Aug. 6, 1957 G. H. DEWITZ 2,802,186

SATURABLE CORE APPARATUS

Filed April 19, 1952

FIG. 1.

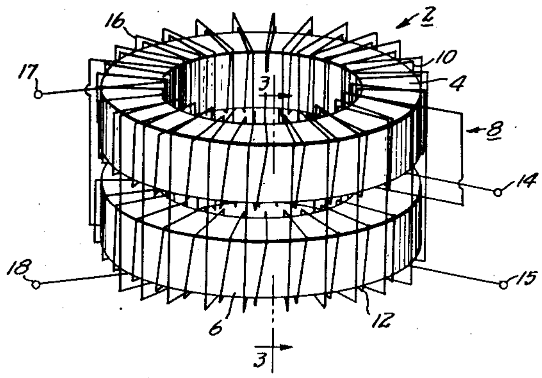


FIG. 3.

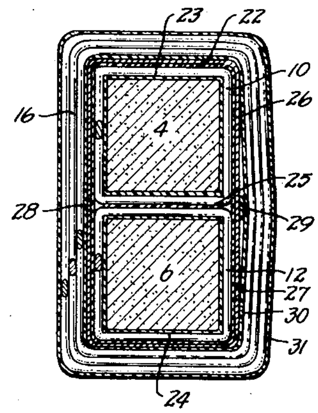


FIG. 2.

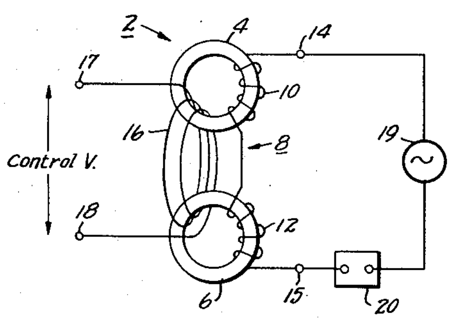


FIG. 4.

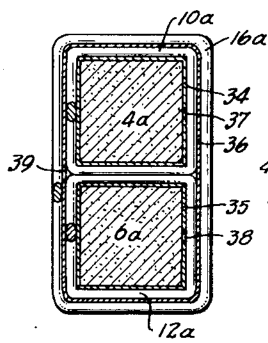


FIG. 5.

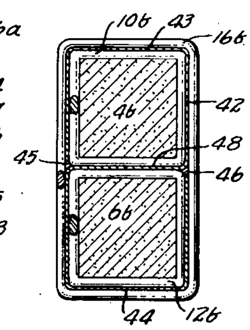


FIG. 6.

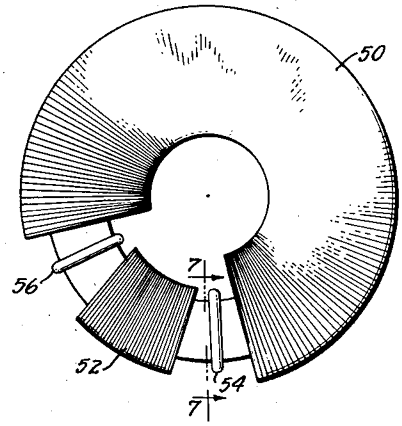
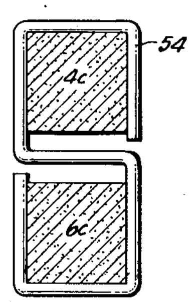


FIG. 7.



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United States Patent Office

2,802,186

Patented Aug. 6, 1957

2,802,186

SATURABLE CORE APPARATUS

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Application April 19, 1952, Serial No. 283,186

13 Claims. (Cl. 336—171)

This invention is in the field of high frequency saturable core magnetic apparatus.

In saturable core magnetic apparatus, current is passed through a control winding on a ferromagnetic core to control the magnetic saturation of the core and thereby control the effective inductance of one or more other windings on the same core.

One of the problems of such apparatus as now used is that the efficiency decreases rapidly and the other operating characteristics become poorer as the operating frequency is increased. With increasing frequency, the hysteresis, eddy current, and dielectric losses within the ferromagnetic material increase sharply.

It is among the objects of the present invention to extend the high frequency range, increase the efficiency, improve the operating characteristics, reduce the core losses and increase the effective "Q" of high frequency saturable core magnetic apparatus.

In using saturable core ferromagnetic apparatus at high frequencies and particularly in extending the upper limit of the frequency range to higher frequencies, one of the important factors is the maintenance of relatively low core losses. By maintaining a relatively low core loss in the high frequency range, such apparatus can be used over a wider range of different frequencies with a good frequency response throughout the whole range, and it is more sensitive so that increased power gain is available, that is, greater changes in the inductance of the controlled winding and greater variations in the output signal are obtained with a given control signal.

The present invention will be described as embodied in an improved magnetic modulator having a pair of separate ring cores with a control winding and a controlled winding around both of them. The ring cores are formed of ferromagnetic ceramic material, as will be described later. A layer of electrically conductive material in the form of a conductive shield is placed between one or more of the windings and the core material and substantially increases the Q of the windings and extends the frequency range. In one embodiment, the conductive shield is formed by a layer of conductive paint sandwiched between layers of insulating film, in another embodiment the surfaces of the core material are painted with a layer of conductive paint.

These and other aspects, objects and advantages of the present invention will be in part pointed out and in part apparent from the following description considered in conjunction with the accompanying drawings, in which:

Figure 1 is a diagrammatic perspective view of a magnetic modulator, generally indicated at **2**;

Figure 2 is a schematic circuit diagram of one method of connecting the magnetic modulator **2**;

Figure 3 is a cross sectional view of one side of the modulator **2** taken along the line **3—3** in Figure 1;

Figures 4 and 5 are views similar to Figure 3 showing other shielding arrangements;

Figure 6 is a top view of a multiple ring core structure showing another shielding arrangement; and

Figure 7 is a sectional view taken along line **7—7** of Figure 6, the windings being omitted to simplify this view.

The magnetic modulator **2** includes first and second ring cores **4** and **6**, respectively, formed from a ferromagnetic ceramic or ferrite material, for example of the kind described by Snoek in U. S. Patents, 2,452,529; 2,452,530; and 2,452,531.

A signal winding, generally indicated at **8**, consists of two series winding portions **10** and **12**, respectively wound on the cores **4** and **6**. The ends of this winding **8** are connected to terminals **14** and **15**. The winding portions **10** and **12** are wound in opposite directions or connected so as to cancel out any flux linkage and to minimize inductive coupling between the winding **8** and a control winding **16** which encompasses both cores **4** and **6**.

The control winding **16** is connected to two terminals **17** and **18** by which a control signal is applied to this winding in order to vary the magnetic saturation of the cores 4 and **6**, thus modulating the signals flowing through the winding portions **10** and **12**.

One possible arrangement for connecting the magnetic modulator 2 is shown in Figure 2. The portions **10** and **12** of the signal winding **8** are connected in series and a high frequency signal to be modulated, for example such as a radio frequency signal from a signal generator **19**, is fed through the winding **8** into a radio frequency load circuit, diagrammatically indicated at **20**.

As pointed out above, in order ot minimize inductive coupling between the signal or controlled winding **8** and the control winding **16**, the portions **10** and **12** of the signal winding **8** are connected so that the voltages which they each induce in the winding **16** are equal and opposite and so cancel. A control current is applied through the terminals **17** and **18**, to the control winding **16**. Any change in the magnitude of this control current changes the saturation of the cores **4** and **6** and hence changes the inductance of the winding **8**. These variations in the inductance of the winding **8** in turn control the high frequency signal current flowing through the load **20**. Thus, the output through the load **20** is modulated in accordance with the fluctuations of the control voltage.

As shown in Figure 3, a layer **22** of electrically conductive material forming an electrostatic shield but not a shorted turn is placed between the winding portions **10** and **12** and the control winding **16**. This shield may be formed of conductive foil or a layer of conductive paint applied to an insulating film surrounding the winding portions **10** and **12**. Figure 3 will be discussed in greater detail in connection with a method for making the apparatus **2**.

The presence of the shield **22** extends the high frequency range of the winding **16**. Without this shield **22**, the winding **16** would be capacitively coupled to the winding portions **10** and **12** and the cores 4 and 6 thereby increasing the core losses and increasing the undesired inter-action between windings **16** and 8.

In the embodiment shown in Figure 4, a broken layer **34** of electrically conductive material forming a grounded electrostatic shield is placed between the winding portion **10***a* and the core **4***a*. A similar shield **35** is placed between the winding portion **12***a* and the core **6***a*, and a shield **36** is placed between the winding **16***a* and both of the cores **4***a* and **6***a*. The presence of any one of these shields **34**, **35**, or **36** increases the efficiency and extends the high frequency range of all of the windings which are thereby electrostatically isolated from the core. For example, the shield **34** improves the operating characteristics of the winding portion **10***a*, and it also improves the characteristics of the control winding **16***a* which is thereby isolated from the core, which, due to poor Q of the dielectric constant of the material, introduces losses if the interwinding capacity of the wires includes the dielectric constant of the material.

These shields 34 and 35 are formed by surrounding each of the cores 4a and 6a, respectively, by a thin layer of conductive paint which is applied directly to the core surface. A small annular gap or insulation space 37 and 38 is left in each of the shielding layers 34 and 35 in order to prevent them from acting as short-circuited turns around the cores. I have found that the use of these shields or conductive layers 34 and 35 increases the high frequency limit of the windings 8a and 16a and results in the improved operating characteristics discussed above. Conductive paint of the type sometimes used for printed electrical circuits is suitable for this purpose. Finely powdered silver dispersed in a small amount of essential oil may be fired at a low temperature on the surface of the cores.

The shield 36, between the signal winding portions 10a and 12a and the control winding 16a is formed of copper foil, or a layer of conductive paint carried by an insulating sheet can be used. An annular insulating gap 39 is provided to prevent this shield from becoming a short-circuited turn. This shield 36 improves the characteristics of the signal winding 8, by decreasing the remaining unbalance current, coupling capacity, and dielectric losses in the windings and cores which are otherwise caused by changes in the control current, especially at low permeabilities. Furthermore, the shield 36 isolates the winding 16a from the winding 8 so that the control action therebetween takes place solely by virtue of changes in the magnetic conditions of the cores 4a and 6a.

The layers of conductive paint 34 and 35 may be replaced by thin layers of conductive foil wound around the cores 4a and 6a, respectively, with the edges thereof separated by small air gaps which serve to prevent short-circuit current in the shields. This arrangement is satisfactory for many purposes but generally is not so desirable as the conductive paint. For one thing, the foil can never be placed in such intimate contact with the cores as the conductive paint and accordingly an increased air gap necessarily exists between the windings and the cores.

In Figure 5, a layer of conductive foil 42 is wound around two magnetic ceramic ring cores 4b and 6b and the signal windings 10b and 12b. This shielding layer has an S-shaped cross section and forms two annular cavities or shields 43 and 44 which, respectively, house the cores 4b and 6b. Each of these cavities has a narrow annular space in the foil, as at 45 and 46 so that the shield does not form a short-circuited turn. The shield or layer of foil 42 also isolates the control winding 16b from the signal winding portions 10b and 12b, respectively, and at the same time the central portion 48 of the layer 42 reduces the mutual electrostatic coupling between the winding portions 10b and 12b in the region between the cores 4b and 6b. If desired, the cores 4b and 6b also can be coated with conductive paint as described in connection with Figure 4.

Figures 6 and 7 illustrate shielding apparatus to be used between two windings on the same core or between two windings either of which encompasses both cores. This shielding can be used in conjunction with any of the foregoing shielding arrangements when required. As before, two ring cores 4c and 6c (Figure 7) of ferromagnetic ceramic material are positioned in axial alignment. A winding 50 extends around the core 4c and may also encompass the core 6c or may be connected in series with a similar winding on core 6c immediately opposite the winding 50.

The winding 50 extends only part way around the core 4c so as to leave room for another winding 52, which may be a radio frequency winding, as for example an antenna winding. The winding 52 extends around the core 4c and may also encompass the core 6c, or it may be connected in series with another similar winding on the core 6c positioned directly opposite the winding 52.

In order to minimize the coupling between the windings 50 and 52 an S-shaped wire 54 is positioned on the cores 4c and 6c as shown in Figure 7. This S-shaped conductor is most conveniently made from a short length of ordinary copper wire, but other materials such as foil or the like can be used. This S-shaped shielding conductor is placed on the cores between one end of the winding 50 and the adjacent end of the winding 52 as shown in Figure 6. Another S-shaped shielding conductor 56 is positioned on the cores between the other ends of these windings.

A method for making saturable core apparatus, for example, such as the embodiment shown in Figures 1, 2, and 3 proceeds as follows. The cores 4 and 6 are each closely surrounded by layers or films of insulating material 23 and 24, respectively, which protect the cores 4 and 6 and also protect the inside of the winding portions 10 and 12. The ferromagnetic ceramic material used in the cores 4 and 6 is extremely hard and tends to be somewhat rough. The insulation films 23 and 24 prevent rough places on the cores 4 and 6 from cutting through the layers of insulating enamel on the wires in the winding portions 10 and 12. There are several ways in which these insulation films can be applied to the cores 4 and 6, for example, as by painting, spraying, dipping, etc., using insulating material in a liquid form which is then allowed to harden. However, I have found that if the cores 4 and 6 are covered with fluid insulating coating material, the penetration of this material into the pores of the ferromagnetic ceramic cores causes a loss of effective "Q." I have found that a preferable method for forming this insulation coating is to wrap the cores tightly with a layer of thermosetting plastic type tape which is suitably formed into a continuous film of insulation by curing in an oven at elevated temperature. An example of such a tape is that sold by the Minnesota Mining and Manufacturing Company of St. Paul, Minnesota, under the trade designation Scotch Weld electrical insulating film No. 70. This tape is then cured by heating thes cores 4 and 6 in an oven at 140° C. Usually it is desirable to continue these insulation layers 23 and 24 all the way around the ring cores 4 and 6, as shown in this embodiment. However, where the very highest frequency operation is important, this insulating tape may be omitted from that portion of the ring cores immediately adjacent the radio-frequency winding portions. For example, referring to Figure 7 for the purpose of making this explanation clear, if the winding 52 is to be operated at the very highest frequency, it is possible to omit any insulating film from the cores in the region adjacent winding 52, that is, for example between the shields 54 and 56. In such case, a small air space is provided by windings formed with spacers on the cores which are removed when the winding is completed.

After the insulation layers 23 and 24 are cured in an oven, the winding portions 10 and 12 are wound tightly around the cores 4 and 6, and the two cores are placed together with an insulating washer 25 between the winding portions 10 and 12. In order to insulate the outside of the windings 4 and 6 and to rigidly secure the two cores firmly together as a single unit, a third layer 26 of thermosetting insulating tape is then wound over both of the winding portions 10 and 12, and the unit 2 is again placed in an oven at elevated temperature to cure the film 26. I have found that thermosetting plastic tape of the type mentioned above has the characteristic that it tends to shrink during the curing process and thus the cores 4 and 6 are bound even more tightly together after the film 26 is cured.

In order completely to fill up any gaps which might otherwise occur in the film 26, the modulator 2 is dipped into a suitable varnish or shellac and allowed to dry. A layer 27 of electrically conductive point forming the shield 22 is then applied to cover substantially the entire surface of the film 26, a small annular gap 28 being left in this paint layer 27 to prevent the circulation of short-circuit current in the shield 22 around the cores 4 and 6. I have found that it is desirable to have the gap 28 arranged symmetrically with respect to all of the windings on the cores 4 and 6. Thus, this annular gap may be located around the inside of the shield 22 or around the outside thereof. I have found that it is usually preferable to locate this gap 28 on the inside of the modulator 2, leaving the peripheral portion of the shield 22 free to receive a grounding connection. A suitable conductive paint is that sold under the trade designation of DuPont silver dispersion No. 4817. Tightly around the outside of the shield 22 is wound one turn of a strip 29 of electrically conductive foil, which serves to provide a connection to the shield 22 whereby it may be grounded. The two ends of the strip 29 are pulled together and brought out from the modulator 2 to provide an external terminal for grounding. I have found that although any good conducting material may be used, silver foil is preferable because its oxide is conductive and hence a good electrical connection is always maintained betwen the strip 29 and the periphery of the shield 22.

In order to secure this strip to the shield and to insulate the shield from the winding 16, a fourth film of insulation is formed therebetween by winding a layer 30 of thermosetting insulating tape around the shield 22 and curing it in an oven. The winding 16 is then wound around the cores 4 and 6 and a final outside insulating film 31 is formed around the unit 2 by winding it once more with a layer 31 of thermosetting insulating plastic tape which is cured in an oven.

It is to be understood that the principles set forth above in connection with dual ring core structures applies equally well to multiple ring core structures using more than two cores.

From the foregoing it will be apparent that the saturable core magnetic units embodying the invention are well adapted to attain the ends and objects set forth herein, that they are economical to manufacture, and that they can be modified readily so as to best fit the needs of each particular use.

I claim:

1. A high-frequency saturable core magnetic apparatus comprising first and second ring cores of ferromagnetic ceramic material, a first winding including first and second winding portions around said first and second ring cores, respectively, and means connecting said winding portions in series, said second winding portion being wound in a reverse sense relative to said first winding portion so that the magnetic fields within said two ring cores caused by a current flowing through said first winding are in opposite directions, a second winding encompassing both of said cores, a substantially closed annular shield of electrically conductive material adjacent two of said winding portions and substantially completely encircling both said first and second cores, said shield being disposed between said first and second winding portions and said second winding and electrostatically isolating said winding portions from said second winding, said shield having a gap therein extending around the length of said annular shield to prevent the flow of short-circuit current therein, and a strip of electrically conductive material in contact with said annular shield and extending around the length of said annular shield, said shield including electrically conductive silver paint in contact with said strip.

2. A high-frequency saturable core magnetic apparatus according to claim 1 and including a second annular layer of electrically conductive material separating said second winding, said second annular layer having an insulating gap therein extending around the length of said ring cores, from said first winding whereby said two windings are isolated and the high frequency range of said second winding is extended.

3. A high-frequency saturable core magnetic apparatus comprising first and second ring cores of ferromagnetic ceramic material, a first winding having first and second

winding portions around said first and second ring cores, respectively, and means connecting said winding portions in series, said second winding portion being wound in a reverse sense relative to said first winding portion so that the magnetic fields within said two ring cores caused by a current flowing through said first winding are in opposite directions, a second winding encompassing both of said cores, and a substantially continuous shield of electrically conductive material surrounding both of said cores and separating said first and second windings from each other, said shield having a substantially S-shape cross section and forming a pair of annular cavities, each of said cavities surrounding one of said cores, said shield having a pair of annular gaps, one of said gaps being in each of said cavity portions, for preventing the flow of short-circuit current around either of said cavities.

4. A high-frequency saturable core magnetic apparatus according to claim 3 and wherein said shield has a central portion separating said first and second winding portions.

5. A high-frequency saturable core magnetic apparatus comprising first and second ring cores of ferromagnetic ceramic material, a first winding including first and second winding portions around said first and second ring cores, respectively, and means connecting said winding portions in series, said second winding portion being wound in a reverse sense relative to said first winding portion so that the magnetic fields within said two ring cores caused by a current flowing through said first winding are in opposite directions, a second winding encompassing both of said cores, and a first and a second S-shaped shield of electrically conductive material, each of said shields forming two substantially closed loops, each one of said loops encircling one of said cores, said first and second shields being adjacent opposite ends of said first and second windings, whereby said windings are electrostatically isolated from each other by said S-shaped shields.

6. A high-frequency saturable core magnetic apparatus comprising first and second ring cores of ferromagnetic ceramic material, a first winding with first and second winding portions around said first and second cores, respectively, means connecting said winding portions in series, said second winding portion being wound in a reverse sense relative to said first winding portion so that the magnetic fields within said two ring cores caused by a current flowing through said first winding are in opposite directions, a first insulating film completely surrounding both of said winding portions and securing said cores together, an annular layer of electrically conductive material near the outer surface of said film, a gap in said conductive layer extending around the length of said annular layer, a strip of electrically conductive material in contact with said layer and extending around the length of said layer, said layer including electrically conductive silver paint in contact with said strip, a second insulating film surrounding said layer and said strip, and a second winding encompassing both of said cores and overlying said second film.

7. A high-frequency saturable core magnetic apparatus comprising first and second annular cores of ferromagnetic ceramic material, first and second films of insulating material covering substantially the entire surface area of each of said cores, each of said films comprising a winding of thermosetting tape placed upon one of said cores and then cured at elevated temperature including a first winding, first and second winding portions around said first and second cores, respectively, and overlying said insulating films, means connecting said winding portions in series, said second winding portion being wound in a reverse sense relative to said first winding portion so that the magnetic fields within said two annular cores caused by a current flowing through said first winding are in opposite directions, an insulating spacer between said winding portions, a third insulating film completely surrounding both of said winding portions and securing said cores together, said film comprising a winding of thermosetting

tape cured at elevated temperature, an annular shield layer of electrically conductive material on the outer surface of said third film, a gap in said annular layer and extending around the length of said annular layer, a strip of electrically conductive material in contact with said layer and extending around the length of said layer, a fourth insulating film of cured thermosetting plastic tape surrounding said layer and said strip, and a second winding encompassing both of said cores and overlying said fourth film.

8. A high-frequency saturable core variable inductance apparatus comprising first and second ferromagnetic ceramic core portions, a first winding around both of said core portions, said first winding including a first winding portion wound around said first core portion and a second winding portion wound around said second core portion, said second winding portion being wound in a reverse sense relative to said first winding portion so that the magnetic fields within said two core portions caused by a signal current flowing through said first winding are in opposite directions, a second winding magnetically coupled to each of said core portions and a pair of substantially continuous layers of electrically conductive silver paint closely adjacent all of the exposed surfaces of each of said core portions separating each of said winding portions from its respective core portion, each of said layers of silver paint having a closed insulating line therein to prevent short-circuit current from flowing in said layers around said core portions, whereby the hysteresis and eddy current losses in said core portions are reduced and the high frequency range and frequency response of said apparatus is extended.

9. A high-frequency saturable core variable inductance apparatus comprising first and second ferromagnetic ceramic cores, a first winding around both of said cores, said winding including a first winding portion wound around said first core, a second winding portion wound around said second core, said second winding portion being wound in a reverse sense relative to said first winding portion so that the magnetic fields within said two cores caused by a signal current flowing through said first winding are in opposite directions, a second winding associated with portions of both of said cores, and a pair of substantially continuous shields of electrically conductive material closely adjacent the exposed surfaces of each of said cores near each of said first and second winding portions, said two shields as seen in cross section defining an S-shape, each of said shields having an insulating gap therein to prevent short-circuit current from flowing in said shield around said cores, whereby the hysteresis and eddy current losses in said core pieces are reduced and the high frequency range and frequency response of said apparatus is extended.

10. A high frequency saturable core variable inductance apparatus comprising a core portion of ferromagnetic ceramic material, a winding around said core portion, a layer of electrically conductive paint applied directly to the surface of said core portion, and a second winding magnetically coupled to said core portion.

11. A high frequency saturable core variable inductance apparatus comprising a core portion of ferromagnetic ceramic material defining a substantially closed magnetically permeable path extending the length of said core, a first winding on said core portion, a layer of electrically conductive paint applied to the surface of said core and substantially completely surrounding said core portion, said layer having a gap therein extending along the length of said core generally parallel to said path, and a second winding magnetically coupled to said core portion.

12. A high frequency saturable core variable inductance apparatus comprising first and second ferromagnetic ceramic core portions, a first winding around one of said core portions, a second winding around the other of said core portions, said windings being connected in series with said second winding being in a reverse sense relative to said first winding so that the magnetic fields within said two core portions caused by current flowing through said first and second windings in series are in opposite directions, a third winding magnetically coupled to each of said core portions, and a layer of electrically conductive paint on the exposed surface of each of said core portions.

13. A high frequency saturable core variable inductance apparatus comprising first and second ferromagnetic ceramic core portions, a first winding around one of said core portions, a second winding around the other of said core portions, said windings being connected in series with said second winding being in a reverse sense relative to said first winding so that the magnetic fields within said two core portions caused by current flowing through said first and second windings in series are in opposite directions, a third winding magnetically coupled to each of said core portions arranged to control the magnetic saturation thereof, a layer of silver paint intermediate at least two of said windings, and a strip of silver foil in contact with said layer of silver paint.

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