United States Patent [19]

Harrold

[11] **3,781,592**

[45] **Dec. 25, 1973**

[54] **RADIAL MAGNETIZED MAGNET**

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[73] Assignee: **Raytheon Company,** Lexington, Mass.

[22] Filed: **June 8, 1972**

[21] Appl. No.: **260,879**

[52] **U.S. Cl.** **315/39.71,** 335/210

[51] **Int. Cl.** **H01j 1/00**

[58] **Field of Search** 335/210, 284, 306; 315/3.5, 5.35, 39.71; 313/84

[56] **References Cited**

UNITED STATES PATENTS

3,665,242	5/1972	Dubravec	335/210 X
3,168,686	2/1965	King et al.	335/306
3,283,200	11/1966	Pallakoff	335/306 X
2,903,329	9/1959	Weber	335/302 X
3,020,440	2/1962	Chang	313/84 X
3,141,116	7/1964	Henne	315/3.5 X
3,205,415	9/1965	Seki et al.	335/302 X

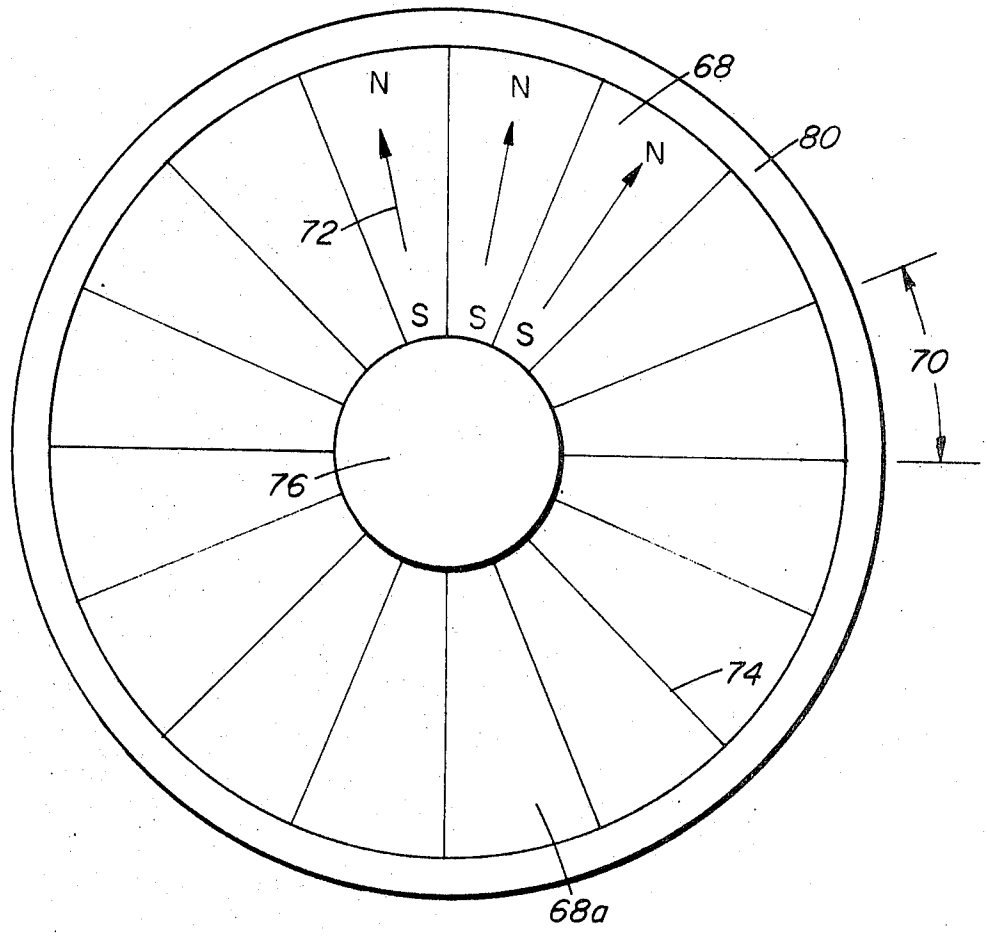
Primary Examiner—George Harris

Attorney—Harold A. Murphy et al.

[57] **ABSTRACT**

A permanent magnet package for electromagnetic devices, including traveling wave tubes, linear beam devices, klystrons, magnetrons, crossed field and backward wave amplifiers or oscillators and the like comprising a plurality of radially oriented linearly polarized members collectively providing a magnetic circuit. A soft iron return path between the assembled multi-segmented magnetized components completes the magnetic circuit. Magnetic materials, such as samarium-cobalt, platinum-cobalt, alnico and ferrite may be utilized.

5 Claims, 11 Drawing Figures



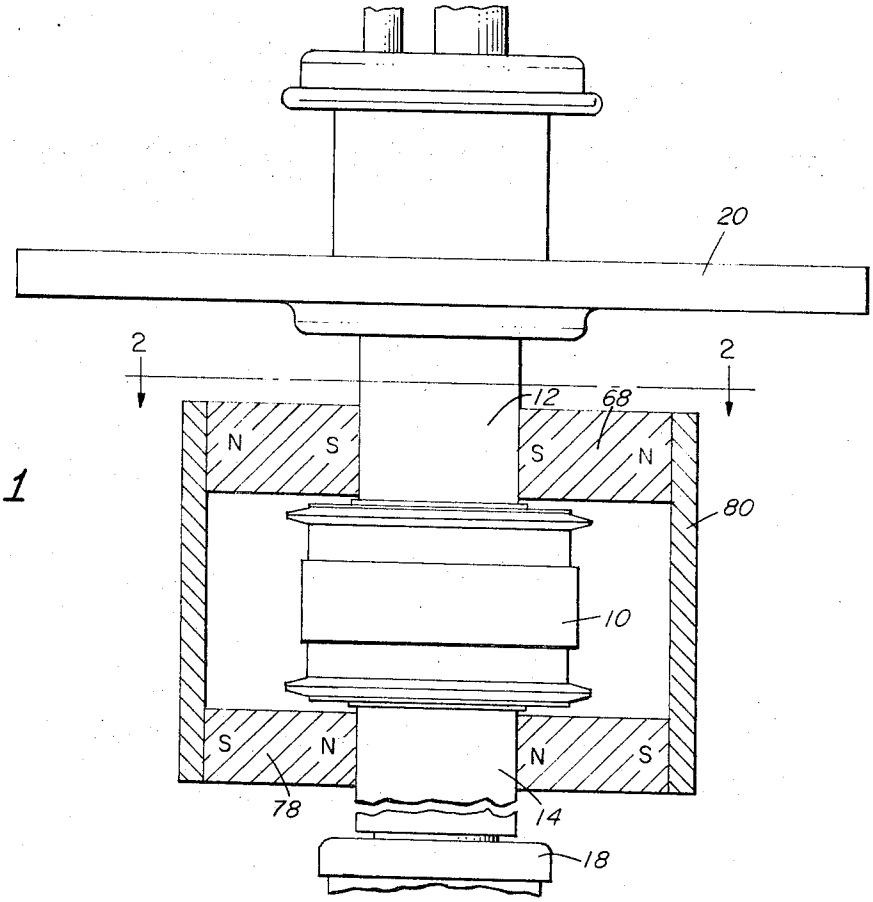


FIG. 1

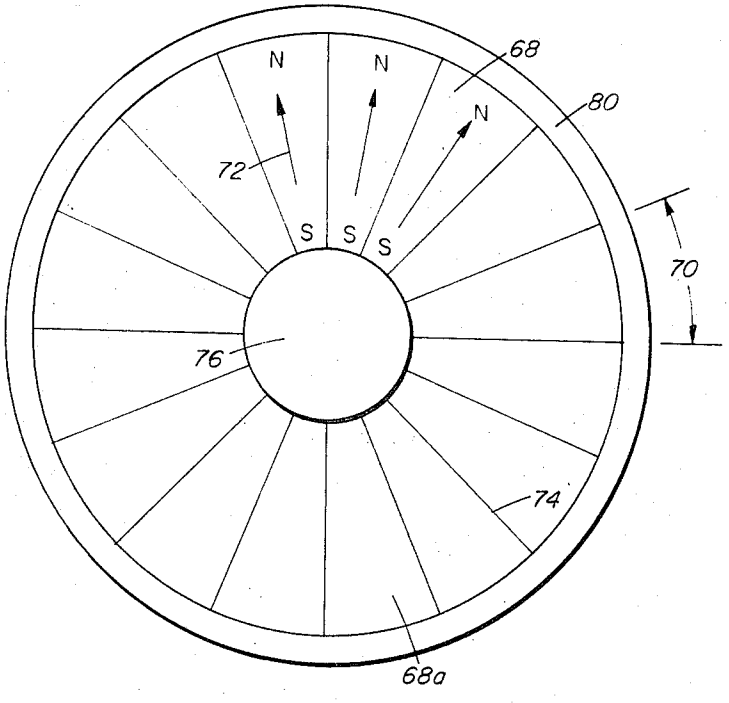


FIG. 2

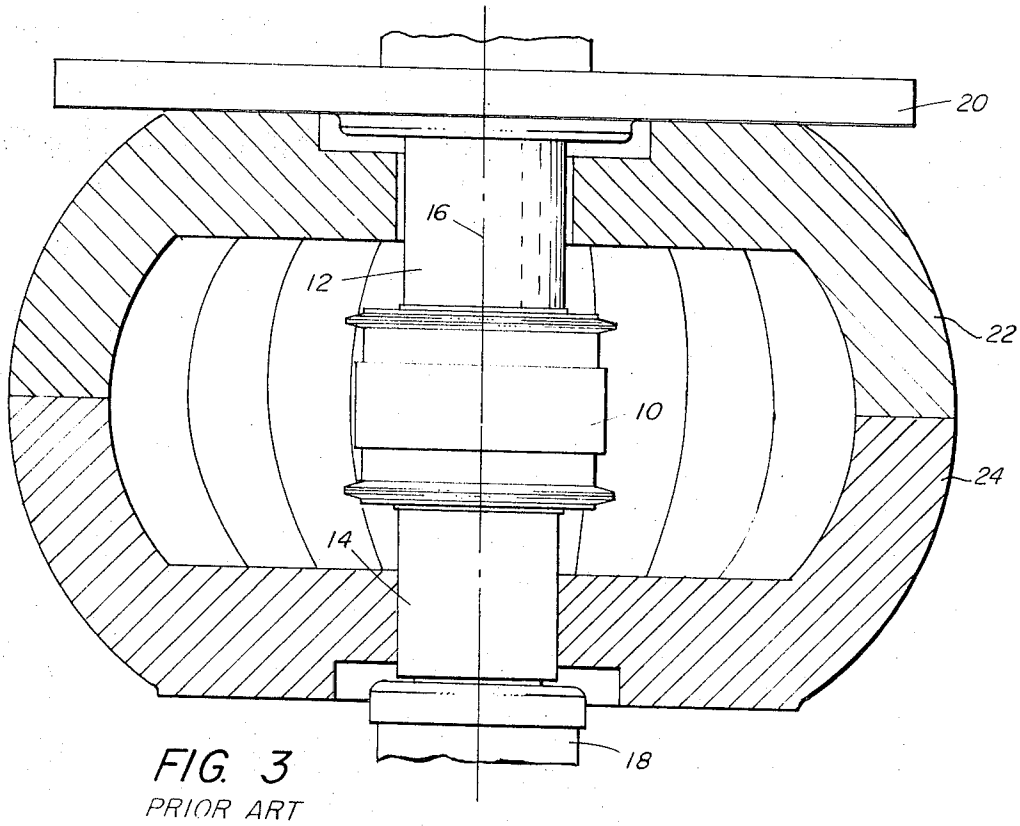


FIG. 3
PRIOR ART

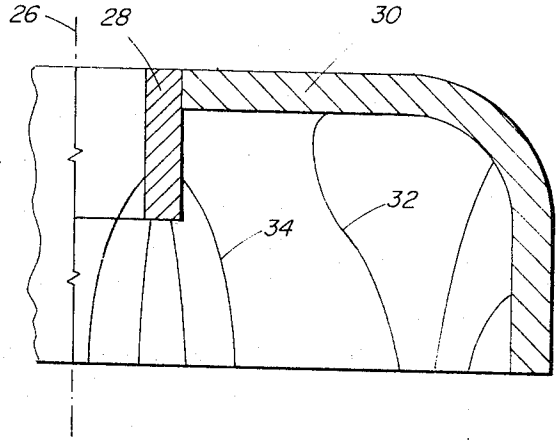


FIG. 4
PRIOR ART

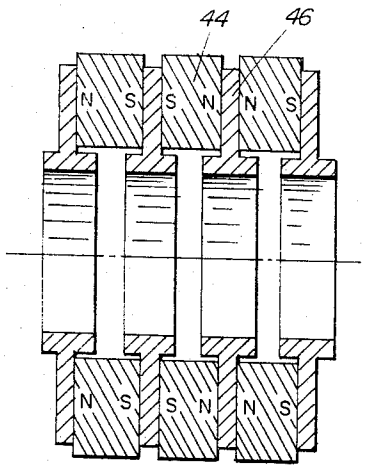


FIG. 5
PRIOR ART

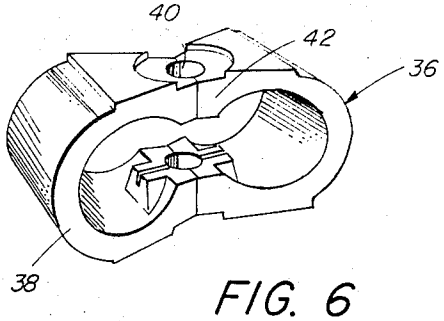
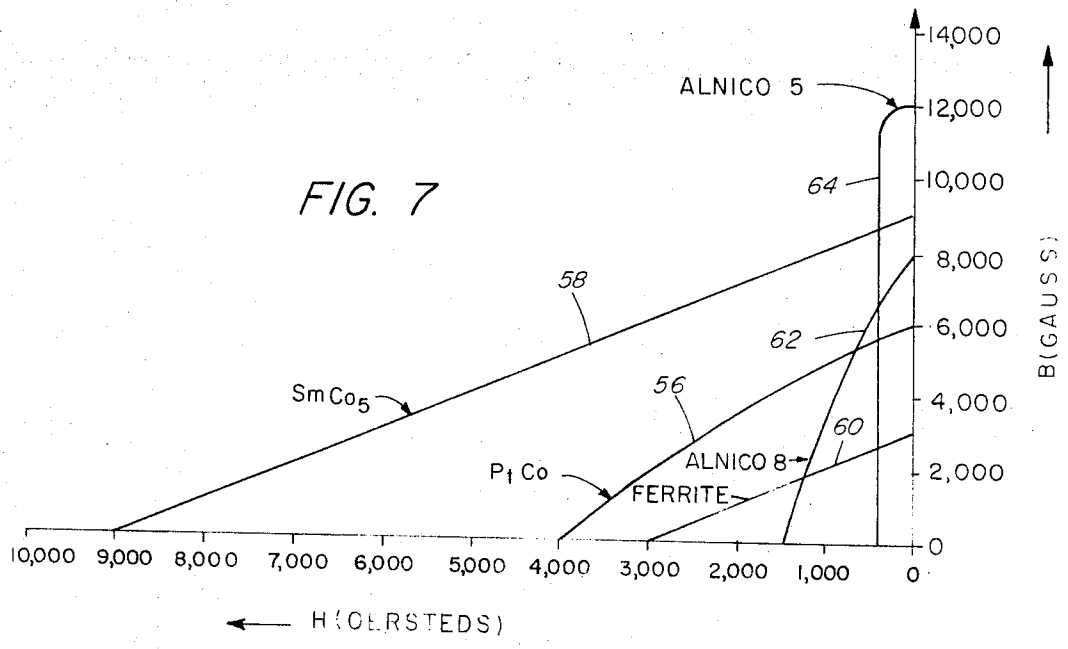


FIG. 6
PRIOR ART

FIG. 7


14,000
12,000
10,000
8,000
6,000
4,000
2,000
0
B(GAUSS)
ALNICO 5
64
58
62
56
60
SmCo5
Pt Co
ALNICO 8
FERRITE
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
H (OERSTEDS)

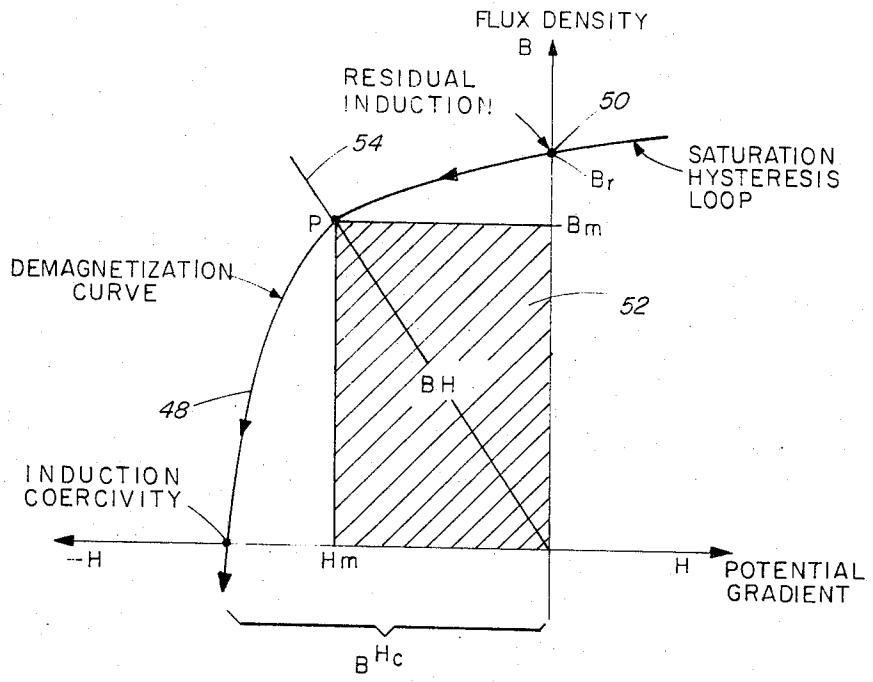

FLUX DENSITY
B
RESIDUAL
INDUCTION
50
54
SATURATION
HYSTERESIS
LOOP
Br
P
Bm
DEMAGNETIZATION
CURVE
52
BH
48
INDUCTION
COERCIVITY
-H
Hm
H
POTENTIAL
GRADIENT
BHc

FIG. 8

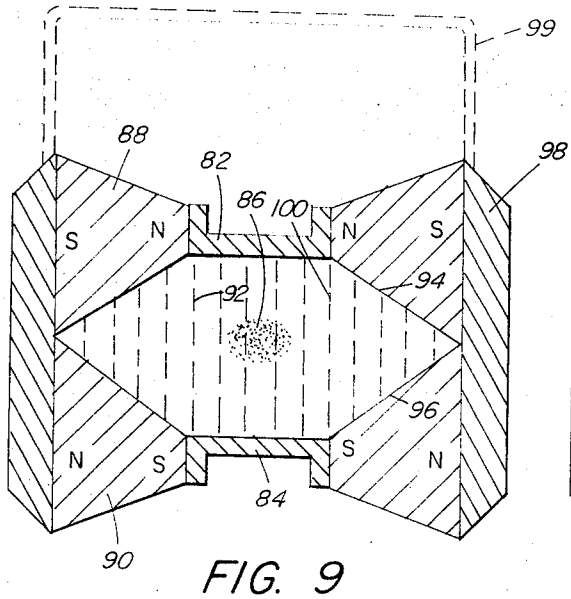


FIG. 9

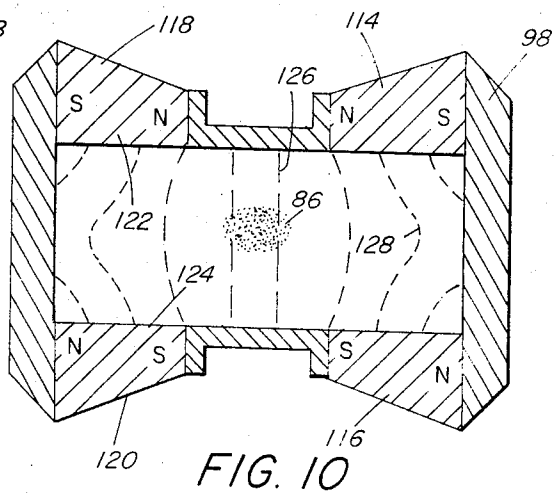


FIG. 10

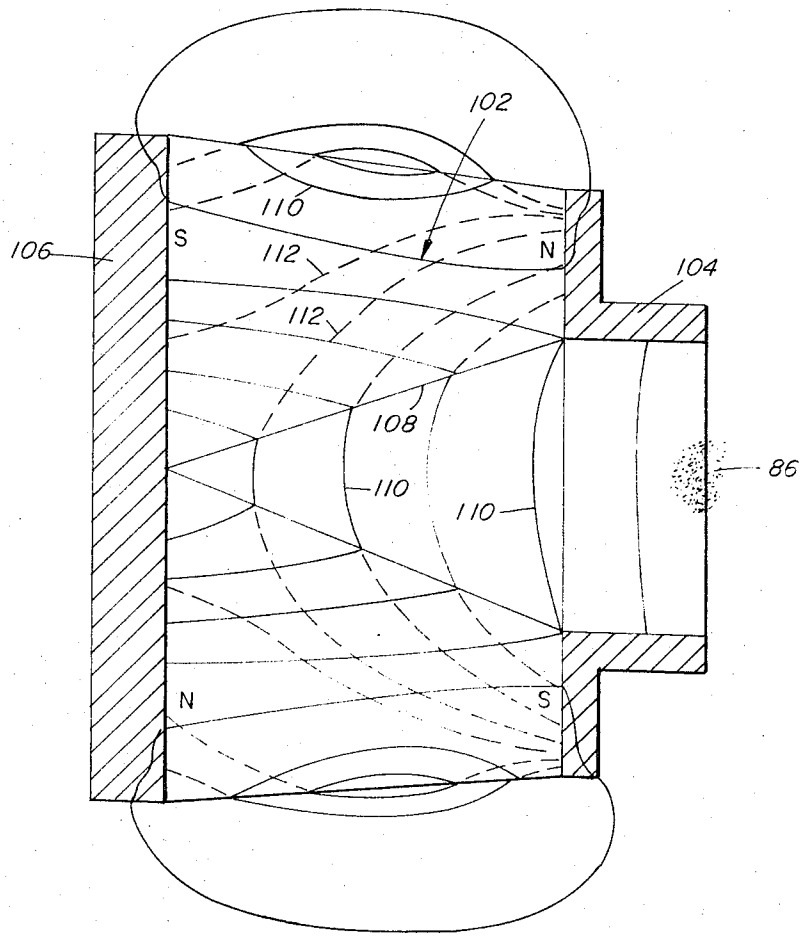


FIG. 11

RADIAL MAGNETIZED MAGNET

BACKGROUND OF THE INVENTION

1. Field of the Invention

The invention relates to electromagnetic energy devices and, more particularly, to permanent magnets for such devices.

2. Description of the Prior Art

Magnetic field producing means for devices such as, for example, the magnetron as well as other devices operating in the microwave region of the electromagnetic spectrum commonly employ permanent magnets with the magnetic fields generally oriented parallel to the axis of the device. The term microwave is intended to define the electromagnetic energy frequency spectrum in the range above 300 MHz to 300,000 MHz or wavelengths of from one meter to one millimeter. Over the years the U-shaped, E-shaped and finally the bowl-shaped permanent magnets have been utilized for microwave devices. As higher average and peak power levels are attained permanent magnets of considerable size and weight are required to produce the high magnetic flux densities required for operation. A saturation level can readily be envisaged where the permanent magnet members could weigh many hundreds of pounds which would place very stringent requirements on the utilization of microwave energy.

An excellent discussion of the numerous applicable devices including crossed field devices as well as linear beam devices and the utilization of permanent magnets for focusing of the electron beams in the interaction region is found in the article "Permanent Magnets For Microwave Devices", IEEE Transactions on Magnetics, Vol. MAG–4, No. 3, Sept. 1968, pps. 229–239, by W. Harrold and W. R. Reid. The development of magnetic materials having relatively high coercivity values and a high maximum energy product have succeeded in pushing the state of the art for microwave devices to higher limits for power output. Some of these materials such as platinum-cobalt which can have a cost of approximately 3500 per kilogram and other rare earth magnet materials, such as samarium-cobalt, have now advanced the state of the art, due to the exceedingly high energy product, to even higher potential levels. A description of the latter material is found in copending U.S. Pat. Application of D. K. Das, Serial No. 778,041, filed Nov. 22, 1968, and assigned to the assignee of the present invention. Certain magnet configurations have also evolved involving a self-shielded magnetic circuit which has found application in such devices as the Amplitron, (a Registered Trademark of the Raytheon Company) for crossed-field amplifier tubes. With the magnetic materials reaching higher coercive force values, a problem arises in that such materials may also display lower permeance coefficient values at the maximum energy product point. Desirably, a more linear slope at this point will obviate the necessity for thick-walled permanent magnet structures to provide a long magnetic path length to area ratio to carry the leakage flux in the back of the magnet. Such thickwalled construction tends to lower the energy product of the permanent magnet material.

In the case of periodic permanent magnet focussing utilized for example in linear beam and traveling wave devices, the polarity of the magnets alternates along the electron path. In such devices the magnet path length to area ratio is relatively limited and, therefore, a magnet configuration using materials having a high coercivity is dictated. Other electromagnetic devices dependent on permanent magnets for their operation are Faraday rotators, gyrators, isolators, and multi-port circulators. Temperature sensitivity of the magnet materials is a critical factor in the advancement of the power handling capabilities in such devices as well as the previously mentioned ones.

In the provision of new and improved magnetic circuits numerous factors must be considered. These factors include: weight, volume, restrictive dimensions, cost, required magnetizing fixtures, stray magnetic fields, external demagnetization influences, shape of the magnet and thermal environment. In numerous electromagnetic devices for airborn applications factors of weight and size are of primary importance. In the case of the high power devices, cost of the new and exotic magnet materials is to be considered. Shielding of externally mounted magnets is also desirable in numerous applications.

To further advance the state of the electromagnetic device art, therefore, new and improved permanent magnet packaging to enable the use of such new materials to evolve more efficient magnetic circuit structures is required.

SUMMARY OF THE INVENTION

The present invention provides a permanent magnet package comprising a plurality of individual radially oriented components which have each been linearly polarized. In one embodiment the components are assembled in what may conceptually be considered to be a bowl magnet configuration. The magnetic circuit path provided concentrates the field density in the optimum areas to provide substantially uniformed parallel flux density lines with a companion opposing radial magnet. There is an absence, however, of the large portion of magnetic material utilized in the prior art to form the return path. A shielding plate of soft iron is utilized at the outermost cylindrical extremity. The overall magnet package is substantially self-shielding. The invention provides for more efficient usage in terms of gap flux per kilogram of magnetic material which in the case of the costly high energy product materials can result in substantial savings. Additionally, the elimination of the bulky magnetic field return paths found in prior art U, E, and bowl-shaped permanent magnets and the replacement of these materials by a soft iron material results in savings in weight. Internal tube components, such as pole pieces, have also been reduced in size and weight. In an illustrative embodiment a radial magnet of a very high energy product material (samarium-cobalt) was employed in a traveling wave device with the total weight of the tube and magnet package being approximately seven pounds. The comparable prior art tube and magnet package with the same electrical parameters weighs twice this value or a total of fourteen pounds. In space application such weight savings are most important.

Other magnet configurations are illustrated including a pyramid or truncated cross section which can be utilized to provide very uniform magnetic field lines in the volume enclosed by the permanent magnets.

BRIEF DESCRIPTION OF THE DRAWINGS

Details of the illustrative embodiments of the invention will be readily understood after consideration of

the following description and reference to the accompanying drawings, wherein:

FIG. 1 is a partial elevational view, partly in cross section, of the illustrative embodiment of the invention in a crossed field device;

FIG. 2 is an elevational view taken along the line 2—2 in FIG. 1;

FIG. 3 is a partial elevational view of a U-shaped permanent magnet structure illustrating a prior art package;

FIG. 4 is a partial diagrammatic representation of a bowl-type magnet illustrating the flux density line distributions;

FIG. 5 is a cross-sectional view of a prior art periodic permanent magnet focussing array for traveling wave tubes;

FIG. 6 is an isometric view of a prior art combined magnetron package including the features of the U-, E- and bowl-shaped permanent magnets;

FIG. 7 is a graph illustrative of the magnetic field characteristics of several magnet materials;

FIG. 8 is a diagrammatic representation of a characteristic magnetization curve for a given magnetic material illustrating the maximum energy product;

FIG. 9 is a cross-sectional view of an alternative radial magnetized permanent magnet package providing a substantially uniform field;

FIG. 10 is a cross-sectional view of a radial magnetized magnet package of another alternative configuration to provide more clearance for internal device components; and

FIG. 11 is a cross-sectional view of a portion of a radial magnetized magnet package for use in focussing linear beam devices.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Referring to FIGS. 3–6 (inclusive) some exemplary embodiments of prior art permanent magnet structures will be reviewed. In FIG. 3 a crossed field amplifier or oscillator device is provided with a cylindrical envelope **10** comprising the anode within which a centrally disposed cathode assembly (not shown) is disposed. Pole piece members of a magnetic material are disposed on opposite sides of the envelope and the magnetic field is oriented parallel to the axis of the device indicated by the line **16.** A tubular cathode support assembly **18** extends from one side of the tube envelope. A mounting plate **20** is also provided for mounting of the device in a socket. A pair of permanent magnets **22** and **24** having a rather substantial cross-sectional area is externally mounted around the tube envelope.

In FIG. 4 the magnetic field density lines for a bowl-type magnet are illustrated. The axis of symmetry designated by the line **26** would be the axis of the applicable device. An inner pole piece cylinder **28** is shown contacting a bowl magnet **30.** In this magnet package configuration the bowl magnet **30** has a predetermined saturation characteristic with a residual flux density generally indicated by the art by the symbol B_m. It is conventional in the magnet art to refer to the intrinsic induction or magnetization as $4\pi M$ where "M" represents the number of unit dipoles per cubic centimeter. For optimum interaction to generate or amplify magnetic energy the magnetic potential gradient lines **32** in the region of the bowl magnet tend to be nonuniform while the gradient lines **34** resulting from the directivity of the pole piece member **28** are more uniformly aligned with the axis of symmetry **26.** In the prior art such materials as the alnico group have provided excellent results in crossed field devices. In some applications the bowl magnets may be replaced by substantially U-shaped structures. In an amplifier rated at three megawatts peak and 25 kilowatts average output power a pair of U-shaped magnets capable of developing approximately 25,000 gauss weigh 18 kilograms each of an alnico material.

Another development in the magnet art is shown in FIG. 6 where the reduced weight of the U- and E-shaped magnets are combined with the reduced flux leakage of the bowl magnets. The magnet **36** is essentially reentrant as are two of the U and E shapes. In this embodiment an increase in the area required to carry the leakage flux in the back of the magnet is gained by increasing the width of the magnet member rather than the thickness in the section **38.** The central portions of the magnet surrounding the axial passageway **40** have a rather substantial thickness indicated in section **42.**

In FIG. 5 permanent magnet field producing means for linear beam devices are shown. A plurality of magnet members **44** with intermediate pole piece members **46** provide a periodic magnet focussing array useful in traveling wave devices. It will be noted that the polarity of the magnets alternates to correspond with the alternation of the energy generated by the interaction of the axial electron beam extending within the tube envelope and interaction with a periodic slow wave structure (not shown). In such devices the external magnetic field is a minute fraction of the external magnetic field surrounding an equivalent uniform field magnet of the types previously discussed. The magnetic field on the axis closely approximates a sinusoid in this embodiment. A limitation does, however, exist in such magnet configurations in that an upper limit for the period length exists beyond which the beam is unstable and cannot be confined. Thus such devices have a limitation in the distance between the pole pieces and the coercive force is of greater significance than the maximum energy product of the magnet. The newer and exotic magnet materials, therefore, are highly attractive due to their high coercivity although many of such materials also display a low permeance coefficient at the point of maximum energy product.

Before proceeding with the discussion of the magnetron assembly of the invention, reference is directed to FIGS. 7 and 8 for a brief discussion of the magnetic characteristics of some of the representative magnetic materials as well as magnetic field behavior with respect primarily to the demagnetization parameters which determine the energy density for particular materials. In FIG. 7 some characteristic graphs of magnetic properties of several materials for use as permanent magnets including the new and exotic materials are shown. The demagnetization curve illustrating the residual induction and coercive force characteristics is plotted. Curve **56** illustrates the properties of platinum-cobalt having a high coercivity of about 4,000 oersteds and a residual induction of about 6,000 gauss to yield an energy product of approximately 9×10^6 gauss-oersteds. This material is also referred to in the aforereferenced article and is represented to have a high cost of approximately $3500 per kilogram. This material as well as other rare earth-cobalt alloys have yielded very high performance, particularly, in air-

borne and spaceborne applications where the high coercivity characteristics are highly desirable.

Curve **58** is representative of one of the rare earth magnetic materials, namely a sintered composition of samarium-cobalt which can yield energy products of 15 $\times 10^6$ gauss-oersteds and higher. Such materials have extremely high coercivity characteristics but the very low incremental permeability of the demagnetization curve indicates a low permeance coefficient is required to operate the material near its maximum energy product. This dictates the need for a thick-walled magnet return path if any of the prior art magnet configurations are utilized. One of the advantages of the new magnet materials is, however, the high coercivity which permits a much larger gap energy density for a small amount of magnet material. In addition to samarium, other rare earth materials such as cerium, praseodymium and lanthanum are referred to in the referenced pending patent application.

Curve **60** is exemplary of the performance characteristics of the ferrite class of magnetic material which have a lower cost although the energy products are only approximately 3.5×10^6 gauss-oersteds but are nevertheless finding wide application in electromagnetic devices.

Curve **62** represents one of the more recently developed high coercivity members of the alnico class such as alnico–8 and –9. Another alnico class material is represented by curve **64** having a rather high residual induction such as alnico–5.

Referring next to FIG. **8** a portion of the hysteresis loop is plotted on a B-H diagram and is designated the demagnetization curve **48.** As is well known in the art the characteristic B indicates the flux density and H is the magnetic potential gradient or field strength. BHc represents the coercivity which is the field strength required to reduce B to zero. The point **50** represents the residual induction or remanence. The symbol B_r is applied to this characteristic. The line extending to the right of the B reference line represents a part of the first quadrant of the hysteresis loop which can be plotted when a sample of magnetic material is measured in a permeameter.

The energy stored in the magnetic field external to a permanently magnetized material is determined by the product of B and H and is referred to in the art as the maximum energy product expressed in terms of gauss-oersteds (1 gauss-oersteds - $\frac{1}{8\pi}$ ergs per cubic centimeter). The product BH for any point P on the demagnetization curve **48** is proportional to the area of the shaded rectangle **52.** The slope of a line **54** connecting point P to the origin of the plot is referred to as the permeance coefficient for a particular material having a flux density B_m at a potential gradient H_m.

Referring to FIGS. **1** and **2** a magnetic circuit assembly is shown for the utilization of magnetic materials having extremely high coercivity without a requirement for a large area magnetic return path. The same crossed field amplifier device is illustrated as that shown in FIG. **3** to point up the significant differences in size and weight of the respective magnet packages. The tube components as well as pole pieces have been similarly numbered as the references in FIG. **3.** The embodiment of the invention comprises a first assembly of radially oriented magnet segment members **68** to collectively define a circular body. Each of the magnet members **68** form a segment of a circle with tapered sidewalls and planar opposing surfaces. In exemplary embodiments for high powered crossed field amplifiers an arc represented by line **70** of approximately 22° 30′ was provided for each segment. The magnet members **68** are linearly polarized as indicated by the arrows **72** with the polar designations represented by N and S. It is possible to provide eight segmented magnet members which are physically united by such means as any of the epoxy resins to form a semicircular section. Another array of eight segmented magnet members **68***a* are similarly secured and the two semicircular sections are joined together at the point indicated by the double line **74** by any suitable securing means. A central axial hole **76** is provided in the assembled structure to accommodate the components of a device such as pole pieces **12** and **14** of the exemplary crossed field amplifier. In the practice of the invention the overall packaged magnets are magnetized by any of the known magnetizing procedures and fixtures.

To complete the magnetic circuit assembly for the applicable device a companion opposing magnet package is provided by means of physically uniting a second assembly of radially oriented linearly polarized segmented permanent magnets **78.** In this magnet package, however, the polar designations are reversed and a complete magnetic circuit is defined with the inner polar designations now N while the outer polar designations are S.

The magnetron circuit assembly including the first and second circular assemblies of the radially oriented linearly polarized segmented magnets are interconnected by an outer cylindrical shell member **80** of a ferrous composition, such as soft iron, to shield and provide a return path for the assembled magnetic field producing means. The member **80** contacts the outer extremeties of the first and second magnet packages. The magnets, particularly those of the high coercive force material, direct the required magnetic fields in the interaction regions where the crossed electric and magnetic fields produce the high electromagnetic energies. The shell member has a reduced wall thickness and lower magnetic path area ratio than the magnet members. The circuit of the present invention generates the required magnetic fields without the external leakage flux problems created by the thick-walled prior art magnet structures. In terms of gap flux per kilogram of material a much more efficient structure is possible with extremely uniform magnetic field flux lines. The shield member **80** has considerably reduced weight and is nonmagnetized.

An exemplary embodiment of the crossed field device shown in FIGS. **1** and **2** for amplification at very high powers and frequencies in the S-band region was provided by the disclosed magnet assembly with gauss values 3700 and higher utilizing a alnico **8***a* material.

In FIG. **9** another embodiment of a radially oriented linearly polarized magnet package is illustrated. In linear beam applications the axial electron beam represented as a cloud of electrons **86** extends along the tube axis and between pole piece members **82** and **84.** Periodic permanent magnet focussing is provided by radially oriented permanent magnet members **88** and **90** having a substantially truncated conical configuration with tapered sidewalls and united to form a circular body with an axial hole. The polar designations are reversed to provide the complete magnetic circuit. The magnetic field gradient lines **100** are substantially uni-

form throughout as a result of this configuration which collectively defines a V-structure. The extra magnetic material in the wider magnet portions near the outer limits of the electron beam trajectory provides for higher gap flux densities in this region. The tapered walls **94** and **96** form the V-shape internally and the outer walls are tapered as well in this embodiment for the extra material. In the shaping and focussing of the fields for such linear beam applications an optional end shield indicated by dashed lines **99** substantially reduces external leakage flux along the back of the magnet members. The ferrous nonmagnetized return path member **98** interconnects the magnet packages and also provides shielding and return path means. The magnet may be of a segmented individually magnetized configuration or a complete body with the domains radially oriented during manufacture.

The evolution of a truncated conical design shown in FIG. **9** may be analyzed with reference being directed to FIG. **11.** A segmented permanent magnet member **102** together with a pole piece member **104** and soft iron return path shield member **106** is shown. The substantially V-shaped wall **108** evolves flux lines represented by the solid lines **110** and field lines represented by the dashed lines **112.** It is noted that while the B and H fields external to the magnet coincide the internal B and H fields do not. In a permanent magnet of nonuniform cross section the tapered configuration of the type shown in the illustration has been demonstrated to provide substantially uniform magnetic fields in the focussing of linear beam devices. The distribution of the magnetic poles by the tapered magnet configuration results in the total number of dipoles being greatly increased on the outside diameter with a smaller number of dipoles arranged around the inner diameter. The pole density distribution, therefore, results in a more uniform concentration of the magnetic flux density in the region surrounding the beam of electrons **86.** The provision of individual linearly magnetized segmented members of high coercive force materials to collectively define a desired radial magnet package configuration results in more efficient periodic permanent focussing of linear beams as well as crossed field devices.

Another embodiment of the invention is illustrated in FIG. **10** wherein the individual truncated magnet segments **114** and **116** are provided with outer tapered walls **118** and **120.** Straight walls **122** and **124** extending perpendicular to the axis of the device provides additional clearance for internal tube components such as slow wave propagating structures in the vicinity of the electron beam. In this configuration the magnetic field flux lines **126** are substantially uniform in the vicinity of the electron beam **86** while a less uniform field distribution results further away from the beam as shown by the lines **128.** The additional room will also provide for clearance of such items as waveguide inputs and outputs.

The resultant radially oriented linearly polarized segmented magnet package in addition to providing more efficient magnetic fields utilizing materials of higher coercivity reduces the need for shims provided for in many of the prior art electromagnetic devices to shape the magnetic circuits.

Many other embodiments, alterations or variations will be readily apparent to those skilled in the art. It is desired, therefore, that the foregoing detailed description of the invention and the preferred embodiments be considered in the broadest aspects and not in a limiting sense.

I claim:

1. A microwave device comprising:

an envelope housing means for the generation or amplification of electromagnetic energy including an anode and a cathode;

magnetic pole piece members extending outwardly from opposing sides of said envelope;

a first circular permanent magnet package contacting one of said pole piece members comprising:

a plurality of radially oriented linear polarized segments of a magnetic material physically secured together;

a second similarly formed permanent magnet package contacting the opposing pole piece member with the polar orientation of the magnetic material dipoles in said first and second magnet packages being opposite to one another; and

means defining a shield and magnetic field return path interconnecting the outermost extremities of said first and second magnet packages.

2. A microwave device according to claim **1** wherein said shield and return path means are formed of a nonmagnetized ferrous material.

3. The device according to claim **1** wherein the magnetic field polar orientations of adjacent members in each of said first and second permanent magnet package are similar.

4. The device according to claim **1** wherein each of said magnetic segments is substantially truncated with tapered sidewalls.

5. The device according to claim **1** wherein each of said magnetic segments is substantially truncated and has a tapered sidewall and a substantially straight sidewall extending along a plane parallel to the envelope axis.

* * * * *