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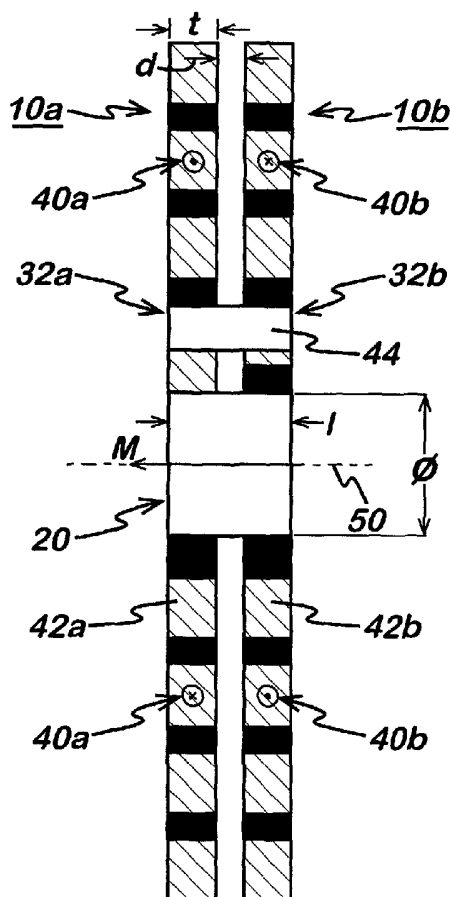
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(54) Title: MAGNETIC FIELD SENSOR



(57) Abstract: A sensor inductor (1) for magnetic fields, particularly of the saturating-core type, has at least one inductor coil (10) which is wound as a planar spiral about a core (20). More preferably a plurality of planar spirals (10a-10d) are stacked along the axis (50) of the core. A pair of adjacent coils (10a:10b) are wound as spirals of opposite sense with the inner ends (32a: 32b) connected together by bridges (44). Two or three such pairs may be used. The plural coils (10a-10d) and the central core (20) may be fabricated using planar selective deposition techniques known from the semiconductor industry. The magnetic core (50) may be a separate entity inserted into an axial hole formed through the stack of coils. A preferred core material is permalloy. Turns width (w), spacing (s) and thickness (t) of the spiral coils is discussed together with the axial spacing (d) between coils and core diameter (Φ)

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Title: Magnetic Field SensorFIELD OF THE INVENTION

5 This invention relates to a magnetic field sensor device and more particularly, though not exclusively to a sensor device for use with a magnetised transducer element which emanates a magnetic field that is a function of an applied torque or force. The invention also relates to a sensor circuit incorporating such a sensor device. Such circuits may be referred to as signal conditioning circuits.

10

BACKGROUND TO THE INVENTION

Magnetic transducers have found increasing application in recent times for measuring torque in a shaft. The magnetised transducer element is carried by the shaft and may be a magnetised region of it. A non-contacting sensor arrangement of one or more sensor devices is located adjacent the region. Non-contacting sensor devices are of particular advantage where the shaft under torque is rotating. Permanently magnetised transducer elements which emanate a torque-dependent magnetic field have the advantage of operating with sensor devices which may be regarded as passive in that they do not require active energisation to induce magnetisation in the transducer element.

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Sensor devices of various types are known including Hall effect and magnetoresistive devices and what are known as saturating or saturable core inductors. Various practical problems arise with each of these devices in the forms in which they are currently available.

25

Hall effect devices are produced in essentially planar form and their maximum sensitivity is perpendicular to the plane of the device. If used with the device plane lying radially, e.g. in respect of the axis of rotation of a shaft, the Hall effect device is sensitive to an axially directed (in-line) component of the magnetic field and is capable of high lateral resolution in the axial direction. Lateral resolution is not as good if the device is oriented at 90° to the radial plane to detect a radial field component. The major disadvantage of Hall effect devices is they have a low sensitivity and low resolution and are not adequate detectors of the small magnetic fields typical of magnetic transducer elements.

Magnetoresistive (MR) devices fall into two kinds: the anisotropic magnetoresistor (AMR); and the giant magnetoresistor (GMR). The latter has been more favoured in recent times. Both types of devices are essentially of planar form and exhibit a change in resistance which is dependent on the area dimensions of the device so that sensitivity has to be balanced against resolution. Also due to the small thickness such devices are limited in the range of magnetic field which they can detect. Although capable of higher lateral resolution than known saturable inductor devices they do not have as good a range as Hall effect devices and, as mentioned, compromise has to be found between resolution and sensitivity.

Saturable core sensor devices comprise an inductor in the form of a coil helically wound on a core. For example, the core may be of the material available from Allied Signal under the designation 2705M. This is a saturable

high permeability, cobalt-based amorphous metallic glass foil. One or more such inductors may be connected into a signal conditioning circuit such as that disclosed in published International application W098/52063. Saturable core sensor devices can be made with high sensitivity and two or more  
5 inductors can be connected in series in the signal conditioning circuit such that they act additively for the magnetic field to be measured but with cancellation of a common external field such as the Earth's magnetic field. A saturable core sensor device has an optimum sensitivity in the direction of the axis of the coil. The response pattern is circularly symmetrical about the axis.

10

The disadvantage of current saturable inductor sensor devices lies in their lack of lateral resolution. Typically they are 4-8 mm in length and 2 mm in diameter. The length dimension determines lateral resolution for a magnetic field component in the direction of the axis. The sensor response is effectively  
15 an integration of the field sensed along the length of the device, and the field may vary in both magnitude and direction over the length.

#### SUMMARY OF THE INVENTION

Consequently, there remains a need for magnetic field sensor devices of both  
20 high resolution and high sensitivity. In accordance with the present invention it is proposed to provide such a sensor device by means of a spiral coil formed about a core. The spiral lies essentially in a plane and the plane is preferably normal to an axis through the core. Such technology can be realised in essentially planar form using fabrication techniques known in semiconductor  
25 manufacture. The sensor device can have a plurality of spatially parallel spiral coils, preferably an even number, all acting on a single core element with a small overall length dimension.

As will be discussed subsequently, while the coils and the insulation (isolation) material on which they are supported can be formed using semiconductor fabrication techniques, the core can be provided as a separate entity which is inserted in an axial hole. The hole is formed during the  
5 fabrication process for the electrical structure or by drilling out after fabrication. The core may be a section of a wire of an appropriate magnetic material such as permalloy. The required magnetic properties are discussed further below.

10 A sensor device embodying the present invention may be connected as the magnetic field-sensitive element in a sensor circuit comprising means for driving the sensor device into or out of saturation, and means responsive to the driving of the sensor device to generate a signal dependent on a parameter of such driving as a measure of a sensed magnetic field.

15

A sensor device embodying the invention may find particular application as the saturable inductor in the signal conditioning circuit disclosed in above-mentioned W098/52063.

20 Aspects and features of the present invention are set forth in the claims following this description.

Preferred circuit arrangements for measuring a magnetic field for employing a saturable inductor in accord with this invention are set forth in Claims 8, 9 and

10. The circuit arrangements themselves are described in WO98/52063 which is hereby incorporated by reference.

The coil(s) employed in the implementation of the invention may be fabricated to small dimensions and referred to as microcoils. We are aware of proposals already made for fabricating microcoils. They have been applied as part of thin film write heads for data storage applications but they are not used as read heads sensing magnetic fields because of their extremely low sensitivity. Another proposal is to use a pair of facing spiral coils to provide an actuator (rather like a solenoid) developing a force between the turns of the coils due to the local interaction of magnetic fields created by current flowing through the coils. The Institute of Micro Technique (IMT) of the University of Braunschweig, Germany, have succeeded in producing a pair of microcoils for this purpose. This coil system has no magnetic core. What is of interest as regards an actuator is the forces generatable between current in the winding turns of one coil and current in the winding turns of the other coil. The work done so far is to verify the feasibility of fabricating the planar spiral coil structures but we are not aware that a practical actuator has yet been made.

It will be appreciated that in the proposals outlined in the preceding paragraph, the spiral coils investigated have not been applied to sensing a magnetic field. In contrast the present invention is directed to a structure for a magnetic field sensing application. The sensor device involves the use of a saturable core. The sensor device embodying the invention is directed towards combining high sensitivity and high resolution as already discussed.

The invention and its practice will be described further with reference to the accompanying drawings.

### BRIEF DESCRIPTION OF THE DRAWINGS

- 5 Fig. 1 shows the structure of a planar spiral coil with core to form a saturable inductor in accord with the invention, and Fig. 1a shows an enlarged portion of the spiral coil annotated with dimensional parameters;

Fig. 2 shows a face view of a pair of spiral coils of opposite winding senses as seen superimposed on one another;

- 10 Fig. 3 shows a diagrammatic axial section through a pair of parallel planar spiral coils structured and interconnected to produce an axial field of the same sense in a central core providing a saturable inductor in accord with the invention;

Fig. 4 is an enlarged view of the central portion of the structure of Fig. 3;

- 15 Fig. 5 is a diagrammatic axial section through another embodiment of a saturable inductor according to the invention using four parallel planar spiral coils in two pairs;

Fig. 6 is an enlarged view of the central portion of the structure of Fig. 5; and

- 20 Figs. 7a and 7b illustrate stages in a fabrication process for the spiral coils and core.

## DESCRIPTION OF PREFERRED EMBODIMENTS

Fig. 1 shows a single layer, spiral coil, saturable inductor 1 formed of a single spiral planar winding 10 extending clockwise (cw) from an outer end portion 31 to an inner end portion 32. The winding comprises a plurality of turns in which a turn may be taken as each 360° traverse of the winding about a central axis 50 with respect to a datum such as the radial line 12. The winding is in the form of a layer of conductive material having, in the illustrated example, a uniform width  $w$  and uniform turns spacing  $s$  better seen in Fig. 1a and a uniform thickness  $t$  perpendicular to the plane of the figure - see Fig. 4. Located and aligned on the central axis 50 is a saturable core 20 assumed to be of circular cross-section, better seen in Figs. 3 and 4. It is preferred for homogeneity (uniformity) of magnetisation across the cross-section of the core 20 that the coil winding is relatively tightly wound to be near circular in any one turn; that is the radius changes relatively slowly as a function of angle about the axis. This is further discussed below. The winding pitch is therefore  $(w + s)$  so that the radius increases by  $(w + s)$  over one turn (angle of  $2\pi$ ). Other relevant dimensional parameters are given on Fig. 4 and following the description of the design and fabrication of a saturable inductor embodying the invention, the effects of relative variation in certain parameters will be discussed. The parameters  $s$  and  $w$  are illustrated in Fig. 1a which shows a portion of two next adjacent turns of spiral 10, the turns being shown shaded.

If positive current flows from end 31 to end 32 the coil generates a magnetic field perpendicular to the coil along the axis 50 to act on core 20. For the cw winding direction shown the axial magnetic field direction will be out of the plane of Fig. 1.

The core material is magnetic preferably with a saturation magnetisation  $B_s$  less than one Tesla ( $10^4$  Gauss). Also the crystalline anisotropy constant (K) and magnetostriction constant ( $\lambda$ ) of the core material should be small in order to minimise noise sources due to internal stress induced in the core material during the deposition process to be described. A suitable material meeting these requirements is Permalloy (a Ni/Fe alloy ( $Ni_{78} Fe_{22}$ ) with other lesser constituents), the K and  $\lambda$  values for which are close to zero. Permalloy can be deposited by means of electroplating, sputtering and other deposition techniques, and can be subsequently etched.

In the planar fabrication technique to be described, it is more convenient to make external connection to the outer end 31 of the spiral coil 1 than to the inner end 32. The convenience of external connections on the outer side of the inductor can be met by a pair of spatially-parallel, spiral coils wound with opposite sense (one cw, one ccw) about the axis 50. The inner ends are connected together and the energisation source applied to the outer ends to energise the coils in series. Having the spirals of opposite sense ensures that they generate magnetic flux in the core in the same sense. The employment of multiple spiral coils is also beneficial to achieving the desired saturation of the core. Also the use of multiple parallel coils is consistent with the use of an axially longer core which is also beneficial in reducing demagnetisation of the core. These factors are further discussed below.

Fig. 2 is a face view of a pair of oppositely wound spiral coils 10a and 10b showing one superimposed on the other (hence the interference pattern), connected at their respective inner ends 32a and 32b and energisable at their

respective outer ends 31a and 31b. The coils act to generate the same sense of magnetic flux in a common core 20. In practice coils 10a and 10b lie in spaced parallel planes normal to axis 50 as is better seen in Figs. 3 and 4.

5 Fig. 3 is a diametric axial view through the pair of coils 10a and 10b in which the winding turns such as 41a, 41b and 42a, 42b are shown shaded. Turns 41a, 42a are within the same spiral coil (10a) but are indicated separately because the current directions in them are opposite relative to the plane of the figure: likewise with turns 41b, 42b of coils 10b. In the diametric section  
10 illustrated the turns of the coils 10a, 10b are axially aligned - superposed as seen in the face view of Fig. 2. A diametric section at 90° to that of Fig. 2 would show the turns staggered or interleaved. Fig. 4 is an enlarged view of the central portion of the structure of Fig. 3. Fig. 4 also illustrates the thickness parameter  $t$  for the coil layers, that is the thickness in the axial  
15 direction.

From Figs. 3 and 4, it can be seen that the core 20 extends through both coils. The inner end portions 32a and 32b, which preferably overlap as seen in a face view, are connected by an axial throughbridge 44 to connect the coils in  
20 series. By connecting the outer ends 31a and 31b to an energisation source (not shown), the currents in the turns on one side of the axis 50 will be as indicated at 40a and 40b with the current directions normal to the plane of the drawing being opposite in the two spirals 10a, 10b as indicated, and on the other side of the axis 50, the directions being the reverse as indicated at 40'a  
25 and 40'b, therefore remaining oppositely directed in the two coils. The currents act additively to produce a magnetic field  $H$  in the core 20 directed along axis 50. The resultant magnetic flux and magnetisation in the core 20 are also essentially in the axial direction.

Fig. 4 also shows other dimensional parameters which are discussed below. These are: the spacing  $d$  between the adjacent layers, the diameter  $\Phi$  of the core 20 and its axial length  $l$ .

5

The above concept is extendable to further pairs of spirals coils as is shown in Figs. 5 and 6. In addition to coil pair 10a, 10b there is another like pair of coils 10c, 10d. The core 20 extends through all four spatially parallel coils. As in Figs. 3 and 4 the winding turns are shown shaded, e.g. 41a, 41d and 42a, 42d. Coils 10a, 10b are connected at their inner ends by bridge 44a; the coils 10c, 10d are similarly connected by bridge 44b. The coils in sequence along the axis have alternating winding sense, e.g. cw-ccw-cw-ccw. The outer end of coil 10b is connected to the outer end of adjacent coil 10c by axially-directed bridge 46 so that the coils are in electrical series connection for energisation by a source (not shown) connected to ends 31a and 31d. The same current flows in each coil. The resultant alternate current directions are indicated at 40a-40d above the axis and at 40'a-40'd below the axis where the directions are reversed. It will be understood that other winding senses and interconnections are possible (e.g. parallel and series/parallel combinations) provided that each coil produces a magnetic field in the core of the same sense. It will also be understood that odd numbers of coils are usable but that by having even numbers all external connections can be made at the outer periphery of the coil assembly.

25 The spiral coils may be any conductive material of low specific resistance, and preferably non-magnetic. Among such conductors are aluminium, copper and

gold. The preference for non-magnetic materials is the avoidance of the creation of parasitic magnetic fields within the conductors themselves.

As already indicated above, the spiral coil structure described above can be implemented using techniques known in the semiconductor and related arts, the structure being fabricated layer-by-layer with the coils at 90° to the orientation shown in Figs. 3-6. Steps in the fabrication are diagrammatically illustrated in Figs. 7a and 7b.

10 Fig. 7a shows an insulating layer or substrate 100 on which is deposited a first layer of conductive material, e.g. Al, Cu, Au, forming a spiral coil 110a using masking, e.g. photo-lithographic, and, if appropriate, etching techniques well known in the art. Also deposited in the first layer is a central boss 120 of the core material such as Permalloy. This is followed by another layer 102 of  
15 insulating material, e.g. an oxide such as AlO<sub>2</sub> or SiO<sub>2</sub>, which is apertured at 122 and 124 as shown in Fig. 7b. The aperture 122 overlays the inner end portion of coil 110a and the aperture 122 overlays the core 124. The deposition of a second spiral 110b above layer 102 also causes deposition of conductive material through aperture 122 to form a bridge connection 144 of  
20 the inner ends of coils 110a and 110b. The core material is deposited through aperture 124 to form a continuation 120' of core 120. The fabrication steps can be repeated to form further planar spiral coils in a stack with adjacent coils axially spaced apart. It will be noted, however, that in accordance with the scheme of Figs. 5 and 6, the next coil layer above 110b would be isolated  
25 from layer 110b at the inner end and a bridging connection made at the outer ends.

The formation of the electrical components of the structure of Figs. 7a and 7b may be separated from the provision of the magnetic core. The structure could be fabricated with the core aperture 124 but without depositing the core material. The core could be inserted into the hole as a separate entity, e.g. a section of a wire of the core material. The aperture 124 could be initially omitted in the layer-by-layer fabrication so that the axial region is composed of the insulating material. The structure thus fabricated may be then drilled to receive the core as a separate entity as just described. It may prove desirable in these circumstances to radially space the inner ends of the coils further from the coil and to compensate for any consequent loss of magnetic field in the core by increasing the thickness  $t$  of the coils. There is a discussion below of various parameters of the sensor device produced in accord with the teaching given above.

The spiral coils in the described embodiments are "circular", that is they are of the  $r = p\theta$  form, where  $r$  is the radius,  $\theta$  is the angle about the axis and  $p$  a constant. Other spiral shapes could be adopted but the desirability of homogeneity of magnetisation in the core should be kept in mind. It is, of course, possible to have a core cross-section other than circular and the winding shape may be selected in relation to the shape of the cross-section.

For the reasons already explained the minimum preferred configuration for a coil system consists of two spirals (Figs. 2 and 3) with a common core. In principle there is no limitation of the winding direction and connection of the spirals of a coil system. As already described, a preferred design for the coil system is to fabricate successive spiral conductor layers with alternating winding directions, to connect the spirals in pairs by a connection made at the inner ends of a pair and to connect successive pairs (assuming there is more

than one pair) at the outer ends of adjacent spirals. This is the design scheme adopted in Fig. 5. The outer ends of the two outermost spirals of the complete group are then used for serial energisation of the group. By this combination of winding direction and interconnection, the current applied to all spirals results in a magnetic flux of the same direction being induced in the common core. Using an even number of spirals per coil system also enables the connecting leads for the circuit into which the saturable inductor is to be connected to be always on the outside of the spirals. By this means there is no need to add a separate layer for a lead from the energising source to connect the central end of a spiral. Using separate leads for contacting each spiral individually would allow the same winding sense to be adopted for each coil but would lead to additional layers which would always result in a poorer flatness of the following layer to be deposited. Flatness of the layers is important in achieving a homogenous field distribution. A balance has to be drawn between the benefits of using more coil layer pairs and the better saturation of the core and enhanced sensitivity on the one hand, and the increasing dimensional errors in the fabrication process and the loss of resolution as the core lengthens, on the other hand. The number of windings of a spiral has to be optimised according to the resulting flux density to be induced in the core and the resistance of the lead (given by the specific resistance and the length of the lead). A higher number of turns does not necessarily increase the resulting flux density to the same factor but increases the overall resistance and thus the power consumption of the coil system. For a given cross section of the lead, e.g. 16  $\mu\text{m}$  (thickness) x 20  $\mu\text{m}$  (width) and of copper, selecting the number of turns for each spiral in the region of twenty (20) is to be preferred in terms of resistance and achievable flux density. Any other cross section of the lead may result in different numbers of turns being preferred.

A set of four spirals can be used to achieve a coil system with more windings and a longer core. Doubling the number of spirals will certainly increase the saturable inductor's resistance (and power consumption) assuming all coils are series connected but will increase the flux density induced in the core by the same factor. More relevant than increasing the number of spirals is the geometry of the core. An axially short core has a worse demagnetisation factor  $N$  ( $0 < N < 1$ ) compared to a longer core, with both having the same core diameter. A large demagnetisation factor  $N$  will then result in a demagnetising field at the open ends of the core which then cannot be fully saturated by the coil system. The longer the core, the lower is the fraction of the core volume that cannot be saturated and thus its influence on system efficiency. Having regard to these factors a spiral number of six (6) (3 pairs) or more is to be preferred to achieve an acceptable demagnetisation factor  $N$  of the core.

15

It is contemplated that magnetic field sensor devices in accord with this invention can be fabricated to have an axial length in the region of 0.1 to 0.2 mm and a diameter in the region of 1 to 2mm.

20 One or more saturable core inductors of the invention may be used as the inductor  $L$  in the signal conditioning circuits described in above-mentioned specification W098/52063 so as to provide an output representing the magnetic field sensed by the inductor(s).

25 Mention has been made above of factors and dimensional parameters which may bear upon the performance of the saturable inductor as a saturating core sensor for magnetic fields. The core should be operated in such a way that it

is highly sensitive to an external magnetic field acting in conjunction with that generated by the coil structure associated with the core. The operation of the saturating core in the presence of an external magnetic field to be detected is to produce an output signal which is a function of the detected field. One way  
5 in which to operate a saturating core for this purpose is disclosed in aforementioned W098/52063.

A study has been made to investigate aspects of the saturating inductor design and the magnetic field distribution in and about it. This study has been  
10 made by way of a computer simulation. In general it is important to adopt a design in which as far as possible the whole of the core is driven into saturation. A fully saturated core may be referred to as homogeneously saturated and the quantitative degree of saturation can be expressed as the homogeneity of saturation.

15

For the computer simulation, the core material was selected to be the previously mentioned Ni/Fe alloy,  $\text{Ni}_{78}\text{Fe}_{22}$ . This material has no crystal anisotropy  $K$  and no magnetostriction  $\lambda$ . Due to the described fabrication process, magnetic properties cannot be known precisely but a good working  
20 estimate can be made for the chosen dimensions, namely: saturation magnetisation  $B_s \approx 0.8\text{T}$ ; coercivity  $H_c \approx 2.4\text{ A/m}$ , and permeability  $\mu_r \approx 1000$ .

The conductor material for the coil(s) was selected to be copper with a cross-section ( $t \times w$ ) of  $8\ \mu\text{m} \times 20\ \mu\text{m}$ . The preferred thickness obtained from the  
25 simulation discussed below is  $16\ \mu\text{m}$ . The spacing  $s$  of the next adjacent turns was selected as  $10\ \mu\text{m}$  giving a pitch ( $w + s$ ) per turn of a spiral coil of  $30\ \mu\text{m}$ .

For the simulation procedure, the current density was considered as that existing in a winding whose width is taken to be the full winding pitch ( $w + s$ ) in which a uniform (homogeneous) direct current density  $J_h$  exists. The value of  $J_h$  is related to the current density  $J$  in the winding width  $w$  by the proportion of actual conductor width  $w$  to the full pitch ( $w + s$ ) to give a current density relationship of  $J_h = J.w/(w + s) = J/1.5$  in the winding example quoted above. The energising current  $I$  was selected as 150 mA which gives a current density  $J = 0.9375\text{kA/mm}^2$  in the simulation model and calculations were based on a uniform current density  $J_h = 0.625\text{kA/mm}^2$ .

The simulations conducted concentrated on magnetic properties only and did not take into account any effects like heat due to current density, the quality of the electrical isolation between turns or inhomogeneities or imperfect material properties (e.g.  $B_s$ ,  $\mu_r$ ,  $H_c$ ). The following aspects of the design were considered.

### Core Material

In order to measure an external magnetic field by saturating the core of an inductor under the influence of the external magnetic field, the saturation magnetisation  $B_s$  of the core has to be low. It is also desirable to have low magnetostrictive effects within the core to reduce noise. This can be achieved by using an amorphous material which has no crystallographic preferred axis, such as a metallic glass. Unfortunately metallic glass cannot be deposited on a substrate. Candidate materials for deposition on substrates are the  $\text{Ni}_{78}\text{Fe}_{22}$  alloy (Permalloy) already mentioned, Nickel itself and other Ni/Fe alloys, such as  $\text{Ni}_{65}\text{Fe}_{35}$ . An Ni core does not saturate sufficiently. The  $\text{Ni}_{65}\text{Fe}_{35}$  alloy

does saturate well as does Permalloy but only the latter has no crystalline anisotropy or magnetostriction. The last-mentioned factors lead to increased noise.

#### Core Diameter ( $\Phi$ )

- 5 To achieve saturation of the core the length of the core should be about the axial length of the stack of planar spiral coils. The aspect ratio of the core (diameter/length) is important because increasing the diameter will increase the demagnetisation factor. This could be counteracted by a core material with a higher coercivity  $H_c$ . However, this then leads to the use of a material
- 10 with greater crystallographic anisotropy which leads to magnetostriction. The problems then arising are discussed under "Core Material" above.

#### Core Length (l)

- A spiral coil is relatively flat - i.e. thin in axial direction - and radially wide. This
- 15 leads to a magnetic field strongly concentrated within the coil and within a stack of closely-spaced coils. Therefore, it is preferred to use a core with the same axial length as the axial length occupied by the stack of spiral coil. Also maintaining the core length low is advantageous in achieving a good axial or lengthwise resolution of the sensor device.

20

#### Number (C) of Spiral Coils

- The use of a plurality or stack of axially separated spiral coils has already been exemplified in the illustrated embodiments of the invention. The effect of each spiral on its immediate neighbours is considerable. The field lines of
- 25 each spiral are closed by the field lines of its adjacent spiral(s), thereby

enhancing the axial field in the core. As already noted an even number of spirals in counter-wound pairs, is preferred and a value of  $C = 4$  is beneficial, while  $C = 6$  or more is better. It is to be noted that as the number of spirals formed by a deposition process as described with reference to Figs. 7a and 7b is increased, there is an increasing likelihood of inaccuracy in the dimensions of each spiral coil formed so that going beyond  $C = 6$  may not necessarily bring the benefits expected. It would also increase the core length.

#### Number (n) of Turns per Coil

As the number of turns of a spiral coil is increased the outer turns have lesser effect on the magnetic flux in the core. For the dimensions contemplated in the practice of the present invention it is presently preferred to use between 20 and 30 turns. Beyond 30 turns the further enhancement of the core flux becomes small.

15

#### Thickness (t) of Conductor Layer

As the layer thickness is increased the overall length of the stack of coils is increased without reducing the uniformity of magnetisation of the core (homogenous magnetisation) even though the volume of core material is increased. In addition a thicker conductor layer (but of the same width  $w$ ) allows the current in the winding to be increased for the same allowed current density. This in turn increases the amount of saturated material in the core. Presently a conductor layer thickness  $t = 16\mu\text{m}$  is preferred.

#### 25 Spiral Coil Spacing (d)

In contrast to the effect of increasing conductor layer thickness, increasing the spacing or separation between adjacent conductor layers, while likewise increasing the length of the core, will reduce the homogeneity of core magnetisation. In the embodiments described a spacing  $d = 10\mu\text{m}$  is preferred.

Claims

1. A magnetic field sensor device of the saturable inductor kind comprising a saturable core and a conductive winding extending about an axis through the core, characterised in that the winding comprises:  
5 at least one coil, the or each coil being wound in a spiral lying essentially in a respective plane.
2. A magnetic field sensor as claimed in Claim 1 in which the or each plane is normal to said axis.  
10
3. A magnetic field sensor device as claimed in Claim 1 or 2 in which the winding comprises two adjacent coils wound in respective spirals of opposite winding sense with the inner ends of the two spiral coils being connected together to provide a series current path between their respective outer ends.  
15
4. A magnetic field sensor device as claimed in Claim 1, 2 or 3 in which at least the spiral coil(s) are fabricated in layer-by-layer fashion and spaced by an insulating material.
- 20 5. A magnetic field sensor device as claimed in Claim 1, 2, 3 or 4 in which the number of spiral coils is at least four.

6. A magnetic field sensor device as claimed in any preceding claim in which the core is of Permalloy material.

7. A sensor circuit for magnetic field sensing comprising:

5 a magnetic field sensor device responsive to a magnetic field;

means for driving said sensor device into or out of saturation; and

means responsive to said driving of said sensor device to generate a signal dependent on a parameter of such driving as a measure of a sensed magnetic field.

10

8. A circuit arrangement for measuring a magnetic field comprising:

a saturable inductor for sensing a magnetic field to be measured;

an oscillator circuit connected to said inductor for driving said inductor with a voltage waveform that causes the inductor to saturate in opposite  
15 directions in successive half cycles;

means including a current-to-voltage converter connected to said inductor to generate an output signal representing the imbalance of saturation in successive half-cycles due to the magnetic field, wherein

said oscillator circuit is operable to drive said inductor to produce an  
20 average current in the inductor per oscillator cycle which is a measure of said imbalance, and

said current-to-voltage converter is responsive to said average current to generate a voltage representing said average current, characterised in that

said saturable inductor comprises at least one magnetic field sensor device as claimed in any one of Claims 1 to 6.

9. A circuit arrangement for measuring a magnetic field comprising:

5 a saturable inductor for sensing a magnetic field to be measured;

an oscillator circuit connected to said inductor for driving said inductor with a voltage waveform that causes the inductor to saturate in opposite directions in successive half-cycles;

10 means connected to said inductor to generate an output signal representing the unbalance of saturation in successive half-cycles due to the magnetic field, wherein

said oscillator circuit comprises means switchable between two states to generate said voltage waveform, and current sensing means connected to said switchable means and responsive to the current through said inductor to  
15 cause said switchable means to switch at substantially equal magnitudes of current in successive half-cycles, characterised in that

said saturable inductor comprises at least one magnetic field sensor device as claimed in any one of Claims 1 to 6.

20 10. A circuit arrangement for measuring a magnetic field comprising; a saturable inductor for sensing a magnetic field to be measured;

an oscillator circuit connected to said inductor for driving said inductor with a voltage waveform that causes current flow in the inductor to saturate the inductor in opposite directions in successive half cycles;

means including a current-to-voltage converter connected to said  
5 inductor to generate an output signal representing the imbalance of saturation in successive half-cycles due to the magnetic field, wherein

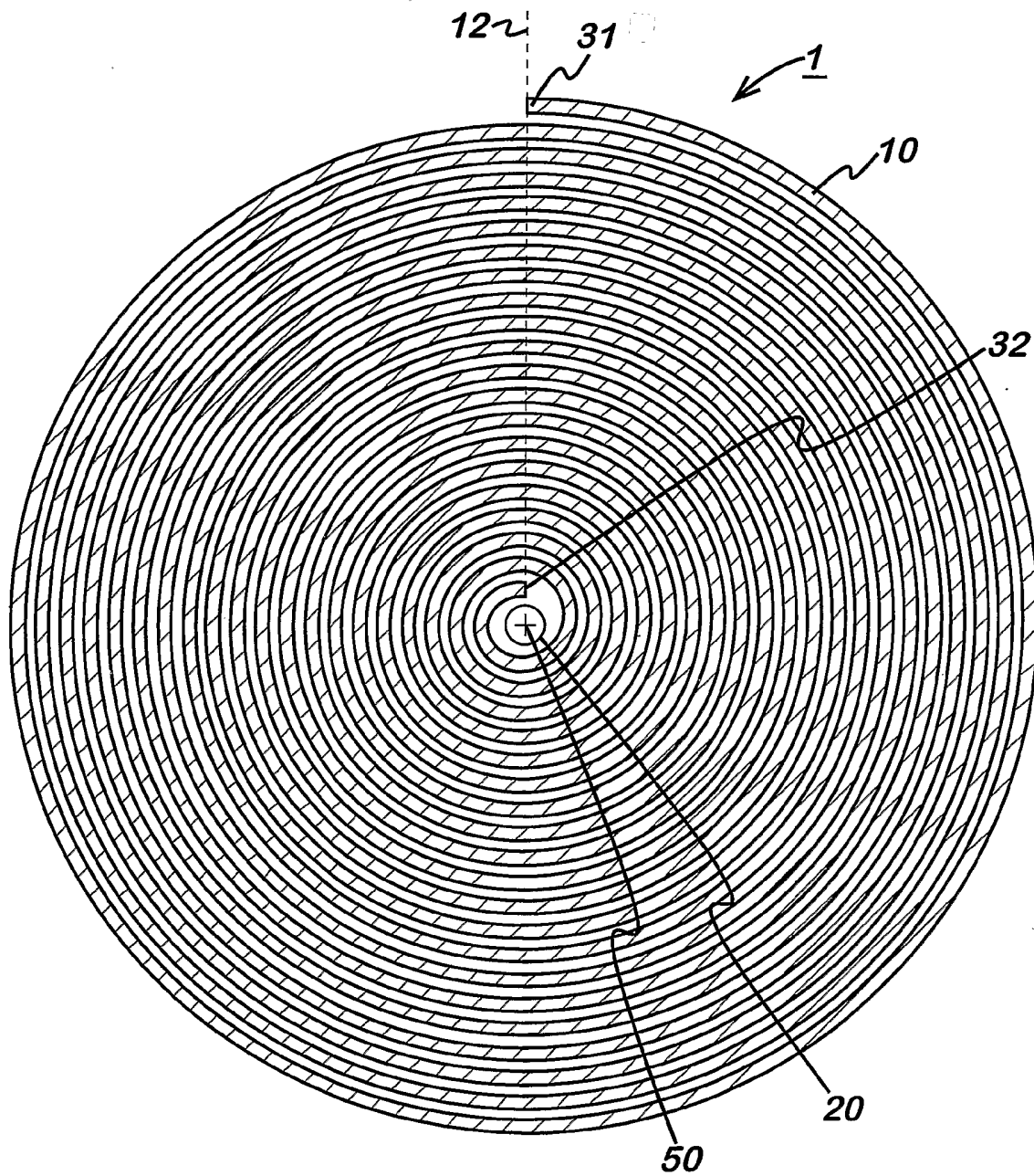
said oscillator circuit is operable to drive said inductor to produce an average current in the inductor per oscillator cycle which is a measure of said imbalance, and

10 said current-to-voltage converter is connected in a circuit path through which inductor current flows and is responsive to said average current in the inductor to generate a voltage representing said average current,  
characterised in that

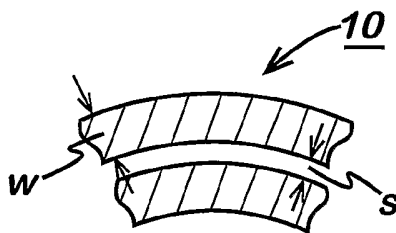
said saturable inductor comprises at least one magnetic field sensor  
15 device as claimed in any one of Claims 1 to 6.

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**Fig. 1**



**Fig. 1a**



**Fig. 2**

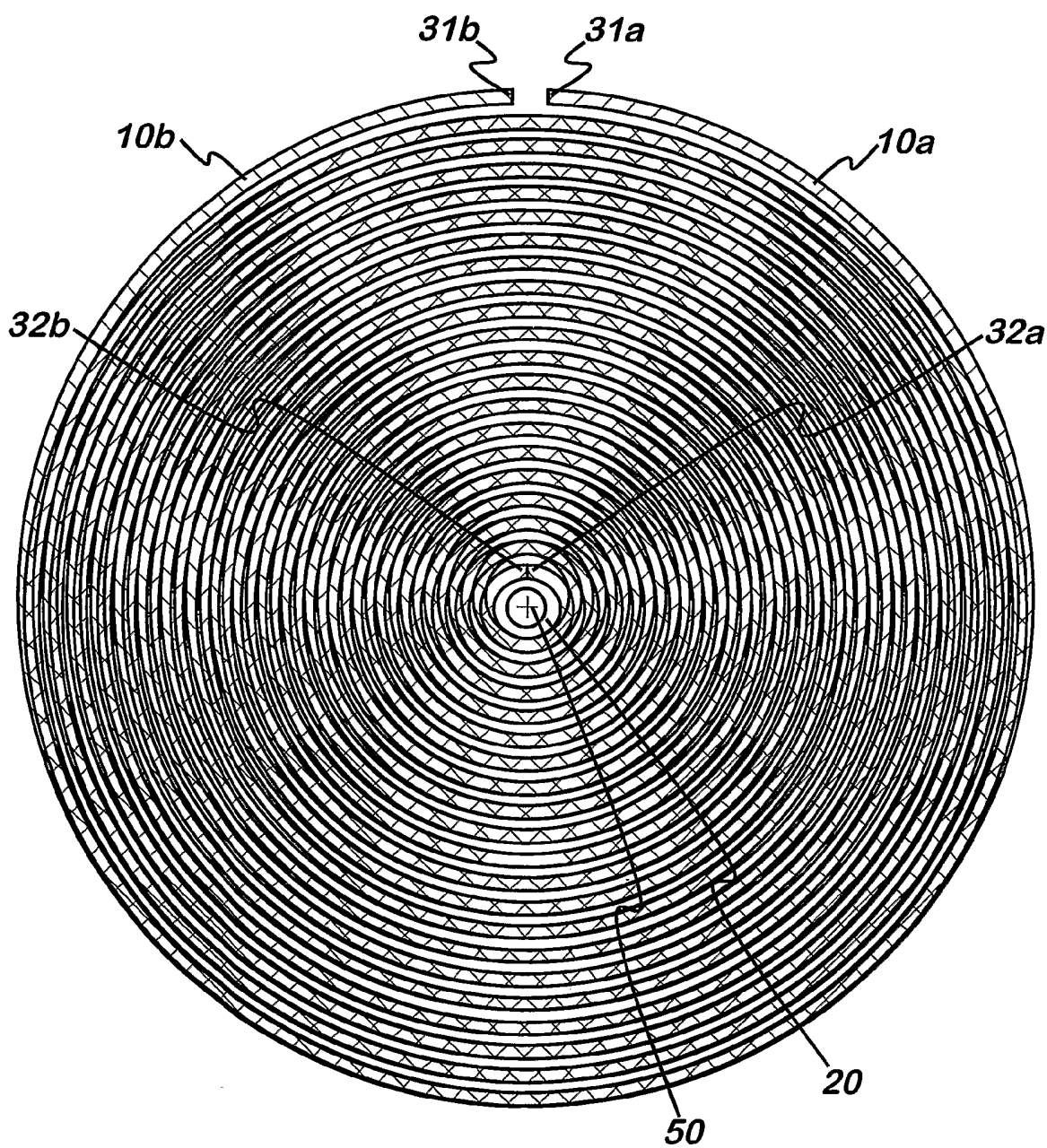


Fig. 3

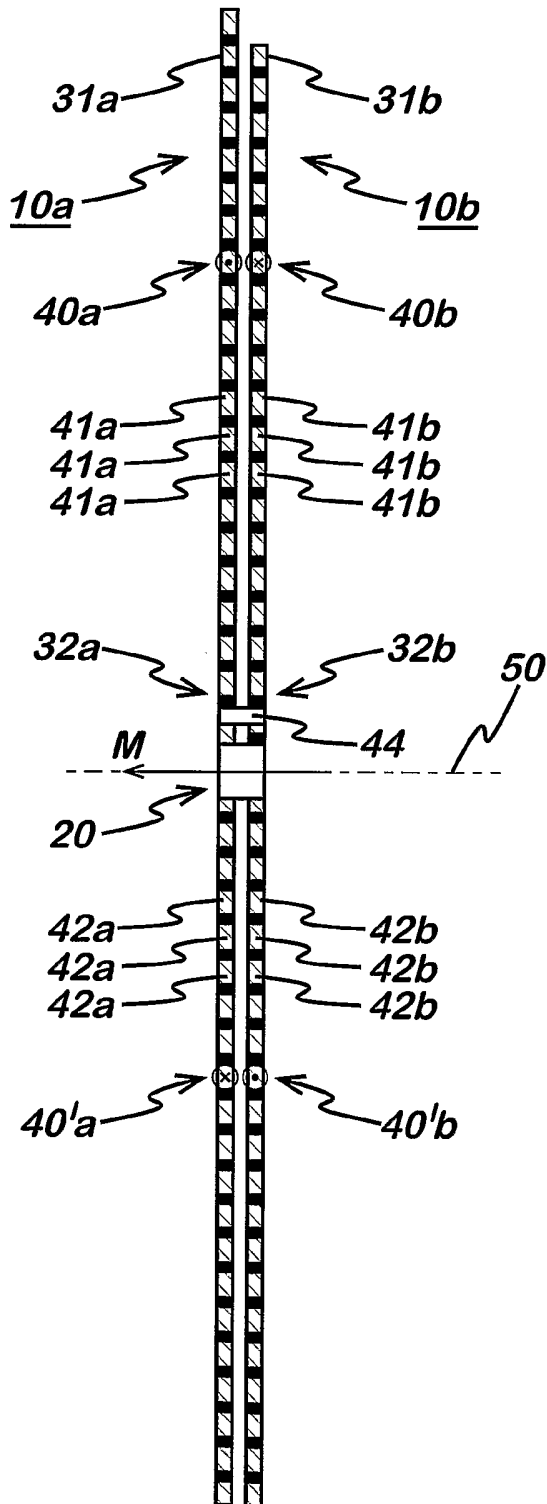
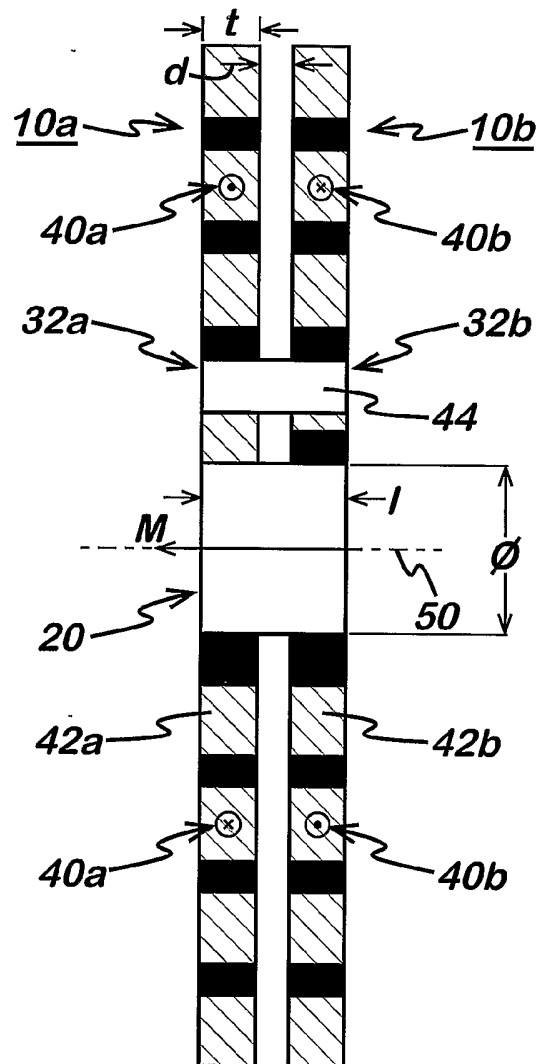


Fig. 4



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Fig. 5

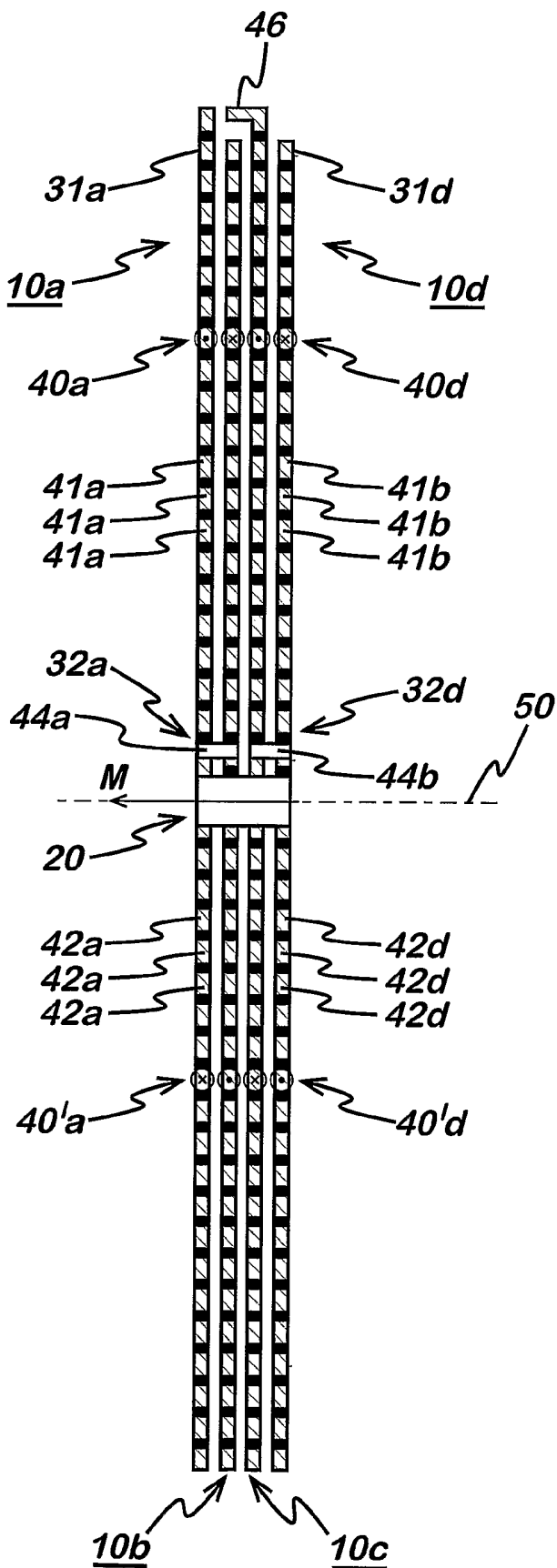
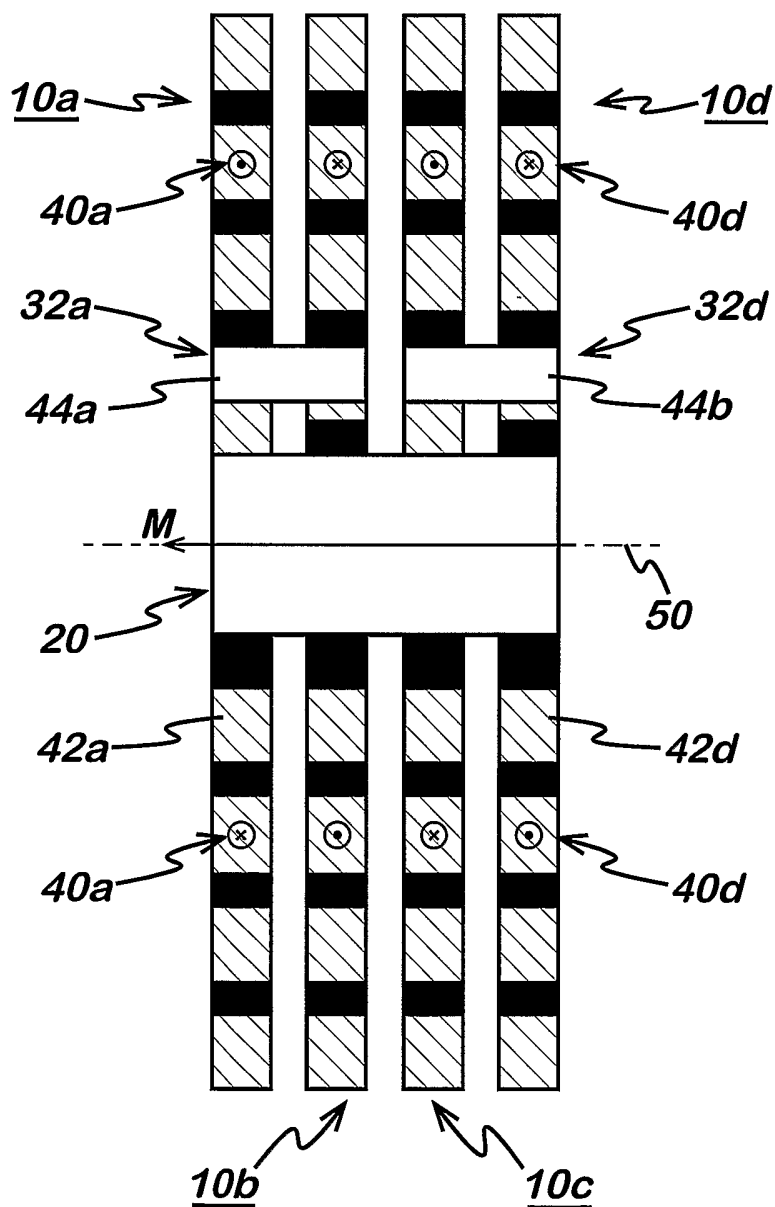
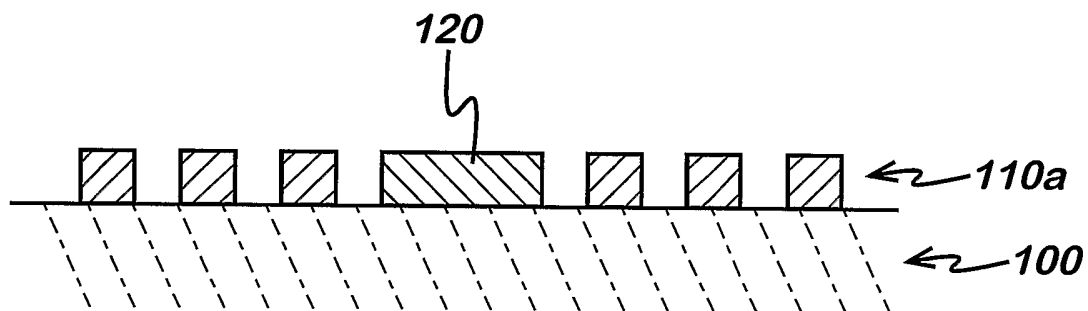


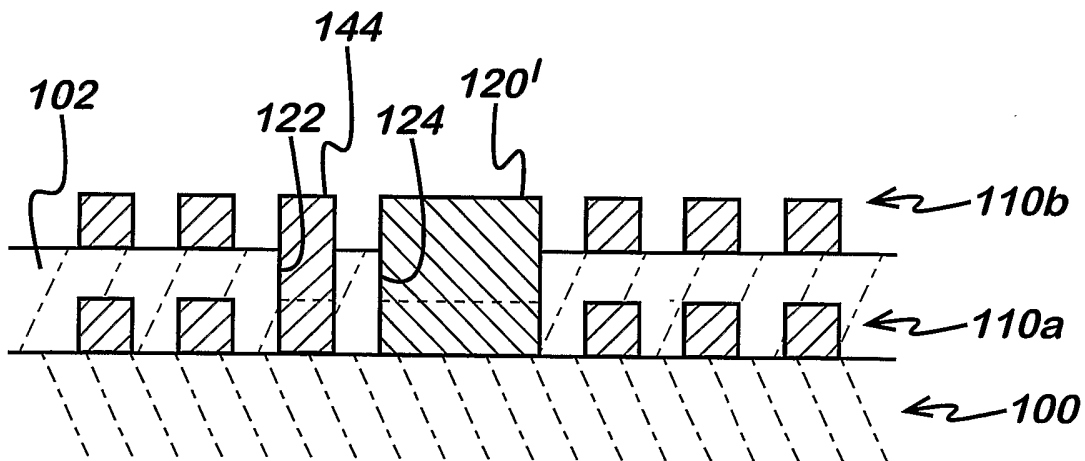
Fig. 6



**Fig. 7a**



**Fig. 7b**



INTERNATIONAL SEARCH REPORT

International Application No  
PCT/EP 02/08820

<b>A. CLASSIFICATION OF SUBJECT MATTER</b> IPC 7 GO1R33/04		
According to International Patent Classification (IPC) or to both national classification and IPC		
<b>B. FIELDS SEARCHED</b>		
Minimum documentation searched (classification system followed by classification symbols) IPC 7 GO1R GO1L		
Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched		
Electronic data base consulted during the international search (name of data base and, where practical, search terms used) EPO-Internal, INSPEC		
<b>C. DOCUMENTS CONSIDERED TO BE RELEVANT</b>		
Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	TSUJIMURA T ET AL: "Electromagnetic system determining the position of tunnelling robots" IEE PROCEEDINGS: RADAR, SONAR & NAVIGATION, INSTITUTION OF ELECTRICAL ENGINEERS, GB, vol. 147, no. 6, 1 December 2000 (2000-12-01), pages 331-336, XP006014435 ISSN: 1350-2395 page 332 -page 335 figures 2-14	1-5,7-10
X	ES 2 036 454 A (ALCATEL STANDARD ELECTRICA) 16 December 1995 (1995-12-16) column 4, line 53 -column 6, line 8 figures 1,4	1-5,7-10
-/--		
<input checked="" type="checkbox"/> Further documents are listed in the continuation of box C. <input checked="" type="checkbox"/> Patent family members are listed in annex.		
° Special categories of cited documents :		
*A* document defining the general state of the art which is not considered to be of particular relevance *E* earlier document but published on or after the international filing date *L* document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified) *O* document referring to an oral disclosure, use, exhibition or other means *P* document published prior to the international filing date but later than the priority date claimed *T* later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention *X* document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone *Y* document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art. *&* document member of the same patent family		
Date of the actual completion of the international search  28 November 2002		Date of mailing of the international search report  06/12/2002
Name and mailing address of the ISA European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016		Authorized officer  Modesto, C

## INTERNATIONAL SEARCH REPORT

Int'l Patent Application No

PCI/EP 02/08820

## C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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A	column 2, line 1 -column 5, line 50 figures 1-4	4-6
A	--- WO 98 52063 A (MAY LUTZ AXEL ;BROKAW ADRIAN PAUL (US)) 19 November 1998 (1998-11-19) cited in the application page 4 -page 17 figures 1,2	6-10
A	--- COHEN L G ET AL: "Effects of coil design on delivery of focal magnetic stimulation. Technical considerations" ELECTROENCEPHALOGRAPHY AND CLINICAL NEUROPHYSIOLOGY, APRIL 1990, IRELAND, vol. 75, no. 4, pages 350-357, XP002222159 ISSN: 0013-4694 the whole document -----	1-4

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Information on patent family members

International Application No

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Patent document cited in search report	Publication date	Patent family member(s)	Publication date
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