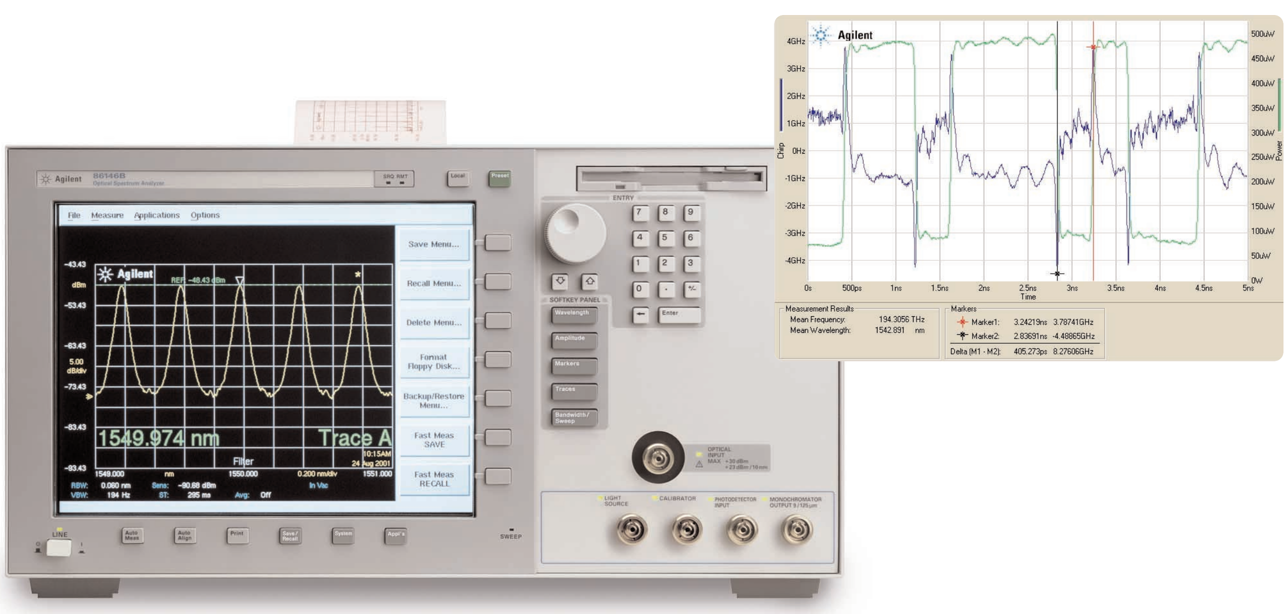
Making Time-Resolved Chirp Measurements Using the Optical Spectrum Analyzer and Digital Communications Analyzer

Application Note 1550-7



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Introduction

This application note covers theory of laser modulation methods, time-resolved chirp (TRC) measurement methods, and applications of TRC measurement data to predict laser performance in a transmission system. Also covered are the details of making laser chirp measurements using the Agilent Technologies 86146B Option TRC software.

Understanding the effects of chirp on the transmission of signals is of great importance to the system designer. Chirp can have two separate detrimental outcomes in a typical transmission system. The first is that the chirp can interact with the fiber dispersion to create a power penalty, which ultimately limits the number of channels or the distance over which the signal can propagate in today's WDM systems. The second is that chirp can broaden the transmitted spectrum limiting the channel spacing by interfering with adjacent channels even in a short-haul ultra-dense WDM environment.

Chirp penalty is defined as the additional signal-to-noise ratio (SNR) required at the receiver (due to laser chirp) to maintain a specified bit error ratio (BER) in a system of specified dispersion. Measuring chirp penalty directly is impossible unless one has a chirp-free transmitter with the identical intensity pattern as the DUT. Because of the impracticality of direct chirp penalty measurements, chirp penalty is often inferred from a path penalty measurement. A path penalty measurement involves substituting a fiber of known chromatic dispersion into the signal path and measuring the additional power (SNR) required to achieve the specified BER. This measurement is tedious and time consuming and assumes that the measurement is dominated by the chirp penalty term. This has led many transmitter and system designers and manufacturers to estimate the chirp penalty using time-resolved chirp data directly or device modeling parameters.

In order to bring the cost of DWDM transmission systems down, lower cost transmitters are being designed and deployed. Controlling the amount of chirp present in these lower cost transmitters is key to their success in the network.

What is Time-Resolved Chirp?

Time-resolved chirp (also referred to as dynamic chirp) quantifies the time variation of both the intensity and the frequency of a transmitter. Figure 1 shows a typical TRC waveform.

Measurements are acquired in the time domain using a trigger synchronous with the PRBS modulation pattern. There are two parts to the TRC measurement. The intensity waveform, P(t), is that which would be received with a wide-band optical receiver. The chirp or frequency waveform, $\Delta f(t)$, indicates that the frequency of the laser is also varying as the laser is modulated with the data. Although the intensity information is in absolute form, it is normal to display the frequency information as the deviation relative to the center frequency of the laser.

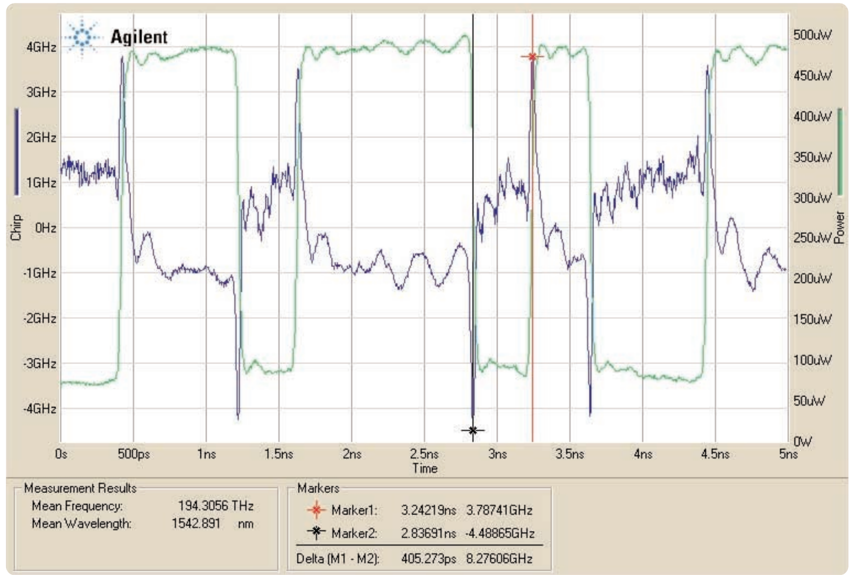

Figure 1. Time resolved chirp measurement

Data from a TRC measurement can be used in two different ways. The first is for the system designer to use TRC data directly to simulate the effects of chirp on the signal transmission. The second is to verify that the operation of the device is consistent with the physical theory. This allows device manufacturers to understand and verify the design, and to control the processes used to produce the devices in order to improve performance for the end user.

Estimating Chirp Penalty

In order to assess the effect of chirp on the transmission of a data stream one needs to first acquire the TRC data over a full pattern (e.g. 2^7-1). By using AM/FM modulation equations and Fourier transform methods one can predict the impact that the chirp will have as the signal propagates through the chromatic dispersion of the fiber.

First a waveform with a carrier frequency is constructed as in Equation 1. For convenience the carrier frequency can be lower than the actual optical carrier without any detrimental consequences as long as there are an adequate number of cycles of the carrier within a bit period (this eases the burden on the length of the arrays for the fast Fourier transform [FFT]). The data from TRC is entered as P(t) and f(t). Once the waveform is constructed, perform an FFT to convert it to the frequency domain. In the frequency domain the chromatic dispersion can be applied as a quadratic phase-versus-frequency transfer function. The inverse FFT of the result reverts to the time domain and includes the applied dispersion effects. By converting the two intensity waveforms (with and without dispersion) to eye diagrams the chirp penalty can be estimated.

Equation 1:

$$E(t) = \sqrt{P(t)}\, cos(2\pi f_c t + \phi(t))$$
$$\phi(t) = 2\pi \int \Delta f(t) dt$$

Figure 2 shows the eye diagram of an electro-absorption modulated laser (EML) (10 Gb/s) with and without the effects of chromatic dispersion. The shape of the eye diagram is dramatically changed after the effects of dispersion. This will result in higher BER under the same signal to noise level, causing the system designer to maintain a higher SNR to achieve the required BER. The ratio of the two SNRs is the chirp penalty, usually expressed in dB.

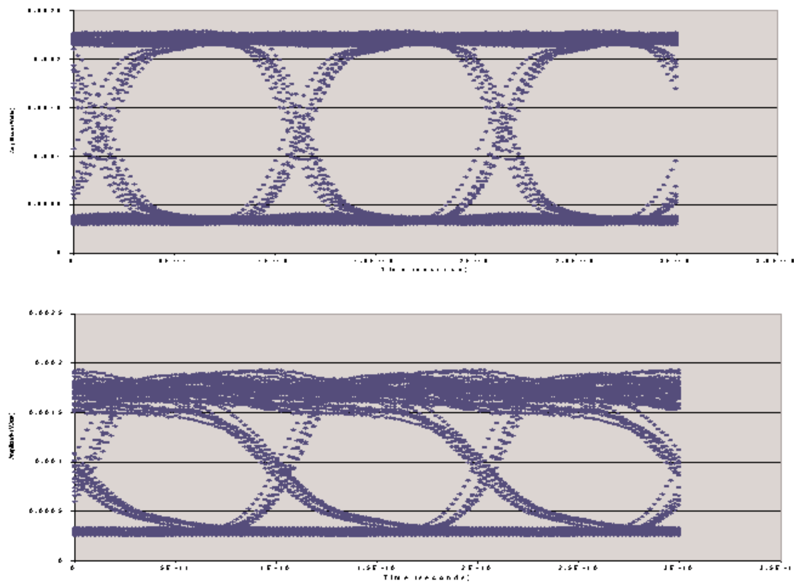

Figure 2. 10 Gb/s eye diagrams without (top) and with (bottom) the effects of chromatic dispersion.

Device Modeling Parameters

In any device, the frequency variation can be modeled as the sum of phase shift term and frequency shift term. An abrupt shift in phase becomes a transient in frequency. The two terms are generally referred to as transient and adiabatic respectively. Equation 2 gives a very general form of the chirp equation. The transient term is that part of the chirp that correlates to dP(t)/dt while the adiabatic term is that which correlates to P(t) directly. This general form of the equation is usually written in more specific terms relating to physical properties of the particular device as seen in the following section.

Equation 2:

$$\Delta f(t) \approx a_{transient} \frac{dP(t)}{dt} + a_{adiabatic} P(t)$$

Laser Modulation Methods

Direct Modulated Lasers

Direct modulated (DM) lasers are the most common, particularly for short reach systems. They are the lowest cost and generally have the highest (least desirable) chirp characteristics. In a DM laser, shown schematically in Figure 3, the diode current will be the sum of two terms. Idc sets the operating point (average power) of the laser, while Idata determines the modulation level. The two terms are adjusted to achieve the desired average power and extinction ratio. DM lasers generally produce more chirp for higher extinction ratios, leading to an optimum setting for trading off SNR and chirp penalty.

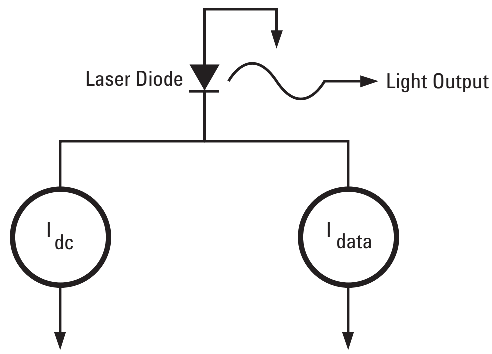

Figure 3. Direct modulated DFB laser

Alpha factor (α) is commonly called the linewidth enhancement factor and is used to predict the frequency behavior of a laser. In an unmodulated laser, small fluctuations in the effective index of refraction (n_e) give rise to random phase variation in the cavity that results in a Lorentzian frequency spectrum or linewidth. Alpha factor is derived from the physical properties of the device relating the phase and intensity variations due to index of refraction variation within the waveguide structure.

In a modulated laser, the presence of the large data signal produces a more dramatic change in n_e. This results in large phase shifts (transient chirp) during the transitions of the data as well as a long-term shift in the laser frequency (adiabatic chirp). Equation 3 gives the formula estimating the chirp of a direct modulated DFB laser. The first term is the transient term while the second and third terms are referred to as adiabatic.

Equation 3:

$$\Delta f(t) \approx \frac{\alpha}{4\pi}\left(\frac{dP/dt}{P} + K_1 P - \frac{K_2}{P}\right)$$

Transient chirp predicts a phase shift $\phi(t)$ in the opposite direction for the two intensity transitions. The frequency transient ($d\phi/dt$) is directly proportional to the rise and fall times. The transient chirp is complicated by the fact that the disruption in phase and gain in the laser excite the natural resonance (relaxation oscillation) within the laser. There is significant loss of energy during this transient while the laser re-stabilizes. In the transient chirp limited regions such as the rising and falling edges alpha can be calculated using Equation 4. In this case the units for α are radians.

Equation 4:

$$\alpha = 2P\,\frac{d\phi/dt}{dP/dt} = 4\pi P\,\frac{\Delta f(t)}{dP/dt}$$

When the laser stabilizes in the new bias condition it is usually at a different frequency. This frequency shift is the adiabatic chirp predicted by the second term in Equation 3. The third term in Equation 3 results from spontaneous emission photons hence the inverse relationship to power. There are other terms to the chirp such as static and transient thermal effects. These terms are usually ignored since they occur on a long time scale such that the high data rates and coding rules for fiber optic systems mitigate their effects. Many laser manufacturers are developing DM lasers optimizing them for lower chirp by using more complicated structures such as strained multiple-quantum wells (MQW).

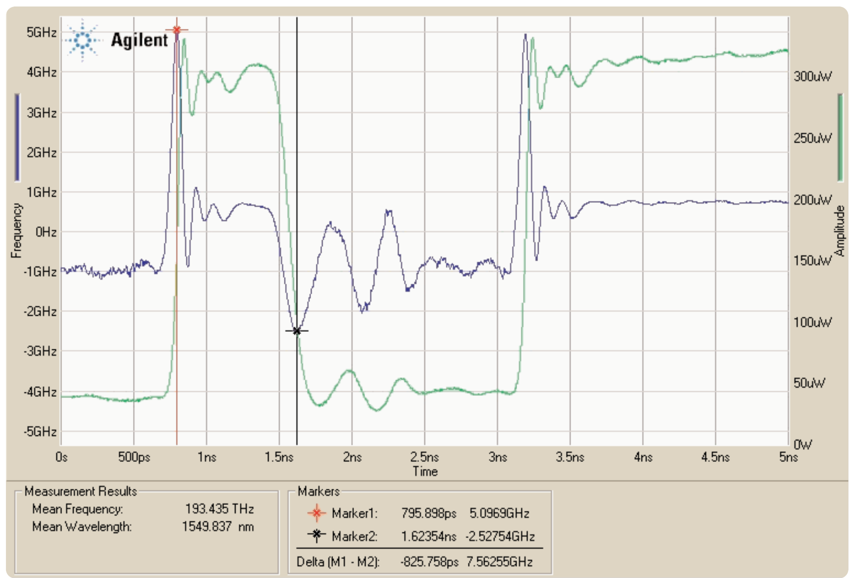

Figure 4. TRC measurement of an Agilent 83430A direct modulated DFB laser

The data in Figure 4 is from a direct modulated DFB laser. There is significant transient and adiabatic chirp. The transitions excite the relaxation oscillations within the device causing ringing in both the intensity and frequency data. Figure 5 shows a spectral measurement of the same device using the Agilent 83453A high-resolution spectrometer (HRS). Note the spectral broadening and the asymmetry from the chirp. The spectrum from the chirp completely masks the intensity modulation spectrum.

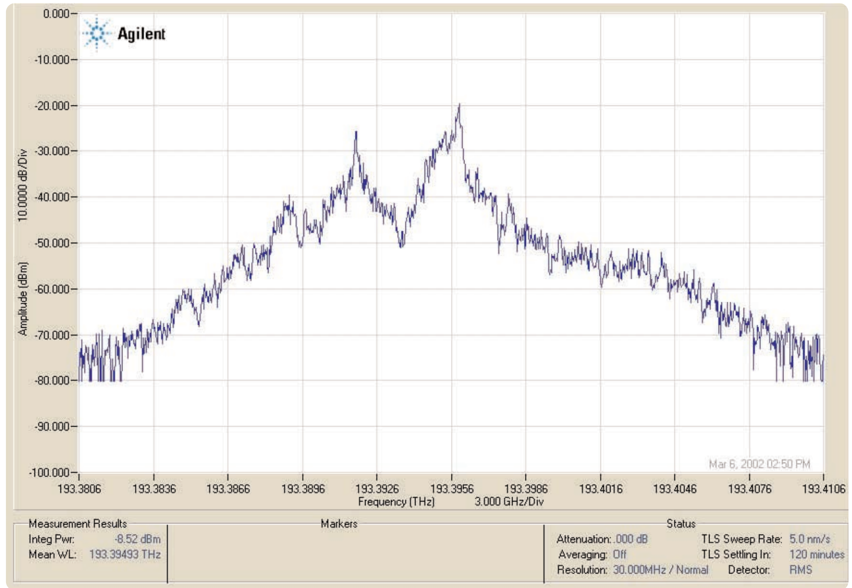

Figure 5. Agilent 83430A spectrum (using High Resolution Spectrometer)

Electro-Absorption Modulated Lasers (EML)

EMLs are lasers with an integrated electro-absorptive modulator (EAM) section usually on the same chip as the laser. This is very cost effective compared with externally packaged modulators and is a step above DM lasers in terms of performance.

In theory, when the modulation element is separated from the laser cavity there is no adiabatic chirp. The constant frequency generated by the laser is only modified in magnitude and phase as the light travels through the modulation section. In practice, other effects such as package electrical parasitics, optical reflections, and thermal interactions can cause adiabatic characteristics.

Figure 6 shows an EML schematically. The current setting the laser is strictly DC meaning that the frequency of the laser is constant. The EAM is driven with a separate data signal (electric field) which controls the waveguide absorption. With EML designs, transient chirp tends to dominate the performance. The ringing from the laser relaxation oscillations is nearly eliminated.

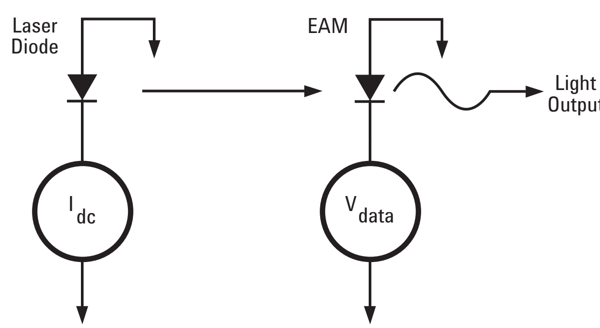

Figure 6. EML (Electro-absorption Modulated Laser)

Note the clear definition of the transients on the rising and falling edge in Figure 7. The two transients with markers on the rising and falling edges are the most significant and correlate directly to dP/dt. The transient that occurs before the rising edge is believed to be from the E-field (Pockels effect) applied to the device before the absorption recovers.

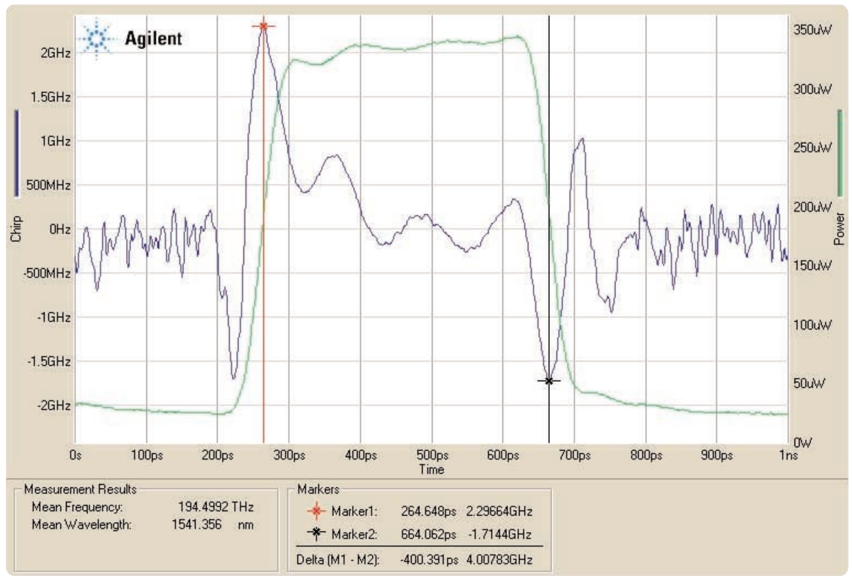

Figure 7. EML TRC

Note the narrower spectrum of the EML device in Figure 8.

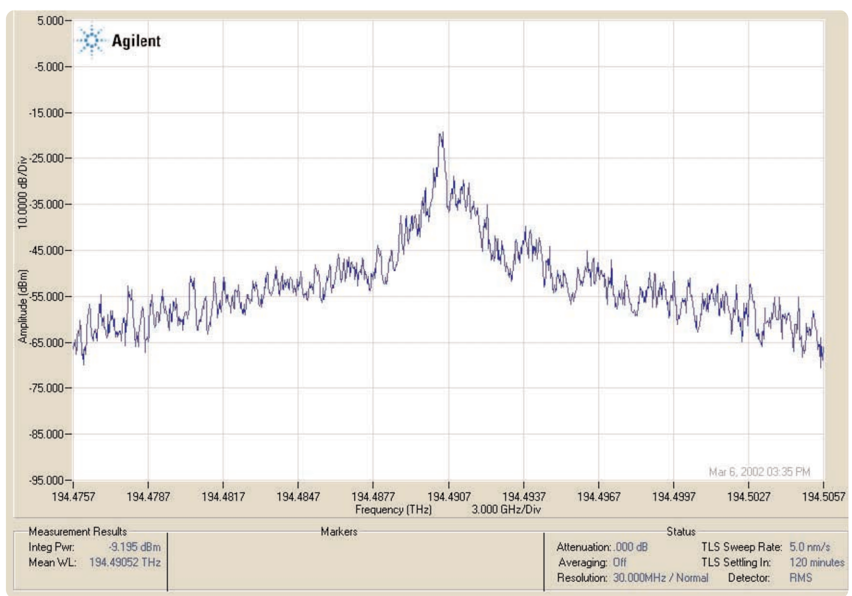

Figure 8. EML spectrum (using High Resolution Spectrometer)

Mach-Zehnder Modulators

Intensity modulators can be made using a Mach-Zehnder configuration as shown in Figure 9. The incoming light is split into two optical paths in a suitable crystalline material such as Lithium Niobate ($LiNbO_3$). The two paths are differentially-phase modulated by electric fields using the Pockels effect, which is a linear change in index of refraction with applied electric field. When the two optical beams are recombined they add vectorally to create pure intensity modulation. The phasor diagram shows that intensity modulation can be free of chirp if the two paths are perfectly aligned.

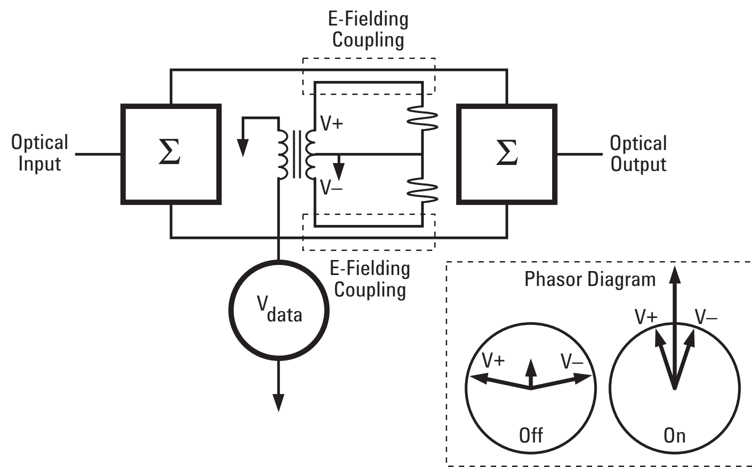

Figure 9. Mach-Zehnder Modulator

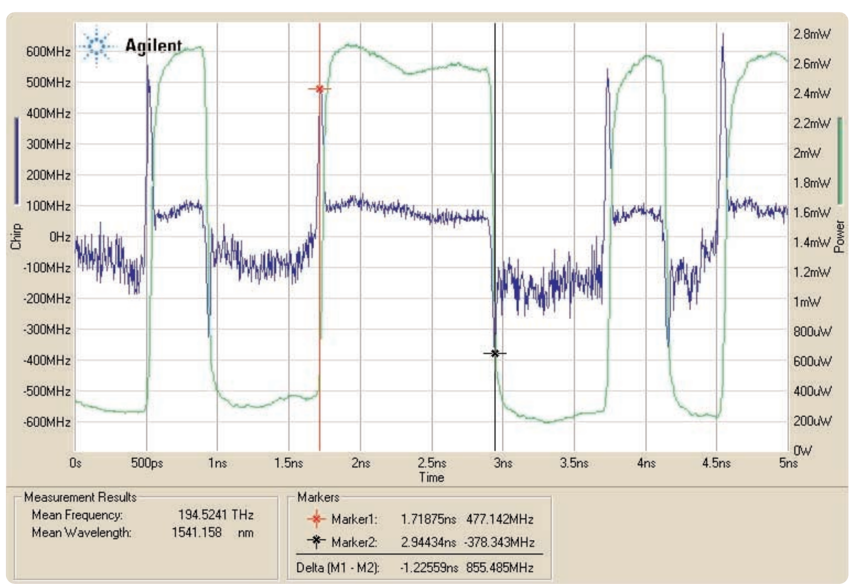

Figure 10. TRC measurement of Mach-Zehnder Modulator

Figure 10 shows the very low chirp of a $LiNbO_3$ NRZ modulator. HRS spectrum in Figure 11 shows the (sin(x)/x)^2 frequency spectrum with near perfect symmetry.

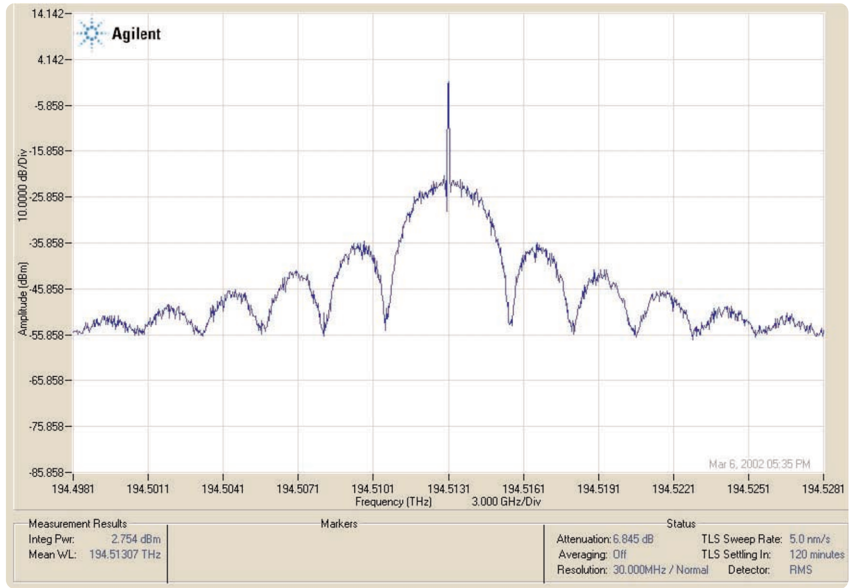

Figure 11. Mach-Zehnder Modulator Spectrum

Chirped Return-To-Zero (RZ) Modulation

$LiNbO_3$ is also used in RZ pulse generation. This technique uses the non-linear behavior of the crystal to generate narrow pulse for each data clock cycle. A separate phase modulator section also driven from the clock provides the desired chirp. The pulses are then gated pulse amplitude modulation (PAM) with the data using a low chirp non-return-to-zero (NRZ) modulator.

In RZ transmission format chirp can be used to an advantage. Properly chirping the pulses can compensate for the chromatic dispersion of the system. A TRC measurement can be used to adjust the chirp level (GHz/sec) and phase of the chirp relative to the center of the pulse.

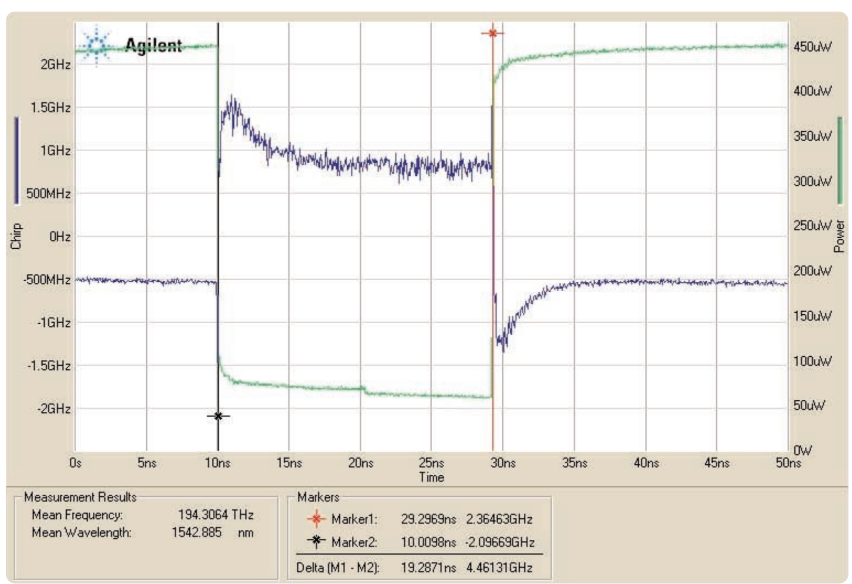

Figure 12.

Sometimes it is helpful setup a slower modulation rate to help in understanding the device behavior. Figure 12 shows an EML modulated at 50 Mb/s. In addition to the fast transients previously shown for this device, there is clearly an adiabatic term with a time constant on the order of 5ns. This is likely due to optical feedback from the EAM section producing a shift in the laser frequency. Figure 13 shows the bimodal nature of the power spectrum.

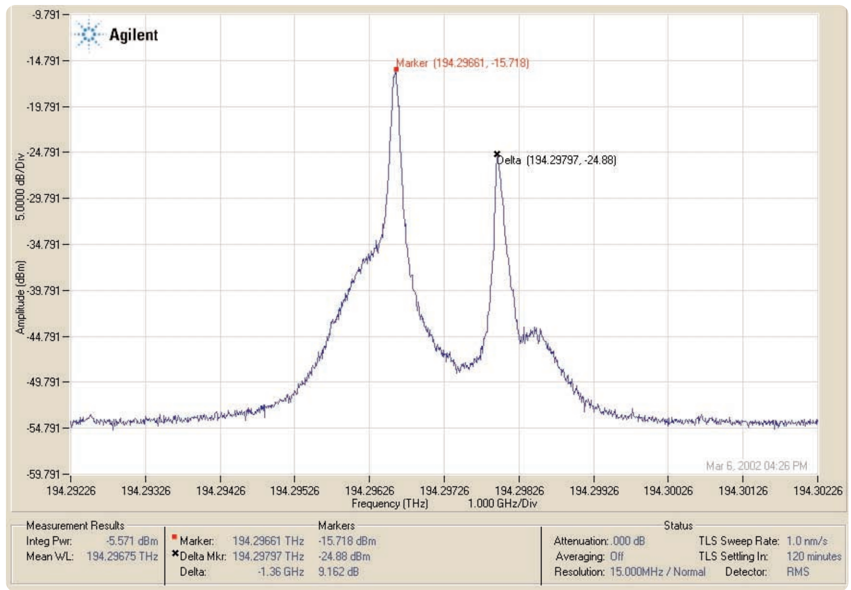

Figure 13.

Measuring Chirp

Chirp measurements can be performed with a variety of methods. For time-resolved chirp (TRC) measurements there is a requirement to modulate the laser with a bit stream simulating the actual way in which the device will be used. One must also supply synchronization to the measurement system in the form of a trigger signal. The *frequency discriminator, optical gating with OSA*, and *OSA monochromator and DCA* methods provide essentially the same Δf(t) and P(t) data.

Another method using lightwave component analyzers (LCAs), such as the Agilent 8703A, can also be used to characterize devices, particularly Mach-Zehnder devices. This method can be used to measure the alpha factor of a $LiNbO_3$ modulator as a function of DC bias and to characterize the static and dynamic balance of the modulator.

Frequency Discriminator Method

This method uses a Mach-Zehnder interferometer as a frequency discriminator as shown in Figure 14. The differential delay between the two paths creates sinusoidal amplitude versus frequency variation. The frequency spacing is called the free spectral range (FSR). The differential delay can be separate paths or the differential delay of the principal states of polarization maintaining fiber (PMF). In this method, the interferometer is used to convert frequency deviations into amplitude variation by tuning the interferometer so that the nominal laser frequency is positioned on the rising and falling part of the sinusoidal function. Subtracting the two waveforms gives the FM term and the sum of the two yields the IM term. Chirp is then calculated using Equation 5.

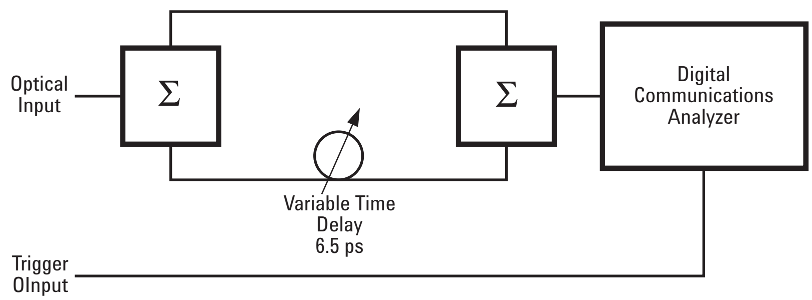

Figure 14. Mach-Zehnder Interferometer + DCA

Equation 5: $$\Delta f(t) = \frac{FSR}{2\pi} \arcsin \left(\frac{FM}{IM}\right)$$

Optical Gating with Optical Spectrum Analyzer Method

The simplest method to understand (but difficult to implement) is a block diagram shown in Figure 15, using a triggered optical gate followed by a conventional optical spectrum analyzer (OSA). This method sets the optical gate to the desired position in time and takes a sweep with the OSA. The data of power as a function of frequency and time is entered as shown in Figure 16. The center-of-mass frequency (wavelength) variation is $\Delta f(t)$ and the total power is $P(t)$. The optical gate is shifted in time slightly and the process is repeated until the entire array is acquired. The width of the pulse to the optical gate and the timing accuracy determine the time resolution. The OSA sweep repeatability and amplitude accuracy determine the frequency and power resolution respectively.

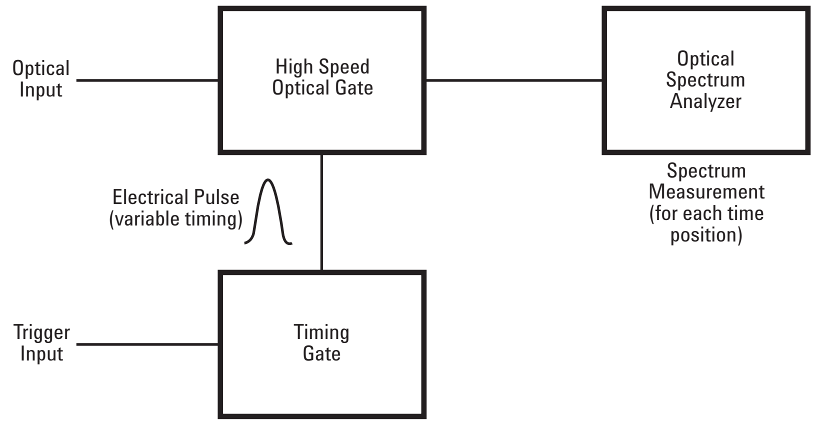

Figure 15. Optical gating + OSA

		Frequency (Hz)					
		f1	**f2**	**f3**	**…**	**Fn**	**Chirp**
Time (s)	**t1**	P(t1,f1)	P(t1,f2)	P(t1,f3)	…	P(t1,fn)	f(t1)
	t2	P(t2,f1)	P(t2,f2)	P(t2,f3)	…	P(t2,fn)	f(t2)
	t3	P(t3,f1)	P(t3,f2)	P(t3,f3)	…	P(t3,fn)	f(t3)
	…	…	…	…	…	…	…
	tn	P(tn,f1)	P(tn,f2)	P(tn,f3)	…	P(tn,fn)	f(tn)

Raw Data:
Power vs. Frequency and Time

$$Chirp = \Delta f\ (t_n) = \Sigma \frac{P\ (t_n, f_i)\ (f_i - f_{mean})}{\Sigma P\ (t_n, f_i)}$$

Figure 16. TRC Raw Data

This technique is similar to frequency resolved optical gating (FROG) used in characterizing the chirp of very narrow (transform limited) pulses. FROG uses a pulsed laser and a non-linear crystal to provide the optical gating. The OSA measures the spectrum of the heterodyne term.

This optical gating method is somewhat impractical for TRC for two reasons:

- The extinction ratio of the optical gate needs to be in excess of the reciprocal of the duty cycle. Measuring TRC over a long pattern length with good time resolution requires extinction ratios in excess of 50 dB.
- It is necessary to take an OSA sweep for each time point, making the measurement very time consuming for many time points.

OSA Monochromator and DCA Method

The block diagram shown in Figure 17 is very similar to the optical gating with OSA method. The difference is that the frequency-resolving element precedes the time-resolving element. For this to work well, the OSA must have very small dispersion since dispersion in the filter leads to altering the timing of the signal arriving at the DCA. The Agilent 86146B OSA has very little dispersion due to its unique double-pass monochromator.

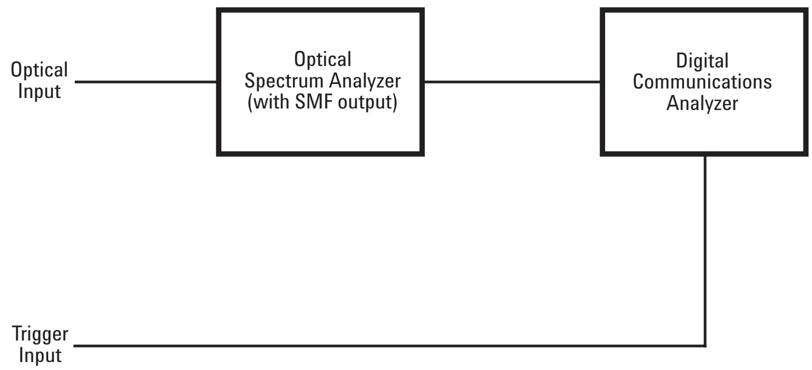

Figure 17. Monochromator + DCA

The measurement process for this TRC method requires accurate control of the OSA filter and single mode fiber output provided in the Agilent 86146B in filter mode. The algorithm first finds the signal to measure, and determines the list of wavelengths from an OSA sweep. The filter is then step tuned through the wavelengths where a DCA trace is acquired for each step. The time domain data is corrected for the small amount of filter dispersion and entered as a column in Figure 16. The data is sorted by time and the chirp is calculated for each time point.

The Agilent TRC method has several unique advantages over other solutions.

- The low polarization dependence of the monochromator makes the measurement very repeatable without having to prevent fiber movement.
- TRC measurements can be made in a multiple-signal WDM environment.
- With the addition of an EDFA in front of the OSA, signals as low as –35 dBm can be measured since the monochromator filters the broad spontaneous emission of an EDFA.
- The Agilent TRC measures the wavelength of the source as part of the measurement allowing an absolute representation of chirp f(t) by simply adding the measured mean frequency Δf(t).
- The instrumentation required is not unique and can provide other transmitter measurements such as sidemode suppression ratio (SMSR) and eye mask tests with a single connection.

Measurement Verification

TRC measurement accuracy must be verified by using simultaneous intensity and phase modulation. The Agilent TRC solution was verified using a $LiNbO_3$ CRZ modulator section operating at 10 GHz. The intensity and phase modulation were adjusted so that the first order sidebands of the phase modulation (J1) were approximately the same as the intensity sidebands. This causes an asymmetry of the sidebands at ±10 GHz from the carrier. The P(t) and the Δf(t) from a TRC result were inserted into equation 1 and an FFT performed. The magnitude of the resultant power spectrum is compared to an OSA trace in Figure 18.

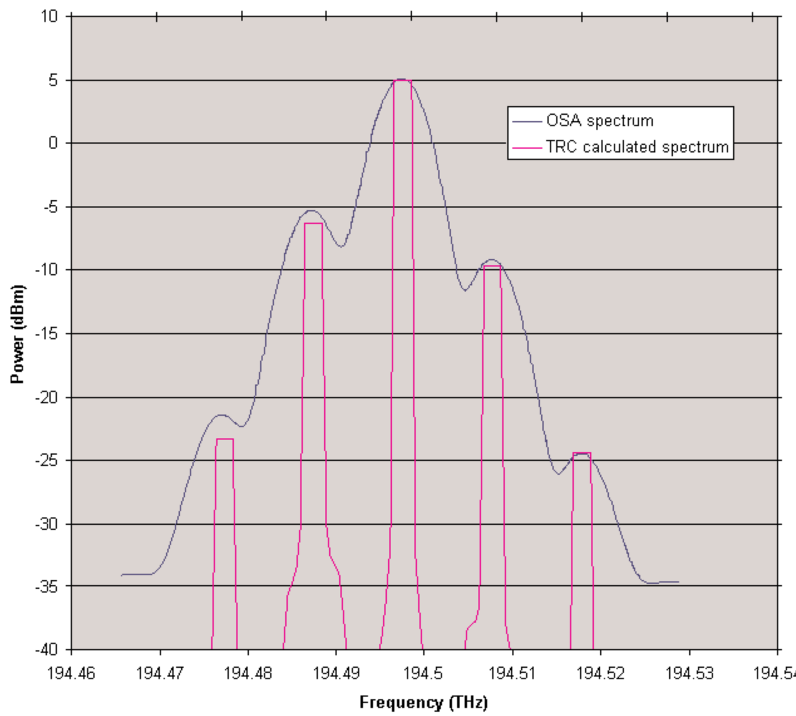

Figure 18.

Agilent 86146B Option TRC Software

The Agilent TRC software provides a measurement using the OSA and DCA method shown in Figure 19 using the Agilent 86146B OSA and the Agilent 86100A/B Infiniium DCA. The TRC software is modular in its design, providing a convenient solution in the form of a user-friendly graphical user interface (GUI) or a documented application programmatic interface (API) for integration into a manufacturing environment. This API allows users to integrate TRC measurement capability into their test executive. The API is documented with programming examples in Visual Basic®, and MS Excel®. The user can also integrate TRC into other MS Windows® programs that support Active-X automation such as National Instruments LabView™ or Agilent VEEpro.

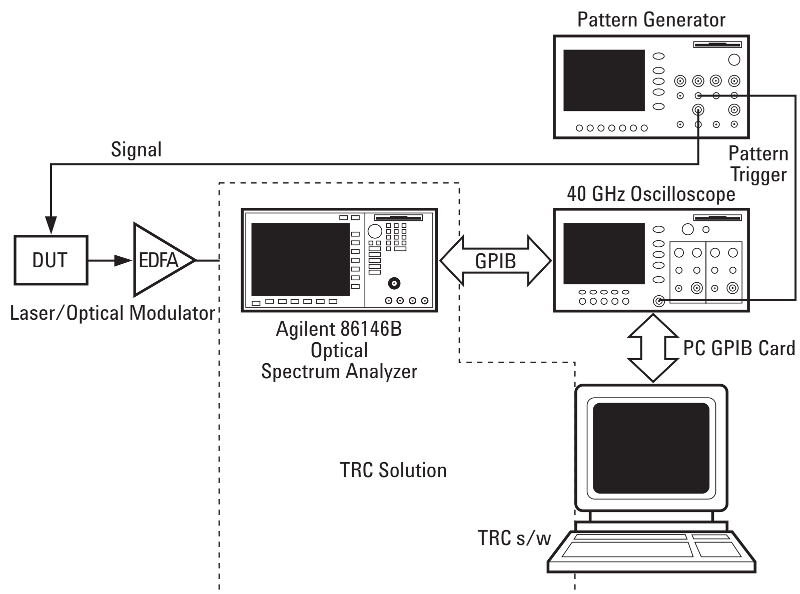

Figure 19. Block diagram TRC solution

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