THE AMATEUR SCIENTIST

A tunable laser using organic dye is made at home for less than $75

Conducted by C. L. Stong

An ideal laser, from the amateur's point of view, would be easy to make, reasonably inexpensive and capable of generating light of any color. An instrument of this kind has been built by J. R. Lankard of the International Business Machines Corporation. He made it at home with ordinary hand tools for less than $75, largely to prove that it could be done.

The amplifying medium of the laser is a dilute solution of organic dye that is periodically "pumped," or illuminated, by a homemade flash lamp. The output is an intense beam of coherent light five millimeters in diameter that can be focused to a point with lenses. The sharpness of the point is limited only by the wave nature of light. The beam can also be spread into a pattern of diverging rays. The color of the coherent rays is determined by the nature of the dye.

Various dyes can be used. Each of them generates light that spans a characteristic portion of the spectrum. The laser can be tuned to generate light of any wavelength within these ranges by means of a diffraction grating. When the laser is pumped at a sufficiently high rate, say 60 pulses per second, the output beam appears to the eye to be continuous. This modification increases the cost substantially, because the size of the power supply must be increased and provisions must be made for cooling the unit.

Like the helium-neon laser, the dye laser consists essentially of a slender amplifying tube, or dye cell. The ends of the tube are closed by a pair of flat windows that face a pair of mirrors. A second tube, the flash lamp, is mounted parallel to the amplifying tube. Both tubes are surrounded by an aluminum tube of elliptical cross section with an interior surface that is highly polished to function as a mirror. The axis of the amplifier tube occupies one focus of the elliptical mirror and the axis of the lamp occupies the other focus. White light emitted by the lamp is thus concentrated by the mirror on the amplifying tube [*see illustrations on opposite page*].

The amplifying tube is filled with an alcohol solution of dye that is known to fluoresce. When such solutions absorb white light, some molecules of dye acquire an abnormal amount of energy and so are raised to what is termed their lowest excited singlet state. Later they spontaneously emit the excess energy as light of longer wavelength. This is the phenomenon known as fluorescence.

If the white light is sufficiently intense, as it is in the dye laser, a majority of the dye molecules absorb more than enough energy to reach the singlet state. Hence they are raised to one or another of the possible higher energy states. From these levels they can also drop back spontaneously to lower energy states by emitting light. Some of these emitted waves, strictly by chance, head toward one or the other of the laser's flat mirrors, which reflect the light waves back into the amplifier tube. Here the waves stimulate other excited molecules to emit excess energy. The resulting emission is identical in color, and so in wavelength, with the stimulating waves. The waves merge and thereafter proceed in lockstep. In effect, the waves that were emitted spontaneously are amplified and continue to accumulate energy as they are subsequently reflected back and forth through the tube [see "Organic Lasers," by Peter Sorokin; SCIENTIFIC AMERICAN, February, 1969].

The flat mirrors of the dye laser are coated with aluminum. One mirror reflects about 92 percent of the incident light and absorbs 8 percent. The other mirror, which has a thinner coating, reflects 74 percent, absorbs 8 percent and transmits about 18 percent. The transmitted portion constitutes the output beam of the laser. In Lankard's apparatus it amounts to about 5,000 watts per pulse, which is a million times more intense than the output of the helium-neon laser! This substantial power and the tunable feature of the laser open new experimental opportunities to amateurs who have been restricted to the helium-neon and argon lasers previously described in this department [see "The Amateur Scientist"; SCIENTIFIC AMERICAN, September, 1964, December, 1965, February, 1967, and February, 1969].

It bears repeating that laser action occurs only if the dye is exposed to white light of sufficient intensity. Lankard developed the required intensity with an extraordinarily simple lamp. It is a tube of fused quartz provided with stainless-steel electrodes and filled with air. The electrodes are connected to the terminals of a 15-microfarad capacitor charged to a potential of 3,000 volts. To flash the lamp Lankard pumps air from the tube. When the pressure falls to about 60 torr, the capacitor discharges through the lamp. The resulting flash consumes some 35 megawatts of power and persists for about two millionths of a second. The capacitor is specially designed to discharge in that brief interval. Ordinary capacitors discharge more slowly and will not work in this application.

The dye emits only a small part of the absorbed energy as coherent light. That part is transformed into heat that causes random differences in density throughout the column of dye and, as a result, random differences in the optical refraction of the fluid. Fortunately the heating effect lags behind the flash by several millionths of a second. By the time the optical distortion becomes substantial the laser light has been emitted.

The dye must be at uniform temperature, however, before the laser can be pulsed again. A convenient method of cooling is to circulate dye continuously through the amplifier tube. The tube consists of an 80-millimeter length of seven-millimeter quartz tubing with a bore of five millimeters. The ends of the tube are closed by flat windows cemented in place at the edges with epoxy cement. Dye solution flows into one end of the tube through a port in the side and out through a similar port at the other end.

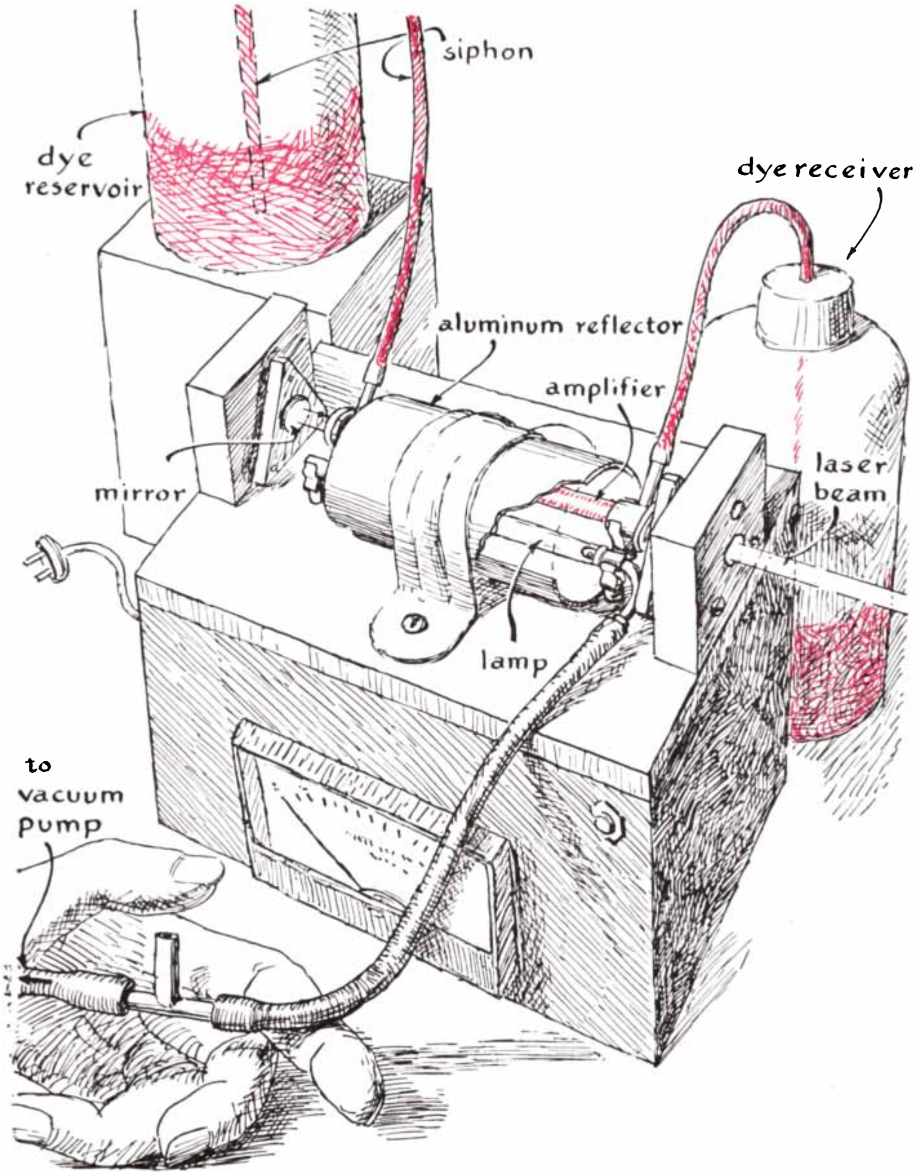
The ports can be made by welding short lengths of quartz tubing, as side arms, near the ends of the amplifier tube. Fused quartz is difficult to soften and manipulate. It must be worked in an oxyacetylene flame. Lankard suggests the use of metal tubing as an alternative. A *T* fitting can be improvised from copper or stainless-steel tubing. The inside diameter of the *T* should be seven millimeters to match the outer diameter of the quartz tube. One end of the crossbar of the *T* can be slipped over the end of the quartz tube and fixed in place with epoxy. The quartz window, which has a diameter of about 10 millimeters and a thickness of one millimeter, is put on the remaining end of the crossbar and held in place while a coat of epoxy is applied to the joint. A short nipple of copper or stainless steel forms the leg of the *T* and functions as the port through which the dye solution flows [*see top illustration on next page*].

Dye solution can be circulated through the laser by a small pump. The cost of the pump can be avoided by siphoning dye solution from an elevated container and discharging it into a similar container at lower elevation. The dye should flow at the rate of about one liter in 15 minutes.

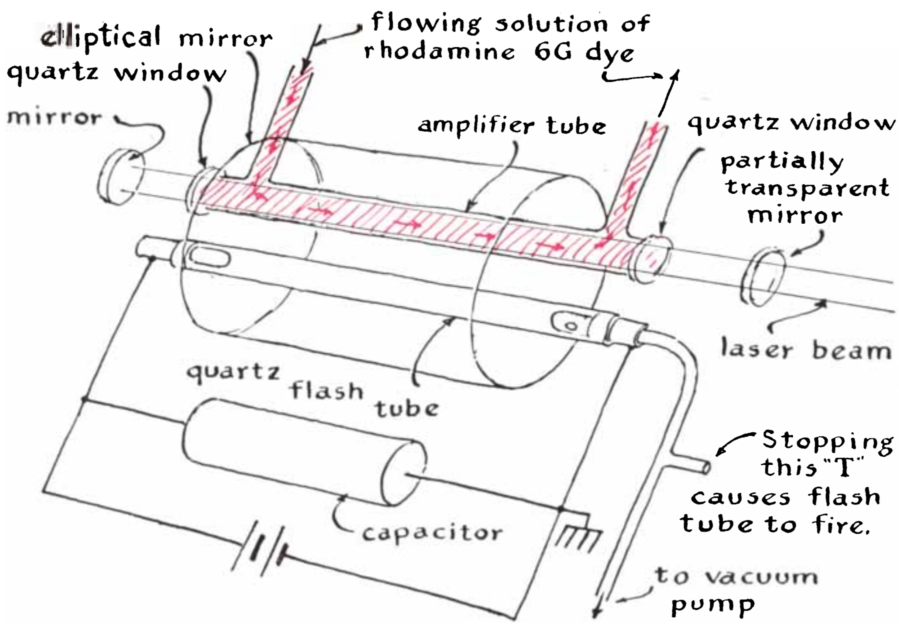
The pump that evacuates the lamp tube can be the sealed compressor from a discarded electric refrigerator that is in reasonably good condition. Connect the exhaust port of the lamp to the inlet tube of the compressor. Usually the inlet tube is the larger of two copper tubes welded into the sealed unit as a pair. The smaller of the tubes resembles a wire about 3/32 inch in diameter; it is actually a capillary that serves as the outlet of the compressor. Cut the capillary by filing a nick about 1/32 inch deep and bending the tube at the nick until it breaks. Run a small hose from the capillary to a bucket of soapy water.

Oil of any kind—indeed, any contamination of the dye—will suppress laser action. Do not use ordinary plastic tubing in any portion of the dye plumbing. Most plastics contain an oily plasticizer that preserves the flexibility of the material. Use glass reservoirs and connect them to the amplifier with either glass or Kodak Polyflow tubing, a plastic that contains no plasticizer. Do not attempt to operate the laser in a room where the air may be contaminated with oil, and remember that mechanical vacuum pumps discharge oily fumes. Such fumes can be minimized by discharging exhausted air from the pump through a container of soapy water.

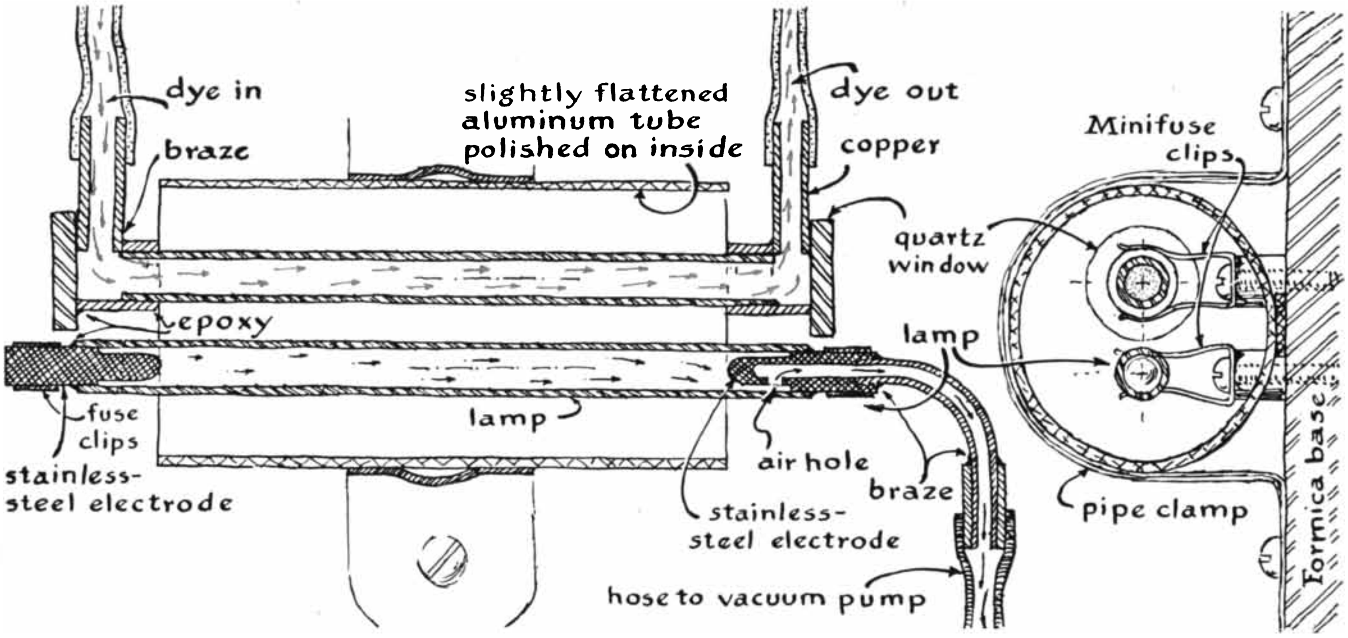
The lamp can be flashed by either of



Elements of the dye laser made by J. R. Lankard



Arrangement of the laser's components

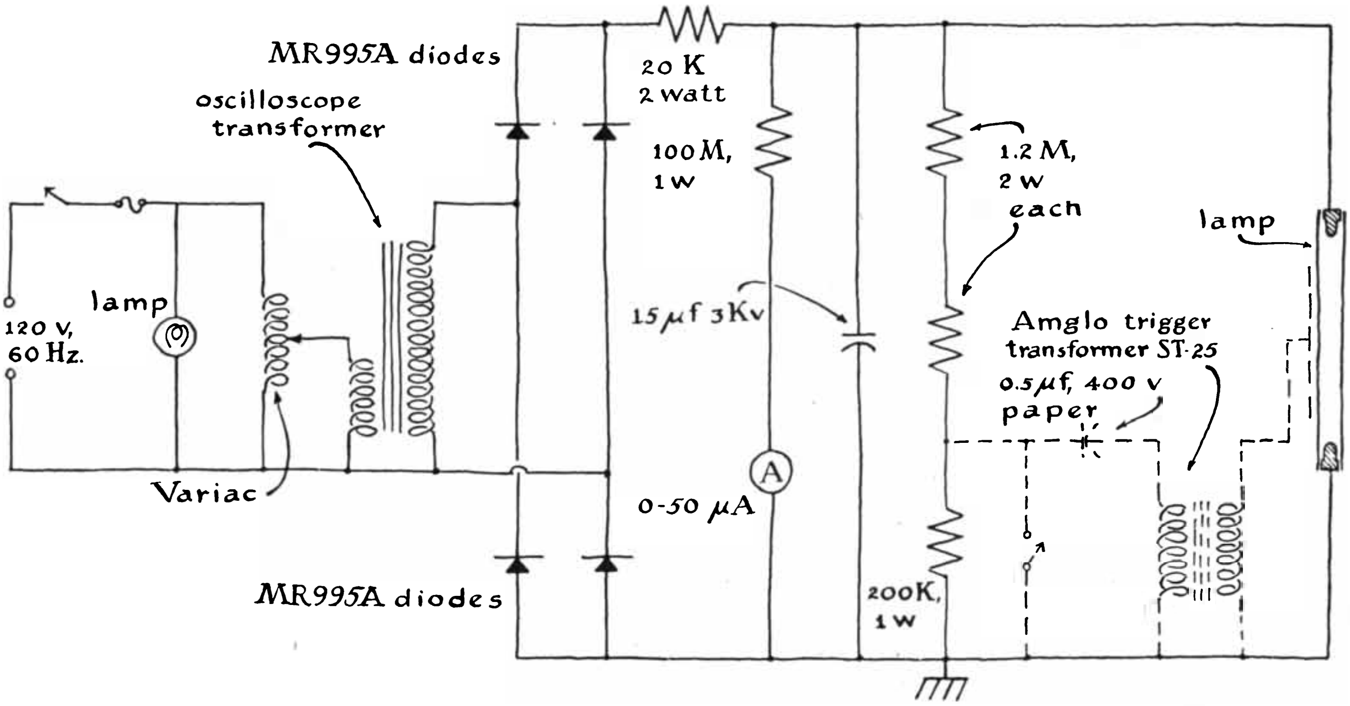


Details of the trigger lamp and the amplifier

two triggering schemes. In the simpler and cheaper of the two a *T* fitting is installed in the tube that leads from the lamp to the air pump. Cut the tube at a convenient point and insert the crossarm of the *T*. Air will be pumped through the open leg of the *T*. To flash the lamp, plug the opening of the *T* with your thumb. When the pressure drops to about 60 torr, the lamp will flash. The grounded side of the power supply must be connected to the electrode through which the air is exhausted or you will get an electric shock when the lamp flashes.

The second scheme is a special triggering transformer in the power supply. This device develops high potential, much like a spark coil, when power is applied to its primary winding. One terminal of the transformer is connected to ground and the other one to a few turns of fine wire wrapped around the middle of the lamp. The lamp is exhausted to a pressure about 10 torr above its normal firing pressure, which must be determined experimentally. Then, with full voltage applied across its terminals by the charged capacitor, the lamp can be fired by applying power to the primary winding of the triggering transformer. High voltage ionizes air inside the lamp and initiates the discharge, as indicated by the broken lines in the illustration below. The scheme is convenient when an experiment requires that the laser be fired electronically by an associated apparatus that includes a switch for closing the triggering circuit.

The lamp must have a port for exhausting the air. A side arm of quartz can be welded to the tube. Alternatively, the air can be withdrawn through one of the electrodes. The electrodes are preferably made from small rods of stainless steel that make a snug fit with the bore of the quartz tube. The diameter of the inner portion of both electrodes should be reduced to about four millimeters



Circuitry of the laser

through a length of about eight millimeters and the end rounded into a polished hemisphere. The portion of reduced diameter, along with about six millimeters of the full diameter of the rod, is inserted into the end of the quartz tube and sealed in place with an external coat of epoxy cement. The reduced diameter provides a 1/2-millimeter space between the metal and the quartz. The space prevents hot plasma from concentrating in the zone where the metal and the quartz make contact. The portion of the rod that extends outside the tube may be of any length convenient for the attaching of leads from the capacitor.

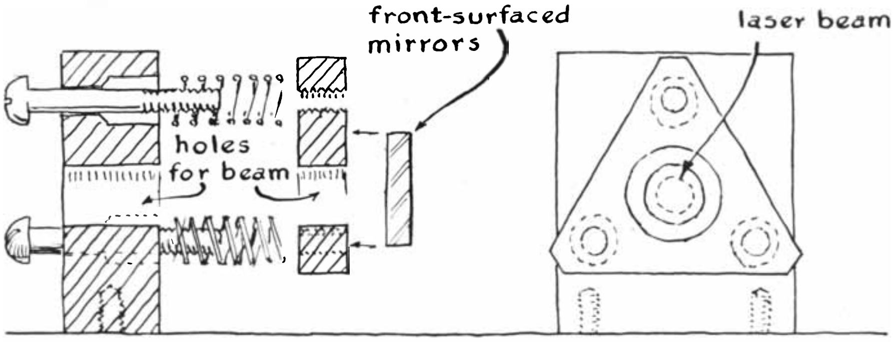
The machining can be done by clamping the rod in the chuck of an electric drill and cutting the metal with a file as the drill turns. Air can be exhausted through a hole about a millimeter in diameter drilled partway through the axis of the rod and joined at a right angle by a hole of similar size drilled from a point close to the shoulder. Do not drill the axial hole completely through the electrode. A tube of copper capillary can be brazed to the outer end of the electrode for attaching the air pump. Connect this electrode to the grounded side of the power supply.

The lamp and the amplifying tube are mounted parallel, 15 millimeters above the base, with their centers separated by about 12 millimeters. The base can be a slab of Formica about 1/2 inch thick. Lankard clamps the tubes in Minifuse clips attached to the base.

The reflector consists of an 80-millimeter length of aluminum tubing that has an inner diameter of about 25 millimeters. The inner surface must be highly polished; the polishing can be done with a small buffing wheel. Bring the surface to a semipolish by applying tripoli to the buffing wheel. After washing the metal with soap and water complete the polish with a clean buff to which rouge is applied.

The polished tube must be converted into an elliptical mirror. Clamp it in a vise and by trial and error exert just enough pressure to deform the metal. When the pressure is released, the tube should spring into an ellipse with its major axis some three millimeters longer than its minor axis. If you squeeze it too much, so that the difference in length is more than three millimeters, correct the error by rotating the tube a quarter of a turn in the vise and squeezing it again.

Mount the reflector to the Formica base with a pipe clamp. The major axis should be made parallel to the base. The Minifuse clips are attached to the base at points such that the axes of the amplifier and the lamp coincide with the focuses of the ellipse, which lie 12 millimeters apart.



Construction of the mirror cells

Cells for supporting and adjusting the position of the mirrors consist of two aluminum plates fastened together with machine screws and helical springs of the compression type [*see illustration above*]. One of the plates, a rectangle that serves as a pillar, is fastened to the Formica base with machine screws. Three holes spaced 120 angular degrees apart admit machine screws that engage threads in the second plate, which can be of triangular form. Compression springs that surround the screws hold the plates apart. A hole about eight millimeters in diameter is drilled through both plates of one cell. The hole is centered in the triangular plate. The partially transmitting mirror is cemented at its edges to this triangle, with the aluminum coating facing the dye cell. The hole functions as an aperture for the output beam. The fully transmitting mirror is similarly cemented with epoxy to the remaining cell.

The power supply can be assembled in a metal box that supports the Formica base. It is extremely important to use the shortest possible leads for connecting the 15-microfarad capacitor to the lamp, preferably leads of copper strap about one millimeter thick and 10 millimeters wide. The leads can be cut from copper flashing of the kind available from lumberyards and tinsmiths. Attach the leads to the screws that fasten the Minifuse clips of the lamp to the base. This construction minimizes the electrical inductance of the circuit and the interval required for the capacitor to discharge. The intensity of the light varies inversely with the rate of discharge.

The microammeter, which can be mounted in one side of the box, functions as a voltmeter, the scale indicating hundreds of volts. A reading of 30, for example, indicates that the capacitor is charged to a potential of 3,000 volts. A potential of 120 volts applied to the primary winding of the oscilloscope transformer appears as 2,400 volts across the terminals of the secondary winding. The rectified voltage that appears across the capacitor is equal to the output potential of the oscilloscope transformer divided by .707; a potential of 120 volts applied to the primary winding develops 2,400/.707, or 3,400 volts, across the capacitor.

This potential exceeds the breakdown rating of the capacitor. To protect the capacitor, Lankard inserts a variable transformer between the power line and the power supply and adjusts the potential to 3,000 volts as the capacitor accumulates charge. Do not omit the three resistors shown at the right in the bottom illustration on the opposite page. They function as bleeders, draining charge slowly from the capacitor. Without this safety provision the capacitor would retain a substantial portion of its lethal charge indefinitely. Never touch the power-supply circuit until the capacitor has been short-circuited, even though the circuit includes bleeder resistors. Short-circuiting can be done by briefly connecting a short length of copper wire across the terminals of the capacitor. The wire should be fixed to a dry wooden handle about a foot long.

Several dyes have been used successfully in the laser, and others are under investigation. A good one for a beginning experiment is rhodamine 6G. This orange dye emits light that spans a spectral range of some 440 angstroms from yellowish-green to red. The molecular weight of the dye is 449. It is used as a 10^{-4} molar concentration in methanol. The concentration can be achieved by dissolving .045 gram of the dye in methanol to make one liter.

An interesting dye, which emits a strong blue laser beam that is tunable from 4,300 to 4,900 angstroms, is 7-diethylamino-4-methylcoumarin, a dye found in commercial detergent whiteners. It has a molecular weight of 231.3 and is used in the laser at a concentration of 75 milligrams of dye per liter of methanol. Another dye, sodium fluorescein, is used at the same concentration as rhodamine 6G but in an ethanol solution. The molecular weight of sodium fluorescein is 370. Laser emission from this dye centers on 5,500 angstroms. Mix the dyes in clean glass containers, and be careful to avoid oily contamination.

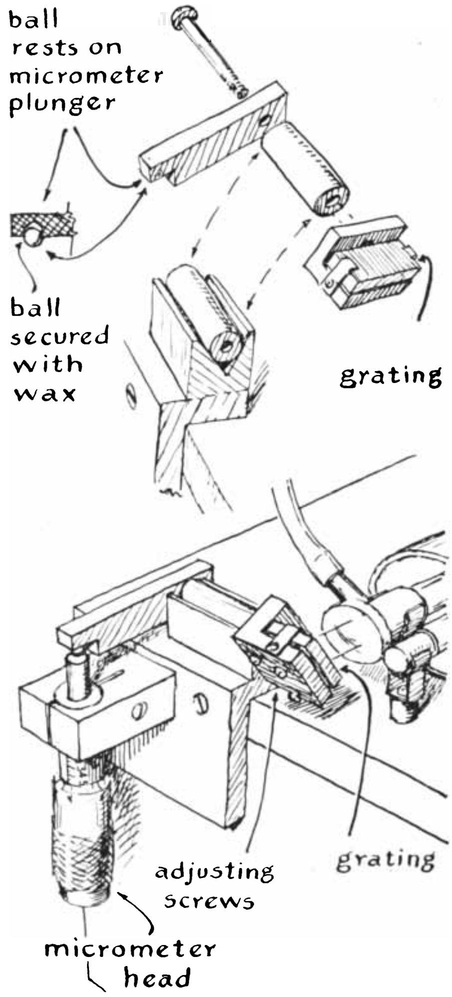
The operation of the fully assembled laser requires one critical adjustment: the mirrors must be positioned so that their surfaces are exactly parallel and perpendicular to the axis of the dye cell. When the surfaces are so aligned, light rays that are emitted parallel to the axis of the amplifier tube are reflected back on themselves and thereafter oscillate between the reflecting surfaces as though trapped in a cavity. Several schemes have been devised for aligning the mirrors. The most convenient one involves the use of an instrument consisting of a small telescope, an optical beam splitter and a source of light. Lankard's instrument consists of a seven-power telescope that is available from the Edmund Scientific Co., 600 Edscorp Building, Barrington, N.J. 08007 (catalogue number 50,249). The telescope comes with a diagonal mirror that deflects the incoming light at a right angle into the eyepiece.

Lankard substituted for the diagonal mirror a beam splitter that is also available from Edmund Scientific, and behind the beam splitter he installed a pinhole aperture and a small incandescent lamp [*see illustration below*]. Rays from the lamp proceed through the pinhole, the beam splitter and the objective lens of the telescope. When the telescope is aimed at a distant mirror that reflects the light back into the telescope, a portion of the incoming light is diverted into the eyepiece by the beam splitter, and an image of the pinhole appears in the eyepiece.

To align the laser, Lankard removes the partially transmitting mirror and, with the telescope, looks through the axis of the empty dye cell at the distant fully reflecting mirror. That mirror is then adjusted to center the image of the pinhole in the eyepiece. The partially transmitting mirror is reinstalled. Two images of the pinhole, usually displaced, now appear in the eyepiece. The partially transmitting mirror is adjusted to bring the two images into exact register. This completes the adjustment. When the laser is thus adjusted, it will emit a pulse of coherent light each time the lamp flashes. The beam appears yellowish in the case of rhodamine 6G dye.

The laser can be tuned to emit any desired spectral line within the range of the dye by substituting a reflecting diffraction grating for the fully reflecting mirror. The grating, which need be no larger than 10 millimeters square, is mounted so that it can be rotated in three planes: its own plane, the horizontal plane and the vertical plane [*see illustration at right*]. The rulings are placed exactly parallel to the horizontal axis of rotation. (The grating, which must be obtained commercially, should be ruled with at least 1,800 lines per millimeter and blazed for 5,000 angstroms in the first order.) When the grating is properly aligned, it reflects light of a single spectral line into the amplifier. The color depends on the horizontal angle the grating makes with the axis of the amplifier tube.

Initially the grating can be set to an angle of about 70 degrees. A colored image of the filament will appear in the alignment telescope. When the image is brought into register with the white image reflected by the partially transmitting mirror, the laser will emit light of the selected color. The output beam can

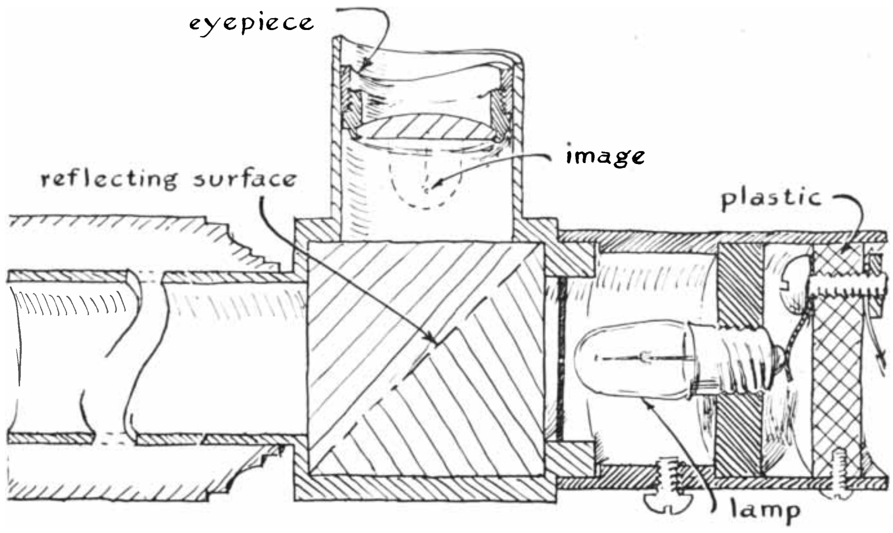


Mounting of the diffraction grating

then be tuned to any other part of the available spectrum (from a shade of green through yellow and to red) by rotating the grating on its vertical axis.

The laser can also be tuned within broad limits by altering the concentration of the dye or—what amounts to essentially the same thing—by altering the length of the amplifier tube. In general the wavelength of the output beam increases with the concentration of the dye or the length of the amplifier tube.

All the materials required for the construction of the dye laser, with the exception of the telescope, beam splitter and diffraction grating, can be obtained from Henry Prescott, 116 Main Street, Northfield, Mass. 01360. Many parts can be improvised from odds and ends. Lankard's instrument came largely from his scrap box. Do not attempt to economize on the 15-microfarad capacitor. Capacitors characterized by higher inductive reactance will not work. Do not substitute other materials for fused quartz. Finally, avoid the laser beam as if it were the flame of an oxyacetylene torch. It can fry tissue, including the tissue in your eye.



Arrangement of the telescope for aligning the mirrors