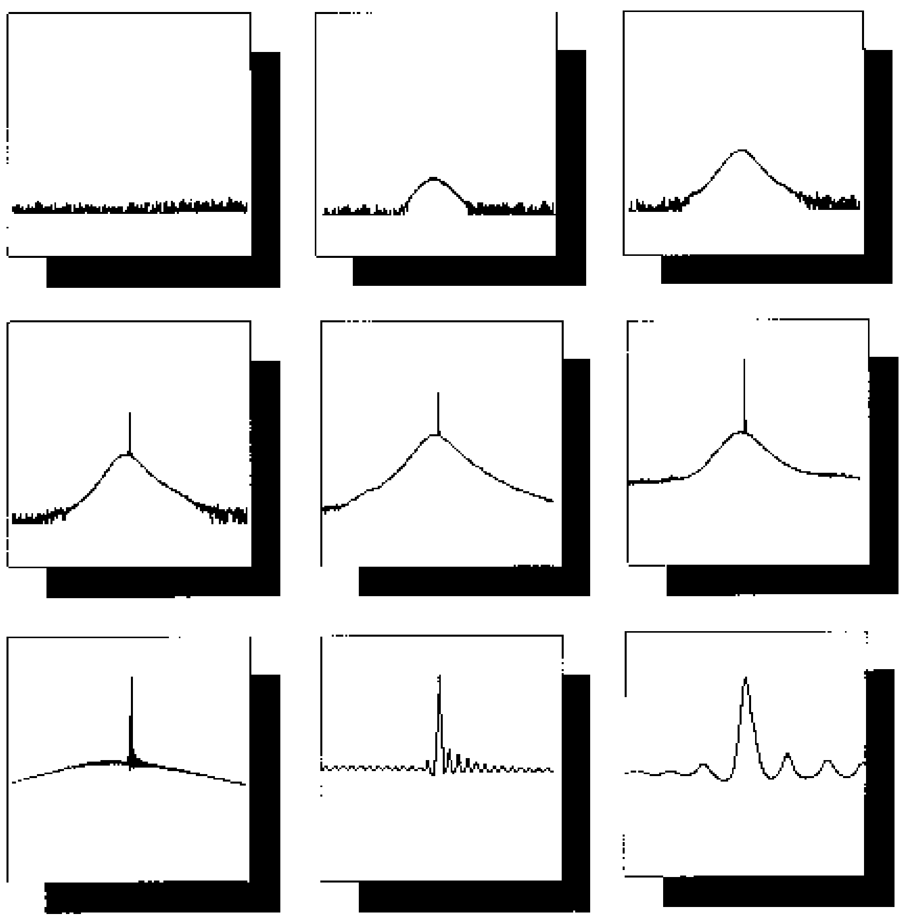
Hewlett Packard

Optical Spectrum Analysis

Application Note 1550-4

Optical Spectrum Analysis Basics



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Introduction

This application note is intended to provide the reader with a basic understanding of optical spectrum analyzers, their technologies, specifications, and applications. Chapter 1 describes interferometer-based and diffraction-grating-based optical spectrum analyzers. Chapter 2 defines many of the specified performance parameters of diffraction-g rating-based optical spectrum analyzers and discusses the relative merits of the single monochromator, double monochromator, and double-pass-monochromator-based optical spectrum analyzers. For readers familiar with electrical spectrum analyzers, some of the same terms are used, but with different definitions. The final chapter of this application note describes light emitting diodes (LEDs) and semiconductor diode lasers, and their parameters that are measured by optical spectrum analyzers.

Optical spectrum analysis

Optical spectrum analysis is the measurement of optical power as a function of wavelength. Applications include testing laser and LED light sources for spectral purity and power distribution, as well as testing transmission characteristics of optical devices.

The spectral width of a light source is an important parameter in fiber-optic communication systems due to chromatic dispersion, which occurs in the fiber and limits the modulation bandwidth of the system. The effect of chromatic dispersion can be seen in the time domain as pulse broadening of a digital waveform. Since chromatic dispersion is a function of the spectral width of the light source, narrow spectral widths are desirable for high-speed communication systems.

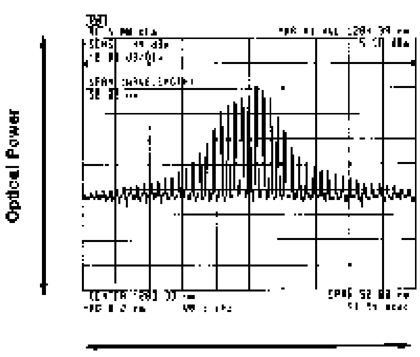

Figure 1. Optical spectrum analyzer measurement of a Fabry-Perot laser.

Figure 1 shows the spectrum of a Fabry-Perot laser. The laser is not purely monochromatic; it consists of a series of evenly spaced coherent spectral lines with an amplitude profile determined by the characteristics of the gain media.

Optical spectrum analyzers can be divided into three categories: diffraction-grating-based and two interferometer-based architectures, the Fabry-Perot and Michelson interferometer-based optical spectrum analyzers. Diffraction-grating-based optical spectrum analyzers are capable of measuring spectra of lasers and LEDs. The resolution of these instruments is variable, typically ranging from 0.1 nm to 5 or 10 nm. Fabry-Perot-interferometer-based optical spectrum analyzers have a fixed, narrow resolution, typically specified in frequency, between 100 MHz and 10 GHz. This narrow resolution allows them to be used for measuring laser chirp, but can limit their measurement spans much more than the diffraction-grating-based optical spectrum analyzers. Michelson-interferometer-based optical spectrum analyzers, used for direct coherence-length measurements, display the spectrum by calculating the Fourier transform of a measured interference pattern.

Chapter I
Types of optical spectrum analyzers

Basic block diagram

A simplified optical spectrum analyzer block diagram is shown in figure 2. The incoming light passes through a wavelength-tunable optical filter (monochromator or interferometer) which resolves the individual spectral components. The photodetector then converts the optical signal to an electrical current proportional to the incident optical power. An exception to this description is the Michelson interferometer, which is not actually an optical filter.

The current from the photodetector is converted to a voltage by the transimpedance amplifier and then digitized. Any remaining signal processing, such as applying correction factors, is performed digitally. The signal is then applied to the display as the vertical, or amplitude, data. A ramp generator determines the horizontal location of the trace as it sweeps from left to right. The ramp also tunes the optical filter so that its resonant wavelength is proportional to the horizontal position. A trace of optical power versus wavelength results. The displayed width of each mode of the laser is a function of the spectral resolution of the wavelength-tunable optical filter.

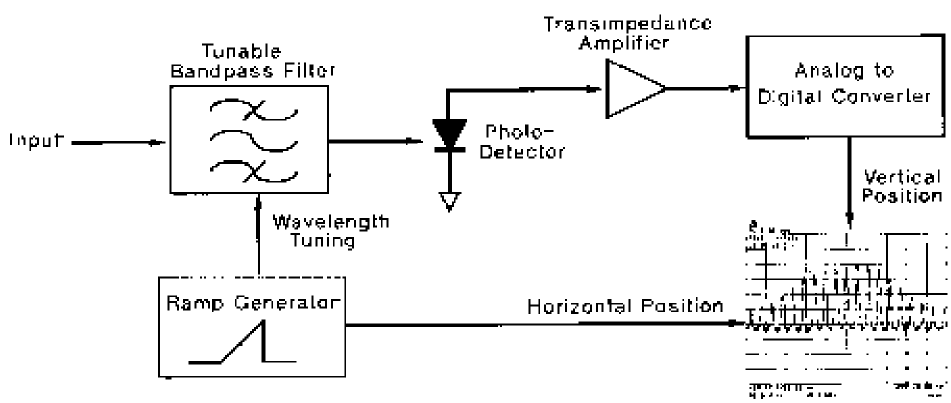

**Figure 2.
Simplified optical spectrum analyzer block diagram.**

Interferometer-based optical spectrum analyzers

Fabry-Perot interferometers

The Fabry-Perot interferometer, shown in figure 3, consists of two highly reflective, parallel mirrors that act as a resonant cavity which filters the incoming light. The resolution of Fabry-Perot-interferometer-based optical spectrum analyzers, dependent on the reflection coefficient of the mirrors and their spacing, is typically fixed, and the wavelength is varied by changing the spacing between the mirrors by a very small amount.

The advantage of the Fabry-Perot interferometer is its very narrow spectral resolution, which allows it to measure laser chirp. The major disadvantage is that at any one position multiple wavelengths will be passed by the filter. (The spacing between these responses is called the free spectral range.) This problem can be solved by placing a monochromator in cascade with the Fabry-Perot interferometer to filter out all power outside the interferometer's free spectral range about the wavelength of interest.

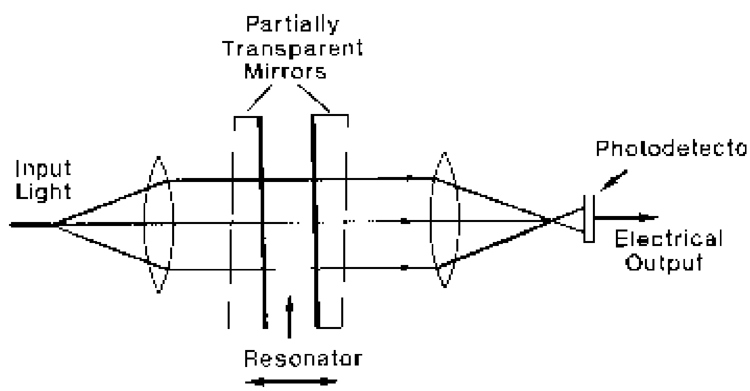

Figure 3. Fabry-Perot-interferometer-based optical spectrum analyzer.

Michelson interferometers

The Michelson interferometer, shown in figure 4, is based on creating an interference pattern between the signal and a delayed version of itself. The power of this interference pattern is measured for a range of delay values. The resulting waveform is the autocorrelation function of the input signal. This enables the Michelson-interferometer-based spectrum analyzer to make direct measurements of coherence length, as well as very accurate wavelength measurements. Other types of optical spectrum analyzers cannot make direct coherence-length measurements.

To determine the power spectra of the input signal, a Fourier transform is performed on the autocorrelation waveform. Because no real filtering occurs, Michelson-interferometer-based optical spectrum analyzers cannot be put in a span of zero nanometers, which would be useful for viewing the power at a given wavelength as a function of time. This type of analyzer also tends to have less dynamic range than diffraction-grating-based optical spectrum analyzers.

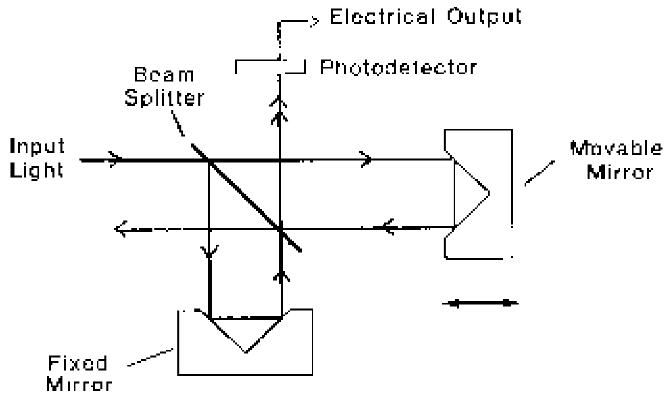

Figure 4.
Michelson-interferometer-based optical spectrum analyzer.

Diffraction-grating-based optical spectrum analyzers

The most common optical spectrum analyzers use monochromators as the tunable optical filter. In the monochromator, a diffraction grating (a mirror with finely spaced corrugated lines on the surface) separates the different wavelengths of light. The result is similar to that achieved with a prism. Figure 5 shows what a prism-based optical spectrum analyzer might look like. The prism separates the different wavelengths of light, and only the wavelength that passes through the aperture reaches the photodetector. The angle of the prism determines the wavelength to which the optical spectrum analyzer is tuned, and the size of the aperture determines the wavelength resolution.

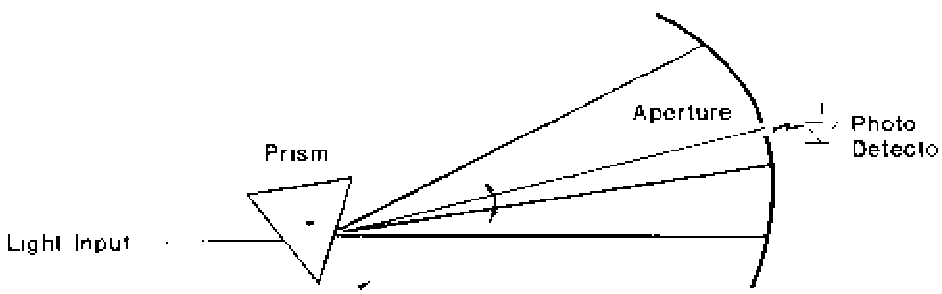

Figure 5.
Concept of prism-based optical spectrum analyzer. Diffraction gratings are used instead of prisms because diffraction gratings provide greater separation among wavelengths of light.

Diffraction gratings are used instead of prisms because they provide a greater separation of wavelengths, with less attenuation. This allows for better wavelength resolution.

A diffraction grating is a mirror with grooves on its surface, as shown in figure 6. The spacing between grooves is extremely narrow, approximately equal to the wavelengths of interest. When a parallel light beam strikes the diffraction grating, the light is reflected in a number of directions.

The first reflection is called the zero-order beam (m=O), and it reflects in the same direction as it would if the diffraction grating were replaced by a plane mirror. This beam is not separated into different wavelengths and is not used by the optical spectrum analyzer.

The first-order beam (m=l) is created by the constructive interference of reflections off each groove. For constructive interference to occur, the path-length difference between reflections from adjacent grooves, must equal one wavelength. If the input light contains more than one wavelength component, the beam will have some angular dispersion; that is, the reflection angle for each wavelength must be different in order to satisfy the requirement that the path-length difference off adjacent grooves is equal to one wavelength. Thus, the optical spectrum analyzer separates different wavelengths of light.

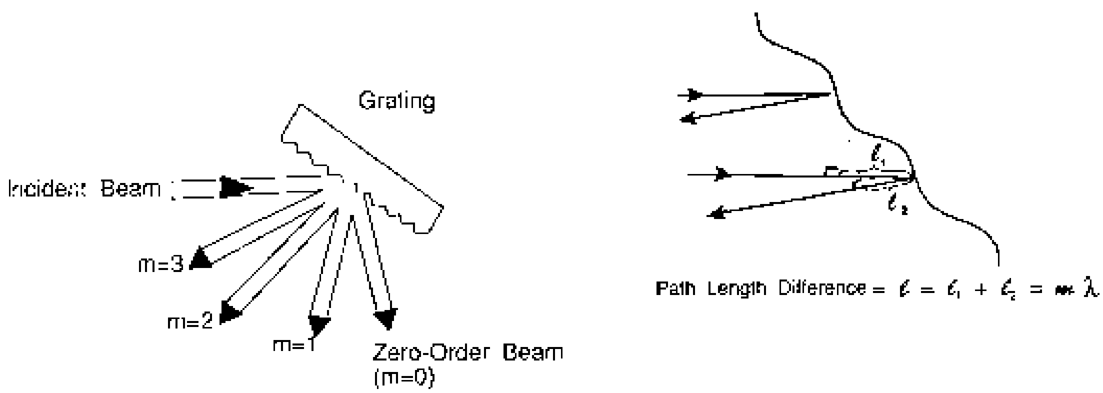

Figure 6.
The diffraction grating separates the input beam into a number of output beams. Within each output beam, except the zero order beam, different wavelengths are separated.

For the second-order beam (m=2), the path-length difference from adjacent grooves equals two wavelengths. A three wavelength difference defines the third-order beam, and so on.

Optical spectrum analyzers utilize multiple-order beams to cover their full wavelength range with narrow resolution.

Figure 7 shows the operation of a diffraction-grating-based optical spectrum analyzer. As with the prism-based analyzer, the diffracted light passes through an aperture to the photodetector. As the diffraction grating rotates, the instrument sweeps a range of wavelengths, allowing the diffracted light -- the particular wavelength depends on the position of the diffraction grating -- to pass through to the aperture. This technique allows the coverage of a wide wavelength range.

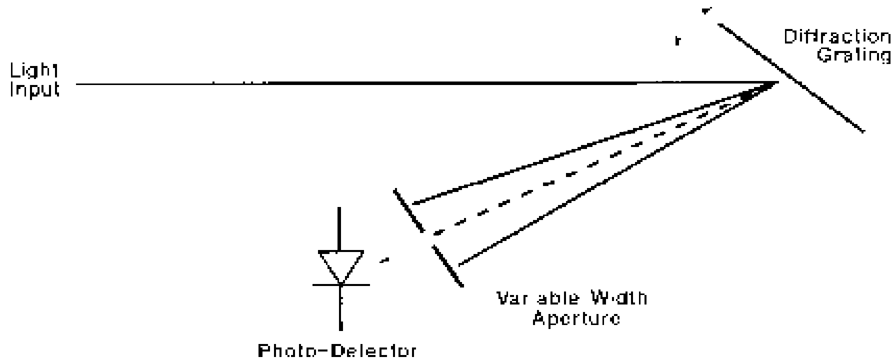

Figure 7.
Diffraction-grating-based optical spectrum analyzer.

Single Monochromator

Diffraction-grating-based optical spectrum analyzers contain either a single monochromator, a double monochromator, or a double-pass monochromator. Figure 8 shows a single-monochromator-based instrument. In these instruments, a diffraction grating is used to separate the different wavelengths of light. The second concave mirror focuses the desired wavelength of light at the aperture. The aperture width is variable and is used to determine the wavelength resolution of the instrument.

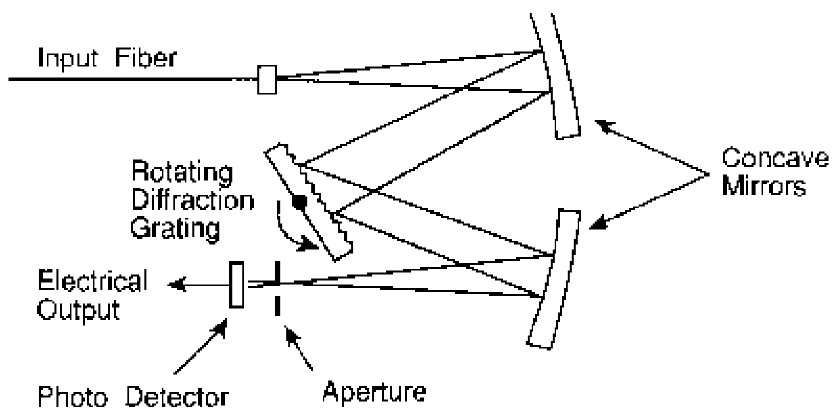

Figure 8.
Single-monochromator-based optical spectrum analyzer.

Double Monochromator

Double monochromators, such as shown in figure 9, are sometimes used to improve on the dynamic range of single monochromator systems. Double monochromators are equivalent to a pair of sweeping filters. While this technique improves dynamic range, double monochromators typically have reduced span widths due to the limitations of monochromator-to-monochromator tuning match; double monochromators also have degraded sensitivity due to losses in the monochromators.

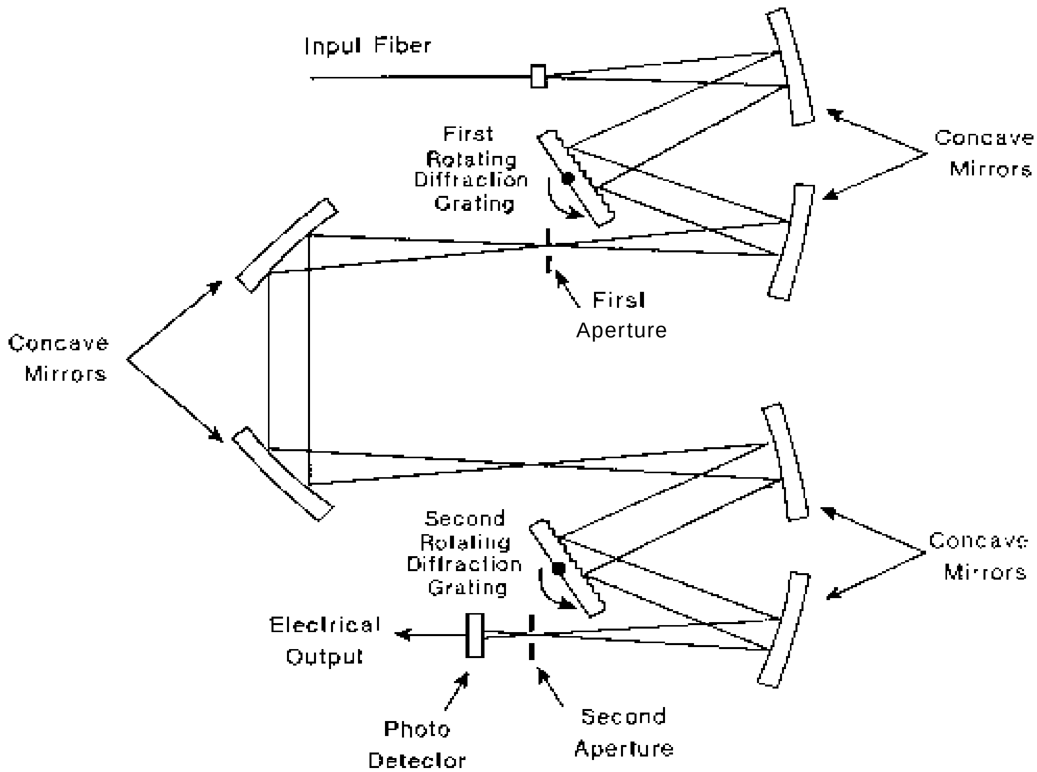

Figure 9.
Double-monochromator-based optical spectrum analyzer.

Double-Pass Monochromator
Hewlett-Packard's HP 71450B/1B/2B optical spectrum analyzers use a unique wavelength-selection scheme -- the double-pass monochromator. The double-pass monochromator provides the dynamic-range advantage of the double monochromator and the sensitivity and size advantages of the single monochromator. Figure 10 shows the double-pass monochromator.

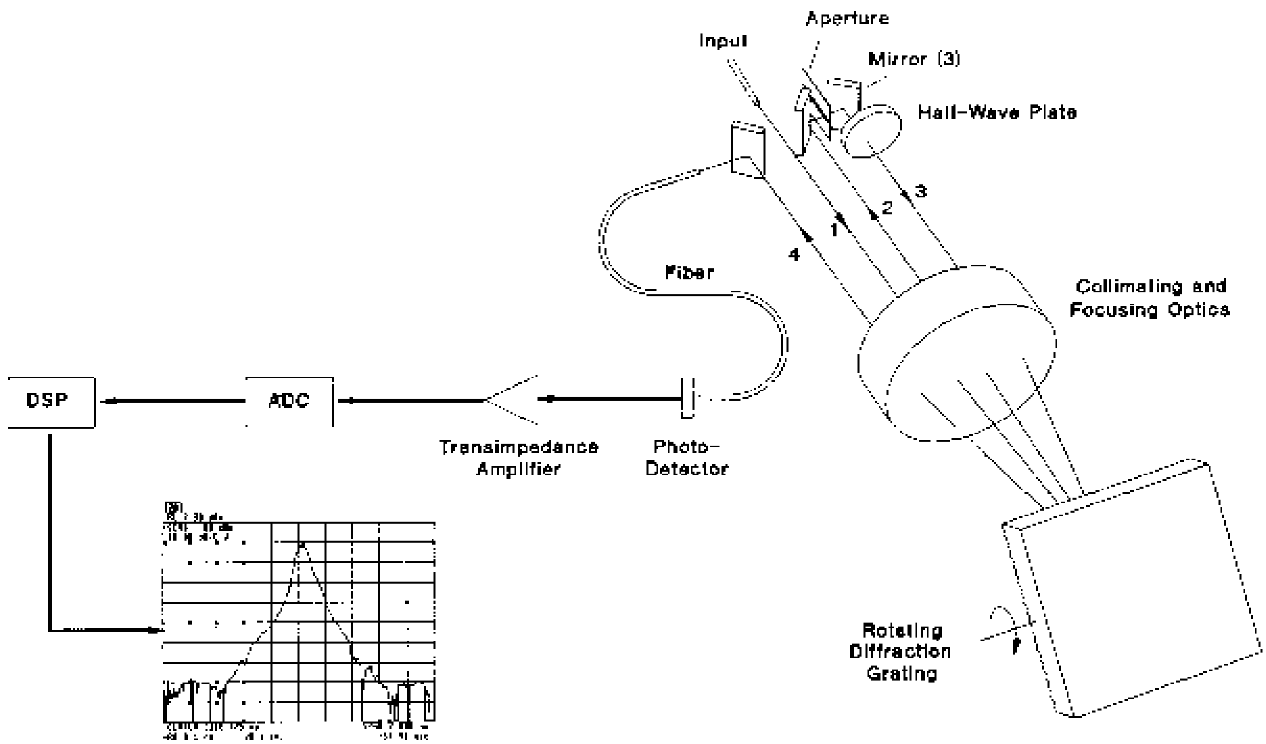

Figure 10.
Block diagram of double-pass-monochromator optical spectrum analyzer.

Wavelength Selective Filtering
The first pass through the double-pass monochromator is similar to conventional single monochromator systems. In figure 10, the input beam (1) is collimated by the optical element and dispersed by the diffraction grating. This results in a spatial distribution of the light, based on wavelength. The diffraction grating is positioned such that the desired wavelength (2) passes through the aperture. The width of the aperture determines the bandwidth of wavelengths allowed to pass to the detector. Various apertures are available to provide resolution bandwidths of 0.08 nm and 0.1 nm to 10 nm in a 1, 2, 5 sequence. In a single-monochromator instrument, a large photodetector behind the aperture would detect the filtered signal.

The Second Pass

This system shown in figure 10 is unique in that the filtered light (3) is sent through the collimating element and diffraction grating for a second time. During this second pass through the monochromator, the dispersion process is reversed. This creates an exact replica of the input signal, filtered by the aperture. The small resultant image (4) allows the light to be focused onto a fiber which carries the signal to the detector. This fiber acts as a second aperture in the system. The implementation of this second pass results in the high sensitivity of a single monochromator, the high dynamic range of a double monochromator, as well as polarization insensitivity (due to the half-wave plate). This process is discussed more completely in Chapter 2.

Wavelength Tuning and Repeatability

Tuning

The wavelength tuning of the optical spectrum analyzer is controlled by the rotation of the diffraction grating. Each angle of the diffraction grating causes a corresponding wavelength of light to be focused directly at the center of the aperture. In order to sweep across a given span of wavelengths, the diffraction grating is rotated, with the initial and final wavelengths of the sweep determined by the initial and final angles. To provide accurate tuning, the diffraction-grating angle must be precisely controlled and very repeatable over time.

Tuning Techniques

Conventional optical spectrum analyzers use gear reduction systems to obtain the required angular resolution of the diffraction grating.

To overcome problems associated with gear driven systems, Hewlett-Packard optical spectrum analyzers have a direct-drive motor system which provides very good wavelength accuracy (1 nm), wavelength reproducibility and repeatability (0.005 nm), and fast tuning speed.

Wavelength Repeatability vs. Wavelength Reproducibility

Wavelength reproducibility, as defined for most optical spectrum analyzers, specifies wavelength tuning drift in a one-minute period. This is specified with the optical spectrum analyzer in a continuous sweep mode and with no changes made to the tuning.

In addition to wavelength reproducibility, Hewlett-Packard specifies an additional parameter: wavelength repeatability. Wavelength repeatability is the accuracy to which the optical spectrum analyzer can be retuned to a given wavelength after a change in tuning.

Wavelength Resolution Bandwidth

Full Width at Half Maximum

The ability of an optical spectrum analyzer to display two signals closely spaced in wavelength as two distinct responses is determined by the wavelength resolution. Wavelength resolution is, in turn, determined by the bandwidth of the optical filter, whose key components are the monochromator aperture, photodetector fiber, input image size, and quality of the optical components.

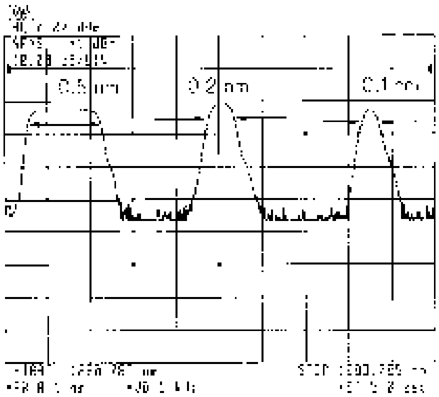

Figure 11.
Three Fabry-Perot laser spectral components, each measured with a different resolution bandwidth.

The wavelength resolution is specified as the filter bandwidth at the half-power level, referred to as full width at half maximum. This is a good indication of the optical spectrum analyzer's ability to resolve equal amplitude signals. The HP 71450B/1B/2B optical spectrum analyzers have selectable filters of 0.08 nm and 0.1 nm to 10 nm in a 1, 2, 5 sequence, which make it possible to select sutticient resolution for most measurements.

Figure 11 shows three spectral components of a Fabry-Perot laser measured with three different resolution bandwidths. In each case, the actual spectral width is much less than the resolution bandwidth. As a result, each response shows the filter shape of the optical spectrum analyzer's resolution-bandwidth filter. The main component of the filter is the aperture. The physical width of the light beam at the aperture is a function of the input image size. If the physical width of the light beam at the aperture is narrow compared to the aperture itself, the response will have a flat top, as shown in figure 11 for the 0.5 nm resolution bandwidth. This occurs as the narrow light beam is swept across the aperture. The narrower resolution-bandwidth filters result in a rounded response because the image size at the aperture is similar in size to the aperture. Each response onscreen is the convolution of the aperture with the optical image.

Dynamic Range

Based on Filter Shape Factor

For many measurements, the various spectral components to be measured are not equal amplitude. One such example is the measurement of side-mode suppression of a distributed feedback (DFB) laser, as shown in figure 12. For this measurement, the width of the filter is not the only concern. Filter shape (specified in terms of dynamic range) is also important. The advantage of double monochromators over single monochromators is that double-monochromator filter skirts are much steeper, and they allow greater dynamic range for the measurement of a small spectral component located very close to a large spectral component. The double-pass monochromator has the same dynamic-range advantages as the double monochromator.

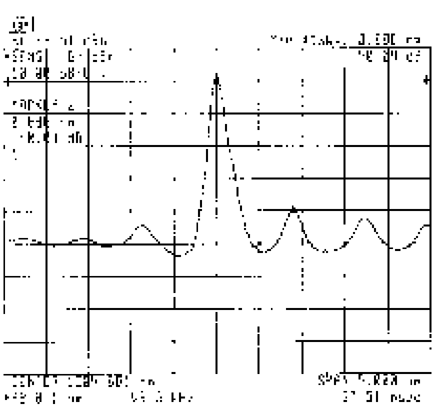

Figure 12.
DFB Laser side mode suppression measurement.

Dynamic range is commonly specified at 0.5 nm and 1.0 nm offsets from the main response. Specifying dynamic range at these offsets is driven by the mode spacings of typical DFB lasers. A –60 dB dynamic-range specification at 1.0 nm and greater indicates that the optical spectrum analyzer's response to a purely monochromatic signal will be –60 dBc or less at offsets of 1.0 nm and greater. In addition to the filter shape factor, this specification is also an indication of the stray light level and the level of spurious responses within the analyzer.

Typical dynamic range limits of single, double, and double-pass monochromators are shown in figure 13. These limits are superimposed over a display of a measurement of a spectrally pure laser, made with the double-pass monochromator. Because of their greater dynamic range, double and double-pass monochromators can be used to measure much greater side-mode suppression ratios than can single monochromators.

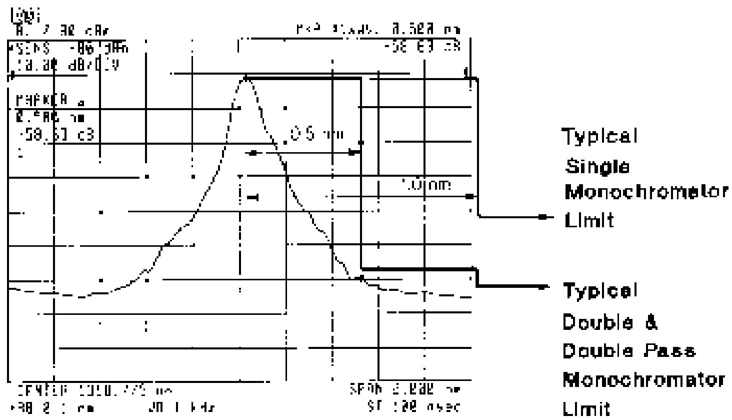

Figure 13. Typical dynamic range limits for single, double, and double-pass monochromators.

Sensitivity

Directly Settable by User

Sensitivity is defined as the minimum detectable signal or, more specifically, 6 times the rms noise level of the instrument. Sensitivity is not specified as the average noise level, as it is for RF and microwave spectrum analyzers, because the average noise level of optical spectrum analyzers is 0 watts (or minus infinity dBm). (For more information on the differences between electrical and optical spectrum analyzers, see the appendix). Figure 14 shows the display of a signal that has an amplitude equal to the sensitivity setting of the optical spectrum analyzer.

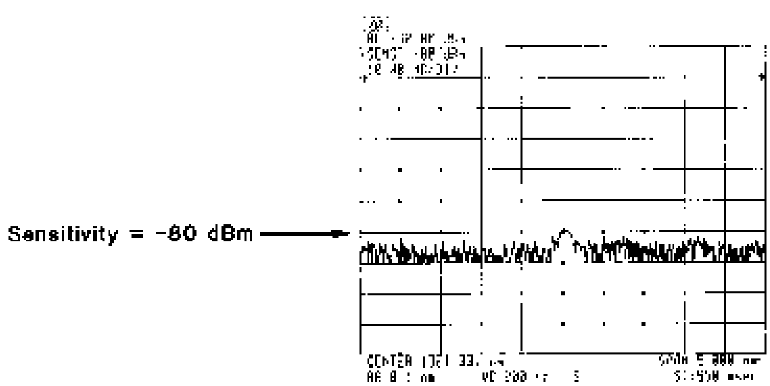

Figure 14. Display of signal with amplitude equal to sensitivity level.

Single monochromators typically have sensitivity about 10 to 15 dB better than that of double monochromators due to the additional loss of the second diffraction grating in double monochromators. The double-pass monochromator has the same high sensitivity of single monochromators even though the light strikes the diffraction grating twice. The high sensitivity is made possible by the half-wave plate and the use of a smaller photodetector that has a lower noise equivalent power (NEP). The sensitivity improvement from the half-wave plate is discussed in the section, “Polarization Insensitivity," later in this chapter.

Sensitivity can be set directly on Hewlett-Packard optical spectrum analyzers, which then automatically adjust to optimize the sweep time, while maintaining the desired sensitivity. Sensitivity is coupled directly to video bandwidth, as shown in figure 15. As the sensitivity level is lowered, the video bandwidth is decreased (or the transimpedance amplifier gain is increased), which results in a longer sweep time, since the sweep time is inversely proportional to the video bandwidth. The sweep time can be optimized because the video bandwidth is continuously variable and just enough video filtering can be performed. This avoids the problem of small increases in sensitivity causing large increases in sweep time, which can occur when only a few video bandwidths are available in fairly large steps.

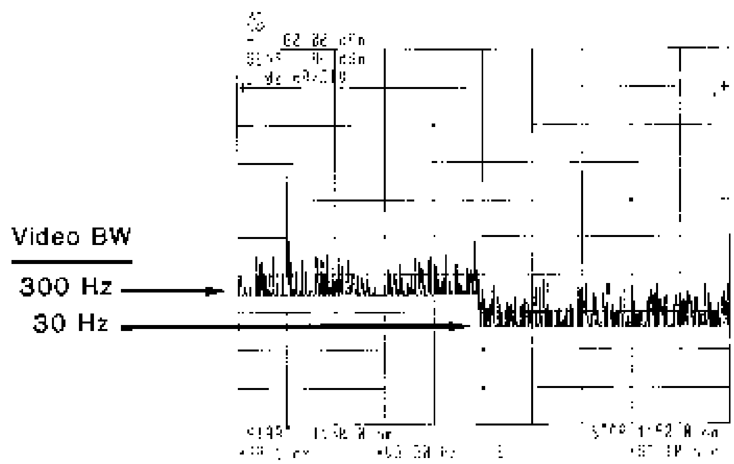

Figure 15. Video bandwidth directly affects sensitivity.

Tuning Speed

Sweep-Time Limits

For fast sweeps, sweep time is limited by the maximum tuning rate of the monochromator. The direct-drive-motor system allows for faster sweep rates when compared with optical spectrum analyzers that use gear-reduction systems to rotate the diffraction grating.

For high-sensitivity sweeps that tend to be slower, the small photodetector and continuously variable digital video bandwidths allow for faster sweep times. The small photodetector reduces the sweep time because it has a lower NEP than the large photodetectors used

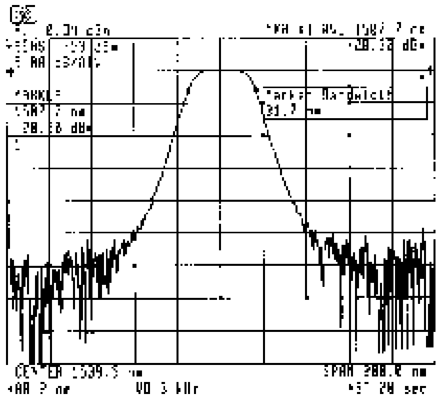

Figure 16.
Improved sweep times, even for high sensitivity measurements that traditionally result in slow sweeps. This plot shows the normalized output of an Erbium amplifier filter that was stimulated by a white-light source.

in other optical spectrum analyzers. Lower NEP means that for a given sensitivity level, a wider video bandwidth can be used, which results in a faster sweep. (Sweep time is inversely proportional to the video bandwidth for a given span and resolution bandwidth.)

The continuously variable digital video bandwidths improve the sweep time for high-sensitivity sweeps in two ways. First, the implementation of digital video filtering is faster than the response time required by narrow analog filters during autoranging. Second, since the video bandwidth can be selected with great resolution, just enough video filtering can be employed, resulting in no unnecessary sweep-time penalty due to using a narrower video bandwidth than is required. Figure 16 shows a 20 second filter-response measurement. This filter, for an Erbium amplifier, was stimulated by a white-light source, and figure 16 shows the normalized response. The purpose of this filter is to attenuate light at the pump wavelength, while passing the amplified laser output of 1550 nm. Due to the low power level of white-light sources, this measurement requires great sensitivity, which traditionally has resulted in long sweep times.

Autoranging Mode

Autoranging mode is activated automatically for sweeps with amplitude ranges greater than about 50 dB. The amplitude range is determined by the top of the screen and the sensitivity level set by the user. With the autoranging mode activated, when the signal amplitude crosses a threshold level, the sweep pauses, the transimpedance amplifier's gain is changed to reposition the signal in the measurement range of the analyzer's internal circuitry, and the sweep continues. This repositioning explains the pause that can occasionally be seen in a sweep with a wide measurement range.

Chopper Mode

The main purpose of the chopper mode is to provide stable sensitivity levels for long sweep times, which could otherwise be affected by drift of the electronic circuitry. The desired stability is achieved by automatically chopping the light to stabilize electronic drift in sweeps of 40 seconds or greater. The effect is to sample the noise and stray light before each trace point and subtract them from the trace point reading. In all modes of operation, Hewlett-Packard optical spectrum analyzers zero the detector circuitry before each sweep.

Improved dynamic range is another benefit of sampling the stray light before each trace point. For measurements requiring the greatest dynamic range possible, some improvement can be obtained with the use of the chopper mode. While this mode does improve dynamic range, it is not required for the analyzers to meet their dynamic range specifications.

Figure 17 shows the improved dynamic range obtained by activating the chopper mode.

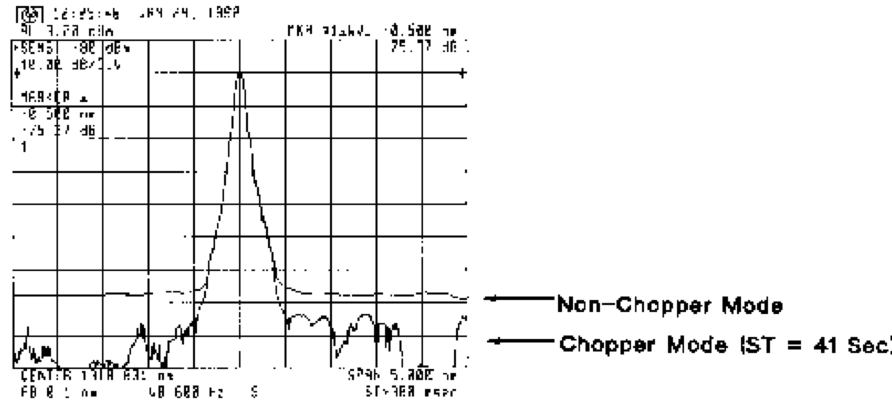

Figure 17.
Dynamic range improvement from chopper mode.

Polarization Insensitivity

Polarization

According to electromagnetic theory, electric- and magnetic-field vectors must be in the plane perpendicular to the direction of wave propagation in free space. Within this plane, the field vectors can be evenly distributed in all directions and produce unpolarized light. A surface emitting LED provides a good illustration of the phenomena. The electric field, however, can be oriented in only one direction, as with a laser. This is called linear polarization and is shown in figure 18. Alternatively, the electric field can rotate by 360 degrees within one wavelength, such as with the vector sum of two orthogonal linearly polarized waves. Circular polarization is the term that describes two orthogonal waves that are of equal amplitude.

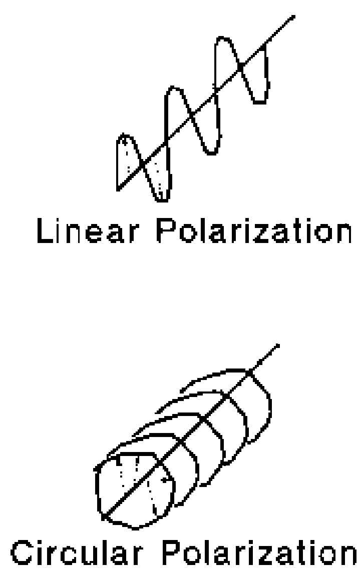

Figure 18.
Linear and circular polarization

Cause of Polarization Sensitivity

Polarization sensitivity results from the reflection loss of the diffraction grating being a function of the polarization angle of the light that strikes it. As the polarization angle of the light varies, so does the loss in the monochromator. Polarized light can be divided into two components. The component parallel to the direction of the lines on the diffraction grating is often labeled P polarization and the component perpendicular to the direction of the lines on the diffraction grating is often labeled S polarization. The loss at the diffraction grating differs for the two different polarizations, and each loss varies with wavelength. At each wavelength, the loss of P polarized light and the loss of S polarized light represent the minimum and maximum losses possible for linearly polarized light. At some wavelengths, the loss experienced by P polarized light is greater than that of S polarized light, while at other wavelengths, the situation is reversed. This polarization sensitivity results in an amplitude uncertainty for measurements of polarized light and is specified as polarization dependence.

Solution to Polarization Sensitivity Problem

To reduce polarization sensitivity, a half-wave plate has been placed in the path of the optical signal between the first and second pass in the double-pass monochromator, as shown in figure 19. This half-wave plate rotates the components of polarization by 90 degrees. The result is that the component of polarization that received the maximum attenuation on the first pass will receive the minimum attenuation on the second pass, and vice versa.

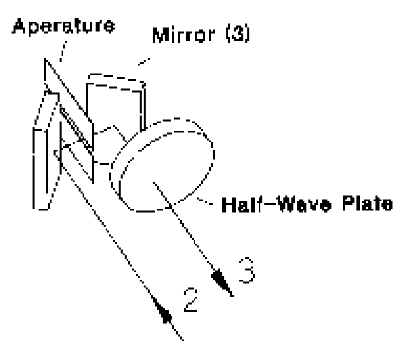

**Figure 19.
Half-wave plate in the double-pass monochromator reduces polarization sensitivity and improves amplitude sensitivity.**

The result is reduced polarization sensitivity, as the total loss is the product of the minimum and maximum losses, regardless of polarization. Also, because the monochromator is polarization insensitive, the monochromator output of the HP 71451B is also polarization insensitive. Other polarization-sensitivity-compensation techniques are currently in use, but none have a monochromator output that is polarization insensitive. This monochromator output allows the monochromator portion of the optical spectrum analyzer to be used as a preselector filter for other signal-processing applications.

Improved amplitude sensitivity over double monochromators is another benefit of the half-wave plate. This improved sensitivity is because the signal polarization can never hit the maximum loss angle twice, as can occur with a double monochromator. This benefit, along with the low NEP of the photodetector, gives Hewlett-Packard optical spectrum analyzers the high sensitivity of single-monochromator-based analyzers while maintaining the high dynamic range of double-monochromator-based analyzers.

Input Coupling

Variety of Input Connectors Available

At the input of Hewlett-Packard optical spectrum analyzers is a short, straight piece of 62.5 µm core-diameter graded-index fiber. Connection to this fiber is made using one of the interfaces listed below. The input end of this fiber is flat. The other end of this fiber, in the monochromator, is angled to help minimize reflections.

Hewlett-Packard optical spectrum analyzers use user-exchangeable connector interfaces, which allow easy cleaning of the analyzer's input connector as well as the use of different connector types with the same analyzer. Available connector interfaces include FC/PC, D4, SC, Diamond HMS-10, DIN 47256, Biconic, and ST.

Chapter 3
Light Emitting Diodes and Semiconductor Diode Lasers

This chapter describes the operation of light emitting diodes (LEDs) and semiconductor diode lasers and describes their parameters which are commonly measured with optical spectrum analyzers.

Hewlett-Packard optical spectrum analyzers have built-in measurement routines that are designed to measure automatically many parameters of LEDs, Fabry-Perot lasers, and distributed feedback (DFB) lasers. These automatic measurement routines are discussed in this chapter.

Light Emitting Diodes (LEDs)

Light emitting diodes produce light with a wide spectral width, and when used in fiber optic communication systems, they can be modulated at frequencies up to about 200 MHz. LEDs have the advantages of low temperature sensitivity and no sensitivity to back reflections. Additionally, the incoherent emitted light is not sensitive to optical interference from reflections.

A light emitting diode generates light by spontaneous emission. This occurs when an electron in a high energy conduction band changes to a low energy valence band, as shown in figure 20.
The energy lost by the electron is released as a photon. For a given material, discrete energy levels represent the different orbital states of the electron. The energy of the released photon is equal to the energy lost by the electron, and the wavelength of the emitted photon is a function of its energy. As a result, the wavelength of the photon is determined by the material used to make the LED.

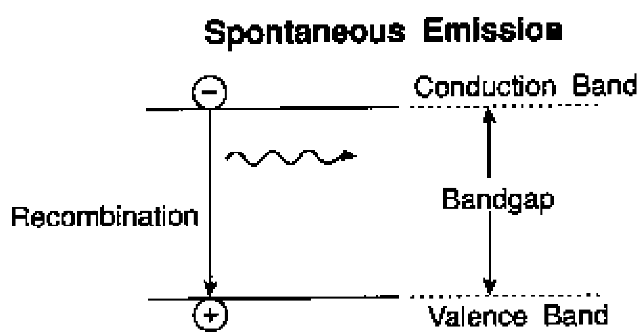

Figure 20. Spontaneous emission. Movement of electrons from conduction band to valence band during recombination.

The difference in energy between the conduction band and the valence band is called the bandgap energy (E.) and is expressed in units of either joules or electron volts (eV). The wavelength of the emitted photon is determined by the bandgap energy as shown:

$$\lambda = \frac{h \cdot C}{E_g} = \frac{1.24\ \mu m}{E_g\ (eV)}$$

Where h (Planck's constant) is equal to $6.62 * 10^{-34}$ Ws^2, c (Speed of light) is $2.998 * 10^8$ m/s, and E_g (bandgap energy of the material) is expressed in units of joules. Alternatively, E_g can be expressed in units of electron volts. (1 electron volt is equal to $1.6022*10^{-19}$ joule.)

These conduction-band electrons are generated by a forward bias placed on the p-n junction of the diode. A forward-biased p-n junction is shown in figure 21. The material on the n-layer side of the junction has immobile positive charges evenly distributed throughout the layer, with mobile negative charges, or electrons, responsible for electrical current flow. Conversely, the material on the player side of the junction has immobile negative charges evenly distributed throughout the layer, with mobile positively charged holes, actually locations of missing electrons, responsible for electrical current flow.

At the junction, the mobile electrons from the n-layer and the mobile holes from the player recombine, producing photons. While LEDs in use today actually consist of multiple layers of semi-conductor material, rather than just the two shown in figure 21, the light-generation process is the same.

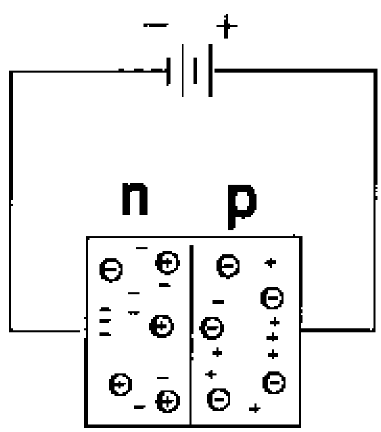

Figure 21. Diagram of forward biased p-n junction showing the location of immobile charges and mobile current camers.

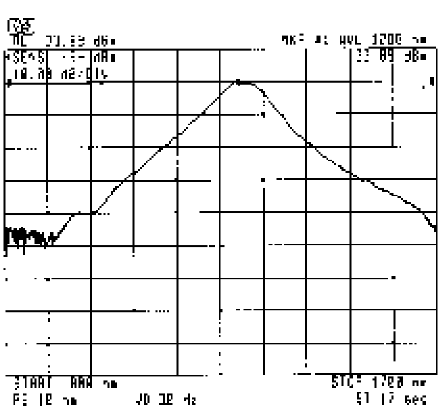

Figure 22. Spectrum of light emitting diode.

Figure 22 shows the spectrum of a light emitting diode. As can be seen, this process results in a broad distribution of wavelengths centered about the wavelength calculated by the above equation. The spectral width is often specified by the full width at half maximum (half-power points of the spectrum). Typical values for full width at half maximum range from 20 nm to 80 nm for LEDs.

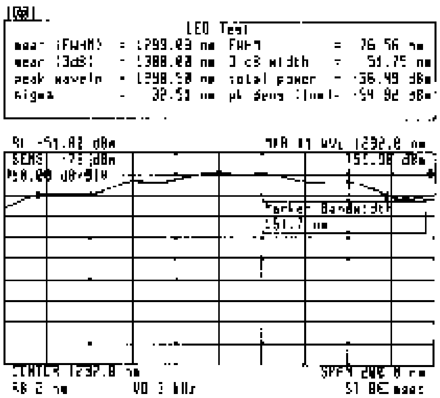

Figure 23. Results of automatic LED measurement routine.

Including those parameters mentioned above, there are many parameters of light-emitting diodes that are commonly measured. These parameters can be automatically measured as shown in figure 23. Some parameters (such as mean wavelength and spectral width) have two methods by which they can be measured. One method takes into account the entire spectrum, while the other takes into account only a few points of the spectrum. The definition of each parameter is described below.

Total Power - The summation of the power at each trace point, normalized by the ratio of the trace point spacing/resolution bandwidth. This normalization is required because the spectrum of the LED is continuous, rather than containing discrete spectral components (as a laser does).

$$\text{Total Power} = \sum_{i=1}^{N} \mathbf{P}_i \cdot \left(\frac{\text{Trace point spacing}}{\text{Resolution bandwidth}} \right) = \mathbf{P}_o$$

Mean (FWHM) - This wavelength represents the center of mass of the trace points. The power and wavelength of each trace point are used to calculate the mean (FWHM) wavelength.

$$\text{Mean (FWHM)} = \overline{\lambda} = \sum_{i=1}^{N} \mathbf{P}_i \cdot \left(\frac{\text{Trace point spacing}}{\text{Resolution bandwidth}} \right) \cdot \lambda_i / \mathbf{P}_o$$

Sigma - An rms calculation of the spectral width of the LED based on a Gaussian distribution. The power and wavelength of each trace point are used to calculate sigma.

$$\text{Sigma} = \sigma = \sqrt{ \sum_{i=1}^{N} \mathbf{P}_i \left(\frac{\text{Trace point spacing}}{\text{Resolution bandwidth}} \right) \cdot (\lambda_i - \overline{\lambda})^2 / \mathbf{P}_o }$$

FWHM *(Full Width at Half Maximum)* - Describes the spectral width of the half-power points of the LED, assuming a continuous, Gaussian power distribution. The half-power points are those where the power-spectral density is one-half that of the peak amplitude.

FWHM = 2.355 * Sigma

3 dB Width - Used to describe the spectral width of the LED based on the separation of the two wavelengths that each have a power-spectral density equal to one-half the peak power-spectral density. The 3 dB width is determined by finding the peak of the LED spectrum, and dropping down 3 dB on each side.

Mean (3 dB) - The wavelength that is the average of the two wavelengths determined in the 3 dB width measurement.

Peak Wavelength - The wavelength at which the peak of the LED's spectrum occurs.

Density (1 nm) - The power-spectral density (normalized to a 1 nm bandwidth) of the LED at the peak wavelength.

Distribution Trace - A trace can be displayed that is based on the total power, power distribution, and mean wavelength of the LED. This trace has a Gaussian spectral distribution and represents a Gaussian approximation to the measured spectrum.

Fabry-Perot Lasers

Lasers are capable of producing high output powers and directional beams. When used in fiber-optic communication systems, semi-conductor lasers can be modulated at rates up to about 10 GHz. However, lasers are sensitive to temperature and back reflections. Additionally, the coherent emitted light is sensitive to optical interference from reflections.

Of the two laser types discussed in this chapter, the Fabry-Perot is the simpler. It is, however, more susceptible to chromatic dispersion when used in fiber-optic systems because it has a wider spectral bandwidth.

A Fabry-Perot laser differs from a light-emitting diode in that it generates light mainly by stimulated emission. Some of the photons are generated by spontaneous emission, as described for the LED. But the majority of the photons are generated by stimulated emission, where photons trigger additional electron-hole recombinations, resulting in additional photons as shown in figure 24. A stimulated photon travels in the same direction and has the same wavelength and phase as the photon that triggered its generation.

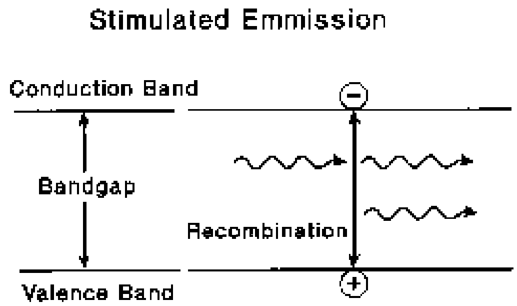

Figure 24. Stimulated emission is the release of a photon, due to an electron-hole recombination, triggered by another photon.

Stimulated emission can be thought of as the amplification of light (laser is an acronym for light amplification by stimulated emission of radiation). As one photon passes through the region of holes and conduction band electrons, additional photons are generated. If the material were long enough, enough photons might be generated to produce a significant amount of power at a single wavelength.

An easier way to build up power is to place a reflective mirror at each end of the region just described so that the photons travel back and forth between the mirrors, building up the number of photons with each trip. These mirrors form a resonator, which is a requirement for laser operation.

Laser operation has two additional requirements. One requirement is that for stimulated emission to occur, a greater number of conduction-band electrons than valence-band electrons must be present. This is called a population inversion. It is achieved by forcing a high current density in the active layer of the diode structure. The second requirement is that the gain exceeds the losses due to absorption and radiation. Part of the radiation losses is the amount of light released at the laser output. As the current increases, the gain increases. The current for which stimulated emissions occur is the threshold current of the laser.

The resonator is often just highly reflective, cleaved surfaces on the edges of the diode. As the light reflects between the mirrors, the photons of a given wavelength must be in phase to add constructively. The resonator acts as a Fabry-Perot interferometer, as shown in figure 25, in that only that light for which the resonator spacing is an integral number of half wavelengths will add constructively. As a result, the spectrum of a Fabry-Perot laser contains multiple discrete-wavelength components, as shown in figure 26.

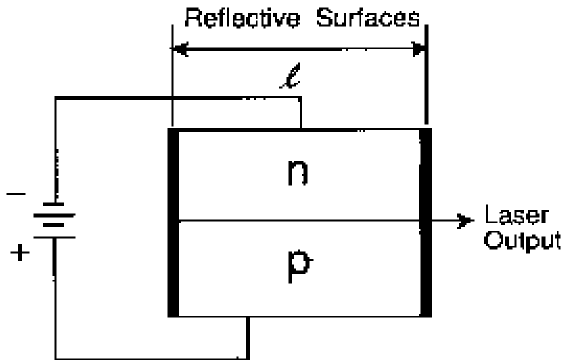

Figure 25. Reflective surfaces at the edges of laser diode act as a Fabry-Perot type resonator.

The possible wavelengths produced by the resonator are given by:

$$f_{res} = \frac{m\,c}{2\,l\,n}$$

Where m = integer

c = speed of light

l = length of cavity

n = refactive index of cavity

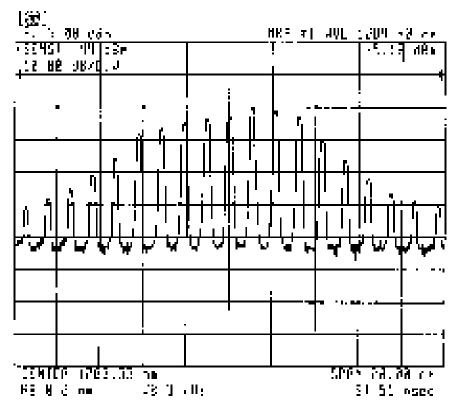

Figure 26. Spectrum of Fabry-Perot laser.

The actual output power at each of these wavelengths is determined by the laser gain and mirror reflectivity at that wavelength. As with the LED, the center wavelength can be determined from the bandgap energy. The separation between the different wavelengths, mode spacing, can be determined from the separation of the mirrors as follows:

$$\text{Mode Spacing} = \frac{c}{2\,l\,n}\ (\text{Hz}) = \frac{\lambda^2}{2\,l\,n}\ (\text{m})$$

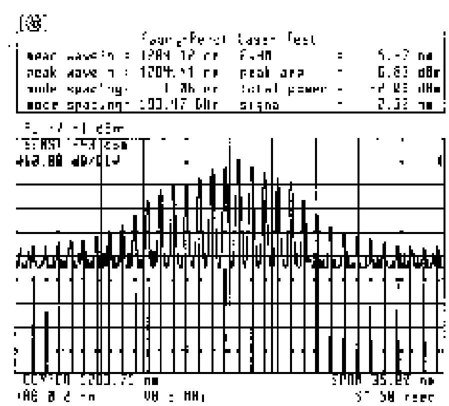

Figure 27. Results of automatic Fabry-Perot laser measurement routine.

Many of the commonly measured parameters of Fabry-Perot lasers are discussed above. As with the LED, Hewlett-Packard optical spectrum analyzers have an automatic measurement routine for Fabry-Perot lasers. The results from the Fabry-Perot laser measurement routine are shown in figure 27. The following parameters are often of interest and are measured by the automatic routine.

Total Power - The summation of the power in each of the displayed spectral components, or modes, that satisfy the peak-excursion criteria. (See below for discussion of peak-excursion criteria.)

$$\text{Total Power} = \sum_{i=1}^{N} \mathbf{P}_i = \mathbf{P}_o$$

Mean Wavelength - Represents the center of mass of the spectral components onscreen. The power and wavelength of each spectral component is used to calculate the mean wavelength.

$$\text{Mean Wavelength} = \sum_{i=1}^{N} \mathbf{P}_i \cdot \lambda_i / \mathbf{P}_o = \overline{\lambda}$$

Sigma - An rms calculation of the spectral width of the Fabry-Perot Laser based on a Gaussian distribution. The power and wavelength of each spectral component is used to calculate the mean wavelength.

$$\text{Sigma} = \sigma = \sqrt{\sum_{i=1}^{N} \mathbf{P}_i \, (\lambda_i - \lambda)^2 / \mathbf{P}_o}$$

FWHM (Full Width at Half Maximum) - Describes the spectral width of the half-power points of the Fabry-Perot laser, assuming a continuous, Gaussian power distribution. The half-power points are those where the power-spectral density is one-half that of the peak amplitude.

FWHM = 2.355 * Sigma

Mode Spacing - The average wavelength spacing between the individual spectral components of the Fabry-Perot laser.

Peak Amplitude - The power level of the peak spectral component of the Fabry-Perot laser.

Peak Wavelength - This is the wavelength at which the peak spectral component of the Fabry-Perot laser occurs.

Peak Excursion - The peak excursion value (in dB) can be set by the user and is used to determine which onscreen responses are accepted as discrete spectral responses. To be accepted, each trace peak must rise, and then fall, by at least the peak excursion value about a given spectral component. Setting the value too high will result in failure to include the smaller responses near the noise floor. Setting the value too low will cause all spectral components to be accepted, but unwanted responses, including noise spikes and the second peak of a response with a slight dip, could be erroneously included.

Peaks Function - The peaks function displays a vertical line from the bottom of the grid to each counted spectral component of the signal. This function is useful to determine if an adjustment of the peak excursion value is required.

Distribution Trace - A trace is displayed that is based on the total power, individual wavelengths, mean wavelength, and mode spacing of the laser. This trace has a Gaussian spectral distribution and represents a continuous approximation to the actual, discrete spectrum.

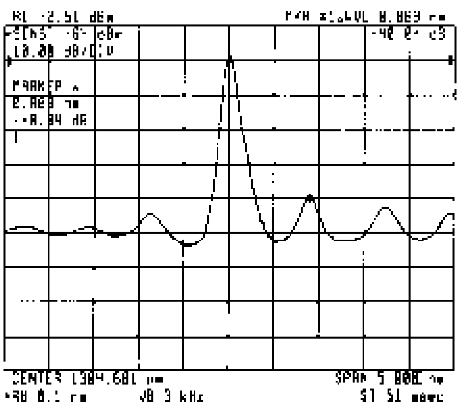

Figure 28. Spectrum of a distributed feedback laser.

Distributed Feedback (DFB) Lasers

Distributed feedback lasers are similar to Fabry-Perot lasers, except that all but one of their spectral components are significantly reduced as shown in figure 28. Because its spectrum has only one line, the spectral width of a distributed feedback laser is much less than that of a Fabry-Perot laser. This greatly reduces the effect of chromatic dispersion in fiber-optic systems, allowing for greater transmission bandwidths.

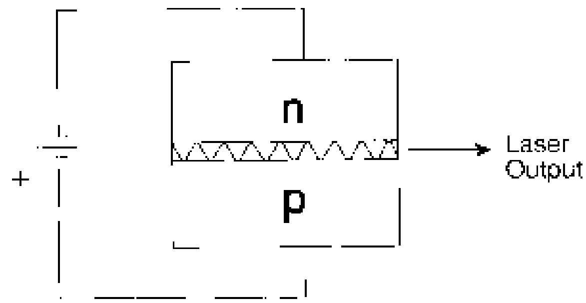

Figure 29.
Distributed feedback lasers use a series of reflecting ridges to reduce the amplitude of all but one of the spectral components of the laser.

The distributed feedback laser utilizes a grating, a series of corrugated ridges, along the active layer of the semiconductor, as shown in figure 29. Rather than using just the two reflecting surfaces at the ends of the diode, as a Fabry-Perot laser does, the distributed feedback laser uses each ridge of the corrugation as a reflective surface. At the resonant wavelength, all reflections from the different ridges add in phase. By having much smaller spacings between the resonator elements, compared to the Fabry-Perot laser, the possible resonant wavelengths are much farther apart in wavelength, and only one resonant wavelength is in the region of laser gain. This results in the single laser wavelength.

The ends of the diode still act as a resonator, however, and produce the lower amplitude side modes seen in figure 28. Ideally, the dimensions are selected so that the end reflections add in phase with the grating reflections. In this case, the main mode will occur at a wavelength halfway between the two adjacent side modes; any deviation is called a mode offset. Mode offset is measured as the difference between the main-mode wavelength and the average wavelength of the two adjacent side modes.

The amplitude of the largest side mode is typically between 30 and 50 dB lower than the main spectral output of the laser. Because side modes are so close to the main mode (typically between 0.5 nm and 1 nm) the dynamic range of an optical spectrum analyzer determines its ability to measure them. Dynamic range is specified at offsets of 0.5 nm and 1.0 nm from a large response. Hewlett-Packard optical spectrum analyzers, for example, specify a dynamic range of –55 dBc at offsets of 0.5 nm and greater, and –60 dBc at offsets of 1.0 nm and greater. This indicates the amplitude level of side modes that can be detected at the given offsets.

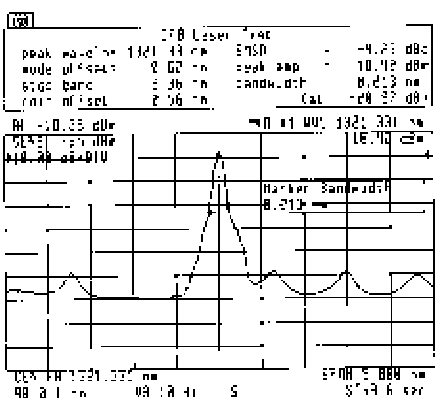

Figure 30.
Results of automatic DFB laser measurement routine.

As with the LED and Fabry-Perot laser, Hewlett-Packard optical spectrum analyzers have an automatic measurement routine for distributed feedback lasers. The results from the DFB laser measurement routine are shown in figure 30. The following parameters are often of interest and are measured by the automatic routine.

Peak Wavelength - The wavelength at which the main spectral component of the DFB laser occurs.

Side Mode Suppression Ratio (SMSR) - The amplitude difference between the main spectral component and the largest side mode.

Mode Offset - Wavelength separation (in nanometers) between the main spectral component and the SMSR mode.

Peak Amplitude - The power level of the main spectral component of the DFB laser.

Stop Band - Wavelength spacing between the upper and lower side modes adjacent to the main mode.

Center Offset - Indicates how well the main mode is centered in the stop band. This value equals the wavelength of the main spectral component minus the mean of the upper and lower stopband component wavelengths.

Bandwidth - Measures the displayed bandwidth of the main spectral component of the DFB Laser. The amplitude level, relative to the peak, that is used to measure the bandwidth can be set by the user. In figure 30, the amplitude level used is –20 dBc. Due to the narrow line width of lasers, the result of this measurement for an unmodulated laser is strictly dependent upon the resolution-bandwidth filter of the optical spectrum analyzer. With modulation applied, the resultant waveform is a convolution of the analyzers filter and the modulated laser's spectrum, causing the measured bandwidth to increase. The combination of the modulated reading and unmodulated reading can be used to determine the bandwidth of the modulated laser and the presence of chirp.

Peak Excursion - The peak excursion value (in dB) can be set by the user and is used to determine which three onscreen responses will be accepted as discrete spectral responses. To be counted, the trace must rise, and then fall, by at least the peak excursion value about a given spectral component. Setting the value too high will result in failure to count small responses near the noise floor.

Peaks Function - The peaks function displays a vertical line from the bottom of the grid to each counted spectral component of the signal. This function is useful to determine if an adjustment of the peak excursion value is required.

References

1. C. Hentschel, Hewlett-Packard Fiber Optics Handbook, January 1988.

2. C. B. Hitz, Understanding Laser Technology, Second Edition, PennWell Publishing Company, Tulsa OK 1991.

Appendix
Optical and Microwave Spectrum Analyzers Compared

Key Functional Blocks

The key signal processing blocks of the Hewlett-Packard optical spectrum analyzers are shown in figure 31. The aperture is the primary resolution-bandwidth filter, and it determines the full-width-half-maximum bandwidth of the analyzer. Secondary filtering is performed by the coupling of the optical signal onto the fiber. This filter has a wider bandwidth than the primary filter, but it is very effective at increasing the filter shape at offsets greater than 0.3 nm from the full-width at half-maximum points on the resolution bandwidth filter. While the secondary filter has very little impact on the full-width at half-maximum bandwidth, it does provide the rejection at close offsets required to give the double-pass monochromator the high dynamic range of double monochromators.

Following the filters is the photodetector, which acts as a power detector on the light signal. The photodetector converts the optical power to an electrical current. This electrical current is converted to a voltage by the transimpedance amplifier. For the purpose of determining the internal noise level and sensitivity of the optical spectrum analyzer, the transimpedance amplifier is the main noise source. The electrical signal is digitized after the transimpedance amplifier. The video bandwidth filter, which helps to determine the sensitivity, is implemened digitally, and then the conversion to logarithmic amplitude values is performed.

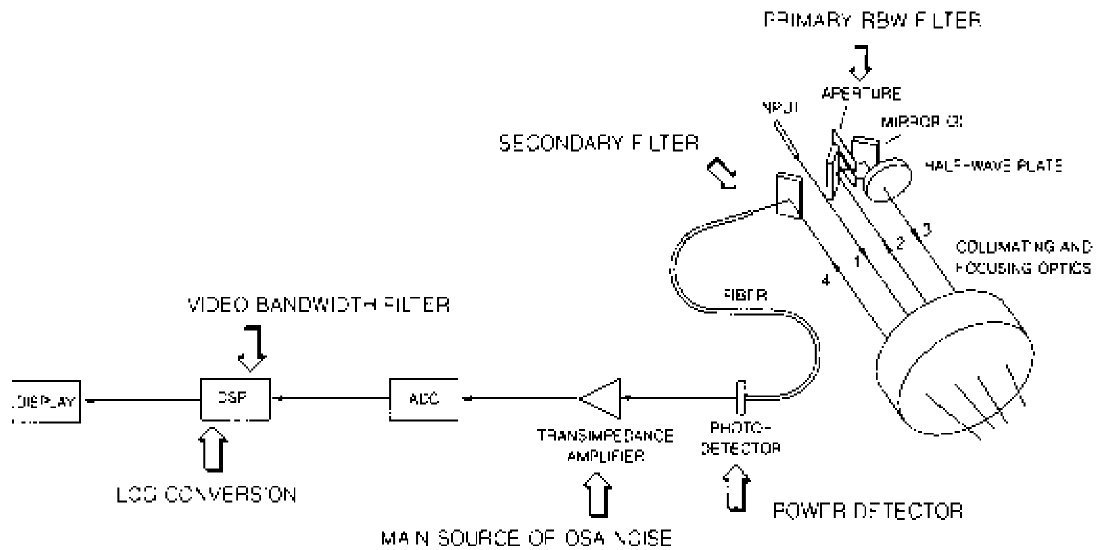

Figure 31. Key signal processing blocks of the Hewlett-Packard double-pass monochromator based optical spectrum analyzers.

Block Diagram Differences

The operation of optical spectrum analyzers is very similar to microwave spectrum analyzers; however there are some differences, especially in relationship to the sensitivity of the analyzer. Figure 32 shows the key signal-processing blocks of the Hewlett-Packard optical spectrum analyzers and the equivalent blocks of a typical microwave spectrum analyzer.

The order of the key signal processing elements is different, and this difference is most noticed in the sensitivity level of the analyzers. As can be seen in figure 32, the most significant source of internal noise for the microwave spectrum analyzer is at the front-end of the instrument, from the input attenuator and mixer to the EF amplifiers. The resolution bandwidth then determines the rms value of the broadband intemal noise.

Reducing the resolution bandwidth reduces the instrument noise level. The signal is then converted to a logarithmic scale by the log amplifier and the envelope of that signal is detected by the detector. The noise signal seen onscreen is this envelope of the original internal noise. As a result, the resolution bandwidth, which had changed the rms value of the original noise, changes the average value of the displayed noise. The video bandwidth filter then determines the peak-to-peak width of the displayed noise, without changing the average level.

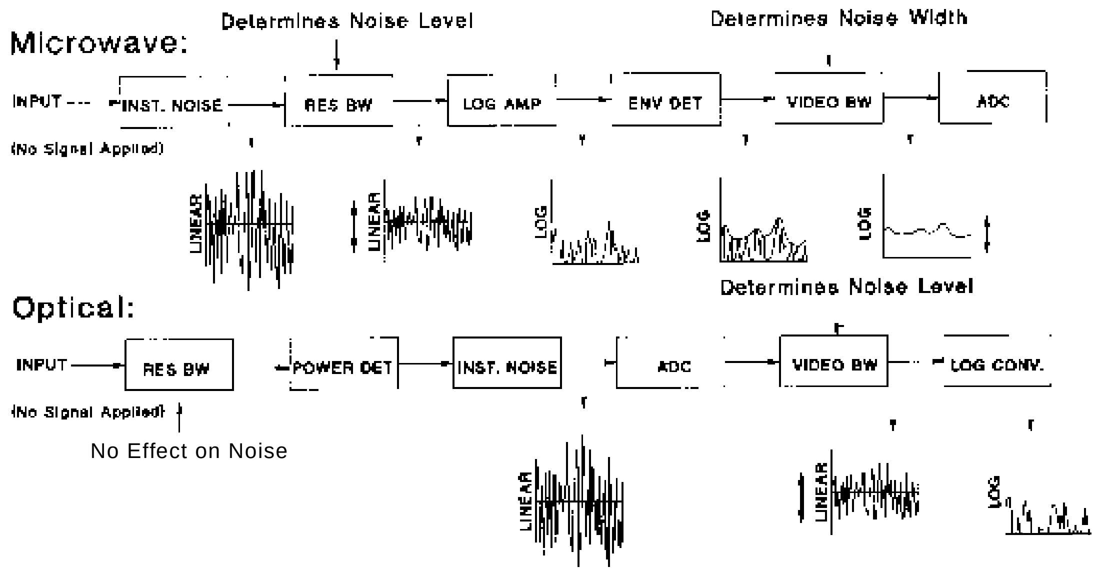

Figure 32. Key signal-processing blocks of Hewlett-Packard optical spectrum analyzers and a typical microwave spectrum analyzer.

The most significant source of internal noise for the optical spectrum analyzer comes after the resolution bandwidth filters and the detector. The resolution bandwidth has no direct effect on the internal noise level. Following digitization, the video bandwidth filter is applied to the internal noise. Since this noise has not been affected by the detector, the average noise level is still 0 V. The video filter in the optical spectrum analyzer affects the rms value of the internal noise but the average remains 0 V. This is the same effect that the resolution bandwidth filter had on the internal noise at that point in the microwave spectrum analyzer. The filtered signal is then converted to a logarithmic scale for display. The average value of the displayed internal noise is 0 W (because the noise source follows the detector), which is equal to minus infinity dBm. As a result, the optical analyzer's noise floor differs because, due to the envelope detector, the microwave spectrum analyzer has a non-zero average noise level. It is the peaks of the noise floor that determine the optical spectrum analyzer's sensitivity. The sensitivity is defined as 6 times the rms noise level. In order to keep the display from being too cluttered, the internal noise is clipped 10 dB below the sensitivity point.

In summary, microwave spectrum analyzers have a non-zero average noise level that is determined by the resolution bandwidth, and the displayed width of the noise is determined by the video bandwidth. The sensitivity of the microwave spectrum analyzer is defined as the average noise level. Optical spectrum analyzers have a zero average (minus infinity dBm) noise level that is not affected by the resolution bandwidth, but the rms level of the noise is determined by the video bandwidth. The sensitivity of the optical spectrum analyzer is defined as 6 times the rms of the noise.

For convenience, operators of Hewlett-Packard optical spectrum analyzers can enter the desired sensitivity, and as a result, the appropriate instrument settings, including video bandwidth and sweep time, are automatically determined and set.

For more information on Hewlett-Packard Test and Measurement products, applications, or services, please call your local Hewlett-Packard sales office. A current listing is available via the World-wide Web through AccessHP at http://www.hp.com. If you do not have access to the internet please contact one of the HP centers listed below and they will direct you to your nearest HP representative.

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