

Lasers & Holography – Phy 1560 & 2010

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Purpose

- Become familiar with the theory, design, and properties of lasers.
- Make a Helium-Neon gas tube lase
- Measure the coherence length of a laser
- Measure the beat frequency of a laser
- Make several holograms to explore the properties holography

Laser Safety Guidelines

The HeNe laser used in this lab is powerful enough to permanently damage your eye. You must wear laser safety goggles whenever the laser is operating, unless all of the following conditions are met:

- The laser tube is properly shielded.
- All laser beams are either attenuated to below 1mW or are divergent.

Never look directly at the laser beam. Remove all watches, jewelry, or other reflective objects from your hands and arms to avoid accidental specular reflections of the laser beam. The optical table is set to waist height to ensure the laser beam is below eye level. Do not bend over or by other means put your eyes at the level of the laser beam. The laser's high voltage power supply could be lethal; never touch any of its electrical wires unless the power supply is off.

Theory

Introduction: Compared with ordinary light like sunlight or light from a light bulb, laser light is relatively *coherent*. This means that the electromagnetic wave emitted is, to a rough approximation, a monochromatic transverse plane wave of a single polarization. This assumption is based on the fact that photons generated by stimulated emission are identical to the incident photon, in that they have the same wavelength, polarization, and direction of propagation. The name “laser” is an acronym for “Light Amplification by Stimulated Emission of Radiation,” so an ideal laser should conform to our assumption of coherence. However, real lasers are complicated by effects that cause their laser light to not be perfectly coherent. For many applications in the sciences, including holography, a highly coherent light source is necessary. The degree of coherence of a laser is characterized by a quantity called the *coherence length*.

Stimulated Emission: Suppose a photon with energy $E = h\nu$ (where h is Planck's constant, ν is the frequency) passes near an electron already in an excited state. If the photon's energy is equal to the energy difference between the excited state and another available state with lower energy, the electron can fall to the lower energy state, emitting a photon with characteristics identical to the original photon (wavelength, direction, etc.). This process is called stimulated emission. Lasers use stimulated emission to generate many identical photons.

The rate of stimulated emission is proportional to the photon density multiplied by the density of electrons in the excited state, while the rate of photon absorption is proportional to the photon density multiplied by the density electrons in the lower state. Because the proportionality constants for both processes are equal (See Griffiths QM, p.350.), there must be a higher density of excited states than of lower energy states in order for stimulated emission to dominate absorption, yielding a net emission of light. This scenario—a higher occupation of an excited state than of a lower energy state—is called a *population inversion*.

The Gain Medium: The gain medium in this experiment - a mixture of helium and neon gas – is sealed in a glass tube that contains an anode and a cathode. (See Figure I.) The energy required to cause lasing in the tube is supplied by applying a voltage between the anode and cathode, called the *energy pump*.

A ~1400 VDC pulse applied between the cathode and anode ionizes atoms in the tube, creating a plasma — a mixture of free electrons, ions, and neutral atoms. Once the tube reaches a steady state, the voltage between the electrodes drops to approximately 1000 V, and a small current between the electrodes maintains the plasma state. In the plasma, high energy electrons collide with neutral He atoms, promoting the He atom into excited states. The most common excited states that result from these collisions are the two lowest excited states of He. Both excited states correspond to $1s^1 2s^1$, but the first has parallel electron spins while the second has antiparallel spins. These excited states are referred to as *metastable* since they have relatively long lifetimes. The energy required to put He atoms into their second excited state is nearly equal to the energy required to put Ne atoms into their fifth excited state, $1s^2 2s^2 2p^5 5s^1$, (not counting levels that result from different electron spin orientations) so a collision between a ground state Ne atom and a He atom in its second excited state will raise the Ne atom directly into the fifth excited state. The relatively long lifetime of the first two excited states of the helium atom, in conjunction with the high helium-to-neon ratio (approximately 7:1) in the laser tube, leads to a high probability of collision of excited metastable helium atoms with ground state neon atoms. This process causes the occupation of Ne’s fifth excited state to exceed that of the second excited state, $1s^2 2s^2 2p^5 3p^1$, and a transition between these two levels results in the emission of a visible photon of wavelength 632.8 nm. This population inversion allows lasing to occur in the visible range.

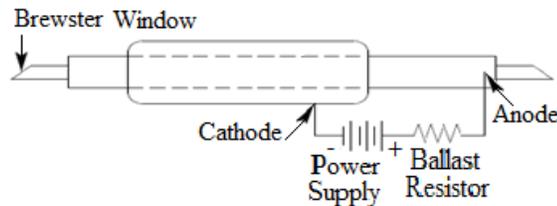


Figure I: Plasma tube used in a laser.

The ends of the plasma tube are sealed by glass plates tilted by an angle equal to Brewster’s angle, given by $\theta_B = \tan^{-1}(n_2/n_1)$ (See Griffiths E&M, p.390), so the glass plates are called Brewster windows. The Brewster windows ensure that any light entering or exiting the gain medium is polarized.

Laser Design & Longitudinal Modes: In order for stimulated emission to dominate, the resonant photons must pass close to the excited atoms so that they can interact. To ensure that they do, a pair of mirrors are configured so that the resonant photons reflect between them, repeatedly passing through the lasing medium—this is called an “optical feedback system.” Various separations and combinations of flat and concave mirrors are possible (see Figure II). A configuration with two spherical concave mirrors sharing a common focus is called a confocal resonator.

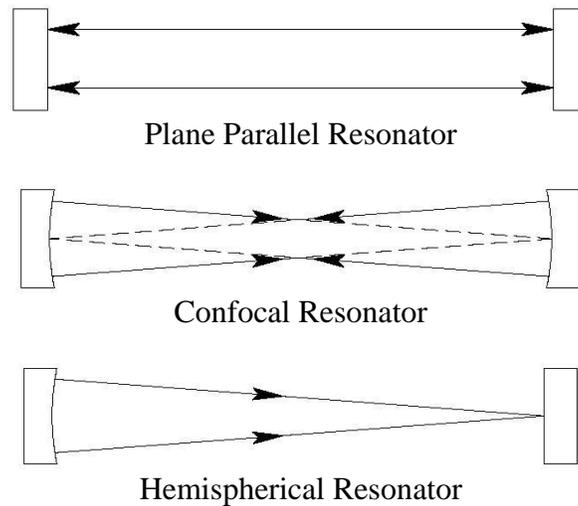


Figure II: Various Possible Resonant Structures

Regardless of the particular resonant structure being used, the photons generated by stimulated emission repeatedly reflect back and forth between the mirrors along the z axis. Therefore there is roughly an equal portion of the plane wave traveling toward the positive z direction as traveling toward the negative z direction, so the electric field between the mirrors is a *standing wave* with nodes at the surfaces of the mirrors. (See Griffiths E&M, p.367.) See Figure III.

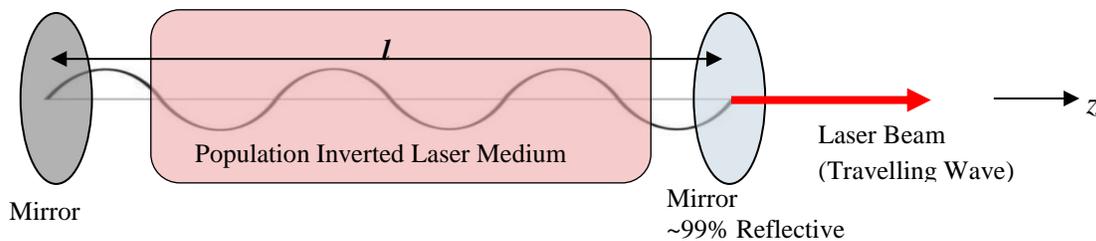


Figure III: Schematic of an ideal laser, with the electric field indicated.

For a standing wave to form, the distance between the mirrors must be an integer multiple of one-half wavelength, i.e.,

$$l = n \frac{\lambda}{2} \quad \text{for } n = 1, 2, 3, \dots \quad (\text{I})$$

Thus for each n , there is a standing wave of wavelength λ given by Equation (I). These various standing waves are called *longitudinal modes*. If a photon is generated with a half-wavelength that is not an integer fraction (1, 1/2, 1/3, 1/4, ...) of the lasing cavity length, it will interfere destructively with its reflection, so the electric field will be sharply attenuated, suppressing any light amplification by stimulated emission at that wavelength.

One mirror is essentially 100% reflective, but the other mirror is only 99% reflective. Thus a small number of the photons escape repeated reflection—this is the outgoing laser beam. We assume that the number of photons leaving the laser cavity is extremely small compared to the photons that form the standing wave inside the cavity, so this slight asymmetry between plane waves propagating toward positive- z and toward negative- z inside the cavity is a small perturbation that does not appreciably disrupt the standing-wave modes.

If only one wavelength of photons can be produced in the transitions of excited atoms, and if there are no broadening effects on these photons, the laser will produce a perfectly coherent outgoing beam. This model will be referred to as the “ideal laser.” Real lasers, however, are not ideal. In practice, laser light is comprised of a range or *band* of wavelengths. There are several mechanisms that can cause this deviation from the theoretical expectation of perfect coherence.

Coherence Length: Suppose a laser emits electromagnetic waves over a range $[\lambda_{\min}, \lambda_{\max}]$. To a high degree of accuracy, all wavelengths are emitted from the laser’s aperture exactly in phase. As the various wavelengths propagate through space away from the aperture of the laser at a velocity $v \approx c$, they gain phase differences relative to one another. The phase difference $\Delta\phi$ between two beams of wavelengths λ_1 and λ_2 emitted in phase from the aperture of the laser (which is located at $z=0$) is given by:

$$\Delta\phi = |\phi_1 - \phi_2| = \left| \frac{2\pi z}{\lambda_1} - \frac{2\pi z}{\lambda_2} \right| = 2\pi z \left| \frac{1}{\lambda_1} - \frac{1}{\lambda_2} \right| \quad (\text{II})$$

We can see that the maximum phase difference between any two components of the laser light is given by the phase difference between the highest and lowest frequencies:

$$\Delta\phi_{\max} = 2\pi z \left(\frac{1}{\lambda_{\min}} - \frac{1}{\lambda_{\max}} \right) \quad (\text{III})$$

Coherence length L is defined as the distance z over which laser light propagates while maintaining a maximum phase difference $\Delta\phi_{\max}$ smaller than $\Phi = \pi$ radians. (Note that in other disciplines that employ lasers, such as optical communications, different choices of Φ are used, e.g. $\Phi = \pi/2$.) Real lasers do not have exact cutoff frequencies λ_{\min} and λ_{\max} but instead have frequency distributions called “optical profiles”, and in that case the quantities λ_{\min} and λ_{\max} can be defined as the wavelengths at which intensity drops below a given threshold value.

Coherence Length of Multimode Lasers: There are many mechanisms which may broaden the band of wavelengths a laser emits, including vibrations and thermal fluctuations that vary the

lasing cavity length, reflection of waves between the mirrors at some nonzero angle relative to the z axis, perturbations to the longitudinal modes due to imperfect reflectivity of the mirrors, and Heisenberg uncertainty in the energy of the photons. However, the dominant cause of nonzero bandwidth is the presence of different longitudinal modes in the lasing cavity. In other words, standing waves with different numbers of half-wavelengths can both cause stimulated emission and hence emit laser light.

If the laser output is composed of a few longitudinal modes, and there are no other sources of variations in output wavelength, then all the photons have a wavelength given by Equation (I), but different photons may have integer values for n . We will call this the “multimode broadening model” of nonzero wavelength bandwidth.

Suppose in the multimode broadening model that the laser output is a combination of only two adjacent modes. That is, the laser is comprised of photons with wavelengths given by Equation (I), but n takes on only two values, and the two values of n differ by 1. This would yield the smallest nonzero bandwidth in the multimode broadening model. According to Equation (I), this would imply:

$$\lambda_1 = \frac{2l}{n} \quad \text{and} \quad \lambda_2 = \frac{2l}{n+1}$$

Plugging these into Equation (III),

$$\Delta\phi_{max} = 2\pi z \left(\frac{1}{\left(\frac{2l}{n+1}\right)} - \frac{1}{\left(\frac{2l}{n}\right)} \right) = 2\pi z \left(\frac{(n+1)-n}{2l} \right) = \frac{\pi z}{l} \quad (\text{IV})$$

By definition L is given by the point z such that $\Delta\phi_{max} = \Phi = \pi$, so,

$$\pi = \pi L \frac{1}{l} \Rightarrow 1 = \frac{L}{l} \Rightarrow l = L$$

Note that this is only true for the assumptions stated: the *only* source of bandwidth broadening is multimode effects, that there are only *two* modes, and that the modes are *adjacent*.

Doppler Broadening: Many designs of lasers eliminate multimode effects (albeit at substantially greater cost). In these lasers, the mechanism for nonzero wavelength bandwidth is one of the others listed at the beginning of the previous section, and their observed coherence lengths are on the order of 100m or greater. However, typical HeNe lasers like the one used in this experiment have substantial multimode effects; the following drawing shows what is usually observed in spectra of typical HeNe lasers:

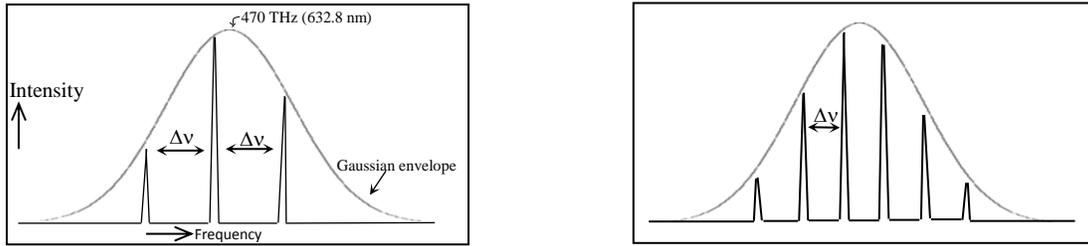


Figure V: Sketch of observed wavelength distributions for a three-mode and a six-mode HeNe laser. The relative intensities of modes follow a Gaussian distribution, as depicted, and the Gaussian envelope's width depends on the design of the laser.

It is clear from Figure V that typical HeNe laser output is composed of a few longitudinal modes, each with a small nonzero width, with their relative intensities following a Gaussian envelope. This is because the photons of the laser light are generated by energy-level transitions in the rapidly moving gas atoms, and thus these photons are subject to Doppler broadening, but lasing occurs only for photons with a half-wavelength equal to an integer fraction of the lasing cavity length. See Fishbane p.1086 for a derivation of Doppler broadening.

Beating of Longitudinal Modes: Equation (I) can be solved for the frequency difference between any two modes. The frequency difference between adjacent modes, $\Delta\nu$, is given by:

$$\Delta\nu = \frac{c}{2l} \quad (\text{V})$$

This is known as the TEM_{00n} mode spacing. (See the next section for an explanation of this notation.) When any two waves separated in frequency by $\Delta\nu$ combine, the resulting wave is bounded by a sinusoidal *envelope wave* with a frequency, called the *beat frequency*, equal to $\Delta\nu$. Therefore, the envelope wavelength for a laser composed of two adjacent modes is given by:

$$\Delta\lambda = \frac{c}{\Delta\nu} = 2l \quad (\text{VI})$$

Similarly, the beat frequency between any two modes can be determined. In this experiment, a high-speed photodetector is used to measure this beat frequency and determine the presence of various modes.

Transverse Modes: In the confocal resonator, as the photons bounce back and forth between the two highly reflecting mirrors, some photons may miss the mirrors, leading to some energy loss. (Figure VI) This spillover changes the wavefront's transverse amplitude and phase profile, causing the transverse mode structures you will observe in the laser. In order for one of these transverse mode patterns to be self-reproducing, the round-trip amplitude gain must overcome the amplitude loss.

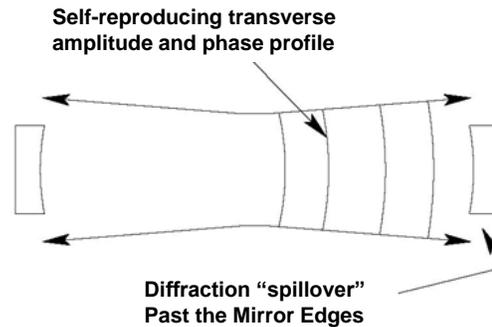


Figure VI: Propagating wavefront.

Transverse electromagnetic mode patterns are labeled TEM_{lm} according to the number of intensity minima that are encountered when the beam is scanned horizontally (l) and vertically (m). (If the nature of the longitudinal node is known, it is labeled with a third index n , for example, TEM_{lmn} denotes that there are l nodes horizontally, m nodes vertically, and n nodes along the z -axis. However we typically do not know the value of n and we drop that subscript.) A confocal resonator will have the lowest order transverse mode pattern, TEM_{00} , and many *higher order* modes. Generally these modes will have greater loss due to diffraction and due to more complex transverse amplitude and phase variations than the TEM_{00} mode. The TEM_{00} mode and some of the higher order modes are shown in Figure VII.

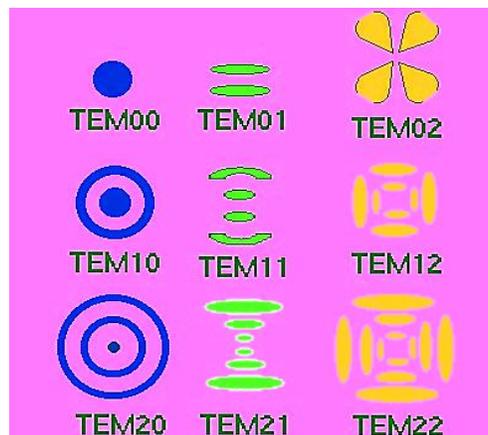


Figure VII: A few of the lower order TEM modes.

Formation of Transverse Modes: Using geometrical optics we can begin to understand how the transverse mode patterns are formed within the confocal resonator. In our model, a transverse mode is the electric field distribution associated with any geometrical ray following a closed path. The simplest mode, TEM_{00} , corresponds to a ray which only bounces back and forth between the two mirrors (see Figure XI). Because of diffraction, the intensity distribution is somewhat more spread out than the ray tracing model would indicate. The next mode, TEM_{01} , can oscillate in the laser cavity only if the bore of the Helium-Neon tube is large enough for it. Higher order modes correspond to closed paths with an even larger number of reflections needed to complete one round trip than the TEM_{01} . Remember, however, that the ray picture is only an approximation to the actual behavior of the transverse modes and a better description follows from wave optics.

Michelson Interferometry: A Michelson interferometer creates a fringe pattern by splitting a beam of coherent light and sending the two resulting beams along paths of different lengths. If the path length difference between the two beams is an even multiple of the coherence length of the laser beam, maximum interference and maximum contrast of all the laser's frequencies occurs. Path differences that are an odd multiple of the coherence length result in minimum interference and minimum intensity difference. The quantity used to measure the difference in fringe intensities is called the fringe visibility, or contrast. The contrast of the fringe pattern is defined by:

$$C = (I_{\max} - I_{\min}) / (I_{\max} + I_{\min}) \quad (\text{VII})$$

where I_{\max} is the maximum intensity in the fringe pattern and I_{\min} is the minimum intensity. Visibility is a periodic function of the path difference. The fringe pattern that you see is the sum of the fringe patterns due to each mode. Therefore by performing Fourier analysis on a plot of the visibility as a function of path difference, the intensity of each mode can be determined [see ten Bosch and de Voigt, "Interferometry Study of the Modes of a Visible-Gas Laser with a Michelson Interferometer", American Journal of Physics, 34, 479 (1966)].

Holography: In a conventional photograph light is reflected off of an object and travels to a piece of film where the two-dimensional intensity distribution of the light is recorded. However, the wavefront of the light contains more information about the object than just the intensity distribution. The wavefront's phase also contains information about the object, in the same way that interference patterns contain information about the slit(s) through which they are produced.

Holography is a technique for recording both the intensity and phase profile of light. The hologram is a diffraction pattern which, when viewed properly, gives a full three-dimensional image of the object. Because a hologram contains information pertaining to the phase profile of light, it is possible to reconstruct the light based on Huygens' Principle. In the reconstruction process, the light will appear to be coming from the original object, and the three-dimensional aspect of the object will be maintained.

A monochromatic light wave reflected from an object contains all the pertinent information - amplitude and phase - about the object illumination. Ordinary photographic methods only record the intensity of the light across the surface of the object. If the phase information is also to be recorded on the film, we must employ some sort of reference indicating the direction from which the light came. Therefore, holography requires two temporally and spatially coherent light beams, called the object and the reference beam. Temporal coherence is achieved when a wavetrain has one frequency and spatial coherence is achieved when all parts of a propagating wavefront are in step with each other. These concepts will become clear through this laboratory experiment.

To understand the process of holography, we will start with the simplest possible situation - a transmission hologram made by two coherent point sources of light. In this case, we have two waves, which emanate from the two point sources, striking a piece of finely grained photographic film. These two beams, called the object and reference beams, are separated by an angle θ_1 . When they arrive at the film, they interfere, constructively in some areas and

destructively in other areas. The result of this interference is fringes on the film: bright in regions of constructive interference and dark in regions of destructive interference.

Next, we want to consider the polarization of the object and reference beams. The interference fringes will be sharper if the electric fields in object and reference beams are parallel to each other. When the laser is vertically polarized, the polarization is perpendicular to the plane of the table and parallel to the film for both the object and the reference beams. If the laser is horizontally polarized, then the polarizations of the beams will have an angular separation of θ_2 and will not be parallel to each other or to the film. In general, horizontal polarization leads to less contrast in the interference fringes, because the orthogonal components of the beams do not interfere and, therefore, cause a more homogeneous exposure of the film.

You may wonder how the amplitude and the phase of the object beam are conserved in this process of creating a transmission hologram. For simplicity, think of the laser beam as consisting of many small “beamlets” of constant amplitude, such that when these beamlets first leave the laser cavity, they are perfectly in phase with each other and can be thought of as a plane wave. In this example, after the laser beam is split into the object and reference beams, the reference beam remains a beam of plane waves of constant amplitude through the duration of its trip to the photographic plate. While the object beam starts its journey from the laser as a beam of plane waves of constant amplitude, when it encounters the object, its beamlets are reflected from the object at various angles and with various intensities. When the object beamlets arrive at the photographic plate, they interfere with the reference beam forming an interference pattern, or grating, as was described earlier. In the places where the object beamlets have the greatest amplitude, the interference pattern has the greatest contrast. In the places where the object beamlets have a smaller amplitude, there is less contrast or a more even illumination. The angle that the object beamlet is reflected from the object will determine the phase. The *larger* the angle between the reference beam and an object beamlet, the *finer* the resulting grating. Thus, the *amplitude*, or intensity, of the object beam is recorded in the *contrast* of the fringe, while the phase is recorded in the *spacing* between the interference fringes.

Viewing the hologram in ordinary light will reveal nothing about the information contained within. In order to observe the image, the film must be placed in a “reconstruction” or “read out” beam, which is a laser beam identical to the reference beam. The hologram is then viewed from the side opposite to the incoming read out beam. What are transmitted through the film are one zeroth-order beam (the actual read out beam) and two first-order beams. One of the first order beams leaves the film at an angle θ_2 . The angle θ_2 is equal to the angle θ_1 , where θ_1 is the angular separation between one of the object beamlets and the reference beam. Thus, this first order beam appears, to the eye, to be a continuation of the original object beam. What the eye sees is a virtual image of the point on the object that emitted the particular object beamlet under the angle θ_1 . The other first order beam lies at an angle θ_2 on the opposite side of the hologram.

How can we prove that $\theta_1 = \theta_2$ and that all of the phase information is retrieved during the reconstruction process? Think of the reference beam as a plane wave that strikes the film at normal incidence, and the object beam as a plane wave striking the film at an angle θ_1 . The wavelength of the laser light is λ , and d is the fringe separation (the distance between regions of maximal constructive interference). So, we can write:

$$\sin \theta_1 = \frac{\lambda}{d} \Rightarrow \lambda = d \sin \theta_1 \quad (\text{VIII})$$

During the reconstruction process, constructive interference occurs when the path difference between two slits, δ is equal to the wavelength of the first order beams. Thus, we get the following:

$$\delta = \lambda = d \sin \theta_2 \quad (\text{IX})$$

Thus, it follows that $\theta_1 = \theta_2$. If the wavelength of the reconstruction beam is equal to the wavelength at which the hologram was made, the reconstructed beam leaves the hologram at the same angle that the object beam left the hologram.

Procedure

Warnings and Notes:

- a) *Put on laser safety goggles before turning on a laser. Once all laser beams are set below 1mW, or are divergent, safety goggles are no longer required. Safety goggles must be worn when the shielding box is opened unless the laser is off or the shutter is closed.*
- b) *The cover over the HeNe tube provides protection from high voltage and potentially harmful spurious reflections. Do not attempt to remove this cover.*
- c) *The optical components used in this lab are fragile and expensive; some, such as the VBS, are very expensive. Please use extra care when working with them.*
- d) *Do not attempt to clean the optical components – particularly the lasing mirrors or the VBS. If a component needs cleaning, ask a TA for assistance.*

Build a Laser:

- 1) With the alignment laser on and set below 1mW, place one of the HeNe tube apertures directly in front of the laser and confirm that the beam shines on the vertical center of that Brewster window. Turn the tube around and confirm that the laser beam shines on the center of the other Brewster window. Adjust the tube height as necessary. See Figure VIII.



Figure VIII:

- 2) Remove the HeNe tube and one at a time, place mirrors #1 & #2 (flat, slender & completely opaque), both of the lasing mirrors (slightly concave, thick & semitransparent) and both adjustable apertures in front of the alignment laser. Confirm that the beam shines on the vertical center of each object. Adjust the objects' heights as necessary. Note: the lasing mirrors are particularly fragile and expensive. Please treat them with extra care.

3) Now that all of the components are set to the same height, set up Figure IX.

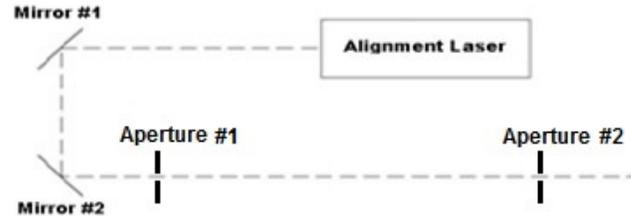


Figure IX: Aperture alignment.

- 4) Use the mirrors to send the beam through the centers of the apertures. Use mirror #1 to position the beam at aperture #1, use mirror #2 to position the beam at aperture #2.
- 5) Remove aperture #2 and place the HeNe tube in the beam path on the optical track. By carefully adjusting the tube's height in the track mounts, you should be able to get the beam to pass straight through the tube. See Figure X. Once this is accomplished, lock the track mounts to the optical rail.

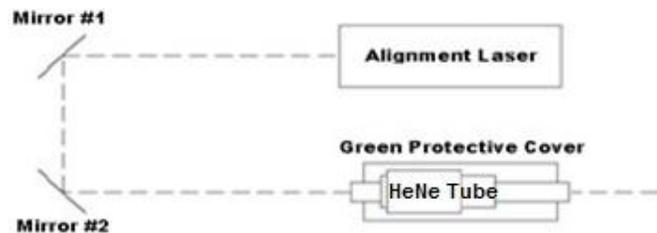


Figure X: Laser alignment.

- 6) If needed, make slight mirror adjustments to get a bright, round, aberration free dot on the screen beyond the HeNe tube.
- 7) Place one of the lasing mirrors ~8 cm from the far end of the HeNe tube such that it reflects back into the tube. Adjust this mirror only until the beam passes back through the HeNe tube and through aperture #1. Repeat this step with the other mirror.
- 8) Place one of the lasing mirrors ~8 cm from the near end of the HeNe tube such that the beam reflects back into the tube. Adjust this mirror only until the beam passes back through the HeNe tube and through aperture #1. This will likely be difficult to do. A helpful trick is to send the mirror's back reflection through aperture #1 - this should indicate the front surface reflection is going through the tube.
- 9) The alignment procedure is now complete. Turn off the alignment laser and turn on the power to the HeNe tube. If everything was adjusted correctly, there should be a bright spot on the screen. If you do not see a spot, try carefully adjusting the last lasing mirror installed – the one on the near side of the tube. Make careful note of its position before you start adjusting, and if adjustments in the X direction do not help, return the mirror to its initial position before attempting adjustments in the Y direction, etc.

Observation of Transverse Electromagnetic Modes:

- 1) Once the tube is lasing, place a short focal length lens after the far lasing mirror. Observe the details of the beam on the screen. The pattern observed corresponds to a transverse mode.
- 2) Carefully adjust one of the lasing mirrors and observe the resultant modes on the screen. Take pictures of several different modes with the camera provided. Identify the modes in these photos (e.g. TEM_{35}) and include them on your report.
- 3) Try to obtain the TEM_{00} mode. This can be done by slowly adjusting the lasing mirrors one at a time. This can be difficult; if the mirrors or the Brewster windows have dust on them it will be more difficult. If you are successful, photograph it, label it and include this in your report.
- 4) Set the beam to a higher order mode. Place aperture #2 somewhere between the lasing mirrors. Slowly close the aperture. What happens to the mode structure? Closing the aperture significantly should generate the TEM_{00} mode without blocking the beam entirely. Using the ray tracing as in Figure XI, explain why this produces the TEM_{00} mode.

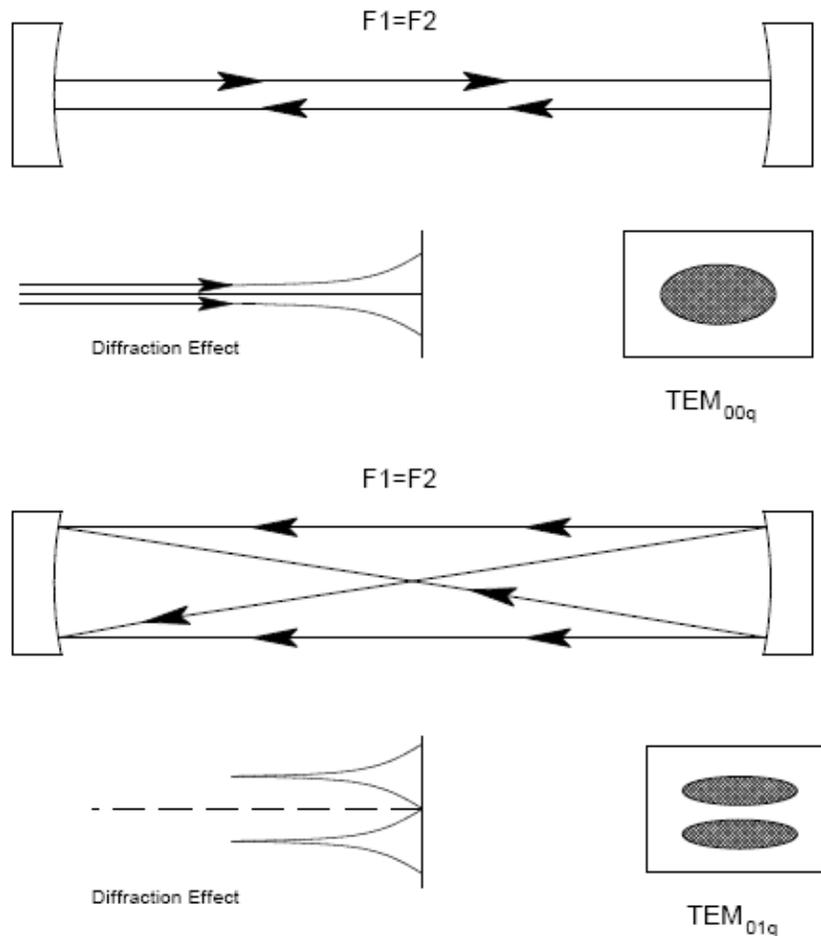


Figure XI: Formation of mode structure.

Note: Use the alignment laser in the following exercises

Beat Frequency:

- 1) Connect the high-speed photodetector to the oscilloscope, set the input impedance to 50Ω and set the time base to 4ns/div .
- 2) Turn on the alignment laser and adjust the position of the photodetector so that the laser beam is centered on the detector crystal.
- 3) Turn on the photodetector and observe the beats on the scope. If you do not get a signal, the laser intensity could be set too high (saturation) or too low. You may need to adjust the variable beam splitter in either case.
- 4) Use the cursors, measurement functions, FFT or other features of the scope to carefully measure $\Delta\nu$. Use $\Delta\nu$ to estimate the coherence length l of the laser.
- 5) Since the high-speed photodetector is battery operated, please remember to turn it off.

Coherence Length Measurement:

- 1) Setup a Michelson Interferometer as shown in Figure XII.
- 2) With the lens removed and mirror 2 at P_2 , align the beam splitter, mirrors, and aperture to get the dominant beam from each mirror on top of each other on the screen.
- 3) Adjust the mirrors until the beams on the screen stay on top of each other as mirror 2 is moved between P_1 & P_2 .
- 4) Set mirror 2 to be the same distance from the center of the beam splitter as mirror 1.
- 5) Position the lens in the setup. There should be an obvious interference pattern on the screen. Take a photograph of this pattern
- 6) Move mirror 2 away from the beam splitter by 2 cm and take an image of the resulting pattern.
- 7) Continue moving mirror 2 in 2 cm intervals and taking images until you get the far end of the rail. Minor adjustments to mirror 2 may be required to get fringes as the mirror is moved back. While the size of the fringes does not determine the contrast, you should have about ten dark fringes to work with each time.
- 8) Load your photos onto one of the lab computers and use "WCIF ImageJ" to create a horizontal profile plot. From this find the average contrast for each image. Plot contrast vs. path length difference.
- 9) What is the coherence length of this laser?

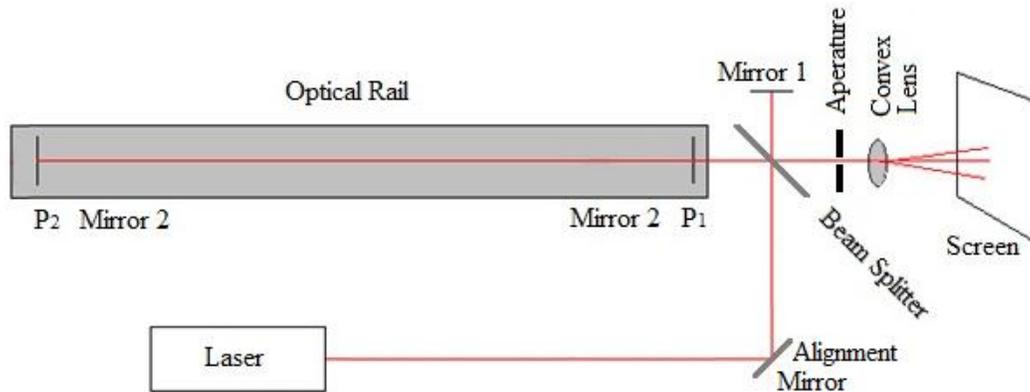


Figure XII: Michelson Interferometer setup for measuring coherence length.

Holography:

Spatial Filter

- 1) See Figure XIII. The location and height of the laser, shutter, variable beam splitter (VBS), and spatial filter (except for the pin hole) are prealigned for you. Please do not adjust them.
- 2) It takes about 30 minutes for the laser to become stabilize. Turn on the laser and make sure the shutter is closed. Leave the laser on while setting up the other components.
- 3) Make sure the pinhole is installed in the spatial filter – The pinhole should have its *concave* side facing away from the laser. Open the shutter and adjust the beam transmitted through the VBS to maximum intensity. *Note: Adjust the VBS by touching its unfinished outer rim. Never touch the finished, gradient coated surface.*
- 4) Close the shutter, remove your safety goggles, and lightly tape a piece of notebook paper over the exit port beyond the spatial filter. With the room lights off and the green bench lights on, carefully place one hand on the X or Y micrometer of the spatial filter. Close the shielding lid as much as possible while keeping your hand inside.
- 5) Open the shutter and watch the paper from the outside of the box as you slowly adjust the X & Y axis of the pinhole. Watch for a patch of red light. It may be helpful at this point to defocus the Z axis a bit. Once the light appears, maximize it. This procedure may require some patience.
- 6) The initial dot will likely be surrounded by diffraction rings. Carefully adjust the Z axis to brighten the central dot and make the diffraction rings disappear. Some touch up adjustment of the X & Y axis will be necessary during this process. The spatial filter is now properly adjusted. Close the shutter. *Note: If you spend more than a day trying to align the spatial filter, ask the TA for assistance.*

Alignment of components

- 7) Setup Figure XIII. Holography is based on interference. Use what you learned about coherence length to determine the appropriate difference between the path lengths of the

object beam (OB) and the reference beam (RB). Path lengths are measured from the variable beam splitter (VBS) to the film.

- 8) Place the film holder so the object is easily visible through the frame. The film etc. will be load in the dark; as other components are placed on the table, position them accordingly
- 9) Make sure all - magnetic bases, screws, post, post holders, etc. are securely fastened in place.

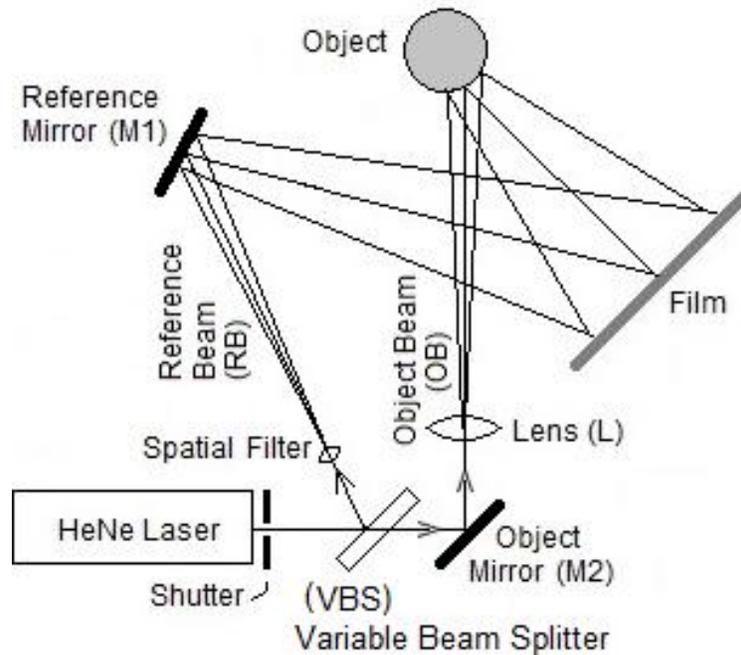


Figure XIII: Setup for making holograms

- 10) The light hitting M1 and M2 should hit these mirrors near their centers.
- 11) Make sure light from M1 hits the center of the film holder and covers most of the film plane.
- 12) Make sure light from M2 illuminates the object and reflects from the object to the film plane.
- 13) Adjust the VBS to maximize the intensity of the OB and minimize the intensity of the RB. This is the correct intensity ratio for taking a hologram.
- 14) Turn off all lights, open the shutter. Check to see if any stray reflections or refractions of the laser light are hitting the film plane. It may be helpful to alternate blocking each beam during this process. Position black cardboard light blockers as necessary.

Loading the Film

- 15) The film holder consists of a metal frame, two large glass slides, a dark green piece of card board and two black metal spring clips. A glass slide goes in the frame first; then the film, then the green card board and last the second glass slide. The two spring clips go on the

sides and hold everything together. Use a piece of developed film to practice putting film in the holder. Remember, you will have to do this in the dark.

16) After practicing loading film, clean the glass plates with the Windex provided. Note: Do not clean any other optics with the Windex!

Taking a Simple Hologram

17) With all lights off, take a piece of film from the film packet. Be sure to put the remaining film back in the packet and close the packet.

18) Avoid touching the film's surface; only touch it at its corners. To help with orientation while working in the dark, note that the film is curved and the emulsion is on the concave side. This side goes toward the laser light.

19) Another way to determine the emulsion side: lick the thumb and forefinger of one hand; gently rub the film between these fingers at one corner. The side that feels slightly sticky is the emulsion side.

20) Position the film in the film holder as practiced in step 15.

21) Set the darkroom timer to 40 sec.

22) Wait ~30 seconds for the table and components to settle before exposing the film. Any vibrations will cause the hologram to be dim, so remain quiet and still during exposure.

23) Being careful not to bump the table or make loud noises, open the shutter and start the timer.

24) When the timer finishes, close the shutter.

25) Put the exposed film in a light tight container, load new film and take an 80 sec exposure.

26) Load a second new film and take a 120 sec exposure.

27) Be sure to make each film so they can be identified after development.

28) Develop the films.

Developing Film

29) Specific directions for developing film are posted on the laboratory wall. These same instructions are posted under Technical Tips & References on the lab wiki. You are expected to read and follow these directions. If you need help, contact a TA.

Viewing a Hologram

30) Place the developed and dried hologram back in the film holder as when it was exposed (same edge up and same side facing the laser), remove the object, and block the object beam. Open the laser shutter and look through the hologram at the former location of the object.

There should be a virtual image where the object used to be. The reference beam may need to be more intense than when the film was exposed.

Additional Holograms

- 31) Use the three simple holograms taken above to determine optimal exposure time. Use this exposure time to take the following holograms. Note: Exposing film only take a few seconds while developing film takes ~20 minutes. It is acceptable practice to take several holograms before developing.
- 32) Double Exposure - The film is exposed twice, but the object is changed between exposures to create an illusion (e.g., a pencil through a solid object etc.).
- 33) Stress Patterns – same as above except between exposures the stress on an object is changed. This is typically done using a can $\sim\frac{3}{4}$ filled with water and a weight on top. After the first exposure, the weight is carefully removed. In the finished hologram the areas experiencing the most stress will be identified by interference patterns.
- 34) Noncoherent path lengths – go back to the simple hologram. Use the same object but now set the difference in path lengths such that they are not coherent. Take a hologram in this configuration at the optimal exposure time.
- 35) Compare this hologram with the hologram taken with coherent path lengths and explain.
- 36) Show your completed holograms to a TA and take photographs of all of your holograms.

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