IEC/PAS 61280-2-10

Edition 1.0
2003-01

PRE-STANDARD

Fibre optic communication subsystem test procedures –

Part 2-10: Digital systems – Time-resolved chirp and alpha-factor measurement of laser transmitters

PUBLICLY AVAILABLE SPECIFICATION

INTERNATIONAL ELECTROTECHNICAL COMMISSION

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The text of this PAS is based on the following document: This PAS was approved for publication by the P-members of the committee concerned as indicated in the following document:

Draft PAS	Report on voting
86C/475A/PAS	86C/496/RVD

Following publication of this PAS, the technical committee or subcommittee concerned will investigate the possibility of transforming the PAS into an International Standard.

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FIBRE OPTIC COMMUNICATION SUBSYSTEM TEST PROCEDURES –

Part 2-10: Digital systems – Time-resolved chirp and alpha-factor measurement of laser transmitters

1 Scope

This part of IEC 61280 sets forth standard procedures for measuring time-resolved chirp on laser transmitters. The calculation of alpha-factor, a measure of transient chirp, is derived from the measured TRC data. Also covered is a means to verify the TRC setups and calculations (Annex A) and a review of laser modulation methods and the relationship of TRC to performance in a transmission system.

2 Background

Understanding the effects of chirp on the transmission of signals is of great importance to the system designer. Chirp can have two separate outcomes in transmission systems. The first is that the chirp can interact with the fibre dispersion to broaden or narrow the pulse along the fibre. This will cause a positive or negative path penalty, which ultimately decreases or increases the distance over which the signal can propagate in a system without regeneration. The sign of the penalty depends upon both the sign of the chirp and the sign of the fibre dispersion. The second is that chirp can broaden the transmitted spectrum limiting the channel spacing by interfering with adjacent channels in an ultra-dense WDM environment, even at short-haul distances.

The path penalty is the apparent reduction of receiver sensitivity due to distortion of the signal waveform during its transmission over the path. A negative path penalty corresponds to an apparent increase of receiver sensitivity. The path penalty is manifested as a shift of the system's BER-curves towards higher or lower input power levels. A positive 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 with specified dispersion.

Measuring chirp penalty directly is difficult because it requires a chirp-free transmitter with the identical intensity pattern as the DUT. Because of this difficulty, chirp penalty is often inferred from a path penalty measurement. A path penalty measurement involves substituting a fibre 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 (or dispersion) penalty using time-resolved chirp data directly or with derived modeling parameters.

IEC technical report 61282-8 (to be published) describes the estimation of dispersion penalty from measured time-resolved chirp data [8].

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 [7].

3 Definition of time-resolved chirp

Time-resolved chirp (also referred to as dynamic chirp) is the time variation of the instantaneous optical frequency of a transmitter. It is typically expressed as $\Delta f(t)$, the difference from the average optical frequency. The instantaneous optical power, $P(t)$, is used in conjunction with $\Delta f(t)$ to completely describe the optical signal.

Measurements are acquired in the time domain using a trigger that is synchronous with a PRBS modulation pattern. As described above, there are two components of TRC measurement. The optical waveform, *P(t)*, is that which would be displayed with a wide-band optical receiver and oscilloscope. The chirp or frequency waveform, *Δf(t)*, indicates that the frequency of the laser is also varying as the laser is modulated with the data. Figure 1 shows a typical TRC result.

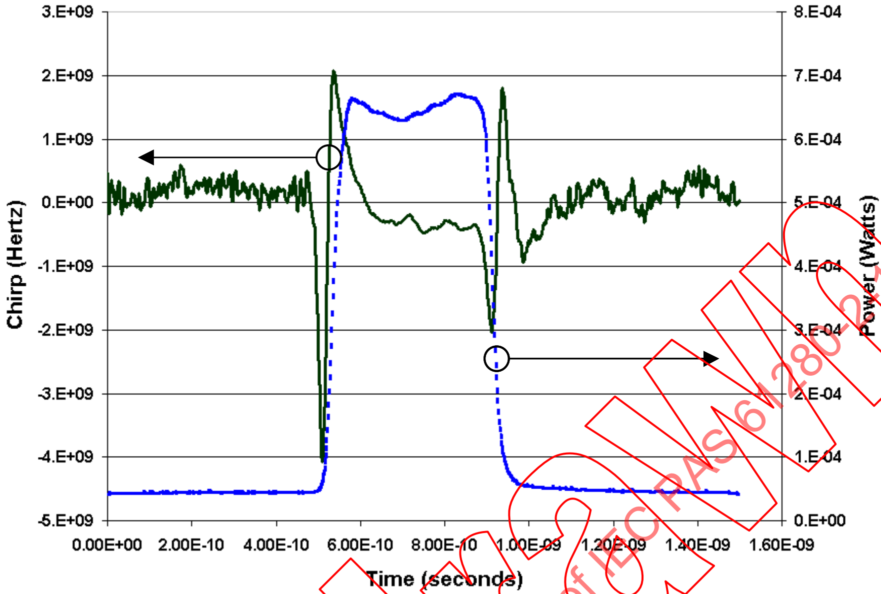


Figure 1– A typical TRC measurement

4 Modeling transmitter behaviour

In a modulated signal, 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. A general equation for chirp is given by [1]:

$$\Delta f(t) = \frac{\alpha}{4\pi}\left(\frac{dP/dt}{P} + \mathrm{K}_1 P - \frac{K_2}{P}\right) \tag{1}$$

where α is the alpha-factor and K_1 and K_2 are adiabatic terms.

Considering only transient chirp, and solving for alpha-factor:

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

where $$\Delta f(t) = \frac{1}{2\pi} d\phi/dt$$

Equation (2) indicates that transient chirp produces a phase shift (Δϕ) proportional to the normalized power change ($\Delta P/P$) and a frequency transient that is directly proportional to the rate at which the phase or power changes.

5 Overview of chirp measurement methods

Time-resolved chirp measurements require to be modulated with a bit stream to simulate the way in which the device is used in a transmission system. Synchronization must be provided to the measurement system in the form of a trigger signal. Three methods theoretically can provide the same values of $\Delta f(t)$ and $P(t)$. They are the *frequency discriminator*, *frequency-resolved- optical gating (FROG)*, and *monochromator* methods.

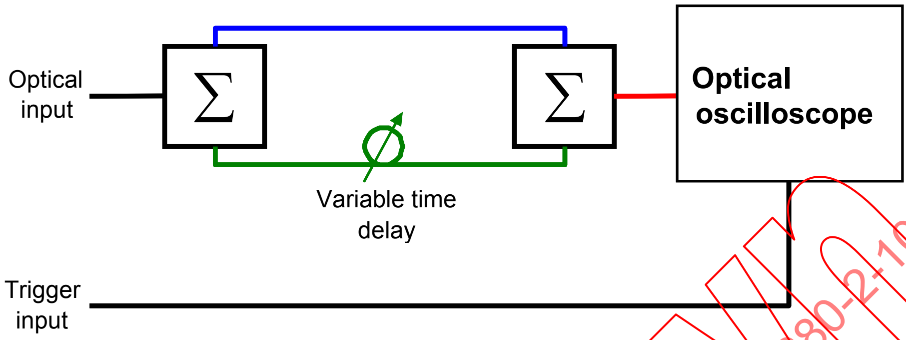


Figure 2 – Simplified diagram for the *frequency discriminator* method

In the *frequency discriminator* method [2][3], a Mach-Zehnder interferometer followed by an optical oscilloscope are typically configured as shown in Figure 10. An optical oscilloscope, sometimes called a digital communications analyser (DCA) consists of a broadband optical-to-electrical converter and a sampling oscilloscope. The differential delay between the two paths creates sinusoidal amplitude versus frequency variation. The frequency spacing is called the free spectral range (FSR). 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 at the quadrature points of the sinusoidal function (Points A and B in Figure 11) and corresponding waveforms are measured on the optical oscilloscope. The optical signal power of the laser transmitter is given by:

$$P(t) = \frac{V_A(t) + V_B(t)}{2} \tag{3}$$

The chirp is calculated by taking the difference of the quadrature waveforms and correcting for the sinusoidal characteristic of the interferometer:

$$V_-(t) = \frac{V_A(t) - V_B(t)}{2} \tag{4}$$

$$\Delta f(t) = \frac{\mathrm{FSR}}{2\pi} \arcsin\left(\frac{V_-(t)}{P(t)}\right) \tag{5}$$

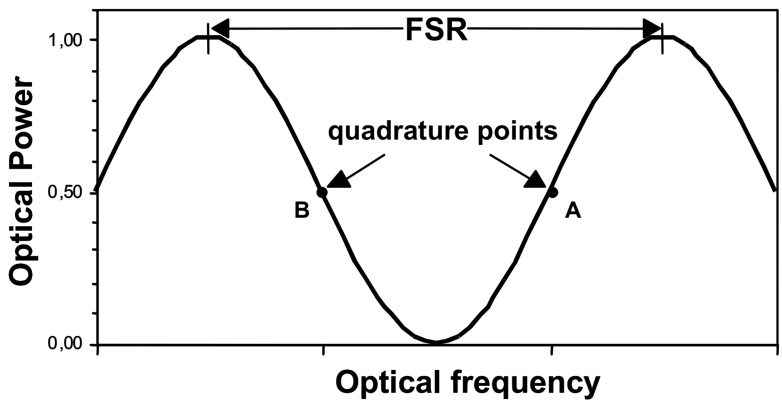


Figure 3 – The frequency discriminator method requires measurement at the quadrature point of the interferometer

The *frequency-resolved optical gating (FROG)* method uses an optical gate followed by an optical spectrum analyser (OSA) as shown in Figure 4. The optical gate is set to a particular position in time, t_i, and a spectrum is measured on the OSA. By varying the optical gate time, Table 1 can be completed. The weighted-average frequency (sometimes called the centre-of-mass frequency) is calculated as follows:

$$\Delta f(t_i) = \sum_{k=1}^{m} \frac{P(t_i, f_k)(f_k - f_{mean})}{\sum_{k=1}^{m} P(t_i, f_k)} \qquad (6)$$

where f_{mean} is the time-average optical frequency

Table 1 – Data collection to calculate chirp

	f_1	f_2	…	f_m	$\Delta f(t)$
t_1	$P(t_1,f_1)$	$P(t_1,f_2)$	…	$P(t_1,f_m)$	$\Delta f(t_1)$
t_2	$P(t_2,f_1)$	$P(t_2,f_2)$	…	$P(t_2,f_m)$	$\Delta f(t_2)$
…	…	…	…	…	…
t_n	$P(t_n,f_1)$	$P(t_n,f_2)$	…	$P(t_n,f_m)$	$\Delta f(t_n)$

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

(1) 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.

(2) It is necessary to take an OSA sweep for each time point, making the measurement very time consuming for many time points.

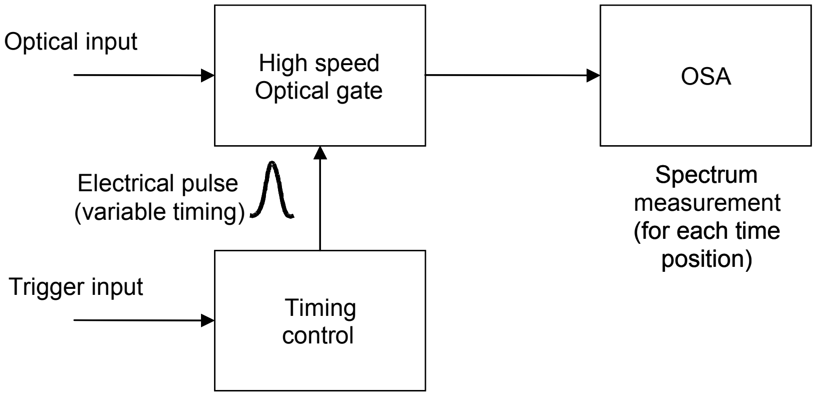


Figure 4 - In the FROG method, the spectrum from an optically gated signal is measured on an OSA

The block diagram of the *monochromator* method [4], shown in Figure 5, is very similar in concept to the FROG method. The difference is that the frequency-resolving element precedes the time-resolving element. For reasonable performance, the OSA must have very low dispersion that is typically achieved with the double-pass monochromator design shown in Figure 6 [5].

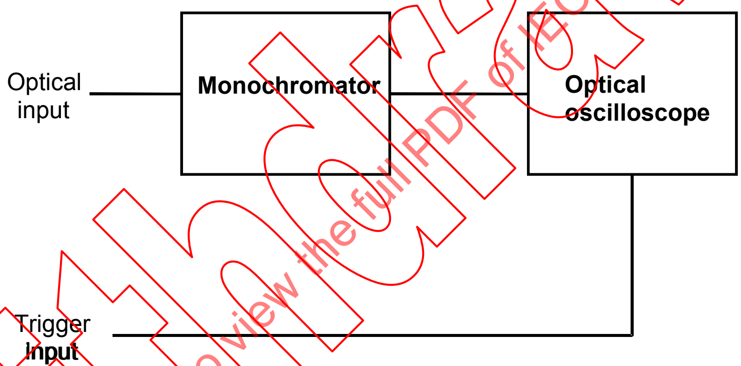


Figure 5 – Simplified block diagram for the *monochromator* method

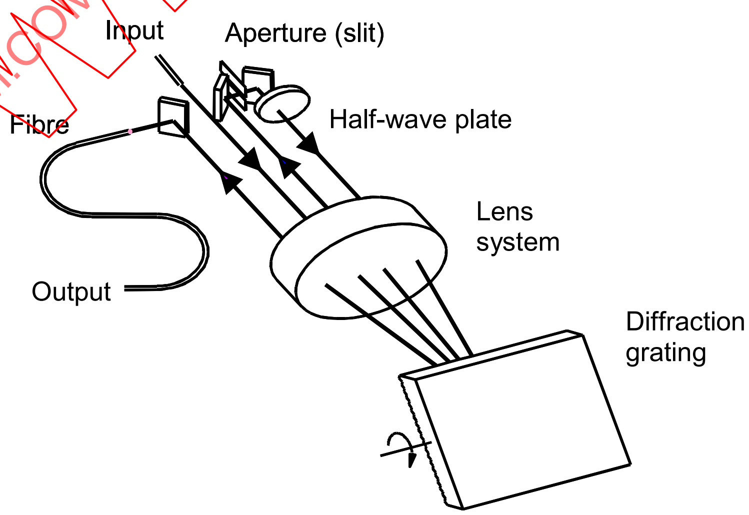


Figure 6 – To obtain low dispersion, a double-pass configuration is typically used

In this method, Table 1 is completed on a column-by-column basis. The monochromator is fixed tuned to f_k and a time waveform, $P(t_1,f_k)$ ... $P(t_n,f_k)$ is measured on the optical oscilloscope. $P(t)$ is measured with the monochromator filter centred on the signal. $\Delta f(t)$ is calculated from (7).

Of the three methods described above, only the frequency discriminator and monochromator methods are practical for TRC measurements. In the following sections, the apparatus and procedures for their implementation are described.

6 Frequency discriminator method

6.1 Apparatus

The setup for the frequency discriminator method is shown in Figure 7.

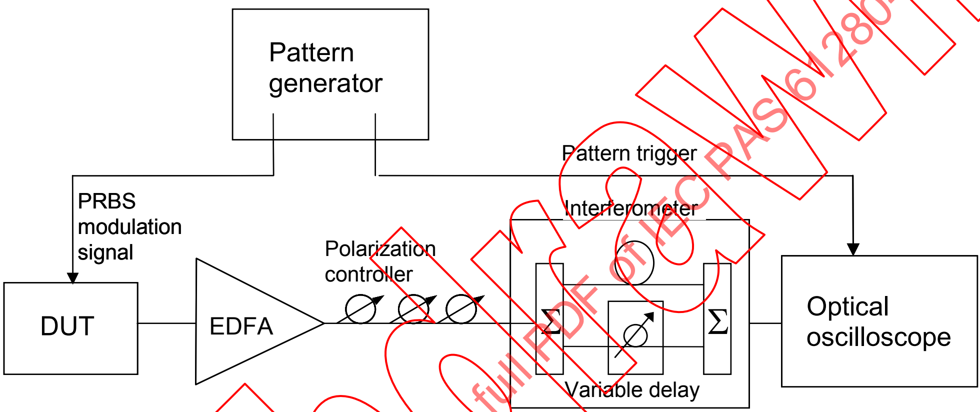


Figure 7 – Setup for the frequency discriminator method

6.1.1 Pattern Generator

The pattern generator supplies the PRBS modulation signal to the DUT and the trigger to the optical oscilloscope. The modulation rate and format are those required by the DUT. The PRBS pattern length should be 2^5-1 or longer. Shorter pattern lengths may be used but may not fully explore pattern-dependent chirp effects. Longer patterns may be used but will increase the measurement time. The trigger signal must be synchronous with the PRBS pattern – not the clock.

6.1.2 EDFA

The erbium-doped fibre amplifier is optional. It is required only if the optical power from the DUT is too low to provide sufficient signal level to the optical oscilloscope. For optical frequencies other than the C or the L-bands, alternative amplifier technologies must be used.

6.1.3 Polarization controller

Because the interferometer is highly polarization sensitive, the state-of-polarization (SOP) at the input to the interferometer must be optimised. The polarization state controller must have the capability to transform any arbitrary SOP at its input to the required SOP at its output. The three paddle or rotating waveplate designs can satisfy this requirement.

6.1.4 Interferometer

This is a Mach-Zehnder type with FSR sufficiently wide to accommodate the peak chirp. The variable delay shall have a range, Δt, in order to be able to set the DUT wavelength to points A and B in Figure 3. The value of Δt is:

$$\Delta t > \frac{1}{FSR} \pm \frac{1}{2f_o} \quad (7)$$

where f_o is the optical carrier frequency.

6.1.5 Optical oscilloscope

The optical oscilloscope consists of a DC-coupled broadband optical-to-electrical converter and a sampling oscilloscope. The combined frequency response of the optical-to-electrical converter and oscilloscope must be at least twice the bit rate and the impulse response should have no ringing, overshoot, or undershoot. It must accept a trigger input and have a means to means to set the trigger and observable time range. The bandwidth shall be greater than twice the bit rate.

6.2 Procedure

1) Connect the equipment as shown in Figure 7. The EDFA is required only if the power from the DUT is insufficient to provide a sufficiently high signal level to the optical oscilloscope.
2) Adjust the time range on the optical oscilloscope to display the desired number of bits.
3) Set the number of optical oscilloscope data points, n, to achieve the required time resolution. A typical value of n is 1000.
4) Adjust the polarization controller to achieve maximum signal level on the optical oscilloscope.
5) Adjust the variable delay element to the quadrature point A in Figure 11 and measure $V_A(t_i)$ where $1 \leq i \leq n$.
6) Adjust the variable delay element to quadrature point B and measure $V_B(t_i)$ where $1 \leq t_i \leq n$.
7) Compute:

$$P(t_i) = \frac{V_A(t_i) + V_B(t_i)}{2} \qquad 1 \leq i \leq n \quad (8)$$

$$V_-(t_i) = \frac{V_A(t_i) - V_B(t_i)}{2} \qquad 1 \leq i \leq n \quad (9)$$

$$\Delta f(t_i) = \frac{\text{FSR}}{2\pi} \arcsin\left(\frac{V_-(t_i)}{P(t_i)}\right) \qquad 1 \leq i \leq n \quad (10)$$

7 Monochromator method

7.1 Apparatus

The setup for the monochromator method is shown in Figure 8.

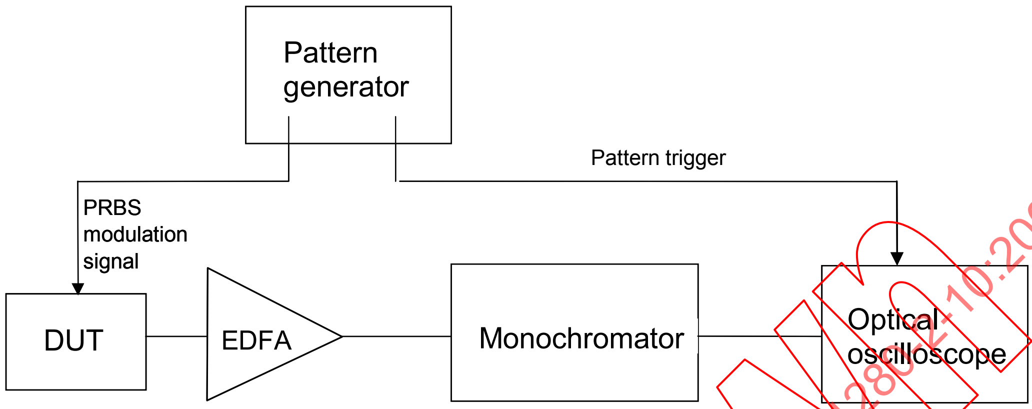


Figure 8 – Setup for the monochromator method

7.1.1 Pattern generator

The pattern generator supplies the PRBS modulation signal to the DUT and the trigger to the optical oscilloscope. The modulation rate and format are those required by the DUT. The PRBS pattern length should be 2^5-1 or longer. Shorter pattern lengths may be used but may not fully explore pattern-dependent chirp effects. Longer patterns may be used but will increase the measurement time. The trigger signal must be synchronous with the PRBS pattern – not the clock.

7.1.2 EDFA

The erbium-doped fibre amplifier is optional. It is required only if the optical power from the DUT is too low to provide sufficient signal level to the optical oscilloscope. For optical frequencies other than the C or the L-bands, alternative amplifier technologies must be used.

7.1.3 Monochromator

The monochromator has a bandwidth adjustable between 100 pm and 500 pm. It is a double pass monochromator arranged so that chromatic dispersion is nomally zero at band centre. In practice, a chromatic dispersion of less than Polarization dependence is less than 0,5 dB and insertion loss is less than 10 dB.

7.1.4 Optical oscilloscope

The optical oscilloscope consists of a DC-coupled broadband optical-to-electrical converter and a sampling oscilloscope. The combined frequency response of the optical-to-electrical converter and oscilloscope must be at least twice the bit rate and the impulse response should have no ringing, overshoot, or undershoot. It must accept a trigger input and have a means to means to set the trigger and observable time range. The bandwidth shall be greater than twice the bit rate.

7.2 Procedure

1) Connect the equipment as shown in Figure 8. The EDFA is required only if the power from the DUT is insufficient to provide a sufficiently high signal level to the optical oscilloscope.

2) Adjust the time range on the optical oscilloscope to display the desired number of bits.

3) Set the number of optical oscilloscope data points, n, to achieve the required time resolution. A typical value of n is 1000.

4) Set the bandwidth of the monochromator to accommodate the spectral width of the DUT. A typical value is 500 pm for a 10-Gb/s NRZ transmitter.

5) Centre the monochromator passband on the transmitter and measure $P(t_i)$ where $1 \leq i \leq n$.

6) Tune the monochromator centre frequency from f_A to f_B in m equal steps where f_A and f_B are the frequencies where the response is 10-dB below the peak. A typical value of m is 10.

7) At each monochromator frequency, f_k, measure $P(t_i,f_k)$ where $1 \leq i \leq n$ and $1 \leq k \leq m$. Refer to Table 1.

8) Compute the absolute frequency for each time slot:

$$f(t_i) = \sum_{k=1}^{m} \frac{P(t_i, f_k)(f_k)}{\sum_{k=1}^{m} P(t_i, f_k)} \qquad 1 \leq i \leq n \qquad (11)$$

9) Compute the time average frequency:

$$f_{mean} = \frac{\sum_{i=1}^{n} f(t_i)}{n} \qquad (12)$$

10) Compute the chirp:

$$\Delta f(t_i) = f(t_i) - f_{mean} \qquad 1 \leq i \leq n \qquad (13)$$

8 Alpha-factor calculations

From the power, $P(t)$, and chirp, $\Delta f(t)$, waveforms calculated in 3.2 or 4.2, alpha factor can be calculated. Three forms of alpha-factor are useful for transient chirp analysis:

Alpha factor vs. time, $\alpha(t)$

Average alpha factor, α_{avg}

Alpha factor vs. power, $\alpha(P)$

8.1 Alpha factor vs. time, $\alpha(t)$

Converting the continuous expression for $\alpha(t)$ given in (3) to discrete form in order to utilize the measured data gives:

$$\alpha(t_i) = \frac{4\pi P(t_i)}{[P(t_{(i+1)}) - P(t_{(i-1)})] \Big/ (t_{(i+1)} - t_{(i-1)})} \Delta f(t_i) \qquad 2 \leq i \leq n-1 \qquad (14)$$

An example plot of □(t) is shown in Figure 9 for an EML along with the plot of $P(t)$. The time range was chosen to show how a varies during the rise time of a single data bit. Alpha shows a large variation over this time period. Typically $\alpha(t)$ is calculated only during transitions of the power waveform, for example, between the 10 and 90 % points. This is because the calculation uncertainties increase when $\Delta P/\Delta t$ is small.

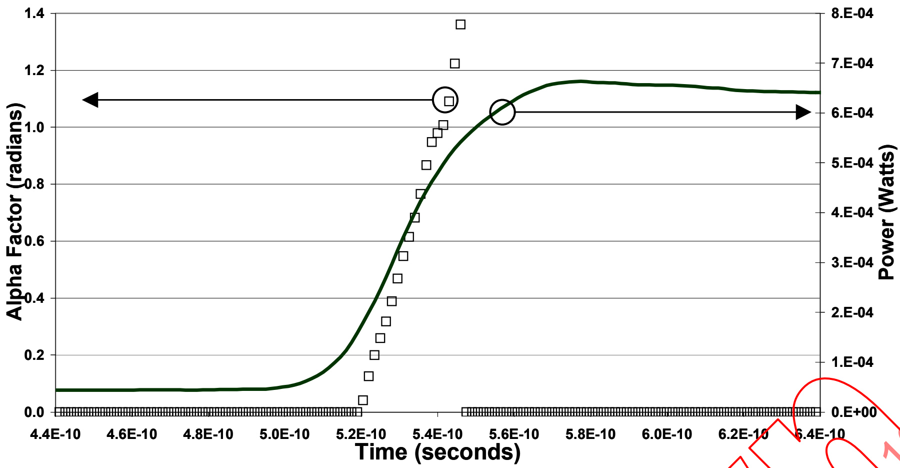


Figure 9 – An example plot of alpha vs. time for an EML

8.2 Average alpha factor, α_{avg}

The average alpha factor is simply the average over the selected time window.

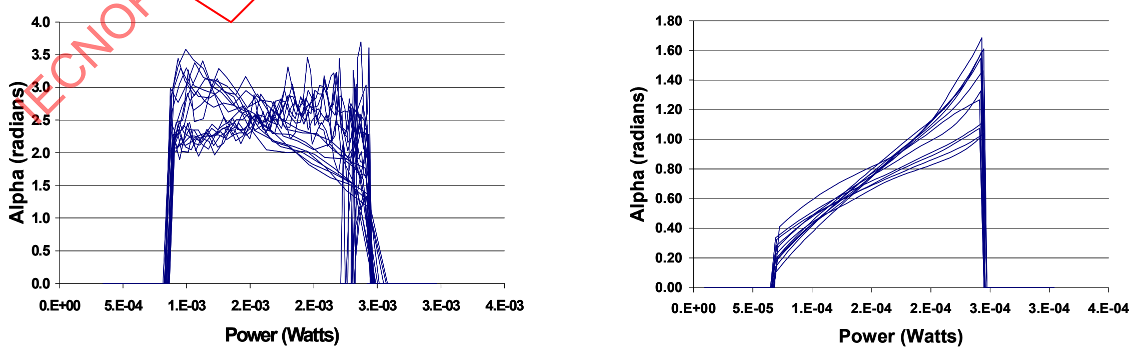
$$\alpha_{avg} = \frac{\sum_{i=1}^{n} \alpha(t_i)}{n} \tag{15}$$

For directly modulated laser, alpha vs. time is theoretically constant so this term has meeting. For an EML, as shown in Figure 17, alpha has variation vs. time so the average value is not as useful.

8.3 Alpha factor vs. power, $\alpha(P)$

A very useful tool for transient chirp analysis is a graph of alpha factor versus power [6]. $\alpha(t)$ is calculated from (15) and is then plotted as an x-y scatter chart with the corresponding value of $P(t)$. Calculations are limited to the transition portions of the power waveform.

Figure 18 shows Alpha factor vs. power graphs for (a) a directly modulated laser and (b) for an EML.



(a) (b)

Figure 10 – Alpha factor vs. power for (a) a DM laser and (b) an EML

Note that for many data transitions, the alpha factor vs. power for the DM varies from about 0,2 to 3,5. For the EML, it is a linear function of power from 0,2 to 1,4. The particular characteristics are dependent on drive level and bias.

9 Documentation

Report the following information for each test:

1. Test date
2. This document number
3. Procedure used: clause 6 or clause 7.
4. $P(t)$ and $\Delta f(t)$

10 Abbreviations

BER	Bit-error ratio
DCA	Digital communications analyser
DFB	Distributed feedback laser
DM	Directly modulated laser
DUT	Device under test
DWDM	Dense wavelength-division multiplexing
EAM	Electro-absorption modulator
EDFA	Erbium-doped fibre amplifier
EML	Electro-absorption modulated laser
FFT	Fast Fourier transform
FROG	Frequency-resolved optical gating
FSR	Free spectral range
NRZ	Non-return-to-zero
OSA	Optical spectrum analyser
PMF	Polarisation maintaining fibre
PRBS	Pseudo-random binary sequence
SLM	Single longitudinal mode
SNR	Signal-to-noise ratio
SOP	State of polarisation
TRC	Time-resolved chirp
WDM	Wavelength-division multiplexing

Annex A

Verification of TRC setup and calculations

The implementation of the TRC hardware and calculations can be verified by making an independent with an alternative. While this is very difficult for signals that have a combination of intensity and frequency modulation, a signal with only phase modulation can be used for this purpose. A pure phase-modulated signal can be generated with a microwave signal driving a Mach-Zehnder phase modulator. By comparing sideband level as measured on an OSA with the amplitude of the frequency (phase) modulation obtained from the TRC measurement setup, the validity of the TRC measurement can be established.

The relationship between OSA spectrum and the chirp is given by:

$$\frac{P_{carrier}}{P_{sideband}} = \frac{J_0^2(\frac{\Delta f}{f_m})}{J_1^2 \frac{\Delta f}{f_m}} \qquad (16)$$

where J_0 is the zero order Bessel function of the first kind

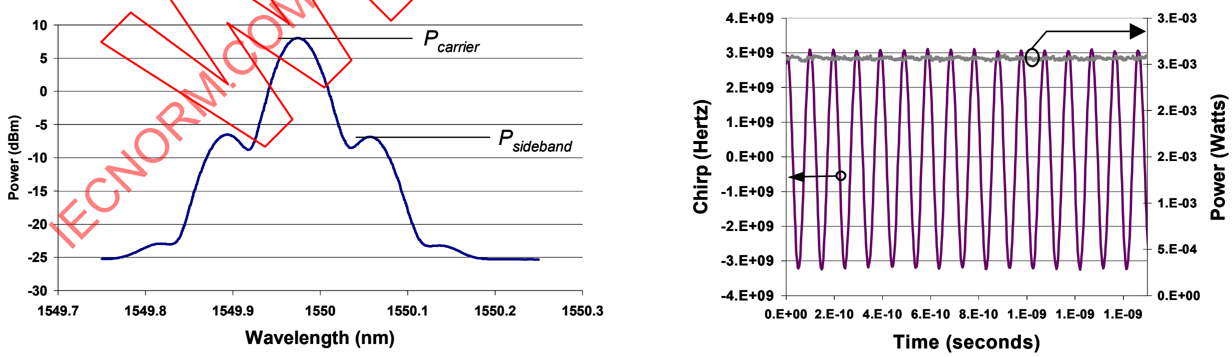
J_1 is the first order Bessel function of the first kind

Δf is the peak chirp

$P_{sideband}$ is the sideband power (watts)

$P_{carrier}$ is the carrier power (watts)

Figure A-1 shows measurements of a 10,25 GHz phase modulated signal on an OSA and a TRC setup. Note the symmetry in sidebands on the OSA and the flat power vs. time on the TRC graph indicate that there is no intensity modulation. Using (17), the correspondence between the two methods can be verified.



(a) (b)

Figure A-1 – Pure phase modulation observed on (a) an OSA and (b) a TRC measurement setup

Annex B

Optical transmitter modulation methods

B.1 Directly modulated laser

Directly modulated (DM) lasers are the most common, particularly for short-reach systems. They are the lowest cost and generally have the highest value of chirp. In a DM laser, shown schematically in Figure B-1, 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 a trade-off between extinction ratio and chirp penalty.

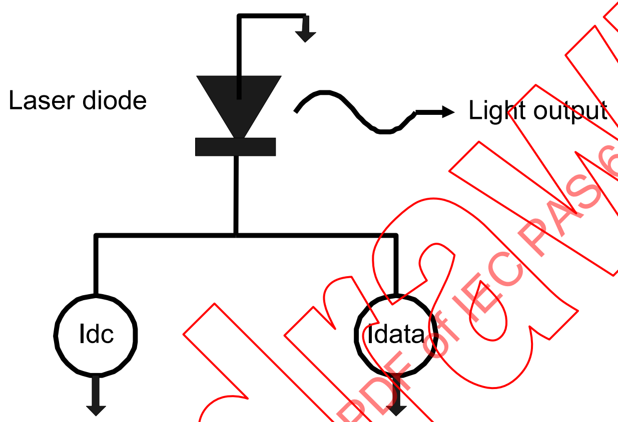


Figure B-1 – Schematic representation of a directly modulated laser

In a DM laser, the presence of the data signal produces a change in the effective index of refraction in the laser cavity. This results in phase shifts (transient chirp) during the data transitions as well as a long-term shift in the laser frequency (adiabatic chirp).

Figure B-2 show *P(t)* and *Δf(t)* for a directly modulated DFB laser. There is significant transient and adiabatic chirp. The transitions excite the relaxation oscillations within the device causing ringing in both the instantaneous optical power and frequency.

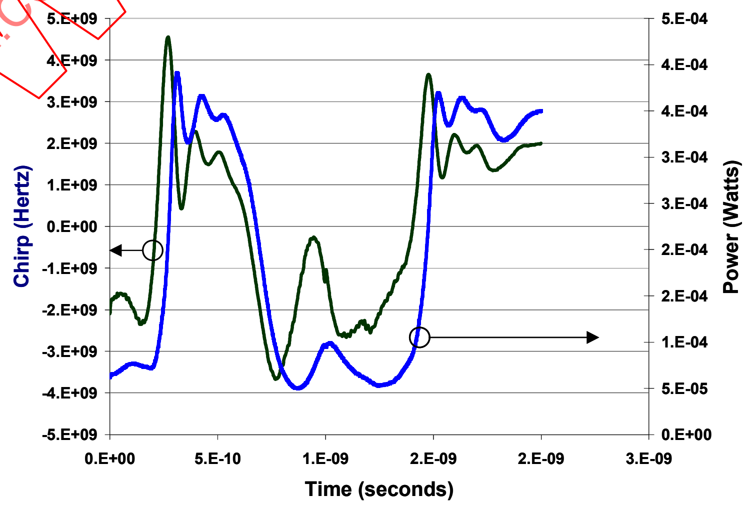


Figure B-2 – A directly modulated laser has significant transient and adiabatic chirp

B.2 Electro-absorption modulator

Electro-absorption modulated lasers consist of a SLM laser, typically a DFB, and an integrated electro-absorptive modulator (EAM) section usually on the same chip. This is cost effective compared to externally packaged modulators and is a step above DM lasers in terms of chirp 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 modified only 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 B-3 shows an EML schematically. The current applied to the laser, Idc, is strictly DC so that the frequency of the laser is constant. The EAM is driven with a separate signal that makes the waveguide more or less absorptive. With EML designs, transient chirp tends to dominate the performance. The ringing from the laser relaxation oscillations is eliminated. In the $P(t)$ and $\Delta f(t)$ plots for an EML in Figure B-4, note the clear definition of the frequency transients on the rising and falling edges of $P(t)$. They correlate directly to the magnitude of dP/dt as predicted in (4). EMLs may also exhibit an additional transient term occurring before the rising edge as shown in Figure B-5. It is believed to be due to a refractive index change due to the E-field applied to the device before the absorption recovers (Pockels effect) [6].

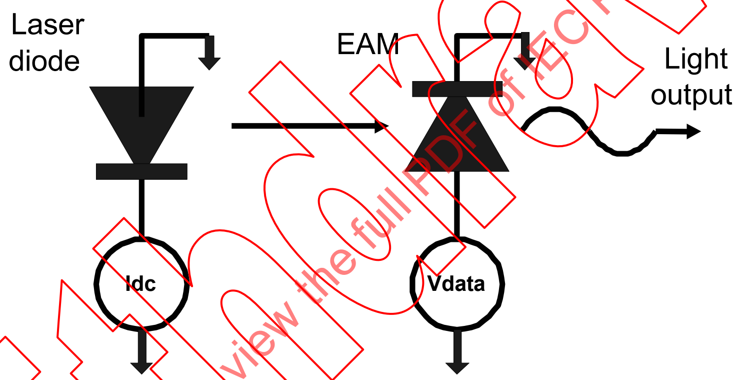


Figure B-3 – Schematic representation of an EML