess capacitance due to the SMA launch into the test board. The next section is a slightly lower impedance of the left half test board (remember the vertical scale is expanded to 1 ohm/division). The next capacitive dip is the excess capacitance of the pad/gold dot interface. The TDR step then encounters the relatively flat impedance profile of the circuit body itself. After transitioning through another gold dot/pad interface and right half test board, the TDR step exits the SMA connector and reflects off an open circuit (indicated by a large positive reflection).



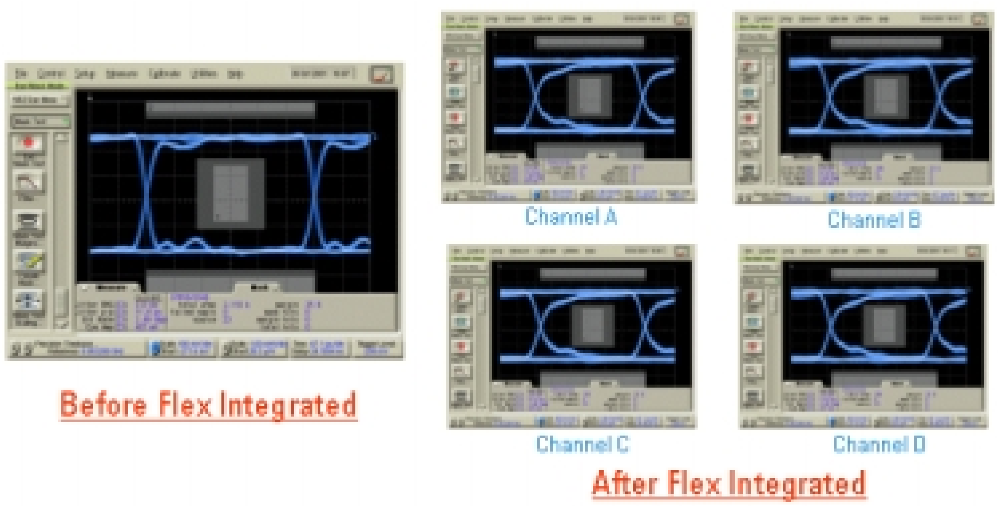
Eye Diagram Analysis of Flex Circuit

Eye diagram analysis was performed on the flex circuit/fixture assembly in order to determine level of compliance to SONET standards. By driving the assembly with the pattern generator of a bit error tester, it was clear that it passed the OC-48 standard at the 2.5 Gb/s data rate. With less margin, but still passing, the assembly was compliant to the OC-192 standard at 10 Gb/s.

OC-48 OC-192

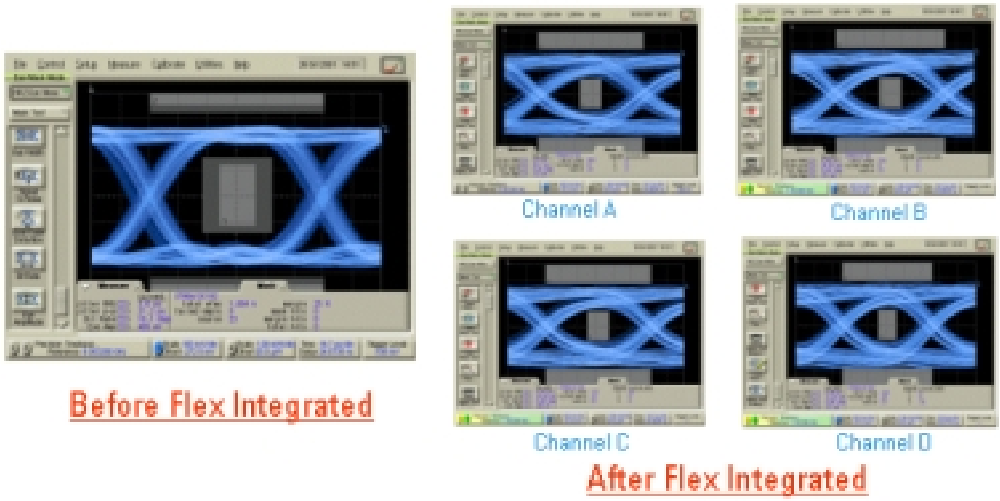
EAM Driver Test Results (2.5Gbps)

The EAM driver passes OC-48 compliance testing with over 25% margin on the test mask.



EAM Driver Test Results (10Gbps)

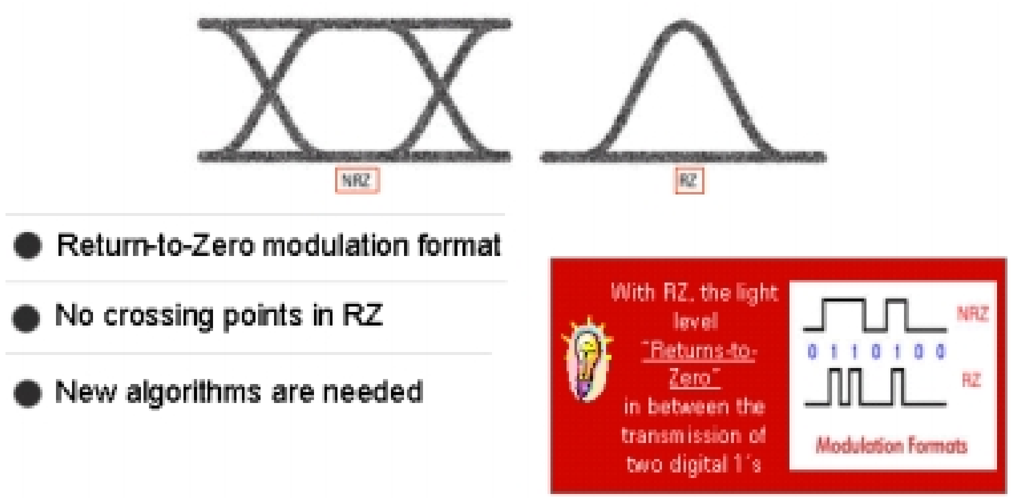
The EAM driver passes OC-192 compliance testing. An interesting observation indicates deterministic jitter is present in this Device Under Test. When viewing the cross section of any one of the eye diagrams, you can see a certain structure within the cross section, somewhat of a “banding”. This is caused by a short word pattern being output from the BERT (a shorter word repeats itself more often than a longer word, in a given length of time). This creates more stress on a device under test that is susceptible to pattern dependent jitter.



Latest Measurement Trend: 40 Gb/s Return-to-Zero waveform analysis

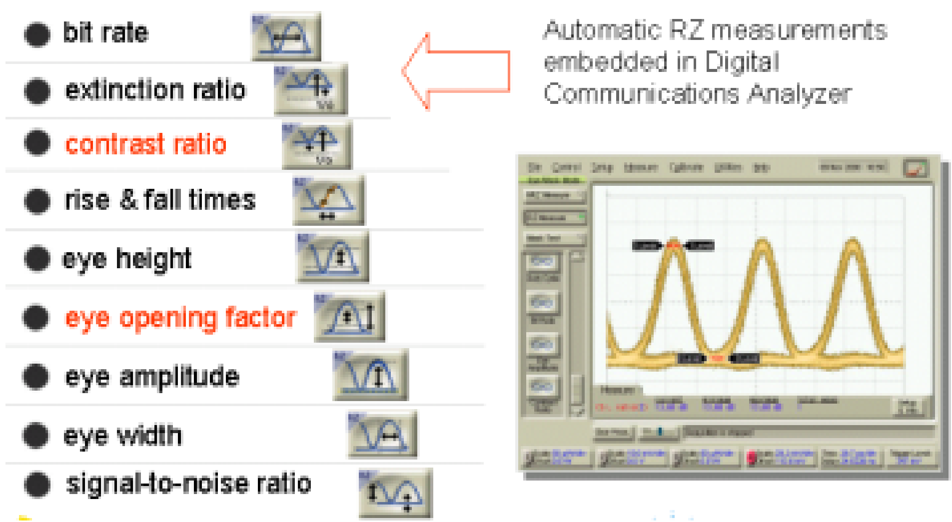
The traditional Non-Return-to-Zero signals that we are familiar with have a very nice characteristic to them…they have what's called crossing points. These are the areas where the transitions from one to zero and from zero to one intersect and form the 'x'. The crossing points are the reference point for NRZ waveform analysis. Bit Rate, jitter, eye opening, etc are all based on where the crossing points are located.

As you can see, the RZ waveform does not have crossing points. This means that new measurement algorithms need to be created in order to characterize the RZ modulation format. New measurement concepts need to be invented, also. Contrast ratio and eye opening factor are measurements needed to fully characterize RZ waveforms. It is noteworthy to mention here that Agilent was the first company to invent the new software algorithms needed to perform RZ measurements.



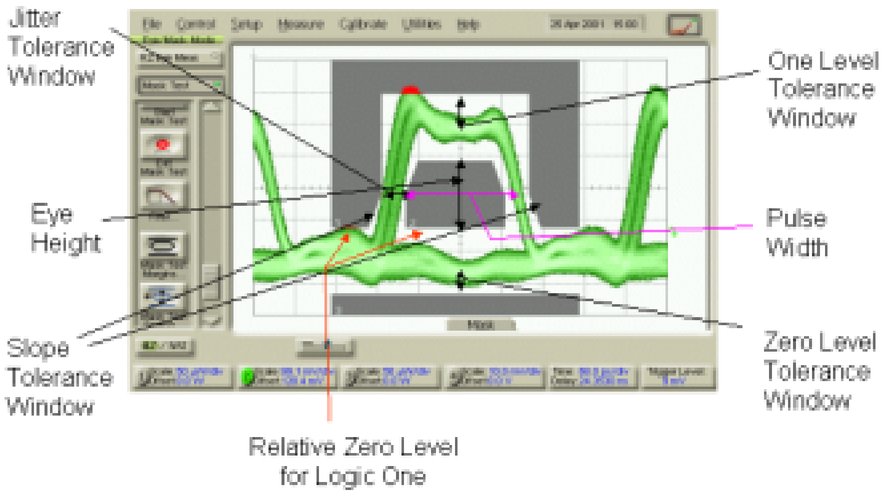
New RZ Measurements

The standard eye diagram measurements are still used for RZ characterization. The new measurements are contrast ratio and eye opening factor. The Contrast Ratio measurement is a ratio of the one level at the center of the eye diagram compared to the one level found midway between the eye diagram peaks. This indicates how well the logic 1 levels return to the logic zero level. This is sometimes referred to as "modulation depth". Contrast Ratio indicates how well a laser transmitter turns off between consecutive ones. Eye Opening Factor is similar to Eye Height, except Eye Opening measures the actual eye opening relative to an ideal, noise free eye. While the eye height measurement uses 3 sigma for noise contribution, the Eye Opening Factor measurement uses 1 sigma.



40G RZ Mask Testing

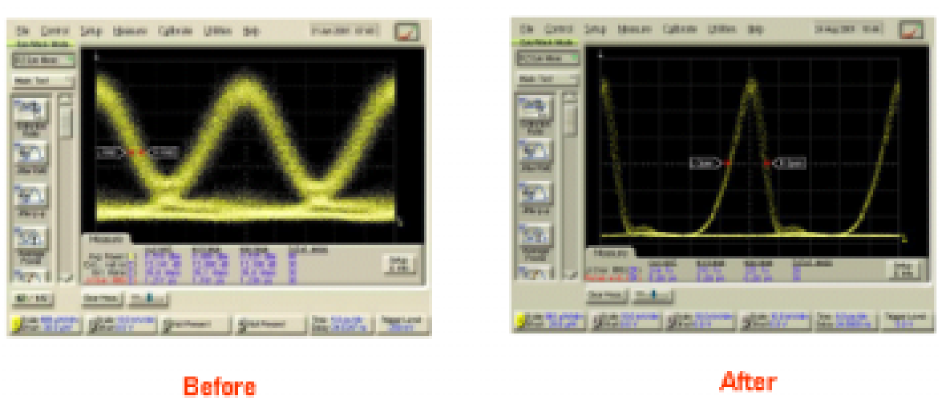
Standard Not-Return-To-Zero (NRZ) masks are readily available in the commercial measurement and testing products, while no standard RZ mask has been established so far. One way to yield a RZ mask is to generate customized masks via creating coordinates for all desired polygons, a process that is tedious and error-prone. Mask changes must be done by editing the file containing the mask description. Another way to process mask changes is to add a generic mask editor function which allows coordinate manipulation directly from the screen, via touch area, markers, dialog boxes, or some combination. However, the generic mask editor is cumbersome and not user friendly. To overcome these obstacles, a hybrid method of RZ mask creation has been developed that is much more appealing and physically sound. This hybrid method reveals a generic RZ/NRZ mask and an efficient way to alter the mask by means of a limited set of physically meaningful mask parameters. This RZ mask creation allows rapid customized symmetric mask creation without sacrificing accuracy and flexibility.



Future Measurement Trends: Optical Sampling Technology

In order to accurately characterize the modulation properties of 40Gb/s laser transmitters, it is necessary to obtain an order of magnitude increase of bandwidth in the test system. This goal is not easily achievable by conventional sampling circuits because they are limited by the semiconductor material switching speeds. Consequently, a new sampling method must be utilized. This sampling method must withstand the rapid pace of component development and the ultra-high data rates that they produce (up to 160 Gb/s). The technology of choice for this challenging application is optical sampling. Agilent Labs Japan and Agilent Labs Palo Alto have collaborated to develop an optical sampling technique that allows more than 500 GHz of bandwidth. Optical experimentation utilizing nonlinear crystalline materials has yielded astonishing results. Eye diagrams as never observed before are now routinely generated on a laboratory bench in a very high throughput environment. Optical sampling technology will no doubt be utilized while characterizing the physical layer of the future 40-160 Gb/s networks.

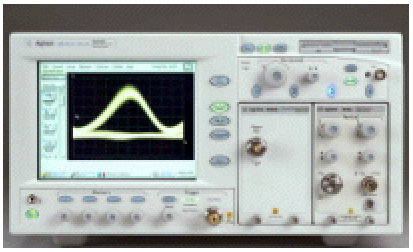
10X Fundamental Leap in Sampling Bandwidth



Summary

Signal integrity has recently become very challenging for high-speed digital designers. As data transmission rates continue to increase, even greater care must be used when designing the physical layer hardware of network equipment. The advent of optical networks and the associated optical components will not alleviate the need for electrical signal integrity analysis, Laser transmitters, laser modulators and laser modulator driver circuits will require state-of-the-art measurement and simulation tools to assure compliance to industry standards. Many useful insights can be obtained by eye diagram analysis, including laser transmitter bandwidth limitations, relaxation oscillation frequency and how dispersion penalty can be improved by altering driver parameters. The performance required by the future optical networks will continue to press the limits of today's innovative high-speed digital design engineers. Optical networking components can be brought to market faster with optimal performance when the right development tools are used in the laboratory. The rapid adoption of these design tools will undoubtedly drive the blazing transmission rates of the 160Gb/s systems of the future.

Resources



Agilent 86100A Digital Communications Analyzer
Agilent 86107A Precision Timebase Module
Agilent 86116A 55G Optical/65G Electrical Module
Agilent 54754A Differential TDR Module
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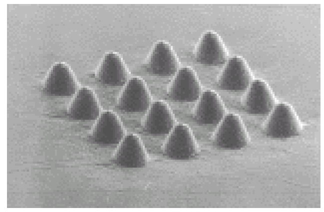
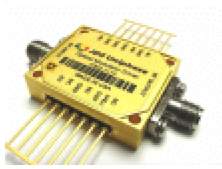


Delphi Gold Dot Interconnects
www.delphiauto.com



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Printed in USA April 22, 2002
5988-6590EN

Agilent Technologies