Haiyin Sun. "Laser Output Measurement."

Laser Output Measurement

Haiyin Sun
Coherent Auburn Group

63.1 Introduction

A laser is a device that emits an optical beam. A laser beam carries a certain amount of optical power. Lasers emit beams in two different ways: continuous wave (CW) or pulsed. A CW laser emits a steady power as shown in Figure 63.1. CW laser power is measured in terms of watts. The power of commonly used CW lasers ranges from a fraction of milliwatts for a small helium neon (He-Ne) laser to tens of kilowatts for a carbon dioxide (CO_2) laser. A pulsed laser emits a pulsed power as shown in Figure 63.2. The pulse can be repeated. The pulse duration and repetition rate vary for lasers of different types and are adjustable for some types of lasers. Pulsed laser power is more easily measured in terms of energy per pulse such as joules per pulse. The term "per pulse" is usually omitted. The energy of commonly used pulsed lasers ranges from a few picojoules for a semiconductor laser to tens of megajoules for a semiconductor laser array. The pulse repetition rate ranges from a single pulse for an excimer laser or

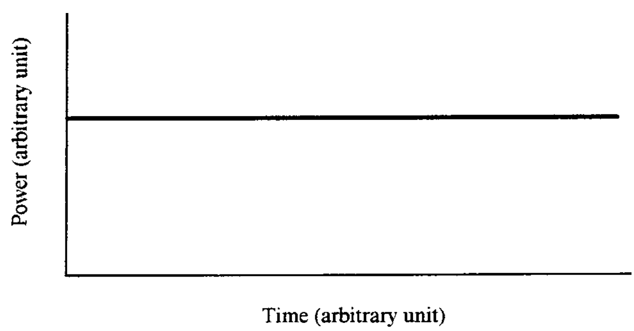

FIGURE 63.1 A CW laser emits a steady power.

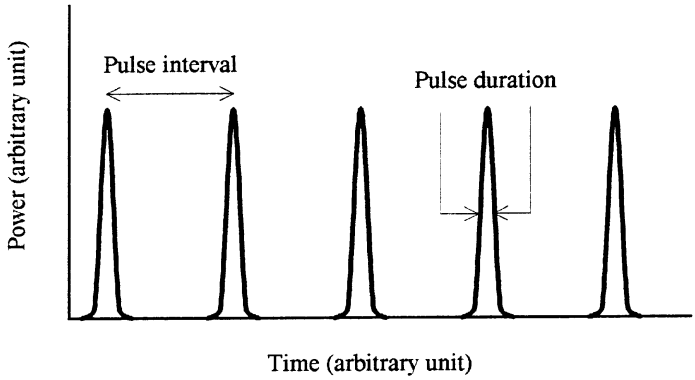

FIGURE 63.2 A pulsed laser emits a pulsed power.

an X-ray laser to hundreds of megahertz for a neodymium:YLF laser. The pulse duration ranges from tens of femtoseconds for a Ti:Sapphire laser up to continuous wave for a CO_2 or He-Ne laser.

A laser beam may contain more than one wavelength (monochromatic) component. One wavelength component may have an optical intensity different from that of another wavelength component. Optical spectral intensity is defined as power per unit wavelength. The optical intensity-wavelength profile of a laser beam is known as the "spectrum." Spectrum measurement usually means measuring the spectral profile. The absolute value of the optical spectral intensity is in fact not important. Figure 63.3 shows a typical spectrum of a multimode semiconductor laser. The wavelength components are inside several bands. Each band may be a "longitudinal mode," and the width of a band is known as the "mode linewidth." Figure 63.4 shows a typical spectrum of a single mode He-Ne laser. There is only one longitudinal mode with a very narrow linewidth. The power of a laser beam can be calculated by integrating over the laser spectrum.

The wavelength of a laser is referred to as the *central wavelength* of the spectrum. But the term "central" is usually omitted. For example, the wavelength is 780 nm for the semiconductor laser shown in Figure 63.3 and is about 632.8 nm for the He-Ne laser shown in Figure 63.4. The wavelength of commonly used lasers ranges from 270 nm in ultraviolet for a neodymium:YAG laser, or even lower for an X-ray laser, to 10.6 μm in infrared for a CO_2 laser. Many lasers have a beam with single longitudinal mode and very narrow linewidth like that shown in Figure 63.4. The spectrum measurement for these lasers then virtually reduces to wavelength measurement.

Power, spectrum, and wavelength are the three most important parameters describing a laser. Laser manufacturers should provide information about these three parameters of their lasers. Some lasers have adjustable power, spectrum, or wavelength. Users often need to measure these parameters to ensure

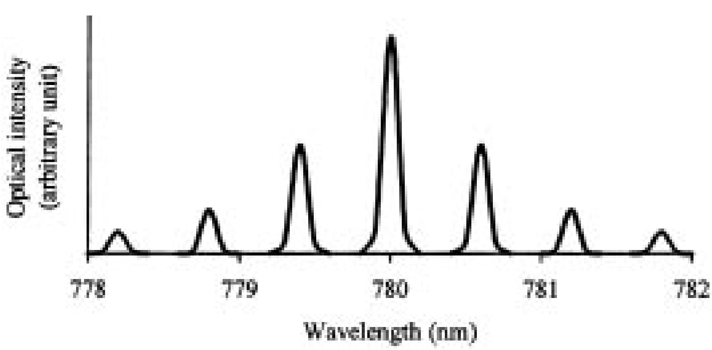

FIGURE 63.3 Spectrum of a multimode semiconductor laser.

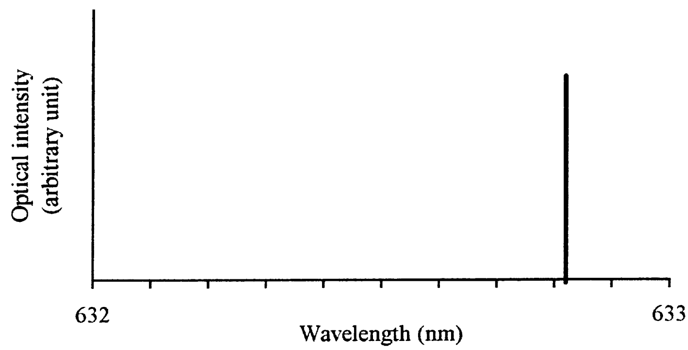

FIGURE 63.4 Spectrum of a single-mode helium neon laser.

appropriate use of these lasers. This chapter discusses the principles and techniques involved in the measurement of laser power, spectrum, and wavelength.

Readers interested in knowing more about laser working principles and characteristics can read laser textbooks such as Reference 1, available in many libraries.

63.2 Measurement of Laser Power

A laser power meter can measure laser power or energy. Figure 63.5 shows the scheme of a laser power meter. The three basic components of a laser power meter are a photodetector, an electronic conditioner, and a display device. The photodetector detects the laser beam under measurement and outputs an electrical response proportional to the laser power. The electronic conditioner processes the response and provides a digital or analog signal for displaying. The display device displays the measurement result in terms of watts or joules. To a large extent, the characteristics of the photodetector used determines the performance of a laser power meter. When selecting or using a laser power meter, the following issues are of primary concern:

1. *Spectral response range.* A photodetector has a certain spectral response range that limits the spectral range of a laser power meter. Some photodetectors have a wavelength-dependent spectral response. Calibration is necessary when using a laser power meter with such a photodetector to measure the power at different wavelengths.
2. *Power range.* The detection threshold and damage threshold of a photodetector usually determine the power range of a laser power meter. Incident laser power lower than the detection threshold can cause measurement error, while incident power higher than the damage threshold can cause permanent damage to the photodetector. Specifically, power range includes CW power range, peak

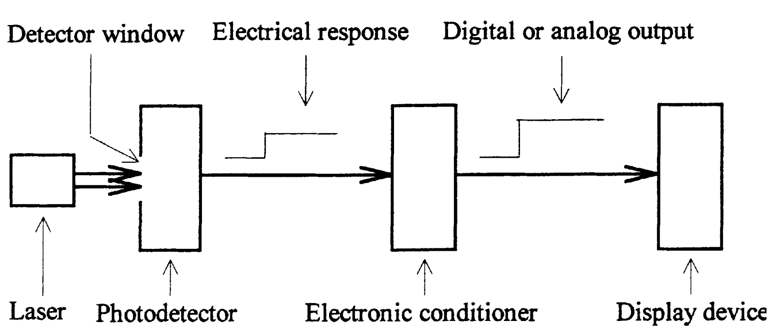

FIGURE 63.5 Scheme of a laser power meter.

power range, spatial power density range, single-pulse energy range, and spatial energy density range. An optical attenuator put in front of the photodetector can raise the damage threshold to as high as megawatt. However, an attenuator will also raise the detection threshold.

3. *Response time.* A photodetector needs a certain time to respond to an incident laser beam. In order to determine the shape of a laser pulse, the detector response time must be shorter than the width of the pulse.
4. *Detector window size.* The input window size of commonly used photodetectors are from a few to tens of millimeters. When the size of a laser beam under measurement is larger than the detector window size, focusing optics must be used to reduce the beam size. Power loss caused by the focusing optics must be excluded to avoid measurement error.

Photodetectors

Three photodetectors are commonly used in laser power meters. They are thermopiles, photodiodes, and pyroelectric probes.

Thermopiles

A thermopile is usually a light absorber disk onto which a ring of thermocouples has been deposited. The absorber converts the laser power incident on it into heat and generates between the absorber and a heat sink a temperature difference proportional to the incident laser power. The thermocouples generate and output an electrical response proportional to the temperature difference. Thermopiles usually have a long response time of a few seconds, a broad and flat spectral response range from 200 nm to 20.0 μm, and a power range of 1 mW to 5 kW for CW lasers or 0.01 J to 300 J for pulsed lasers. Because of the flat spectral response, calibration is independent of wavelength. Thermopiles are primarily used to measure moderate to high power output of CW lasers, moderate to high energy output of single-shot pulsed lasers, and the energy output of pulsed lasers with a repetition rate higher than 10 Hz.

Photodiodes

Silicon and germanium photodiodes are widely used as photodetectors. A photodiode absorbs the photons (laser beam) incident on it and utilizes the photon energy to create free carrier pairs (electrons and holes). These free carriers form a response current in an external circuit. The responsivity of a photodiode in amps/watt is given by

$$R\left(\frac{A}{W}\right) = \eta_D \frac{e}{h\nu} \qquad (63.1)$$

where R = current produced by the photodiode for per watt of incident power, η_D = detection efficiency, e = electron charge (1.6×10^{-19} C), and $h\nu$ = photon energy. Since a typical photon energy is 2 eV $\approx 3 \times 10^{-19}$ J, $e/h\nu$ is of the order of 0.5 A/W. Normal detection efficiencies η_D exceed 0.5 at optical wavelengths (500 to 800 nm), leading to typical responsivities of 0.25 A/W. Silicon photodiodes have a narrow spectral response range (400 nm to 1.1 μm). The response peak is at about 800 nm. Germanium photodiodes also have a narrow spectral response range (800 nm to 1.8 μm). The response peak is at about 1.5 μm. Photodiodes usually have a power range of 1 nW to 50 mW for CW lasers or 1 pJ to 1 μJ for pulsed lasers, and a short response time of about 100 ms. Photodiodes are best for measuring low power output of CW lasers or low energy output of pulsed lasers. Because their spectral response is wavelength dependent, calibration is always required when measuring the power of lasers with different wavelengths. Manufacturers should attach a calibration data sheet to their laser power meters that use a photodiode as the detector. Several other semiconductor photodetectors with different spectral response ranges are available commercially. For example, the spectral response ranges are from 1.0 to 3.6 μm, 1.0 to 5.5 μm, and 2 to 22 μm for indium arsenide photodetectors, indium antimonide photodetectors, and mercury cadmium telluride photodetectors, respectively.

Pyroelectric Probes

A pyroelectric probe uses a ferroelectric material that is electrically polarized at a certain temperature. The material is placed between two electrodes. Any change in temperature of the material caused by the absorption of laser power produces a response electric current in the external circuit. Pyroelectric probes are primarily used to measure the energy of pulsed lasers because they only respond to the rate of temperature change. Pyroelectric probes usually have a spectral response range from 100 nm to 100 μm, a response time as short as a few picoseconds, and a pulsed energy range from 10 nJ to 20 J.

Integration Spheres

Integration spheres are designed to collect the power of highly divergent laser beams, such as semiconductor laser beams, since these beams can overfill the input window of a photodetector and cause considerable measurement error. Figure 63.6 shows the scheme of an integration sphere. The hollow spherical cavity has a diffusive internal wall and at least two windows. The reflectivity of the internal wall is high and slightly wavelength dependent. The highly divergent laser beam under measurement is incident into the sphere from one window. The photodetector of a laser power meter is mounted on another window. A baffle is used to prevent the photodetector being directly hit by the incident beam. The sphere can collect all the incident laser power and convert the power into a diffusive radiation proportional to the power. The laser power meter measures the radiation and displays the laser power under measurement based on the calibration data of the integration sphere.

Readers interested in knowing more about laser power meters can read References 2 through 4 or contact manufacturers. Section 8.1 of this handbook provides more information about photodetectors.

63.3 Measurement of Laser Spectrum

An instrument that can measure a laser spectrum is known as an optical spectrum analyzer. An optical spectrum analyzer consists of two basic components: an optical device and a laser power meter. The optical device can select and output a certain wavelength band of a polychromatic laser beam incident on the device. The central wavelength of the output wavelength band can be scanned over a certain range by the scan of the optical device. The laser power meter measures the power of the optical device output. The width of the output wavelength band usually does not change. Therefore, the power measured by the power meter is proportional to the optical spectral intensity. Since the absolute value of the optical spectral intensity is not important in the measurement of spectrum, the laser power meter sometimes can be as simple as a photodiode combined with a voltmeter. As the optical device is scanned, the power meter outputs the power (optical spectral intensity) as a function of the wavelength, and thereby measures the spectrum. Diffraction gratings and scanning Fabry-Perot interferometers (SFPI) are two widely used optical devices for spectrum analysis.

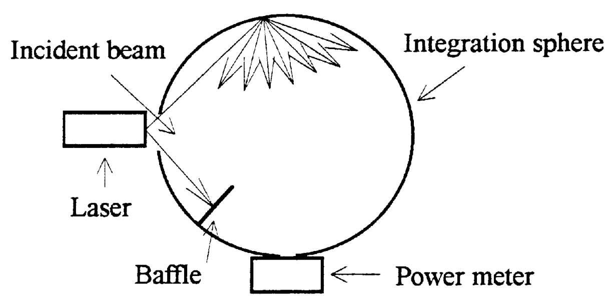

FIGURE 63.6 Scheme of an integration sphere.

Light Interference

Most optical spectrum analyzers make measurements utilizing light interference. The wave theory of light can explain interference. A single mode narrow linewidth laser beam can be described by its electric field $E(z)$:

$$E(z) = A\exp[-i\phi(z) + i\alpha(t)] \tag{63.2}$$

where A = amplitude, $\phi(z) = 2\pi z/\lambda$ = phase, λ = laser wavelength, z = coordinate in the direction of beam propagation, and $\alpha(t)$ = a phase factor that varies fast with time t. The intensity of the laser beam is given by:

$$I = |E(z)|^2 = A^2 \tag{63.3}$$

Two-Beam Interference

A beam splitter such as a partially transparent plate can split a laser beam into two described by:

$$E_1(z) = A_1\exp[-i\phi(z) + i\alpha(t)] \tag{63.4}$$

$$E_2(z) = A_2\exp[-i\phi(z) + i\alpha(t)] \tag{63.5}$$

where A_1 and A_2 are the amplitudes. Let the two beams propagate through two different distances, z_1 and z_2, respectively, and then be recombined into one. The intensity of the recombined beam is:

$$I = |E_1(z_1) + E_2(z_2)|^2 = A_1^2 + A_2^2 + 2A_1A_2\cos\frac{2\pi(z_2 - z_1)}{\lambda} \tag{63.6}$$

Equation 63.6 shows that I varies sinusoidally as $|z_2 - z_1|$ is varied. Such a phenomenon is known as *two-beam interference*. When $|z_2 - z_1| = m\lambda$ (m is any integer), I takes the maximum value of $(A_1 + A_2)^2$ and the situation is called "constructive interference." When $|z_2 - z_1| = (m + 1/2)\lambda$, I takes the minimum value of $(A_1 - A_2)^2$, and the situation is called *destructive interference*. Combining two beams with the same wavelengths but from two different lasers results in:

$$I = A_1^2 + A_2^2 + 2A_1A_2\cos\left[\frac{2\pi(z_2 - z_1)}{\lambda} + \alpha_2(t) - \alpha_1(t)\right] \tag{63.7}$$

where $\alpha_1(t)$ and $\alpha_2(t)$ = two different phase factors of the two lasers, respectively. For broadband lasers, $\alpha_1(t)$ and $\alpha_2(t)$ are uncorrelated, and they vary rapidly and randomly. The last term at the right-hand side of Equation 63.7 can contribute to I only in a time-averaged way, and the time average of this term is zero. For narrowband lasers, a beat is obtained at the differential frequency of the two lasers, and I varies sinusoidally in time for any fixed $z_2 - z_1$. The time average of the last term in Equation 63.7 is also zero. Thus, I always equals a constant of $A_1^2 + A_2^2$, no matter how $|z_2 - z_1|$ is varied.

Multibeam Interference

Interference can occur among any number of beams obtained by splitting one laser beam. Let a laser beam with unit amplitude be split into $N (N > 1)$ beams, the amplitudes of these N beams fall off progressively, and the phase difference between two successive beams be a constant $\Delta\phi$. These beams can be described by $E_k(z) = \rho^k\exp[-i\phi(z) - ik\Delta\phi + i\alpha(t)]$, where $k = 0; 1; \ldots; N - 1$, and $\rho < 1$. Then, these N beams are recombined. Multibeam interference occurs among these beams. The intensity of the recombination of these beams is given by:

$$I = \left|\exp[-i\phi(z) + i\alpha(t)]\sum_{k=0}^{N-1}\rho^k\exp(-ik\Delta\phi)\right|^2 = \frac{1 + \rho^{2N} - 2\rho^N\cos(N\Delta\phi)}{1 + \rho^2 - 2\rho\cos(\Delta\phi)} \tag{63.8}$$

Equation 63.8 shows that *I* is a function of ρ and *N*, and is a periodic function of $\Delta\phi$. More information about the wave theory of light and light interference can be found in many advanced optics textbooks such as Reference 5.

Diffraction Gratings

A diffraction grating can spatially disperse a polychromatic laser beam into its monochromatic components and is the most widely used optical device for analyzing optical spectrum covering a relatively wide range. Several different types of diffraction gratings are available. A planar reflective diffraction grating is a collection of many small, identical and slit-shaped grooves ruled on a planar high reflective surface. Figure 63.7 shows two grooves of such a grating, an incident laser beam with three wavelength components $\lambda_1 < \lambda_2 < \lambda_3$ and three diffraction beams marked by m = 0, 1, and 2, respectively. The beams are in the plane defined by the grating normal and the groove normal. The grooves illuminated by the incident beam generate diffraction beams with the same amplitude since the grooves are identical. Multibeam interference occurs among the diffraction beams. The phase difference $\Delta\phi$ between two adjacent diffraction beams of a grating is given by:

$$\Delta\phi = \frac{2\pi}{\lambda} d[\sin(\theta_1) + \sin(\theta_2)] \tag{63.9}$$

where d = groove period, θ_1 = angle between the incident beam and the grating normal, θ_2 = angle between the diffraction beams and the grating normal (θ_2 is not marked in Figure 63.7.), and $d[\sin(\theta_1) + \sin(\theta_2)]$ = path difference between two adjacent diffraction beams. Constructive interference among the diffraction beams occurs at

$$\Delta\phi = 2m\pi \tag{63.10}$$

where m = an integer known as the *diffraction order.* Combining Equations 63.9 and 63.10 results in

$$d[\sin(\theta_1) + \sin(\theta_2)] = m\lambda \tag{63.11}$$

Equation 63.11 is known as the *grating equation* and shows that, for a given θ_1 and m, θ_2 is a function of λ. θ_2 gives the diffraction beams a propagation direction in which *I* has the maximum value. The

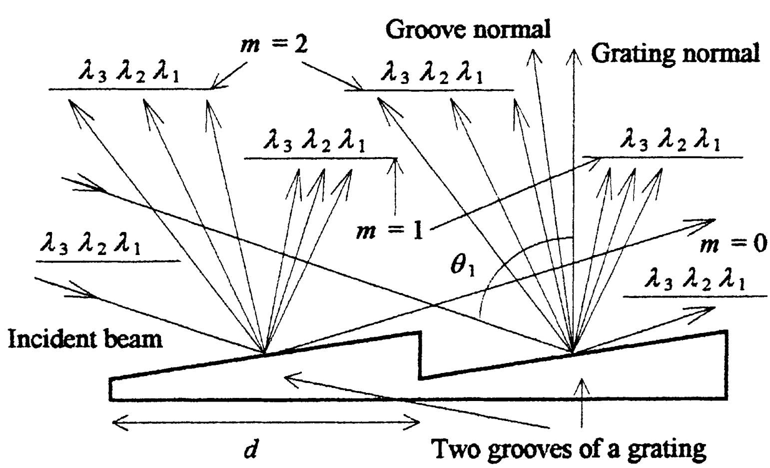

FIGURE 63.7 Two grooves of a planar reflective diffraction grating. The grating disperses an incident beam containing three wavelengths, $\lambda_1 < \lambda_2 < \lambda_3$. There are three diffraction beams with diffraction order m = 0, 1, 2.

angular dispersion resolution of a grating is defined by $d\theta_2/d\lambda$ and can be obtained by differentiating equation (63.11). The result is:

$$\frac{d\theta_2}{d\lambda} = \frac{m}{d\cos(\theta_2)} \tag{63.12}$$

where θ_1 is assumed to be a constant. Large $d\theta_2/d\lambda$ is often desired and can be obtained by the use of a small d, a large θ_2 close to 90°, and a large m. Usually, θ_2 must be smaller than 80° to maintain the proper functioning of the grating and $d \approx \lambda$; Equation 63.11 shows that the largest possible value of m is 2. Equations 63.11 and 63.12 also show that $m = 0$ leads to $\theta_2 = -\theta_1$ and $d\theta_2/d\lambda = 0$. That means that, in the zero diffraction order, the grating does not disperse the incident beam, and all the diffraction beams propagate in the same direction, $\theta_2 = -\theta_1$. Commonly used diffraction gratings have a groove density from 300/mm ($d \approx 3.33$ µm) to 2400/mm ($d \approx 420$ nm). The corresponding dispersion resolution for $m = 1$ is from $d\theta_2/d\lambda = 4 \times 10^{-4}$ rad/nm to $d\theta_2/d\lambda = 3.4 \times 10^{-3}$ rad/nm. The intensity of the diffraction beams of a grating can also be described by Equation 63.8 with $\rho = 1$. That is:

$$I = \frac{\sin^2\left(\frac{N\Delta\phi}{2}\right)}{\sin^2\left(\frac{\Delta\phi}{2}\right)} \tag{63.13}$$

Equation 63.13 is plotted in Figure 63.8 for $N = 5$ and 20, respectively. Equation 63.13 shows that I is a periodic function of $\Delta\phi$. I reaches maximum of N^2 at $\Delta\phi = 2m\pi$ and zero at $\Delta\phi = 2k\pi/N$ (k is any integer, but $k \neq mN$). The fringe width $\Delta\phi_w$ of I is given by

$$\Delta\phi_w = 2\left[2m\pi - \frac{2(mN-1)\pi}{N}\right] = \frac{4\pi}{N} \tag{63.14}$$

Equation 63.14 shows that the resolution of a grating is proportional to N, since the resolution can be defined as $1/\Delta\phi_w$.

Most advanced optics textbooks (e.g., Reference 5) study gratings, and manufacturers' catalogs (e.g., Reference 6) give a product-oriented description of gratings.

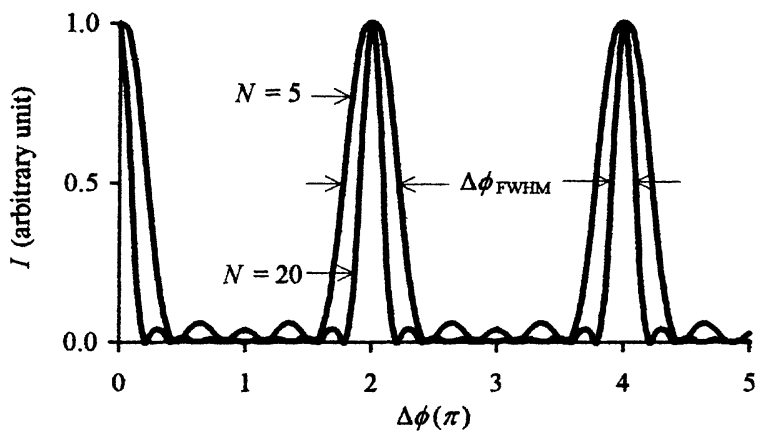

FIGURE 63.8 Multibeam interference intensity I is a periodic function of the phase difference $\Delta\phi$ between two adjacent beams. I is plotted for beam number $N = 5$ and 20, respectively. The full fringe width at half maximum power $\Delta\phi_{FWHM}$ of I decreases as N is increased.

Monochromators

Monochromators are instruments widely used for optical spectrum analysis. Various types of monochromators have been developed. Figure 63.9 shows the scheme of a simple monochromator. The laser beam under measurement is incident through the entrance slit, two concave spherical mirrors collimate the beam, the grating disperses the beam, then one concave spherical mirror focuses the beam on the exit slit, and a laser power meter measures the power of the beam passing through the exit slit. The grating is mounted on a rotator. The position of the two slits are fixed. For any given grating orientation, θ_1 and θ_2 are known. The wavelength λ of the diffraction beams passing through the exit slit can be calculated using Equation 63.11. By rotating the grating and recording the power measured as a function of the corresponding λ, we can measure the spectrum. The widths of the two slits are Δs_1 and Δs_2, respectively, and are adjustable. The three mirrors image the entrance slit on the exit plane. The image width $\Delta s_1'$ of the entrance slit is proportional to Δs_1. Equation 63.15 gives the measurement resolution of a monochromator:

$$\Delta s \frac{d\lambda}{ds} = \frac{\Delta s d\lambda}{f\ d\theta_2} \tag{63.15}$$

where $d\lambda/ds$ is the linear dispersion resolution, Δs equals the larger of $\Delta s_1'$ and Δs_2. $d\lambda/d\theta_2$ is the inverse of the angular resolution of the grating used, and f is the focal length of the focusing mirror. Equation 63.15 shows that reducing the widths of the two slits can increase the measurement resolution. However, the slits must be wide enough to allow enough laser power passing through for measurement. The grating rotation angular resolution also affects the measurement resolution of a monochromator. The resolution of commonly used monochromators is from 0.1 to 1 nm. Monochromators usually have a moderate price and measurement resolution. A product-oriented description of monochromators can be found in manufacturers' catalogs such as Reference 7.

Scanning Fabry-Perot Interferometer

Another widely used optical spectrum analyzer is a scanning Fabry-Perot interferometer (SFPI). An SFPI consists of two slightly wedged transparent plates with flat surfaces as shown in Figure 63.10. The two inner surfaces of the plates are set parallel to each other and are high-reflecting coated. The distance D between the two inner surfaces can be adjusted by a piezoelectric device. The two outer surfaces have a

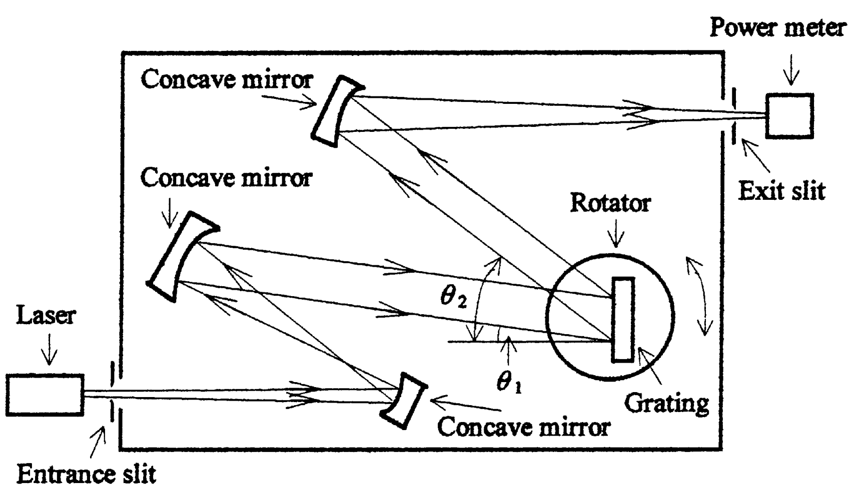

FIGURE 63.9 Scheme of a simple monochromator.

small angle between them, so that reflections of the two outer surfaces can not interfere with the reflections of the two inner surfaces. The medium between the two plates is usually air with a unit refractive index. The laser beam under measurement is collimated by a lens and incident on the SFPI. The beam transmitted through the SFPI is focused by another lens onto the photodetector of a laser power meter. When a beam with unit amplitude is incident at angle θ on the inner surface of an SFPI, multiple reflections take place at the two inner surfaces and produce a series of transmitted beams whose amplitudes fall off progressively. In Figure 63.10, only three incident rays with a few reflections are plotted. The phase difference between two successive transmitted beams is:

$$\Delta\phi = \frac{4\pi D}{\lambda\cos(\theta)} \tag{63.16}$$

Interference occurs among the amplitude of the transmitted beams. The intensity of the combination of the transmitted beam is given by:

$$I = \left| T \sum_{k=0}^{\infty} R^{k} \exp(-ik\Delta\phi) \right|^2 \tag{63.17}$$

where R and $T = 1 - R$ = the power reflectivity and transmission coefficient of the inner surfaces of the SFPI, respectively, and the reflectivity of the outer surfaces of the SFPI is neglected. The laser power meter measures the power of the transmitted beams. Note that Equation 63.8 can be reduced to Equation 63.17 by letting the amplitude → T, $\rho \to R < 1$, and $N \to \infty$. Therefore, the I obtained in Equation 63.17 can also be described by the curve shown in Figure 63.8. The full width at half the maximum (FWHM) power of I can be found by solving Equation 63.17. The result is:

$$\Delta\phi_{\text{FWHM}} = 4\sin^{-1}\left(\frac{1-R}{2R^{1/2}}\right) \tag{63.18}$$

When R is close to 1, the right-hand side of Equation 63.18 is close to zero. We have:

$$\Delta\phi_{\text{FWHM}} = \frac{2(1-R)}{2R^{1/2}} \tag{63.19}$$

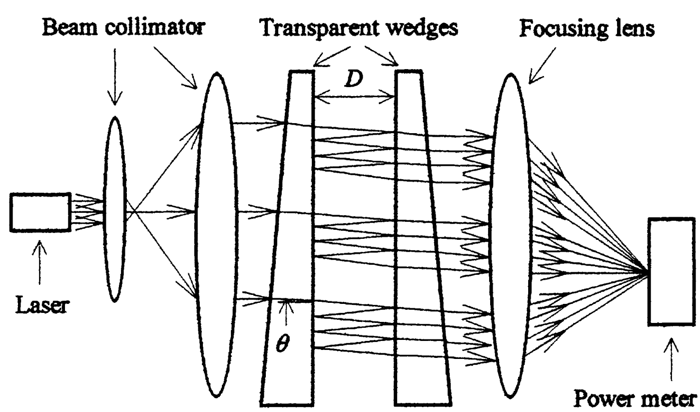

FIGURE 63.10 Scheme of a scanning Fabry-Perot interferometer. Only three incident rays and a few reflections are plotted.

Equation 63.19 shows that the fringe width of I reduces as R is increased, because larger R results in more reflections between the two inner surfaces of the SFPI. In an SFPI, the beam is usually arranged to incident at normal on the inner surface. θ becomes zero. Combining Equations 63.10 and 63.16 results in:

$$\lambda = \frac{2D}{m} \tag{63.20}$$

where λ is the wavelength at which the peak of I appears. Figure 63.8 shows that an SFPI functions like a multibandpass filter. The central wavelengths of the bands (fringes) are given by Equation 63.20 and can be adjusted by adjusting D. The FWHM of the bands is given by Equation 63.19. The spacing between two adjacent bands in terms of wavelength can be obtained by differentiating Equation 63.20 with respect to m, eliminating m and letting $\Delta m = 1$. The result is:

$$\Delta\lambda = \frac{\lambda^2}{2D} \tag{63.21}$$

$\Delta\lambda$ is known as the free spectral range (FSR) of an SFPI. The laser beam under measurement must have a wavelength bandwidth smaller than the FSR to ensure that the beam can transmit only through one band. When D is scanned, the transmitted wavelength is scanned, and the laser power meter measures and outputs the beam spectrum. The measurement resolution of an SFPI is limited by $\Delta\phi_{\mathrm{FWHM}}$. Most SFPIs have an $R > 0.95$ to reduce the $\Delta\phi_{\mathrm{FWHM}}$. The characteristics of an SFPI can be described by the fringe finesse F, defined as:

$$F = \frac{2\pi}{\Delta\phi_{\mathrm{FWHM}}} = \frac{\pi R^{1/2}}{1-R} \tag{63.22}$$

where 2π is the period of the fringes given by Equation 63.10 in terms of phase. An SFPI usually has a resolution of FSR/100. For $\lambda = 500$ nm and $D = 5$ mm, the FSR is 0.025 nm, and the resolution is 0.00025 nm. Compared with monochromators, SFPIs are more expensive, and they have much higher resolution and a much smaller wavelength range.

More information about SFPIs can be found in many advanced optics textbooks such as Reference 5 and Chapter 6.5 of this handbook. A product orientated description of Fabry-Perot interferometers can be found in manufacturers' catalogs such as Reference 8.

63.4 Measurement of Laser Wavelength

For single-mode and narrow-linewidth lasers, the spectrum measurement reduces to wavelength measurement. Laser wavelength can be measured to a higher accuracy by the use of techniques that are not much different from those used to measure the spectrum. A laser wavemeter is an instrument designed to measure the wavelength without knowing the details of the spectrum.

Michelson CW Laser Wavemeter

Figure 63.11 shows the scheme of a widely used Michelson CW laser wavemeter that consists of a Michelson interferometer (MI), a laser power meter, and a computer system for data processing. The MI has two optical arms formed by a beam splitter and two mirrors, respectively. Mirror M_1 can be moved by a stepper motor driving system, and thereby the arm length z_1 can be changed. The position of mirror M_2 is fixed, and the arm length z_2 cannot be changed. Two lenses collimate the laser beam under measurement. The beam splitter splits the collimated beam into two. The two beams propagate in the

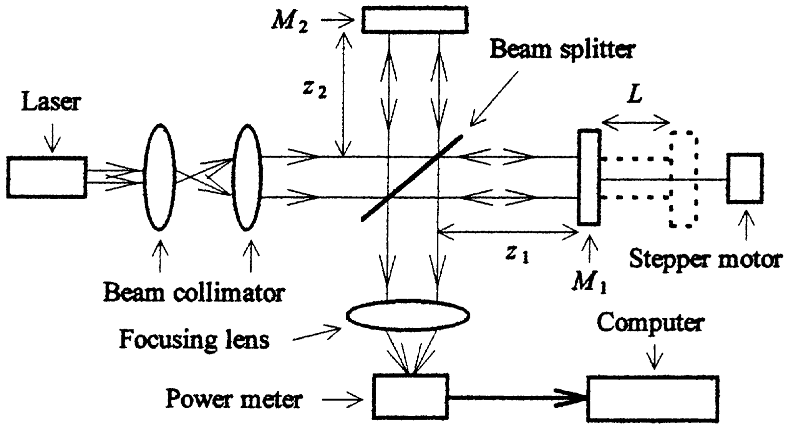

FIGURE 63.11 Scheme of a Michelson CW laser wavemeter.

two arms and are reflected by the two mirrors back to the beam splitter, respectively. Then the beam splitter recombines the two beams. Interference occurs between these two beams. Another lens focuses the combined beams onto the photodetector of a laser power meter. The computer system processes the output data of the laser power meter. The intensity I of the two combined beams can be described by Equation 63.6. As M_1 is moved, z_1 is changed, the path difference $|z_2 - z_1|$ between the two optical arms varies, and I varies periodically. The computer counts the number of the varying period of I, known as *counting the fringes*. Equation 63.23 relates the wavelength λ under measurement, M_1 moving distance L, and the counted fringe number $m + \Delta m$ by:

$$(m + \Delta m)\lambda = 2L \tag{63.23}$$

where m = an integer, Δm = a fraction, and the factor of 2 is introduced because the beam round trip distance is considered. A He-Ne laser with accurately known wavelength λ_H is used as a calibration source. For the He-Ne laser, there is the relation:

$$(m_H + \Delta m_H) = 2L \tag{63.24}$$

where m_H is another integer and Δm_H is another fraction. Combining Equations 63.23 and 63.24 results in:

$$\lambda = \frac{m_H + \Delta m_H}{m + \Delta m}\lambda_H \tag{63.25}$$

For L = 500 mm and $\lambda \approx 500$ nm, Equations 63.23 and 63.24 give $m \approx 2 \times 10^6$ and $m_H \approx 2 \times 10^6$. If Δm and Δm_H can be counted to an accuracy of 0.1, Equation 63.25 can provide six significant digits. Thus, λ can be calculated to a relative accuracy of about 10^{-6}. The commonly used commercial Michelson CW laser wavemeters have a relative measurement accuracy from 10^{-4} to 10^{-7}. The measurement range is usually from 400 nm to 1.1 μm, limited by the spectral range of the silicon photodetector used.

Steadily moving M_1 over a distance of 500 mm or so can take several seconds, and the computer is counting fringes during the entire moving period of M_1. Several seconds is much longer than the pulse duration of most pulsed lasers. Thus, the computer will miss fringes in the period of time between two successive pulses when measuring the wavelength of a pulsed laser, and the measurement result will be erroneous. To measure the wavelength of pulsed lasers, the laser wavemeter must not have any moving parts and must be capable of taking data instantaneously.

More information about MIs can be found in many advanced optics textbooks such as Reference 5 and Chapter 6.5 of this handbook. Reference 9 presents a comprehensive study about the design and development of a MI CW laser wavemeter that achieves an accuracy of a few parts in 10^9.

Pulsed Laser Wavemeter

Figure 63.12 shows the scheme of a Fizeau pulsed laser wavemeter, which consists of a Fizeau wedge, a charge coupled device (CCD) linear sensing array with 1024 pixels, a computer system for data processing, and an optical collimation system. The Fizeau wedge is made of a transparent material such as glass. The wedge has two flat surfaces. The angle α between the two surfaces is a few milliradians. The optical thickness $l(x)$ of the wedge is about 2 mm and varies linearly along the wedge. The optical system collimates the laser beam under measurement. The collimated beam is incident on the wedge. Both surfaces of the wedge reflect the incident beam. The two reflected beams form tens of spatial interference fringes on the CCD array. The CCD array detects the interference fringes and sends the data to the computer for processing. A Fizeau wavemeter does not have any moving parts and can measure the wavelength of pulsed lasers. It can be shown that the fringe period p is proportional to the wavelength λ under measurement by:

$$p = F_1(\alpha)\lambda \tag{63.26}$$

where $F_1(\alpha)$ is a function of α. A He-Ne laser with accurately known wavelength λ_H is used separately as a calibration source. The He-Ne laser also forms spatial interference fringes on the CCD array with a fringe period p_H proportional to λ_H by:

$$p_H = F_1(\alpha)\lambda_H \tag{63.27}$$

The data processing algorithm used in Fizeau wavemeters has two steps. λ is first calculated by combining Equations 63.26 and 63.27:

$$\lambda_1 = p\frac{\lambda_H}{p_H} \tag{63.28}$$

In Equation 63.28, the symbol λ_1 denotes the wavelength calculated in the first step because λ_1 is still not accurate enough. The data processing algorithm can calculate the fringe period p and p_H to an accuracy of higher than $10^{-4}p$ and $10^{-4}p_H$ utilizing the 1024 sensing data provided by the CCD array. Thus, Equation 63.28 can provide λ_1 to an accuracy higher than $10^{-4}\lambda_1$, and λ must fall somewhere inside the range:

$$\lambda_1 - 10^{-4}\lambda_1 < \lambda < \lambda_1 + 10^{-4}\lambda_1 \tag{63.29}$$

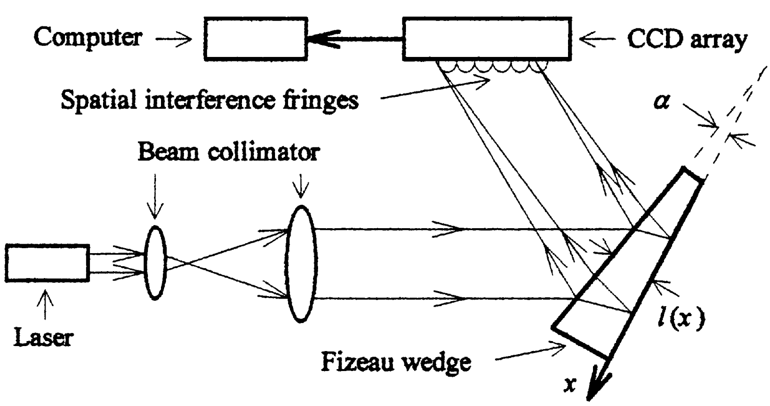

FIGURE 63.12 Scheme of a Fizeau pulsed laser wavemeter.

Any point on the CCD array corresponds to a point on the wedge with a certain optical thickness $l(x)$. It can be shown that at a given point on the CCD array, there is such a relation for λ and λ_H that:

$$(m + \Delta m)\lambda = F_2[l(x)] \tag{63.30}$$

$$(m_H + \Delta m_H)\lambda_H = F_2[l(x)] \tag{63.31}$$

where m and m_H are two integers and are unknown, Δm and Δm_H are two fraction orders at this point on the CCD array and can be measured, $F_2[l(x)]$ is a function of $l(x)$, and $l(x)$ is the thickness of the wedge at the point corresponding to the point on the CCD array. In the second step of the data processing, λ is calculated by combining Equations 63.30 and 63.31. The result is:

$$\lambda_2 = \frac{m_H + \Delta m_H}{m + \Delta m}\lambda_H \tag{63.32}$$

In Equation 63.32, we use the symbol λ_2 to denote the wavelength calculated, because λ_2 is still not necessarily equal to λ. A number of test m and m_H values are inserted into Equation 63.32 and result in a number of different λ_2 values. It can be shown that only one combination of m and m_H can result in a λ_2 that falls inside the range of Equation 63.29. This λ_2 is accepted as λ. m and m_H are of the order of 10^5, and Δm and Δm_H can be measured to an accuracy of 0.01. Therefore, Equation 63.32 can provide λ to an accuracy of $10^{-6}\lambda$. The commercial Fizeau pulsed wavemeters have a measurement accuracy of $10^{-5}\lambda$. The measurement spectral range is from 400 nm to 1.1 μm, limited by the CCD array, which is made of silicon material. More information about Fizeau wedges can be found in many advanced optics textbooks such as Reference 5 and Chapter 6.5 of this handbook. Readers interested in learning more about the design and development of Fizeau pulsed wavemeters will find Reference 10 to be a good starting point.

63.5 Instrumentation and Components

Table 63.1 lists a few companies manufacturing photodetectors, laser power meters, diffraction gratings, monochromators, scanning Fabry-Perot interferometers, Michelson CW laser wavemeters, and Fizeau pulsed laser wavemeters. The price ranges of these instruments and components are also listed in Table 63.1. Table 63.2 lists the address of these companies. These two tables are far from exhaustive. Interested readers could consult two excellent books, *Laser Focus World Buyers Guide* [11] and *Photonics Buyers' Guide* [12]. These two books are published annually and contain up-to-date information about most optical and laser manufacturers in U.S.A and their products.

TABLE 63.1 Manufacturers, Components and Instruments, and Price Ranges

Product Description	Manufacturer	Approx. Unit Price
Thermopile for laser power meters	Coherent, Newport	\$500–\$2,000
Photodiode head for laser power meters	Coherent, Newport	\$500–\$1,000
Pyroelectric probe head for laser power meters	Coherent, Newport	\$900–\$1,200
Laser power meter (including one detector head)	Coherent, Newport	\$1,00–\$5,000
Integration sphere	Newport, Oriel	\$1,300–\$2,500
Diffracting grating	Milton Roy	\$100–\$4,000
Monochromator	Milton Roy, Oriel	\$1,000–\$7,000
Scanning Fabry-Perot interferometer	Burleigh Instruments	\$7,000–\$16,000
Michelson CW laser wavemeter	Burleigh Instruments	\$7,000–\$25,000
Fizeau pulsed laser wavemeter	New Focus	\$1,200

TABLE 63.2 Addresses of Companies Listed in Table 63.1

Burleigh Instruments, Inc. Burleigh Fishers, NY 14453 Tel: (716) 924-9355	Coherent, Inc. Photonics Division 2303 Lindbergh St. Auburn, CA 95602 Tel: (530) 889-5365	Milton Roy Instruments 820 Linden Ave. Rochester, NY 14625 Tel: (716) 248-4000
New Focus, Inc. 2630 Walsh Ave. Santa Clara, CA 95051 Tel: (408) 980-8088	Newport Corp. 1791 Deere Ave. Irvine, CA 92714 Tel: (800) 222-6440	Oriel Corp. P.O. Box 872, 250 Long Beach Blvd. Stratford, CT 06497 Tel: (203) 377-8282

63.6 Defining Terms

Continuous wave (CW) laser power: Laser power that does not vary with time.
Pulsed laser power: Laser power that lasts only a short period of time.
Laser spectrum: Laser power-wavelength profile.
Laser wavelength: The spatial period of a laser electric field.

References

1. J. Hecht, *The Laser Guidebook, 2nd ed.*, New York, McGraw-Hill, Inc., 1992
2. R. DeMeis, Choose the right detector and meter to test beam strength, *Laser Focus World*, 31 (6): 105–113, 1995.
3. W. DeCosta, Power and energy meters meet measurement needs, *Laser Focus World*, 31 (5): 199–203, 1995.
4. G. Shelmire, How to make accurate laser output measurements, *Laser Focus World*, 29 (4): 241–248, 1993.
5. M. Born and E. Wolf, *Principles of Optics, 6th ed.*, Oxford, Pergamon Press, 1980.
6. C. Palmer (ed.), *Diffraction grating handbook*, *2nd ed.*, Rochester, Milton Roy Instruments, 1993.
7. Product catalog, Oriel Corp., Stratford, CT.
8. Product catalog, Burleigh Instruments, Inc., Fishers, NY.
9. J. Monchalin, M. Kelly, J. Thomas, N. Kurnit, A. Szoeke, F. Zernike, P. Lee, and A. Javan, Accurate laser wavelength measurement with a precision two-beam scanning Michelson interferometer, *Appl. Opt*., 20, 736–757, 1981.
10. B. Faust and L. Klynning, Low-cost wavemeter with a solid Fizeau interferometer and fiber-optic input, *Appl. Opt*., 30, 5254–5259, 1991.
11. *Laser Focus World Buyers Guide*, Nashua, NH, PennWell Publishing Co., 1996.
12. *Photonics Buyers' Guide*, Pittsfield: Laurin Publishing Co., 1996.