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J. F. DILLON, JR

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SINGLE CRYSTAL INDUCTOR CORE OF MAGNETIZABLE GARNET

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FIG. 1

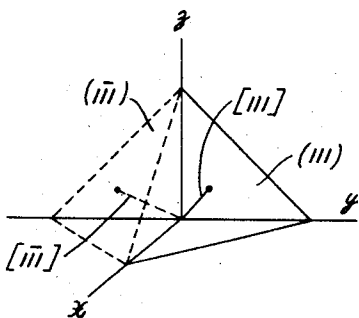


FIG. 2

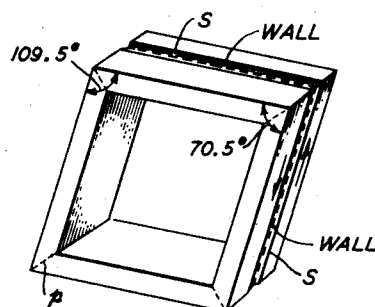


FIG. 3

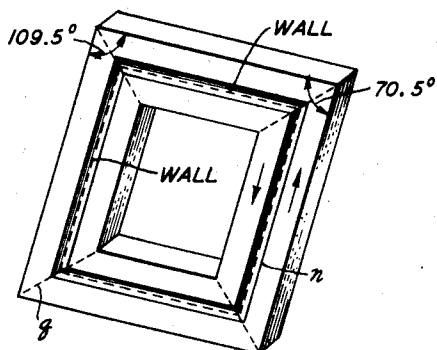


FIG. 4

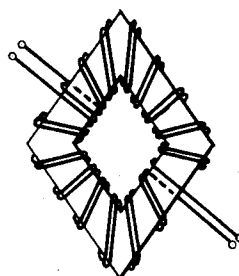
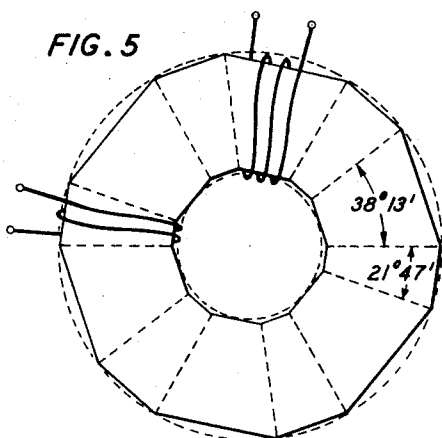


FIG. 5



INVENTOR  
J. F. DILLON JR.

BY  
Harry C. Hart  
ATTORNEY

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## SINGLE CRYSTAL INDUCTOR CORE OF MAGNETIZABLE GARNET

Joseph F. Dillon, Jr., Madison, N.J., assignor to Bell Telephone Laboratories, Incorporated, New York, N.Y., a corporation of New York

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This invention relates to an electrical inductance element of which the ferromagnetic core is composed of a single crystal of a suitable material, and in particular of a single crystal of yttrium-iron garnet or a single crystal of one of the ferromagnetic rare earth-iron garnets.

Principal objects of the invention include an improvement in the performance of a ferromagnetic cored inductance element by reduction of flux leakage from the core, increase, of its permeability and consequently inductance of the element, and improvement of the hysteresis loop of its magnetization characteristic.

Related objects are to effect a substantial reduction in the size of an element required to yield a prescribed inductance and to provide a practical miniature inductance element.

Within recent years a number of new ferromagnetic materials, broadly known as ferrites, have come into wide use, as have inductance elements having cores formed of these materials. While they have many interesting and valuable properties they also have certain defects and are open to certain objections. It has recently been discovered that a polycrystalline material having a garnet-like crystal structure has valuable ferromagnetic properties. This discovery was reported by F. Bertaut and F. Forrat in vol. 242 of Comptes Rendus, at page 382 (January 16, 1956). The present invention is based on the discovery that still more valuable properties and consequently important ferromagnetic behavior are obtainable with any one of a group of garnet-like materials when it is formed into a single crystal and the core is then cut from this crystal in a particular fashion having to do with the orientation of the legs of the core with respect to the crystallographic axes.

Of the many chemically different mineral garnets, one known as Grossularite is identified by the formula



It is not ferromagnetic. Certain artificial garnet-like materials, notably yttrium-iron garnet (hereinafter termed "YIG") and certain rare earth-iron garnets (hereinafter termed "REIG") not found in nature are to the contrary, ferromagnetic. The chemical formula of YIG is



The constitution of this material may be varied without altering its crystalline form and without destroying its ferromagnetic properties by the dilution of the iron in Formula 2 by aluminum, gallium, scandium or chromium. Furthermore, the yttrium atoms, or some of them, may be replaced, again without alteration of the crystalline structure or destruction of the ferromagnetic properties, by any of the rare earth elements having atomic numbers 62 through 71, to form REIG.

Thus, in general, the materials with which the invention is concerned may be designated by the formula



where A may be yttrium or any one of the rare earth

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elements having atomic numbers 62-71 or mixtures of these, and where B may be iron, or iron diluted with aluminum, gallium, scandium or chromium.

YIG and REIG are distinguished by electrical resistivity that may be several orders of magnitude greater than that of other magnetic materials commonly employed, including, in most cases, the ferrites, and by correspondingly low eddy current losses. These properties and others are expected to lead to the use of YIG and REIG in magnetic cores and in various other magnetic structures. The material as it has existed heretofore has been in the form of a polycrystalline aggregate which can be powdered, compressed into the form desired, and sintered.

The objectives of the present invention are achieved in an inductance element that has a magnetic core fabricated from a single, large, pure, mechanically sound crystal of YIG or REIG. For use at room temperatures and, indeed, at all temperatures above that of liquid helium, the core may take the form of an integral closed polygonal ring, the leg members of which are oriented with reference to certain axes of the crystalline material in a manner to be described.

The crystalline structure of YIG and REIG, like that of the natural mineral garnets, is cubic. In respect of certain of their magnetic properties, the crystals are anisotropic: thus, for the purposes of the present invention, it is significant that their intrinsic induction is much more easily directed along certain axes or directions through the crystalline material than along others. Such reference directions are commonly designated the "directions of easy magnetization" and they are related to the crystallographic axes in a definite manner that is known or determinable for any magnetic material.

In YIG, for example, one of the directions of easy magnetization is the [111] direction and, since the structure is cubic, there are seven other equivalent directions. These eight equivalent directions are customarily designated by the symbol  $\langle 111 \rangle$ . Each of these eight directions is likewise inclined equally to the three mutually perpendicular crystallographic axes.

One feature of a monocrystalline core embodying the invention is that each of the legs of the core lies along one of the directions of easy magnetization of the crystalline material. In this connection it is noted that one may trace out in any crystal of cubic structure, while following only directions of easy magnetization, a number of multisided closed figures, among which are four-sided planar figures that are parallelograms. One such figure in a material in which [111] is a direction of easy magnetization, for example, is a rhombic or diamond-shaped one that lies in a (110) crystal plane and of which one pair of opposite sides extends in the [111] direction and the other pair of opposite sides extends in, say, the  $[1\bar{1}1]$  direction.

Another feature of an inductance device in accordance with the invention is that each leg of the integral core structure essentially constitutes in itself no more than two magnetic domains. That is, in each of these major parts of the core the magnetization is substantially confined to a single direction, or to two anti-parallel directions, aligned with the longitudinal dimension of the leg. Further, each of these domains is joined at its ends with domains that are like-directed around the core: there is no significant aggregation of magnetic poles (ideally, none) and any flux is completely confined.

The nature of the present invention and its various features, objects and advantages will appear more fully from consideration of the specific embodiments herein-after described with reference to the accompanying drawings.

In the drawings:

Fig. 1 is a diagram illustrating the relation of certain significant planes and directions to the crystallographic axes;

Fig. 2 is a perspective illustration of a rhombic core, showing its relation to the crystallographic axes;

Fig. 3 is an illustration of a core alternative to that of Fig. 2;

Fig. 4 is a diagram showing a transformer embodying the invention; and

Fig. 5 is a plan view of a core for use at extremely low temperatures.

Pursuing further the example of a cubic crystalline material in which the  $[111]$  direction is a direction of easy magnetization, Fig. 1 shows the three mutually perpendicular crystallographic axes,  $x$ ,  $y$ ,  $z$ , of the material and, in solid lines, the  $[111]$  direction and a  $(111)$  plane. The corresponding direction  $[1\bar{1}\bar{1}]$  and a  $(1\bar{1}\bar{1})$  plane in another octant are also shown in dotted lines, and it will be evident that there are corresponding directions and planes in each of the other octants also. Each of six pairs of these directions defines a plane that is parallel to one of the axes  $x$ ,  $y$ ,  $z$ , and inclined at 45 degrees to the other two axes. One plane so defined is the  $(110)$  plane and, because of the prevailing cubic symmetry, the other planes so defined are equivalent and may be given the same designation for present purposes. Similarly the  $[111]$  direction and its equivalents may all be designated  $\langle 111 \rangle$  directions.

Fig. 2 shows diagrammatically a rhombic core and its relation to the crystallographic axes. In this core, each of the four legs of which the polygonal ring is constructed is of a uniform rectangular cross-section of which the dimension extending perpendicular to the face of the core is large compared with the dimension parallel to the face of the core which, as indicated above, lies in the  $(110)$  crystallographic plane. As a result of this construction a wall, which separates magnetic domains polarized in one direction from adjacent domains polarized in the opposite direction, lies in the plane of the face of the core as indicated by the broken line.

Fig. 3 shows a core alternative to that of Fig. 2 in which the opposite is true: the rectangular cross-section of each leg has a longer dimension in the plane of the face of the core and a shorter dimension perpendicular to the core face. As a result of this construction the interdomain wall extends perpendicularly to the plane of the core face as shown by the broken line.

The large aspect ratio of the cross-section of each leg of the cores of Figs. 2 and 3 provides high stability for the orientation of the interdomain wall as dictated by energetic considerations.

The four legs of each of the cores of Fig. 2 and extend in  $[111]$  directions. The angles that the  $[111]$  directions make with each other can be readily determined by geometric calculation. The acute angle of the rhombus turns out to be  $2 \sin^{-1} 1/\sqrt{3}$  or about 70 degrees, and the obtuse angle is its supplement or about 110 degrees.

Consider, now, the disposition of the magnetization in one of the legs of the core of Fig. 2 or 3. In the demagnetized state of the core the material is spontaneously magnetized in a manner suggested by the arrows, that is, the magnetization is opposite directed in the two parts of the cross-section, termed domains, that are separated, in Fig. 2 by a wall parallel to the diamond-shaped faces and, in Fig. 3 by a wall perpendicular to these faces. Throughout each such domain the magnetization is uniform in strength and direction. The magnetization in each leg is linked with magnetization in adjacent legs so that the magnetization is continuous around the core and completely closed on itself, being clockwise on one side of the domain wall and counter-clockwise on the other. If a sufficient longitudinal magnetic field be applied to

the several legs, as by means of a coil on the core, it in effect shifts the position of the wall, and changes the net flow of flux around the core. In this fashion the wall may shift all the way from the position in which it is shown to one of the  $(110)$  faces which bound the core, or to the other.

The end walls of the domains in Figs. 2 and 3 lie in diagonal planes through the rhombus, and one of them is shown in dotted lines at  $p$  in Fig. 2, and at  $q$  in Fig. 3. Each is inclined at an angle of either 35 degrees and 16 minutes or 54 degrees and 44 minutes to the length of the leg.

In a core of perfectly rectangular cross-section there exists no preferred position for the movable domain wall unless it be coincident with one or the other of the  $(110)$  surfaces between which it may move. In consequence the initial state of magnetization of the core of a perfectly rectangular cross-section is usually not neutral but, to the contrary, unbalanced and often to a random extent.

For many engineering uses it is desirable that, in the absence of an applied magnetic field, the magnetization of the core be completely neutral. In accordance with a further aspect of the invention such neutrality can be achieved by arranging that the core include some feature by virtue of which there exists a preferred central position for the domain wall. Because of energy considerations a domain wall tends always to adopt a position in which its area is minimized. In the case of a core having the configuration shown in Fig. 2 a peripheral notch or slot,  $S$ , cut in the  $(112)$  faces, parallel with the  $(110)$  faces, serves this purpose and in the rest condition of the core the domain wall locates itself in the plane of the slot.

In a core having the configuration of Fig. 3, even with a perfectly rectangular cross-section of the legs, a location in which the area of the domain wall is minimized is to be found at the bounding plane of the hole through the core, and the domain wall tends to adopt this position in which the magnetization of the core is unbalanced. Balance may be obtained by cutting a slot or notch  $N$  in the plane of either or both of the  $(110)$  faces and roughly midway between the inner and the outer bounding faces of the core, which lie in  $(112)$  planes. The depth of the slot must be so great that the area of the domain wall where it is located at the slot is less than the domain wall area located at the inner bounding faces of the hole, despite the greater length of a domain wall in the former location as compared with that of a domain wall in the latter location.

For complete magnetic balance the precise location of the slot can be determined from geometrical considerations in dependence on the lengths of the legs of the core in the directions of magnetization and their widths in the two directions perpendicular to it.

Fig. 5 shows diagrammatically a complete inductance device with windings of insulated wire applied to the core and brought out to two pairs of terminals to constitute a transformer. Each winding should extend completely around the core with a view to providing uniformly distributed excitation and thereby to preserve to the fullest the relative freedom of the structure from magnetic flux leakage. One winding only will be needed if the element is to serve as an auto-transformer or choke coil or the like.

At extremely low temperatures, i.e., in the range below 4.2 degrees K., obtainable by immersion in liquid helium, the anisotropy of YIG has been found to depart considerably from that which obtains at higher temperatures and in a fashion such that the crystallographic directions of easiest magnetization are no longer the  $\langle 111 \rangle$  directions but rather the  $\langle 123 \rangle$  directions. This permits the construction of a core cut in a single crystallographic plane, namely the  $(111)$  plane, having three, six, or twelve legs. Hence, for operation at these temperatures

a core may be constructed as shown in Fig. 5 where the radial lines represent the fixed domain walls. The angles between adjacent domain walls are alternately 21 degrees and 47 minutes and 38 degrees and 13 minutes. This polygon approximates a circle, and hence it is surmised that a circular toroidal ring will operate in substantially the same fashion as the polygonal ring of Fig. 5. This is indicated by a broken line showing an outer circle subscribed about the outer polygon and an inner circle inscribed within the inner polygon. This polygonal or circular toroid may be provided with one or more coil windings in conventional fashion to provide an inductance element.

It is expected that REIG behaves in the same way at the very low temperatures.

Measurements of the ferromagnetic resonance behavior of YIG at microwave frequencies, specifically at 9,000 megacycles per second and 24,000 megacycles per second have confirmed the identities of the directions of easiest magnetization, as set forth above. Specifically, the resonance measurements have confirmed that, at ordinary temperatures, the directions of easiest magnetization are the  $\langle 111 \rangle$  directions and that at temperatures of 4.2 degrees K. or below, they are the  $\langle 123 \rangle$  directions. Incidentally, these resonance experiments have revealed that absorption curves of YIG are substantially narrower than corresponding curves for the ferrites.

Single crystals of yttrium-iron garnet have been grown by J. W. Nielsen by the following processes.

One hundred grams of lead oxide (PbO) were placed in a platinum crucible along with seventy grams of iron oxide ( $\text{Fe}_2\text{O}_3$ ) and 3.5 grams of yttrium oxide ( $\text{Y}_2\text{O}_3$ ). The mixture, in its crucible, was placed in an oven containing an atmosphere principally of oxygen. It was then raised to a temperature 1325 degrees C. and held at that temperature for five hours. Thereafter the crucible with its contents was cooled at the rate of 5 degrees C. per hour to 900 degrees C. the crucible was withdrawn from the oven and cooled to room temperature and its contents, now a solid mass, was extracted from the crucible. Examination of this mass revealed that it was composed of three phases of which the first was now solidified, and composed chiefly of lead oxide, the second was magnetoplumbite of crystalline form and the third was individual crystals of yttrium-iron garnet of significant dimensions. The crystals of these last two compounds were separated from the mass by dissolving it in 6-normal nitric acid which does not attack the crystals.

When the foregoing process was modified to the extent that eighty grams of lead oxide were employed instead of one hundred, the final mass contained four phases instead of three, of which yttrium-iron garnet was again one, and in the same quantity.

The garnet crystals were finally separated from those of magnetoplumbite on the basis of their respective morphologies, by examination.

What is claimed is:

1. As an article of manufacture, a core formed from a single crystal of non-metallic magnetic material and

comprising a plurality of integral legs together forming a closed ring, each of said legs lying along a direction of easy magnetization and having a substantially rectangular cross section characterized in that the rectangular cross section is altered by a recess formed in a face of said leg and extending parallel with the direction of said leg and the directions of magnetization therein, the recess in each leg being also parallel with and midway between adjacent faces thereof and continuous with the recesses in adjacent legs.

2. An article as defined in claim 1 wherein the crystal is of a magnetizable material having the chemical type formula



where A may be yttrium or any one of the rare earth elements having atomic numbers 62-71 or mixtures thereof, where B may be iron or iron diluted with aluminum, gallium, scandium or chromium, and where O is oxygen.

3. An article as defined in claim 1, wherein the material of the core is yttrium-iron garnet.

4. An article as defined in claim 1, wherein the material of the core is a rare earth-iron garnet.

5. An article as defined in claim 1, wherein the cross section of each leg has at least two opposite wide faces and an aspect ratio substantially in excess of unity, and the recess is formed in one of the two wide faces of each leg.

6. An article as defined in claim 5 wherein the wide faces of said legs lie in planes perpendicular to the plane of the ring.

7. An article as defined in claim 5, wherein the long dimension of the cross section of each leg extends parallel to the plane of the ring.

8. An article as defined in claim 1, wherein the ring comprises four legs disposed in the form of a hollow parallelogram, and each leg extends in a  $[111]$  direction of the crystalline material of the core.

9. An article as defined in claim 1, wherein the material of the ring is yttrium-iron garnet and the ring comprises four legs disposed in a hollow parallelogram having two oppositely located interior angles of 70.5 degrees, the two remaining interior angles being 109.5 degrees.

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