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Course Title: Laser Theory

A report on

Cavity Optics

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Chapter 6

Cavity Optics

To ensure sustained laser action, mirrors are required in most cases. Mirrors form a resonating cavity which traps the photons produced by the gain medium and assists the laser action. The mirrors are often not just two simple flat mirrors, instead different configurations of mirrors are used in practical lasers to enhance the stability and gain. In this chapter we explore the cavity resonators in detail.

6.1 Requirements For A Resonator

Resonator: An optical cavity or optical resonator is an arrangement of mirrors that forms a standing wave cavity resonator for light waves. Optical cavities are a major component of lasers, surrounding the gain medium and providing feedback of the laser light. A laser requires a resonator (or laser cavity), in which the laser radiation can circulate and pass a gain medium which compensates the optical losses.

Necessity of a resonator: The ratio of stimulated rate of emission and spontaneous rate of emission is given by

$$\frac{r_{\text{stimulated}}}{r_{\text{spontanous}}} = \frac{c^3\rho}{8\pi h\nu^3}, \tag{6.1}$$

where ρ is the energy density of the photons and ν is the frequency of the emission. From Eq. 6.1 we can conclude that for stimulated emission to exceed the spontaneous rate (which is the pre-requisite for laser action), ρ must be extremely high. To ensure the required high value of photon flux, cavity mirrors are required, which will increase the number of photons in each oscillation by trapping them.

Basic components of a resonator: The basic components of a laser cavity is shown in Fig. 6.1. The total reflector has a very high reflectivity. It reflects almost all the light incident on it. Hence it is called *High Reflector (HR)*. On the other hand the partial reflector has less reflectivity than the HR. It transmits a part of the incident light on it, which is the output of the laser, hence it is called *Output Coupler (OC)*.

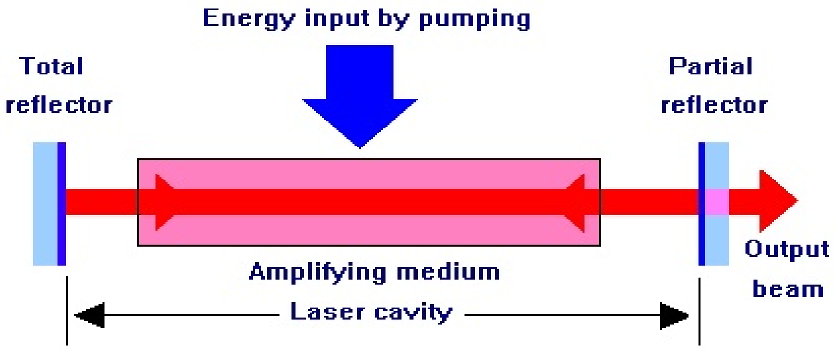

Figure 6.1: Components of a laser cavity

The only exception for the need of a resonator is found when the lasing medium has extremely high gain, in which case gain in single pass is sufficient to maintain lasing action. Example of this type laser is copper-vapor laser, which requires minimal or no feedback.

6.2 Gain And Loss In A Cavity

When the total losses in the laser exceeds the gain of the medium, the laser will fail to oscillate. The total loss in a laser system is due to a number of different processes, the most important ones include:

1. Transmission at the mirrors (defines the output of the laser)

2. Absorption and scattering at the mirrors

3. Absorption in the laser medium due to transitions other than the desired transition

4. Scattering at optical inhomogeneities

5. Diffraction losses at the mirrors

From Fig. 6.2, we can see that even small losses have a large effect on the output power of a laser. As a result, losses in a real laser must be kept as low as possible. Mirrors are often sealed directly into the ends of the tube so that there were no windows in the optical path to increase loss. The example of this kind cavity is found in He-Ne laser. Though in many lasers, cavity mirrors must be isolated from the discharge to prevent attack from the plasma.

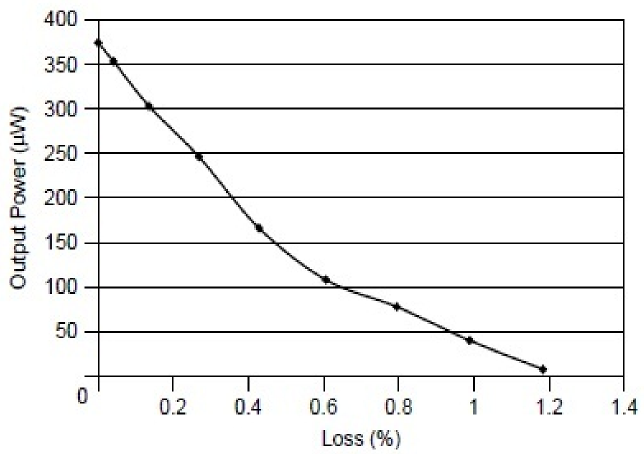

Figure 6.2: Effect of cavity loss on output power in a laser.

External optics: External optics is required when a laser uses a wavelength selector. In these cases, the ends of the plasma tube must be capped with an optical window. To minimize losses, optical windows are angled at the Brewster angle, which polarizes the output of the laser since loss is essentially zero in one polarization and very significant in the other polarization. Most tubes contain two windows, one at each end of the tube, and each must be aligned in the same optical axis. As Fig. 6.3 shows, where two Brewster windows are used, they should be oriented such that the intracavity beam does not shift overall position as it passes through both windows.

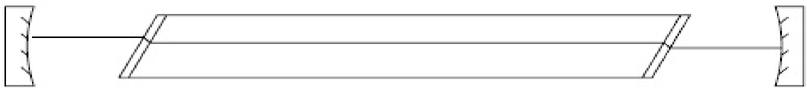

Figure 6.3: Brewster window in a gas laser.

The optimal angle can be determined from the Fresnel equation as the angle at which reflection is reduced to zero. This angle depends on the index of refraction of the window material itself according to

$$\theta = tan^{-1}\left(\frac{n_2}{n_1}\right) \tag{6.2}$$

where n_2 is the index of refraction of the window and n_1 is the index of refraction of the surrounding media.

6.3 Resonator As An Interferometer

Interferometer: Any of several optical, acoustic, or radio frequency instruments that use interference phenomena between a reference wave and an experimental wave or between two parts of an experimental wave to determine wavelengths and wave velocities, measure very small distances and thicknesses, and calculate indices of refraction.

A laser cavity generally acts as an interferometer into which an integral number of waves must fit. The cavity is resonant at wavelengths such that the number of waves inside the cavity is an integer–these are standing waves inside the cavity. At all other wavelengths, destructive interference causes any wave inside the cavity to be extinguished. Several important terms related to laser resonator are defined below:

Longitudinal modes: The resonant wavelengths which can create standing wave inside the laser cavity are called longitudinal modes.

Free spectral range: The modes of the resonator are spaced apart at regular intervals of frequency. The spacing of modes is called the free spectral range (FSR) of the interferometer. This is shown in Fig. 6.4.

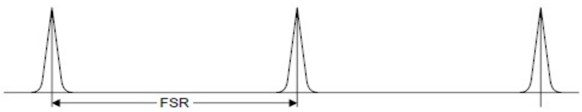

Figure 6.4: Free spectral range (FSR) of an interferometer.

If the distance between the two cavity mirrors is L, the condition for the standing wave in the cavity is

$$m\frac{\lambda}{2} = L \tag{6.3}$$

where m is an integer, called mode number. So the free spectral range (FSR) of resonant modes in the cavity is given by

$$\Delta\nu = m\frac{c}{2L} \tag{6.4}$$

where $\Delta\nu$ is the FSR in hertz.

Spectral width and Finesse: The sharpness of the resonant peaks for an interferometer (FWHM) is defined by

$$\delta = \frac{\nu_f}{F}, \tag{6.5}$$

where δ is the spectral width (FWHM) in hertz, ν_f is the frequency of the first mode ($m = 1$), and F is the finesse of the interferometer. Finesse is the ratio of the mode separation (FSR) to the spectral width. Finesse is a function of the reflectivity of cavity mirrors:

$$F = \frac{\pi\sqrt{R}}{1 - R} \tag{6.6}$$

where R is the total reflectivity of both mirrors. As the reflectivity of cavity mirrors increases, the spectral width of the peaks becomes very narrow, and in most lasers the reflectivity of the cavity mirrors is very large.

6.4 Longitudinal Modes

Doppler broadening in gas lasers leads to a gain curve in which the gain of the laser peaks at a center wavelength. The laser will oscillate at only those wavelengths, which satisfy the following two conditions:

- The gain at that wavelength must be more than the total loss in the laser.
- The laser cavity must be resonant at that wavelength.

So the actual output of the laser will be a series of closely spaced wavelengths which follow the general envelope of the curve and exist at points where the gain exceeds losses in the cavity. The possible output is shown in Fig. 6.5. The number of modes that will oscillate simultaneously may be determined by dividing the spectral width of the laser by the FSR.

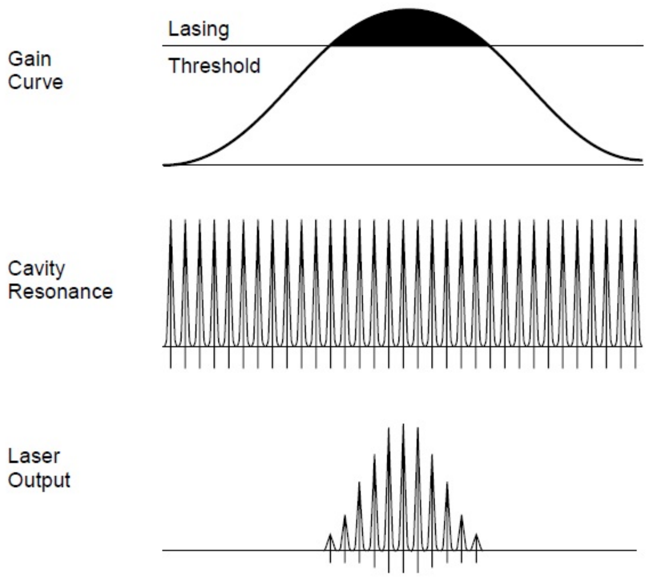

Figure 6.5: Origin of longitudinal modes.

6.5 Wavelength Selection In Multiline Lasers

For most applications, it is desired to operate a laser on a single wavelength. Single-line operation on these lasers can be achieved by selective feedback in which the optics are designed to reflect only a single wavelength. Different methods which can be employed to select a specific wavelength from the multiple oscillating wavelengths in the laser cavity, are discussed hereafter.

First Method The first method of wavelength selection is to design the cavity optics themselves to be highly reflective at a single wavelength (or a set of chosen wavelengths) and transmissive (which represents a loss in the cavity) at all others. This method is commonly used with heliumneon lasers, in which it is necessary to suppress the strong infrared transition to boost output on the 632.8 nm red line. In a green HeNe laser, optics are designed carefully to reflect light centered at 543.5 nm but to transmit wavelengths such as the red.

Second method The addition of a prism between the plasma tube and the HR allows selection of a single line, since only one unique wavelength can make the path through the prism, reflecting off the HR and back through the prism in exactly the same path. By changing the angle of the prism and HR relative to the lasers axis, this arrangement allows tuning through a large range.

Third method the HR may be replaced by a diffraction grating which, in a similar manner, reflects only a single wavelength of light back into the plasma tube for amplification. Practically prisms have lower losses than diffraction gratings and so are used in lower-gain (e.g., argon) lasers, where even small losses can significantly impair output power (or halt oscillation completely). Diffraction gratings, on the other hand, feature higher angular dispersions of incident wavelengths and so are easier to tune when multiple wavelengths are close together or the medium has a large continuous wavelength range, such

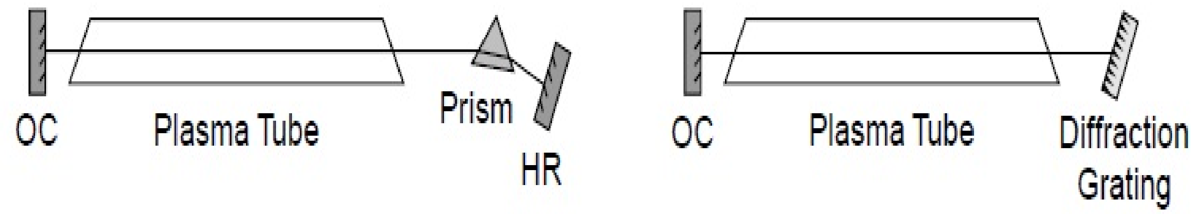

Figure 6.6: Wavelength-selection optics.

as a dye laser. Figure 6.6 shows different wavelength selection optics.

6.6 Single-Frequency Operation

An etalon is a compact interferometer. It can be used to ensure single-frequency operation of a laser. A laser can be made to operate on a single mode (and hence a single frequency), if an etalon is designed such that it is resonant only at wavelengths spaced farther apart than the gain bandwidth of the laser.

For example: the gain bandwidth of the argon laser (broadened primarily by Doppler effects) is about 5 GHz. Inside this 5 GHz range there are many longitudinal modes. For a 90 cm laser cavity the modes will be spaced 167 MHz apart, for a total of 30 modes. If an etalon is designed such that it is resonant only at wavelengths spaced farther apart than 5 GHz, the laser can be made to operate on a single frequency. Only when a resonant peak of the etalon and a longitudinal mode of the laser have the same frequency will the laser have enough gain to oscillate. Figure 6.7 depicts this concept schematically.

Practical considerations: A practical etalon consists of a glass slide (usually quartz, to reduce absorption) coated on either side with a slightly reflective thin-film coating. The etalon acts as an interferometer which is resonant only at certain wavelengths. It is inserted inside the cavity of a laser, which has a wavelength selector in the cavity so that only a single line oscillates. The

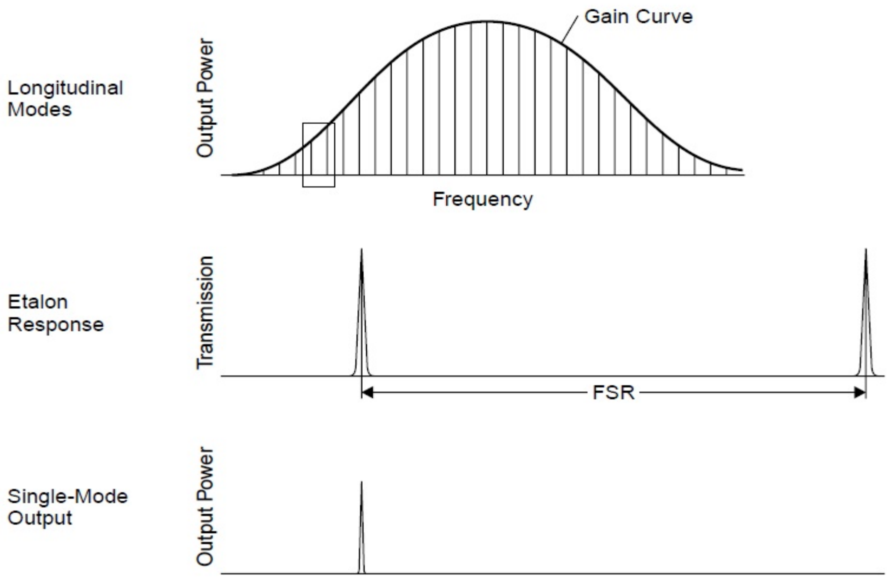

Figure 6.7: Selection of a single mode with an etalon.

etalon is always tilted with respect to the optical axis of the laserwere it not, it would act as a simple mirror, which would not select wavelength. The use of a etalon in a gas laser is shown in Fig. 6.8.

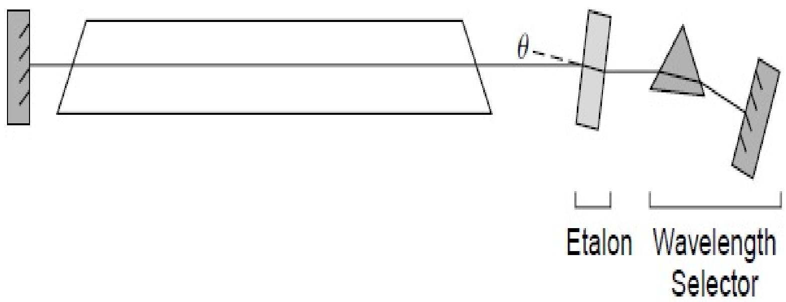

Figure 6.8: Intracavity etalon use in a gas laser.

Mathematical expressions: Figure 6.9 shows that an incoming beam (beam 1) enters the etalon and is refracted. It refracts again upon exit and leaves the etalon as beam 2, but a portion of the beam (about 20% for a typical etalon used with a low-gain gas laser) is reflected from the coating on the side of the etalon and is reflected back into the etalon along path ab. The beam is reflected again, becoming bc, and is refracted upon exit, becoming beam 3. If the difference in path length between beams 2 and 3 is an integral number of wavelengths, constructive interference occurs and the transmission of the etalon is seen as nearly 100%. Conversely, when the paths are not separated by an exact number of wavelengths, beam 3 exits the etalon with a phase different from that of beam 2. Destructive interference occurs in this case, and the transmission is seen as low for the filter.

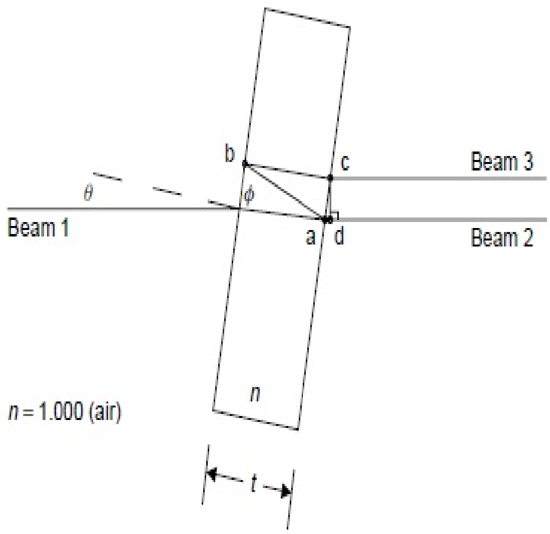

Figure 6.9: Intracavity etalon use in a gas laser.

We can express the condition for constructive interference (i.e., maximum transmission) as the point where the path length for beam 3 is an integer number:

$$N\lambda = n(distance\ a - b + distance\ b - c) + distance\ a - d \tag{6.7}$$

where N is an integer. Geometrically, we can express this (the condition for exit beams to all be in phase) as a function of the angle at which incident light is refracted in the etalon:

$$N\lambda = 2nt\ cos\phi. \tag{6.8}$$

If we use small angle approximation, we can replace ϕ with θ/n. Finally we get the spacing of resonant peaks (the FSR) of this etalon is found to be

$$FSR = \frac{c}{2nt}. \tag{6.9}$$

Walk-off loss: Tuning of the etalon can be accomplished by changing the angle of the device with respect to the optical axis of the laser. But the interfering beams (beams 2 and 3 in the figure) will separate (distance cd increases) as the etalon is tilted, resulting in what is termed walk-off loss. This complication usually prevents angle tuning of an etalon in a low-gain laser, but there is an alternative method of temperature tuning for this types of etalons. By controlling the temperature carefully, any one of the longitudinal modes within the gain bandwidth can be selected.

Air spaced Etalon: Etalons may be constructed using air (or another gas) as a spacer. In this etalon two partially reflective optical windows are separated by a mechanical mount designed to keep them perfectly aligned (the two knobs protruding from the device allow alignment of the optics). The entire etalon may be tuned by either changing the angle of the entire etalon in the cavity or changing the gas and gas pressure within the device, which affects the index of refraction. The latter is usually preferred, to prevent walk-off losses.

Coherence length: Coherence length is the distance over which the phases of multiple wavelengths (longitudinal modes) in the output beam stay reasonably in phase with each other. If the output beam consists of many longitudinal modes (each at slightly different frequencies), they will interfere destructively at some point, destroying the coherence of the beam. If, on the other hand, the output beam consists of a single extremely narrow (in frequency spread) mode, the beam will stay coherent for a great distance. Coherence length is hence related to spectral width: The wider the spectral width, the shorter the coherence length. It is defined (in units of meters) as

$$l_c = \frac{c}{\Delta\nu}, \tag{6.10}$$

where $\Delta\nu$ is the spectral width.

6.7 Characterization Of A Resonator

Resonators may be characterized in terms of frequency or wavelength behavior by a number of parameters, including finesse and free spectral range (discussed earlier). In terms of optical loss, two additional parameters are also used to characterize the resonator: the total loss coefficient (γ_r) and the photon lifetime (τ_c).

Total loss coefficient: Total loss coefficient is the sum of all the loss components in the laser medium. Different loss coefficients are discussed hereafter.

Losses at each mirror are expressed as loss coefficients (γ_1 for one mirror and γ_2 for the other mirror) as if the loss was distributed throughout the entire laser:

$$\gamma_1 = \frac{ln(1/R1)}{2l}, \tag{6.11}$$

where R_1 is the reflectivity of the mirror and L is the cavity length.

The other primary loss, due to absorption or scattering in the lasing medium, and designated γ_a, is usually given as a property of the medium itself in units of m^{-1} or cm^{-1}. Where the gain medium spans the entire distance between cavity mirrors, such as the case with most helium-neon gas lasers, one may simply use this number directly; however, where the gain medium is shorter than the cavity, e.g., in a solidstate laser where the rod is relatively short in length, we must spread out the loss across the cavity as per the following approximation:

$$\gamma_a = \frac{2^* \gamma^*_{\mathrm{rod}} l_{\mathrm{rod}}}{2l}. \tag{6.12}$$

In this case the numerator evaluates to the (dimensionless) total loss for a round-trip through the rod which is then spread out across the length of the cavity ($2l$).

So now an overall distributed-loss coefficient (γ_r) can be used to describe the total cavity losses as

$$\gamma_r = \gamma_a + \gamma_1 + \gamma_2. \tag{6.13}$$

Photon lifetime: Photon lifetime (τ_c) refers to the average time that a photon spends in the cavity of a laser before passing through the output coupler (OC) and becoming part of the output beam or being absorbed in the lasing medium itself. Photon lifetime is given by

$$\tau_c = \frac{1}{c\gamma_r} \tag{6.14}$$

Photon lifetime is also related to the spectral linewidth of laser output by

$$\Delta\nu = \frac{1}{2\pi\tau_c}. \tag{6.15}$$

This is also a mechanism by which laser lines are broadened, called *lifetime broadening*.

6.8 Gaussian Beam

The Gaussian output beam (also called a TEM_{00} beam) has the lowest electromagnetic mode structure possible. It is spatially the purest laser beam possible and is characterized by the lowest divergence of any mode; it is limited only by diffraction. The beam is characterized in intensity in both axes by

$$I(y) = I_0\, exp\left(-\frac{2y^2}{w^2}\right), \tag{6.16}$$

where I_0 is the maximum intensity of the beam, y the distance from the center of the beam, and w the radius of the beam. From the Eq. 6.16 it can be noted that the radius of the beam (also called the spot size) expands as we move away from the laser, so the calculation of intensity applies to a cross section of the beam at an arbitrary distance away from the laser.

Beam waist and spot size: Inside a cavity consisting of two concave mirrors with radius of curvature equal to exactly the distance between them (an arrangement called a symmetric confocal resonator) the beam converges at the center of the gain medium in what is called the

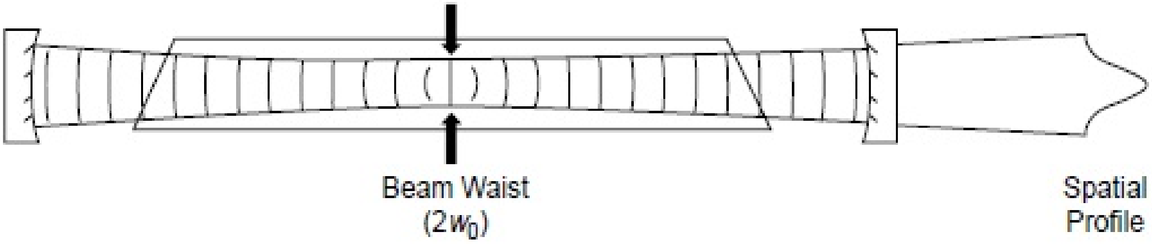

Figure 6.10: Gaussian beam inside a laser cavity.

beam waist denoted as w_0 in Fig. 6.10. This is the smallest spot size of the beam, and the width of the laser beam at this point is governed by the wavelength and the separation of the cavity mirrors according to

$$w_0 = \left(\frac{\lambda L}{2\pi}\right)^{1/2} \tag{6.17}$$

where λ is the wavelength of the laser and L is the distance between the cavity mirrors. It should also be noted from Fig. 6.10 that the volume of the amplifier utilized in the laser process is not the entire volume of the gain medium. A Gaussian beam in a laser cavity does not utilize the entire lasing volume and will hence not render the highest output power for a given laser. Higher-order modes can often utilize the gain medium more effectively than a Gaussian (TEM_{00}) beam can.

Angle of divergence: Inside the cavity, the wavefronts of the Gaussian beam do not stay constant but rather, deviate. At the beam waist wavefronts are plane, but as they move toward the cavity mirrors the shape changes to match that of the radius of curvature of the mirrorsessentially that of a spherical wave. Wavefronts exiting the laser through the output coupler also have this characteristic shape, and upon exiting through the OC diverge at an angle of

$$\theta = \frac{\lambda}{\pi w_0} \tag{6.18}$$

where θ is the half-angle of the divergence. It defines the the divergence of the exit beam. Since divergence is a function of wavelength as well as beam waist, laser beams are inherently more collimated if they are of shorter wavelengths and have large beam waists (e.g., in the case of a large gain medium).

6.9 Resonator Stability

The definition of stability of a laser cavity is that a beam reflects perfectly back on itself and is completely trapped within the cavity. In this situation, any ray within the cavity can retrace itself exactly after one round trip through the cavity. If one mirror is partially transmitting, the beam that passes through the mirror (which becomes the output beam) continues to diverge.

Resonator parameter for stability: Stability of a laser cavity can be determined from resonator g parameters, one representing each mirror, which define the beam path relative to the entire cavity. g parameter is given by

$$g = 1 - \frac{L}{r}, \tag{6.19}$$

where L is the distance between the cavity mirrors and r is the radius of curvature. These parameters are defined in Fig. 6.11, which shows a generalized laser cavity with concave mirrors.

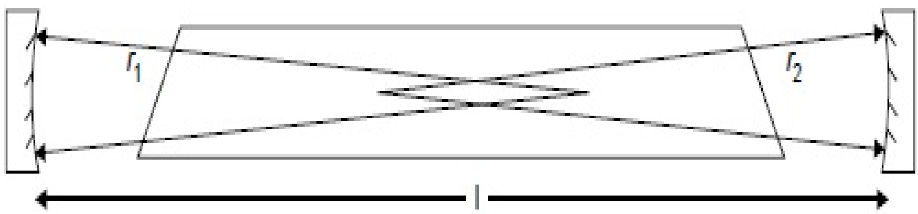

Figure 6.11: Parameters for resonator stability.

Stability, then, is defined as the condition where

$$0 \leq g_1 g_2 \leq 1 \tag{6.20}$$

where g_1 and g_2 are the g parameters for each mirror. In the case of a plane mirror, the radius is infinity, so the corresponding g parameter is 1.

6.10 Common Cavity Configurations

Different configurations are for the laser cavity. The most common configurations are discussed hereafter.

Plane mirror resonator Plane mirror resonator is a resonator with two plane mirrors (Fig. 6.12). Parameters g_1 and g_2 are both equal to unity (1), so the arrangement is stable although stability is marginal (i.e., the product of $g_1 g_2$ is 1). In practical terms, marginally stable means extreme difficulty in alignment, and a cavity that can become misaligned very easily, usually resulting in the ceasing of lasing oscillation. For this reason, two plane mirrors are rarely used.

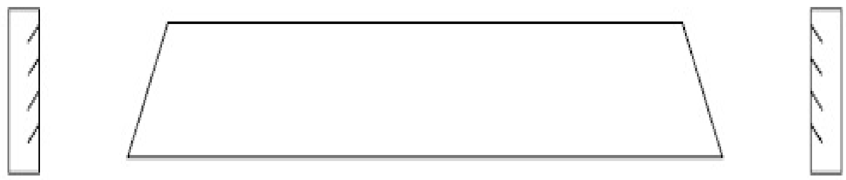

Figure 6.12: Plane mirror resonator.

Confocal resonator A true confocal arrangement (Fig. 6.13) in which the radius of both mirrors is exactly equal to the separation between the mirrors (i.e., L) has g parameters equal to $g_1 = g_2 = 0$. The product of the g parameters is hence zero again, so this arrangement is stable.

The confocal configuration yields the smallest average spot size of any stable resonator with the beam waist being $w_0^2 = L(\lambda/2\pi)$ occurring at the center of the resonator and the largest spot size $w_1^2 = L(\lambda/\pi)$ occurring at each mirror. This defines the diameter of the output beam if collimated (by a lens) at that point. The confocal arrangement

Figure 6.13: Confocal resonator.

is extremely tolerant to misalignment of either mirror. A small angular tilt of either mirror still maintains the center of curvature of one mirror on the surface of the second cavity mirror. It is also forgiving of manufacturing tolerances in the radius of the cavity mirrors. Because of this feature, it is an excellent choice for a research laser, where frequent alignment may be required or where alignment cannot be performed by rocking or other means.

Concentric resonator A concentric configuration (shown in Fig. 6.14) in which the radius of each mirror is exactly $L/2$. It represents a confocal resonator, where the radius of curvature is reduced to its lowest limit.

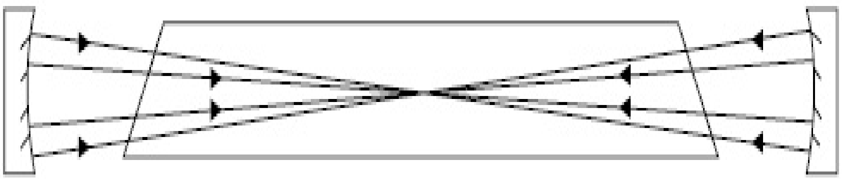

Figure 6.14: Concentric resonator.

From the point of view of stability, this cavity is stable unless the radius of curvature of the mirrors is even slightly under $L/2$, in which case the arrangement becomes unstable (this may occur due to alignment or simply, manufacturing tolerances). This arrangement also suffers from difficulties in alignment since the focus of each mirror is coincident and hence difficult to align precisely. A cavity of this type features a larger waist diameter and hence better utilization of large tube bores. Compared to the true confocal arrangement, these cavities are more tedious to align.

Spherical-Plane resonator Spherical-Plane resonator uses a combination of a long radius spherical mirror (with the radius at least equal to and sometimes much longer than the cavity length) and a plane mirror (shown in Fig. 6.15). This arrangement is the most popular for low and medium-power lasers such as HeNe and argon lasers. It is used in many commercial gas lasers (e.g., large-frame argons) where the OC is spherical and the HR plane allows the use of various optical configurations. While the OC stays in place, the rear optic may be changed to a wavelength selector for single-line use or a broadband reflector for multiline use.

Figure 6.15: Spherical-Plane resonator.

Concave-Convex resonator Concave-Convex resonator uses a a concave and a convex mirror are used (shown in Fig. 6.16). Again, this arrangement is stable within the confines set out by the g-parameter equation. Concave-convex resonators can utilize much more of the lasing volume since the smallest spot size, at the focus of the concave mirror, is outside the cavity. These types of cavities are very sensitive to misalignment, though, so are rarely used in commercial lasers.

Figure 6.16: Concave-Convex resonator.

Unstable resonator: Not all lasers use stable resonators, and for certain high-power lasers such as excimer and carbon dioxide TEA lasers, unstable resonators are a popular option. Examples of unstable lasers are shown in Fig. 6.17. Because these resonators are not stable, light is not trapped in the cavity, at least for many round trips, so this arrangement is suitable only for use with high-gain lasers.

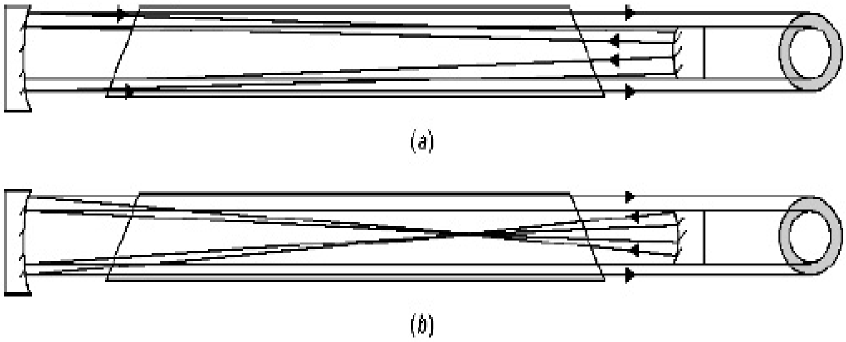

Figure 6.17: Unstable resonators.

It can be noticed from Fig. 6.17 that an unstable resonator utilizes a large volume of the lasing medium, allowing efficient extraction of energy. The biggest apparent problem with this configuration is that the shape of the beam is not Gaussian, so cannot be focused to a sharp point. In reality, it can be focused to almost as sharp a point (certainly better than many stable resonators yield when operating in high-order modes), so is quite suitable for materials-processing applications.

6.11 Spatial Energy Distributions: Transverse Modes

Transverse mode: A transverse mode of a beam of electromagnetic radiation is a particular electromagnetic field pattern of radiation measured in a plane perpendicular (i.e., transverse) to the propagation direction of the beam. Transverse modes occur in radio waves and microwaves confined to a waveguide, and also in light waves in an optical fiber and in a laser's optical resonator.

In an ideal situation, energy would be stored throughout the entire lasing medium in a consistent manner and the entire lasing volume would be utilized. In reality the nature of the cavity gives rise to electromagnetic modes in which standing waves are set up not only in the longitudinal direction (i.e., the length of the cavity; these modes vary slightly in frequency) but also in the transverse direction. These represent alternative solutions to the wave equation which defines the beam. With energy stored in various areas of the lasing medium, the patterns formed are manifested in the output beam as well, which can assume shapes such as those shown in Fig. 6.18.

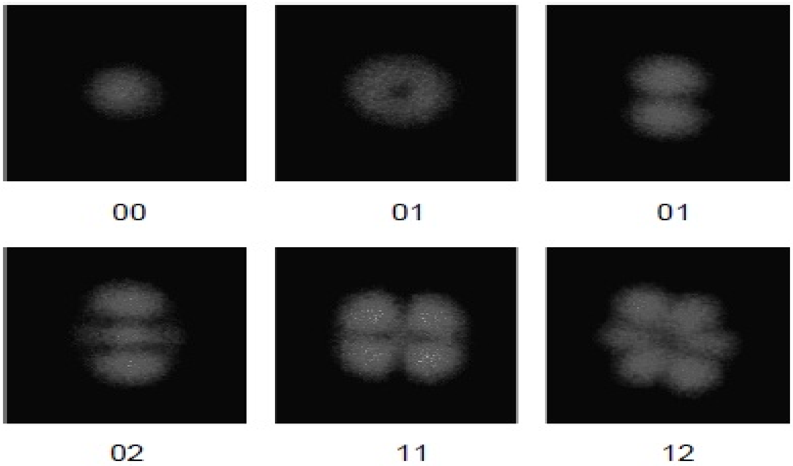

Figure 6.18: Transverse electromagnetic modes.

In many cases, the highest power output from a particular laser can be obtained on a high-order mode in which the volume of the gain medium is utilized more effectively than is possible with the TEM_{00} mode. This is evident by the fact that the TEM_{11} mode and some other higher-order modes are considerably brighter than lower-order modes shown in Fig. 6.18. This fact can be exploited (in reverse) to limit a laser to operation to TEM_{00} mode.

6.12 Limiting Modes

High-order modes consume a larger volume of the gain medium than do low-order modes. For this reason, many small-bore lasers often operate exclusively in TEM_{00} mode. This effect can be exploited to prevent a laser from oscillating in higher-order modes by placing an aperture of the proper size inside the cavity so that only the TEM_{00} mode will fit through it, as illustrated in Fig. 6.19. Higher-order modes will be extinguished because the loss imposed on them by the aperture will be greater than the gain provided by the active lasing medium.

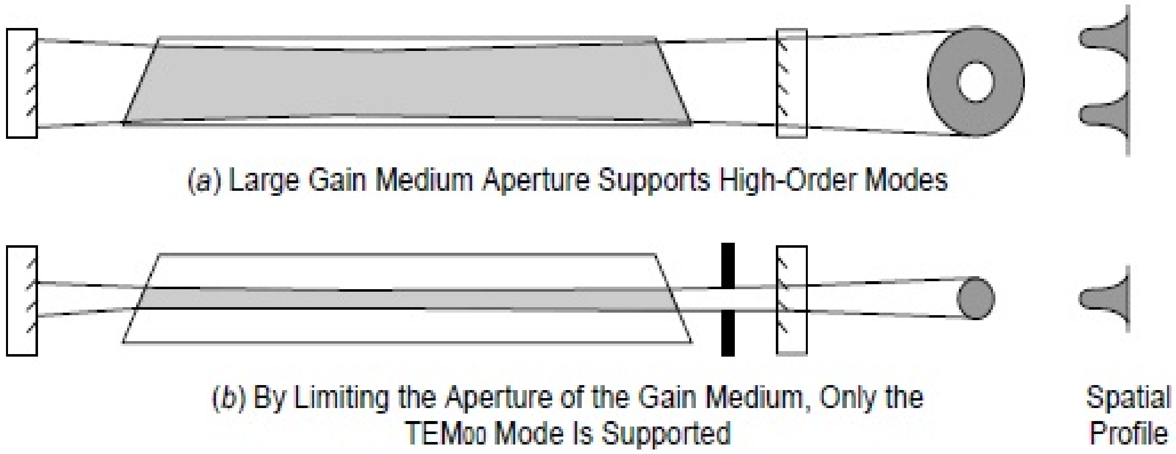

Figure 6.19: Transverse electromagnetic modes.

Lasers oscillating in high-order modes usually produce more power than do similar lasers limited to the TEM_{00} mode. Still, the beam purity of the TEM_{00} mode is often sought after, especially for applications where minimum beam divergence is required.

6.13 Resonator Alignment: A Practical Approach

Different methods are used for the alignment of cavity optics, depending upon the diameter (bore) of the laser gain medium. For large-bore lasers, a visible alignment laser is used, whereas, for small bore lasers autocollimator is used for alignment process. These two approaches are discussed hereafter.

Visible alignment laser: The alignment of large-bore lasers like carbon dioxide laser or YAG laser is relatively easier. A small visible alignment laser, such as HeNe or red diode laser can be used to align the mirrors. This technique works only for lasers where the visible alignment beam can pass through the cavity optics. The configuration is shown in Fig. 6.20. The alignment procedure involves two steps.

Alignment of the high reflector (HR) The alignment process begins by removing the output coupler (OC) and aligning the beam from the HeNe laser such that it enters the front of the laser, passes through the gain medium, reflecting off the HR back through the gain medium, and exiting the laser. When a card with a small hole in it is placed in front of a HeNe laser, the HR is easily aligned such that the beam reflected from the HR and exiting the laser is parallel to the beam entering the laser. Visually, the mirror is aligned when the reflected and original beams become one.

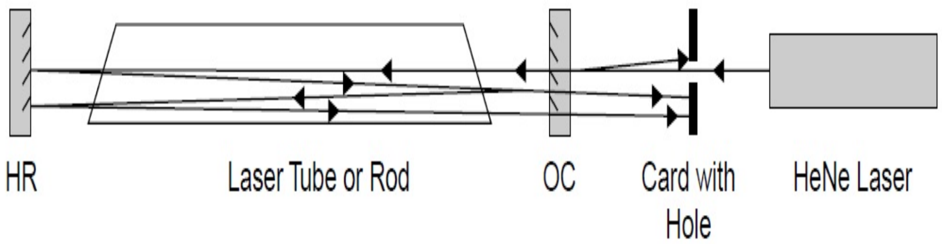

Figure 6.20: Alignment using a small HeNe laser.

Alignment of the output coupler (OC) The OC may now be replaced and aligned in a similar manner, but in this case there will be a plethora of reflections since some rays will reflect from the OC, striking the HR, and then exit to be seen on the card as shown in Fig. 6.20. Still, the the first reflection from the OC (the second brightest spot) can be identified and aligned so that all spots on the card converge to a single spot. At that point by definition, the mirrors are parallel.

Autocollimator alignment: For small-bore lasers such as HeNe and argon lasers (where the inside diameter of the plasma tube is 1 mm or less), the alignment of an external laser beam down the bore is very difficult. In many cases it is difficult to distinguish total internal reflection (from the almost parallel angle of the alignment laser) from the alignment beam itself, so an autocollimator is often used. The configuration is shown in Fig. 6.21. The steps involved in the alignment procedure are discussed next.

Alignment of the high reflector (HR) The autocollimator produces a beam of collimated light (i.e., light with parallel rays), which is then directed through the laser tube, reflected from the cavity mirror at the far end, and back through the tube to be seen by the observer. An incandescent lamp is used as a light source, and when the mirror is aligned properly, the observer will see an image of the filament.

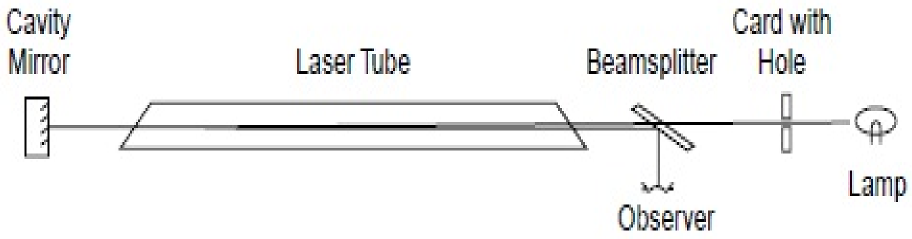

Figure 6.21: Alignment using an autocollimator.

Alignment of the output coupler (OC) The alignment of OC can be achieved using the autocollimator by removing the (just aligned) HR, installing the OC, and aligning it separately in a manner similar to that used for the HR. The location of the autocollimator is changed to the rear of the laser. The alternative is a search procedure in which the mirror is rocked with the laser energized until aligned. As the search pattern progresses with the mirror scanning up and down and side to side, a blink of laser light will be observed. At this point the mirror is aligned in the horizontal (sideways) direction. The adjusting screw for the vertical axis is now adjusted until a continuous beam appears.

Adjustment for maximum output Finally, both the OC and HR mirrors are adjusted for maximum output. More specifically, the mirrors are adjusted to ensure that they are parallel. After first alignment, the mirrors may not be perfectly perpendicular to the tube, as shown in the top diagram of Fig. 6.22, in which the path of the intracavity beam is shaded. In this situation the mirrors are parallel to each other, with a clear path through the gain medium allowing oscillation. But the utilization of the volume of the gain medium is poor, so power output will be much lower than when the mirrors are fully optimized and perpendicular to the tube, so that the entire volume of the laser tube is used as depicted in the lower diagram of the Fig. 6.22.

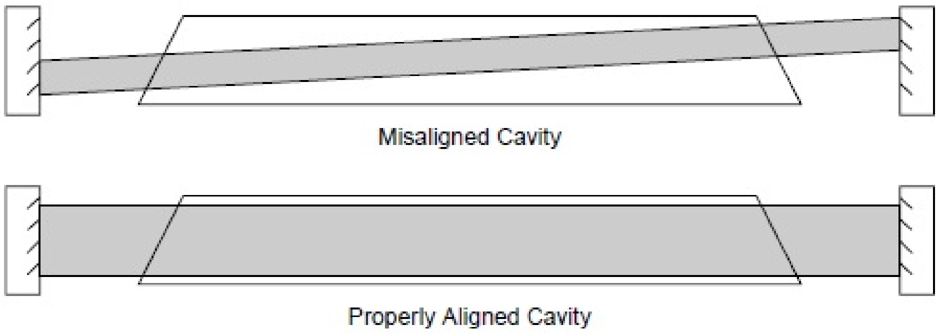

Figure 6.22: Possible misalignment of the mirrors.