## A Method for Rapidly Orienting Single-Crystal Garnet Spheres

### The Need for Oriented Garnet Spheres

In today's rapidly expanding microwave technology, more and more devices utilizing spheres of single crystal yttrium iron garnet (or hybrid variations of YIG) are being developed. The most common of these are the gyromagnetic coupler-type power limiter and the tunable YIG filter. In each of these applications, a sphere of single crystal YIG is used as the coupling element between two otherwise isolated transmission lines,[1-4] and is biased to ferrimagnetic resonance by means of an applied dc magnetic field perpendicular to the orthogonal RF magnetic field components at the sphere.

Yttrium iron garnet is an anisotropic material and the internal anisotropy fields vary greatly with temperature. Clark, Brown and Tribby[5] have shown that, although it is impossible to eliminate the anisotropy fields, it is possible to find an orientation of the YIG crystal such that the contribution of these anisotropy fields to the effective biasing fields, and hence the RF resonant frequency, is nearly constant over a wide temperature range. It is the purpose of this communication to discuss a new technique for accomplishing this orientation in a practical device, and for permanently positioning the sphere once the orientation is attained.

### Present Techniques

Depending on the specific application and the frequency, the size of the YIG sphere may vary from 0.015 inches to 0.250 inches. The problem then is one of orienting, to within about $\pm 1$ degree of an arc, a very smooth sphere (surface roughness of less than one-quarter micron has been obtained) in a given direction with respect to its crystallographic axes. A technique which has been used successfully is to expose the sphere to an x-ray beam to obtain a Laue pattern photograph. The photograph is analyzed to determine the actual orientation of the sphere, and the sphere is then rotated into the desired orientation by means of a vernier-calibrated holding head with two planes of rotation. The sphere must be mounted in some way so as to "capture" the orientation, and another x-ray photograph taken to check the alignment. In practice, this procedure is very tedious, requiring at least three and sometimes many more photographs (especially in the case of the smaller spheres), each requiring about 30 minutes for exposure, development, analysis and repositioning of the sphere. Thus the orienting of the sphere is time consuming and expensive, not to mention (in the case of a production run) the extensive use of an important research tool for an assembly job.

### Magnetic Alignment

Yttrium iron garnet has a simple cubic crystal structure with axes of "easy magnetization" along the ⟨111⟩ directions, or the body diagonals. There are four such axes in the material, any two of which intersect at an angle of 70.5 degrees. If an external magnetic field greater than the anisotropy fields is applied to the crystal, the electronic magnetic moments (spins) tend to align in the direction of the applied field. These spins, in turn, apply a torque to the crystal in such a direction as to align an easy axis parallel to the applied magnetic field, if the crystal is free to rotate. Simply allowing a YIG sphere to rotate under the influence of an applied magnetic field does not, however, orient the sphere in a unique direction. Only one of the four ⟨111⟩ axes is located in this manner and the sphere is free to rotate in the [111] plane perpendicular to that axis. If, however, the position of another ⟨111⟩ axis is fixed, the orientation of the crystal is uniquely determined.

A device has been developed by Sperry which will align and "capture" YIG spheres by utilization of these magnetic properties. It has been named RApid Sphere ORientor, or RASOR. Fig. 1 shows two electromagnets positioned so that the directions of their applied fields interesect at an angle of 70.5 degrees, corresponding to the angle between any two body diagnonals of a cube, as depicted in Fig. 2. A platform is positioned at the intersection point of the electromagnets at such an angle that, if a YIG sphere is placed on it and aligned with two ⟨111⟩ axes along the electromagnet axes, the perpendicular to the plane of the platform will coincide with the desired direction of alignment. A sapphire bearing of the type used in watch construction is mounted on the platform at the intersection of the axes of the magnets as shown in Fig. 3. The YIG sphere is placed in the tapered recess in the sapphire. The motion of the sphere is observed by the use of a microscope while the electromagnets are alternately energized. Beginning from a random axis orientation of the sphere on the platform, the probability is that, as the magnets are energized alternately, the sphere will oscillate with decreasing amplitude until it comes to rest with one easy axis parallel to each electromagnet. It is possible, however, for the sphere to be positioned in such a way that it will never stop moving, but will continue to oscillate through a swing of 40 degrees. The probability of this occurrence has not been calculated, but it seems to occur for about 10 per cent of the alignment attempts. It is a simple matter, when this "nonalignment" position exists, to manually distrurb the sphere to a more favorable position, and then begin the orientation process again. The possibility of the sphere's continued nonorientation movement makes it inadvisable to attempt orientation without observing the motion. Fig. 4 is a photograph of the RASOR with the microscope mounted for viewing the sphere.

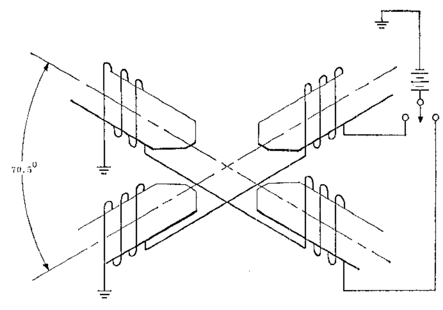


Fig. 1—Electromagnet positions.

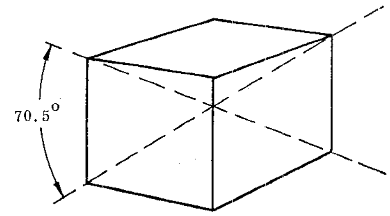


Fig. 2—Cubic crystal showing two ⟨111⟩ axes.

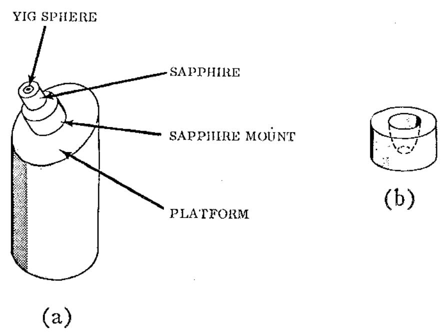


Fig. 3—(a) Platform with sapphire bearing and YIG sphere mounted. (b) Sapphire bearing much enlarged.

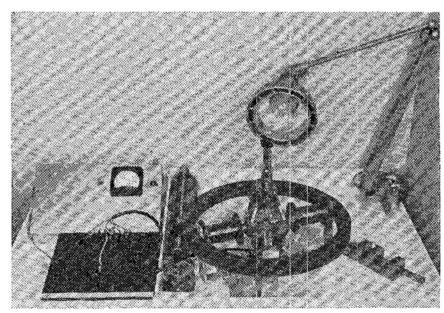

Fig. 4—Photograph of RASOR.

A number of techniques have been tried at Sperry to "capture" the sphere once it has been oriented. The most satisfactory method has been, as is often the case, the simplest. As indicated in Fig. 5, a brass collar has been fabricated which fits the brass sapphire mount very closely. A one-sixteenth-inch brass rod slides within the collar with a slip fit. One end of the rod is turned down to 0.020 inches and a 0.023-inch ball mill is used to put a cup in the tip (for 0.023-inch spheres). The collar is positioned and the cup filled with cement. The rod is carefully

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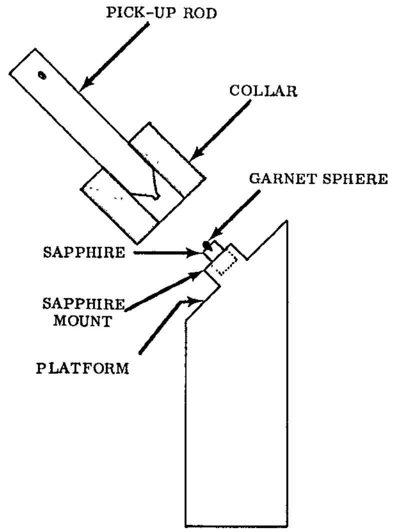


Fig. 5—Sphere mounting platform and pickup mechanism.

lowered until it touches the sphere, resulting in the sphere being cemented with the desired axis along the rod axis. Then the sphere can easily be mounted in whatever fixture is most adaptable to the device in question without losing the orientation.

Other investigators have oriented YIG spheres magnetically,[6,7] but to the authors' knowledge, this is the first attempt to orient single-crystal YIG spheres by means of switched magnetic fields.

The accuracy which has been achieved to date is $\pm 3$ degrees of the desired orientation in 100 percent of the attempts, with four out of five being aligned to within $\pm 1$ degree. This data refers to a sphere of 0.023 inch diameter. The same device can be used to orient larger spheres with the expectation of even greater accuracy.

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## Superconducting Pulse Power Supply

A method of storing large quantities of of electrical energy inductively, using superconducting coils operating in liquid helium, has been developed. The stored energy can be released in the form of a high-power pulse of short duration in the order of milliseconds. An experimental device consisting of a 1200-joule storage coil and a superconducting discharge switch was operated successfully in the circuit shown in Fig. 1.

The superconducting switch $S_s$ consists of a long wire of superconducting material which is wound noninductively on a suitable coil form. A wire material is selected which has a high resistivity in the normal state and a high critical current density in the superconducting state. Switching is accomplished by a superconducting-to-normal transition in wire 1. This can be obtained thermally, by increasing the temperature of wire 1 to above its critical temperature; or magnetically, as shown in Fig. 1, by generating an external field greater than the critical field of the wire.

Charging of the energy store is obtained with $S_1$ and $S_2$ closed. $S_s$ is then in the normal state and a field is generated in $L$. When the current in $L$ is stabilized to its maximum value, $S_2$ is opened causing $S_s$ to become superconducting. Upon opening $S_1$ the current in $L$ is diverted to the switch $S_s$ and a persistent current is set up in $L$ and $S_s$ since this circuit has absolutely no resistance. Energy can then be kept in storage for an indefinite period of time as long as the low temperature environment is maintained. A pulsed energy discharge occurs in the load upon closing $S_2$, which causes wire 1 to go normal and build up a high resistance (large compared to the load resistance).

For a resistive load $R$, the output pulse voltage may be represented by[1]

$$E_t = I_0 kt \left(1 + \frac{kt}{R}\right)^{(R/Lk-1)} \exp^{-R/Lt}$$

where $I_o$ is the current in $L$ prior to switching and $k$ is the rate of increase of resistance in wire 1 in ohms/sec. Values for $k$ in the order of $10^5$ohms/sec have been obtained.

The efficiency of the discharge can be found from Fig. 2, where $Q_{out}$ represents the energy delivered to the load and $Q_{stored}$ the stored energy in $L$ ($\frac{1}{2}LI_o^2$) prior to switching. Efficiencies greater than 90 per cent have been obtained and even higher efficiencies are potentially possible.

The advantage of this method of energy storage compared to that of capacitor banks is that by this method energy can be stored at much higher densities. For instance, a field of 100 kilogauss represents a field energy of 40 joules/cm$^3$. In capacitors the obtainable energy densities are generally limited to about 0.3 joule/cm$^3$.

Experiments using a laser flash tube as a load were recently performed and have indicated the feasibility of this approach for operating high-energy laser systems.

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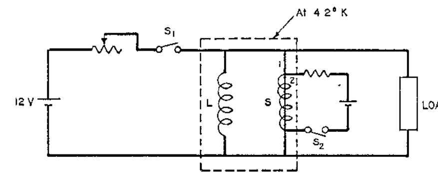


Fig. 1—Superconducting inductive energy storage system.

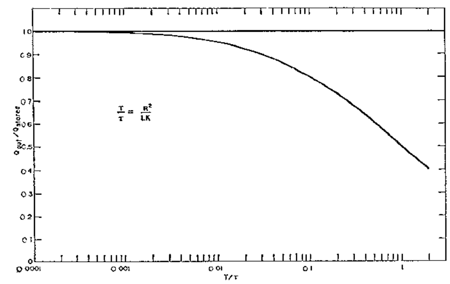

Fig. 2—$Q_{out}/Q_{stored}$ vs $T/\tau$.

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