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DESIGN SPECIFICATIONS FOR OPTICAL LASER RUBY RODS

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WHEN specifying the design of solid-state configurations, such as ruby rods, to be used as the active elements in optical masers, a number of considerations are involved, all of which reflect directly on the present state of the art in crystal growing techniques and the skills and facilities available for precision fabrication.

Much of the effort expended over the past two years in the field of optical masers has been directed toward the development of better materials and new configurations of finished ruby laser rods. Also, improved means of material selection and measurement of the mechanical and optical parameters have received considerable attention.

It is expected that over the next few months many new and improved materials will be made available to the design engineer and scientist for performing experiments that will eventually lead to continuous wave operation, increased efficiency, higher output power levels, improved beam angle characteristics, narrower band width and a more coherent light beam.

With the increased availability of more solid-state laser materials, it is necessary that the designer knows to what practical limits the important mechanical parameters of a laser rod can be controlled by the precision fabricator.

Because of strains produced in growing raw crystals—lineage (deviation of the crystals' axis) and dislocations which are present to varying degrees in most laser crystals—the state of the art in precision fabrication is somewhat further advanced than present crystal growth techniques. This gives the designer an opportunity to specify tolerances which will allow him to study various host materials and doping elements knowing that variations in fabrication tolerances will not (within certain limits) affect to any great extent the operation of the optical maser. It is important, however, that these minimum limits in fabrication tolerances be observed, otherwise the effects of fabrication variations will become quite prominent.

Because of variations in raw material quality, as in synthetic ruby, it is possible to obtain finished laser rods from the precision fabricator made from material which has been optically inspected and graded for quality. Specifying "selected materials" in this manner does result in cost increases over normal prices for "non-selected material". However, it offers the scientist who has completed his preliminary investigations an opportunity to perform more sophisticated experiments using the same basic raw material but of superior quality.

Values for threshold level, beam divergence, reflectivity of end coatings and other parameters pertaining to the operation of the finished laser rod can also be supplied with the rod by the precision fabricator, at nominal cost. Such a material and operating characteristics analysis is also available to the scientist who already has materials and/or finished laser rods he wishes to have inspected.

FIG. 1. Interference fringes on the optical-interferometer screen check the end faces of a ruby rod for flatness within 1/20 of a sodium wavelength. Instrument at right checks parallelism of end faces to within 1 second of arc. On table are ruby rods and three rough cuts from ruby disc boules.

Data taken from recent measurements of ruby laser rods fabricated from "non-selected material" and having controlled deviations in flatness and parallelism of the end faces indicated that a flatness poorer than 1/10 wavelength (reference sodium light) had considerable effect on the laser beam spread, and parallelism poorer than 2 seconds of arc directly affected the amount of threshold energy required to stimulate laser action.

The accuracy of a standard optical interferometer allows flatness measurements to 1/20 wavelength (sodium light) by comparing the surface of a known standard with the surface under test. The pattern which is observed is similar to that seen on a contour map, the flatness of the surface in question being determined by the straightness of the interference fringes or lines.

An autocollimator—to measure parallelism—is essentially a telescope having an internal brightly illuminated scale which is projected, *via* a highly collimated light beam, simultaneously onto both polished end faces of the laser rod under test. The relative positions of the two reflected images of the scale, as viewed in the telescope, indicates the relative angular position of the surfaces under test.

Tolerances on the length and diameter of most laser rods having flat and parallel ends are not extremely critical and are usually determined by the variations in the mechanical assembly designed to hold the rod. Practical limits for the fabricator, however, are ± ·001″ on the diameter and ± ·005″ on the length of the rod

Although the ends of the rod may be parallel and flat, it is important that the ends of the rod are also directly opposite each other (a right cylinder), otherwise a part of the useful reflected light (that which is travelling perpendicular to the end faces) will lose its effectiveness. As a result there will be a decrease in efficiency and increased beam divergence. The 90° angles between the end faces of the rod and the cylindrical surface can readily be held within ± 1 minute of arc thus insuring a nearly perfect right cylinder.

Concerning orientation of the ruby rod with respect to one of its crystallographic axis, one of the more accurate approaches is to measure the deviation of the crystal axis through the ruby blank using X-ray diffraction techniques, and then grind the cylindrical surface of the rod parallel or perpendicular to the specified axis. By X-ray diffraction techniques it is possible to measure the deviation of the crystal axis within ± 10 minutes of arc.

The end faces of a laser rod having flat and parallel ends, and the reflecting surfaces of rods fabricated into special configurations, should be polished to the finest optical finish, free from digs and scratches so as to provide an exceptionally good transmitting and/or reflecting surface.

The cylindrical surface of a laser rod can be supplied with either a fine ground or clear polished finish.

A clear polished finish on this surface will result in a somewhat lower relative threshold value but will increase the activity of spurious modes due to internal reflection by the highly polished walls. Spurious modes decrease the available population density and reduce the overall efficiency. A rod having a fine ground cylindrical surface will require a relatively higher amount of input energy to exhibit laser action but will also offer improved efficiency due to absorption rather than reflection of light energy not travelling parallel to the axis of the rod.

When specifying the purchase of a laser rod, every detail must be covered to insure optimum operating characteristics. It is not enough to state merely that the rod exhibit laser action.

Of all solid-state laser materials which have been so far developed, the versatility, ease of fabrication and performance of ruby (chromium doped sapphire) has made it the most prominent. Two ruby rod sizes available from stock from most suppliers are 2½″ in length by ¼″ in diameter and 2″ in length by ¼″ in diameter, doped with 0·05% weight Cr_2O_3 : Al_2O_3, 0° oriented (C-axis of the crystal parallel to the rod axis), and fabricated from "non-selected" material.

Most laser rods fabricated to date have been under 3″ in length and ⅜″ in diameter. This size range is compatible with the power of most optical pumps which are readily available and allows greatest flexibility for basic research in various materials and rod configurations.

A concentration of 0·05% : Cr_2O_3 appears to be optimum for ruby in most applications. Heavier concentrations of chromium have yielded laser action at wavelengths other than 6943 Å which is commonly associated with 0·05% ruby. Chromium concentrations both heavier and lighter than 0·05% may require more power to stimulate laser action or may show no laser action whatsoever. Studies are being made to more clearly determine the effects of doping on the operation of the ruby laser rod.

A 0°-oriented ruby will display an elliptically or circularly polarized beam. A ruby laser rod fabricated such that the C-axis is perpendicular to the rod axis (90° orientation) will display a beam that is polarized in one direction.

When comparing the threshold level *vs.* temperature characteristics of 0° and 90° oriented ruby, it has been determined that the 0° rod has a much steeper slope. As a result the 90° rod is a better choice for room temperature operation and the 0° rod a better choice for operation at liquid helium temperatures. This choice would be made if one desires to realize the maximum number of laser actions per unit time.

with inputs of only 35 to 50 joules. The sapphire overlay is a sheath which encircles the body of the ruby rod over its entire length.

The sapphire overlay helps focus the pumping light so that its intensity is increased in the central area where the ruby rod is located, thus effectively increasing the capture-cross-section of the ruby rod. The sapphire overlay also effectively increases the conduction cooling area of the composite rod, and being an excellent heat conductor at liquid helium temperatures (nearly 200 times greater than copper) readily dissipates heat developed during operation.

TABLE I

Solid-state Optical Maser Materials

Crystal	Dopant	Output Wavelength (Å)	Input Wavelength (Å)	Approximate Illumination Threshold (w/cm.*)	Maximum Operating Temperature (K)
Pink Ruby ..	Chromium (0·05%)	6,943	4,000 5,500	700	350
Dark Ruby ..	do. (0·50%)	7,030 7,008	4,000 5,500	300	77
Calcium Fluoride ..	Uranium (0·05%)	22,000 26,000	5 500 8,900 11,000	10–50	280
do. ..	Samarium (0·05%)	7,080	6,300	20	40
Barium Fluoride ..	Uranium	22,000 26,000	5,500 8 900 11,000	10–50	280
Calcium Tungstate ..	Neodymium (0·10%)	10 600	5,800	1	295
do. ..	Praseodymium	10,470	4,500 5,000 17 500	10	100
do. ..	Thulium	19,100	4,700	60	77
do. ..	Holmium	20,500	4,500	150	77
Strontium Molybdate ..	Neodymium	10,600	5,800	8	280

* Illumination threshold is expressed in watts of light at the designated input wavelengths per sq. cm. of crystal side-wall area.

Data Courtesy: Bell Telephone Laboratories.

Lower input energy required to stimulate laser action (lower threshold) also minimizes internal heating caused by absorption of excess light energy at frequencies that do not stimulate laser action. A slower rate of internal heating results in a slower rate of threshold rise with time.

There have been many developments in the improvement of ruby* for laser applications over the past 1½ years. A rod fabricated to 1/10 wavelength flatness and 2 seconds parallelism from "non-selected" material, cut from the most recently developed laser quality ruby, and having dimensions of 2½" in length by ¼" in diameter, will exhibit laser action in the 100 to 200 joules range of input energy at room temperature. (The actual threshold level is also dependent upon the associated optics of the pump.) Some of the original ruby laser rods and light pumps required 2,000 to 3,000 joules of input energy to stimulate laser action.

The sapphire overlay has contributed most to date in lowering the threshold level of ruby, to the extent that laser action has been achieved

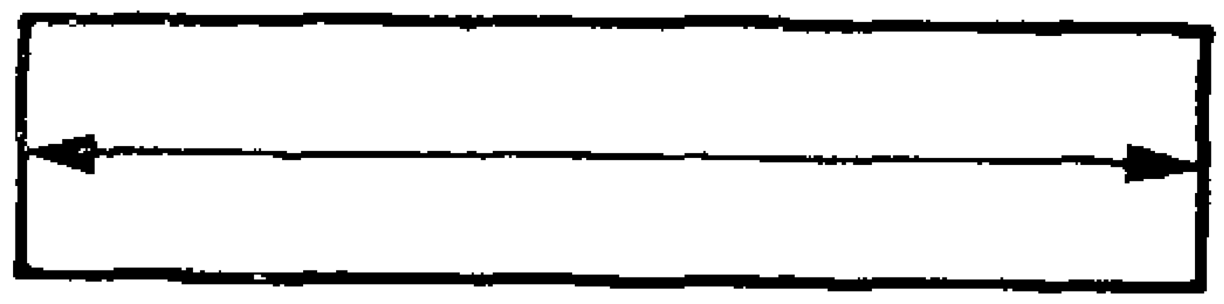
A sapphire overlay can be supplied in two ways. By the first method a build-up of sapphire on the ruby rod (to the desired wall thickness) is accomplished during the crystal growth technique. Such rods are available in lengths up to 1¼" having a ruby diameter of ·080" and sapphire overlay diameter up to ·200".

The second form of overlay is a sapphire rod, drilled lengthwise and optically polished at the inner diameter The ruby rod is then optically polished on its outer diameter until a tight piston fit into the sapphire cylinder is obtained. This second form of composite rod can be supplied in lengths from 1¼" to 4".

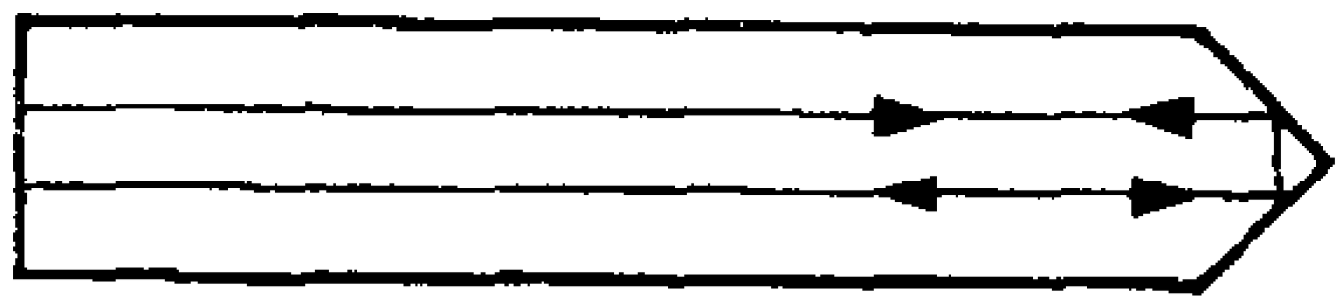
Either of the two sapphire overlay forms can be fabricated into the desired final end configuration.

* Linde Crystal Products Department, Division of Union Carbide Corporation, East Chicago, Indiana.

Laser quality ruby up to 3" long by ½" in diameter of 0°, 60° and 90° orientation, and up to 8" long by ¾" in diameter of 60° and 90° orientation, is available to the precision fabricator in the standard 0·05% or special chromium dopings.



1 FLAT AND PARALLEL



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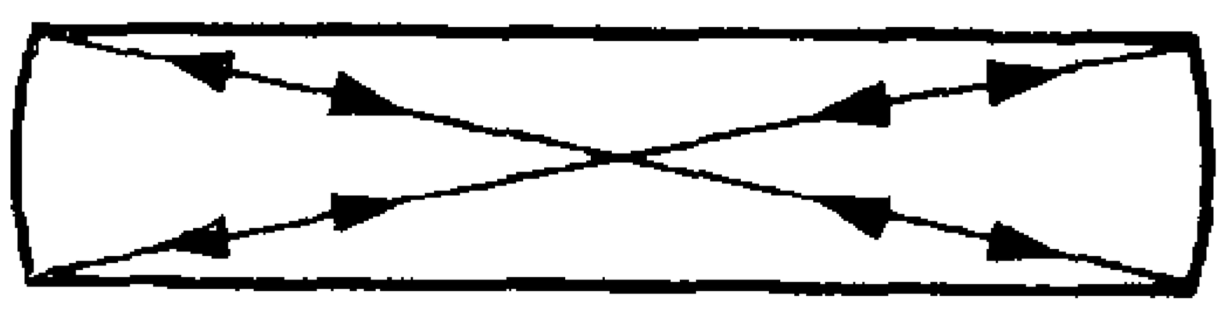

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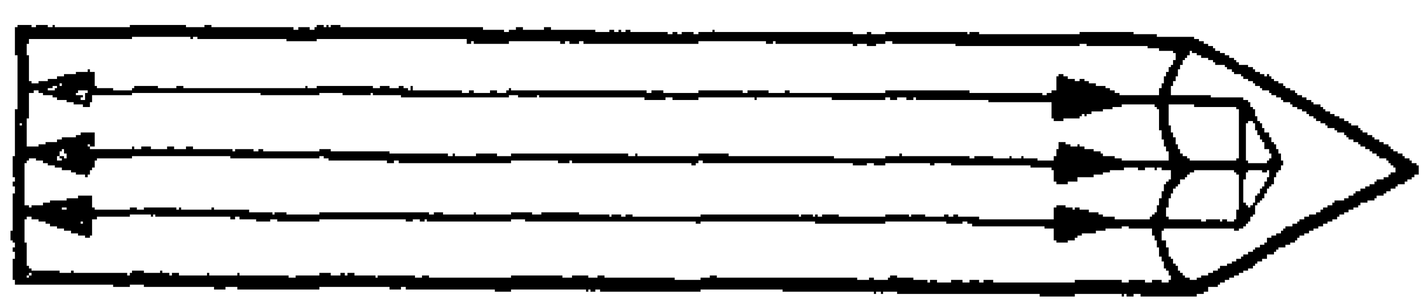
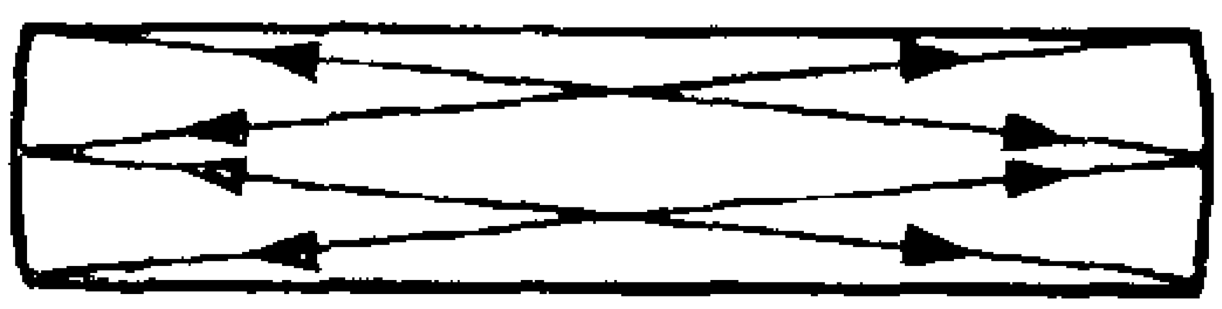


4. CORNER CUBE



5. CONFOCAL

Above are the five end configurations presently used in laser rod experimentation. Variations in the output beam characteristics are obtained by altering the internally reflected light. Configurations 1, 2 and 4 all generate a plane wave front. Configurations 2 and 4 utilize a multiple light path to provide increased efficiency and total internal reflection. Configurations 3 and 5 generate spherical wave fronts.

The size of the rod is related to its power-handling capabilities. However, no firm data are available to substantiate an absolute power to size ratio.

In addition to ruby rods having flat and parallel ends, other configurations have been manufactured or suggested. Some of the more common types are those having conical or faceted end configurations which eliminate the need for reflective coatings since they provide "total internal reflection". Since the reflection is accomplished in many cases by the critical angle at which the light beam strikes the reflecting surface, angle tolerances of ± 10 seconds of arc or less are in order.

Another configuration which generates a spherical wave-front and offers increased efficiency in operation is the confocal rod which has a convex radius at each end, this radius being equal to the length of the rod. The matching of the radius to the length of the rod is critical and should be held to within at least ± ·001". The "parallelism" of the two end faces, however, is not critical. The convex surfaces are optically polished spherical to within ¼ wavelength of sodium light.

A new configuration which has received some attention is the ruby tube having flat and parallel ends. The hole drilled lengthwise down the centre of the ruby rod allows insertion of a light source which, when fired, must transmit all its radiated energy through the ruby surrounding it thus eliminating the possibility of wasted light energy which is common in many other pumping schemes, except perhaps for the elliptical cage with the ruby rod and flash tube at the foci.

Although most of the special configurations which have been manufactured to date (many of which have been proprietary) offer some unique characteristic, none compare with the solid rod having flat and parallel ends for ease of manufacturing in large quantities. Most of the special configurations have to be manufactured singly or in very small quantities.

There are many new materials which are coming into prominence as active elements in solid-state optical masers. In addition to the possibility of doping sapphire with elements other than chromium, there are other crystalline materials already available, doped with various transition elements. Such materials as calcium fluoride doped with uranium or samarium, barium fluoride doped with uranium, and calcium tungstate doped with neodymium, are a few which have received considerable attention and show some promise of supplementing ruby. Also, certain glasses doped with rare earths have been announced that exhibit laser action.

Certainly in the future there will be a large selection of materials to choose from to meet buyers' requirements for output frequency, power-handling capabilities, size, operating temperature and other parameters.