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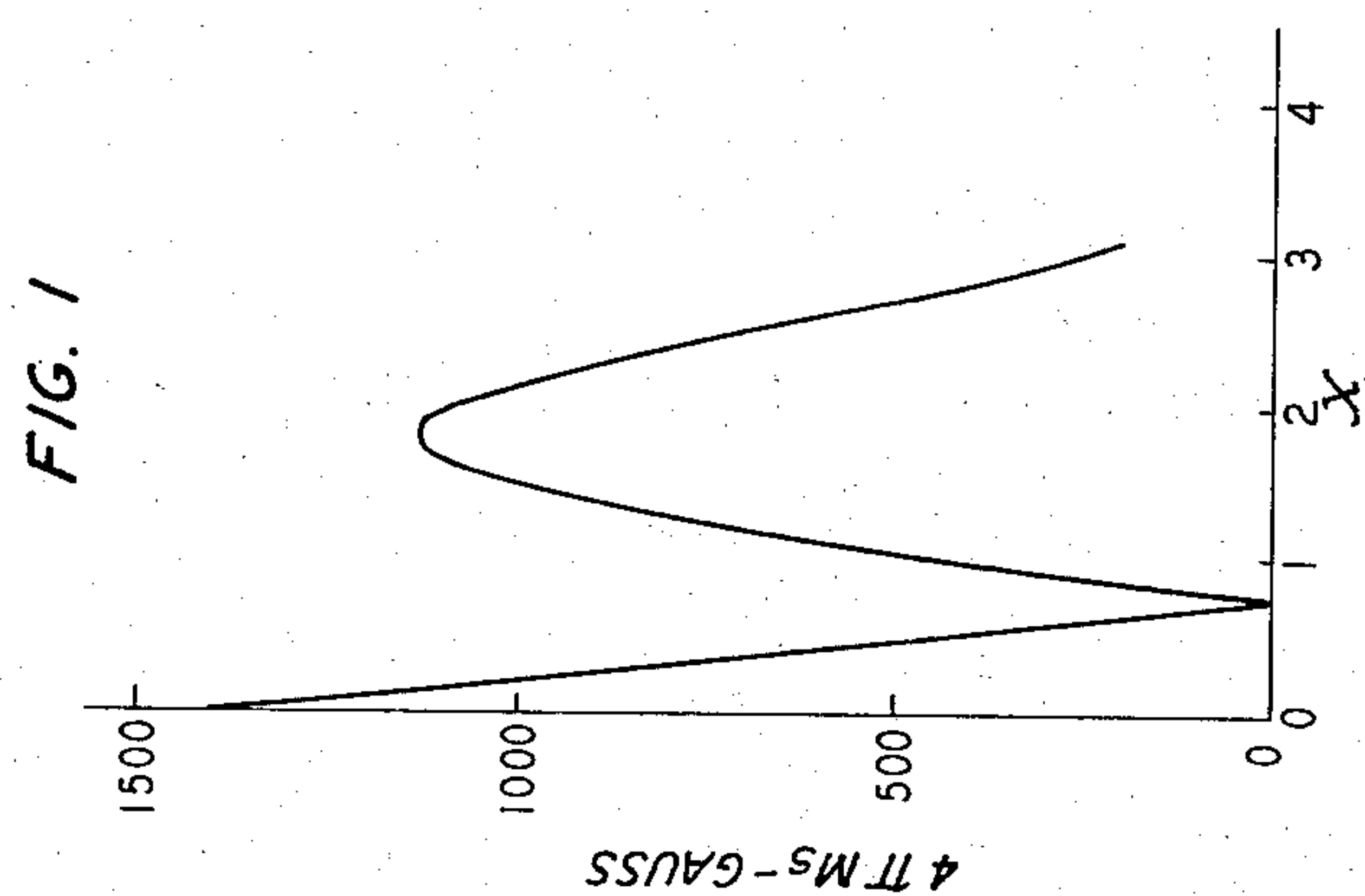
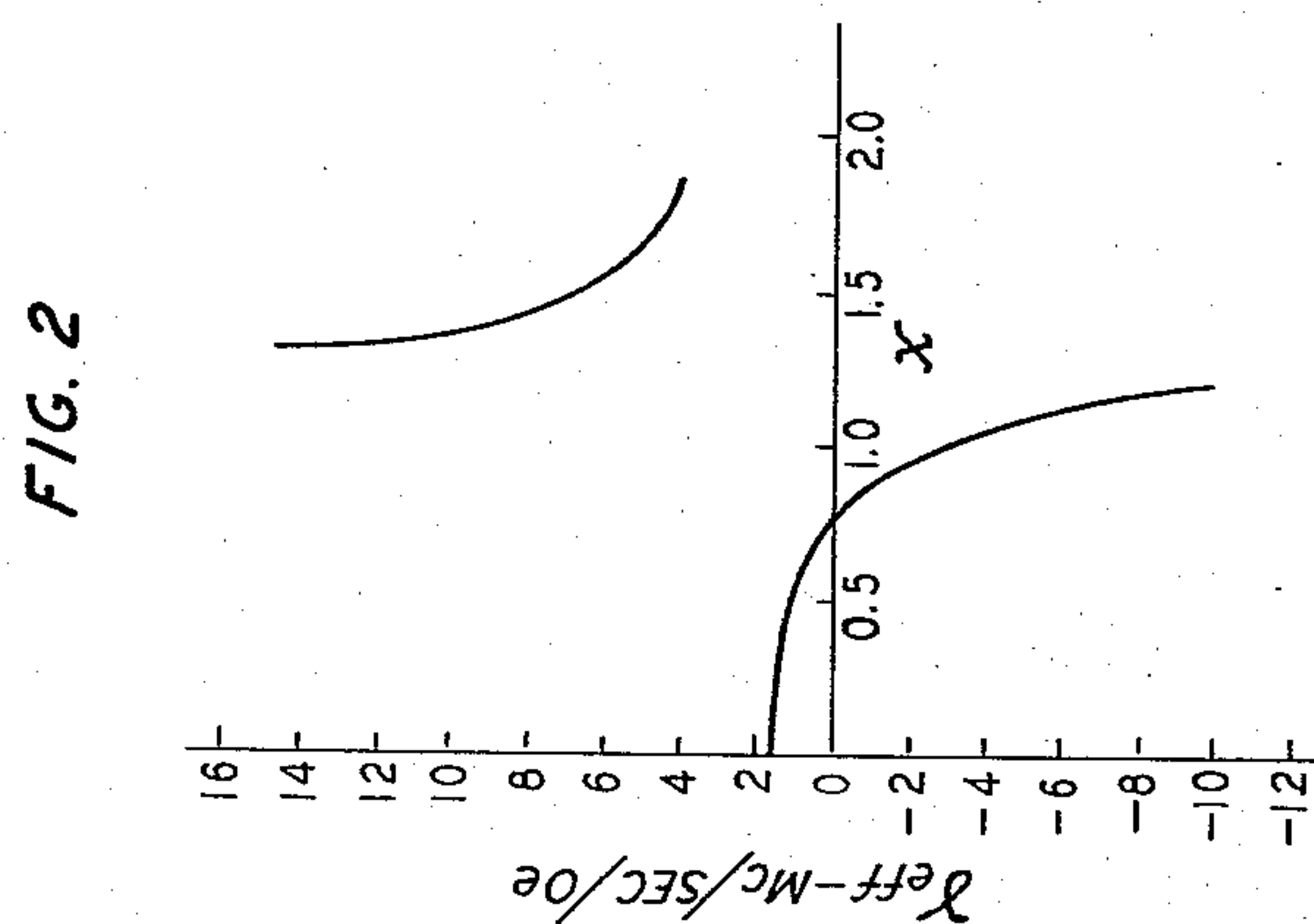
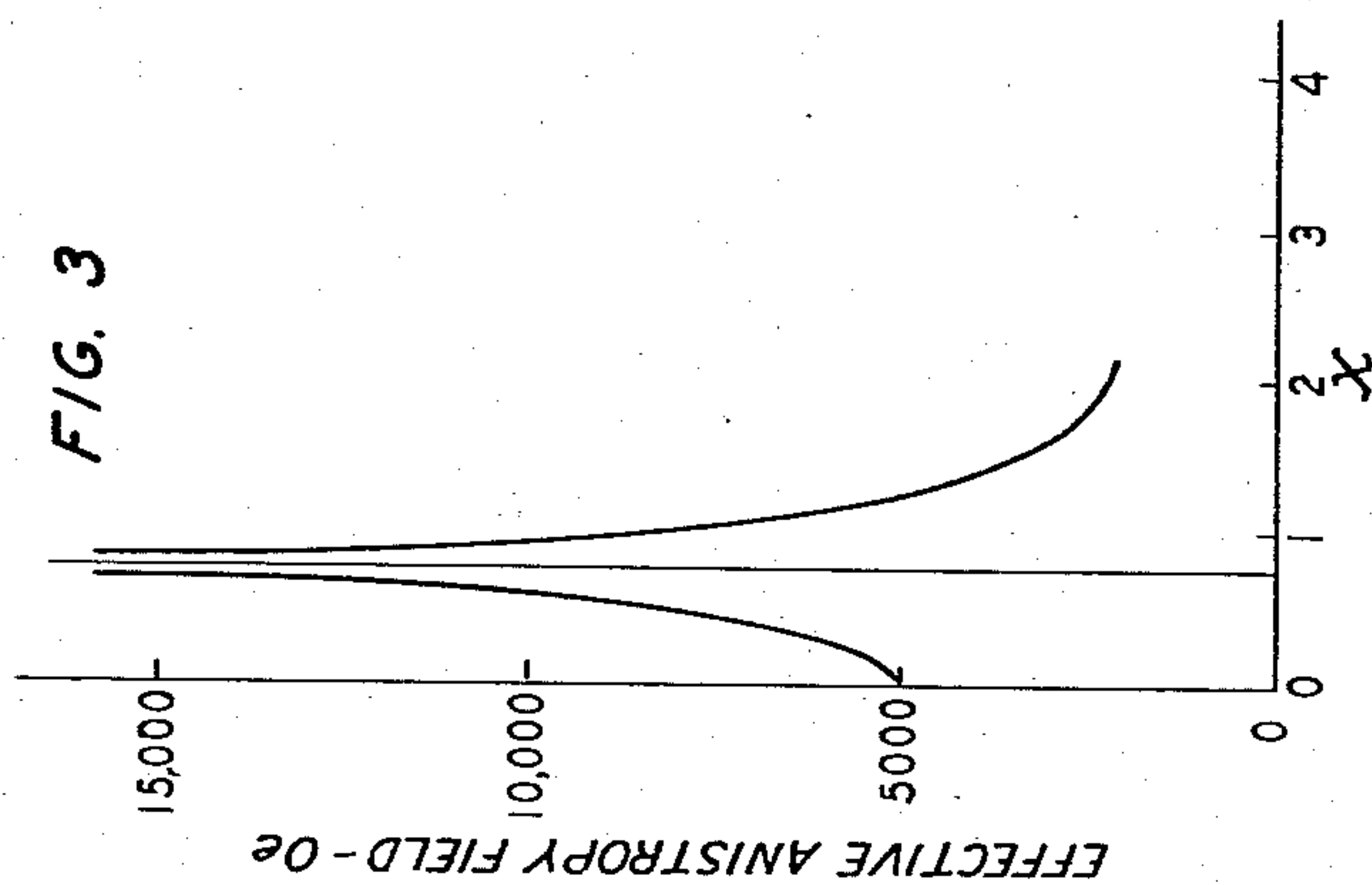
R. C. LE CRAW ETAL

3,356,929

MICROWAVE DEVICES UTILIZING Eu-Fe GARNET CONTAINING Ga

Filed July 1, 1964

3 Sheets-Sheet 1



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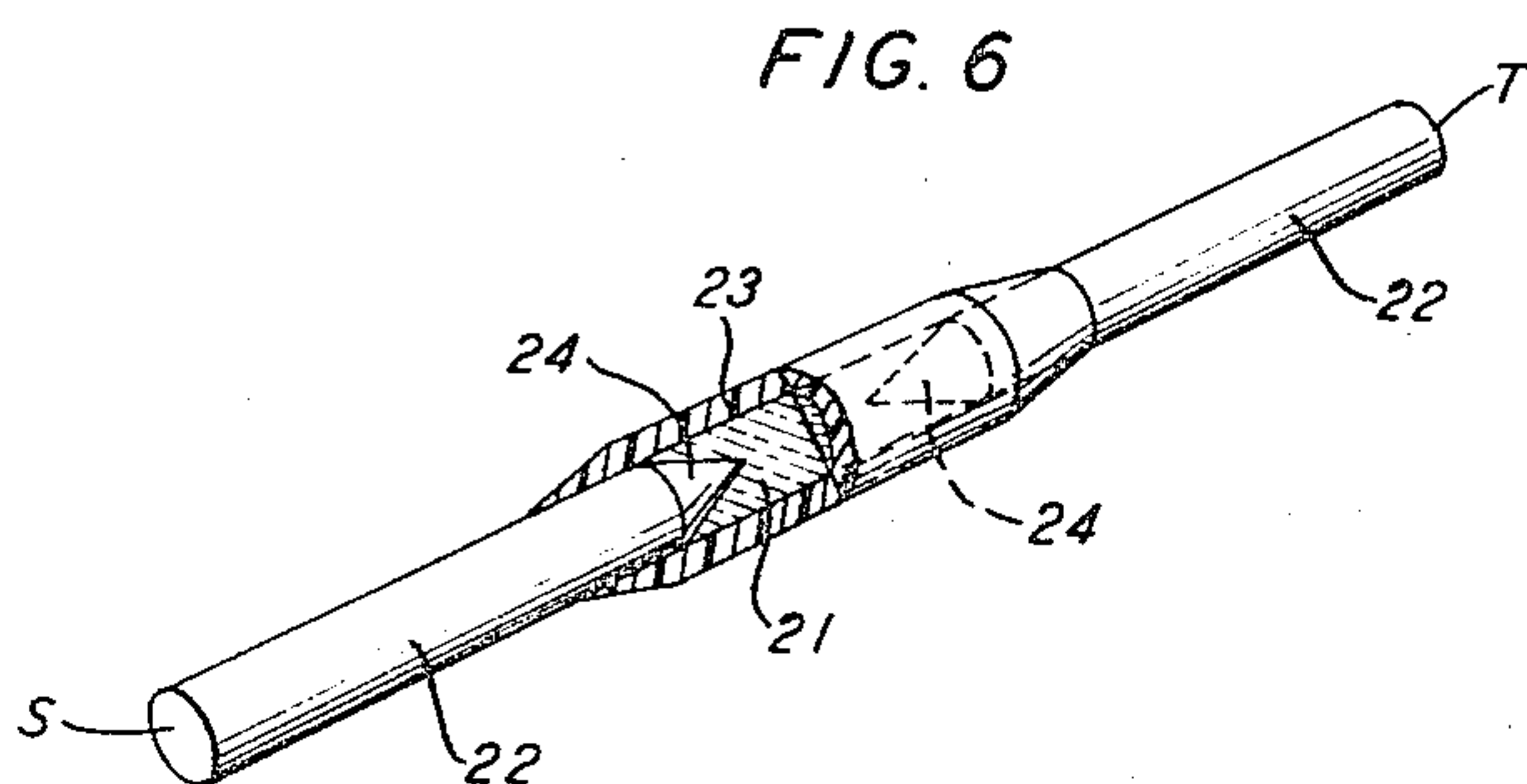
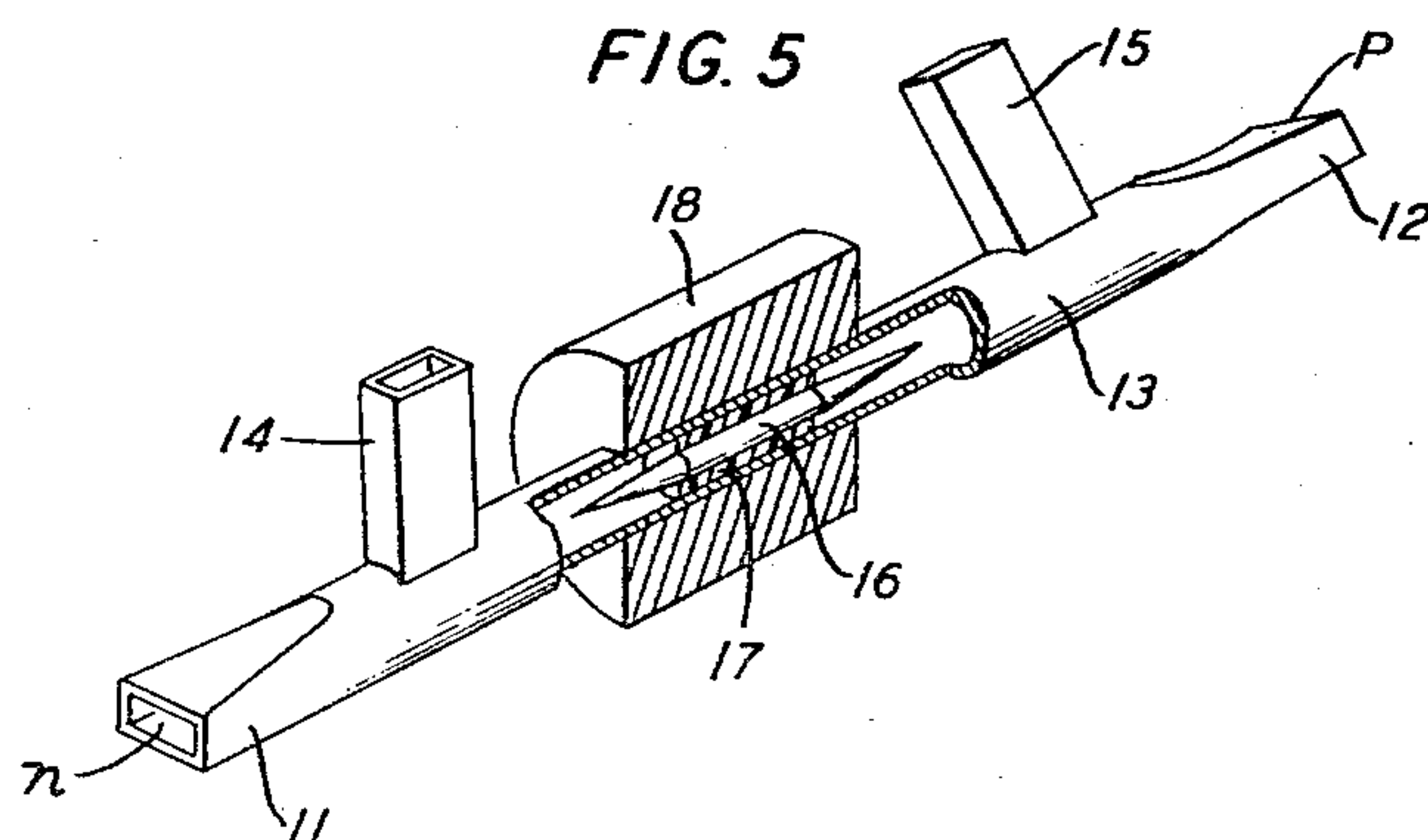
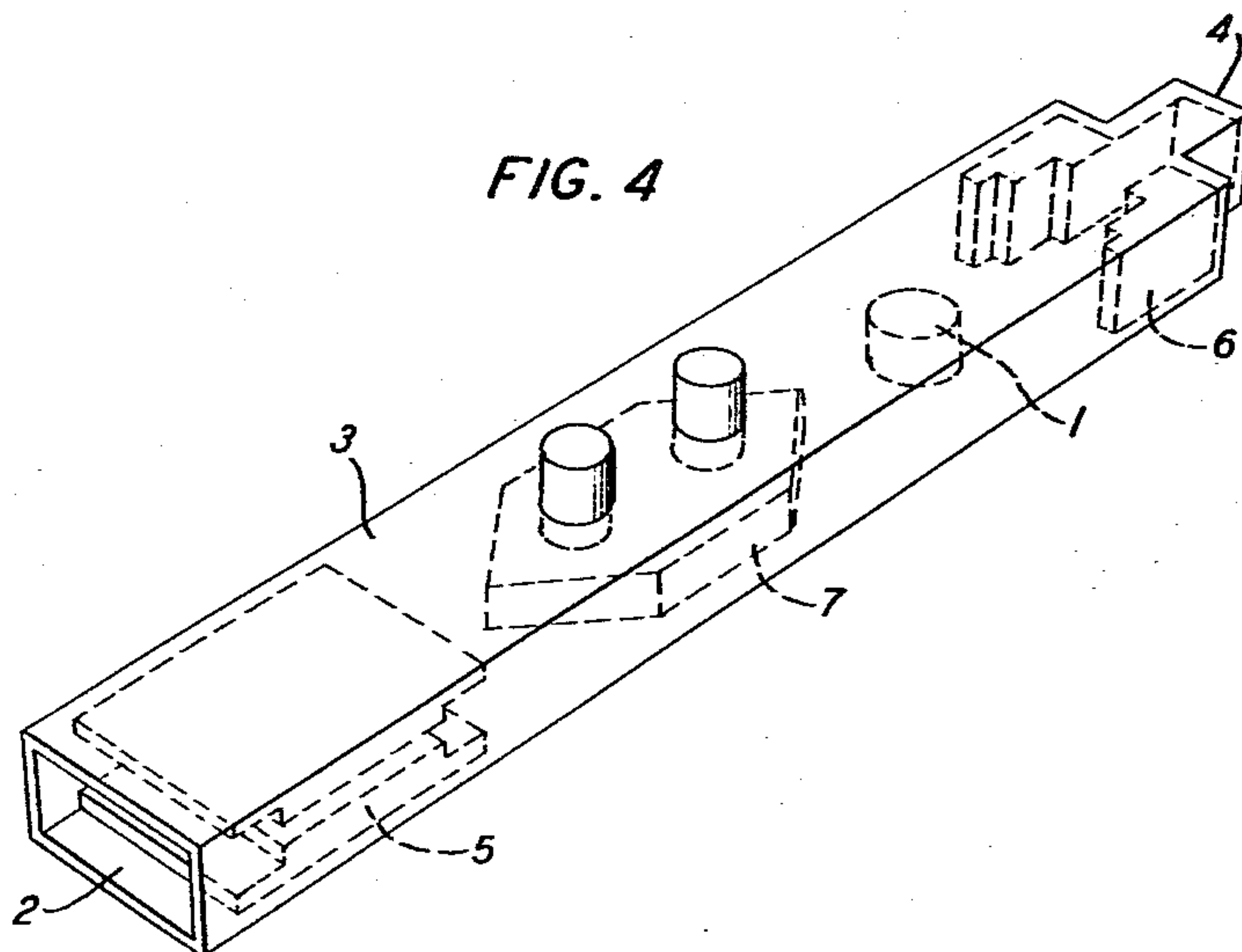
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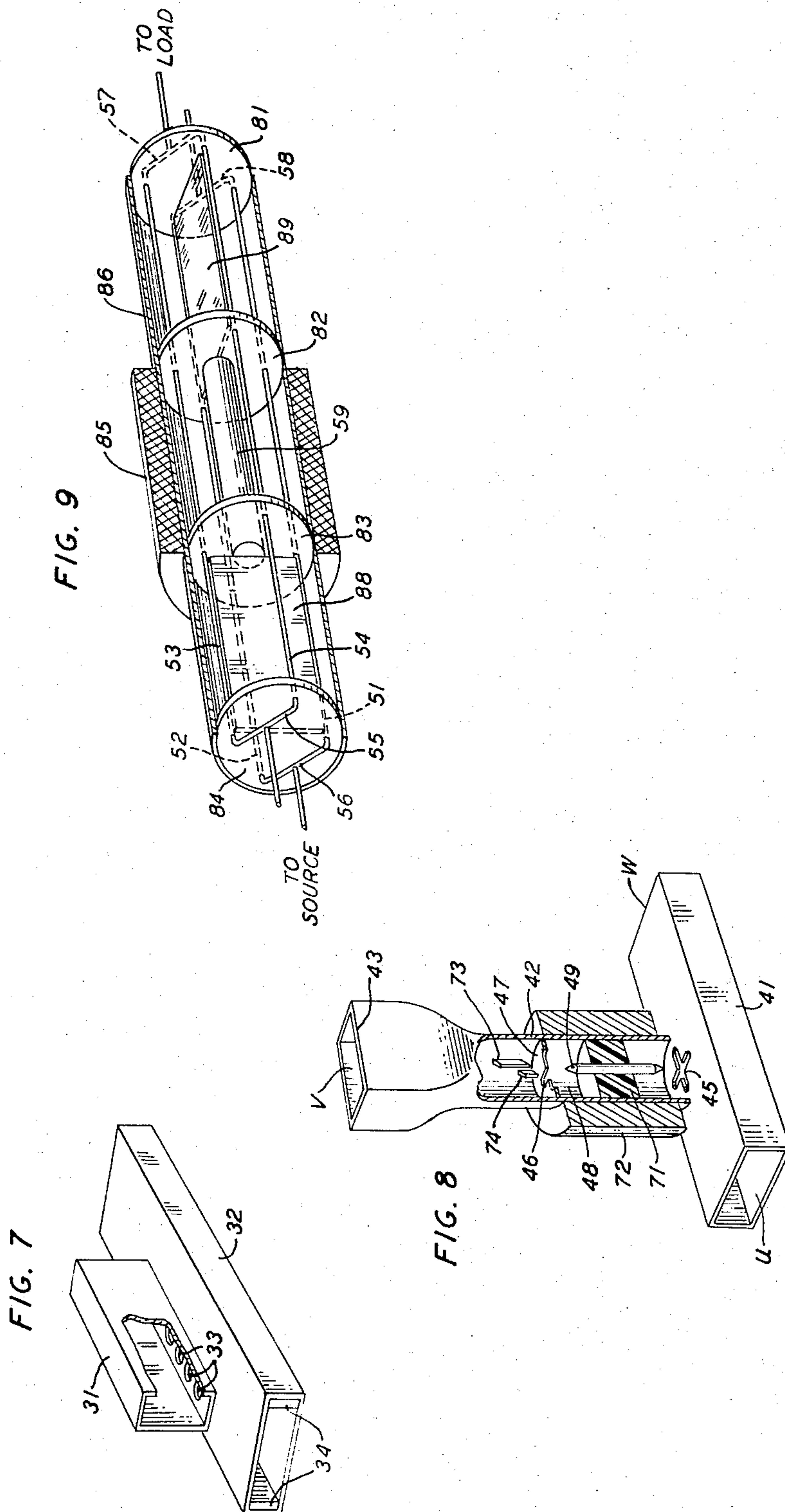
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3,356,929

MICROWAVE DEVICES UTILIZING Eu-Fe GARNET CONTAINING Ga

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7 Claims. (Cl. 321-69)

This invention relates to magnetic compositions of matter useful as the active elements in microwave devices and to devices constructed of such material. It is the nature of these materials and related devices that they are useful over a frequency range extending well above 50 gigacycles per second.

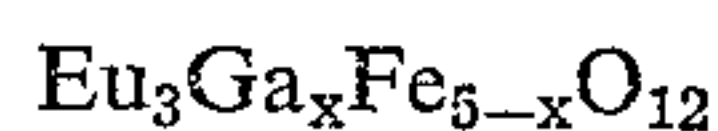
Microwave technology has reached a high state of development over the past decade. Commercial circuitry, particularly in communications, utilizes a vast array of circuit elements for controlling energy over such frequency range. A large family of these devices, including isolators based on rotation, absorption, and field displacement circulators, phase shifters, switches, frequency multipliers, etc., make use of magnetic materials biased to saturation and beyond.

It is well known that the frequency capability of this class of devices is directly dependent on the gyromagnetic activity of the material, coupled with the line width. For most of these devices, line width is desirably narrow to permit operation close to resonance without incurring the large associated absorption loss.

The relationship between frequency capability and gyromagnetic activity is discussed in the description of the frequency multiplier, in which operation depends on biasing to a resonance point set by the fundamental frequency to be introduced into the device.

Operation of any of the above devices to frequencies of the order of a small number of gigacycles per second is feasible for many of the commonly used ferrite or garnet materials. Most of these manifest gyromagnetic ratios of approximately 2.8 megacycles per second per oersted, so permitting operation at 5 gigacycles per second, with applied fields of the order of 1.5 kilo-oersteds. Fields of this order are generally available from simple solenoids and even by use of carefully designed, shaped pole permanent magnets. Operation at significantly higher frequencies, however, requires the use of biasing fields of 10 kilo-oersteds or higher. Such field values are inconveniently large for most purposes.

The essence of the instant invention is the discovery of the unusually high gyromagnetic ratios in a specific range of magnetic garnet compositions. The compositional range is conveniently defined in atomic units as



in which x is from 0.8 to 1.8. Magnetic, chemical, and physical properties of this material are suitable for device use. Claimed embodiments of the invention include the devices set forth above, operation of which is dependent upon crystalline bodies of the specified composition.

Description of the invention is facilitated by reference to the drawings, in which:

FIG. 1, on coordinates of saturation moment on the ordinate and x in the general formula $\text{Eu}_3\text{Ga}_x\text{Fe}_{5-x}\text{O}_{12}$ on the abscissa, is a plot of the dependence of this magnetic property on composition;

FIG. 2, in units of gyromagnetic ratio on the ordinate and x on the abscissa, is a plot showing the interdependence of these properties, clearly delineating the composition region for angular momentum compensation;

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FIG. 3 is a plot of cubic anisotropy constant on the ordinate against x on the abscissa;

FIG. 4 is a perspective view of a frequency doubling configuration, operation of which is based on the inclusion of an element of a composition of this invention;

FIG. 5 is a perspective view, partly in section, of a Faraday rotation type of circulator mounted in a hollow metallic waveguide utilizing an element of a composition herein;

FIG. 6 is a perspective view, partly in section, of a round dielectric waveguide containing a garnet composition of this invention for producing Faraday rotation;

FIG. 7 is a perspective view, partly in section, of a direction coupling device utilizing nonreciprocal field displacement, operation of which is based upon use of an element of a composition herein;

FIG. 8 is a perspective view, partly in section, of a device having a garnet-loaded resonance cavity; and

FIG. 9 is a perspective view, partly in section, of a garnet-loaded, nonreciprocal attenuating device employing a balanced wire line transmission system.

It is well known that the effective gyromagnetic ratio of a ferromagnet is given by the ratio of the net magnetization to the net angular momentum,

$$\gamma_{\text{eff}} = \frac{\sum M_i}{\sum \frac{M_i}{\gamma_i}}$$

in which the index i denotes a particular magnetic sublattice, M_i represents the magnetization, and γ_i is the gyromagnetic ratio of the i th sublattice. Since the individual sublattice magnetizations are either parallel or antiparallel to the net magnetization, it is possible to obtain materials for which the net angular momentum $\sum M_i/\gamma_i$ is nearly zero, and γ_{eff} , the effective gyromagnetic ratio, is very large. These materials are obtained by selective substitution of nonmagnetic ions for magnetic ions. This technique is known as angular momentum compensation and is described, for example, in "Microwave Ferrites and Ferrimagnetics," Lax and Button, McGraw-Hill Book Co., Inc., 1962, pages 248, et seq.

While this technique has resulted in large gyromagnetic ratios in a number of ferrimagnetic materials, they have always been accompanied by very small saturation moments and by very broad ferromagnetic resonance line widths. The practical advantage of such increased gyromagnetic ratios has, in this manner, been lost for most device applications. The present invention derives from the discovery that angular momentum compensation of europium-iron garnet by use of gallium provides ferrimagnetic materials with large effective gyromagnetic ratios which manifest saturation moments and ferromagnetic resonance line widths entirely suitable for device use.

Referring again to FIG. 1, it is seen that the saturation magnetization, $4\pi M_s$, plotted in units of gauss, drops from a value of about 1300 for pure $\text{Eu}_3\text{Fe}_5\text{O}_{12}$ to a compensation point at an x value of about 0.75. For larger amounts of gallium, the moment increases, reaching a turnover point for gallium inclusion of the order of 1.75 in the formula. While the experimental apparatus utilized was not sensitive to moment direction, theory, as substantiated by the slope of the magnetization curve before and after a value of x equals 0.75, suggests that this value represents a true magnetic compensation point, and that the portion of the curve representing larger substitutions would properly be drawn as extending into the fourth quadrant.

FIG. 2 is a plot showing the dependence of the gyromagnetic ratio on x in the formula. It is seen that this quantity, crucial to the device uses herein, peaks in ab-

solute value at an x value of about 1.2 This is the approximate angular momentum compensation point for the materials of this invention and represents the preferred composition. The specified range of x values from 0.8 to 1.8 set forth above directly results from study of data of the type here depicted. It is seen that these limits define a compositional range manifesting $|\gamma_{\text{eff}}|$ values of a minimum of about three. This characteristic, taken together with the narrow line width and other properties, defines a range of materials usefully incorporated in the devices herein and in gyromagnetic devices in general.

Study of FIG. 3, in conjunction with FIG. 1, reveals the nature of the dependence of the effective anisotropy field on composition. It is seen that the values of the effective field over the compositional range of concern are within suitable limits for device applications.

The waveguide configuration for frequency doubling shown in FIG. 4 depends for its operation on cylindrical post 1, which is constructed of a composition herein. This device, which is otherwise conventional, provides for the introduction of vertically polarized electromagnetic waves 2 into guide 3 and for exiting of horizontally polarized electromagnetic energy at end 4. Structure 5, which restricts the dimension corresponding with the direction of the H vector of the output energy, acts as a cutoff for the frequency-doubled output. Structure 6 serves a similar function for the input energy in restricting the horizontal dimension corresponding with the H vector for the input, so as to prevent its exiting together with the desired output. Structure 7 is an adjustable phase shifter which, by effectively increasing or decreasing the dielectric constant for frequency-doubled energy, permits the attainment of an optimum constant and, consequently, the reinforcement of output by any frequency-doubled waves which have been rejected by structure 5.

In FIG. 5, rectangular waveguides 11 and 12 are tapered smoothly into a circular waveguide 13. The rectangular waveguides 14 and 15 are joined to the circular waveguide 13 near a rectangular guide 11 at the left-hand end, and near a rectangular guide 12 at the right-hand end, respectively. If imaginary planes be passed through each of the four rectangular waveguides 11, 12, 14, and 15, parallel to the longest dimension of the rectangular section, the positioning of the guides 11 and 14 will be such that the planes mentioned above for this pair of guides will intersect perpendicularly. Similarly, the guides 12 and 15 are set at right angles to one another at the right-hand end p of the drawing shown. The planes passing through the guides 11 and 12 are, further, inclined to one another at an angle of 45 degrees, and the waveguides 14 and 15 are similarly relatively inclined at an angle of 45 degrees.

In sum, there are two pairs of guides, 11 and 14, and 12 and 15, the members within a pair being disposed at right angles. Both members of one pair, say waveguide 12 and waveguide 15, are rotated 45 degrees with respect to the members of the first pair, however, so that for any member of either of the two pairs of perpendicular waveguides there is a corresponding member of the other perpendicular pair inclined to the first member at an angle of 45 degrees.

Within the circular waveguide 13 is a pencil 16 of the garnet materials considered herein, mounted in a non-magnetic dielectric material 17, such as, for example, polystyrene foam. Surrounding the garnet pencil 16, enclosed in the circular waveguide 13, is a magnetic source 18, such as an electromagnet or permanent magnet, capable of producing a longitudinal magnetic field.

In a magnetic field, a garnet element has the property of rotating the plane of polarization of an incident plane polarized wave. The rotation produced in the element 16 shown, for example, is determined by the nature of the garnet used, by the dimensions of the garnet element 16, and, in addition, by the strength of the magnetizing field from the field source 18, and by the specific geometry

of the waveguide 13 and the mounting of the element 16 therein. The sense of the Faraday rotation is determined by the direction of the magnetizing field.

In the circulator shown in FIG. 5, for example, the length of the element 16 and the strength and direction of the magnetizing field from the source 18 may be chosen to give a 45-degree counterclockwise rotation viewed from n to p , in FIG. 5, for waves passing through the element 16 from n to p . In passing from p to n , waves are rotated in the same sense by the garnet.

Thus, waves electrically polarized perpendicular to the longest dimension of the rectangular section of the waveguide 11 pass the guide 14 and penetrate the garnet 16. As the geometry of the guide 14 is such as to transmit only waves polarized perpendicularly to those entering at 11, the waves entering 11 are unaffected by passing the guide 14. In the garnet, a 45-degree counterclockwise rotation results, and the wave plane is oriented for transmission out through guide 12. Again, the outgoing wave is unaffected by the guide 15 set at right angles to the plane of the polarized wave in guide 12. If a wave enters the guide 12, reversing the direction of transmission in the original illustration, it passes guide 15, is rotated by the garnet in the same sense as before, and is thus, this time, oriented for transmission through the guide 14. By similar considerations, waves entering guide 14 are made to exit through the guide 15; and waves entering the guide 15 leave, after rotation, by waveguide 11.

A more detailed explanation of the device described above is to be found in U.S. Patent 2,748,352, issued to S. E. Miller.

FIG. 6 shows a Faraday rotation device comprising a garnet loading 21 in a round dielectric waveguide 22. The garnet 21 comprises the materials considered later herein, and the waveguide 22 may consist of any dielectric material having a dielectric constant materially different from that of air, such as, specifically, polystyrene or polyethylene.

Electromagnetic waves are transmitted through dielectric media similar to that used in the construction of the waveguide 22 without a conductive shield surrounding the transmitting medium. The wave is guided by the dielectric, with a portion of the energy conducted in a field surrounding the rod. By joining the dielectric rod 22 with the garnet segment 21, a portion of the wave energy can be led through the ferromagnetic material and can be thereby affected. As in FIG. 5, permanent magnets or electromagnets, not shown, are used to produce a horizontal magnetic field in the region of the garnet and rotation of the wave traversing the garnet is effected. Tapered portions 24 of the dielectric rod 22 fit into conical hollows in the garnet rod 21 to assure matching and to minimize possible radiation loss. An additional cylindrical cover 23 of dielectric material is provided over the garnet segment to aid in maintaining a constant energy field which might otherwise be disrupted by disparity between the indices of refraction of the garnet material 21 and the dielectric 22.

In operation, a linearly polarized wave, for example, introduced at s into the waveguide 22 is propagated through the garnet 21 and emerges at t with a rotation in the angle of polarization. Means, not shown, may be provided for utilizing the rotation observed in the construction of a circulator, as in FIG. 5, or the segment of the circuit shown in FIG. 6 may be adapted to other purposes.

A complete and detailed explanation of devices employing garnet-loaded dielectric waveguides is to be found in U.S. Patent 2,787,765, issued to A. G. Fox.

FIG. 7 shows a multibranch network in which gyromagnetic materials are used to create field displacement effects. Shown are two rectangular metal waveguides 31 and 32. The guide 31 is placed with one narrow wall contiguous to a wide wall of the guide 32, and is so located as to lie off the center line of said guide 32. Apertures 33, extending through the contiguous walls of the guides 31

and 32, are used to couple the guides 31 and 32 electromagnetically. These apertures, lying on the center line of the narrow wall of the guide 31, are displaced, as is the guide 31 itself, from the center line of the guide 32.

Within the guide 32, and in the region of the coupling apertures 33, are means for producing a non-reciprocal displacement of the magnetic field pattern therein, comprising, in this case, two slabs 34 of a garnet material as later described herein. Means, not shown, such as a solenoid or permanent magnet, are provided for creating a uniform magnetic field in each of the garnet slabs 34, so that said slabs are magnetically polarized at right angles to the direction of propagation of wave energy in the waveguide 32. Both slabs 34 are polarized in the same direction.

In a rectangular waveguide such as that shown in FIG. 6 as 32, the magnetic field of a dominant mode wave being propagated through the waveguide will be such that a clockwise-rotating and a counterclockwise-rotating component of the magnetic intensity will be found respectively at one or the other extremity of the longest rectangular dimension of the waveguide wall. That is, depending on the direction of wave propagation, the direction of the polarization at one of the waveguide walls will be clockwise or counterclockwise, with rotation in the opposite sense being found in the magnetic intensity at the other wall for a given direction of wave propagation. Upon reversing the direction of propagation, the sense of the polarization at each wall also reverses.

By biasing the garnet loadings 34 in a magnetic field perpendicular to the length of the waveguide 32, as previously mentioned, each element being polarized in the same direction, the electron spins and associated moments within the garnet can be caused to precess about the line of the biasing magnetic field on the garnet, producing a magnetic moment rotating in a plane normal to the biasing field, or, that is, in the plane of the magnetic component of the waves propagated along the waveguide 32. The rotating moment produced by electron spin in the garnet will correspond, on one side of the waveguide or the other, to the rotating component of the magnetic intensity of the wave, resulting in a permeability less than unity for one of the garnet strips 34. On the other side of the waveguide 32, the biasing field produced precession with a moment in a sense opposite to the rotating component of the wave's magnetic field, resulting in a permeability greater than unity for this second garnet strip.

The discrepancy in permeability for the two strips 34 results in a displacement of the normal field pattern. Without the biasing magnetic field applied to the garnet slabs 34, the magnetic field intensity of the propagated wave in the waveguide 32 is null along the center line of the waveguide, rising to a maximum at the sides of the guide. When a biasing field is applied to the garnet, the field pattern of the wave may be distorted to give a null value in the region immediately beneath the off-center coupling apertures 33. No coupling results in this case. Reversing the direction of wave propagation in the waveguide 32, without changing the direction of the bias on the garnet elements 34, will result in a displacement of the null field area to a point on the other side of the center line of the waveguide 32, away from the coupling apertures 33. Coupling of the guides 31 and 32 will result for this direction of wave propagation.

Thus, for one direction of propagation through the waveguide 32, coupling with the guide 31 results, while reversing the propagation direction will produce no coupling with the guide 31.

A more detailed explanation of the device discussed above, and other field-displacement devices, is to be found in U.S. Patent 2,849,683, issued to S. E. Miller.

FIG. 8 is a perspective view, partly in section, of waveguide structures coupled by a chamber containing a gyromagnetic garnet element to produce a three-branch circulator.

In the drawing, a hollow rectangular waveguide 41 is abutted by a second waveguide 42 of a type capable of supporting circularly polarized waves. The guide 42 is tapered smoothly into a rectangular waveguide 43 which will transmit linearly polarized waves only. Means, such as positioned metal fins 73 and 74, are so disposed at the junction of waveguides 42 and 43 as to interconvert circularly polarized waves in guide 42 to and from linearly polarized waves in guide 43, by introducing a 90-degree phase shift in selected components of the impinging waves.

A resonant cavity 48 is formed in the lower portion of the waveguide 42, said cavity being bounded at the top by a perforated reactive diaphragm 47 and at the bottom by the waveguide 41. The diaphragm 47 is so positioned as to render the length of the cavity 48 a multiple of one-half of the guide wavelength of the waves to be transmitted therethrough. Apertures 45 and 46 couple wave energy to and from guides 41 and 42 and guides 42 and 43, respectively.

The aperture 45 is of such geometry and is so positioned, by techniques known to those skilled in the art, relative to the waveguides 42 and 41, that for waves transmitted through waveguide 41 from *u* to *w* in the diagram, a circularly polarized wave will be introduced into the cavity 48, while for those waves transmitted through the guide 41 from *w* to *u*, a wave circularly polarized in the opposite sense will be found in the cavity 48.

Within said cavity 48 is mounted an element 49 of a gyromagnetic garnet of the kind later considered herein. The garnet 49 is mounted in a material 71 of low dielectric constant, such as "polyfoam." Surrounding the cavity 48 in which the garnet 49 is located are means 72, such as solenoidal winding, for producing a steady polarizing magnetic field parallel to the direction of wave propagation in the waveguide 42.

In a gyromagnetic garnet similar to that of the element 49 in the drawing, polarized by a biasing magnetic field, the permeability presented to circularly polarized waves transmitted therethrough is different for waves polarized in opposite senses, as earlier mentioned. When the sense of the wave polarization is coincident with the sense of the rotating magnetic moment associated with the precession of electron spins in the garnet, the permeability of the garnet has a value above unity. When the senses of the wave and the moment in the ferrite are opposite, the permeability of the garnet is less than unity for biasing fields insufficient to produce resonance in the garnet. Depending on the strength of the field, further, the garnet permeability may take values less than zero.

The circulator shown in FIG. 8 employs this gyromagnetic property of the garnet element 49 in its operation. For illustration, let the position of the aperture 45 be such as to produce a counterclockwise polarized wave in waveguide 42 when a wave is transmitted along guide 41 from *u* to *w*. Further, let the biasing field from the source 72 be in a direction as to permit transmission of such a polarized wave through the garnet element 49 in the cavity 48. When the cavity 48 is made of a length which is a multiple of the half wavelength of the transmitted wave, by positioning of the diaphragm 47, the cavity 48 is resonant for the wave, and the wave, after conversion by the fins 73 and 74 appears as a linearly polarized wave at *v*.

A wave transmitted in waveguide 41 from *w* to *u*, however, will be clockwise polarized in waveguide 42, in this example. The biasing field on the ferrite 49 produces a low permeability for such a wave, and no resonance or transmission of terminal *v* ensues. Waves introduced at *w*, thus, emanate only at *u*.

The introduction of wave energy at *v* results, for the position of the fins 73 and 74 chosen, in the introduction of a counterclockwise rotation. Such a wave, as seen earlier, will be resonant in the cavity 48, and will be coupled into the waveguide 41. Passage through the aperture 45 by such a counterclockwise polarized wave will

result in a wave, the magnetic components of which are characteristic of waves being transmitted from u to w in the example under discussion, and emergence of the wave at w will result. By adjustment of the size of the apertures 45 and 46, the impedances of the terminals u , v , and w , which terminals are coupled by the apertures through the cavity 48, can be matched as to give transmission without reflection along the paths u to v , v to w , and w to u , so that the element pictured is a nonreciprocal circulator.

In FIG. 9 is shown a millimeter wave circuit element, which may be used as an isolator, suitable for connection directly into a two-wire balanced line transmission system. The embodiment pictured comprises two pairs of parallel conductors 51, 52, 53, and 54, equally spaced and symmetrically aligned relative to each other. The conductors are bridged in pairs by connecting elements 55, 56, 57, and 58.

Thin discoid dielectric spacers 81 through 84 are longitudinally placed along the line to support the conductors in their above-described relationship. Spacers 82 and 83, in addition, may serve to support a gyromagnetic garnet body 59 comprising materials of the type herein later described. A shield 86 serves to support the structure and protects the conductors 51 through 54 from external mechanical and electrical influences. A longitudinal magnetic field is supplied by a winding 85 to polarize the ferrite 59. Control of the energizing field is provided so that strengths sufficient to produce a ferromagnetic resonance condition in the garnet 59 may be produced if desired.

Loading vanes 88 and 89 are disposed, respectively, between the wire pairs 51 and 53 at the right-hand end of the circuit element shown, and between the pairs 52 and 54 at the left-hand end. The vanes, of a material having a high dielectric constant, extend longitudinally between the wire pairs mentioned for a length sufficient to introduce a 90-degree delay in a voltage between the conductors comprising a pair.

When a voltage, balanced with respect to ground, is applied between the bridges 55 and 56, the voltage between conductors 54 and 53 is delayed 90 degrees by the vane 88. Similarly, a 90-degree shift in voltage between the lines 52 and 51 is produced by the dielectric material 88. In consequence, a circularly polarized wave is produced by the four-wire system in the region of the garnet loading 59. Upon passing the loading 59, the vane 89 re-introduces 90-degree voltage delays in the conductors, in a fashion similar to the operation of the vane 88, so that a balanced voltage is again applied to the load on the far side of the garnet body 59.

If the rotation produced in the polarized wave in the region of the garnet 59 is similar in sense to the precession of electron spins and the moment associated therewith in the garnet, the wave is transmitted almost unaffected by the conductors 51 through 54 from the source to the circuit load. If the polarized wave rotates in a sense opposite to the rotating magnetic component generated in the garnet 59, however, almost no transmission past the garnet is observed when the garnet is excited to its resonant frequency by the magnetic source 85. Since attempted transmission in opposite directions through a circuit element such as that shown in FIG. 9 will produce waves polarized in opposite senses in the supporting conductors 51 through 54, the element shown may be used as an isolator, permitting transmission in one direction only, when the garnet biasing field is maintained in a constant direction and at a strength producing ferromagnetic resonance condition in the garnet material 59.

A more complete and detailed description of the balanced wire transmission system described above, and others, is to be found in U.S. Patent 2,892,161, issued to A. M. Clogston, and assigned to the assignee of this application.

Workers in the art are familiar with various techniques for growth of garnet compositions, all of which are applicable to these compositions. For most of the uses de-

scribed, particularly where the devices are to be utilized in the high frequency ranges, for which these materials are particularly suitable, single crystals are preferred or are even necessary. Suitable growth techniques include the various types of random nucleation. Fluxes that may be utilized include the lead oxide of J. W. Nielson U.S. Patent 2,957,827, the lead oxide-lead fluoride flux of J. W. Nielsen U.S. Patent 3,050,407, and the lead oxide-boron oxide flux of J.P. Remeika U.S. Patent 3,079,240, all of which patents are assigned to applicants' assignee. Seeded growth using the same fluxes or others, flame fusion, and crystal pulling may result in larger single crystalline sections where such are required.

Many of the results reported herein resulted from measurements made on crystals grown in lead oxide-boron oxide. The general process utilized in the growth of crystals from this flux is set forth in detail in U.S. Patent 3,079,240 at column 2, line 20, et seq.

The following is a tabulation of eight garnet compositions herein. This table contains four columns, the first of which designates example number; the second, the value of x in the formula; the third, the starting amount of gallium in terms of grams of gallium oxide, Ga_2O_3 ; and the fourth, the starting amount of iron oxide, Fe_2O_3 , again in grams. The amount of europium oxide, Eu_2O_3 , was 16 grams for each of Examples 1 through 6. Measured γ_{eff} values for these compositions range from a minimum of about 6 up to 30 or greater.

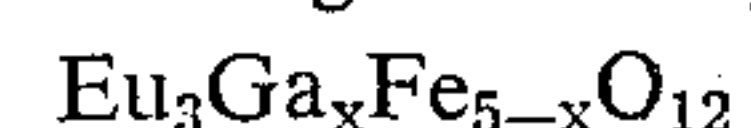
Example	x (in grams)	Ga_2O_3 (in grams)	Fe_2O_3 (in grams)
1	1.28	7.20	19.80
2	1.6	8.96	18.04
3	1.65	9.00	18.00
4	1.00	5.70	21.30
5	1.12	6.38	20.02
6	1.50	8.44	18.56

The invention has necessarily been described in terms of a limited number of embodiments. From a compositional standpoint, the invention has been traced to characteristics of the pure system $Eu_3Ga_xFe_{5-x}O_{12}$, in which x equals from 0.8 to 1.8. It is well known that magnetic garnet compositions may contain additional ingredients, either as unintentional impurities or as intentional inclusions. For the purposes herein, it is considered that unintentional inclusions should be limited to a maximum of the order of one percent, with the line broadening impurities, manganese, silicon, cobalt and the rare earths being kept to total content of a maximum of 0.1 percent. Intentionally added ingredients should generally be restricted to partial substitutions for europium, usually for the purpose of tailoring magnetic moment, and should not exceed 30 percent of the europium in the formula on an atomic basis.

The invention generally derives from the discovery that Ga^{3+} ions manifest an unusually strong preference for tetrahedral sites in europium-iron garnet not seen in other lattices, for example an yttrium-iron garnet or for other ions in other systems. This, in turn, results in an angular momentum compensation point for an appreciable saturation moment. Compositions at and about the angular momentum compensation point defined above manifest unusually high effective gyromagnetic ratios, so permitting operation of harmonic generators, isolators, and other related devices at higher frequencies for given applied magnetic fields. Variations on the devices shown and a host of devices not shown, operation of which may beneficially share the advantages set forth, are known to those skilled in the art. All such variations are to be considered within the scope of this invention.

What is claimed is:

1. A microwave component having a g value of at least four (4) and consisting essentially of



in which x equals from 0.8 to 1.8.

2. Component of claim 1, in which x equals approximately 1.20.
3. A microwave component having a g value of at least four (4) and comprising a single crystal of the composition $\text{Eu}_3\text{Ga}_x\text{Fe}_{5-x}\text{O}_{12}$, in which x represents from 0.8 to 1.8, together with means for introducing and extracting electromagnetic energy.
4. Component of claim 3, in which the said electromagnetic energy is substantially plane polarized.
5. Component of claim 4, in which the extracted energy is a harmonic of the introduced energy, and in which the said means comprise guide sections, the major axes of which are normal to each other.
6. A microwave component having a g value of at least four (4) and comprising at least one waveguide and a gyromagnetic garnet body of a composition comprising $\text{Eu}_3\text{Ga}_x\text{Fe}_{5-x}\text{O}_{12}$, in which x equals from 0.8 to 1.8.
7. Component of claim 6, together with means for sub-

jecting the said body to electromagnetic energy of a frequency of at least 50 gigacycles per second.

References Cited

UNITED STATES PATENTS

2,748,352	5/1956	Miller	333—14
2,849,683	8/1958	Miller	333—1.1
2,892,161	6/1959	Clogston	333—24.2
2,922,876	1/1960	Ayres et al.	333—24.1
2,938,183	5/1960	Dillon.	
3,079,240	2/1963	Remeika.	
3,164,768	1/1965	Stiglitz et al.	321—69
3,229,193	1/1966	Schaug-Pettersen et al.	321—69
3,260,852	7/1966	Hetter	307—88.3

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