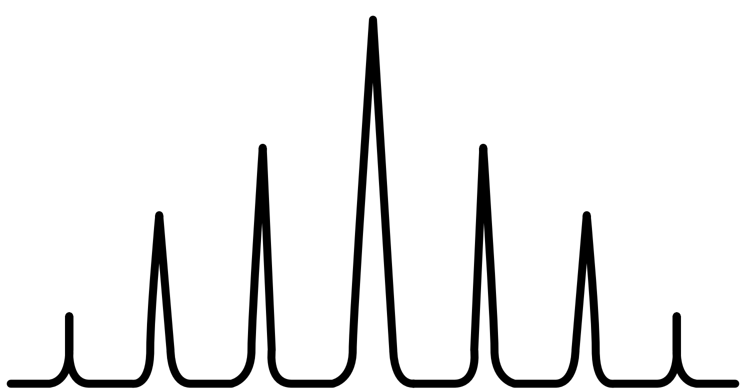
# Accurate Characterization of Source Spectra Using an Optical Spectrum Analyzer

Application Note 1550-5



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An optical spectrum analyzer performs power versus wavelength measurements, a very useful tool for characterizing broadband sources such as light emitting diodes (LEDs) and semiconductor lasers. This application note will give a descriptive overview of how each light source emits light and how the important parameters can be measured using an optical spectrum analyzer (OSA).

## Source overview

This section will give a brief overview of lasers and LED sources.

**Background**

Laser is an acronym for Light Amplification by the Stimulated Emission of Radiation. Let us look at what each term means and how they all work together to produce light.

Lasers are monochromatic sources, which in theory means they produce light at one single wavelength, but in practice there is a narrow wavelength range in which light is emitted.

Coherence is an important property of lasers. Lightwaves are coherent if they are all in phase with each other. The peaks and valleys of coherent lightwaves are aligned (Figure 1a); the peaks and valleys of incoherent lightwaves are not (Figure 1b). In order to have coherent light, all the lightwaves must have the same wavelength.

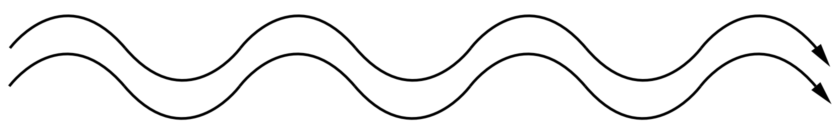


*Figure 1a. Coherent waves*

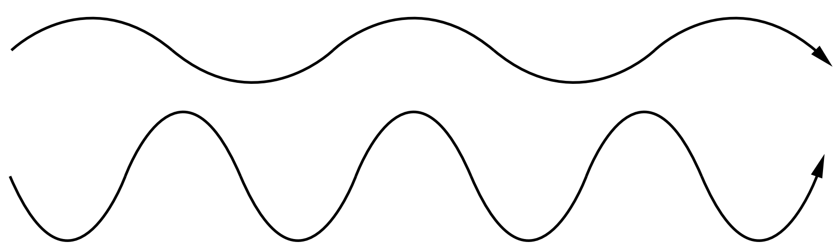


*Figure 1b. Incoherent waves*

There are many different types of lasers, but for the purposes of this application note we will look at lasers used in the fiber-optic communication technology, mainly semiconductor lasers. They are used because they are very small in size, yet can produce a few milliwatts of light power. Another important feature is that by varying their current, emitted light power can be controlled.

**Theory of operation**

Semiconductor conductivity is determined by the number of charge carriers available to conduct electric current, conductivity ranges between that of a good conductor (such as metal) and that of an insulator (such as glass). The electrons of a conductor are free to move by way of electric current, while the electrons of an insulator cannot. By adding impurities to semiconductor material we are able to influence its electrical properties and create what is referred to as p-type and n-type regions. A p-type region is doped with impurities that have fewer electrons than atoms. Therefore, “holes”, where there is room for electrons, are created. An n-type region is where impurities are added such that there is an excess of electrons. The excess holes in the p-type and electrons in the n-type regions play an important role in the process of light emission.

Figure 2 demonstrates the two energy bands that exist in semiconductor material. The conduction band is at a higher energy level where electrons can freely move about. The valence band is where the electrons form bonds with adjacent atoms. The distance between the two is called the band gap. Electrons must release energy that exceeds the band gap when they drop from the conduction band down to valence band. This energy is released as a photon of light.

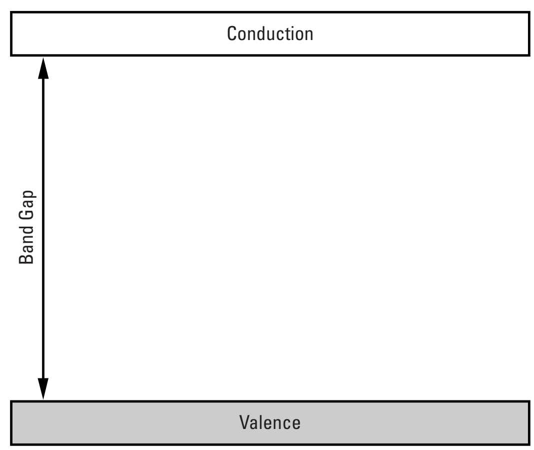



***Figure 2. Conduction band and valence band***

The wavelength of light released is proportional to the band gap energy by the following formula:

$$E_{\text{band gap}} = h \times \nu_{\text{band gap}}$$

where:
h = Plank’s constant = $6.62 \times 10^{-34}$ = J-s
$\nu$ = frequency of the photon released
E = energy of the band gap

If we substitute wavelength for frequency, plug in the value for Plank’s constant and express the energy in electron-volts, we have:

$$E_{\text{band gap}} = \frac{1.24\ \mu\text{m}}{\lambda}$$

This formula helps illustrate the dependency of the wavelength of photons and the band gap energy of the material.

Now let us take a look at how this junction of p-type and n-type material can produce light. When we forward bias the junction by applying a negative voltage to the n-type material and a positive voltage to the p-type material the following happens: Electrons from the n-type section recombine with holes in the p-type material, dropping into the valence band and releasing their energy at the junction. In materials such as GaAs this energy is primarily released as light (Figure 3).

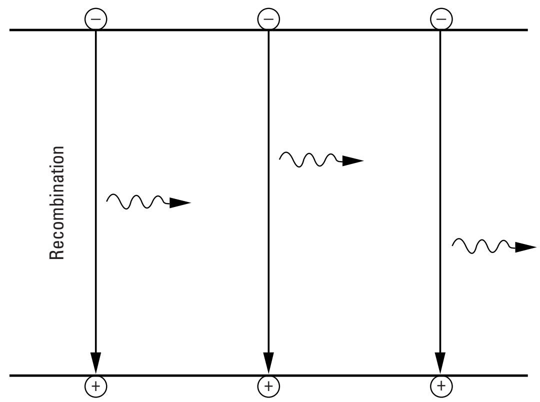



***Figure 3. An electron releases it's energy as light and recombines with a "hole".***

This light emission from the recombination of electrons and holes is the basic mechanism behind LEDs and lasers. In the case of an LED, a forward biased junction emits light by way of electron/hole pair recombination. The junction of a basic LED emits light in every direction as shown in Figure 4.

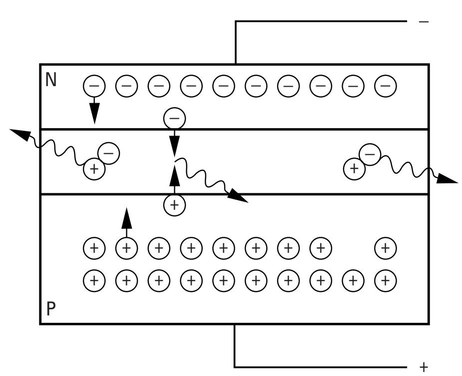


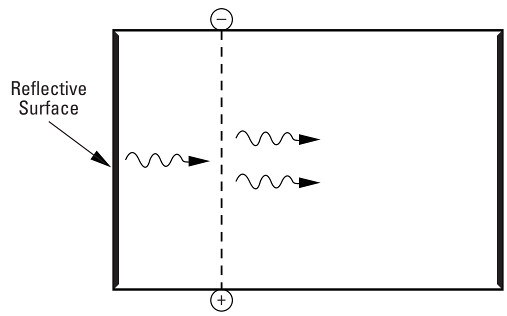

***Figure 4. An LED emits light in every direction.***

LEDs do not generate light in a manner as focused as lasers. They produce light by way of spontaneous emission and not stimulated emission.

Lasers are closely related to LEDs. They each:
• generate light by recombining electrons and holes
• have light output that is proportional to the drive current
• have an output wavelength that depends on the material's band gap

In spontaneous emission light is generated in all directions. If we use two reflective materials (e.g. mirrors) we are able to confine the photons in a region, thus stimulating other electrons to release their energy as light, in turn producing more photons. Therefore we generate light by way of stimulated emission. Due to the process of stimulated emission, laser diodes emit basically monochromatic light. The type of semiconductor material used determines the peak wavelength. For example, Gallium-Aluminum-Arsenide (GaAlAs) emits light at a peak wavelength of 850 nm. As the light reflects between the mirrors, the photons of a given wavelength are amplified by adding up constructively. The following formula demonstrates the possible wavelengths produced in a laser cavity:

$$\lambda = 2*L*n/m$$




Where
n = the refractive index in the cavity
m = an integer
L = the cavity length (mirror spacing)
$\lambda$ = peak wavelength

If the laser cavity is much longer than the wavelength, which is usually the case, more than one wavelength will be emitted (see Figure 5). Looking at the spectrum (amplitude versus wavelength) of lasers, each individual spectral laser line is referred to as one mode. This type of laser is known as a Multiple Longitudinal Mode laser (MLM). An example of a MLM type laser is the Fabry-Perot (FP) laser. When there are multiple longitudinal modes, the source has a greater spectral width. Recall from our discussion about coherence of sources, the greater the spectral width of the source is, the less coherent the source becomes.

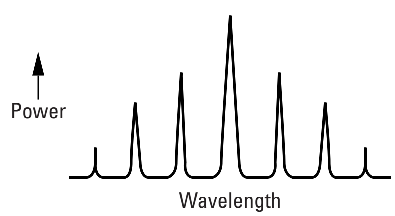



***Figure 5a. Wavelengths in multiple longitude modes***

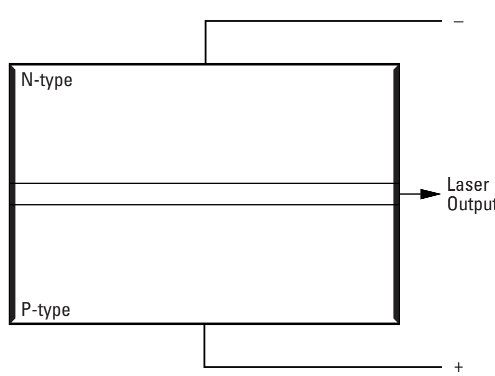



***Figure 5b. Forward bias junction of a Fabry-Perot laser***

Some applications require a laser to emit light only at a single narrow wavelength range (e.g. Dense Wavelength Division Multiplexing (DWDM) application). One approach to limit laser oscillation to a single longitudinal mode, is the distributed feedback laser (DFB). DFB lasers contain a diffraction grating that scatters light back into the active region. Feedback from the grating causes interference effects that allow oscillation only at the wavelengths at which the interference is constructive, reinforcing the generated light (Figure 6).

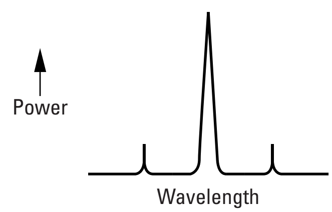



***Figure 6a. Single longitudinal mode***

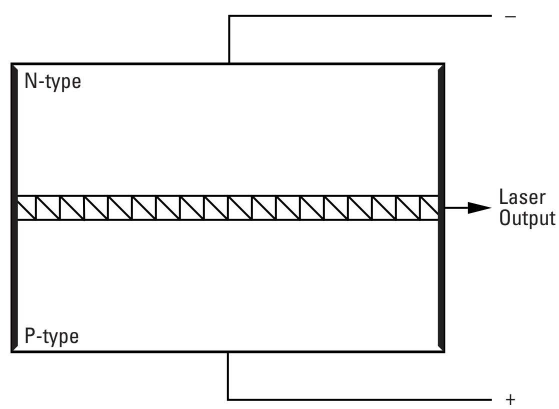



***Figure 6b. A forward bias junction of a DFB laser***

Summary of typical specification of the sources discussed is illustrated in Table 1.

***Table 1.***

| | **LED** | **Fabry-Perot** | **DFB** |
|---|---|---|---|
| **Wavelength** | 780, 850, 1300 nm | 850 or 1310 nm | 1550 nm |
| **Total power** | Few μW | Few mW | 3 to 50 mW |
| **Spectral width** | 30 to 100 nm | 3 to 20 nm | 0.08 to 0.8 pm |

## LED Measurements

There are many parameters of LEDs that are commonly measured. These parameters can be automatically measured as shown in Figure 7.

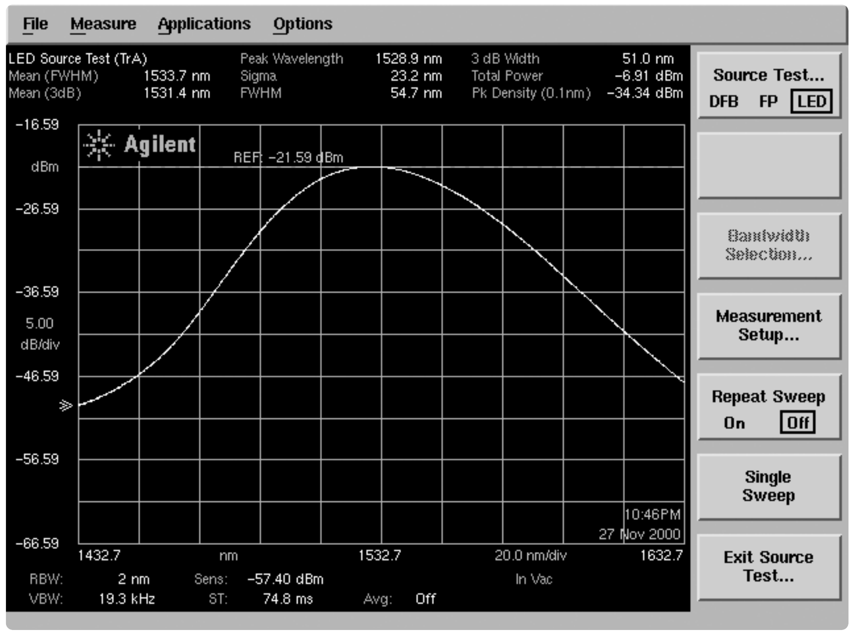



***Figure 7. Agilent 86140B optical spectrum analyzer source application LED measurement***

**Total power**

When the OSA measures an LED source, the spectral width of this source is much wider than the OSA resolution bandwidth (RBW) used. The OSA trace points represent spectral density (mW/nm) and not absolute power. Over wide wavelength ranges, the ratio of OSA slit width/wavelength also causes the effective RBW to change. Therefore the integration formula takes both dependencies into account by using internal calibration data.

$$\text{Total power, } P_o = \sum_{i=1}^{n} p_i \left(\frac{\text{trace point spacing}}{\text{RBW}}\right)$$

where:

n is the number of trace points

$p_i$ is the power of a single trace point

**3 dB width**

The 3 dB width is determined by finding the peak of the LED spectrum, and dropping down 3 dB on each side. The spectral width of the LED is determined by the separation of these two points because each has a power spectral density equal to one half the peak power spectral density.

**Peak density (1 nm)**

The power spectral density normalized to a 1 nm bandwidth of the LED at the peak wavelength is referred to as the peak density. Peak wavelength is the highest trace point and is where the peak of the LED spectrum occurs.

$$\text{Peak Density} = \frac{P_{peak}}{\text{RBW}\ (\lambda_{peak})}$$

**Sigma**
Sigma is the RMS value of spectral width of the LED based on a Gaussian distribution. The value of sigma ($\sigma$) is calculated by the following formula:

$$\text{Sigma} = \sigma = \sqrt{\sum_{i=1}^{n} \frac{p_i}{P_o} \left( \frac{\text{trace point spacing}}{\text{RBW}} \right) (\lambda_i - \bar{\lambda})^2}$$

where:

$\bar{\lambda}$ is mean wavelength (FWHM) as defined below.

$\lambda_i$ is the wavelength of a single trace point.

$p_i$ is the power of a single trace point.

$P_o$ is total power as defined.

**Mean wavelength**
This wavelength represents the center of mass for all the trace points. The total power and wavelength of each trace point is used to calculate the mean wavelength.

$$\bar{\lambda} = \sum_{i=1}^{n} \frac{p_i}{P_o} \left( \frac{\text{trace point spacing}}{\text{RBW}} \right) \lambda_i$$

**Center wavelength**
Center wavelength is the average of two wavelengths determined in the 3 dB width measurements. Typically the values of mean wavelength and center wavelength are similar.

**Full Width Half Max (FWHM)**
FWHM describes the spectral width of the half power points of the LED. Half power points are where power spectral density is one half of the peak amplitude. FWHM value and the 3 dB width values are typically very close to one another. This parameter is calculated using sigma value.

FWHM = 2.355 * $\sigma$

See Appendix 1.

## Fabry-Perot Measurements

Many of the commonly measured parameters of Fabry-Perot lasers will be discussed in this section. The optical spectrum analyzer has an automatic measurement routine for Fabry-Perot lasers. The results from the Fabry-Perot laser measurement routine are shown in Figure 8. The following parameters are often of interest and are measured by the automatic routine.

Measurement attributes are calculated using the entire set of trace points in order to provide more repeatable results. This is particularly useful for devices that exhibit significant levels of fluctuation in the distribution of optical energy among the spectral modes.

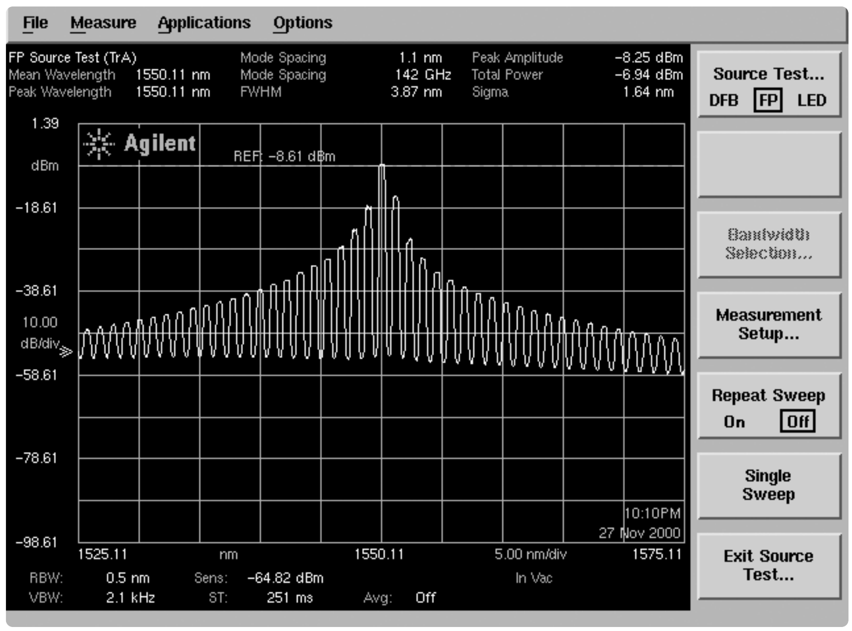



***Figure 8. Agilent 86140B optical spectrum analyzer source application Fabry-Perot measurement***

### Total power

Total power is the summation of the power at each trace point, normalized by the ratio of the trace point spacing and the resolution bandwidth.

$$\text{Total power} = \sum_{i=1}^{n} p_i \left( \frac{\text{trace point spacing}}{\text{RBW}} \right)$$

**Mean wavelength**
Mean wavelength represents the center of mass of the trace points, normalized by a ratio of the trace point spacing and the resolution bandwidth. The power and wavelength of each trace point are used to calculate the mean (FWHM) wavelength.

$$\bar{\lambda} = \sum_{i=1}^{n} \frac{p_i}{P_o} \left( \frac{\text{trace point spacing}}{\text{RBW}} \right) \lambda_i$$

**Sigma**
Sigma is the RMS value of spectral width of the LED based on a Gaussian distribution. The power and wavelength of each spectral component is used to calculate mean wavelength.

$$\text{Sigma} = \sigma = \sqrt{\sum_{i=1}^{n} \frac{p_i}{P_o} \left( \frac{\text{trace point spacing}}{\text{RBW}} \right) (\lambda_i - \bar{\lambda})^2}$$

where:

$\bar{\lambda}$ is mean wavelength (FWHM).

$\lambda_i$ is the wavelength of a single trace point.

$p_i$ is the power of a single trace point.

$P_o$ is total power as defined.

**FWHM**
Full Width Half Max describes the spectral width of the half power points of the laser, assuming a continuous, Gaussian power distribution. The half power points are where power spectral density is one half of the peak amplitude. This parameter is be calculated using the sigma value.

$$\text{FWHM} = 2.355 * \sigma$$

**Mode spacing (in nm)**
Mode spacing is the *average* wavelength spacing between the individual spectral components of the Fabry-Perot laser.

Mode spacing (in GHz) is the average frequency between the individual spectral components of the FP laser.

**Peak amplitude and peak wavelength**
The peak amplitude is the power level of the peak spectral component or mode of the Fabry-Perot laser. The wavelength at which the peak amplitude occurs is the peak wavelength.

## Distributed feedback laser measurements

The results from the DFB laser automatic measurement routine performed by an Agilent optical spectrum analyzer are shown in Figure 9. The following parameters are often of interest and are measured automatically.

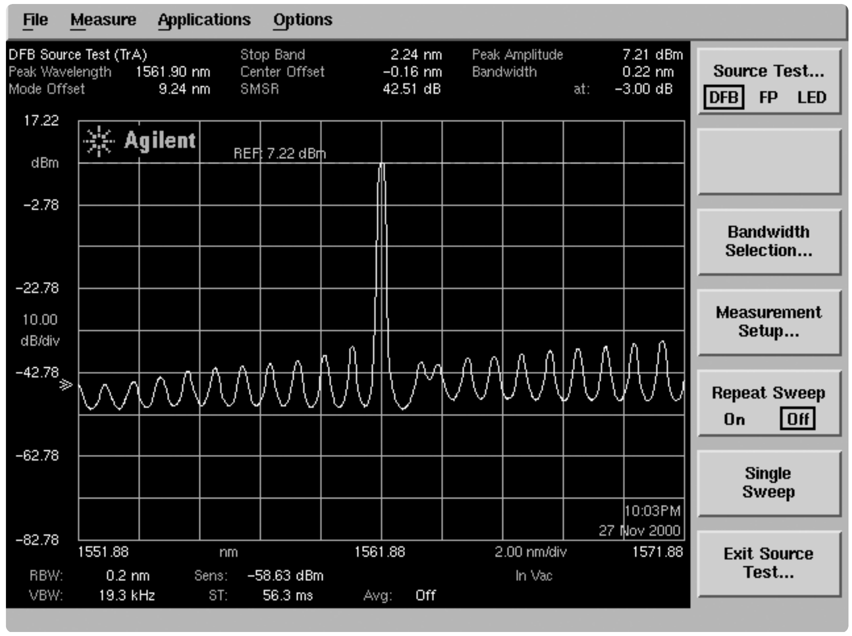



***Figure 9. Agilent 86140B optical spectrum analyzer source application DFB laser measurement***

**Peak amplitude and peak wavelength**
The power level of the main spectral component or the main mode of the laser is the peak amplitude. The wavelength at which the main mode of the laser occurs is the peak wavelength.

**Side mode suppression ratio (SMSR)**
SMSR is the amplitude difference between the main mode and the largest side mode.

**Mode offset**
Mode offset is a measure of the wavelength separation between the main mode and the largest side mode, within current trace span. Negative values indicate the next highest mode lies to the left of the main mode and positive values indicate the next highest mode lies to the right of the main mode.

**Stop band**
The wavelength spacing between the upper and lower side modes adjacent to the main mode is referred to as the stop band.

**Center offset**
This is a measurement that indicates how well the main mode is centered in the stop band. This value equals the wavelength of the main mode minus the mean of the upper and lower stop band component wavelengths.

**Bandwidth**
This is the main spectral component of the DFB laser. Due to the narrow linewidth of most DFB lasers, the result of this measurement for an unmodulated laser is limited by the resolution bandwidth of the optical spectrum analyzer.

Chirp and linewidth are important measurements for lasers, but they are beyond the scope of this application note. For more information, please refer to “Agilent Lightwave Signal Analyzers, Measure Relative Intensity Noise” product note, publication number 5091-2196E and “Agilent Lightwave Signal Analyzer Application Note”, publication number 5954-9137E for Chirp and line width measurement techniques.

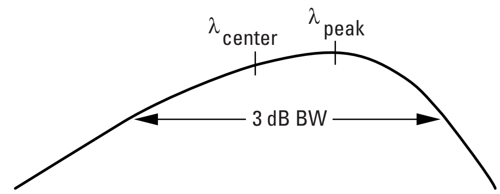
## Conclusion

There are many important parameters to consider when designing and testing light sources. As we discussed, an optical spectrum analyzer is the best, preferred and most popular tool for analyzing the spectrum of light sources. These parameters can be measured automatically using the source application of an Agilent 8614xB optical spectrum analyzer.

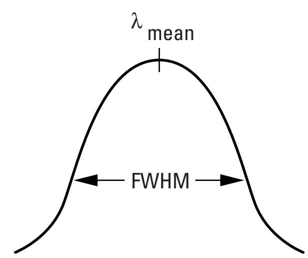
## Appendix I.

FWHM measurement assumes a Gaussian shaped trace as follow:

Trace (measured)




Gaussian

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"Understanding Fiber Optics", by Jeff Hecht, third edition, published by Prentice Hall, ISBN 0-13-956145-5.

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