Chapter 11  
Test and Measurement

11.1 Introduction

This chapter deals with measurement and characterization of the critical parameters for fiber optic devices and links. These parameters include quantities such as optical power, extinction ratio, rise and fall time, bit error rate, wavelength, and spectral width. Measurement methods are crucial for evaluation of existing devices and systems as well as for validation and debugging of new designs. Without accurate test and measurement methods, the critical relationship between theory and real world breaks down, effectively rendering most engineering efforts meaningless.

We will start this chapter by an overview of the various elements that are required for a successful test or measurement experiment. Among these are a clear understanding of the physics involved in the test and a knowledge of the working principle and limitations of the test equipment used. Moreover, the set-up used in experiment must be designed carefully so that the parameter or quantity that is being tested is isolated from the influence of other factors that can disturb the measurement.

The remainder of the chapter deals with some of the most common tests that characterize fiber optic devices and links. These include optical power measurement, time domain analysis of optical waveform, optical and electrical spectrum analysis, sensitivity tests, as well analog tests for parameters such as modulation depth and harmonic distortion. In each section we will discuss both the quantities of interest that need to be tested or measured and the operating principles behind the common test instruments that are used for these measurements.

11.2 Test and measurement: general remarks

As noted above, test and measurement techniques are the crucial links that bridge the gap between theory and reality. Theories are always based on models that involve simplifications and approximations of reality, and it is through experiment, test, and eventually measurements that the relevance and success of these models and the theories that are based on these models can be determined. This is true both in pure science and in applied fields such as engineering. As a result, a great deal of effort has gone into the theories and techniques involved in test and measurements, including those related to fiber optics [1–6].

It is worthwhile to have a brief discussion about the different elements that are needed for a successful experiment design, be it a simple measurement or a complex system level test. Figure 11.1 summarizes some of these factors.

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An experiment typically involves a design step. First and foremost, the goal of the experiment must be defined clearly. This goal can be a simple quantity measurement or a complex system-level test involving many measurements. Once the goal is identified, a test methodology must be chosen that can clearly achieve the defined goal. We can think of test methodology as a detailed flow chart that spells out every intermediate step process, instrument, software, measurement, calibration, algorithm, etc., that will be used during the experiment. The methodology must take into account factors such as the target accuracy of the tests, the range and linearity of the parameters involved, and the effects of other system or environmental parameters on the experiment. Moreover, the experiment design should include applicable statistical provisions and analysis. For instance, oftentimes the accuracy of an experiment or measurement can be improved by averaging the results over a number of repeated tests or a larger sample size.

Any experiment is based on a set of theories, and knowledge of these theories is necessary both for the design of the experiment and for the interpretation of the results. For instance, fiber optic-related tests are often based upon a mixture of electrical, physical, and optical theories. Moreover, oftentimes an experiment is based on certain mathematical foundations, theorems, or principles. A frequently encountered example in engineering is the Fourier analysis that relates time and frequency domain quantities.

Another crucial element that plays a critical role is the test equipment and instruments. It is important to take into account the inherent shortcomings of all test
equipment that show up in the form of limitations such as inadequate range, insufficient bandwidth, noise floor, and limited accuracy. Another important point to consider is that in order to conduct a measurement, the test equipment oftentimes has to disturb the very quantity that it is trying to measure. For example, the input impedance of an oscilloscope port or the parasitics of the oscilloscope probe can disturb the voltage of the node whose waveform is being measured.

The experiment design should also take into account the issue of standards. Standards of measurement are especially key in those areas where the quantity to be measured has a strong element of “definition” to it. This means the measured value strongly depends on how that quantity is defined or tested, or on how the test results are interpreted. There are a wide range of standards for fiber optic tests and measurements, for instance the FOTP series of documents from the Telecommunication Industry Association (TIA) [7]. We will return to the subject of standards in Chapter 12.

Maintenance and calibration of test instruments is also very important [8]. Without periodic calibration, a test instrument can deviate from its expected performance and yield erroneous measurements. As a result, and if possible, it is good practice to have some means of independently verifying the calibration of test instruments. For example, the accuracy of an optical power meter can be verified if a standard laser source is available. Alternatively, it is always possible to compare the measurement results obtained through different instruments if more than one piece of instrument for a particular measurement is available. Obviously if two instruments report different values for the same measurement, they both need to be calibrated and verified because at least one of them is out of calibration.

Figure 11.1 is intentionally organized in the form of a flow chart with a main loop. The reason is that a well-designed experiment should take into account the possibility of something going wrong and not meeting the goals of the experiment. In that case, some or all of the above-mentioned factors must be revisited, and the root cause of the problem should be identified. The problem can result from a simple reason, for instance a wrong setup on an instrument, or it could be due to deeper reasons, for example a flaw in the theory behind the experiment. Thus, it may take several iterations before the experiment is tailored and tuned so that the defined goal can be achieved.

In the reminder of this chapter, we will review the test procedures and instruments for measuring the most common parameters in fiber optic links.

11.3 Optical power

One of the most fundamental parameters in optical links is optical power. For instance, the average power of an optical transmitter is a critical measure of the physical distance its signal can reach. Similarly, the sensitivity of an optical receiver, which is the minimum optical power that the receiver can work with, is a figure of merit that determines the link budget that the receiver can support.
As noted in Chapter 3, optical power can have several meanings. The instantaneous power associated with the optical frequency is a quantity that oscillates at twice the optical frequency. Therefore it cannot be measured directly and it is almost never used in any practical application. More practical quantities related to power include average and instantaneous power. In fiber optics, oftentimes average power is the primary quantity of interest.

The average optical power is a convenient parameter that is widely used to characterize, among other things, light output of transmitters and sensitivity of receivers. The optical power is usually measured in units of decibel-milliwatt, which we introduced in Chapter 1, and which we repeat here for reference:

$$P_{\text{dBm}} = 10 \log_{10} (P_{\text{mW}})$$

Here $P_{\text{dBm}}$ is power in units of dBm, and $P_{\text{mW}}$ is power in mW. The convenience of average power lies in the fact that it can be measured easily with an optical power meter using a broad area detector, schematically shown in Fig. 11.2.

**Fig. 11.2.** Optical power meter based on a broad area detector

Using a large detector has the advantage of reducing the dependence of measurement on coupling efficiency, because all the optical power exiting from a fiber is collected by the detector. Naturally, a large detector has a slower time response, but this is not an issue when it comes to measuring average power. Most optical power meters have several instrument settings that need to be considered for accurate measurement.

- **Wavelength:** It is important to set the wavelength of the light that is to be measured correctly. This is because the responsivity of photodetectors is not constant across wavelengths, and the instrument uses the wavelength setting in order to calibrate the responsivity. Without correct wavelength settings, the power measurement may be off by as much as 1 dB.
• **Time Constant:** It is usually possible to set the time constant over which power measurements are averaged. The time constant settings can change from a fraction of second to seconds. Using a longer time constant setting is advantageous in terms of filtering noise effects and is preferred whenever possible.

• **Range:** Most modern equipment automatically select the correct range for a particular measurement. However, if the equipment does not include this feature or if this feature is optionally disabled (for instance when the device is controlled through a GPIB interface) the correct range must be selected. The typical dynamic range for most power meters is at least tens of decibels. When the magnitude of the power is completely unknown, it is a good practice to start from a higher range and select lower ranges afterward.

• **dBm/mW:** It is usually possible to select between logarithmic and linear measurements. As noted before, in most cases power measurements are carried out in logarithmic units. The dBm logarithmic scale is very convenient when it comes to measurements that involve comparing power levels, dynamic range, gain or loss, and power penalties.

11.4 Optical waveform measurements

A wide variety of signal parameters are related to the optical waveform. In general, these parameters can be divided into two categories. We discussed these parameters in Chapter 3 in terms of the optical signal itself. In this chapter, our focus is on measurement aspects, especially with respect to the instruments that are used for these measurements.

11.4.1 Electrical oscilloscopes with optical to electrical converter

One way to measure these parameters is to use an electrical oscilloscope in conjunction with an optical to electrical (OE) converter [9]. Naturally, the choice of the bandwidth of the scope, the optical to electrical converter, and the interconnecting signals is important. Lack of sufficient bandwidth on any of these components can cause an inaccurate representation of the time features of the signal. In general, the rise-time (or fall-time) value measured on a scope is given by

\[ t_{measured}^2 = t_R^2 + t_{OE}^2 + t_{scope}^2 + t_{cable}^2 \]  

(11.2)
where \( t_R \) is the actual rise-time (or fall-time) of the optical signal and \( t_{OE} \), \( t_{scope} \) and \( t_{cable} \) are related to the nominal bandwidth of the OE converter, oscilloscope, and the interconnecting cables as\(^1\)

\[
t = 0.35 / BW
\]

From Eq. (11.2), it can be seen that to capture high-frequency features of a signal accurately each of the components used in a setup must have a much wider bandwidth.

Using an OE converter requires additional calibration of the vertical axis, because in electrical oscilloscopes the vertical axis is calibrated in volts. One way to achieve this calibration is by measuring the average optical power with an optical power meter and correlating the results with the average voltage reading in the oscilloscope.

Modern oscilloscopes are often based on digital sampling of the signal. A high-speed analog to digital converter converts the signal into a series of digital data which is then stored in the memory and shown on the display. Working with such sampling scopes requires some caution. For instance, changing the time scale may cause some high-frequency details of the signal to be lost. Also, aliasing effects, resulting from under-sampling of signals, are a possibility [10–12].

11.4.2 Digital communication analyzer (DCA)

Measurement of high-speed optical signals is an active topic and both optical and electrical domain solutions have been proposed [13]. In most applications, digital sampling techniques are used to capture optical waveforms [14,15]. Specifically, manufacturers have come up with digital scopes specifically targeted for fiber optic applications. Sometimes called digital communication analyzer (DCA), these instruments are essentially a digital scope with a front-end optical-to-electrical converter and equipped with additional software to accomplish a variety of measurements.

From the stand point of capturing the optical waveform, in optical communication the challenge is that the involved frequencies may be too high, thus requiring extremely high-speed ADCs at the front end. For example, to represent a 10 Gbps signal accurately, we may need up to 20 GHz of analog bandwidth, which translates to at least 40, but preferably more, Giga samples of sampling per second. Achieving such sampling rates is difficult and expensive. For higher speed signals, it could simply be impractical.

DCAs solve this problem by using a sampling technique known as \textit{equivalent time sampling} (ETS). [16] To do this, they take advantage of the fact that often times we are not interested in the shape of each and every individual bit or wave-

\(^1\) As noted in Chapter 3, the relationship between rise and fall times and bandwidth depends on the shape of the edges. Equation (11.3) is based on an exponential shape, which is more typical for RC time constants encountered in electrical components.
form in a signal. Instead, we would like to know certain properties of the signal as they relate collectively to all the bits or waveforms. In digital signals, this is typically done by the eye pattern, which is built from superposition of waveforms from many individual bits.\(^2\) For instance, the rise-time measured in an eye pattern can be interpreted as a measurement averaged over many individual rise-times. However, the utility of such “averaged” measurements is not limited to digital signals and any repetitive pattern can be captured using ETS.

The principles of ETS are shown in Fig. 11.3, which shows a repetitive but otherwise arbitrary waveform. To capture the waveform, a trigger input that is synchronized with the repetition rate of the main signal is needed. Thus, each trigger event indicates the starting point of another window within which the waveform can be sampled. Next, the waveform is sampled once within each window, while the sampling point is moved forward in each subsequent window. In this way, the waveform can be scanned from beginning to the end after many windows. The sampled points can be stored in memory and used to reconstruct the shape of the waveform. It is evident from this description that the reconstructed waveform is not displayed as a function of real time, and that is why the time axis is called equivalent time.

\[\text{Trigger 1, Trigger 2, Trigger 3, Trigger } n-1, \text{ Trigger } n\]

\[\text{Sample Sample Sample Sample Sample}\]

\[\text{Reconstructed waveform}\]

\[\text{Equivalent Time}\]

**Fig. 11.3.** Reconstruction of a fast waveform by equivalent time sampling

\(^2\) For a more detailed discussion of eye patterns, see Chapter 3.
Typically, a DCA has two display modes. In the oscilloscope mode, the stored samples from the waveform are displayed only for a limited time before being discarded and replaced by new points. The display's persistence time can be set anywhere from a fraction of second to a few seconds. When the persistence time is short, the displayed waveform responds quickly to the changes in the actual waveform. When the persistence time is long, the displayed waveform maintains features of the physical waveform for a longer time. It is also possible to use an infinite persistence mode, where the display reflects a captured point forever (or until the display is erased). This mode is sometimes called the eye-mask mode and can be utilized to analyze the long-term behavior of the waveform. For example, the DCA may be left to run in this mode for days, after which the display contains a visual record of the behavior of the waveform. We will discuss this mode further in a later section.

As can be seen from Fig. 11.3, the waveform is reconstructed slowly and after many triggers, and this can only be done because an independent trigger input is (and should be) available. Thus, unlike traditional oscilloscopes, the instrument cannot trigger on the signal itself (i.e., edge trigger, level trigger, etc.) Moreover, only those features of the waveform are captured that are repeated in every waveform. For example, if a singular spike occurs in only one window, it is unlikely for it to coincide with the sampling point in that window, and therefore it will not be captured. However, the advantage of this technique is that the ADC at the front end of the scope needs only to sample once in a window. This would be a much lower rate compared to the required “real-time” sampling rate, dictated by the Nyquist theorem.3 As a result, signals with much higher frequency components can be displayed and analyzed using this technique. Signals with bandwidths as high as 80 GHz can be handled by modern DCAs [17].

Another feature that makes DCAs particularly useful for fiber optic measurements is that most of them have standard “plug-in” modules that incorporate a calibrated high-speed optical to electrical converter. The instrument can display the waveform directly in the optical domain. Moreover, the manufacturers provide a variety of built-in software tools for measuring a wide range of parameters. In the next section, we will discuss some of these parameters briefly.

To increase the accuracy of waveform measurements, the signal-to-noise ratio at the input of the DCA must be maximized. This is because a DCA, like any other receiver, has an input sensitivity and a noise floor. If the amplitude of the signal gets close to the noise floor, the measurements will no longer be accurate. In general, the optical power of the signal should be kept close to the maximum level the DCA can accept. Consequently, the signal-to-noise ratio will be maximized, and measurements will be more accurate. Of course, this is only possible when the signal has enough optical power to begin with, so that by adding an optical attenuator the signal can be attenuated to the appropriate level for the DCA. On the other

3 According to Nyquist theorem, in order to accurately reconstruct a signal, it should be sampled at a rate at least twice as high as the highest frequency components of that signal.
hand, if the optical power is already low compared to DCA’s noise floor, an optical amplifier may have to be used to increase the signal-to-noise ratio.

Most DCAs have several low-pass filters built in that can be applied to the waveforms. These filters are defined by various standards and are generally used in eye mask measurements for digital signals (we will discuss eye mask tests later in this chapter). The effect of these filters is to remove high-frequency components of the signal. For instance, a typical OC48 filter is a low-pass Bessel-Thomson filter with a bandwidth of 1.87 GHz. Naturally, using a low-pass filter affects the optical eye. For example, rise and fall times will be slower, high-frequency laser relaxation oscillations will be removed, and in general the eye diagram will look cleaner and smoother.

An eye pattern, after passing through the appropriate filter, is effectively band limited according to the bandwidth requirements of the corresponding receiver. Thus, for instance, an eye pattern after going through an OC48 filter looks like what an OC48 receiver “sees” from that signal. Because of this band limiting effect, it should be ensured that the right filter is selected for each application.

### 11.4.3 Amplitude related parameters

Using a DCA, a number of parameters related to the amplitude (or instantaneous power) of an optical signal can be characterized. As noted in Chapter 3, these parameters mainly include optical “1” and “0” levels, overshoot, optical modulation amplitude (OMA), and extinction ratio. Alternatively, the built-in software provided with a DCA can be used. A point to notice in amplitude measurements is that they are referred to the average value of a distribution. Fortunately, most DCAs are equipped with built-in software that can capture a histogram of this distribution within any given window in an eye pattern. For example, Fig. 11.4 shows a typical histogram of the 0 and 1 levels within a predefined box in an optical eye diagram.

![Histogram Windows](image)

**Fig. 11.4.** Histogram of the distribution of 0 and 1 levels
The optical 1 and 0 levels correspond to the mean value of the distribution. By setting the corners of the histogram window, the statistical details of the signal can be examined more accurately.

An important parameter in digital signals is extinction ratio (ER), defined as the ratio of an optical “1” to an optical “0” level, in decibels. Most DCAs already have a predefined routine for measuring extinction ratio. However, in spite of the conceptual clarity of ER, accurate ER measurements are infamously difficult and affected by a number of uncertainties [18–20]. Among these is noise in the 0 and 1 levels, which makes it difficult to assign an exact value to the 0 and 1 levels. Also, signal oscillations especially at the 0 state can affect ER measurements, because they impact the exact value of the 0 state. Moreover, it becomes increasingly difficult for DCAs to resolve very high ERs, say, beyond 15 dB. This is because at such high ERs the 0 level gets very close to the actual dark level, or the noise floor of the DCA. Consequently, it becomes increasingly difficult to measure higher ERs.

11.4.4 Time-related parameters

Main time-related parameters include rise and fall time, eye width, and jitter. As noted before, it is important to ensure that when performing these measurements the equipment has sufficient bandwidth and that no additional filters are added to the signal path. In a DCA any time measurement, like amplitude measurement, is referenced to a distribution of events in time. Therefore, using time histogram features available in most DCAs is a valuable tool for signal analysis.

This is very obvious in jitter measurements. Figure 11.5a illustrates a typical jitter histogram for a representative eye pattern. If the distribution is Gaussian, it can be readily characterized by its rms and peak-to-peak value. The rms value refers to the standard deviation width of the distribution, and the peak-to-peak value, although theoretically unbounded, can be limited within a certain number of standard deviations in either side of the mean value. The number of $\sigma$s used depends on the bit error rate.4 Note, however, that jitter distribution is not always Gaussian. More often than not, jitter can be broken down into a deterministic and a random component. The random component can be characterized by a Gaussian, but the deterministic component is a function of the particular system under test.

For example, if the eye pattern shows a “double edge,” the deterministic component can be attributed to the time delay between the two edges. This is shown in Fig. 11.5b. It can be seen that a time histogram gives a much more complete picture of the nature of jitter. The above discussion sets the basis for other time-related measurements as well. For example, two other important parameters in a digital signal are rise time and fall time ($t_R$ and $t_F$). For optical signals, they reflect the speed of the modulating electrical circuit as well as the frequency response of the laser or the external modulator.

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4 For a more detailed discussion of jitter refer to Chapter 3.
As shown in Fig. 11.6, the transition time for each of the rising and falling edges is a distribution and the mean value of the distribution should be used as the reference point for the edge. Both rise-time and fall-time can be measured either from 10 to 90% point or from 20 to 80% in a signal. Using the 20–80% levels typically provides more consistent results. On the other hand, using the 10–90% levels renders the measurement more sensitive to signal distortions and noise. For instance, in Fig. 11.6, \( t_r \) and \( t_f \) are based on the 90 and 10% levels. It can be seen that in this case the fall-time is disproportionately affected by a plateau in the falling edge. On the other hand, the 80–20% fall-time is much less sensitive to the same plateau.
11.4.5 Mask measurement

In a mask measurement, the shape of an eye pattern is laid against a pre-defined mask, which essentially verifies that the eye pattern is sufficiently open in time and amplitude [18]. It also ensures that the amount of noise in the 0 and 1 levels does not exceed the value set by the mask. In general, an eye mask determines the minimum acceptable “quality” for a particular digital signal, such that a non-conforming signal results in mask violations or hits. Figure 11.7 illustrates a mask test for an ideal eye diagram. Mask tests are typically performed in the infinite persistence mode of a DCA using the appropriate low-pass filter for that application. This will usually remove overshoot and laser relaxation oscillations that are normally out-of-band for many lower data rate applications, and in general will yield a “cleaner” eye pattern.

However, in-band distortions will pass through, and if they are large enough, they can cause mask hits. In cases where there is no mask hit, it is common to define a mask margin value. The mask margin can be measured by increasing the size of the mask and making it tighter around the eye pattern. The mask is made larger until it overlaps with the actual eye at some point. Mask margin is the percentage by which the mask has to increase in size before the first hit occurs. In Fig. 11.7, the original mask is shown by dashed lines and the extra margin is shown by the dotted area.

Certain factors can impact the accuracy of a mask test. As noted before, it is important to take into account the noise floor of the DCA itself. If the optical signal is weak and close to the noise floor, the mask margin can suffer. Moreover, any phase change between the data and the trigger signal will directly translate to a shift (and therefore “smearing”) in the displayed eye. High-frequency phase shift, or jitter, will lower the mask margin. Low-frequency phase shift, also known as wander, can affect long-term measurements. In short, a mask test is a simulta-
neous reflection of both the signal itself and the noise floor of the equipment and the phase noise between the signal and the trigger.

11.5 Spectral measurements

The shape of a waveform in time domain does not provide any information about the spectrum of the signal. As discussed in Chapter 4, different laser structures have different spectral characteristics, resulting in differences in wavelength, spectral width, and spectral shape. The spectral characteristics of a signal have a direct impact on the amount of attenuation and dispersion the signal experiences as it propagates through the fiber. In this section we will discuss the principles of optical spectrum measurements.

11.5.1 Optical spectrum analyzer (OSA)

The main instrument used in the analysis of an optical spectrum is an optical spectrum analyzer (OSA). [21–24] In principle, an OSA works the same way as an electrical spectrum analyzer, with the difference that the frequencies involved are at much higher optical frequencies [25]. In both cases, the signal is passed through a variable narrowband filter, which only passes a very narrow range of frequencies from the signal. The filter is then swept across the frequencies of interest and its output is displayed as a function of the frequency. Figure 11.8 illustrates the concept behind a generic spectrum analyzer.

![Schematic diagram of a frequency spectrum analyzer](image)

**Fig. 11.8.** Schematic diagram of a frequency spectrum analyzer

Because the phase information of the signal is lost, the equipment effectively displays the energy spectrum density of the signal, \( S(f) \), given by
where $X(f)$ is the Fourier transform of the time domain signal $x(t)$. In reality, the displayed signal is the convolution of the response of the filter and the spectrum of the signal. Thus, Eq. (11.4) holds if the bandwidth of the variable filter is very narrow compared to the spectral features of the signal. If this assumption does not hold, the displayed signal would be smoothed out as a result of the wider bandwidth of the filter and the spectral details of the signal will be lost.

In an optical spectrum analyzer, the variable filter must be capable of tuning its pass-band across the optical frequency range of interest. Many optical devices can act as an optical filter. For instance, we know that a Fabry–Perot resonator acts as a wavelength-selective device based on its length [26]. Thus, by changing the length of the cavity we can implement a variable optical filter. Another possibility is using a prism to split light into its constituent spectral components and then using a narrow slit to select only a specific band for further analysis. The advantage of this approach is that the prism maps the spectrum into the spatial domain, and therefore the filter has to be a spatial filter, i.e., a slit. However, a prism is not the best device to decompose the spectrum, because it has not enough dispersion in infrared. A better device for this purpose is a grating, which consists of a large number of closely spaced slits on a reflective or transmissive substrate. This is the basis of operation of most OSAs [27,28]. Figure 11.9 shows the block diagram of an OSA based on a reflective grating.

![Fig. 11.9. Schematic of an optical spectrum analyzer based on reflection grating](image-url)

Typically the light is brought to the equipment with a fiber where it is culminated and directed toward the grating. The grating separates the wavelengths, and a second slit acting as a spatial filter selects a narrow band. The light that passes
through the slit is then focused on a detector, which converts the optical power to an electrical signal. After initial amplification the analog signal is digitized and goes through further signal processing. Eventually, the optical power is used as the vertical scale in a display. The horizontal scale is driven by a ramp generator which rotates the grating. Thus, the horizontal location of the trace in the display corresponds to the angular location of the grating, which in turn determines the range of wavelengths that go through the slit and detected by the detector. As a result, the display traces the optical power of the signal as a function of wavelength.

Figure 11.10 shows the typical settings and measurements available in an OSA. The left-hand side of the figure shows the settings that are available to the user. The wavelength settings control the horizontal scan that sets the start and stop wavelength points. Alternatively, a center wavelength and a wavelength span can be indicated. The level controls deal with the vertical axis of the display. The vertical axis can be changed between linear and logarithmic (dBm) scales. In most cases the logarithmic scale is used as it provides much more dynamic range in displaying the waveforms. In either case, the scale of the display grid can also be chosen (dB or mW per division), which determines the vertical span of the displayed waveform. The reference level selects the reference point for the vertical axis, so that changing it will shift the displayed waveform up or down. Several additional parameters related to the way the signal is scanned and displayed can also be set.

![Typical OSA controls and measurements](image-url)
For instance, the OSA can be configured to scan the input signal continually or it can be set to perform a single scan. The resolution setting determines the bandwidth of the bandpass optical filter. Using higher resolution yields more details in the spectrum of the signal, but it will take longer to scan the waveform. Usually, resolutions of up to 0.1 nm can be achieved with standard OSAs. Using averaging enables the display to show the average of several scans. This is a useful feature when dealing with noisy signals or when measurements at very low optical powers are needed.

Figure 11.10 also shows some of the typical measurements that an OSA can perform on a waveform. Most OSAs are equipped with internal software that can automatically perform a number of key measurements. Among the most common measurements are optical power and wavelength for each of the peaks in the spectrum. Measurements of spectral width (SW) and side mode suppression ratio (SMSR) are also routine tests.\(^5\)

In addition to automatic test routines, OSAs provide means of making direct measurements on the waveform. For instance, Fig. 11.10 shows a knob that can be used to move a marker along the waveform. At each point, the equipment displays the wavelength and the optical power. Using this feature, the user can perform direct measurements on various features of the waveform.

OSAs are versatile tools that can perform a host of spectral measurements on a signal, and their test capabilities suffice for most general applications. In some cases, however, the measurement accuracy of an OSA is not sufficient, in which case other test equipment specifically targeted for a particular measurement should be used.

### 11.5.2 Wavelength meters

One example where the accuracy of a typical OSA can be insufficient is when the wavelength of a signal must be measured with great precision, say, with ±0.001 nm accuracy. This is usually the case in WDM applications where wavelength spacing and stability of adjacent channels is of great importance. Wavelength meters are capable of measuring the wavelength of an optical signal with much more accuracy compared to an OSA.

Wavelength meters typically utilize interferometric principles to increase the measurement accuracy. For instance, in a Michelson interferometer, the optical signal is split into two beams in two branches and is then made to interfere with itself. When the length of one of the branches is varied, the output of the interferometer goes through successive minima and maxima, as a function of the length change. By counting these peaks, the wavelength of the light can be determined. Other methods are based on Fizeau, or Fabry–Perot interferometer effects, Doppler effect, and heterodyne principles [29–32].

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\(^5\) For a discussion of these and other spectral parameters refer to Chapter 3.
11.6 Link performance testing

Instruments like power meters or spectrum analyzers measure parameters associated with an individual device or test. However, it is also necessary to measure the performance of a system that consists of several individual elements. A prime example is a complete link, consisting of an optical driver, a laser, optical fiber, and an optical receiver. The ultimate measure of performance for a digital link is bit error rate (BER), which refers to the ratio of correctly received bits to the total number of bits sent [33]. Not only an entire link, but also many digital circuits and systems can be tested for BER, examples include receivers or clock and data recovery circuits. For the purpose of our current discussion, unless otherwise stated, we refer to the system being tested as device under test (DUT).

11.6.1 Bit error rate tester (BERT)

A typical BER test includes sending a known pattern of data through the DUT and comparing the data stream coming out of the DUT with the pattern that goes into the DUT. Figure 11.11 shows a schematic diagram of a commonly used bit error rate tester (BERT) for this purpose.

![Schematic diagram of a bit error rate tester (BERT)](image)

The BERT is divided into two main blocks, a transmitter (TX) and a receiver (RX) unit. The user controls and interfaces are shown in the left side of the figure,
while the instrument’s signal inputs and outputs are shown on the right side. The BERT measures the DUT’s BER as well as a variety of error statistics.

The user inputs include frequency, pattern, signal levels, and a delay between the receiver clock and data. The pattern and frequency inputs control a pattern generator that creates a test pattern simulating the real data traffic that the DUT is likely to encounter. The most common patterns for testing BER are pseudo-random (PRBS) patterns of different lengths, usually PRBS-7, PRBS-23, and PRBS-31. These patterns simulate random data traffic within their lengths, with longer patterns representing more random data. In most BERTs, there are options to define other user patterns too, usually to allow for stressing the DUT in some particular aspect.

The TX block has three main outputs. The data output includes a physical signal that represents the intended pattern. This pattern is usually applied to the DUT. There is also a clock output, which enables the RX block to synchronize with the TX block. Finally, the TX block provides a trigger output. This output is not used directly within the BERT. However, it is very useful if other tests are to be conducted. For example, it allows the use of a DCA for eye pattern analysis. The trigger output can be driven from two sources. It can either replicate the clock (or some divided version of the clock) or it can provide a trigger pulse every time the pattern generator has gone through the entire pattern and starts sending the pattern from the beginning again. As indicated in Fig. 11.11, the voltage level of these outputs can also be controlled by the user.

The RX section has two main inputs: a clock and a data input. The data output from the TX section is applied to the DUT and the output of the DUT goes to the data input of the RX section. On the other hand, the RX section uses the clock input to generate an exact replicate of the data pattern. An error analyzer compares this copy with the data it is receiving from the DUT bit by bit. As a result, the analyzer can determine the ratio of the bits that do not match the expected value (and therefore are considered errors) to the total number of received bits. This ratio, by definition, is the BER of the DUT.

Note that there is a time delay associated with the DUT and the electrical (or optical) interconnects in the setup. Therefore, the RX section must be able to change the delay of the received signal with respect to the pattern it generates internally to synchronize and match the two. This so-called clock and data alignment process is accomplished through a variable delay that can either be controlled by the user or optimized by the BERT. The alignment is optimized by changing the delay until the BER is minimized. This process is equivalent to changing the sampling point in time within an eye pattern. Placing the sampling point in the middle of an eye pattern will minimize the BER. On the other hand, by changing the delay, the sampling point can effectively be moved across the eye pattern, and by mapping the resulting BER vs. time delay the effective jitter at various BERs can be measured.

To accomplish the comparison between the two copies of the signal, the bit analyzer and the pattern generator need to run at exactly the same frequency. Usually, this is achieved by running both the pattern generator and the analyzer from
the same clock source. This is the configuration shown in Fig. 11.11: the clock output from the TX section is connected directly to the clock input of the RX section. However, the clock can also be extracted from the output of the DUT using a clock and data recovery (CDR) circuit. Using a CDR becomes necessary whenever the phase difference between the clock and data is not constant. In such cases, a one time clock-data alignment will not work and a CDR provides continuous clock-data alignment. This is usually necessary in sensitivity testing, which is the topic of the next section.

11.6.2 Sensitivity measurement

A common use of a BERT system is in measuring sensitivity and sensitivity penalties associated with various phenomena that affect sensitivity. As we noted in Chapter 9, sensitivity is defined as the minimum optical power that a receiver can work with, while maintaining a given BER. Sensitivity is the most crucial parameter that characterizes a digital receiver, and therefore measuring both sensitivity and sensitivity penalties is very important. Figure 11.12 shows a setup for measuring sensitivity using a BERT.

![Fig. 11.12. Measurement setup for sensitivity tests](image)

The electrical data output from the BERT drives an electrical to optical (EO) converter. This is essentially a “golden” transmitter that generates a well-controlled, high-quality optical signal. The optical signal is then sent through a given length of fiber. At the other side of the fiber, there is a variable optical attenuator. After the optical signal passes through the attenuator, it goes to a beam splitter which divides the optical power in half. One branch of the splitter goes to an optical power meter and the other branch goes to the DUT or the receiver whose sensitivity is being measured. Note that the optical power received by the DUT is the same as the power that goes to the power meter (assuming a 50/50 splitting...
ratio). Therefore, the power meter shows the optical power received by the DUT. The DUT converts the optical signal back to an electrical signal. The electrical signal is then applied to a clock and data recovery (CDR) unit, which extracts the clock out of the signal. The retimed data and the extracted clock are then sent back to the BERT’s receiver for error analysis.

As noted in the previous section, the BERT’s input clock can be driven directly from BERT’s output clock. However, in this setup, because the optical signal travels through fiber, it may be necessary to use a CDR to remove random phase variations due to a long stretch of fiber. In this setup, by varying the optical attenuator, the level of optical power received by the DUT can be changed, while at each power level, the BERT can measure the bit error rate. Because the occurrence of errors is a random process, to get more accurate BER results for any given power level, it is necessary to run the test long enough to acquire a sufficient number of errors. Reasonable confidence levels may require as many as 100 errors, although this may be impractical for low BERs.

Using this setup, a number of measurements can be performed. The simplest test is to measure the receiver’s sensitivity at zero dispersion. In this case, instead of a long fiber, a short fiber jumper with negligible dispersion is used and the attenuation is set to a nominal level. The link should be able to run error free at this point (BER=0). The attenuation is then increased until a relatively high error rate is observed. Next, the attenuation is reduced gradually until the BER falls below a desired level, say $10^{-12}$. The power measured by the optical power meter at this point is the sensitivity of the receiver at zero dispersion.

The receiver’s performance can also be characterized more accurately by measuring the waterfall curves. This is especially useful in estimating the sensitivity at lower BERs, where it is impractical to run a test long enough to acquire sufficient number of errors for statistical confidence. Using this setup, the received power can be scanned across a number of equally spaced power levels, and at each point the BER can be measured. The plot of the BER vs. power level is the waterfall curve corresponding to the particular parameters used in the test.

### 11.6.3 Sensitivity penalty tests

The setup shown in Fig. 11.12 can also be used for a variety of sensitivity penalty measurements. Sensitivity penalty refers to the increase in optical power needed to compensate the degrading effects of a specific phenomenon on sensitivity, measured in decibels.

A common type of sensitivity penalty is associated with dispersion and is known as dispersion penalty. As discussed in Chapter 5, when optical signals travel in fiber they suffer from a variety of dispersion effects. Thus, dispersion penalty refers to the additional amount of optical power needed to compensate sensitivity degradation due to dispersion for a given length of fiber and at a given

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6 See Chapter 9 for a discussion of waterfall curves.
wavelength. To test dispersion penalty, the sensitivity of a receiver is first characterized with a minimum length of fiber, as discussed before. Then, the fiber jumper is replaced with the desired length of fiber, usually in the form of a fiber spool. Fiber spools are available in various lengths of fiber, typically from a few kilometers up to 100 km. Next, the optical attenuator is adjusted and the sensitivity of the receiver is characterized again. Obviously, as a result of the attenuation of fiber, the power level reaching the attenuator is going to be much lower, and therefore much less attenuation is needed to reach the sensitivity point. The power difference, in dB, to achieve the same BER level with and without the fiber spool is the dispersion penalty. For instance, a 1 dB dispersion penalty means that when a fiber spool is inserted in the link, the power at the receiver must be 1 dB higher to achieve the same target BER as before. Of course, this penalty is a function of several parameters, including bit rate, wavelength, length and design of fiber, and the type of optical transmitter used in the link.

This methodology can also be used to measure other types of power penalties. For example, we can measure the sensitivity penalty as a function of the extinction ratio (ER) of the transmitter. The process will be the same: the sensitivity is characterized when the transmitter (E/O converter) is set at a given reference ER. Then the ER is changed, and for every new value of ER sensitivity is re-measured. Thus, the sensitivity penalty associated with ER changes (specifically, lower ERs) can be characterized.

11.7 Analog modulation measurements

Although a majority of fiber optic links are based on digital transmission, fiber optic links based on analog formats are still in use in several applications, including CATV and microwave feeds. In a typical analog link, several carriers or channels at different frequencies are simultaneously modulated on the optical signal. It should be noted that frequency, in this context, refers to the electrical modulation frequency, and not to the optical frequency. Thus, a composite analog signal consisting of several sub-carriers modulate a single optical carrier. In this section, we discuss the lightwave signal analyzer (LSA), which is the primary tool for analog signal analysis and measurements. We will also discuss some of the main measurements that can be performed with an LSA.

11.7.1 Lightwave signal analyzer (LSA)

In general, signals can be analyzed in time or in frequency domain. For some applications, time domain analysis is very effective, as many important features of the signal, such as rise- and fall-time, or the shape of the waveform, are inherently time domain features. This is usually the case for baseband signals. In fiber optic
communications, digital links are typically baseband, and therefore time domain analysis is the main tool in studying and characterizing them. The major tool for measurements in time domain is the oscilloscope or platforms based on an oscilloscope, such as the DCAs we considered previously.

On the other hand, for non-baseband signals where several frequency carriers exist simultaneously, usually frequency domain analysis provides a better insight into the nature of the composite signal. In RF applications, the electrical spectrum analyzer provides a convenient tool for analyzing signals in frequency domain. In principle, the same techniques can be used to analyze optical signals [34–36]. The lightwave signal analyzer (LSA) is an instrument that essentially integrates an RF spectrum analyzer with an OE converter front end. The LSA provides a convenient instrument for measurements of parameters such as modulation depth, relative intensity noise (RIN), inter-modulation interference, signal harmonics, laser relaxation frequency, and modulation frequency response [37]. These parameters are not only essential for characterization of analog signals, but are also useful tools in the analysis of digital signals in frequency domain.

![Diagram of a lightwave signal analyzer (LSA)](attachment:image.png)

**Fig. 11.13. Principals of operation of a lightwave signal analyzer (LSA)**

Figure 11.13 shows the block diagram of an LSA. The input optical signal goes through an optical attenuator which brings down the optical power to a suitable level for the instruments detector. The light is focused on an optical detector which is followed by a wideband linear amplifier. The detector recovers the electrical signal from the optical carrier, and the linear amplifier provides additional gain and provides a suitable signal for further signal processing. An optical power meter is also provided that measures the average power in the signal. The output of the linear amplifier is fed to a variable narrow band filter whose bandpass is controlled by a sawtooth or ramp generator. The output of the filter, which represents the frequency contents of the signal in a narrow band, goes through further
signal processing and ultimately drives the vertical axis of the display. The horizontal axis of the display is synchronously scanned with the bandpass of the filter, yielding the frequency spectrum of the signal.

A few points should be noted about the LSA. First, notice that the LSA is essentially a frequency spectrum analyzer shown in Fig. 11.8 preceded by an optical detector. Therefore, in principle, the same measurements that can be done with an LSA can also be done with an OE converter and a standard electrical spectrum analyzer. However, the advantage of an LSA is that it is already calibrated in terms of the optical power whereas such calibrations must be performed by the user if an OE converter along with a spectrum analyzer is used.

Another point to note is the apparent similarity between the schematic diagram of the LSA and that of the OSA shown in Fig. 11.9. However, it should be noted that in an OSA the filtering is done in the optical domain and at optical frequencies (wavelengths), as opposed to the LSA where the filtering is done in electrical domain and at much lower frequencies. Therefore, what an OSA displays should not be confused with what an LSA displays, as they represent totally different frequency domains.

11.7.2 Signal parameter measurements

Because the LSA essentially displays the signal in frequency domain, it shares many settings with ordinary electrical spectrum analyzers. Settings like start and stop frequency, and the bandwidth and reference level, are common. One difference is that in an LSA the units for the vertical axis can be chosen between optical dB or electrical dB. Because in optical to electrical conversion optical power is linearly converted to current, and because electrical power is proportional to the square of current, a distinction must be made between electrical and optical power changes. This distinction is reflected in the logarithmic units of optical dB ($\text{dB}_{\text{OPT}}$) and electrical dB ($\text{dB}_{\text{ELC}}$) where

$$
\text{dB}_{\text{OPT}} = 10 \log \frac{P_1}{P_2} = 10 \log \frac{I_1}{I_2} = \frac{1}{2} \times 20 \log \frac{I_1}{I_2} = \frac{1}{2} \times 10 \log \left( \frac{I_1}{I_2} \right)^2 = \frac{1}{2} \text{dB}_{\text{ELC}}
$$

Thus, for instance, a 10 dB change in optical power is equivalent to a 20 dB change in electrical power.

Figure 11.14 shows a representative spectrum on an LSA and the parameters that can be measured from the test. The average power of the signal is displayed on the average power bar in the left side of the screen. The modulated signal shows as a spike at the modulation frequency, $f_o$. From the display, the signal average power, modulation power, and modulation frequency can readily be meas-
ured. A particularly important parameter for analog systems is the *modulation depth*, MD, defined as

$$MD = 10\log \frac{P_{f_0}}{P_{AVG}}$$  \hspace{1cm} (11.6)

where $P_{f_0}$ is the power at the intended modulation frequency and $P_{AVG}$ is the average power in the signal. From the LSA display, MD can be measured easily as the difference between the average power and the power in the main signal.

![Fig. 11.14. Spectrum measurements using a lightwave signal analyzer (LSA)](image)

It is also common to express MD as a linear percentage, which can be calculated directly from Eq. (11.6).

When a linear system is modulated at the frequency $f_0$, the output should only have a component at $f_0$. However, lasers and optical modulators are not completely linear devices, and therefore whenever they are modulated at a particular frequency, harmonics of that frequency will also show up in the spectrum. In Fig. 11.14, the second and third harmonics of the main signal, located at $2f_0$ and $3f_0$, are marked. The *harmonic distortion* associated with the $n$th harmonic, $D_n$, is defined as

$$D_n = 10\log \frac{P_{f_n}}{P_{f_0}}$$  \hspace{1cm} (11.7)
Again, this distortion can easily be measured from the LSA’s display. For example, the 2nd harmonic distortion in dBs is simply the difference between the peak powers at $2f_0$ and $f_0$. The total harmonic distortion, THD, is defined as

$$THD = 10\log\frac{\sum P_{f_n}}{P_{f_0}}$$ (11.8)

To obtain THD, the power in each harmonic (up to a reasonable number) must be measured from the display. These powers then need to be added and divided by the power in the main signal.

LSAs can also be used to characterize inter-modulation distortion (IMD) [38]. In a perfectly linear system several signals with different carrier frequencies can be present simultaneously without affecting each other. However, any nonlinearity causes the appearance of additional signals at sum or difference frequencies. Depending on the number of carriers present, the number of spurious frequencies multiplies. Thus, if the carriers are at frequencies $f_1, f_2, \ldots, f_n$, 2nd order IMD involves terms at $f_i \pm f_j$, 3rd order IMD involves terms at $f_i \pm f_j \pm f_k$, etc. IMD can be a serious problem in CATV systems where several channels are modulated on the same optical carrier. Using an LSA, both the frequencies and powers of these beat terms as well as their relative location to the main signals can easily be determined.

Figure 11.14 also shows another important quantity, the signal’s relative intensity noise (RIN). RIN is a measure of the noise power caused by random optical intensity variations that always accompany any optical source [39–41]. Because noise is always a function of bandwidth, it is common to refer to intensity noise spectral density, in other words, the amount of noise present per hertz of bandwidth. Moreover, to remove the needed calibrations resulting from the responsivity of the detector, the noise is normalized to the average power present in the signal. In this way, any responsivity variations are cancelled out because they affect the average power and noise power in the same fashion. Thus, RIN is defined as

$$RIN(f) = 10\log\frac{P_N^2(f)}{P_{AVG}^2}$$ (11.9)

The units of RIN are dB/Hz. The reason the powers appear as squared is that noise power as measured by any receiver is proportional to the square of current, and the current is proportional to the optical power. Thus, the noise power in a receiver is proportional to the square of optical power. It can be seen from Eq. (11.9) that in general RIN is a function of frequency. For instance, the RIN in the spectrum of a laser typically reaches a maximum at the relaxation oscillation of the laser.

LSAs can be used to measure RIN [42]. As can be seen from Fig. 11.14, RIN can be measured at any given frequency as the ratio of the noise at that frequency to the average power. Note that RIN can also be integrated over a frequency range,
yielding the total intensity noise within that range. If the frequency range is narrow enough, or if the RIN is flat over the range, the total noise power can be obtained by simply multiplying the RIN spectral density by the bandwidth.

11.8 Summary

Test and measurement methodologies constitute an important part of fiber optic design and validation. In this chapter we reviewed some of the most common test instruments and measurements that are used in fiber optic links.

One of the most common measurements is optical power testing. Power is the main parameter in an optical link, at both transmitting and receiving ends. Average power measurements are done using power meters that utilize broad area detectors. These detectors are typically thermally stabilized silicon or InGaAs PIN diodes. Silicon diodes are used for shorter wavelengths, while InGaAs is usually used for longer wavelengths in the 1310 and 1550 nm window. In a standard power meter the wavelength must be set so that the equipment can use the proper calibration factor to calibrate out the wavelength dependence of the detector and report an accurate result.

An optical signal is characterized by the instantaneous optical power, and signal measurements are part of time domain measurements which require an oscilloscope-type platform capable of displaying the optical waveform. While an OE converter and a standard oscilloscope can in principle accomplish this task, the most common tool used for this purpose is a digital communication analyzer, or DCA. Usually DCAs have an optical input port which allows for a direct connection to an optical signal. Moreover, DCAs are internally calibrated to optical power, and they include software utilities for testing a variety of additional parameters. Another advantage of a DCA is that by sampling in equivalent time, it can provide an effective bandwidth much higher than what is available in a standard digital scope. Thus, a DCA provides a convenient way of measuring a large number of time domain parameters on a given optical signal. The most important of these parameters include the shape of the signal, rise- and fall-time, optical modulation amplitude, overshoot, extinction ratio, jitter, and compliance mask tests. Time domain measurements are particularly useful for analysis of digital signals, where they are sometimes grouped together as eye pattern analysis.

Frequency domain analysis is another important area for measurements. Here one needs to distinguish between two separate frequency domains: optical frequencies and signal frequencies. Optical frequencies are related to the wavelength or spectrum of the light. The most common tool for optical frequency analysis is an optical spectrum analyzer, or OSA. An OSA can display the wavelength components of an optical signal. Thus, facts like whether an optical source is single
mode or multimode can readily be determined by an OSA. Typical parameters an OSA can measure include peak wavelength(s), spectral width (SW), and side mode suppression ratio (SMSR).

The other frequency range for which a variety of parameters need to be measured is the signal or electrical frequency range. These measurements are specifically significant for analog applications, where oftentimes several channels are frequency multiplexed on a single optical carrier. In principle, a calibrated electrical spectrum analyzer preceded by an OE converter is capable of performing signal spectrum measurements. This is the operating basis of a light spectrum analyzer or LSA. An LSA has an optical input, with the convenience of providing calibration in both optical and electrical power units. Parameters that can be measured by an LSA include modulation depth (MD), distortion, total harmonic distortion (THD), inter-modulation distortion (IMD), and noise parameters such as relative intensity noise (RIN).

References

Test and Measurement


