Experiment 3: Laser Assembly, Alignment, and Stability

Objective: To assemble, align, and examine the stability of a helium-neon laser consisting of a gas-filled discharge tube placed inside an optical cavity.

Preparation: Read pages 1-2 of the HeNe Laser Guide appended to these instructions.

Introduction: The laser is probably the most important scientific tool invented in the latter half of the 20th century. In this experiment you are to assemble a gas laser composed of three basic parts: a helium-neon discharge tube that provides *light amplification by stimulated emission of radiation*, an optical cavity composed of two mirrors that trap light and thereby enhance the stimulated emission generated within the discharge, and a power supply. To simplify assembly, the discharge tube already contains a 60 cm radius-of-curvature concave mirror called a high-reflector; its reflectivity at the lasing wavelength of 632.8 nm is 100%. Equipped with this mirror, the discharge tube provides half of the optical cavity as well as the active medium. The other end of the tube, sealed with a window oriented at Brewster's angle, transmits all light that is vertically polarized. Your task is to place the second mirror, a flat 99% reflecting mirror, at an appropriate location and orientation to make the laser lase.

Prediction: Begin the experiment by formulating a prediction regarding the tightness with which light *is trapped* as it reflects back and forth inside the hemispherical cavity depicted in Fig. 1. The flat mirror lies a distance L from the center of a concave mirror with radius-of-curvature is R. The heavy lines in the figure represent the mirrors viewed side on, and the lighter lines represent radii of curvature for the concave mirror and normals to the flat mirror. To develop a prediction, invoke the law of reflection governing incident and reflected rays relative to a reflecting surface. The law asserts that $\theta_{\text{incident}} = \theta_{\text{reflected}}$, where the angles are measured relative to a *normal* to the surface at the point where the rays strike the surface. Letting Fig. 1 guide you, invoke this law multiple times for the cases $L < R$, $L = R$, and $L > R$. Using a ruler and sharp pencil, extend rays "a" and "b" to the left and then back and forth between the mirrors in accordance with the law of reflection. Determine whether these rays "leak out" of one cavity more readily than another. Then formulate your prediction regarding the tightness of trapping for the three cases.

Procedure. **Part A**: A flat mirror called an output coupler, which completes the cavity but lets 1% of the light escape as an output beam, resides in the black mirror mount that permits high-resolution adjustment of the *orientation* of the mirror about vertical and horizontal axes. The translation stage beneath this mount permits variation of the cavity length L. Position this stage so that the flat mirror is 10 cm from the Brewster window, and align the stage so that the mirror is perpendicular to the laser axis; use a knurled screw to anchor the stage to the optical bench.

After turning on the discharge, adjust the red knob on the mirror mount so that the vertical post extending up from the mirror slants a few degrees back towards the discharge tube.

Now, being careful not to touch the window or the mirror, grasp this post with your left thumb and index finger and gradually rock it back and forth a few degrees in a vertical plane. Next use your right hand to adjust the black knob, which permits rotation about a vertical axis. The best approach calls for a small adjustment of the black knob (using your right hand) followed by the left-hand-driven rocking of the vertical post. The two motions should be performed in succession. This type of systematic search should eventually produce a flash of light on the flat mirror. At this point, stop adjusting the black knob and allow the vertical post to return to its equilibrium. Then advance only the red knob until lasing is continuous. Tweek both knobs to maximize brightness. *Do not look directly into the laser beam!*

Part B: The remainder of this experiment involves the *stability* or tightness of light trapping of the cavity. A cavity of length L will be stable (light will be trapped) if it satisfies $0 < g_1 g_2 < 1$, where $g_1 = 1 - L/R_1$ characterizes the cavity and radius of curvature of mirror #1 (the concave high-reflector with $R_1 = 60$ cm) and $g_2 = 1 - L/R_2$ characterizes the cavity and curvature of mirror #2 (the output coupler with $R_2 = \infty$). Investigate the implications of this inequality by evaluating g_2 and substituting it into the inequality to determine the minimum and maximum values of g_1 consistent with good cavity stability: g_1^{min} = ____ and g_1^{max} = ____. In light of these limiting values of g_1, what are the minimum and maximum lengths L_{min} = _____ and L_{max} = _____ for this cavity? Do these results agree with your prediction?

By now you realize that a test of the stability of this laser requires its elongation to L = 60 cm or more. Proceed by repositioning the translation stage so that the flat mirror is about 30 cm from the Brewster window (corresponding to $L \approx 55$ cm). Locate the high reflector by looking through the slotted window at the left end of the discharge tube; the glass "cap" on the end of the metal tubing is the high reflector. Screw down the stage once again, and use the search procedure to reestablish lasing. Once the laser is lasing, rotate the large knob to increase L. When the laser stops lasing, tweek the mirror orientation to reestablish lasing. If successful, increase L still further. Continue until you can no longer sustain laser oscillations. The laser cavity has become unstable. Does the final, limiting length L agree with your prediction?

Part C: As time permits, ponder the following questions:

(i) From a practical standpoint, why would a *concave* rather than a flat output coupler (the mirror that you translate) be a poor choice for this particular experiment?

(ii). Why must the reflectivities of both mirrors approach 100%?

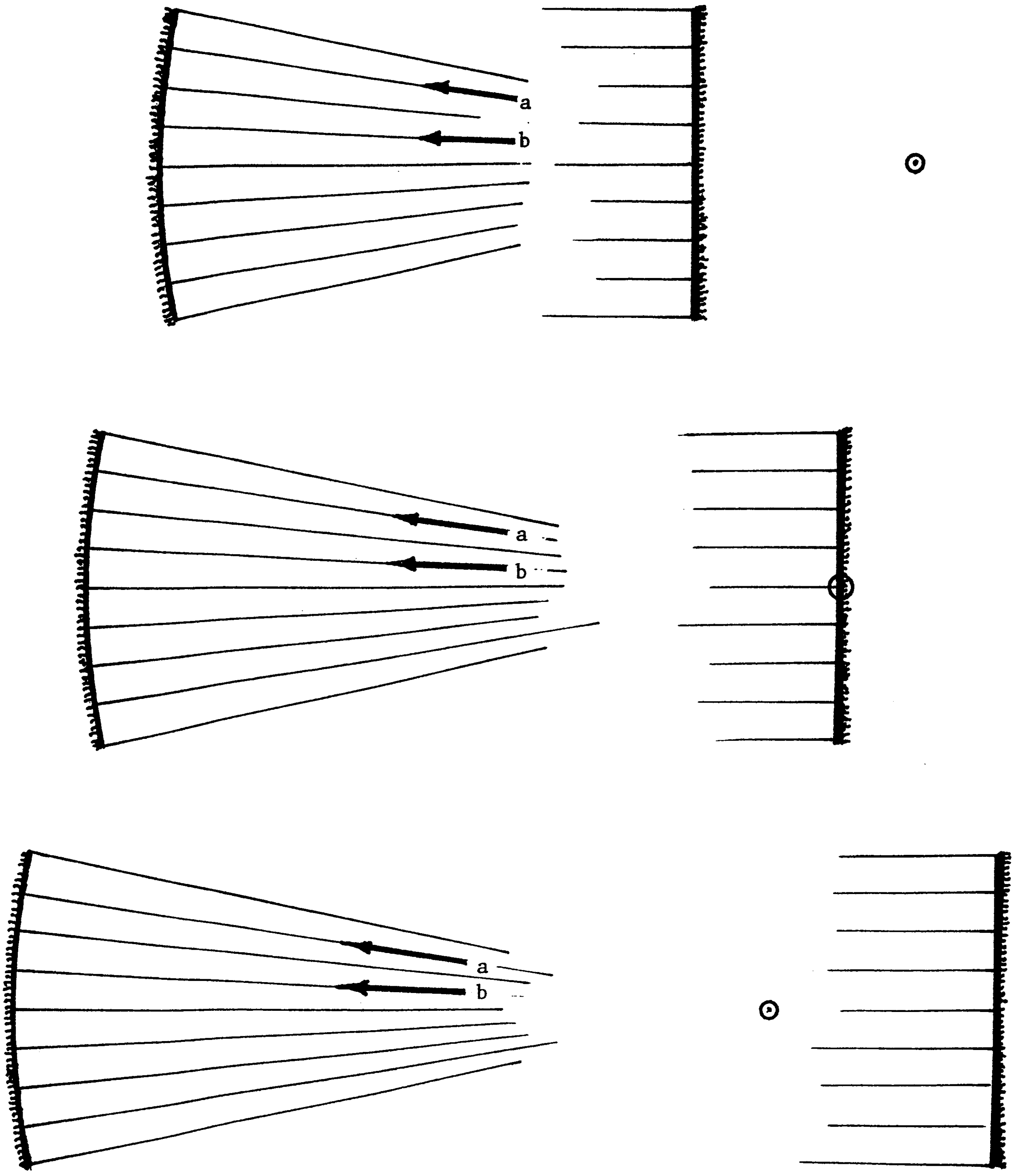

Fig. 1. Depiction of hemispheric cavities for cases L < R, L = R, and L > R. The arrows a and b represent light rays being launched toward the concave mirror. The dot represents the center of curvature of the concave mirror.

Experiment 4: Transverse Characteristics of a Laser Beam

Objective: To analyze and photograph the transverse profile and divergence of a laser beam. This experiment involves Gaussian beam parameters and transverse mode structures.

Preparation and apparatus: Read pages 2-3 and 5-6 of the HeNe Laser Guide appended to these instructions. This experiment employs an open HeNe laser based on a Melles Griot plasma tube with an internal high-reflector (60 cm radius), an external output coupler (60 cm radius, 98.6% reflectivity), a thin "etalon" (uncoated 0.15 mm thick coverslip), a lens-less Polaroid camera with a 2 cm shutter opening, a separate HeNe laser, x-y recorder, fibre optic bundle, RCA 4840 photomultiplier with power supply, and a good HeNe mirror in mount.

Background: Although the directionality of a laser beam is one of its most salient features, the notion that a laser beam is a tight bundle of non-divergent rays is wrong. All laser beams sooner or later show *divergence*, and many exhibit interesting profiles. Consider a gas laser pointing in the +z direction. The cylindrical symmetry of the gas discharge and the use of spherical mirrors dictate that the beam be "Gaussian" in shape and therefore exhibit the following properties:

Property 1: Apart from mode details discussed below, the intensity I(r) of a Gaussian beam is maximum at its center (at r = 0) but drops off radially according to

$$I(r) = I(0)\exp(-2r^2/\omega^2) \quad , \qquad (1)$$

where the radius r is measured from the center of the beam. The parameter ω, called the *waist* of the beam, is the distance from beam center to the beam periphery where the intensity is $1/e^2 = 0.135$ of its maximum. This waist $\omega(z)$ increases with distance z along the beam according to

$$\omega(z) = \omega_0 (1 + z^2/z_0^2)^{1/2} \quad ,$$

where z is measured from the point where the beam exhibits its minimum waist ω_0. The *confocal* beam parameter

$$z_0 = \pi\omega_0^2 n/\lambda \qquad (2)$$

provides a useful measure of the divergence of the beam because, in the distance z_0, the beam waist ω undergoes an initial 41.4% expansion starting from ω_0. In Eq. (2) the index of refraction n is on the order of unity and λ is the laser wavelength. Initially the beam divergence is curved, (resembling a brass horn), but this curvature soon gives way to a more conical divergence whose half-angle is

$$\theta = \lambda/\pi\omega_0 n \quad . \qquad (3)$$

Property 2: In addition to its divergence, a laser beam can exhibit the various transverse mode patterns shown in Fig. 1. Each of these "transverse electromagnetic mode" or TEM_{mn} mode patterns is uniquely characterized by a pair of integers m and n which specify the number of nulls that cut across the beam profile as one scans the pattern first horizontally and then vertically. The TEM_{00} profile is rotationally symmetric and exhibits the smallest waist. For many applications, the TEM_{00} is the most desirable mode, and a laser that emits a pure TEM_{00} beam is said to be a “single (transverse) mode laser.” Note that the other, higher-order modes have larger radii. To generate these higher order modes, the discharge tube must have a large bore. Conversely, a narrow-bore tube or a small aperture inside the laser cavity can suppress higher order modes.

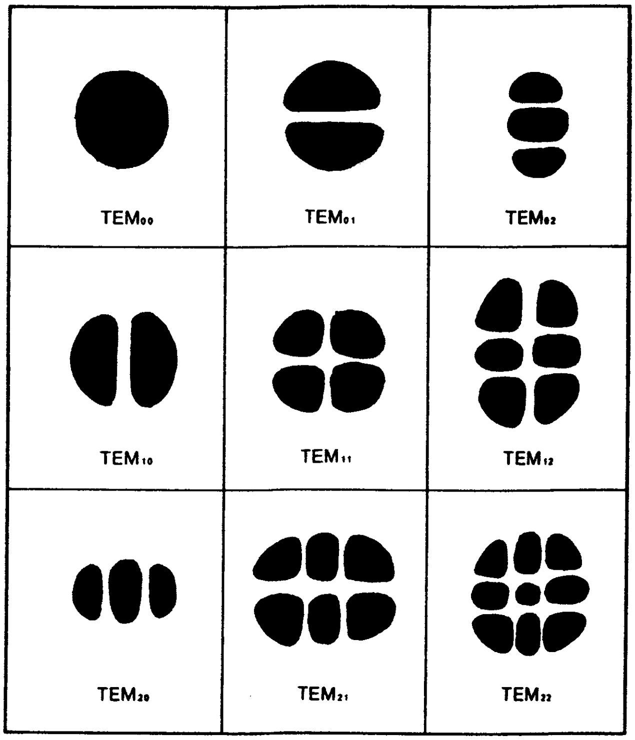

Fig.1. Various TEM_{mn} mode patterns.

The frequency of the light in a laser beam depends not only on the integer index q that appears in the standing-wave expression $q(\lambda/2) = L$ but also upon the transverse character of the beam. For a long laser whose mirrors have radii of curvature $R >> L$, the frequency for a given TEM_{mn} mode is

$$f_{mnq} = \{ q + (m + n + 1)\, \pi^{-1}(2L/R)^{-1/2} \}\ c/2L$$

which, for very large radii R, becomes $f_q = qc/2L$. The index q is typically 10^6 for a gas laser.

Part A: We begin this exercise by verifying that the intensity of a TEM_{00} laser beam exhibits the Gaussian shape predicted by Eq. (1) and inferring the magnitude of the minimum waist ω_0. To simplify matters, we use a laser whose beam is several cm in diameter by the time it crosses the bed of an x-y recorder. The pen on the recorder holds an optical fibre so that as the pen is swept manually with the X-CHANNEL ZERO control, the fibre sweeps across the laser beam and samples its intensity profile. The opposite end of the fibre bundle leads to a photomultiplier that converts the light into a voltage which drives the Y-CHANNEL of the same recorder. Hence, by scanning the recorder pen smoothly in the X direction, the system records the beam's bell-shaped intensity profile $I = I(x)$.

(i). To proceed, measure the peak-to-baseline height $I(0)$ of your bell-shaped beam profile. Draw a line on your chart parallel to the baseline of the profile but $0.135\ I(0)$ above it. Since this line intersects your profile at the $1/e^2$ points, the horizontal separation between the two intersections is 2ω. Also measure the total distance D through which the beam diverges (6-8 meters).

(ii). Use the results of part (i) to determine the conical half-angle $\theta = \omega/D$. Then use Eq. (3) to infer the minimum waist ω_0, taking $\lambda = 633$ nm and $n = 1.0$. Finally determine z_0 using Eq. (2). Typical results for this particular laser are $\omega_0 = 0.2$ mm and $z_0 = 25$ cm.

Part B: The remainder of this exercise involves higher-order TEM_{mn} modes. We employ a laser with a large-bore discharge tube so that modes with indices m and n as large as 10 are present. In the present experiment, however, we want to observe and photograph individual TEM_{mn} modes. To select one mode while suppressing the others, we insert into the cavity a thin sheet of glass called an "etalon", which rotates about a horizontal axis transverse to the laser beam.

The laser power is greatest when the etalon is oriented at the *Brewster angle* (i.e. parallel to the slanted window on the discharge tube). As the etalon is rotated in either direction away from the Brewster angle, suppression of transverse modes increases. Through careful adjustment of both the angle and transverse position of the etalon (the etalon's thickness is irregular) and by slightly misorienting the output coupler, one can discriminate (via interference effects) against all but a single TEM_{mn} mode.

Once you have observed the profiles of several modes and practiced mode separation, rotate the camera into position. Choose a shutter speed of 1/250 sec and hold a neutral density filter in front of the camera to reduce the intensity of the beam. Notice that the back of the camera slides into three positions so that three different modes can be photographed on a single sheet of film. The lower-order TEM_{mn} modes photograph best because their nulls are broadest and deepest. Start by setting the back of the camera in position 1. Cock the shutter and maximize the isolation of a single laser mode (view it on a card in front of the shutter) and shoot. *Before shooting again, advance the camera back to position 2.* Select a different mode, cock the shutter, and shoot again. Advance the camera back one more time, choose a final mode, and shoot. To develop the film, pull out the white tab horizontally, and then smoothly pull out the larger black tab. Development of the film begins when the black-tabbed packet is pulled free from the camera. After a development time of about 100 sec, tear open the packet, being careful not to touch the chemical residue on the edges of the film. Throw the backing and border paper directly into the trash.