Single Axial Longitudinal Mode Operation

THEORY OF LONGITUDINAL MODES

In a laser cavity, the requirement that the field exactly reproduce itself in relative amplitude and phase each round-trip means that the only allowable laser wavelengths or frequencies are given by

$$\lambda = \frac{P}{N} \text{ or } \nu = \frac{Nc}{P} \tag{10.20}$$

where λ is the laser wavelength, ν is the laser frequency, c is the speed of light in a vacuum, N is an integer whose value is determined by the lasing wavelength, and P is the effective perimeter optical path length of the beam as it makes one round-trip, taking into account the effects of the index of refraction. For a conventional two-mirror cavity in which the mirrors are separated by optical length L, these formulas revert to the familiar

$$\lambda = \frac{2L}{N} \text{ or } \nu = \frac{Nc}{2L}. \tag{10.21}$$

These allowable frequencies are referred to as longitudinal modes. The frequency spacing between adjacent longitudinal modes is given by

$$\Delta\nu = \frac{c}{P}\ . \tag{10.22}$$

As can be seen from equation 10.22, the shorter the laser cavity is, the greater the mode spacing will be. By differentiating the expression for ν with respect to P we arrive at

$$\delta\nu = -\frac{Nc}{P^2}\delta P \text{ or } \delta n = -\frac{Nc}{2L^2}\delta L. \tag{10.23}$$

Consequently, for a helium neon laser operating at 632.8 nm, with a cavity length of 25 cm, the mode spacing is approximately 600 MHz, and a 100-nm change in cavity length will cause a given longitudinal mode to shift by approximately 190 MHz.

The number of longitudinal laser modes that are present in a laser depends primarily on two factors: the length of the laser cavity and the width of the gain envelope of the lasing medium. For example, the gain of the red helium neon laser is centered at 632.8 nm and has a full width at half maximum (FWHM) of approximately 1.4 GHz, meaning that, with a 25-cm laser cavity, only two or three longitudinal modes can be present simultaneously, and a change in cavity length of less than one micron will cause a given mode to "sweep" completely through the gain. Doubling the cavity length doubles the number of oscillating longitudinal modes that can fit under the gain curve doubles.

The gain of a gas-ion laser (e.g., argon or krypton) is approximately five times broader than that of a helium neon laser, and the cavity spacing is typically much greater, allowing many more modes to oscillate simultaneously.

A mode oscillating at a frequency near the peak of the gain will extract more energy from the gain medium than one oscillating at the fringes. This has a significant impact on the performance of a laser system because, as vibration and temperature changes cause small changes in the cavity length, modes sweep back and forth through the gain. A laser operating with only two or three longitudinal modes can experience power fluctuations of 10% or more, whereas a laser with ten or more longitudinal modes will see mode-sweeping fluctuations of 2 percent or less.

SELECTING A SINGLE LONGITUDINAL MODE

A laser that operates with a single longitudinal mode is called a single-frequency laser. There are two ways to force a conventional two-mirror laser to operate with a single longitudinal mode. The first is to design the laser with a short enough cavity that only a single mode can be sustained. For example, in the helium neon laser described above, a 10-cm cavity would allow only one mode to oscillate. This is not a practical approach for most gas lasers because, with the cavity short enough to suppress additional modes, there may be insufficient energy in the lasing medium to sustain any lasing action at all, and if there is lasing, the output will be very low.

The second method is to introduce a frequency-control element, typically a low-finesse Fabry-Perot etalon, into the laser cavity. The free spectral range of the etalon should be several times the width of the gain curve, and the reflectivity of the surfaces should be sufficient to provide 10 percent or greater loss at frequencies half a longitudinal mode spacing away from the etalon peak. The etalon is mounted at a slight angle to the optical axis of the laser to prevent parasitic oscillations between the etalon surfaces and the laser cavity.

Once the mode is selected, the challenge is to optimize and maintain its output power. Since the laser mode moves if the cavity length changes slightly, and the etalon pass band shifts if the etalon spacing varies slightly, it important that both be stabilized. Various mechanisms are used. Etalons can be passively stabilized by using zero-expansion spacers and thermally stabilized designs, or they can be thermally stabilized by placing the etalon in a precisely controlled oven. Likewise, the overall laser cavity can be passively stabilized, or, alternatively, the laser cavity can be actively stabilized by providing a servomechanism to control cavity length, as discussed in Frequency Stabilization.

The Ring Laser: The discussions above are limited to two-mirror standing-wave cavities. Some lasers operate naturally in a single longitudinal mode. For example, a ring laser cavity, (used in many dye and Ti:Sapphire lasers as well as in gyroscopic lasers) that has been constrained to oscillate in only one direction produces a traveling wave without the fixed nodes of the standing-wave laser. The traveling wave sweeps through the laser gain, utilizing all of the available energy and preventing the buildup of adjacent modes. Other lasers are "homogeneously broadened" allowing virtually instantaneous transfer of energy from one portion of the gain curve to another.

FREQUENCY STABILIZATION

The frequency output of a single-longitudinal-mode laser is stabilized by precisely controlling the laser cavity length. This can be accomplished passively by building an athermalized resonator structure and carefully controlling the laser environment to eliminate expansion, contraction, and vibration, or actively by using a mechanism to determine the frequency (either relatively or absolutely) and quickly adjusting the laser cavity length to maintain the frequency within the desired parameters.

A typical stabilization scheme is shown in figure 10.11. A portion of the laser output beam is directed into a low-finesse Fabry-Perot etalon and tuned to the side of the transmission band. The throughput is compared to a reference beam, as shown in the figure. If the laser frequency increases, the ratio of attenuated power to reference power increases. If the laser frequency decreases, the ratio decreases. In other words, the etalon is used to create a frequency discriminant that converts changes in frequency to changes in power. By "locking" the discriminant ratio at a specific value (e.g., 50 percent) and providing negative feedback to the device used to control cavity length, output frequency can be controlled. If the frequency increases from the preset value, the length of the laser cavity is increased to drive the frequency back to the set point. If the frequency decreases, the cavity length is decreased. The response time of the control electronics is determined by the characteristics of the laser system being stabilized.

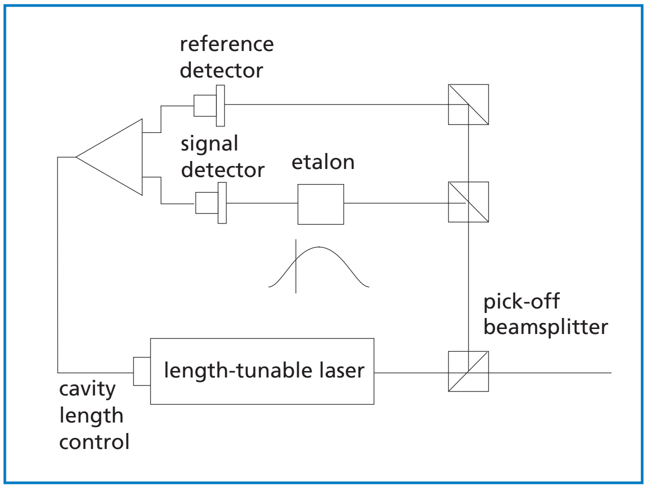

Figure 10.11 **Laser frequency stabilization scheme**

Other techniques can be used to provide a discriminant. One common method used to provide an ultrastable, long-term reference is to replace the etalon with an absorption cell and stabilize the system to the saturated center of an appropriate transition. Another method, shown in figure 10.12, is used with commercial helium neon lasers. It takes advantage of the fact that, for an internal mirror tube, the adjacent modes are orthogonally polarized. The cavity length is designed so that two modes can oscillate under the gain curve. The two modes are separated outside the laser by a polarization-sensitive beamsplitter. Stabilizing the relative amplitude of the two beams stabilizes the frequency of both beams.

The cavity length changes needed to stabilize the laser cavity are very small. In principle, the maximum adjustment needed is that required to sweep the frequency through one free spectral range of the laser cavity (the cavity mode spacing). For the helium neon laser cavity described earlier, the required change is only 320 nm, well within the capability of piezoelectric actuators.

Commercially available systems can stabilize frequency output to 1 MHz or less. Laboratory systems that stabilize the frequency to a few kilohertz have been developed.

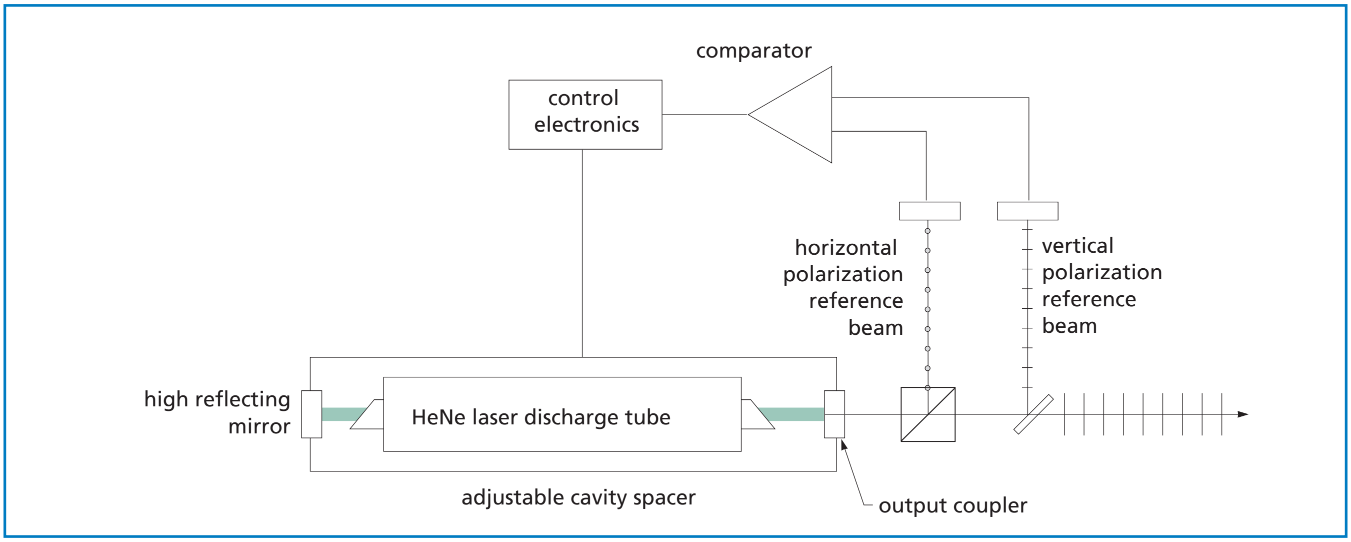

Figure 10.12 **Frequency stabilization for a helium neon laser**