

# **E. K. A. ADVANCED PHYSICS LABORATORY**

## **PHYSICS 3081, 4051**

### **THE He-Ne LASER AND OPTICAL RESONATORS**

#### **1) The Laser**

A laser produces electromagnetic radiation which is both spatially coherent and of narrow spectral width via a mechanism known as Light Amplification by Stimulated Emission of Radiation. The first working laser was developed in 1960 by Theodore Maiman at Hughes Research Laboratories. Since then laser technology has proliferated, with uses in industry, medicine, research, military and law enforcement, as well as in numerous commercial devices including CD and DVD players, laser pointers, bar code readers and printers. Lasing can be achieved in crystals such as rubies, in semiconductors, in chambers filled with dye, or in tubes filled with gas.

In this experiment we will construct a simple cavity employing a tube filled with He and Ne gas excited by electrical discharge to create a visible laser in the red portion of the spectrum. He-Ne lasers are widely used in low-power laser applications because of their reliability and low cost.

#### **2) The He-Ne Laser**

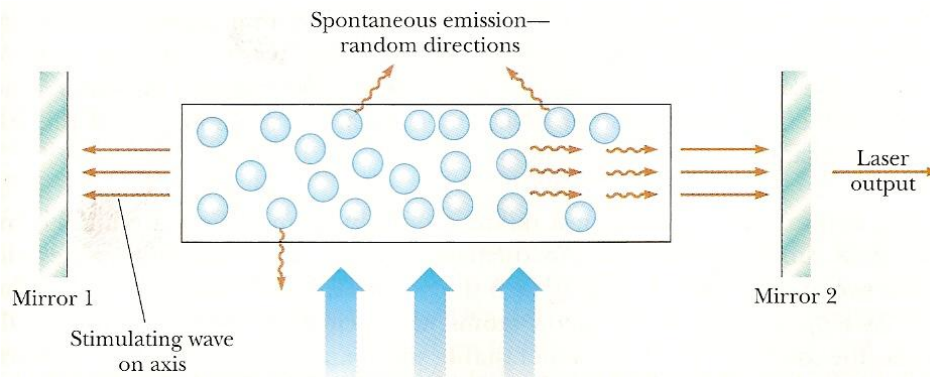
An electrical discharge in a mixture of He and Ne gas produces an environment for optical radiation at  $\lambda = 632.8$  nm, resulting in a highly coherent, polarized beam, provided that three conditions are met:

1. The system must be in a state of population inversion, in which an excess of atoms exist in higher energy states than in lower energy states, in contrast to the usual Boltzmann equilibrium. This is achieved by “pumping” the system with the electrical discharge.
2. The excited state of the system must be metastable; when this condition is met, decay of the excited states may be induced by stimulated emission before they decay spontaneously. The rates for stimulated and spontaneous emission are given by the so-called Einstein coefficients; a derivation of the detailed conditions required may be found in any standard optics text.
3. The emitted photons must be confined long enough to stimulate further emission from other excited atoms before exiting the system.

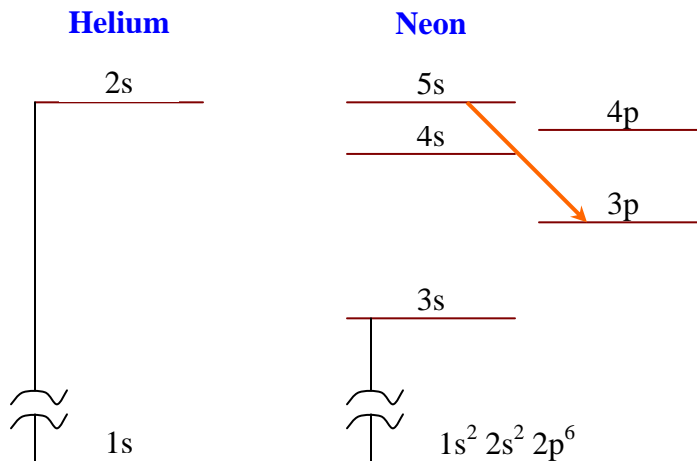
In the He-Ne system, a low-pressure mixture of helium (~90 %) and neon (~10 %) is contained in a narrow-bore tube, as seen in Figure 1 below. An electrical current (typically a few tens of mA) ionizes the gas inside the tube, forming a plasma of many helium atoms in metastable states. In these states one of the valence electrons of helium has been raised from the

$1s$  ground level to the  $2s$  excited level (Figure 2). Quantum mechanical selection rules prevent this excited state from decaying by photon emission back to the ground state, so the helium atom will remain in this excited state for a long time.

Further, the  $2s$  helium level and the  $4s$  and  $5s$  neon levels match very closely in energy, so collisions between helium and neon atoms may transfer enough energy so that a neon electron is raised to the  $4s$  or  $5s$  level with a larger probability than for lower excited levels. Upon exciting a neon atom in this way, the helium atom drops back to the ground state. But there are about ten times as many helium atoms as neon atoms, so the rate of occurrence of collisions bringing neon electrons to the  $4s$  and  $5s$  levels is high, ensuring that there are more neon electrons in the  $4s$  or  $5s$  levels than in lower excited levels, thus creating a population inversion. A number of alternative downward transitions are available to these excited neon electrons; the transition of interest in this experiment is  $5s \rightarrow 3p$ , and emits a photon with  $\lambda = 632.8$  nm.



**Figure 1:** Schematic diagram of the laser cavity. A narrow tube containing helium and neon gas is placed in a resonant cavity formed by two mirrors. An electrical current ionizes the gas, and photons with  $\lambda = 632.8$  nm are produced. Radiation emitted along the optic axis is amplified by multiple passes across the cavity and transmitted outside by the slightly transparent mirrors.



**Figure 2:** Schematic diagram of the energy levels of neon and helium electrons. The match between the  $2s$  excited state of helium and the  $4s$  and  $5s$  excited states of neon makes possible for the laser action to occur (see text).

Confinement of the emitted photons is realized by the use of reflecting mirrors at the ends of the system. Each emitted photon has a chance of passing close to a second excited neon atom and stimulating the emission of an identical additional photon. When the end mirrors are carefully aligned so that each photon traveling parallel to the optic axis makes many passes through the cavity, the cavity's effective length is increased dramatically, and a powerful beam of coherent radiation is produced. One of the mirrors allows about 1% transmission of the laser radiation outside the cavity; therefore, the internal beam is about 100 times more powerful than the output beam.

**CAUTION: when the cavity is lasing, there will be some radiation transmitted through both ends since the other end also allows some transmission. Never look along the optic axis into the laser, from either end, or otherwise allow the beam to be directed into your eye.**

### 3) The Resonant Cavity: Longitudinal Modes

In this experiment the He-Ne tube is placed in a resonating cavity consisting of two mirrors whose separation  $L$  can be varied. To first order, the resonant frequencies (longitudinal modes) of such a resonator are given by:

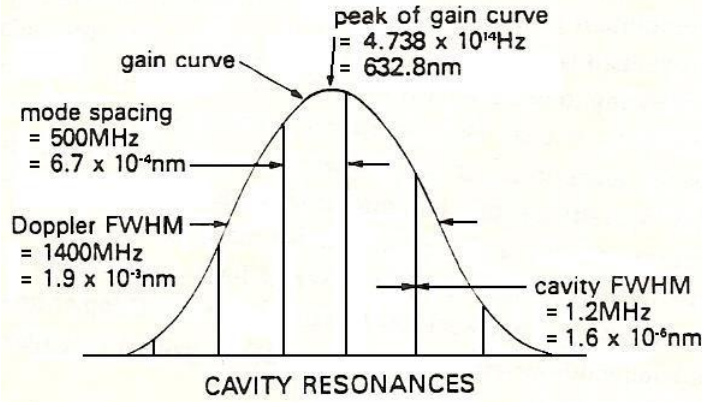
$$\nu_{res} = q \frac{c}{2L} \quad (1)$$

where  $c$  is the velocity of light and  $q$  is an integer, equal to the number of wavelengths in a round trip through the cavity. For a cavity of  $L=50$  cm length,  $q \sim 10^8$  and the spacing between adjacent laser modes sustained is  $\Delta\nu = \frac{c}{2L} = 300$  MHz.

When the mirrors are properly aligned lasing ensues and an intense beam of coherent light is produced at those frequencies  $\nu_{res}$  within the gain bandwidth of the active He-Ne medium.

Next, we consider the intrinsic width of the 632.8 nm spectral line. This transition has a characteristic timescale, implying that there is some uncertainty as to the actual energy due to the uncertainty principle:  $\Delta E \Delta t \geq \hbar/2$ . This causes the photons to be distributed with some characteristic linewidth, since there is a minimum uncertainty in energy associated with each transition. In addition to this natural linewidth, random thermal motion of atoms within the He-Ne plasma results in Doppler shifting, further broadening the spectral line.

It turns out in this case that the linewidth of a resonant cavity mode is much narrower than the Doppler-broadened linewidth of the Ne transition. Thus multiple resonant modes falling within the physical linewidth will be amplified, as seen in Figure 3 for a spectral line supporting 6 longitudinal modes.



**Figure 3:** Doppler-broadened gain curve supporting 6 longitudinal modes or cavity resonances. The gain curve has a peak at 632.8 nm. The width of the gain curve is indicated as the Doppler FWHM. The mode spacing is given by the above formula,  $\Delta\nu = \frac{c}{2L}$ . The linewidth of a single laser mode is shown as the cavity FWHM.

#### 4) The Resonant Cavity: Transverse Modes

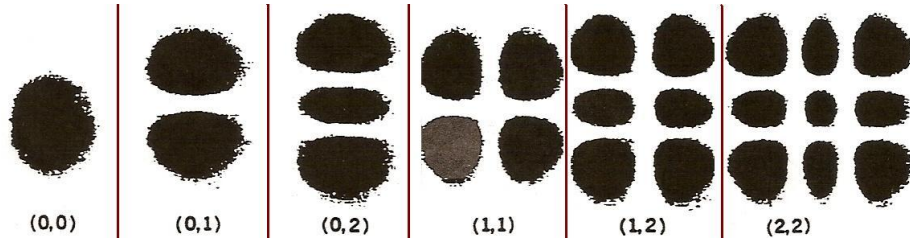
A lasing cavity also exhibits transverse modes, describing the distribution of beam intensity along a plane perpendicular to the optic axis. Equation (1) refers to the longitudinal modes in a cavity's lowest order transverse mode, which has a simple Gaussian intensity distribution in a plane perpendicular to the optic axis. Higher order transverse modes exist and are labeled  $TEM_{mnq}$ , whose profiles are described by Hermite-Gaussian polynomials. The first two subscripts,  $m$  and  $n$ , describe the amplitude distribution transverse to the optic axis, while the third subscript  $q$  is the axial mode number having the same definition as in Equation 1; the fundamental transverse mode is labeled  $TEM_{00q}$ .

For the most general case of a resonator made up of two mirrors with radii of curvature  $b_1$  and  $b_2$ , separated by a distance  $L$ , the resonant frequencies associated with a given  $TEM_{mnq}$  mode are given by:

$$\nu_{mnq} = \frac{c}{2L} \left\{ q + \frac{1}{\pi} (1 + m + n) \times \cos^{-1} \left[ \left( 1 - \frac{L}{b_1} \right) \left( 1 - \frac{L}{b_2} \right) \right]^{\frac{1}{2}} \right\}. \quad (2)$$

*Exercise:* verify that for  $m=n=0$ , with plane-parallel mirrors ( $1/b_1 = 1/b_2 = 0$ ), the resonant longitudinal modes are given by Equation (1).

Stated in a different way, the higher-order transverse modes are those in which the perpendicular irradiance distribution exhibits one or more nulls (Figure 4). The subscripts  $m$  and  $n$  indicate the number of nulls along two orthogonal axes perpendicular to the cavity axis. The fundamental mode  $TEM_{00}$  has a gaussian irradiance distribution with no nulls, and compared to the higher-order modes, experiences the least diffraction loss, has the least angular divergence, and can be focused to the smallest possible spot. For these reasons, it is often desirable that in practical applications the laser should be used in this mode. The irradiance distribution for a few selected transverse modes is shown in Figure 4.



**Figure 4:** The irradiance distribution of several transverse modes  $TEM_{mnq}$  (same  $q$ ) of the lasing cavity. The subscripts  $m$  and  $n$  are identified as the number of nodes along two orthogonal axes perpendicular to the axis of the lasing cavity.

An arbitrary field of electromagnetic radiation at frequency  $\nu_0$  incident on a resonating cavity can be decomposed into a large number of transverse modes  $TEM_{mnq}$ . Each of these modes will be resonant and will be transmitted by the cavity for mirror separations satisfying:

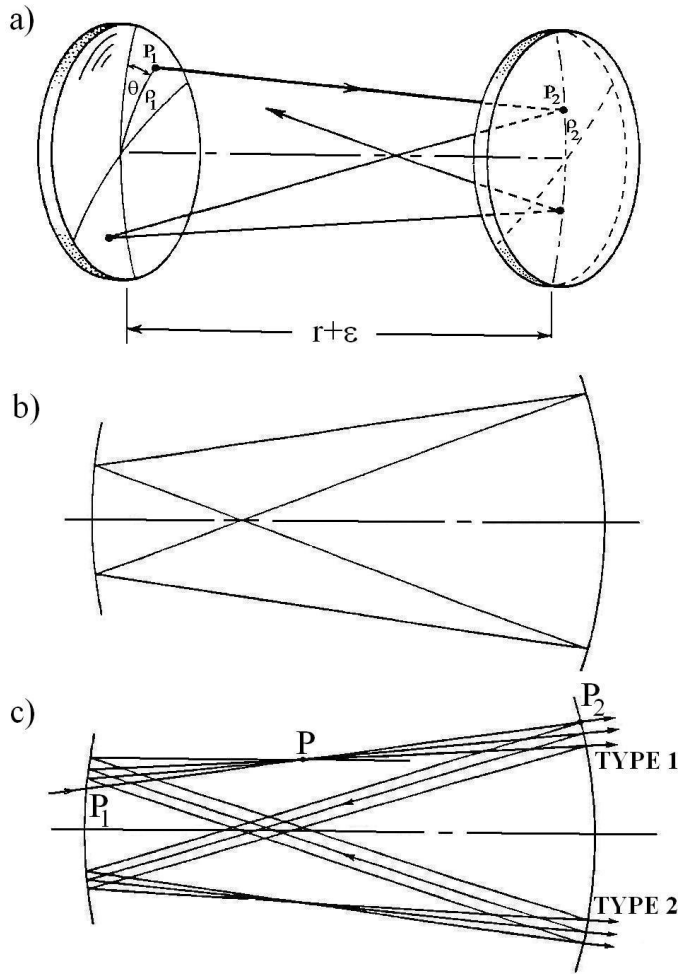
$$L = \frac{c}{2\nu_0} \left\{ q + (1 + m + n) \times \cos^{-1} \left[ \left( 1 - \frac{L}{b_1} \right) \left( 1 - \frac{L}{b_2} \right) \right]^{\frac{1}{2}} \right\}. \quad (3)$$

Thus, by carefully adjusting the alignment of one of the adjustable cavity end mirrors, you can observe the various transverse modes.

#### 4) The Fabry-Perot interferometer: Studying the longitudinal modes

The longitudinal mode structure of the laser cavity may be determined by observing the light transmitted through a Fabry-Perot interferometer that is placed in the path of the laser emission. The mirror separation in this interferometer can be varied by an amount of the order of  $\lambda$ , allowing the frequency distribution of incident radiation to be determined.

The Fabry-Perot interferometer is the most commonly used of the multiple-beam interferometers, such as the famous Michelson-Morley interferometer. A spherical Fabry-Perot interferometer is composed of two identical spherical mirrors separated by a distance very nearly equal to their radius of curvature. When light from a source lying close to the axis is incident, a circular interference pattern is produced.



**Figure 5:**

a) Schematic diagram of a spherical Fabry-Perot resonator. Each of the mirrors has a radius of curvature  $r$ , and they are separated by  $r + \epsilon$ .

b) A paraxial ray entering the resonator at point  $P_1$  is reflected four times off the surfaces of the mirrors and it falls upon itself after this (i.e., is reentrant).

c) Due to aberration, a general ray is not reentrant, but follows a path such as the one shown in Figure 5c). The rays will continue to intersect themselves in the vicinity of the central plane of the spectrometer, where a circular fringe pattern is produced.



**Figure 6:** An example of the pattern of circular fringes formed in the central plane of a Fabry-Perot interferometer. The pattern can be observed when the Fabry-Perot is set in the “fringe display” mode of operation (described in the instruction manual for the model 470 interferometer).

## 5) Experimental details regarding the operation of the Fabry-Perot:

If the diameter of the incident laser beam is much smaller than the diameter of the first off-axis fringe, the interferometer acts as a narrow bandpass filter transmitting only the wavelength that satisfy the resonance condition:

$$4r = n\lambda . \quad (4)$$

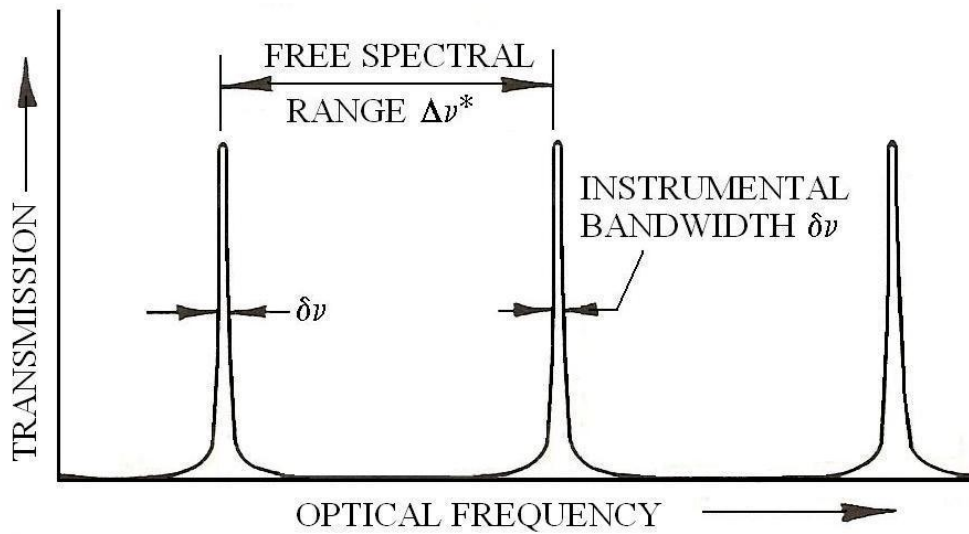
In this resonance condition, a bright spot appears at the center of the fringe display. The frequencies transmitted by the Fabry-Perot (see Figure 7) form a set of equidistant spectral lines with

$$\nu_n = \frac{c}{\lambda} = n \frac{c}{4r} \quad (5)$$

and

$$\Delta\nu^* = \nu_n - \nu_{n-1} = \frac{c}{4r} \quad (6)$$

Our interferometer has two identical facing concave mirrors separated by approximately  $r = 0.94$  cm. It follows that  $\Delta\nu^* = 7.979$  GHz  $\approx 8$  GHz.  $\Delta\nu^*$ , the spacing between adjacent resonant modes, is termed the *free spectral range*.



**Figure 7:** The transmission of a Fabry-Perot as a function of frequency. The frequency separation between two successive transmission maxims is  $\Delta\nu^*$ , the free spectral range. The width of each transmission maximum is  $\delta\nu$ , the instrumental bandwidth.

Because of radiation losses upon successive reflections, and losses as the laser passes through the air between the mirrors, the transmitted lines centered on  $\nu_n$ , have a finite width  $\delta\nu$ , known as the instrumental bandwidth, as seen in Figure 7. The *finesse* of the instrument is defined as

$$F = \frac{\Delta\nu^*}{\delta\nu} . \quad (7)$$

The finesse is a measure of the spectral resolving capability of the Fabry-Perot and is determined by a number of factors, of which the reflectivity of the mirrors is one of the most important.

The transmitted wavelengths can be varied simply by varying the mirror separation,  $d$ . The required change in mirror separation is very small: a distance of the order of a quarter of the

incident wavelength is enough to scan through a complete free spectral range. This can be seen from the following argument:

Let us assume that the resonance condition  $4d = n\lambda$  at a given wavelength  $\lambda$ , and that we shift the mirror separation by  $\lambda/4$ . We write the wavelength  $\lambda'$  satisfying the new resonance condition,  $4(d + \frac{\lambda}{4}) = n\lambda'$ , as  $\lambda' = \lambda + \Delta\lambda$ . It follows that  $\Delta\lambda = \frac{\lambda}{n}$  and, using  $n = \frac{4d}{\lambda}$ , we obtain  $\frac{\Delta\lambda}{\lambda^2} = \frac{1}{4d}$ . Since  $\nu = \frac{c}{\lambda}$ , the frequency shift corresponding to  $\Delta\lambda$  is  $\Delta\nu \approx c \frac{\Delta\lambda}{\lambda^2} = \frac{c}{4d} = \Delta\nu^*$ , the free spectral range.

However, the Fabry-Perot cannot scan beyond  $\Delta\nu^*$ , because the resonance condition is satisfied again (in order  $n+1$ ) for the wavelength  $\lambda$ ,  $4(d + \frac{\lambda}{4}) = (n+1)\lambda$ , and the spectrum repeats itself.

It should be noted that the free spectral range  $\Delta\nu^*$ , while dependent on the mirror separation, is not affected significantly by typical changes in mirror separation that may occur during a scan of the free spectral range. The shift in  $\Delta\nu^*$  caused by a change in mirror separation of  $\lambda/4$  is  $\delta(\Delta\nu^*) = \frac{c}{4d} - \frac{c}{4d + \lambda} \approx \frac{c}{4d} \cdot \frac{\lambda}{4d}$ , corresponding to a relative change  $\frac{\delta(\Delta\nu^*)}{\Delta\nu^*} \approx \frac{\lambda}{4d}$ . At  $\lambda = 632.8 \text{ nm}$ , the relative shift is  $\frac{\delta(\Delta\nu^*)}{\Delta\nu^*} = \frac{632.8 \text{ nm}}{4 \times 0.94 \text{ cm}} = 1.7 \times 10^{-5}$ , which is clearly negligible.

The key element of the system we are using is the Fabry-Perot etalon, comprised of a fixed and an adjustable mirror, and a thermally-compensated rigid spacer tube. The spacer tube includes a piezo-electric ceramic section that increases in length by about  $10^{-5} \text{ cm}$  with the application of 50 V, sufficient to scan across the entire free spectral range; we do this by applying a time-varying voltage to the piezo-electric section (we will use a triangular wave).

## Experiment

The He-Ne tube, the adjustable cavity end mirror and the Fabry-Perot interferometer are mounted on a rail to allow easy alignment and adjustment. It is also possible to mount lenses and other adjustable mirrors on the rail as the need may arise.

1) The first goal is to align the mirrors to achieve lasing, for several different separations between the two mirrors. This is accomplished by making the radiation from the discharge tube reflect back on itself, increasing the cavity's effective length and enabling sufficient stimulated emission of photons.

*Coarse adjustment* of the adjustable mirror may be achieved by loosening the set screw on the mirror stand and manually moving the mirror.



*Fine adjustment* is made with the two knobs on the mirror's reverse side; one knob adjusts the mirror horizontally, and the other adjusts the mirror vertically. Both knobs have a finite travel range, so you must use the coarse adjustment technique to get "in the ballpark" and fine-tune using the knobs.

**HINT:** *It is helpful to use a small piece of paper to trace the beam as it travels from the He-Ne tube to the adjustable mirror and back to accurately direct the beam back into the cavity. This is also useful for tracing out the beam once lasing is achieved; "laser jocks" frequently carry around a business card for just this purpose.*

**HINT:** *Alignment is very critical; the range over which lasing will occur is generally less than one full turn of either adjustment knob! So make your adjustments slowly.*

**HINT:** *If you are not able to achieve lasing within a half hour or so, ask one of the instructors for help, as there may be something wrong with the system, or the mirrors may need cleaning to improve their reflectivity. Despite the sensitivity of alignment, this should not take an inordinate amount of time.*

**HINT:** *Once you get the system lasing, never adjust two or more degrees of freedom at once! Only adjust one knob at a time: If you lose lasing, then you only have to turn that one knob back and forth until you "find" the lasing area again. Otherwise you have to search through multiple degrees of freedom to find that needle in a haystack. (This is good advice in general.)*

**NOTE:** Do not make any adjustments to the set screws holding the He-Ne discharge tube. The tube is easily cracked, so please ask an instructor if you think the tube needs to be adjusted.

2) Examine and describe the far field radiation pattern as a function of the mirror separation and mirror alignment. This is accomplished by expanding the laser beam with a short focal length lens and using a mirror to direct the beam onto the laboratory wall or a piece of white paper. The transverse modes are observed by slightly adjusting the adjustable cavity end mirror using the fine knobs (one at a time!). Take pictures of the transverse irradiance distribution with a digital camera for as many modes as you can see.

*Are the various transverse modes stable in time?*

*Are some more stable than others?*

*What happens if you tap on the table or the mirror?*

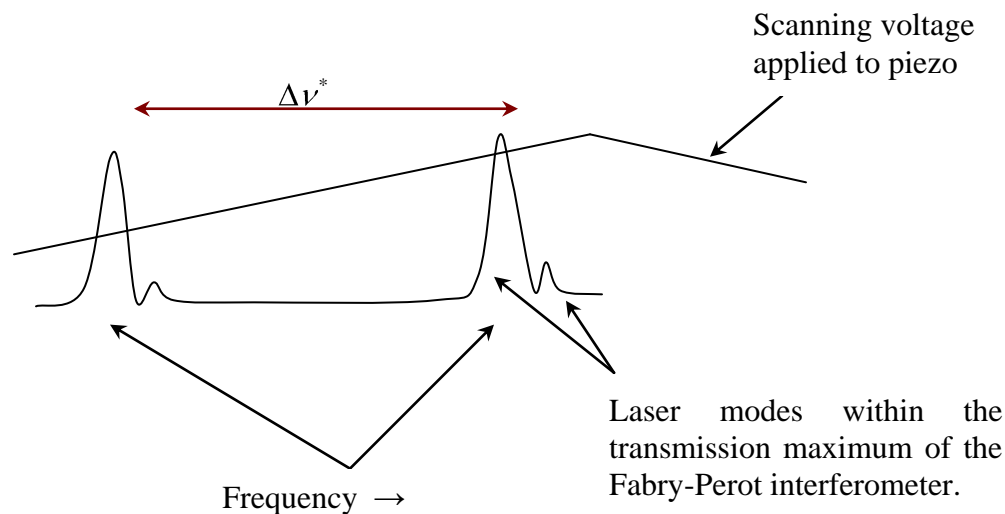
*What is the highest-order TEM mode that you are able to observe?*

3) Examine and describe the longitudinal mode patterns of the He-Ne laser as a function of the mirror separation and alignment. You will want to direct the beam into the Fabry-Perot interferometer, which will be mounted on the rail. Alignment is somewhat tedious, so take your time!

- a) Follow the instructions in the interferometer manual for aligning the interferometer.

A triangular signal triggered by a variable frequency source is input to a servo amplifier and to channel 3 of an oscilloscope. The output of the interferometer detector is input to channel 2. The servo amplifier provides the sweep drive for the interferometer. It also provides an output equal to 1/100 of the sweep drive that is displayed on channel 1 of the scope. Channel 1 allows identification of the mode response displayed in channel 2. Channel 3 provides the trigger for the temporal sweep.

Using these inputs on the oscilloscope, you can simultaneously view the waveform being sent to the piezo-electric unit, and the intensity of light transmitted by the Fabry Perot, as seen in Figure 8. The waveform being sent to the piezo may be adjusted using the function generator and the servo-amplifier on the shelf underneath the optical bench.



**Figure 8:** Repetitive spectrum display of the laser modes than can be obtained using the Fabry-Perot interferometer. The frequency separation between two adjacent transmission maxims of the Fabry-Perot falling on the same slope of the scanning voltage is the free spectral range  $\Delta\nu^*$ .  $\Delta\nu^*$  is used for spectrum calibration.

- b) Map out the overall gain profile, as depicted in Figure 8. You should adjust the gain of the servo-amplifier that provides the scanning voltage to the Fabry-Perot to make sure that two transmission maxima occur on the same increasing or decreasing voltage slope; in this way the repetitive display can be used to calibrate the spectrum, since the free spectral range of the Fabry-Perot is known (8 GHz). You can also adjust the bias, i.e. the dc voltage offset, but do not allow the dc offset to increase unnecessarily.

*How stable are these modes in time?*

*How sensitive are they to mechanical disturbances of the optical bench?*

By taking photographs of the oscilloscope display, you may quantitatively analyze the pattern as seen in Figure 8.

- c) Find the frequency spacing between the laser modes using the calibrated display obtained in part b), and compare with Equation 1. Estimate the uncertainty of the measurements.
  
- 4) Examine and describe the frequency mode pattern for the self-contained commercial Melles-Griot laser, which has been factory-adjusted to lase in the TEM<sub>00</sub> mode. Compare the overall gain profile with that obtained from the adjustable-mirror separation laser.

The commercial laser may be directed into the Fabry-Perot using adjustable mirrors. *There is no reason to move the He-Ne discharge tube from its cradle, and since it is easily damaged, it should not be moved.*

*How does the commercial laser compare to your "homemade" one?*