PHYSUN3081
Spring 2020 Intermediate Laboratory Work
The HeNe Laser

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1 Introduction

1.1 Learning Objectives

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, and investigate its frequency (longitudinal) and spatial mode profiles. He-Ne lasers are widely used in low-power laser applications because of their reliability and low cost.

1.2 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. The precursor to the laser was the maser, which works via the same physical principle but for microwaves.

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.

It is interesting to note that the first maser made was right here in Pupin Hall by Charles H. Townes, James P. Gordon, and Herbert J. Zeiger [1]! Perhaps in this very same room as well :). In many ways the work you will perform will follow in their proud history.

2 Theory

2.1 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 lasing conditions are met:

- 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

- 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.
- The emitted photons must be confined long enough to stimulate further emission from other excited atoms before exiting the system.

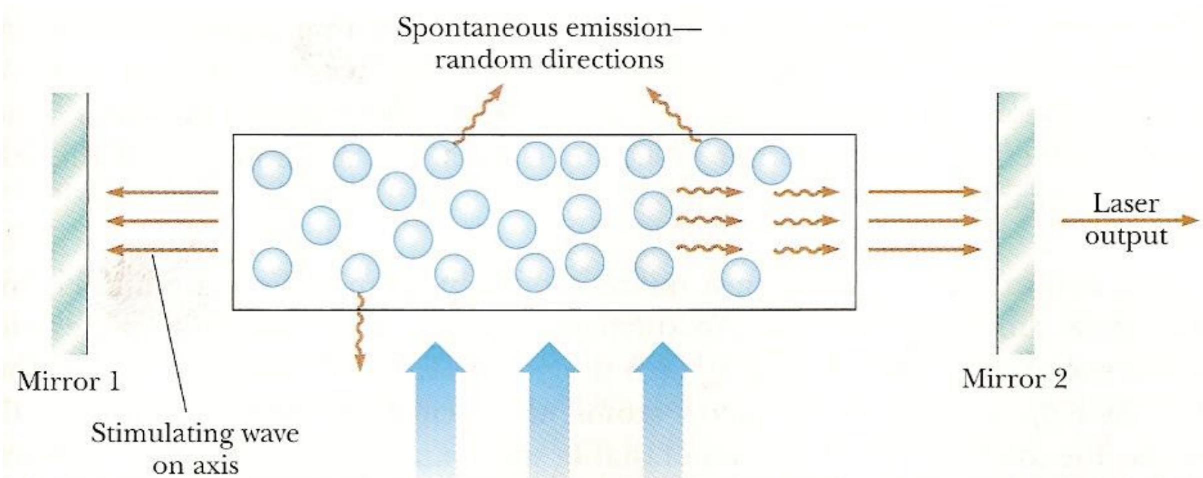

Figure 1: Schematic diagram of the laser cavity. A narrow tube containing helium and neon gas is placed in a resonant cavity formed by two mirrors. An electrical current ionizes the gas, and photons with = 632.8 nm are produced. Radiation emitted along the optic axis is amplified by multiple passes across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

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. 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* and *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 = 632.8 nm.

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

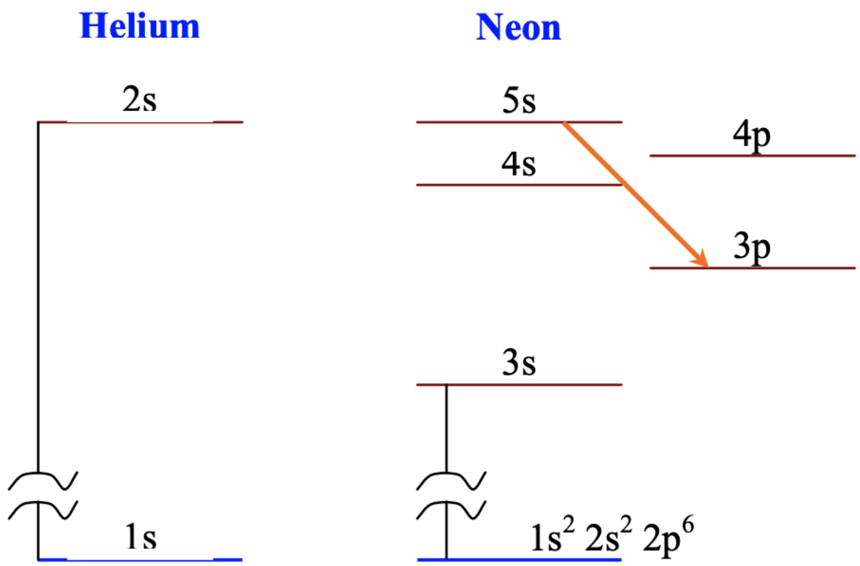

Figure 2: Schematic diagram of the energy levels of neon and helium electrons. The match between the *2s* excited state of helium and the *4s* and *5s* excited states of neon makes possible for the laser action to occur (see text).

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.

2.2 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:

$$\nu_{res} = q\frac{c}{2L} \tag{1}$$

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 length $L = 50$ cm, $q = 10^8$ and the spacing between adjacent laser modes sustained is

$$\Delta\nu = \frac{c}{2L} = 300 \text{ MHz} \tag{2}$$

When the mirrors are properly aligned lasing ensues and an intense beam of coherent light is produced at those frequencies ν_{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:

$$\Delta E \Delta t \geq \frac{\hbar}{2} \tag{3}$$

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 HeNe plasma results in Doppler shifting, further broadening the spectral line.

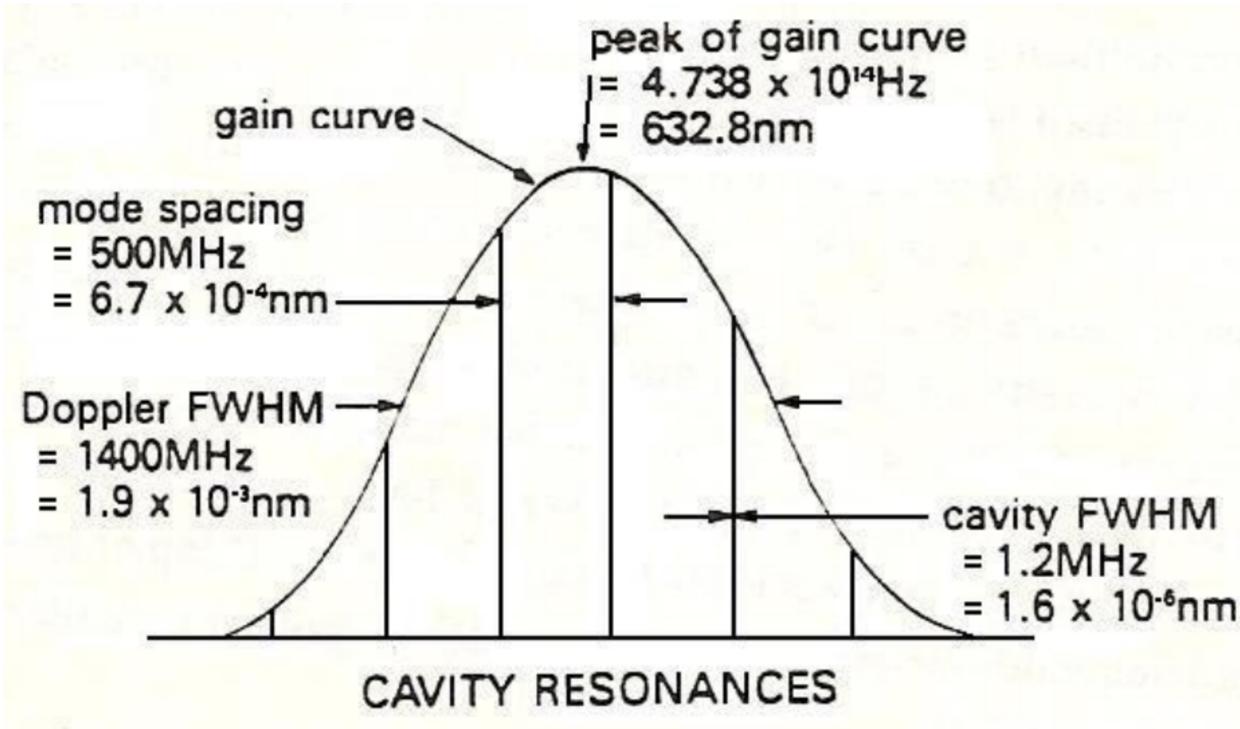

Figure 3: Doppler-broadened gain curve supporting 6 longitudinal modes or cavity resonances. The gain curve has a peak at 632.8 nm. The width of the gain curve is indicated as the Doppler FWHM. The mode spacing is given by the above Equation 1. The linewidth of a single laser mode is shown as the cavity FWHM

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.

2.3 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:

$$\nu_{mnq} = \frac{c}{2L}\left\{q + \frac{1}{\pi}(1+m+n) \times \cos^{-1}\left[\left(1-\frac{L}{b_1}\right)\left(1-\frac{L}{b_2}\right)\right]^{\frac{1}{2}}\right\} \tag{4}$$

Exercise: Verify that for $m = n = 0$, with plane-parallel mirrors ($b_1 = b_2 = \infty$), the resonant longditudinal

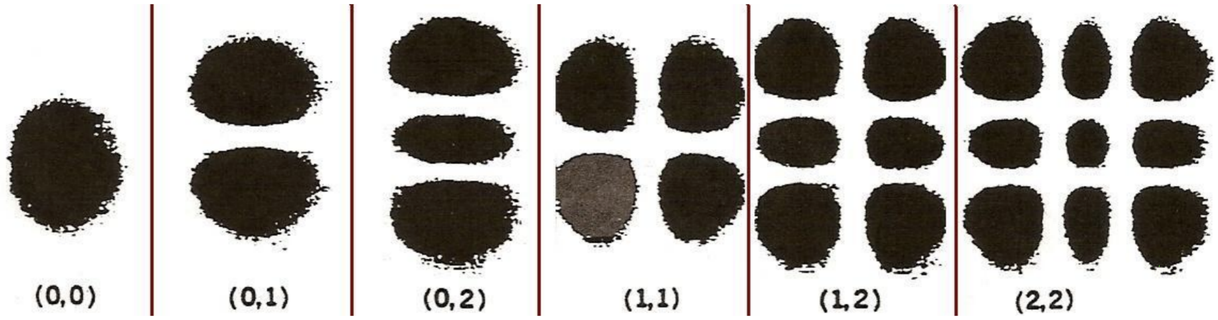

Figure 4: The irradiance distribution of several transverse modes TEM_{mnq} (same q) of the lasing cavity. The subscripts m and n are identified as the number of nodes along two orthogonal axes perpendicular to the axis of the lasing cavity.

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.

An arbitrary field of electromagnetic radiation at frequency ν_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:

$$L = \frac{c}{\nu_0}\left\{q + (1+m+n)\times\cos^{-1}\left[\left(1-\frac{L}{b_1}\right)\left(1-\frac{L}{b_2}\right)\right]^{\frac{1}{2}}\right\} \tag{5}$$

There is an excellent article written about the HeNe laser in Appendix B.

2.4 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 λ, 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.

2.4.1 How it works

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:

$$4d = n\lambda \tag{6}$$

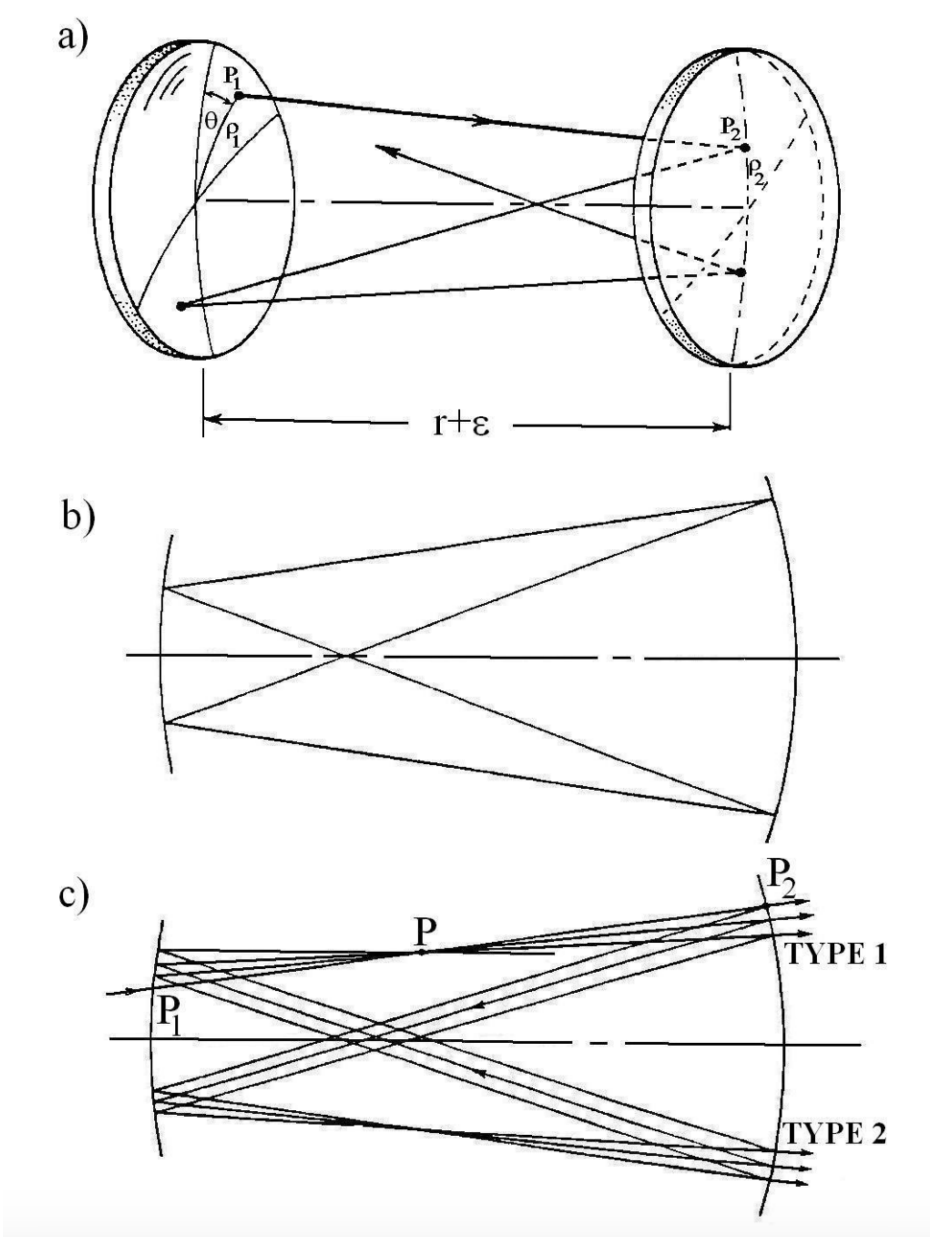

Figure 5: a) Schematic diagram of a spherical Fabry-Perot resonator. Each of the mirrors has a radius of curvature r, and they are separated by r_+. b) A paraxial ray entering the resonator at point P1 is reflected four times off the surfaces of the mirrors and it falls upon itself after this (i.e., 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.

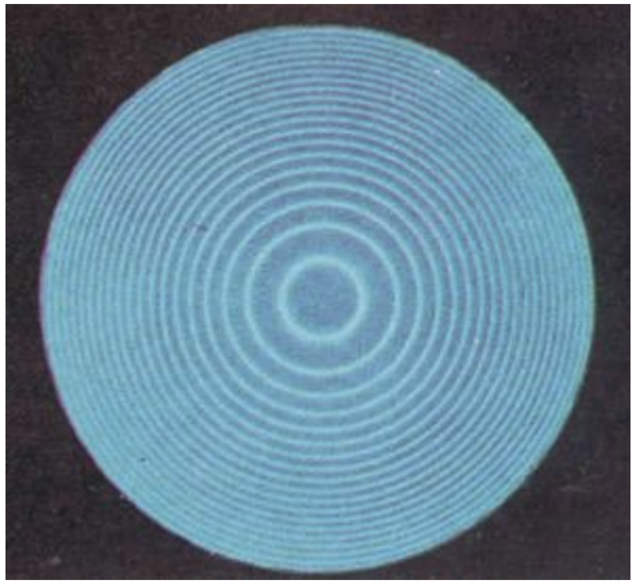

Figure 6: An example of the pattern of circular fringes formed in the central plane of a Fabry-Perot interferometer. The pattern can be observed when the FabryPerot is set in the “fringe display” mode of operation (described in Appendix A).

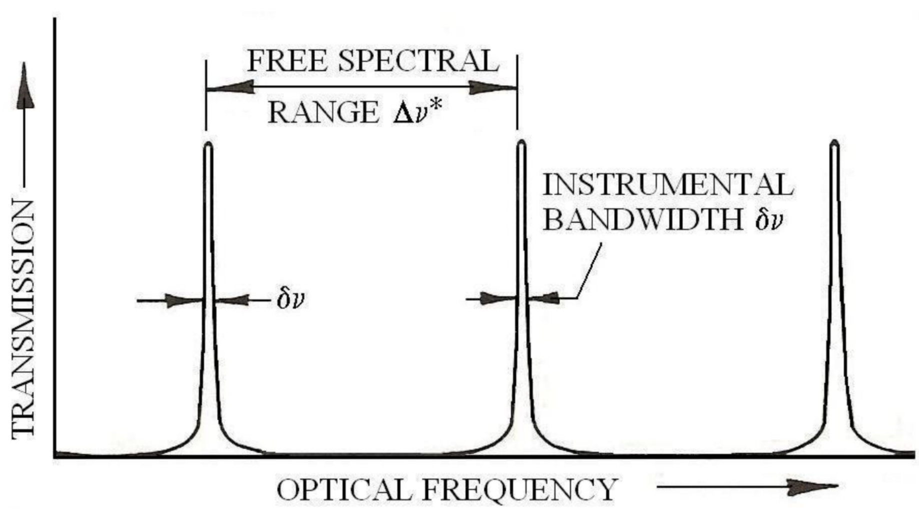

Figure 7: The transmission of a Fabry-Perot as a function of frequency. The frequency separation between two successive transmission maxims is $\Delta\nu^*$, the free spectral range. The full width half maxima (FWHM) of each transmission maximum is $\delta\nu$, the instrumental bandwidth.

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

$$\nu_n = \frac{c}{\lambda} = n\frac{c}{4d} \qquad \Delta\nu^* = \nu_n - \nu_{n-1} = \frac{c}{4d} \tag{7}$$

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**.

Because of radiation losses upon successive reflections, and losses as the laser passes through the air between the mirrors, the transmitted lines centered on ν_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

$$\mathcal{F} = \frac{\delta\nu^*}{\delta\nu} \tag{8}$$

$\mathcal{F}$ 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 $\frac{\lambda}{4}$.

Let us assume that the resonance condition Equation 6 occurs as a given λ and we increase the mirror separation d by $\lambda/4$.

New resonance condition:

$$4\left(d + \frac{\lambda}{4}\right) = n\lambda' \tag{9}$$

It follows that

$$\Delta\lambda = \frac{\lambda}{n} \tag{10}$$

Using

$$n = \frac{4d}{\lambda} \quad \text{to obtain} \quad \frac{\Delta\lambda}{\lambda^2} = \frac{1}{4d} \tag{11}$$

We find

$$\Delta\nu \approx c\frac{\Delta\lambda}{\lambda^2} = \frac{c}{4d} = \Delta\nu^* \tag{12}$$

We see here that the fabry-perot cannot distinguish between frequencies larger than $\Delta\nu^*$ as the resonance equation occurs again for periodic increases.

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} cm with 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).

3 Experiment

3.1 Aligning the Laser

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.

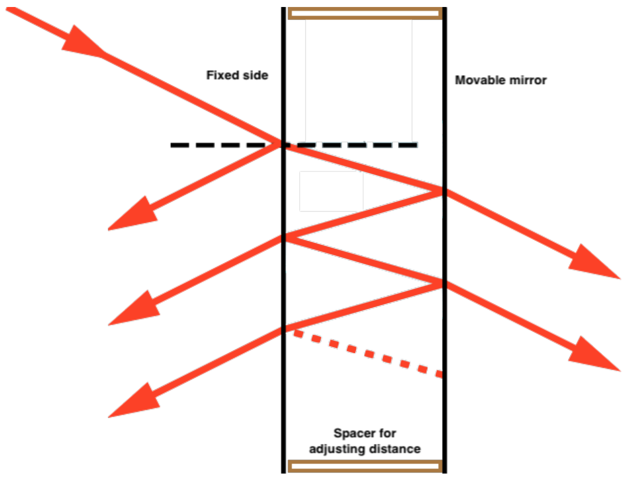

Figure 8: An illustration of the fabry-perot etalon. One side of the mirror is fixed and a spacer tube and piezo-electric ceramic section is affixed on the mirror with a second mirror on the other end. A laser beam entering one end would have multiple internal reflections inside the cavity, transmitting a small percentage of light through the second mirror with each bounce. Whether we observe constructive or destructive interference from the output would depend on the optical path difference of each transmitted beam.

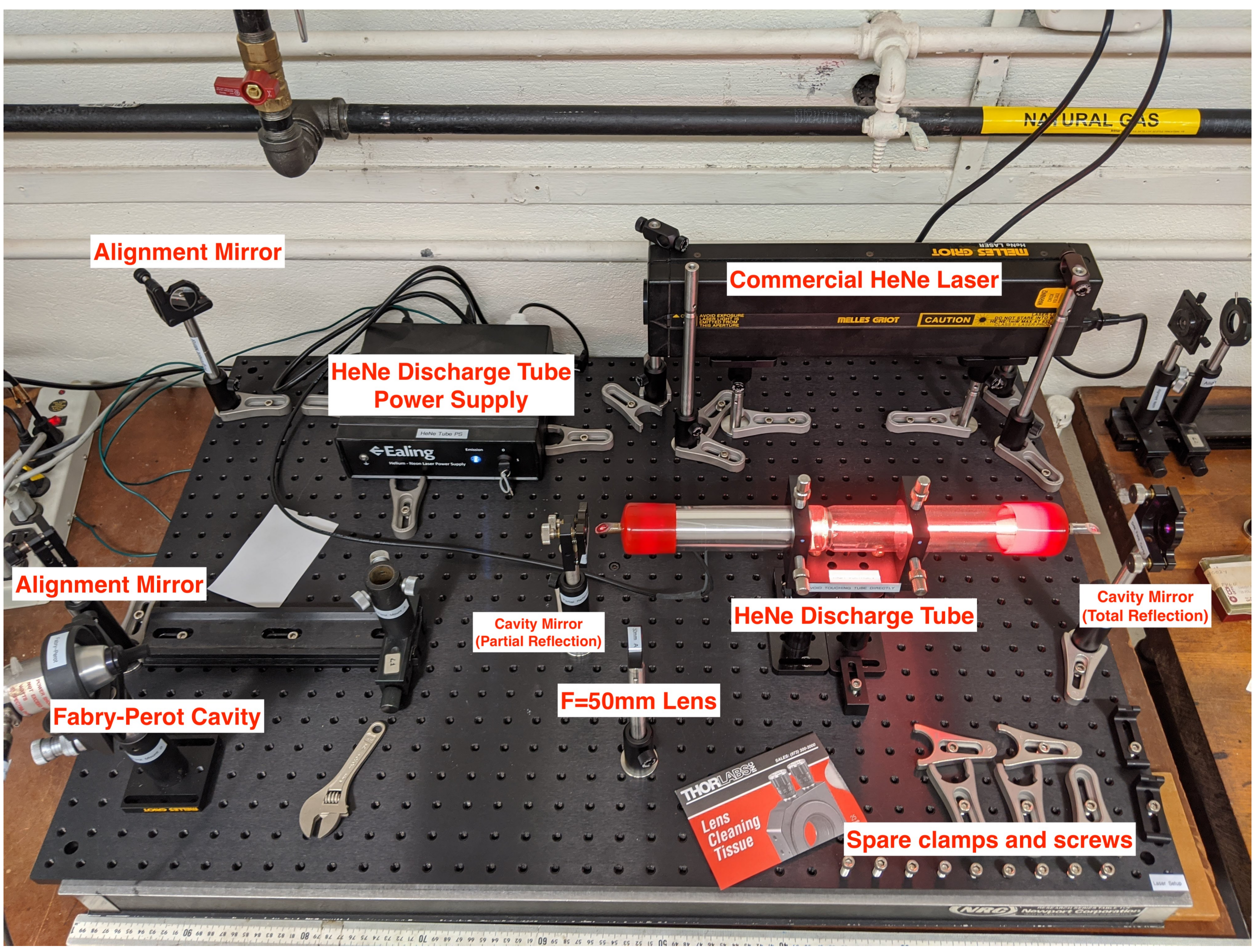

Figure 9: Schematic diagram experimental setup. Various apparatus are labelled in the diagram.

Note that as in Figure 5, the orientation of the mirrors matters!! The concave sides should be used to create a stable cavity for lasing.

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.

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.

3.2 Observing TEM Modes

Examine and describe the far field radiation pattern as a function of the mirror separation and mirror alignment. This is accomplished by redirecting the laser beam using the additional mirrors provided to a far flat surface (either a large piece of paper or the wall), and expanding the beam using a short focal length lens. 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 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?

3.3 Observing the longitudinal modes

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. Alignment is somewhat tedious, so take your time!

It is massively preferred to utilise the additional pair of mirrors to guide the beam into the fabry perot for measurement.

Follow the instructions in the interferometer manual for aligning the interferometer, and maximize the signal/peak height.

A triangular signal triggered by a variable frequency source is input to a high gain operational amplifier (op-amp) and to channel 1 of an oscilloscope. The output of the interferometer detector is input to channel

2. The op-amp drives the piezo ceramic in the fabry-perot, changing the cavity length. Channel 1 allows identification of the mode response displayed in channel 2. Once you have obtained the data for the cavity laser, repeat the measurement for the commercial HeNe laser.

You can extract the data from the oscilloscope to a USB drive.

- How stable are these modes in time?
- How sensitive are they to mechanical disturbances of the optical bench?
- What is the $\Delta\nu^*$ and $\delta\nu$ of the fabry-perot? Estimate the uncertainty.
- From the above can you deduce the $\mathcal{F}$ of the cavity? How does it compare with the quoted value of 150?
- How does the spectrum of your lab-built laser compare with the commercial laser?
- In the experiment you are also provided with a photodiode (Thorlabs DET36A), by directing the laser onto the photodiode and measuring the voltage, can you provide an estimate for the power of the laser? How does this compare to the commerical laser?

4 Additional Notes

4.1 Aligning HeNe tube to mirrors

The alignment of the cavity laser is an involved process and should not be undertaken lightly. If you find the setup to be grossly misaligned, please contact your TA for assistance and follow the full realignment procedure below. Adjust laser tube so that mirror (output coupler) is centered in the beam horizontally and vertically; the beam when not lasing can be seen as a large spot with concentric circles of light. Then, look for the back reflection around the sides of the Brewster window (the angled mirror on either end of the HeNe tube).

Alignment is accomplished by two fine adjustments on output coupler. Adjust the tilt of the output coupler window to put the reflected beam in the center of the Brewster window.

4.1.1 Total Realignment Procedure

1. Remove cavity mirrors and HeNe discharge tube.
2. Turn on alignment laser.
3. Using the 2 alignment mirrors and the alignment iris, align beam through the iris at various points along the fixed horizontal platform. Beam height = 7 in.
4. Beam height and path should be somewhat fixed now. The goal now is to align all the optics to the beam path.
5. For this step, the HeNe tube does not need to be on. Set up the HeNe discharge tube, and adjust the 4 knobs to adjust the alignment of the tube to match the beam.
   Note:It is important to check and ensure that the beam does not get deflected in the tube; Ensure that you do not apply too much torque that can damage the glass tubing.
6. Once done, install the post clamps to maintain the height, screw down the feet with feet clamps (Thorlabs CL5A). and remove the HeNe discharge tube for now.
7. Install the total reflecting mirror. You can use the alignment notch to narrow the beam size for better alignment. Beam should be hitting the center of the mirror by eye. Be careful with the orientation of the mirror, only works one way!!

8. Using the adjustment knobs on the total reflecting mirror mount, adjust so that the reflected beam should be co-propagating with the incident beam. You should be able to see the reflection going back into the Alignment Laser aperture.

9. Once that mirror is aligned (First cavity mirror), install the second cavity mirror, noting carefully the same direction and ensure that the incident alignment beam hits the center of the mirror. AFAIK the quoted curvature is 60 cm, however optimal lasing conditions is at $\sim$ 46-50 cm.

10. Similarly ensure the retro-reflection is aligned with the incident beam.

11. For finer alignment, you should see a finite amount of light leaving the total reflection mirror (reflectivity ¿99%) as well, and align the beams so you can maximally bright spot post-mirror.

12. Fine adjustments of both cavity mirrors to ensure the beam reflections propagates inside the cavity overlaps. (You can use a card/piece of white paper to look at the beam inside the cavity. If it well aligned you should see it expand due to finite divergence and power buildup inside the cavity)

13. A good sign that everything is well aligned at this point is that you should see interference rings post-cavity and at the edge of the propagating laser beams in the cavity region when you use a white sheet of paper.

14. Reinstall HeNe tube, small adjustments of the cavity mirror mount knobs should get it lasing. If it does not lase, you may have to repeat the alignment procedure from Step 8 at different different cavity mirror distances.

A video demonstration of a similar setup can be found here.

4.2 Observing Transverse Modes:

Use mirror 1 and 2 to redirect laser beam through the lens and observe the image cast onto a distant flat surface. Carefully adjust the alignment of the outcoupling cavity mirror to see if you can generate higher order spatial modes.

The ease of generating these modes would depend on the cavity length as well (Distance between the cavity mirrors).

4.3 Fabry-Perot Setup

4.3.1 Driving the Piezo Crystal

Do not mix up the **Fabry-Perot Interferometer** for the **laser cavity**!!

The Fabry-Perot is used to observe the frequency modes of the laser. Only 2 or 3 modes of the cavity fall within the line width of the He-Ne transition. A piezoelectric crystal linearly translates one of the mirrors of the Fabry-Perot. The distance it moves is linear with the applied voltage.

Set the function generator (Wavetek Model 182A) to drive a triangular waveform at 50 Hz, a BNC tee branches out one path to Ch 2. of the oscilloscope, alternatively it can also be triggered using the Sync Out signal, the second path goes to the high voltage DC operational amplifier (Burleigh)

Set reasonable values for the amplitude and frequency of the driving wave such that you will observe 2 to 3 modes per cycle.

Question: *If you set the driving frequency to be too high (a few MHz), you will see a broadening of the peaks on the oscilloscope. What is the cause of this effect?*

4.3.2 Aligning Fabry-Perot Interferometer

Align the Fabry-Perot so that incoming beam is reflected back on itself by interferometer mirror. Incoming and reflected beam observed as two spots on face of FP.

Vertical adjustment requires slightly loosening lock screw and pivoting by hand. Longitudinal modes of laser shift back and forth in frequency as length of cavity changes due to vibrations and thermal effects. You should see multiple peaks on the oscilloscope and the trace can be extracted onto a USB device. Measure the position difference between longitudinal modes on in the photographs. The pattern is repeated (different orders in the FP). Use the known spacing between orders (free spectral range) to calibrate and calculate the frequency difference of the longitudinal modes. Compare with what is expected based the cavity length and the laser wavelength. Repeat for several cavity lengths.

5 Appendix

A Fabry-Perot Interferometer Manual

Spectra-Physics

MODEL 470
INTERFEROMETER

Instruction Manual

LASER INSTRUMENTS DIVISION
1250 W. Middlefield Road, Mountain View, California 94042
Alsfelder Strasse 12, 6100 Darmstadt, West Germany

B/470 11/1976 ©

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ADDENDUM

The Model 470 Optical Spectrum Analyzer has two detector configurations which, if used incorrectly, will give substantially reduced performance.

The Model 471 detector with a clear anodized case was standard until September 1974. It contains a 1.5 KΩ load resistor and should be used only when displaying the output of the spectrum analyzer on an oscilloscope or strip chart recorder having a high input impedence. The resistor serves to convert the current from the photodiode into a voltage.

The Model 471 detector with a black anodized case is standard after September 1974 (unless otherwise noted on the order). The load resistor has been removed to allow the detector to be used with the Model 476 Interferometer Driver (whose vertical amplifier requires a current input). If the detector output is to be fed directly to an oscilloscope input, a 1.5 KΩ resistor should be placed across the input.

If you have any questions, please contact your local Spectra-Physics field sales engineer or customer service department.

SECTION ONE—INTRODUCTION

UNPACKING

The Model 470 Spectrum Analyzer was carefully packed for shipment. **If the packing box is damaged, have the shipper's agent present for unpacking.**

The 470 is shipped with the mirrors prealigned and tested at the factory. The Model 471 photodetector, mirror adjusting tool, aperture, and circular polarizer will be in their separate slots within the walnut case. The 35 X 45 mm cutouts in the foam insert are for storage of extra mirror sets or the 470A beamsplitter attachment.

INSPECTION

The 470 should be inspected as soon as possible after it is received. The analyzer should have an audible buzz when hooked up to a ramp voltage source of approximately 100 volts @ 0.1 second duration.

DESCRIPTION

The Spectra-Physics 470 Spectrum Analyzer is a mode degenerate, spherical mirror, Fabry-Perot interferometer for use in high resolution optical spectroscopy. It can be used as a scanning spectrum analyzer (completing a single scan in less than a millisecond), as a static fringe interferometer, or as a tunable optical filter with a bandpass of between 10 and 100 MHz (i.e.: between 0.001 and 0.01 nm, or 1 to 10 pm). The light-gathering power and transmission of the Model 470 Spectrum Analyzer are exceptionally high, and it is generally possible to trade off spectral resolution for light-gathering power, and vice-versa. This type of optical spectrum analyzer is exceptionally simple to use and retains its internal alignment indefinitely. The alignment between the source of light and the spectrum analyzer is not critical and is facilitated by the built-in optical system.

The Model 470 is available with two different free spectral ranges (2GHz and 8GHz) and with mirrors coated for two different spectral regions. It is intended primarily for observing laser spectra and for recording the spectral characteristics of scattered laser radiation. It is particularly effective in the latter application because of its high light-gathering power. The Model 470 Spectrum Analyzer can also be used to spectrally filter laser radiation or to observe spectra of narrowband incoherent sources.

DEFINITION OF TERMS:

d = Mirror separation = radius of curvature

ρ = Radius of incoming light

λ = Wavelength

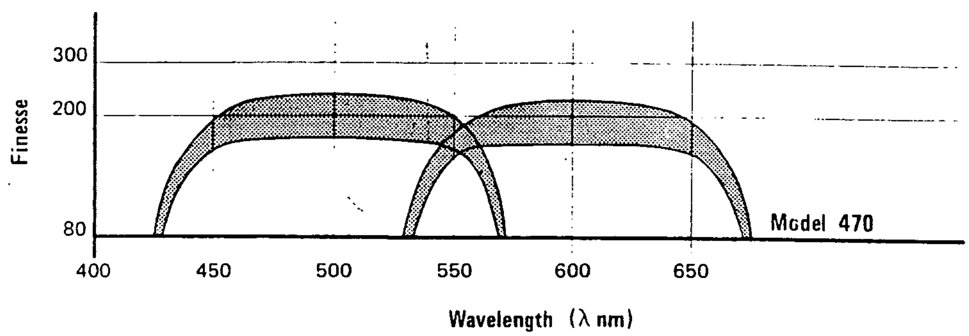
F.S.R. = Free Spectral Range

F = Finesse

C = Speed of light = 2.99793×10^{10} cm/sec

SPECIFICATIONS

Model	Operating Wavelength	Free Spectral Range	(Max.) Bandwidth	(Min.) Finesse	Aperture
470-01	450-550 nm	2 GHz	13 MHz	150	Entrance
470-02	450-550 nm	8 GHz	53 MHz	150	Aperture 19 mm
470-03	550-650 nm	2 GHz	13 MHz	150	With isolator 13 mm
470-04	550-650 nm	8 GHz	53 MHz	150	With pinhole 2 mm



The transmission curve for a spherical mirror Fabry-Perot interferometer used in this way is shown in Fig. 2-2.

A number of the characteristics of a spherical mirror Fabry-Perot interferometer are conveniently illustrated by the transmission curve shown in Fig. 2-2.

FREE SPECTRAL RANGE (F.S.R.)

Free spectral range is the separation (measured either in terms of frequency, wavenumber, or wavelength) between adjacent transmission maxima (or 'orders'); hence, the maximum spectral bandwidth of incoming light which can be observed without overlapping orders. Expressions for the free spectral range of a confocal spherical mirror interferometer of spacing d are:

$$\Delta\nu^* = c/4d \text{ (frequency)} \qquad \Delta\sigma^* = 1/4d \text{ (wavenumber)}$$

$$\Delta\lambda^* = \lambda^2/4d \text{ (wavelength)}$$

INSTRUMENTAL BANDWIDTH

The apparent or observed spectral width of a true monochromatic spectral line:

$\delta\nu$ (frequency) $\delta\sigma$ (wavenumber) $\delta\lambda$ (wavelength)

FINESSE

The finesse of a multiple-beam interferometer may be defined as the ratio of the free spectral range to the instrumental bandwidth. As such, it is a fundamental measure of the spectral resolving capability of the instrument. The finesse may be interpreted as the effective number of beams contributing to the multiple beam interference and is thus analagous to the number of rulings on a diffraction grating.

$$F = \Delta\nu^*/\delta\nu = \Delta\sigma^*/\delta\sigma = \Delta\lambda^*/\delta\lambda.$$

The finesse of an instrument is determined by a number of factors, chief among which are the reflectivity of the mirrors and the surface figure of the mirrors. The approximation for high reflectivity reflection-limited finesse is given by:

$$F_r = \pi R/(1 - R)^2 \simeq \pi/2(1-R).$$

SPECTRAL RESOLVING POWER

This is defined as the ratio of the frequency (or wavelength) to the instrumental bandwidth in frequency (or wavelength) units:

$$RP = \nu/\delta\nu = \sigma/\delta\sigma = \lambda/\delta\lambda.$$

The transmitted wavelength can be varied simply by varying the mirror separation, d. The required change in mirror separation is very small: a quarter-wavelength change is sufficient to scan through a complete free spectral range. The central fringe width (the diameter of the central spot in the interference pattern when the instrument is set at resonance with an incoming monochromatic beam) determines the upper limit on both the diameter and angular divergence of the incoming beam which can be used without appreciable degradation of finesse. This central spot diameter, for a specified finesse F, is given by:

(3) $D_s = 2(d^3\ \lambda/F)1/4$

In order to achieve a finesse of F, the incident beam diameter should be appreciably smaller than this value for D_s. If the beam diameter is just D_s, then the realizable finesse will be approximately 0.7F.

In a similar way, the angular divergence of the incident beam should be restricted to an angle of less than:

(4) $\theta_s = 2(\lambda/Fd)1/4$

in order to approach an observed finesse F.

ETENDUE

The net light-gathering power of an instrument of this type is expressed quantitatively in terms of its etendue. Etendue is defined as the product of the maximum allowed aperture area and the maximum allowed solid angle divergence which will permit a realization of a specified finesse.

$$\text{etendue} = U = (\pi D_s^2/4).\ (\pi\theta_s^2/4) = \pi^2 d\lambda/F.$$

It is worth pointing out that, in order to realize a finesse F with a given aperture, the mirrors must be perfectly spherical to within approximately $\lambda/2F$ across that aperture. This requirement often dictates the use of a restricted aperture for very high spectral resolution.

In normal use as a scanning spectrum analyzer, the Model 470 employs an auxiliary lens as shown in Fig. 2-3. This lens makes the use of the Model 470 with a laser more convenient by increasing the effective aperture diameter at the expense of reducing the acceptable angular divergence of the incoming beam. The upper limits on the beam diameter and angular divergence in order to realize a finesse of approximately 0.7F with the auxiliary lens in place are given by:

(5) $D_L = (f/d)D_s$, and $\theta_L = D_s/f$,

where f is the focal length of the auxiliary lens (approximately 5cm) and D_s is the spot diameter given by eq(3).

SECTION THREE—OPERATION

SCANNING MODE

Initial Alignment

The Model 470 Spectrum Analyzer should be initially set up so that its longitudinal axis is approximately coincident with the incoming light beam. Alignment is greatly facilitated by the use of a Spectra-Physics Model 381 Optical Mount, which securely holds the Spectrum Analyzer and allows a wide range of angular orientations. The auxiliary aperture and circular polarizer are removed from in front of the lens (see Fig. 3-1), and the incoming beam is directed into the center of the lens aperture. When properly aligned, the incoming beam will be reflected (by the interferometer mirror) back along itself. This is particularly easy to accomplish when the source is a laser, since both the incident and reflected beams will be clearly visible as spots on the lens surface. Alignment consists of putting the incoming spot in the center of the lens and then making angular adjustments to superpose the return spot on the incoming spot. If the source is a plane-polarized laser, then the circular polarizer should be replaced over the lens aperture in order to eliminate feedback from the spectrum analyzer to the laser (this type of feedback produces laser frequency instability). The auxiliary aperture can also be replaced if maximum spectral resolving power is desired. Note: Rotate the polarizer for maximum signal through the spectrum analyzer.

When using the Model 470 Spectrum Analyzer with an incoherent source, initial alignment is most conveniently obtained by temporarily replacing the incoherent source with a low power gas laser.

Scanning and Final Alignment

There are a number of techniques for operating the Model 470 Spectrum Analyzer in the scanning mode; some of these are illustrated in Fig. 3-2. One of the simplest methods requires the use of an auxiliary oscilloscope capable of supplying a horizontal sweep voltage of 50 volts or more (this output is labelled SAWTOOTH on some oscilloscopes). The horizontal sweep voltage is connected to the scanning voltage terminal of the spectrum analyzer, and the sweep speed is initially set to 2 ms/cm. Triggering is set to LINE, thus providing 30 scans/second with a duration of 20 ms/scan. The detector output is next applied to the input of the oscilloscope's vertical amplifier. The resultant scope display will be a stable and linear plot of the source's spectrum. For best results, a resistive load of $\approx$ 1.5 kΩ should be used across the leads of the detector.

A free spectral range will be scanned in the time taken to change the mirror separation by ¼ wavelength. If the Spectra-Physics Model 476 Scanning Interferometer Driver is used, the spectral dispersion, position of the displayed spectra,

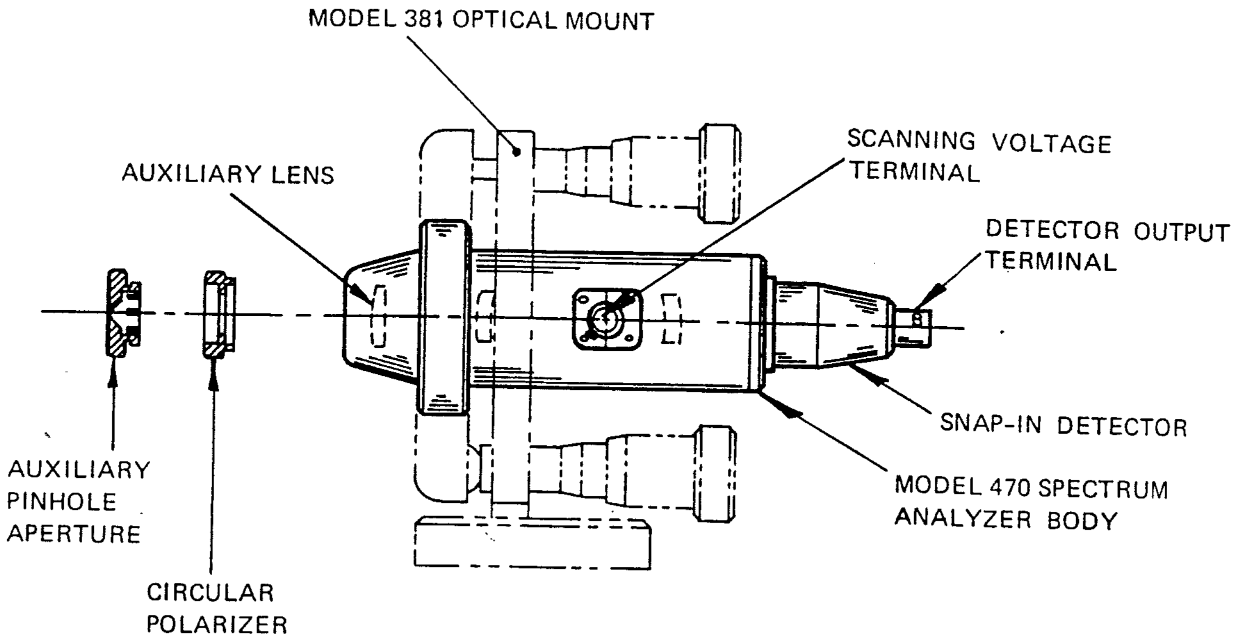


Figure 3-1 Model 470 Spectrum Analyzer Components

repetition rate, and amplitude of the signal can be varied over a continuous range. As long as the scan voltage exceeds approximately 50 volts, the spectral scan will cover in excess of one free spectral range, thus providing a repetitive spectral display. This repetitive feature of the display can be used to calibrate the observed spectrum, since the free spectral range of the spectrum analyzer is known to be either 2 Ghz (0.0667 cm^{-1}) or 8 Ghz (0.2667 cm^{-1}).

Once the initial spectral display is obtained, the alignment of the spectrum analyzer relative to the source can be adjusted to optimize the displayed spectrum.

Note: Although the suggested scan rate (2 ms/cm with line triggering) is convenient for most purposes, it is possible to scan at any other rate up to about one kHz. Above this scan rate, a sawtooth driving voltage invariably produces a distorted response. Although not recommended, higher scan rates can be obtained using sinusoidal scanning voltages. If necessary, in the absence of a scanning voltage source, direct line voltage can be used to give quite satisfactory results which will be linear over several free spectral ranges on either side of zero voltage.

FRINGE DISPLAY MODE

When a quasi-collimated beam of light is incident along the axis of a spherical mirror Fabry-Perot interferometer, a pattern of multiple beam interference fringes is formed in the plane lying midway between the mirrors and perpendicular to their axis. In order to observe this fringe pattern most conveniently, the incident light should be directed into the rear aperture of the Model 470 where the snap-in detector is normally located. The auxiliary lens can be now used to observe the fringe pattern. Since the focal plane of the auxiliary lens is approximately coincident with the plane in which the fringes are localized, the fringes will be seen in sharp focus by an otherwise unaided visual observer or by a camera focused at infinity (Fig. 3-3).

Reference 1 contains a detailed discussion of the accurate interpretation of spherical mirror Fabry-Perot fringe patterns.

OBSERVING SCANNED SPECTRA WITH WEAK SOURCES

Because of the exceptionally high light-gathering power, or etendue, of the Model 470 Spectrum Analyzer, it is especially well-suited for observing weak spectra with high resolution. There are a number of optical arrangements which can be used to bring the light into the Spectrum Analyzer and thence to the detector, but the setup shown in Fig. 3-4 is particularly versatile and allows a convenient trade-off between light-gathering power and spectral resolution.

As shown in Figure 3-4, both the auxiliary lens and the snap-in detector are removed. Since the (source area) X (source solid angle) product has an upper limit equal to the instrumental etendue, the user must determine whether he wishes to limit the source area, the source solid angle, or both. Refer to Section 2, Fig. 2-3. Lens L_1 is selected to form an image of the source in the vicinity of the central plane of the interferometer (the exact image location is not important). The size of this image should be on the order of the central fringe spot size. Lens L_2, on the other side of the spectrum analyzer, relays the image of the source to the plane of an adjustable aperture stop, A_2. Another adjustable aperture stop, A_1, is located at lens L_1. The detector, which would ordinarily be a photomultiplier, is located just behind aperture A_2. In this arrangement, aperture stop A_1 serves to limit the solid angle of light collected from any point on the source, and stop A_2 effectively limits the size of the part of the source from which light is detected. For highest spectral resolution at the expense of light, both stops are closed down.

Initial alignment of this system is most easily accomplished by substituting a laser for the incoherent source during the alignment.

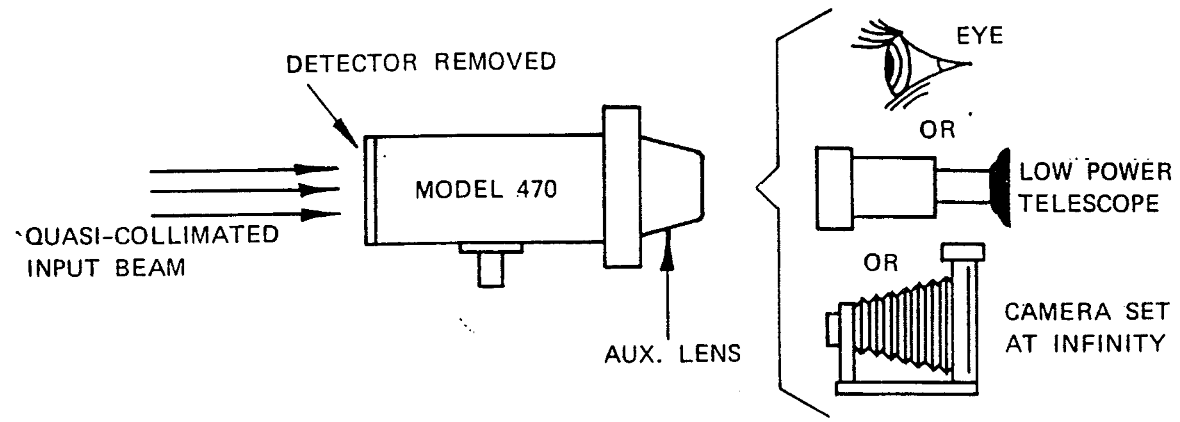


Figure 3-3 Optical Setup for Observing Fringe Patterns

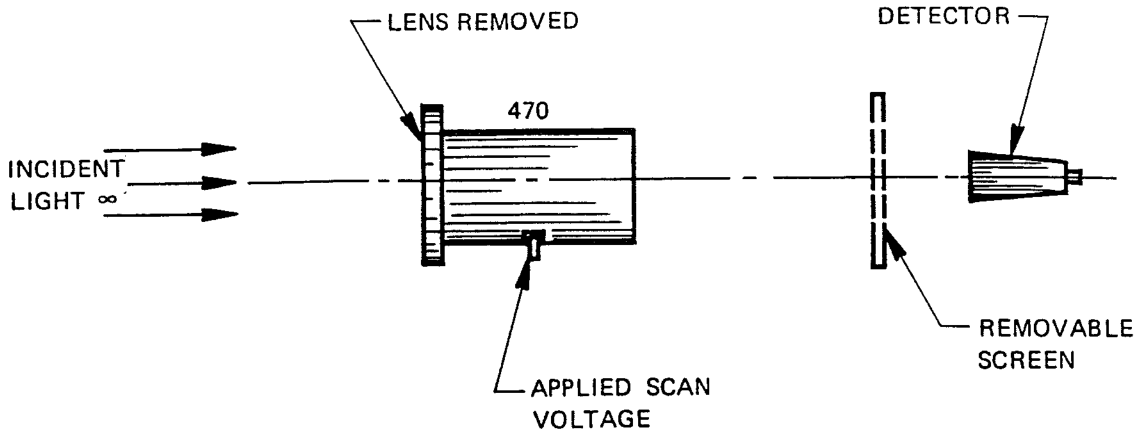


Figure 3-6 *Mode-Matching Setup*

Remove the screen, observe the scan displays, and touch up the tilt alignment as required. As the proper alignment is approached, the spectral display at every other spectral peak will increase in amplitude while the remaining portion approaches zero. This procedure is somewhat inefficient in that much of the light in the collimated beam fails to reach the detector.[1]

As an alternate procedure, one can use the technique described by Fork[2] for mode matching to a general curved mirror cavity. This is more efficient in that greater than 70% of the available light will be transmitted. However, the alignment requires x, y, and z axis translation as well as angular adjustments.

References

(1) "The Spherical Mirror Fabry-Perot Interferometer", M. Hercher, Applied Optics 7, 951 (May, 1968)

(2) "A Scanning Spherical Mirror Interferometer for Spectral Analysis of Laser Radiation", R. L. Fork, D. R. Herriott, & H. Kogelnik, Applied Optics 3, 1471 (1964).

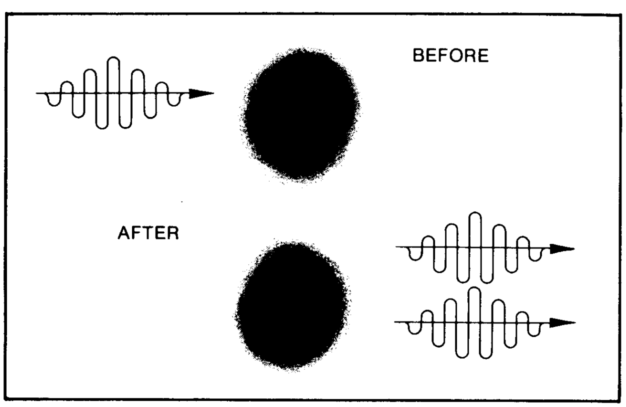
B HeNe Laser Article

HOW DOES A HELIUM NEON LASER WORK?

All lasers depend for their operation on the phenomenon of stimulated emission of radiation. For this to occur, it is necessary for some atoms to exist in an excited energy state. In an excited atom an electron may decay to a lower energy level, emitting a photon of energy $E = h\nu$, where h is Planck's constant and ν is the photon frequency. This is spontaneous emission of radiation, or luminescence. If the emitted photon passes close to another atom in a similar excited state, it may induce an identical transition. In this case the emitted and stimulating photons will be identical in every respect, having the same frequency, phase, direction, and polarization – they will be spatially and temporally coherent. This is stimulated emission of radiation.

To achieve laser oscillation it is necessary to make the probability of stimulated emission exceed that of spontaneous emission and absorption. This is done by creating a population inversion, in which more atoms exist in an excited energy state than in some lower state to which direct radiative transition is possible. This situation must be maintained or laser action will cease.

In the helium neon system, a mixture of helium and neon gases is contained in a narrow bore tube. These gases are replenished as needed from a reservoir. The mixture is predominantly helium, with about 10% neon. Various isotopic mixtures have been used to improve the power output and stability of lasers. Melles Griot helium neon lasers are filled with a proprietary mixture which has the effect of maximizing the ratio of beam power to plasma volume. An electrical discharge ionizes the gas inside the narrow bore. The plasma so formed contains many helium atoms in metastable states. In these states one of the valence electrons has been raised from the 1s and 2s level, where it will remain for a long time, the downward transition being forbidden by the selection rules of quantum mechanics. Neon has an atomic number of 10, and has 10 electrons normally residing in the $1s^2 2s^2 2p^6$ configuration. Collisions between metastable helium atoms and neon atoms cause one of the neon electrons in the 2p level to be raised to the 4s or 5s levels. The energy match between the 2s helium levels and the 4s and 5s neon levels is very close. It is therefore much more probable that this excitation will occur than one to the 3s or 3p levels. On exciting a neon atom in this way, the helium atom drops back to the ground state. However, because there are many more helium atoms than neon, the metastable collision probability remains high. For neon laser action to occur, it is necessary to maintain a greater population of neon atoms with electrons in the 4s and 5s levels than in the 3p level. This condition is satisfied by the selective excitation process just described, and by the low natural population of the 3p levels. A number of alternative downward transitions are available to the excited neon electrons. The major neon laser line transitions are indicated on the energy level diagram.

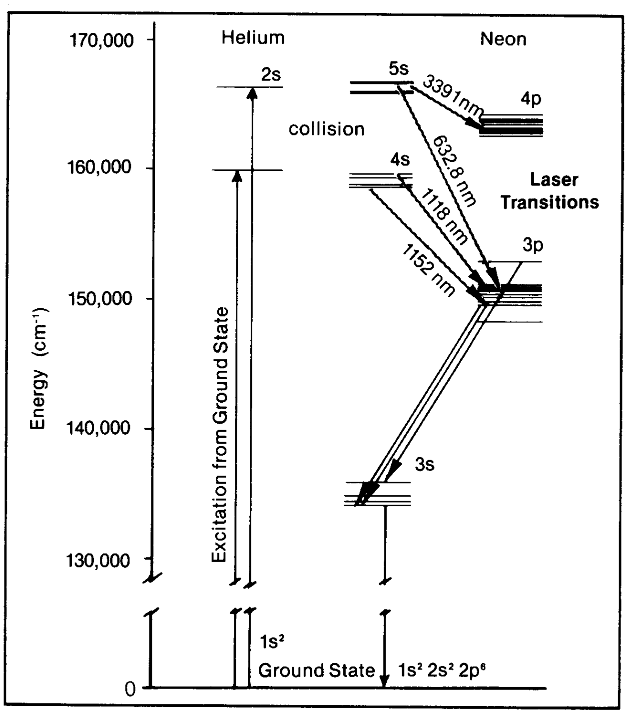


STIMULATED EMISSION, an artist's conception.

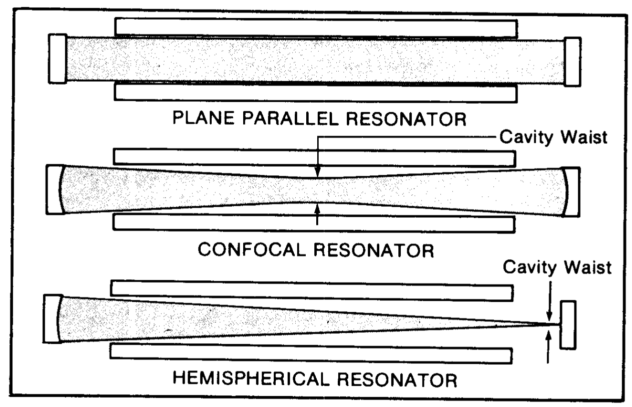
Some of the radiation emitted will be in a direction approximately parallel to the tube bore. The rest will be emitted through the tube walls and does not contribute to the laser operation. For a photon traveling along the bore, there is a chance of passage close to a second excited neon atom and stimulation of the emission of another identical photon. The probability of this occurrence depends on the gas density and length of the bore. For a single pass along the bore the probability is on the order of 10%.

Mirrors are placed at either end of the tube, reflecting photons many times along the length of the bore. In this way the likelihood of stimulated emission is further increased. Each stimulated photon is capable of stimulating another, and each is in perfect coherence with those already present. In this way, light amplification is achieved.

The two mirrors form a resonant optical cavity, and it is this cavity which is responsible for the selective gain characteristics of the laser. Cavity mirrors are coated to have a very high reflectance at the laser wavelength of interest, but to transmit unwanted laser lines. By retaining only the desired wavelength photons in the bore, amplification is restricted to only this wavelength. Similarly, misdirected radiation of the desired wavelength escapes from the cavity and is not amplified, giving rise to the highly directional nature of the laser output. In order to make use of the desired laser radiation, some of it must be allowed to escape from the cavity as a beam. In practice, one of the mirrors is coated to permit about 1% transmission at the laser wavelength. It is this 1% of light which escapes that forms the usable output of the laser. It follows that the internal beam is 100 times more powerful than the output beam.



ENERGY LEVEL DIAGRAMS for helium and neon. Levels are identified in spectroscopic notation, and major laser transitions are shown.

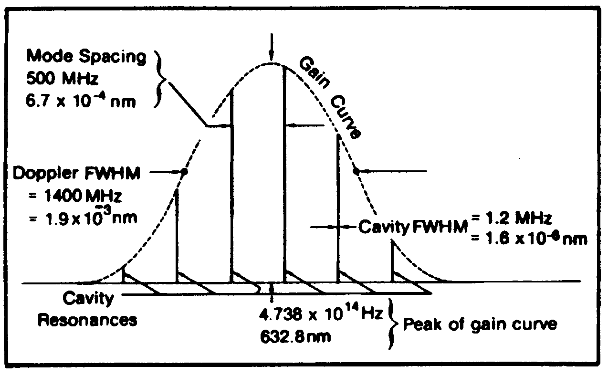


LASER CAVITY TYPES, showing the shape and size of the active plasma volume. The most popular cavity for HeNe lasers is the quasi-hemispherical cavity, because of its stability and short length. To obtain a quasi-hemispherical cavity, the hemispherical cavity is shortened very slightly.

Various shapes of resonant cavity have been used. The plane parallel resonator, perhaps the most obvious choice, is never used. It has the theoretical advantage of fully utilizing the available plasma volume to obtain high efficiency, but is inherently unstable and has large diffraction losses.

The confocal resonator has two equal radius concave spherical mirrors, each placed at the center of curvature of the other. The cavity utilizes a large fraction of the plasma volume and produces high power. It is less sensitive to alignment, but is slightly sensitive to mirror separation. The confocal resonator is rarely used when TEM_{OO} output is required.

The hemispherical resonator has a plane mirror at the center of curvature of a concave spherical mirror. The resonator becomes quasi-hemispherical if this mirror separation is slightly reduced. This quasi-hemispherical configuration is easy to adjust and produces highly coherent output. The disadvantage of this cavity is that it only utilizes about one-third the volume of available plasma due to the focusing effect of the concave mirror. This inefficiency limits the power output. However, its ease of adjustment, and stability once aligned more than outweigh the disadvantage of power limitation. Quasi-hemispherical cavities are, therefore, the most commonly used in commercial lasers.



DOPPLER BROADENED GAIN CURVE supporting 6 longitudinal modes or cavity resonances. The gain curve is of the same shape as the line profile in spontaneous emission.

The presence of an optical cavity leads to longitudinal modes of oscillation. Only the light wavelengths which correspond to standing waves are amplified. Out of phase reflections are quickly lost through destructive interference. In order for a mode or standing wave to exist, the round trip cavity length must be exactly equal to an integer number of wavelengths:

$2L = m\lambda$ (where m is a large integer).

This corresponds to the series of resonant frequencies

$\nu = \frac{mc}{2L}$ (where c = velocity of light).

These frequencies each define an extremely narrow band within which laser oscillation can occur. The frequency separation of these longitudinal modes or resonances is

$$\Delta\nu = \frac{c}{2L},$$

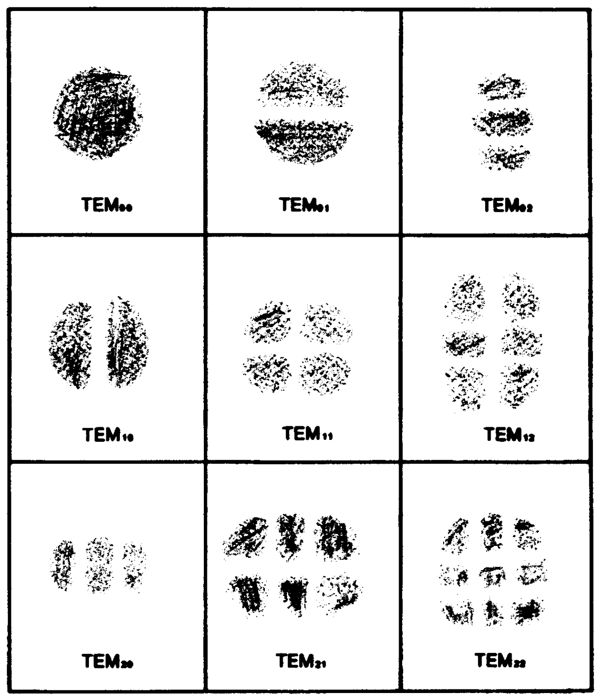
and is inversely proportional to the length of the cavity. Thus, for a 50cm cavity length, the mode spacing will be:

$$\Delta\nu = \frac{3 \times 10^{10}}{2 \times 50} \text{ Hz}$$

$$= 300 \text{ MHz}$$

In order for these modes to exhibit optical gain, their individual frequencies must lie within the finite spectral line width of the natural atomic transition. The net effect of random thermal atomic motion within the plasma is to produce a Doppler broadened spectral line. Modes which fall within the Doppler broadened spectral envelope will be amplified. The linewidth of a single laser mode is extremely narrow compared with the Doppler linewidths ordinarily encountered in atomic-spectroscopy.

In addition to longitudinal modes, the cavity can support a number of Transverse Electric and Magnetic modes (TEM



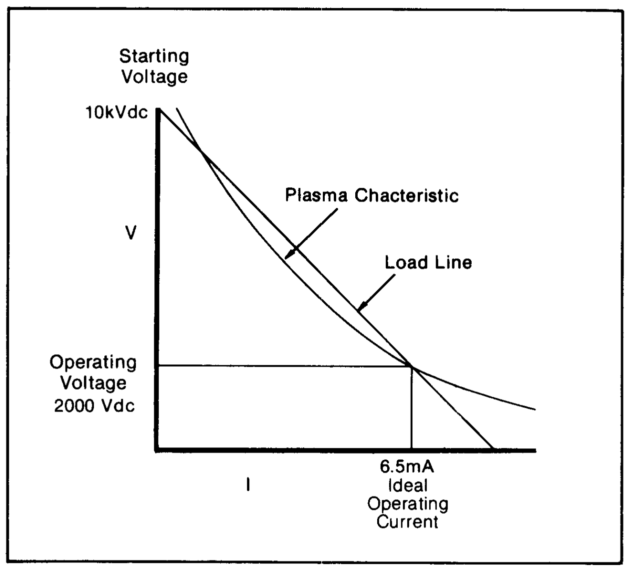
TRANSVERSE ELECTRIC AND MAGNETIC MODES of a laser cavity, with identification, and showing nulls of the irradiance distribution. The solid regions represent the interiors of irradiance contours arbitrarily selected to best reveal distribution shape.

modes). These are modes in which the irradiance distribution along the electric and magnetic field vectors exhibits one or more nulls. At small angles from the cavity axis it is possible to obtain a different series of standing waves, each of which can produce a stable mode of oscillation and gain. Transverse modes are identified by their irradiance distributions and are designated TEM_{pq}, where the subscripts p and q refer to the number of nulls along two orthogonal axes which are perpendicular to the cavity axis. The lowest order TEM_{OO} mode has a Gaussian irradiance distribution. This mode experiences the minimum possible diffraction loss, has minimum divergence, and can be focused to the smallest possible spot. For these reasons, it is often desirable that the laser should be restricted to operation in this fundamental mode. Higher order modes have a larger spread and usually suffer high diffraction losses. A mode often encountered in practice is the "doughnut" mode (TEM^*_{01}), which is a combination of TEM_{01} and TEM_{10}, having a central minimum and a bright ring.

Lasers are sometimes designed to exclude all but the fundamental mode, and sometimes to permit higher order modes. The exact design requirements depend on the type of cavity in use. If higher orders are to be excluded, the bore size must be held very close to the fundamental mode diameter. This may result in diffraction of some wanted radiation out of the beam. With a confocal resonator it is very difficult to exclude high order modes. Most TEM_{oo} mode lasers use quasihemispherical resonators. In this case, beam collimation quality is limited only by diffraction. Most helium neon lasers have an output beam divergence of 0.8 to 1.5 milliradians (beam angular diameter).

The polarization of laser radiation is an important effect which occurs as a direct result of the stimulated emission process. Just as the stimulated photon is in phase, frequency, and directional agreement with the stimulating photon, so it also carries the same state of polarization. The resonant cavity sets up standing waves of constant linear polarization. This results in alternate longitudinal modes having orthogonal states of polarization. Likewise, adjacent transverse modes have orthogonal states of polarization. The resultant polarization depends upon the precise mix of modes present, and this mix may change rapidly with time. So called "randomly polarized" lasers have an indeterminate combination of orthogonally polarized radiation. To eliminate this uncertainty, laser outputs are often deliberately linearly polarized. A single Brewster angle window is placed in the cavity, effectively eliminating one state of polarization, and preventing it from being amplified. The output is more stable and has a known state of polarization, namely the p-polarization defined by the window.

Electrically, helium neon lasers function as negative resistors. They require a high voltage in order to strike the discharge and then as current flows the voltage required to sustain operation is reduced. A ballast resistor is connected in series with the laser to provide safe minimum impedance. The output of the laser is a function of the d.c. discharge current. In order to optimize the laser performance, a particular operating current is chosen, and the power supply is designed to maintain this current with very low ripple.



CHARACTERISTIC OPERATING CURVE OF A HeNe LASER. The curve is typical of other low pressure gaseous discharges, such as advertising signs.

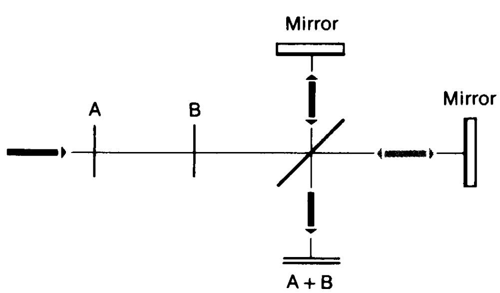
CHARACTERISTICS OF LASER LIGHT

The helium neon laser delivers relatively intense coherent electromagnetic radiation at 632.8nm. It is able to do this reliably, for many hundreds of hours, without variation of output power or beam direction, at modest cost. The temporal coherence of a laser is a measure of the ability of the beam to produce interference effects as a result of differences in path lengths, and is important in interferometry and holography. The spatial coherence is of importance in applications where it is necessary to focus all of the laser's output into an extremely small spot.

Both temporal and spatial coherence have long been sought for industrial and laboratory optical applications. Before the laser was invented, monochromatic sources with various degrees of coherence were in use. The relatively low output levels available, and the Doppler broadening of most atomic sources, were such that only limited applications were ever achieved.

TEMPORAL COHERENCE

If the phase at a particular instant in time along a traveling wavefront is the same as its phase after the wave has traveled a distance x in x/c seconds, for all values of x, the wave is defined to be perfectly temporally coherent. Michelson interference fringes are a direct result of temporal coherence, and they are visible only over the distance in which the temporal coherence is maintained. For conventional sources this distance is rarely more than a few millimeters, whereas for a multimode HeNe laser it is typically 20 to 30 centimeters. That this distance is not infinite demonstrates that lasers are not perfectly monochromatic or perfectly coherent. Off-the-shelf lasers are good enough, however, to permit precise interferometric measurement of distances hundreds of times longer than was formerly possible.



MICHELSON INTERFEROMETER, with path difference adjusted so as to superimpose wavefronts A and B in the output beam, where they will interfere if their separation in the input beam did not exceed the radiation coherence length. The interferometer measures coherence length, and coherence length is the measure of temporal coherence.

Visibility of interference fringes is defined as

$$V = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} ,$$

where I_{max} and I_{min} are the maximum and minimum observed fringe intensities. Unity visibility is associated with full temporal coherence. Zero visibility (absence of fringes) corresponds to $I_{max} = I_{min}$, and is associated with complete incoherence.

The minimum path length difference for which V is zero (i.e., fringes vanish) is called the coherence length (S_c). The time delay corresponding to this length is the coherence time (Δt). These are related by $S_c = c\Delta t$. The uncertainty relation between time and frequency leads to $\Delta\nu \, \Delta t = 1$, where $\Delta\nu$ is the line width (frequency spread) of the non-monochromatic laser output line. Lasers operating in a single longitudinal mode have linewidths of approximately 1 MHz. A typical FWHM for a commercial multimode HeNe laser is $\Delta\nu \cong 1500$ MHz, because the Doppler broadened bandwidth provides an envelope for the gain of a number of longitudinal modes.

SPATIAL COHERENCE

Correlation of phase in light beams transverse to the direction of travel is best illustrated by Young-type interference fringes. The light from two transverse portions of the same beam is allowed to interfere, producing fringes. Visibility is defined as above. Visibility of unity will again correspond to complete coherence, whereas visibility of less than unity implies partial coherence.

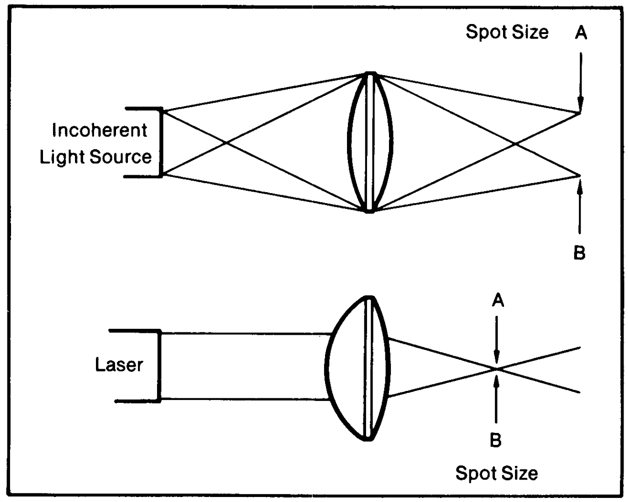
Spatial and temporal coherence are independent of one another; a source may be spatially coherent while temporally incoherent and vice versa. The mode discrimination properties of the laser cavity produce spatial coherence, and the Doppler broadened bandwidth limits temporal coherence.

DIRECTIONALITY AND ENERGY DENSITY

The extreme directionality of laser radiation follows directly from the coherence of the stimulated emission process. Because all of the stimulated photons are alike in every way, they carry no information about the location of the excited neon atoms they come from. Thus all of the excited neon atoms are functionally equivalent, and the laser output radiation behaves as if it all had originated in a tiny imaginary volume, having dimensions of the order of a wavelength, situated precisely on-axis at the center of the cavity waist. This remains true regardless of the size or shape of the active plasma volume.

When an off-axis neon atom is stimulated to emit a photon, the appearance presented to the outside world is that this photon originates on-axis. This behavior is attributable to transverse coherence. When a neon atom far from the waist plane is stimulated to emit, the photon still appears to come from the waist plane. This behavior is attributable to temporal coherence far in excess of the monochromaticity requirements of the beam optics formulas. Because all the coherent energy output of the active medium is effectively funneled by stimulated emission through that tiny imaginary volume, energy densities in focused laser beams can far exceed the highest energy densities actually occurring in the source plasma, a situation impossible with spontaneous emission.

When we look at an extended incoherent source, such as the surface of an incandescent solid or the spontaneous emission of a gaseous discharge, we can plainly see that it is extended.



FOCUSABILITY COMPARISON for light from laser and conventional sources. Extended sources have extended images. The laser is the functional equivalent of a true point source situated at the center of the cavity waist.

This is because the photons carry directional information telling us which parts of the source they come from. Laser radiation carries no such information.

SPECKLE

A smooth but diffuse reflector has a surprising appearance under HeNe laser illumination. Though the beam irradiance distribution may be very smooth, the apparent distribution at the surface is granular. The granule size is approximately the size of the resolution element of the eye. Neighboring granules vary enormously in brightness. A bright granule looks bright because of cooperative in-phase reflections from two or more area elements within the granule, directed at the eye. Such interference is possible because coherence length exceeds the scale of surface roughness. Speckle is a great nuisance in laser imaging and holography, but carries information valuable in non-contacting metrology. Radar "glint" is the same effect on a larger scale, and hampers radar imagery.

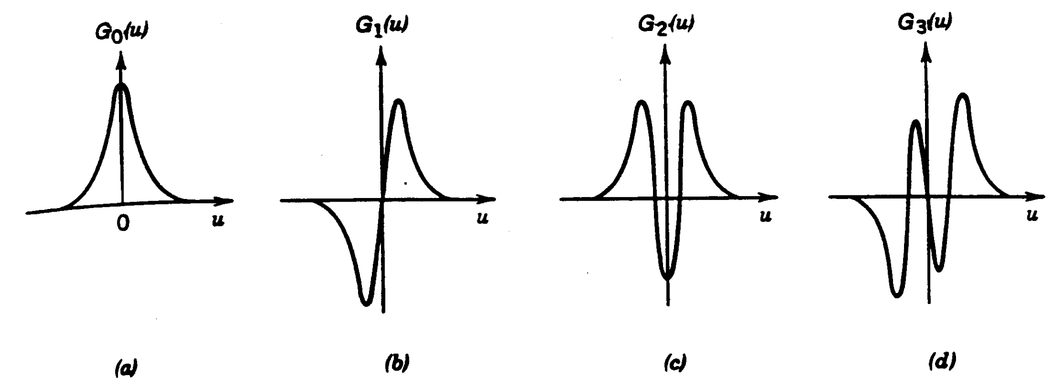


Figure 3.3-1 Several low-order Hermite-Gaussian functions: (*a*) $G_0(u)$; (*b*) $G_1(u)$; (*c*) $G_2(u)$; (*d*) $G_3(u)$.

where

$$G_l(u) = H_l(u)\exp\left(\frac{-u^2}{2}\right), \qquad l = 0, 1, 2, \ldots, \qquad (3.3\text{-}10)$$

is known as the **Hermite–Gaussian function** of order l, and $A_{l,m}$ is a constant.

Since $H_0(u) = 1$, the Hermite–Gaussian function of order 0 is simply the Gaussian function. $G_1(u) = 2u\exp(-u^2/2)$ is an odd function, $G_2(u) = (4u^2 - 2)\exp(-u^2/2)$ is even, $G_3(u) = (8u^3 - 12u)\exp(-u^2/2)$ is odd, and so on. These functions are shown in Fig. 3.3-1.

An optical wave with complex amplitude given by (3.3-9) is known as the Hermite–Gaussian beam of order (l, m). The Hermite–Gaussian beam of order (0, 0) is the Gaussian beam.

Intensity Distribution

The optical intensity of the (l, m) Hermite–Gaussian beam is

$$I_{l,m}(x, y, z) = |A_{l,m}|^2\left[\frac{W_0}{W(z)}\right]^2 G_l^2\left[\frac{\sqrt{2}x}{W(z)}\right]G_m^2\left[\frac{\sqrt{2}y}{W(z)}\right]. \qquad (3.3\text{-}11)$$

Figure 3.3-2 illustrates the dependence of the intensity on the normalized transverse distances $u = \sqrt{2}\,x/W(z)$ and $v = \sqrt{2}\,y/W(z)$ for several values of l and m. Beams of higher order have larger widths than those of lower order as is evident from Fig. 3.3-1.

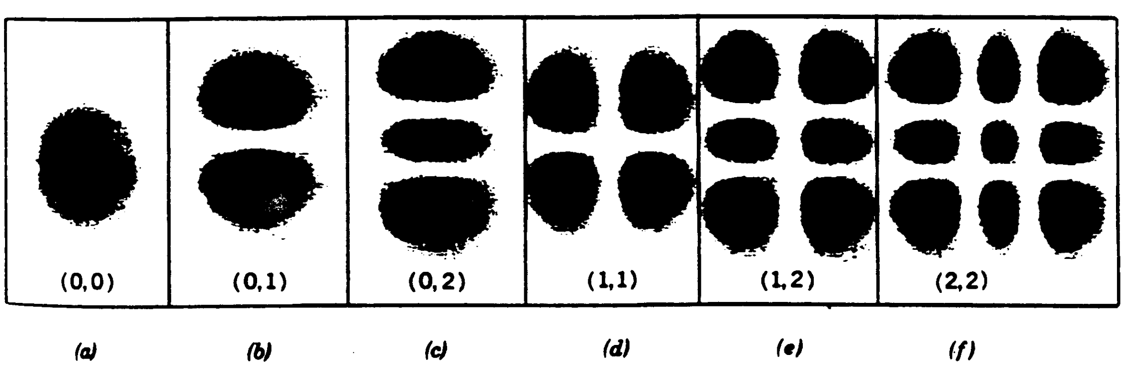


Figure 3.3-2 Intensity distributions of several low-order Hermite–Gaussian beams in the transverse plane. The order (l, m) is indicated in each case.

References

[1] A. L. Schawlow and C. H. Townes. Infrared and optical masers. *Phys. Rev.*, 112:1940–1949, Dec 1958.