Fundamentals of Spectral Analysis

The Fabry-Perot Spectrum Analyzer

A Fabry-Perot interferometer can be used as a filter to produce an extremely narrow linewidth, or it can be used with a detector to resolve fine spectral details. Its passband is typically in the range of 5×10^{-5} to 10^{-1} cm^{-1} (1.5 MHz to 3 GHz). By physically adjusting the cavity spacing, this passband can be made to scan over a small wavelength region to allow precise spectral tuning. An optical spectrum analyzer based on this interferometer can really be thought of as a very-high-resolution spectrometer with a relatively narrow range of spectral coverage.

FABRY-PEROT INTERFEROMETER THEORY

The Fabry-Perot interferometer is a simple device which relies on the interference of multiple reflected beams. Figure 11.19 shows a schematic of a Fabry-Perot cavity.

Incident light undergoes multiple reflections between the coated surfaces which define the cavity. Each transmitted wavefront has undergone an even number of reflections (0, 2, 4, . . .). Whenever there is no phase difference between emerging wavefronts, interference between these wavefronts produces a transmission maximum. This occurs when the optical path difference is an integral number of whole wavelengths, i.e., when

$$m\lambda = 2t_{op}\cos\theta + \delta \qquad (11.16)$$

where

m is an integer, often termed the order

t_{op} is the optical thickness

θ is the angle of incidence, and

δ is the phase change upon reflection (a constant term that can be ignored in most cases).

At other wavelengths, destructive interference of transmitted wavefronts reduces transmitted intensity toward zero (i.e., most, or all, of the light is reflected back toward the source). Transmission peaks can be made very sharp by increasing the reflectivity of the mirror surfaces. A simple Fabry-Perot interferometer transmission curve is shown in figure 11.20. The ratio of successive peak separation to full width at half-maximum (FWHM) transmission peak is termed *finesse*. High reflectance results in high finesse, or high resolution.

Some Fabry-Perot interferometers are constructed from solid materials such as glass or fused silica. For temperature stability reasons, fused silica is preferred. In these interferometers, the gap between the mirror surfaces is fixed for any specific angle of incidence and temperature, and the transmission versus wavelength pattern is stationary. However, in most Fabry-Perot interferometers, air is the medium between high reflectors; therefore, the optical thickness, t_{op}, is essentially equal to d, the physical thickness. The air gap may vary from a fraction of a millimeter to several centimeters. If this gap is made to vary slightly, in a predictable way, the transmission peaks of the Fabry-Perot will shift as a function of wavelength.

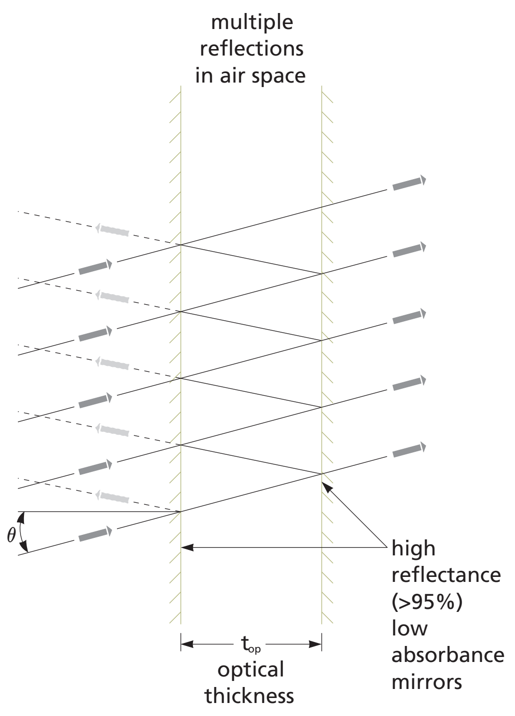

Figure 11.19 **Schematic of a Fabry-Perot Interferometer**

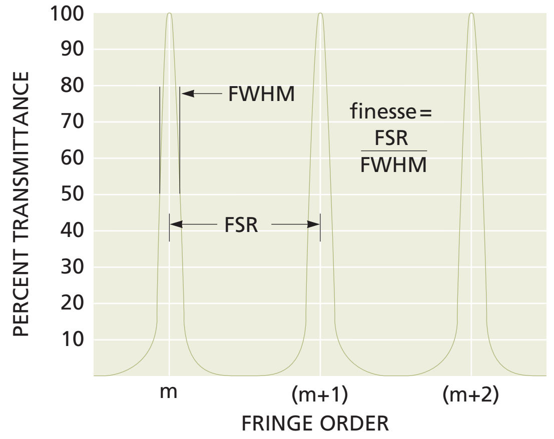

Figure 11.20 **Transmission pattern showing the free spectral range (FSR) of a simple Fabry-Perot interferometer**

As the separation of the mirrors is varied, typically by a ramp voltage applied to piezoelectric spacers, the transmission peak will shift over the FSR (i.e., the frequency space between the adjacent transmission peaks). Each peak occurs when the multireflected beams within the interferometer cavity are in phase at the exit surface. The small percentages transmitted at each reflection (less than one percent) reinforce and produce bright transmission peaks which may then be detected by a silicon or germanium detector.

The art of the Fabry-Perot interferometer design hinges on this apparently simple requirement — controlling the spacing between the mirrors. Even the most minute thermal or mechanical inconsistency will cause the parallelism between the mirrors to change, thus destroying the interference pattern. Great care must be taken in design and manufacture to avoid and prevent these problems and to provide an instrumental solution that is both stable and reliable.

CONFOCAL AND PLANO CONFIGURATIONS

Two practical configurations exist for a Fabry-Perot interferometer: the plano configuration, consisting of a pair of plane-parallel mirrors facing each other, and the confocal configuration, in which the radii of a pair of concave mirrors are equal to their separation. A more general case, in which the radii are substantially longer than the separation, is also possible, but this arrangement can produce anomalous transmission peaks which are difficult to interpret.

For both the confocal and the plano configurations, each spectral component of the incoming radiation produces a transmission peak when the cavity mirror separation d matches a multiple of the spectral wavelength λ. The relationship for a confocal configuration is $d=m\lambda/4$, where m is a large integer called the fringe order. In this instance, the optical round-trip path is four passes through the cavity. For the plano configuration, a round trip consists of only two passes, and the relationship is $d=m\lambda/2$ (ignoring phase changes on reflection). Thus, for any wavelength there will be a transmission peak every time the scanning mirror separation gives an integral value of m for that wavelength.

This results in a spaced-apart, comblike structure of transmission peaks corresponding to the different integral values of m. For each and every spectral line or mode in the incoming beam there will be a similar comb of peaks, and thus a sequence of identical spectra will be displayed across the screen as the mirror separation is ramped through a succession of interference orders m. Adjacent fringe orders are separated by the FSR — $c/4d$ Hz for the confocal configuration and $c/2d$ Hz for the plano configuration. In both cases, the separation between peaks is linear with frequency, as shown in the real-world example given in figure 11.21.

Note, however, that if the range of incoming wavelengths is greater than the FSR of the interferometer, there will be an overlapping of different fringe orders, and the displayed spectrum will be confusing and difficult to interpret.

The sharpness of individual peaks (the resolution of the spectral analyzer) is a function of the "finesse" of the Fabry-Perot interferometer. The value of the overall finesse is determined by the reflectance of the mirrors (the reflectance finesse, $\mathcal{F}_r$, given by:

$$\mathcal{F}_r = \frac{\pi (R_1 R_2)^{1/4}}{1-(R_1 R_2)^{1/2}} \tag{11.17}$$

where R_1 and R_2 are the reflectances of the two mirror coatings) and the quality of the interferometer's construction (the defect finesse, $\mathcal{F}_d$). As the finesse increases, the peaks of the transmission spectrum become narrower. Normally, reflectance finess predominates unless cavity spacing is very small. Overall transmission, however, may drop as the result of increased absorption. When the reflectance of both interferometer mirrors is the same (i.e., $R_1=R_2=R$), as is the case with a spectrum analyzer, the formula for reflectance finess becomes

$$\mathcal{F}_r = \frac{\pi (R)^{1/2}}{1-R}. \tag{11.18}$$

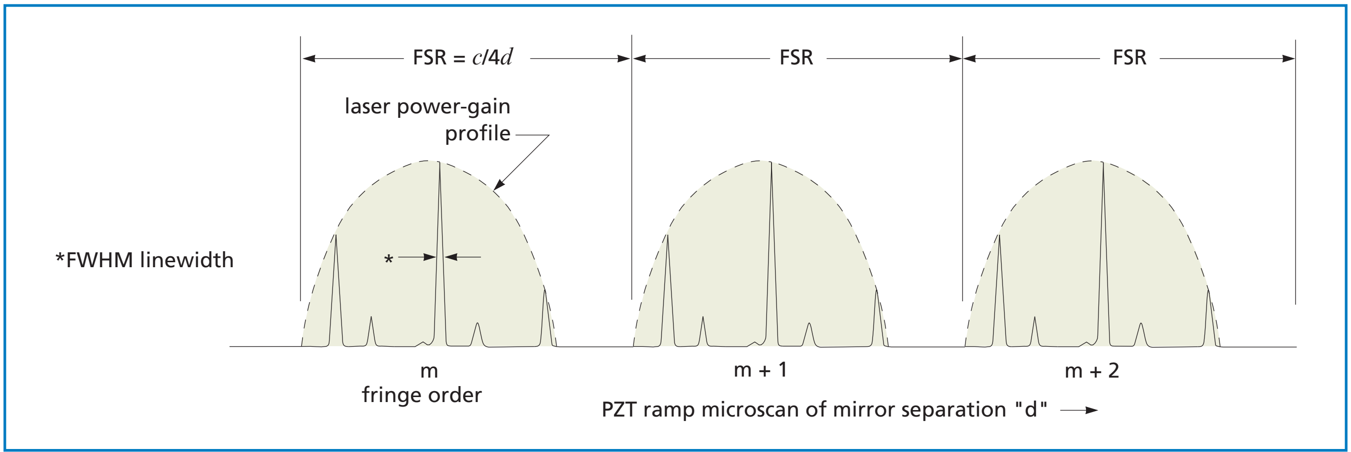

Figure 11.21 **A confocal interferometer scan over three free spectral ranges showing the output of a helium neon laser.**

The FWHM is given by the ratio of the FSR to the finesse. Thus, for a high-resolution spectrum, the FSR should be small and the finesse high.

The defect finesse results from the inevitable residual imperfections in manufacture. As the cavity spacing becomes small, overall surface defects, such as deviation from absolute parallelism or from absolute flatness (sphericity in a confocal interferometer), tend to predominate, but surface microroughness also contributes to the total defect finesse value.

SPECTRUM ANALYZER CONFIGURATION

Laser spectrum analyzers are most often based on the confocal Fabry-Perot design. The common focus and the reentrant optical path leads to very low diffraction losses, good light-gathering capacity (*étendue*) , and easy alignment of the cavity to the laser's optical beam. A major advantage of the confocal design is that the cavity modes are degenerate in frequency. No mode-matching is needed, and each observed laser line or mode represents a genuine signal, not just an instrumental artifact, as can so easily happen with other curved mirror arrangements. Indeed, the confocal spectrum analyzer shown in figure 11.22 should normally be operated slightly misaligned to the laser beam so that there is less chance of feedback to the laser source and resultant mode pulling. This misalignment is achieved without the excitation of spurious interferometer modes. Nonconfocal interferometer arrangements suffer primarily from their need to be mode-matched to the incoming laser beam. Failure to do this will cause spurious transmission fringes resulting from the higher-order transverse modes in the interferometer itself. Unfortunately, it is very difficult to separate stray data generated from these fringes from actual data from the laser beam under test. Other problems, such as the need to optically isolate the interferometric cavity from the laser cavity and the requirement that the laser operate in only a single transverse mode, compound the difficulty of using a nonconfocal Fabry-Perot for spectral analysis. The confocal spectrum analyzer avoids these problems; it is simple to align and adjust, and its output is easy to interpret.

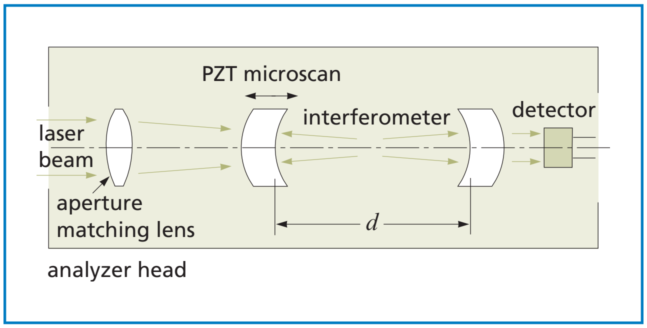

Figure 11.22 **A schematic diagram of a spectrum analyzer**

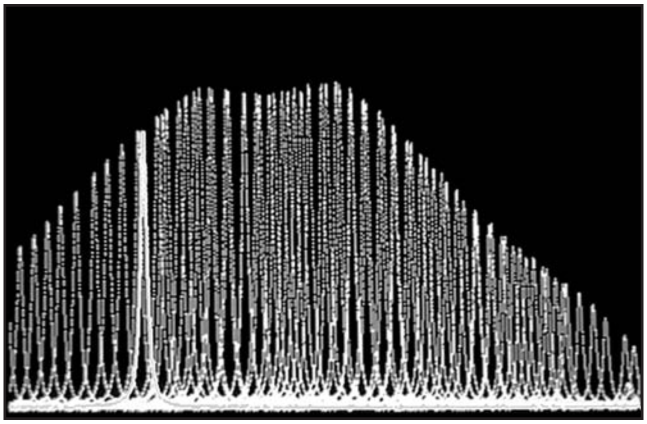

Figure 11.23 **Lasing medium gain curve traced by oscilloscope with spectrum analyzer**

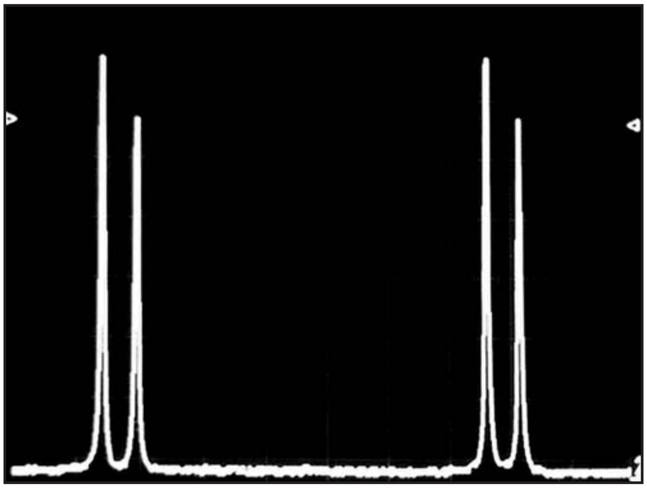

Figure 11.24 **Two laser modes displayed twice during spectrum analyzer scan**

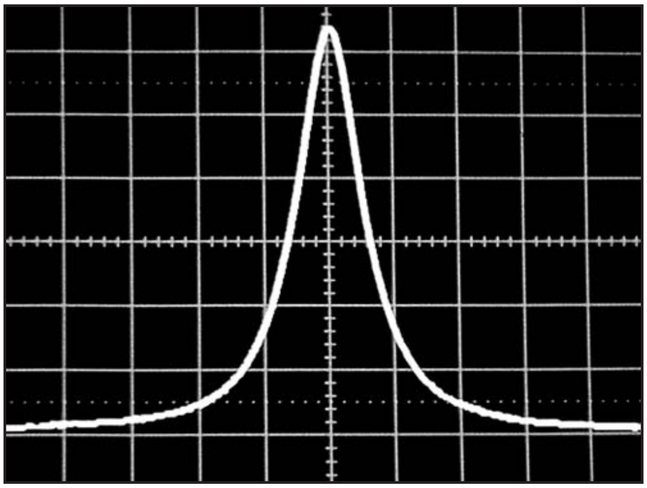

Figure 11.25 **Single mode display using spectrum analyzer**

Measuring Wavelength

When working with a laser, it is usually quite important to know the wavelength the laser is producing. With many this is not typically a problem because the wavelength is defined to within a small fraction of a nanometer by the physics of the lasing system. The red helium neon line is always at 632.8 nm, the main blue argon-ion wavelength is always at 488.0 nm, and so forth. However, when working with a tunable wavelength laser, or a laser than can experience significant wavelength drift as a function of temperature (e.g., a typical semiconductor diode laser), having an instrument available to determine the wavelength quickly with an acceptable level of accuracy is very useful.

Many systems have been developed over the years to measure the wavelength of light, whether from a laser, a lamp, or the output of an optical experiment. Traditionally, the light to be measured was collected and fed into a spectrometer or grating monochromator. If the native accuracy of the monochromator readout was not sufficient, the result could be compared to the readout for closely spaced atomic lines from a spectral source that bracketed the unknown wavelength, using proportional techniques. For highly accurate readings, however cumbersome long-path instruments were required, and, under the best of circumstances, wavelength measurement was a time-consuming task.

The advent of computers gave rise to a new class of instruments, the wavemeter, a table-top instrument that one could shine the unknown light into and receive an immediate readout of the wavelength to a level of accuracy that rivaled the best monochromator systems.

INTERFEROMETRIC WAVEMETERS

For absolute accuracy and precision wavemeters, interferometric techniques have proven the most practical. One common device is based on the scanning Michelson interferometer shown in figure 11.26.

The incident beam is split between a fixed path and a smoothly varying path. Both beams are reflected back and recombined at the beamsplitter to produce a sinusoidal interference pattern which results from the smoothly changing phase relationship between the beams. The unknown wavelength of the incident light, λ, can be calculated using the Michelson interferometer equation:

$$m\lambda = 2nd. \tag{11.19}$$

In this equation, m is the number of fringes recorded as the scanning mirror of the Michelson interferometer moves through the distance, d. The refractive index, n, of the medium (typically air) between the mirrors of the interferometer is included to account for the difference between the physical path distance and the optical path distance. The accuracy of this wavelength calculation depends primarily on the precision to which the

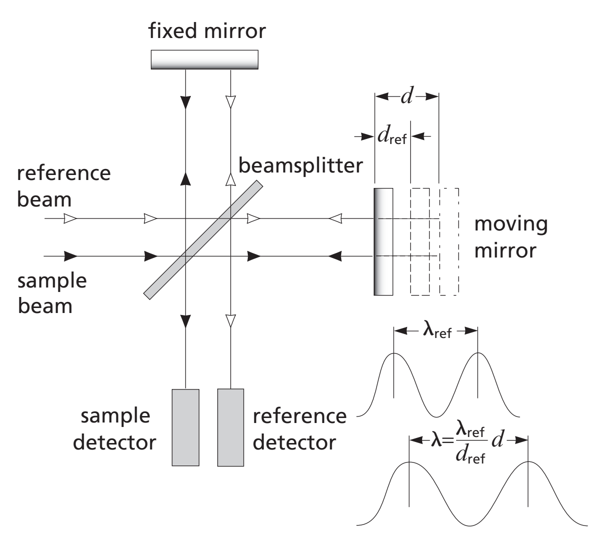

Figure 11.26 **A Michelson interferometer-based wavemeter**

displacement of the scanning mirror is known. In order to obtain highly accurate wavelength measurements, a reference laser with an accurately known wavelength is measured simultaneously to determine the scanning mirror displacement in terms of this wavelength. With this type of instrument, measurements with an accuracy of ±2 ppm can be obtained.

Interferometric wavemeters can be very accurate, but they are also very expensive, making them unsuitable for routine laboratory applications requiring accuracy of a few tenths of a nanometer.

SEMICONDUCTOR-BASED WAVEMETERS

A new technique, used in the WaveMate™, may be the optimum solution for every-day low-resolution (~0.5 nm) measurements. In this technique, wavelength measurement is accomplished with a single photosensor consisting of two stacked silicon photodiodes, as shown in figure 11.27.

The absorption characteristics of the first photodiode acts as a filter for the second photodiode. The two photodiodes have different spectral response curves (see figure 11.29).

By comparing the output of the two photodiodes, an intensity-independent signal unique for the wavelength of the incident beam is obtained.

WaveMate consists of a sensor head and a console for processing and display. The sensor head contains the photodiode, photoamplifiers, thermostat and a variable neutral density filter. In the console both signals are error corrected and the wavelength is then calculated and displayed.

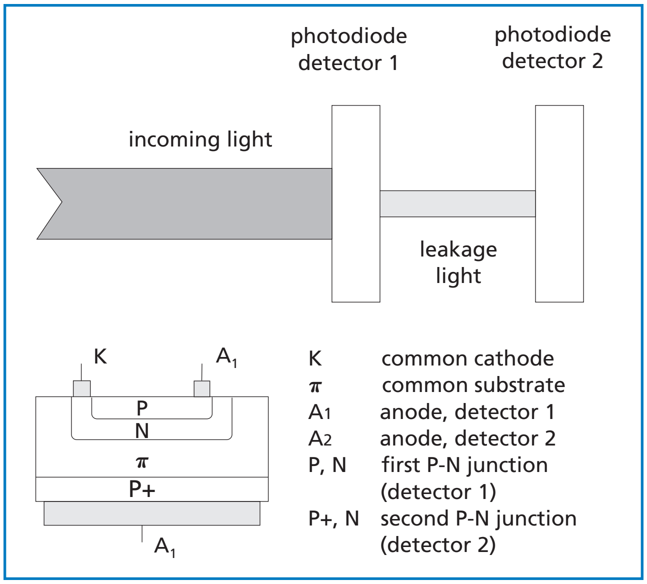

Figure 11.27 **Dual-photodiode wavelength sensor structure**

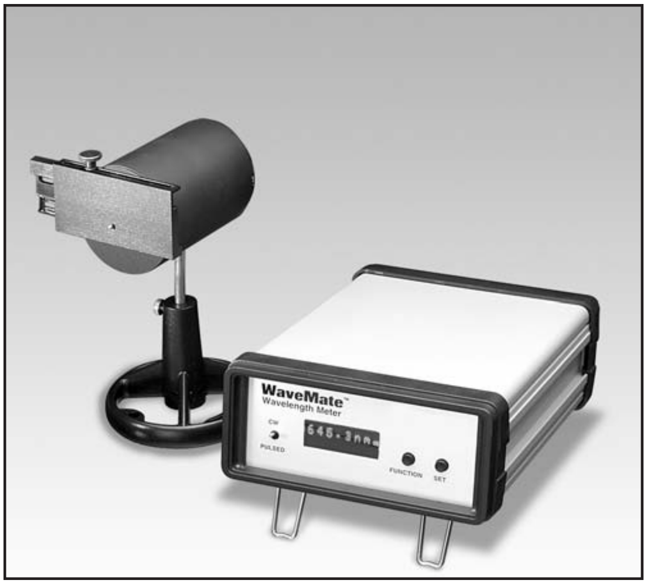

Figure 11.28 **WaveMate™ wavelength meter**

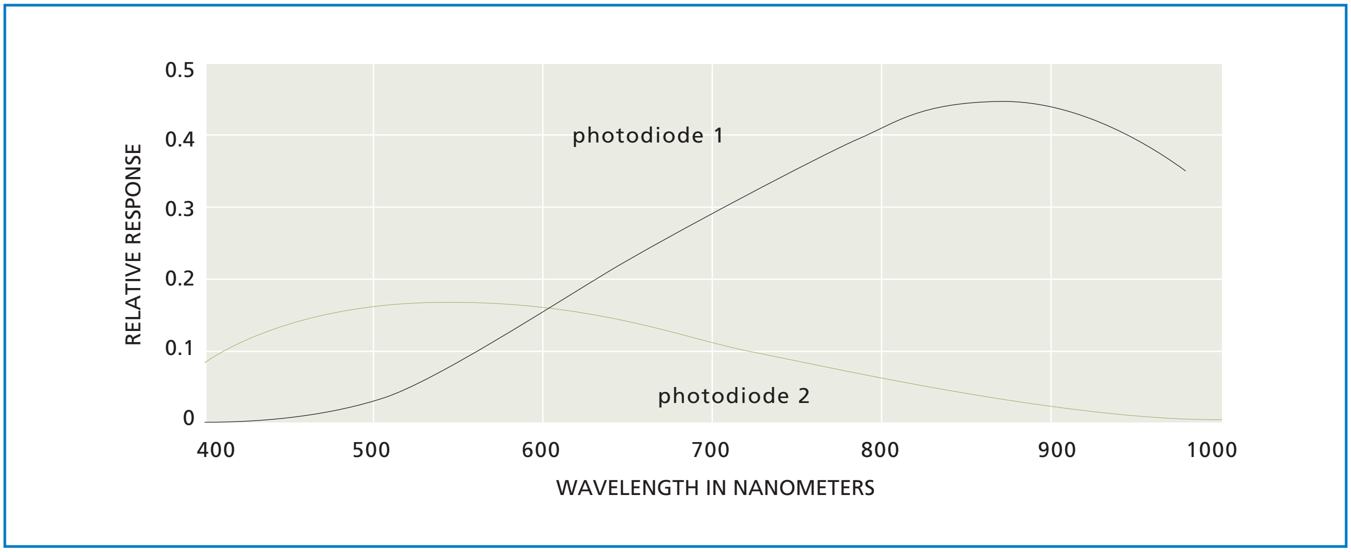

Figure 11.29 **Spectral response curves of the photodiodes**

Introduction to Laser Beam and Spectral Measurement

Spectrometers, Monochromators, and Spectrophotometers

A spectrometer is an instrument used to determine the wavelengths (and their relative intensities) present in a source of light. A monochromator is an instrument used to separate out a single specific wavelength or wavelength band present in a source of light. The spectrophotometer is an instrument used to determine the wavelengths present in the light reflected from an object.

All of these instruments share the same basic operating principal—light from a source passes through, or is reflected by, a dispersing element which spreads the light into its spectral colors. A detector then measures the intensity of the output at various points in the spectrum. The distinction among the instruments, illustrated in figure 11.30, is in the configuration of the source of light, the dispersing element, and the detector.

In a spectrometer, the source is a lamp (or the output of an experiment), the dispersing element is stationary, and the detector is an array of detectors.

In a monochromator, the source is a lamp (or the output of an experiment), the dispersing element rotates, and a single detector is fixed in place.

In a spectrophotometer, the source is the light reflected from a sample, the dispersing element is stationary, and the detector is an array of detectors.

In most cases, the dispersing element is a ruled or holographic grating. In the monochromator, the detector is typically a photodiode or a photomultiplier tube. In the spectrometer and spectrophotometer, the detector is typically a linear CCD or CMOS detector with individual pixel readouts.

SPECTROMETER THEORY

A Czerny-Turner spectrometer is shown schematically in figure 11.31.

Light enters the optical bench through a slit and is collimated by a spherical mirror. A plane grating diffracts the collimated light; a cylindrical mirror then focuses the resulting diffracted light. An image of the spectrum is projected onto a one-dimensional linear detector array.

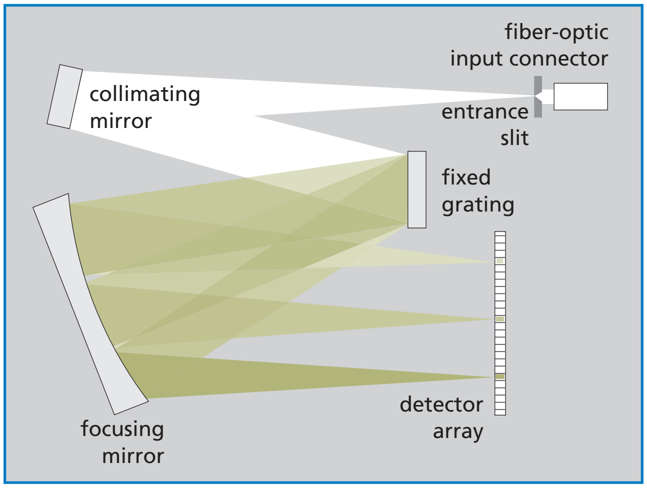

Figure 11.31 **Schematic of symmetric Czerny-Turner spectrometer**

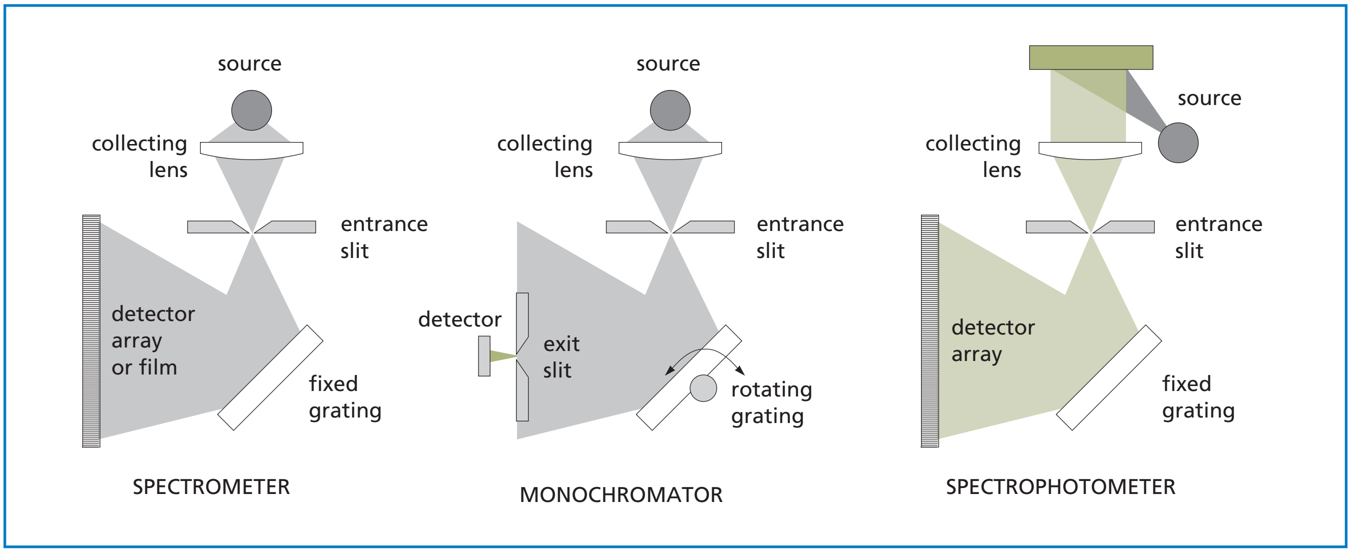

Figure 11.30 **The spectrometer family**

The fundamental grating equation is as follows:

$$\sin\alpha + \sin\beta = 10^{-6} kn\lambda \qquad (11.20)$$

where

α is the angle of incidence in degrees
β is the angle of diffraction in degrees
k is the diffraction order (an integer)
n is the grating density in lines/mm
λ is the wavelength of light in nm

and the angular separation (angular dispersion) between two wavelengths, in radians, is given by

$$\frac{d\beta}{d\lambda} = \frac{kn}{\cos\beta} \times 10^{-6} \qquad (11.21)$$

The separation of the wavelengths at a detector is defined as the linear dispersion of the system. For a detector that is perpendicular to the diffracted beam (the case for a monochromator), linear dispersion is given by

$$\frac{d\lambda}{dx} = \frac{\cos\beta}{knL_b} \times 10^{-6} \qquad (11.22)$$

where L_b is the distance from the focusing lens to the detector. For a spectrometer with a planar detector (see figure 11.32), the distance L_b changes with β, and the linear dispersion formula becomes

$$\frac{d\lambda}{dx} = \frac{\cos\beta\cos^2\gamma}{knL_h} \times 10^{-6} \qquad (11.23)$$

where

$\gamma = \beta_h - \beta$
β_h=is the angle between the perpendicular to the detector and the grating normal
L_h=the perpendicular distance from the focusing lens to the detector.

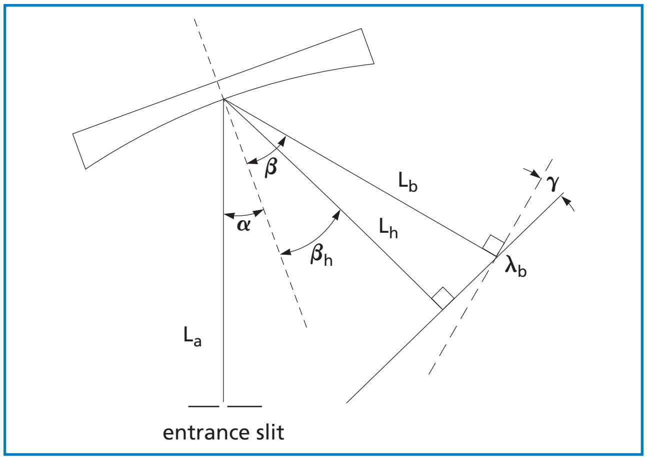

Figure 11.32 **Spectrometer configuration** (curved grating replaces planar grating and focusing lens.)

From these equations it is clear that increasing the distance from the focusing mirror to the detector spreads the spectrum over a wider area, increasing the dispersion and, in principle, increasing the resolving power of the instrument.

RESOLVING POWER

Resolution is the ability of an instrument to separate adjacent spectral lines, and is given by the equation

$$R = \frac{\lambda}{\delta\lambda} \qquad (11.24)$$

where $\delta\lambda$ is the difference in wavelength between two spectral lines of equal intensity. It may be shown that

$$R = \frac{\lambda}{\delta\lambda} = knW_g = kN \qquad (11.25)$$

where

W_g=the illuminated width of the grating and
N=the total number of grooves in the gratings.

Using the earlier equations, it can also be shown that

$$\frac{d\lambda}{dx} = Wg\,\frac{\sin\alpha + \sin\beta}{\lambda} \times 10^{-6} \qquad (11.26)$$

Obviously, the resolving power of a spectrometer depends on the width of the grating, the geometry, and the wavelength to be resolved. The size of the incoming light at the entrance aperture is determined by the slit width or, in the absence of a slit, the fiber diameter.

WAVELENGTH AND ORDER

Unlike a dispersing prism, a diffraction grating does not produce a single spectra, but instead it produces multiple spectra determined by the equation

$$k\lambda = \text{constant} \qquad (11.27)$$

where k is an integer. Consequently, for a broad spectral source, the spectra will overlap. For example, at the detector location for 800 nm, output at 400 nm, 266.6 nm, and 200 nm will also be present. Consequently, filters must be used to eliminate the higher-order spectra.

BLAZED GRATINGS

Blazed gratings are designed to produce maximum efficiency at a specific wavelength. This is accomplished by forming the grooves in such a manner that the incident and refracted angle, at that wavelength, are equal (the Littrow condition). A grating that is blazed for a first-order wavelength, will also be blazed for the corresponding higher-order wavelengths.