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Laser Teaching Center

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MODES OF OPERATION OF VARIOUS He-Ne LASERS AND CONFIGURATIONS.

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In this study I observed the operation of several lasers and studied the behavior of both longitudinal and transverse modes. First I examined the longitudinal mode characteristics of several different lasers using a polarizer and photodetector. Then I built an open-cavity adjustable-length Helium-Neon (He-Ne) laser and began to study the transverse operation of the laser. These experiences were very interesting and I learned a great deal about the practical applications of the theory I had learned in my classes.

The longitudinal mode characteristics of lasers are not very complicated. The theory that describes them is fairly simple although the practice is somewhat less so. During the experiment I examined a variety of lasers and studied the characteristics of the longitudinal modes. I learned a fair amount from this but did not discover anything unusual.

The longitudinal modes of a laser are those modes that will laze at slightly different frequencies. Any frequency that has a gain high enough to equal or exceed the losses of the lazing cavity can laze. The gain of a given frequency is a function of the chemicals used as a gain medium, in my experiment neon, and the rate at which it is being pumped, the efficiency of which is increased by the presence of helium in a He-Ne laser. However only a few of those frequencies will laze. This is because the frequencies which can laze must also satisfy the boundary conditions of having a zero electric (and magnetic) field at the mirrors at either end of the lazing cavity. This means that only those frequencies half of whose wavelength multiplied by any positive integer equals the length of the cavity and which has a gain sufficiently high overcome the cavity losses can laze. Since, as the laser continues to operate its temperature increases, the length of the cavity will increase over time, thus changing the frequency of the modes of the laser and thus slightly changing the operating wavelength. This change can be measured with appropriate equipment and thus the mode structure can be examined.

Experimentally examining the modes of operation of a laser is fairly straightforward. The fact that alternating lazing modes are always polarized orthogonally to one another means that by placing a polarizer in the path of a laser beam shining on a photodiode connected to an oscilloscope the lazing modes of the laser can be isolated or forced to interfere with one another. Forcing the two orthogonally polarized modes to interfere with one another allows, with a photodiode with a small enough dead time, the spacing between the modes to be analyzed and compared with experimental predictions. I used this technique on several different lasers and in all cases got answers that agreed with the theory to 4 percent or less. The most likely source of error was that the length of the tubes was not available in all cases. Typical values for the mode spacing are 250MHz for a long laser and 1GHz or more for a short one. Besides the interference between the alternating polarities of the modes the effect of the power supply can be examined. All lasers in this experiment were powered via a standard 120V 60Hz AC wall outlet and despite having been converted into a few mA of greater than a kV of DC power there were still slight (<2%) intensity fluctuations at 120Hz which were attributable to imperfect AC to DC conversion inside the laser's power supply. These fast oscillations are not the only thing which can be determined through a study of the longitudinal modes however.

The larger-time-scale fluctuations of the intensity of the modes at a given polarization of several lasers were examined as the laser was warming up. This last was necessary because after the laser has been on for a while (~1 hr) the cavity temperature has reached an equilibrium and the cavity no longer expands meaning that the modes no longer change. The large-scale (about 2 sec) fluctuations are caused by a mode of one polarization no longer being able to laze but instead allowing another mode, of a different polarization, to do so. This change in the intensity of a given polarization over time allows an experimenter to determine the rate of expansion of the cavity. In theory with this knowledge a person can determine the temperature in the room if the gain versus frequency curve, the loss of the cavity, and the thermodynamic properties of the cavity are known. Although I was not able to calculate the temperature owing to a lack of computer-based data acquisition systems I did notice that in one of the lasers the intensity of the modes would quickly change from low to high or vice-versa (depending on the polarization of the modes) which is unusual since a more sinusoidal intensity versus time chart would be expected. This is most likely to be due to competition between the modes for the limited amount of gain that the laser has available. The shorter lasers exhibited a large and easily noticeable change in intensity over a fairly long time scale.

In the longer laser bores no significant fluctuations were found in the long-time-scale intensities because the much larger number of modes that "fit" into the lazing wavelengths of the cavity means that the loss of one lazing mode in preference for another was not as significant a factor and therefore was lost in the much larger fluctuations of the two polarizations interfering with one another. An attempt to minimize this effect was done by modifying the rotation of the polarizer but even then no noticeable fluctuations occurred. If the reduced power of one mode was being made up for by an increasing power in another mode of the same polarization then it is possible that there would be little or no intensity fluctuations on a long time scale. If this is the case for the longer lasers this would be desirable in many situations as a relatively constant power could easily be obtained without the need to reach a thermal equilibrium first. The long-time-scale fluctuations of the He-Ne lasers I examined proved to yield nothing of great interest as time and materials limited the extent to which they could be studied.

The long- and short- time-scale oscillations and fluctuations of the modes of various lasers were studied without great difficulty. The short time-scale oscillations in intensity due to interference between the orthogonally polarized modes of a laser cavity allows the experimenter to verify the length of a cavity or to examine the change in cavity length with temperature. Also the existence of slight fluctuations in intensity because of imperfect conversion to DC means that in order to get a perfectly constant power laser some form of battery or fuel cell as a power supply is needed. The longer-scale fluctuations in intensity occur as the laser expands because of the heat generated during the pumping process. Both the short and long term polarization-based fluctuations are because of longitudinal mode effects in lasers and while most lasers deliberately suppress any transverse modes other than TEM00 other, more exotic modes, are also worth study.

The longitudinal modes exist because of the length of the bore of the cavity while the radius of the cavity causes the existence of transverse modes. The equation for the transverse modes is very complicated but can be simplified by making it a function of a few integer terms. Studying these modes leads to an improved understanding of the operation characteristics of lasers and how to better force TEM00 operation.

The transverse modes of a laser exist because the cavity has some finitely small width which allows for a difference in intensity at different points away from the axis. These modes are designated by TEM(l,m) as in the formula:

$$\nu_{l,m,n} = \frac{c}{2L}\left\{n + \frac{1+l+m}{\pi}\arccos\left(g_1\, g_2\right)^{1/2}\right\}$$

In practice this means that l is the number of vertical dark lines in the mode and m is the number of horizontal dark lines in the lazing mode. The TEM00 mode is what one normally thinks of when one thinks of lasers: a single bright spot that fades with increasing radius. The higher-order modes have a variety of shapes depending on the l and m numbers but are always less well collimated, and therefore more lossy, than the TEM00 mode. These modes can form a superposition, or combination, of modes which allows for a wide variety of appearances of individual modes of operation. For example the superposition of the TEM01 and the TEM10 modes forms an annulus (doughnut-shape). The study of these exotic modes is one of the reasons for the creation of the open-cavity He-Ne laser that I made.

The open-cavity He-Ne laser was fairly easy to build. The Laser Teaching Center

(LTC) already had an aluminium chassis containing two rings with adjustable screws to both hold and align the tube and a mounting point for a power supply. The tube itself and the power supply for same were purchased from Professor Goldwasser of Drexel who maintains an extensive FAQ on all things electronic in addition to lasers at www.repairfaq.org and who later kindly visited the LTC to give a talk and provide demonstrations of various laser and optics-related topics. The tube itself was a large (~1mm) bore He-Ne laser with an internal High Reflectivity (HR, 99.9+% reflective at 632.8nm with a focal length of 60cm) mirror at the anode end of the cavity and a brewster window (piece of glass set at brewster's angle) at the other. This setup kept the gas contained, forced a laser polarization parallel to the angle of incidence (by making it less lossy than the perpendicular polarization) and absorbed the 1 and 3 micrometer wavelengths that would otherwise be prevalent over the normal 632.8nm red all while reducing losses in the desired wavelength to almost nothing (absorption of the glass still added some small losses). This bore, of course, would not laze without another Output Coupler (OC, 99% reflective) mirror placed in the beam-path and aligned properly along it. Thumbnails of the laser both in operation and not can be seen in appendix A.

The alignment procedure is fairly straightforward although tedious and time-consuming. First both the adjusting screws of the mirror mount are unscrewed until they are just beneath the surface of the mount. Then the mount is roughly aligned by eye being sure to position it such that the mirror is tilted slightly above and away from the actual aligned position. Then the laser is turned on and the mirror is "rocked" in its mount while the surface is examined. If a small red dot appears briefly then adjust the vertical-adjustment screw until the dot recurs and lasing will have been achieved. Otherwise screw in the mirror's horizontal-adjustment screw one quarter of a turn and repeat the "rocking" motion and search for the red dot. When the red dot has been achieved constantly then the laser is lazing and experimentation can begin. This procedure takes a large amount of time so, using a few screws in the table and a few posts as spacers, I devised a system by which the laser, once aligned, could be made to laze continuously (or nearly so) while the cavity length is adjusted. This made experiments concerning the effect of cavity length much easier to accomplish quickly.

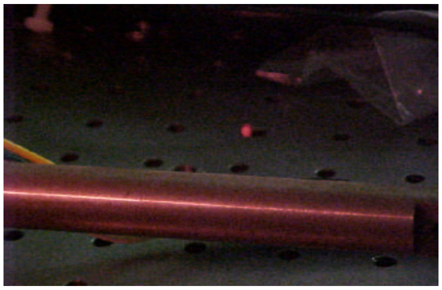
The effect of cavity length on the mode(s) of operation of a laser was examined using the open, variable-length cavity described earlier as was found to be significant. At total distances less than the focal length (cavity length <30cm) the external mirror could be adjusted over a broad continuum of angles to achieve lazing in a variety of superpositions of high-order modes. These modes were of such high-order and were superpositioned with each other so that it was difficult to impossible to determine exactly what modes were lazing. At cavity lengths greater than 30cm but less than 45 cm lower order modes and superpositions were found. In this area the modes TEM(0,1) + TEM(1,0), TEM(0,1), TEM(1,2), TEM(0,2), TEM(0,2) + TEM(2,0), TEM(0,4), TEM(0,3), TEM(3,1) and, of course, TEM(0,0) were all found to be able to be made to laze. In the far area (~50cm) only the (0,0), (0,1), and (1,0) modes could be made to laze and at 55cm only the 0,0 mode was seen. A single human hair placed internal to the cavity and mounted on a rotation stage or lens holder was use to isolate individual modes of lazing in a superposition by adding it oriented perpendicular to the desired mode thus adding a large loss to the undesired mode, preventing it from lazing. This allowed for the examination of the superposition of TEM(0,2) and TEM(2,0) as noted above. In order to view these modes easily a lens was used as a beam expander and the beam was then projected onto a piece of paper. Several of the resulting images are shown in appendix B. Even though the results of the lasing are interesting while manipulating the setup one should always be careful to observe all safety precautions.

When working with high voltages and laser light one should always remember safety. While a complete review of the needed safety procedures is well outside the scope of this document a few items should be noted. The B-window reflected the laser light returning from the external mirror somewhat and therefore to improve safety the tube should be oriented so that this reflection lands on a piece of paper placed specifically for the purpose or a block of some sort is placed around the B-window end of the bore. This later is preferable since it also adds electrical safety to the device by preventing accidental contact with the cathode of the bore although it does make access to the cathode and B-window more difficult. While keeping safety in mind it is still possible to make some interesting and useful observations of the open-cavity setup.

As expected exactly what mode(s) were lazing was a function of the total length of the cavity, the curvature of the mirrors (which was fixed for this experiment), the shape of the lazing bore, and the alignment of the mirrors. It was found that when multiple modes of lazing were available that the more complicated the mode structure was the closer to perfectly aligned was the mirror. This was easily confirmed by noting that the simplest mode, the TEM0,0 mode, would laze only weakly in the middle area and (when either the vertical or horizontal adjustment screw was turned constantly) only at the beginning and end of the lazing adjustment and also by noting that as the cavity length was expanded for a particular alignment the modes moved from a TEM0,2 to a TEM0,1 and then to a TEM0,0 before lazing ended as the loses due to imperfect alignment overcame the gain of the bore. These experiments demonstrated that nothing unexpected was occurring and that the experimental evidence and theory agree with each other quite well.

Another optical property, Rayleigh scattering, can be observed easily through examination of the cavity. Rayleigh scatting is a form of scattering off of particles (in this case dust particles) in which the majority of the light scattered is in the same general direction as the incedent light. This can be observed in any laser by noting that the intermittent dots of light are more frequent the closer the eye comes to the beam path. The open-cavity laser makes it easier and safer to observe because the great intensity inside the cavity makes the scattered light much more prominent but if the eye of the observer is placed in the plane formed by the adjustable side of the chasis then the eye cannot be put directly into the beam path, making accidental eye injury almost impossible. Figure 1 is a picture of this scattering effect. While this was not the intended use of the open-cavity laser it is still a useful benefit.

Fig. 1:



Overall the open-cavity setup is useful for demonstration of the various transverse modes possible to obtain in a laser as well as being a good demonstration item for students to examine for themselves a variety of optical properties including stability conditions, modse of operation etc. and has the potential to be used in other experiments in the future. Making the setup was fairly easy although mirror alignment was sufficiently tedious that an effort was made to create an arrangement that would allow the laser's cavity length to be adjusted without losing alignment or even necessitating the deactivation of the laser.

As a total research experience I learned about the behavior of laser modes both transverse and longitudinal in general and as applied in the specific to a variety of He-Ne lasers. I learned about and performed experiments on mode interference, mode-swapping, and high-order mode generation. I also learned about the practical need for safety measures aimed toward the prevention of injury due to high-intensity light and high-voltage electricity. Overall I learned a lot about lasers and their problems and applications as well as had an interesting experience while conducting these experiments.

Appendix A: Some pictures of the lasing cavity