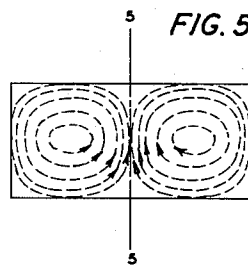
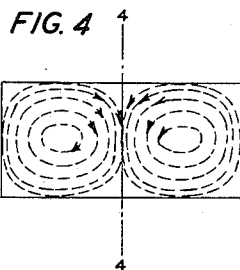
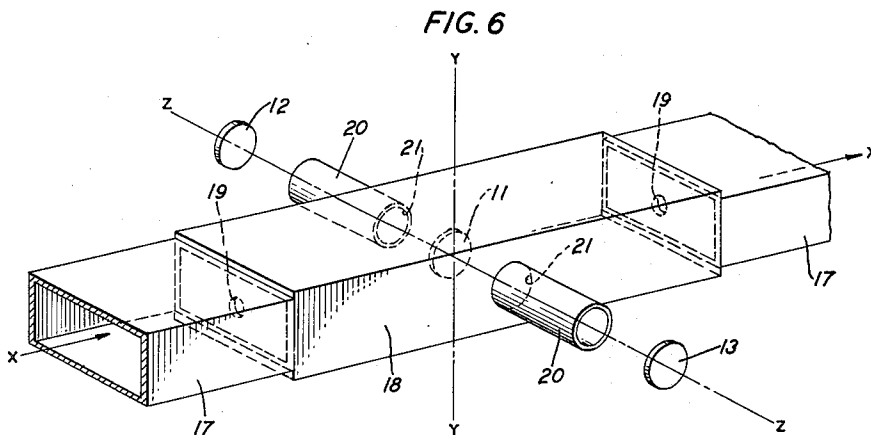
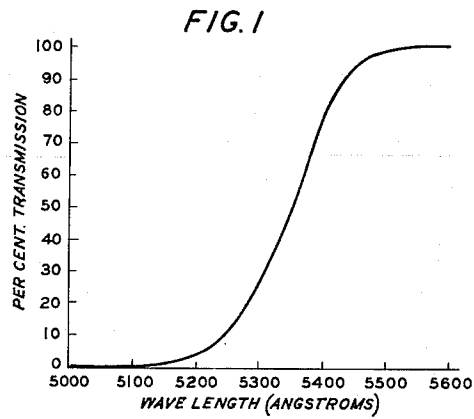


Filed Feb. 15, 1957

LIGHT MODULATOR

2 Sheets-Sheet 1



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Filed Feb. 15, 1957

2 Sheets-Sheet 2

FIG. 2

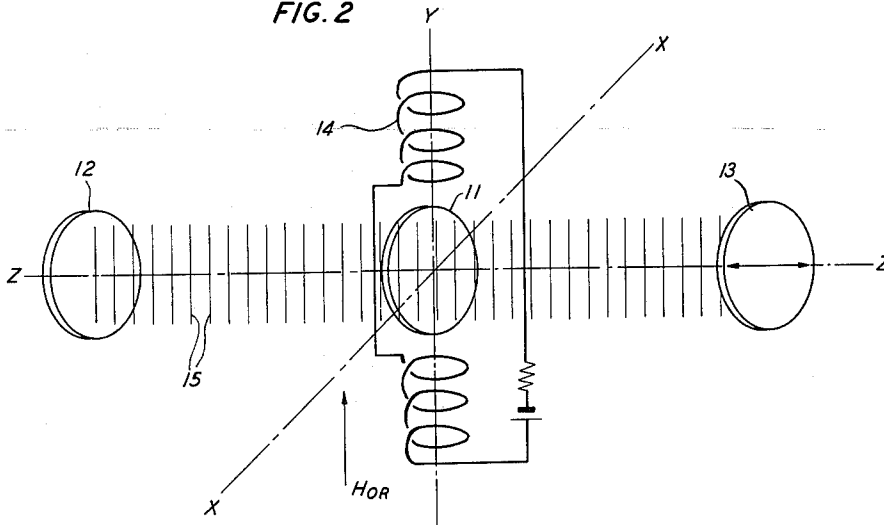
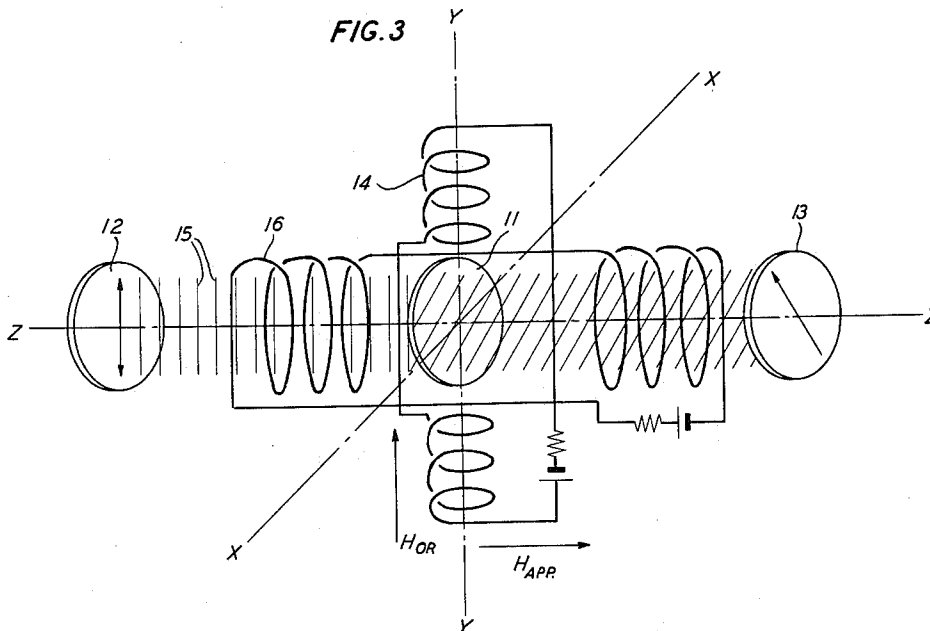


FIG. 3



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LIGHT MODULATOR

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Filed Feb. 15, 1957, Ser. No. 640,481

8 Claims. (Cl. 38—61)

This invention relates to light modulating devices utilizing a transparent ferrimagnetic materials to produce Faraday rotation, and in particular relates to devices which utilize a transparent ferrimagnetic yttrium-iron garnet or one of the ferrimagnetic rare earth-iron garnets.

In general, the comparative magnitudes of the coefficient of specific rotation (degrees per centimeter) in the Faraday rotation, and in particular relates to devices ultimately on the fraction of electrons in the substances whose spins line up in the same direction. Magnetic materials, that is materials in which there is a large resultant unpaired electron spin, will show greater specific rotations in the Faraday effect than will materials having fewer or no unpaired electrons. In devices using the Faraday effect, then, it is most desirable to have such magnetic materials with large specific rotations as the transmitting and rotating media.

Most magnetic materials, however, have electron bands lying so closely above the ground state that light of wavelengths shorter than those of light in the infra-red at about 16,000 Angstroms is completely absorbed. When magnetic materials are prepared in sections thin enough to transmit wavelengths of light in the infra-red, the visible, or the ultraviolet, path length through the specimen is so short that the amount of Faraday rotation observable is small, despite the high specific rotation of the material. On the other hand, for non-magnetic materials which are transparent to light into and beyond the visible spectrum, the specific rotation is so small that inordinately long paths through the materials are required to show rotation of any considerable magnitude.

A group of synthetic ferrimagnetic materials has been newly discovered, however, the members of which have unfilled electron bands sufficiently far above the ground state to be transparent in relatively thick layers into and beyond the visible spectrum. These materials are structurally similar to the naturally-occurring non-magnetic mineral garnet Grossularite, $\text{Ca}_3\text{Al}_2(\text{SiO}_4)_3$. The ferrimagnetic synthetic materials are yttrium-iron garnet, $\text{Y}_3\text{Fe}_2(\text{FeO}_4)_3$, and rare earth-iron garnets of the formulae $\text{M}_3\text{Fe}_2(\text{FeO}_4)_3$, where M is at least one of the rare earth elements having an atomic number between 62 and 71 inclusive. The ferrimagnetic properties of yttrium-iron garnet are not destroyed, nor is its crystalline form changed, by dilution of the yttrium atoms therein with rare earth elements of the kind described. Further, the trivalent iron of the yttrium-iron and rare earth-iron garnets may be diluted with atoms of aluminum, gallium, scandium, or chromium or mixtures of these without change of crystal structure or complete loss of magnetic properties.

Thus, a general formula for the materials in question may be written as



where A may be yttrium or any one of the rare earths of atomic number 62 to 71 inclusive, or mixtures of any

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of these rare earths with each other or with yttrium, and where B may be iron, or iron diluted with aluminum, gallium, scandium, or chromium, or mixtures of these diluents with iron.

- 5 In Table I below, the specific rotation of yttrium-iron garnet, representative of the aforementioned group of ferrimagnetic materials, is compared with the specific rotation obtainable in a number of representative non-magnetic materials. The specific rotations of the non-magnetic materials were calculated from the Verdet's constants in the Handbook of Chemistry and Physics, Chemical Rubber Publishing Company, Cleveland, 37th edition, 1955-56, page 2764, for a magnetic field intensity of 10,000 gauss and an angle of 0 degrees between the direction of the magnetic field and the path of light.

Table I

Material:	Specific rotation (degree per centimeter)
20 Calcium fluoride (fluorite)-----	1.5
Carbon (diamond)-----	2.1
Jena glass (light flint)-----	5.3
Jena glass (very heavy flint)-----	14.8
Potassium chloride (sylvite)-----	4.8
25 Sodium chloride (rock salt)-----	6.0
Stannous chloride-----	37.5
Zinc sulfide, β -----	37.5
Yttrium-iron garnet-----	>1000

- 30 The ferrimagnetic materials mentioned above may be prepared in sections transparent to infra-red light and light of shorter wavelengths. Yttrium-iron garnet, for example, is one of these materials with an absorption cut-off first appearing in the green, transmitting with rotation light of wavelengths longer than those of green light. The fact that the absorption cut-off is in the green indicates that light of such frequency corresponds most closely with a natural frequency of some of the atoms of the synthetic garnet. Since there is greatest interaction of light of this frequency with the atoms of the garnet, green light will show the greatest specific rotation. Light of longer wavelength will show smaller values of the specific rotation. Light of shorter wavelength than green will be absorbed by this material.

- 45 Because of the slight variation of specific rotation with wavelength, polychromatic linearly polarized light is rotationally dispersed in passage through an yttrium-iron garnet. Rotation is thus most easily observed using monochromatic light. Because rotation is greatest in the green, monochromatic green light, for example the 5461 Angstrom mercury line, is particularly desirable for viewing the rotation in yttrium-iron garnet.

- 50 Only those regions of the garnet in which the magnetic ions of the crystal are aligned to have a component of their spin-orbital magnetic moment parallel or antiparallel to the direction of propagation of an incident beam of polarized light will interact with the electromagnetic wave. That is to say, only those regions of the garnet crystal in which the magnetization has a component either parallel or antiparallel to the direction of propagation of the light beam will be effective in rotating the plane of polarization. In regions which have no component of the magnetization so oriented, no interaction results. In the absence of an orienting magnetic field applied to a garnet crystal, some magnetic domains of the garnet will have a magnetization with a component parallel or antiparallel to the direction of the transmitted polarized wave. Other domains will have no such component.

- 70 If visible monochromatic light is polarized by passing through a polarizing Nicol prism, then passed through a crystal of yttrium-iron garnet, and then viewed through

a second analyzing Nicol prism aligned at right angles to the polarizing prism, the domain structure of the garnet will be apparent. Those domains with no component of magnetization parallel or antiparallel to the incident beam will not rotate the beam. Light transmitted by these domains will be extinguished by the analyzer. Those domains which are aligned with a component of magnetization parallel to the incident beam will rotate the beam during its passage through the garnet crystal. Light so rotated will be passed by the analyzer to an extent dependent on the amount of rotation of the light out of the plane of polarization created by the polarizing prism toward the plane of polarization which is completely passed by the analyzing prism. Those domains which have a component of magnetization antiparallel to the direction of propagation of the incident beam will similarly rotate light passing therethrough, but will rotate it in a sense opposite in direction, but equal in magnitude, to that effected by domains with a component of magnetization equal in magnitude but aligned parallel to the direction of propagation of the incident beam. The domains of a garnet crystal can thus become visible through the analyzer as light and dark patterns in the viewing field.

The application of an external orienting direct-current magnetic field to a crystal of garnet, of strength sufficient to saturate the crystal magnetically, will align the magnetic atoms of the garnet to form a single domain whose direction is fixed by the orienting field. By orienting the entire crystal with its magnetization perpendicular to the direction of propagation of an incident linearly polarized light beam, the crystal may be made to pass the beam without any rotation. By orienting the entire crystal so that the magnetization is parallel or antiparallel to the incident beam, rotation of the entire beam in one rotational sense or the other may be accomplished. By orienting the crystal so that its magnetization has a component in the direction of the incident polarized wave, some rotation less than the maximum rotation possible is brought about. When linearly polarized visible light passed through such a crystal of garnet is viewed with an analyzing prism oriented perpendicular to the polarizing prism while the direction of the orienting field applied to the garnet is varied, the light field viewed will be uniform in intensity over the field, but the intensity of the entire viewing field will be variable between complete transmission and complete extinction as the orienting magnetic field applied changes the magnitude of that component of the magnetization of the crystal measured along the direction of propagation of the light wave.

A variety of devices may be constructed to bring about and utilize this phenomenon. Magnetic shutters, for example, may be constructed. The Faraday rotation effect has also been used in the microwave transmission arts to construct devices such as isolators, gyrators, circulators, and modulators. Analogous devices may now be made which affect waves of frequency higher than microwaves in the same manner in which the aforementioned devices are used with microwaves. Because of the large specific rotation shown by ferrimagnetic yttrium-iron garnet and the ferrimagnetic rare earth-iron garnets, inordinately long path lengths through the materials are not required. Devices may be constructed, then, which are impossible practically to construct using other materials showing the Faraday effect in that portion of the spectrum of frequency higher than microwave and infrared frequencies.

In the accompanying drawings:

Fig. 1 is a plot of the absorption curve of yttrium-iron garnet;

Fig. 2 is a schematic view showing a light beam transmitted by a crystal of yttrium-iron garnet or rare earth-iron garnet in which view no rotation of the light beam is effected because of the particular choice of direction

of an orienting direct-current magnetic field applied to the garnet crystal;

Fig. 3 is a schematic view of the same device in which the orienting direct-current magnetic field has been modified by the application of a second magnetic field which will give the magnetization of the transmitting crystal a component in the direction of propagation of the incident beam, effecting rotation of the beam;

Fig. 4 is a schematic plan view of the magnetic field, at the beginning of a wave cycle, within a microwave resonant cavity resonating in the TM_{21} mode;

Fig. 5 is a schematic plan view of the magnetic field in the resonant cavity of Fig. 4 viewed one-half period later; and

Fig. 6 is a schematic perspective view of a microwave resonant cavity similar to that in Figs. 4 and 5, and associated waveguides, in which cavity a crystal of yttrium-iron or rare earth-iron garnet has been mounted.

In Fig. 1, the percent transmission of a crystal of yttrium-iron garnet has been plotted along the ordinate as a function of wavelength, in Angstrom units, plotted on the abscissa. If the "cut-off" is arbitrarily defined as that point at which there is 50 percent absorption, the curve shows the cut-off in yttrium-iron garnet at about 5360 Angstroms. Transmission has been measured, for purposes of the plot, without regard to polarization of the incident light.

In Fig. 2 is shown a body 11, for convenience shown as a thin disc of a single crystal of yttrium-iron garnet or rare earth-iron garnet. Monocrystalline material is preferred and is described in the embodiments herein. However, in less critical applications dense polycrystalline garnet bodies may be used if dispersion within the bodies is sufficiently low to preserve transparency. The face of disc 11 is shown perpendicular to an axis designated the z axis. The disc lies in the plane of the orthogonal x and y axes, which are mutually orthogonal to the z axis. On either side of body 11 are mounted polarizing prism 12 and analyzing prism 13. Prism 12 is aligned in the figure to pass light linearly polarized parallel to the y axis. Coils 14, mounted on both sides of garnet body 11 and along the y axis, set up a direct-current magnetic field, designated H_{or} , in Fig. 2. The field is sufficiently strong to saturate the ferrimagnetic body 11. The magnetization of garnet body 11, in such a direct-current field as H_{or} , is aligned in the direction of the field. Because the field and the magnetization of the crystal are orthogonal to the direction of propagation of monochromatic light beam 15 passing through garnet body 11, the body has no rotational effect on beam 15. Analyzing prism 13 stops beam 15 when oriented at 90 degrees to polarizing prism 12.

In Fig. 3, coil 16 has been added to the apparatus schematized in Fig. 2. Coil 16 is energized to create a direct-current magnetic field H_{app} , in a direction parallel to the direction of propagation of light beam 15. Because of the presence of the magnetic field H_{app} , the magnetization of the ferrimagnetic garnet body 11 now has a component in the direction of propagation of light beam 15. A rotation of beam 15 results on passage through body 11, and analyzing prism 13 must be rotated to a new position in order completely to extinguish beam 15 on its emergence from garnet body 11. For purposes of Fig. 3, the rotation is shown as a clockwise rotation viewed from analyzing prism 13.

Though in both Figs. 2 and 3 the orienting direct-current magnetic field H_{or} has been depicted as lying along the y axis, it is to be understood that the direction of the field may be along any line in the xy plane. Any such orientation will fail to give a component parallel or antiparallel to the direction of propagation of light beam 15.

Also the direction of the direct-current magnetic field H_{app} may be in any direction lying outside the xy plane. Any field direction other than one in the xy plane has a component parallel or antiparallel to the direction of

propagation of beam 15 and will cause some rotation of beam 15 if the field is sufficiently strong to affect the magnetization of body 11. When the field H_{app} is directed to give a component antiparallel to the direction of propagation of beam 15, the rotation produced in the beam will be opposite in sense from that produced by a field having a component parallel to the direction of propagation, but equal in magnitude to the first-mentioned antiparallel component. For example, in Fig. 3, reversing the direction of H_{app} by 180 degrees would cause a rotation of beam 15 equal in magnitude to that actually pictured, but counterclockwise in sense when viewed from the analyzing prism 13.

It can be seen further that the relative magnitudes of the magnetic fields H_{or} and H_{app} may be independently varied. If the value of the field H_{or} is decreased to zero, and the value of the field H_{app} raised to a value sufficient to saturate body 11 magnetically, then the magnetization of body 11 may be aligned parallel to the direction of propagation of beam 15, accomplishing maximum rotation of beam 15 for a given thickness of garnet body 11.

Because H_{or} and H_{app} may be considered as the resolved components of a single magnetic field, there need be no more than a single magnetic field applied to body 11 to accomplish any of the results described above. Such a field may be varied in direction and magnitude, continuously or intermittently, with any frequency to bring about changes in the magnetization of the ferrimagnetic body 11.

Finally, the orientation of body 11 with respect to the x, y, and z axes need not be that depicted in Figs. 2 and 3. The body may be spatially oriented to lie in any plane. The length of the light path through a disc such as that shown for convenience in Figs. 2 and 3 will vary with the orientation of the disc relative to beam 15, of course, but the crystal itself may be magnetized to have a component of magnetization parallel or antiparallel to the direction of propagation of beam 15, or to have no such component, regardless of its orientation with respect to the beam.

In practice, the cubic crystal structure of the ferrimagnetic yttrium-iron garnets and ferrimagnetic rare earth-iron garnets is magnetically anisotropic. The intrinsic induction of the materials is more easily directed along certain axes through the crystals, which axes define "directions of easy magnetization." It is often desirable to grind the crystals so that the path of a propagated beam, or the direction of an applied magnetic field, has a fixed orientation to a direction of easy magnetization, or to one specific direction of easy magnetization if there are several. In such cases, if the crystal is ground to present a particular face to the incident beam, or to an applied field, choice of orientation of the crystal in space will be limited if the intended benefits are to be obtained. In the class of devices described below, for example, it is preferred to grind an yttrium-iron garnet single crystal used in the device in such a manner that an orienting magnetic field can be applied along one of several equivalent directions of easy magnetization in the crystal. With an orienting field along such a direction, the narrowest ferromagnetic resonance lines are shown by yttrium-iron garnet.

Ferromagnetic resonance is a phenomenon which has been explored widely in the microwave transmission arts. Certain magnetic materials, such as the ferrimagnetic yttrium-iron garnet and ferrimagnetic rare earth-iron garnets here discussed, and more commonly that class of materials known as ferrites, show strong absorption of certain radio frequency microwaves when the materials are oriented in a direct-current magnetic field applied perpendicular to the direction of transmission of the microwaves. Maximum absorption, or resonance, occurs at that microwave frequency which corresponds with a natural frequency of precession of the magnetization of the materials around the axis defined by the orienting applied

field. The phenomenon of resonance and the conditions under which it is produced are discussed, for example, in *Spectroscopy at Radio and Microwave Frequencies*, by D. J. E. Ingram, Butterworths Scientific Publications, London, 1955, pages 194-200. The phenomenon is analogous in the ferrites and in the ferrimagnetic garnet materials described herein.

Yttrium-iron garnet and the rare earth-iron garnets are thus unique not only because they are ferrimagnetic materials which transmit and modulate waves of higher frequency than those in the infra-red with higher specific rotations than do other substances transparent in the same region, but also the garnets are adaptable to having such modulation controlled at radio frequencies because they are capable of ferromagnetic resonance. Figs. 4, 5, and 6 are explanatory of how such high-frequency modulation of a light beam can be effected.

Fig. 4 shows a plan view of a microwave resonant cavity containing a full standing wave resonating in the TM_{21} mode. The broken lines of the figure represent the direction of the magnetic vector associated with each half-wave at a time corresponding with the beginning of a wave cycle. It is apparent that in the plane bisecting the cavity crosswise, along line 4-4, the magnetic fields of each half-wave are reinforced by coinciding in direction.

Fig. 5 shows the same cavity as that in Fig. 4 one-half period later. The magnetic fields have now reversed in direction. In the bisecting plane along line 5-5 the direction of the reinforced field has reversed by 180 degrees. Such a reversal in the direction of the field will occur twice each cycle, returning the direction of the magnetic field in the crosswise bisecting plane at the end of the wave cycle to its original position at the beginning of the cycle. Such a rapidly oscillating field may be used as the H_{app} of Fig. 3 to cause precession of the magnetization in a garnet single crystal at resonance, and thus to supply a rapidly oscillating component of the magnetization along the direction of propagation of a light beam penetrating the crystal.

In Fig. 6 is shown a device in which a microwave radiofrequency field is used in such a manner. Along the axis designated as the z axis, body 11, conveniently shown as a disc, of monocrystalline yttrium-iron garnet or rare earth-iron garnet is mounted. This mounting is similar to the mounting of bodies 11 in Figs. 2 and 3. Along the x axis are waveguides 17 leading into and out of resonant cavity 18 through apertures 19. Along the z axis, chimneys 20 are mounted on both sides of cavity 18, connecting with cavity 18 through apertures 21. Apertures 21 and chimneys 20 are of such dimensions that no leakage of microwave power from cavity 18 occurs. An orienting direct-current magnetic field, supplied for example by electromagnetic coils (not shown), is impressed on body 11 so that the magnetization of body 11 is aligned in a direction in the xy plane. As depicted above in Figs. 4 and 5, microwaves resonating in cavity 18 produce an oscillating radiofrequency magnetic field lying in the crosswise bisecting plane of cavity 18, here taken as the yz plane. Since body 11 is mounted in Fig. 6 to have its broad face perpendicular to this bisecting yz plane, the oscillating magnetic field can produce a component of the magnetization of body 11 perpendicular to its broad face. Ordinarily, the magnetic radiofrequency fields will have little effect on orienting the magnetization of the garnet body 11. However, if the microwave frequency and the strength of the orienting field mentioned above are chosen to produce a resonance condition in the garnet body, significant orientation of the magnetization of the body can be effected because of the effect of the radiofrequency waves in inducing precession of the magnetization around an axis in the direction of the orienting field.

A beam of light (not shown) projected through polarizing prism 12 into cavity 18, through body 11, and

to analyzing prism 13 will be rotated by body 11 by an amount dependent on the magnitude of the impressed radiofrequency magnetic field at resonance, and dependent in sense on the rapidly changing direction of that radiofrequency field. Modulation of the light is observable through the polarizing prisms. For example, by appropriate relative settings of polarizer 12 and analyzer 13 of Fig. 6, transmission of light through the system may be effected once or twice each cycle.

For an yttrium-iron garnet discs 50 mils in diameter, and 2.9 mils in thickness, microwave resonance at 24,019 megacycles has been observed in an orienting direct-current field of 7804 oersteds. A disc of yttrium-iron garnet of such thickness shows a maximum rotation of about 3 degrees per mil in the green, corresponding with a specific rotation in the green of greater than 1000° per centimeter, as noted in Table I above.

Single crystals of yttrium-iron garnet have been prepared by the following process. One hundred grams of lead oxide, PbO, were placed in a platinum crucible with seventy grams of iron oxide, Fe₂O₃, and 3.5 grams of yttrium oxide, Y₂O₃. The crucible was raised to a temperature of 1325° C. in an atmosphere principally of oxygen and held at that temperature for five hours. The crucible was then cooled to 900° C. at a rate of 5° C. per hour in the oven, then removed from the oven and allowed to cool to room temperature. The resultant solid mass was composed of a lead oxide phase, a phase consisting of crystalline magnetoplumbite, and a third phase of yttrium-iron garnet crystals of significant dimensions. The two crystalline phases were separated from the lead oxide matrix by dissolving the latter in 6 N nitric acid, to which the crystals are impervious. Yttrium-iron garnet may then be separated from the magnetoplumbite phase by examination. The rare earth-iron garnets may be prepared as single crystals by similar procedures.

Though specific embodiments of the invention have been herein shown and described, it is to be understood that they are illustrative only, and are not to be construed as limiting on the scope and spirit of the invention.

What is claimed is:

1. A light transmitting and rotating medium of material selected from the group consisting of yttrium-iron garnet and rare earth-iron garnets, a source of polarized light for directing polarized light through the said medium, means for analyzing such polarized light transmitted through the said medium, and magnetic means arranged so as to produce a magnetic field acting upon said medium, said medium being essentially magnetically saturated by the influence of said magnetic means, said magnetic means adapted to further provide a magnetic field component in the direction of propagation of the polarized light through the medium.

2. The apparatus of claim 1 in which the medium is yttrium-iron garnet.

3. A light transmitting and rotating medium of material selected from the group consisting of yttrium-iron garnet and rare earth-iron garnets, a source of polarized light for directing polarized light through the said medium, means for analyzing such polarized light transmitted through the said medium, magnetic means arranged so as to produce two separate magnetic fields acting upon said medium, said medium being essentially magnetically saturated by the influence of said magnetic means, a first magnetic field having a direction approximately coinciding with said direction of propagation, and a second

magnetic field having a direction approximately normal to said direction of propagation.

4. The apparatus of claim 3 including means for varying the magnitude of at least one of the fields so as to vary the resultant direction of the net field and correspondingly vary the degree of rotation of the polarized light transmitted through the said medium.

5. A light transmitting and rotating medium of material selected from the group consisting of yttrium-iron garnet and rare earth-iron garnets, a source of polarized light for directing polarized light through the said medium, means for analyzing such polarized light transmitted through the said medium, magnetic means arranged so as to produce a magnetic field acting upon said medium, said medium being essentially magnetically saturated by the influence of said magnetic means, said magnetic means adapted to further provide a magnetic field component in the direction of propagation of the polarized light through the medium, and additional means arranged to act on the medium to produce a radio frequency magnetic field in the said medium, the said radio frequency magnetic field having a component normal to the said axis and of a frequency approximately corresponding with the resonance frequency of the said medium.

6. The apparatus of claim 5 including means for varying the magnitude of the said unidirectional field so as to correspondingly vary the resonance frequency of the said medium.

7. In combination, a microwave cavity, a light transmitting medium of a material selected from the group consisting of yttrium-iron garnet and rare earth-iron garnets positioned within said cavity, means providing polarized light for transmission through the medium, means for analyzing the light transmitted through the medium, and means supplying microwave energy to the cavity for providing a varying magnetic field in the medium along the path of light transmission for varying correspondingly the amount of Faraday rotation experienced by the light in its passage through the medium, further characterized in that the transmitting medium is magnetically biased near ferromagnetic resonance at a resonant frequency of the cavity.

8. The combination of claim 7 characterized in that the transmitting medium is monocrystalline yttrium-iron garnet.

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