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(54) Title: A COIL ARRANGEMENT

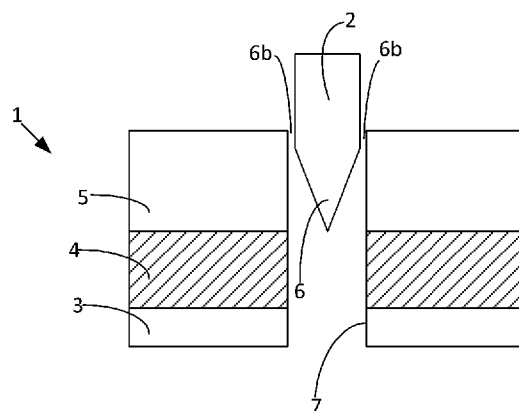


Figure 1a

(57) Abstract: A coil arrangement for an inductive power transfer system comprising a core (32, 33) having a region of decreased permeability (34), a coil (45) associated with the core, and a tuning slug (35) which is moveable along an axis adjacent the region of decreased permeability in order to adjust the inductance of the coil arrangement, the tuning slug (35) having an effective permeability which varies along said axis.



## A COIL ARRANGEMENT

### FIELD OF THE INVENTION

The present invention is in the field of wireless power transfer systems. More particularly, but not exclusively, the invention relates to magnetically permeable  
5 cores incorporated into transmitter coils, receiver coils and inductors in resonant and non-resonant circuits of wireless power transfer systems.

### BACKGROUND OF THE INVENTION

10 In the production of winding cores for inductors, manufacturing variations causing small variations in inductance can significantly affect performance, especially for resonant circuits. One particular kind of ferromagnetic core used in the production of inductors is known as a "gapped core". The ferromagnetic core may be shaped into a circle or rectangle or other suitable shape with a  
15 section removed to form an air gap. These are typically used to address saturation and other performance issues. It is difficult to trim gapped cores as the introduction of small amounts of magnetically permeable material into the air gap can result in a significant change in inductance.

20 One solution is to introduce a moveable magnetic slug however this can result in significant non-linear changes in inductance of a wound gapped core. To obtain better precision, a fine screw thread is cut on the face of the slug and the faces on either side of the air gap are correspondingly tapped. However, the precision machining required to achieve precise trimming can be expensive.

25

It is an object of the invention to provide an improved coil arrangement or to at least provide the public with a useful choice.

**SUMMARY OF THE INVENTION**

According to one exemplary embodiment there is provided a coil arrangement for an inductive power transfer system comprising:

- a. a core having a region of decreased permeability,
- 5 b. a coil associated with the core, and
- c. a tuning slug which is moveable along an axis adjacent the region of decreased permeability in order to adjust the inductance of the coil arrangement, the tuning slug having an effective permeability which varies along said axis.

10

According to another exemplary embodiment there is provided a coil arrangement for an inductive power transfer system comprising:

- a. a core having a region of decreased permeability and a bore passing through the region of decreased permeability;
- 15 b. a coil associated with the core, and
- c. a tuning slug which tapers at one end and is movable along the bore into the region of decreased permeability to adjust the inductance of the coil arrangement.

20 According to another exemplary embodiment there is provided a coil arrangement for an inductive power transfer system comprising:

- a. a core having a region of decreased permeability and a bore passing through the region of decreased permeability;
- b. a coil associated with the core, and
- 25 c. a tuning slug having progressively increasing effective permeability from one end thereof and being movable along the bore into the region of decreased permeability to adjust the inductance of the coil arrangement.

It is acknowledged that the terms “comprise”, “comprises” and “comprising” may, under varying jurisdictions, be attributed with either an exclusive or an inclusive meaning. For the purpose of this specification, and unless otherwise noted, these terms are intended to have an inclusive meaning – i.e. they will be taken to mean an inclusion of the listed components which the use directly references, and possibly also of other non-specified components or elements.

Reference to any prior art in this specification does not constitute an admission that such prior art forms part of the common general knowledge.

10

#### **BRIEF DESCRIPTION OF THE DRAWINGS**

The accompanying drawings which are incorporated in and constitute part of the specification, illustrate embodiments of the invention and, together with the general description of the invention given above, and the detailed description of exemplary embodiments given below, serve to explain the principles of the invention.

- Figure 1a** shows a cross sectional view of a tuning slug having a conical end engaged in a bore of a core in a first position;
- 20 **Figure 1b** shows a cross sectional view of a tuning slug having a conical end engaged in a bore of a core in a second position;
- Figure 1c** shows a cross sectional view of a tuning slug having a conical end engaged in a bore of a core in a third position;
- Figure 2** shows a plan view of the core and tuning slug shown in Figure 1a;
- 25 **Figure 3** shows a cross sectional view of a tuning slug having a wedge shaped end engaged in a bore of a core;
- Figure 4** shows a cross sectional view of a tuning slug having an elliptical end engaged in a bore of a core;

- Figure 5** shows a cross sectional view of a tuning slug of composite construction engaged in a bore of a core;
- Figure 6** shows a shows a cross sectional view of a tuning slug having a partial conical end engaged in a bore of a core;
- 5 **Figure 7** shows a shows a cross sectional view of a tuning slug having a single step conical end engaged in a bore of a core;
- Figure 8** shows a cross sectional view of a tuning slug having a multi-step conical end engaged in a bore of a core;
- Figure 9** shows a cross sectional view of a two part tuning slug engaged in  
10 a bore of a core;
- Figure 10** shows a cross sectional view of a tuning slug having an elliptical end engaged in a bore of a core having inverted regions of permeability;
- Figure 11** shows a cross sectional view of a tuning slug advanced and  
15 retracted into a bore of a core by an actuator;
- Figure 12** shows a coil arrangement in which the core has a gap formed by a layer of low permeability;
- Figure 13** shows a coil arrangement in which the core is formed in two parts  
20 with a gap that is adjustable by relative movement of the two parts;
- Figure 14** shows a coil arrangement in which the core has an internal gap adjacent its bore;
- Figure 15** shows a coil arrangement in which the core has an external gap a  
25 gap and the tuning slug is in the form of a ring moveable along the core adjacent the gap;
- Figure 16** shows a transmitter and receiver coil pair; and
- Figure 17** shows a tuning slug having a cavity at one end engaged in the bore of a core.

**DETAILED DESCRIPTION OF EMBODIMENTS OF THE INVENTION**

Referring to Figures 1 and 2 a first core topology will be described. The core 1 is of annular form having a slug 2 located within its central bore 7. Core 1 consists of a first layer 3 of high permeability material, a second layer 4 of lower permeability material and a third layer 5 of high permeability material. References in this specification to “permeability” are to magnetic permeability. Layers 3 and 5 may be formed of a material such as ferrite. The second layer 4 may have lower permeability than layers 3 and 5 due to the entire volume of the layer 4 being formed of lower permeability material or due to part of the layer 4 being a low permeability material, such as air, and the remainder being a high permeability material such as layers 3 and 5 (e.g. a gapped core). This same core 1 construction will be referred to in Figures 1 to 9. In all the following example the cores are circular in plan although it will be appreciated that other shapes may be employed.

The tuning slug 2 may be moved between two extreme positions shown in Figures 1a and 1c, which allows for adjusting the inductance of a coil wound on the core 1 (ie trimming). A gap 6b is maintained between the sides of the tuning slug 2 and the core layers 3 and 5 so that even when the tuning slug is fully extended as in Figure 1c, an area of low permeability is retained in order to avoid saturation of the core at high coil currents. The gap 6b may be formed of low permeability material such as a plastic sleeve or air. Figure 1b shows the tuning slug in an intermediate tuning position. As with the size of the core air gap 4, the size of the side gaps 6b can be designed depending on the requirements of the coil arrangement as would be appreciated by those skilled in the art. For simplicity of explanation and drawing, subsequent figures 3 – 17 illustrating alternative tuning slug configurations do not show these side gaps between the tuning slug and core.

The tuning slug 2 in Figure 1 may be formed of a high permeability material such as ferrite. Slug 2 tapers towards its distal end 6 to form a conical end in cross-section along the axis of the tuning slug. Tuning slug 2 is moveable (i.e. may be raised and lowered) along an axis adjacent the region of decreased permeability 4 to tune an inductor. It will be appreciated that the volume of high permeability material of the slug introduced to bridge the flux between layers 3 and 5 only gradually increases due to the tapered form of the distal end 6. This allows for fine tuning of an inductor with relatively coarse control of movement of slug 2 with respect to core 1. Where slug 2 is threaded and engages with a thread formed in bore 7 of core 1 this allows a relatively coarse thread to be employed. Tuning slug 2 may alternatively slide within bore 7 and be fixed in place when tuned, for example by gluing.

Referring now to Figure 3 an alternative embodiment utilizes a tuning slug of a different shape with the core 1 shown in Figures 1 and 2. In this case the slug has a wedged distal end 9. This design may be simpler to form but still only progressively introduced the volume of high permeability material to bridge the flux between layers 3 and 5.

Referring now to Figure 4 an alternative embodiment utilizes a tuning slug of a different shape with the core 1 shown in Figures 1 and 2. In this case the slug has a distal end 11 that is elliptical in cross-section along the axis of the tuning slug. This design may avoid undesirable heating caused by a sharply pointed end in some applications.

Referring now to Figure 5 an alternative embodiment utilizes a tuning slug of a different shape with the core 1 shown in Figures 1 and 2. In this case the slug is formed of a high permeability section 12 and a low permeability section 13. Whilst shown in this drawing as two distinct sections it will be appreciated that

the slug could be formed in one piece with the material that the slug is formed from having varying permeability along its length. This would require only a simple slug shape to be formed.

5 Figures 6 to 8 show variants of the tuning slug cross-sectional shape including a slug 14 with a reduced conical tip 15 shown in Figure 6; a slug 16 with two conical sections 17 and 18 joined by a cylindrical section 19; and a slug 20 having a stepped conical tip 21. Whilst a range of cross-sections for the distal end of the slug have been shown it will be appreciated that there are a range of possibilities  
10 that may be appropriate in different applications. Figure 17 shows a further variant in which instead of removing material from the outside a cavity 60 may be formed in slug 59. Slug 59 is moveable within bore 61 of core 62. In this case cavity 60 is of generally elliptical form but the shape may be varied as appropriate for the application. This design may be easily formed by drilling a  
15 cavity of desired shape or moulding etc.

Figure 9 shows a variant in which the tuning slug is formed by a first slug 22 having a frusto-conical end 23 and a second slug 24 having a conical end 25. This arrangement allows slug 22 (and thus slug 24) to be moved for coarse  
20 adjustment and slug 24 to be moved relative to slug 22 for fine adjustment.

Figure 10 shows a variant in which the core is formed of a layer of high permeability material 26 surrounded by layers 27 and 28 of lower permeability material. Slug 29 is moved axially to tune as in the previous embodiment. This  
25 embodiment also shows a tuning slug having a more rounded or hemispherical head compared with the angled pointed heads or tips of some previous embodiments.

Figure 11 shows a modification of the embodiment of Figure 4 in which an actuator 31 advances and retracts slug 30 within bore 7. The actuator 31 may be a linear actuator, piezo actuator etc. Actuator 31 may be controlled by a control circuit which monitors the frequency of operation of an IPT circuit to actively tune the inductor or to effect power flow control.

Referring now to Figure 12 a coil arrangement according to one embodiment is shown including a main core section 32 and a secondary core section 33 formed of a high permeability material, such as ferrite, separated by a spacer 34 formed of a low permeability material. A tuning slug 35 formed of high permeability material is moveable along bore 36 to effect tuning by introducing high permeability material to bridge the flux between core sections 32 and 33. A coil 45 is provided about the core 32.

Referring now to Figure 13 a coil arrangement according to another embodiment is shown including a main core section 37 and a secondary core section 38 formed of a high permeability material, such as ferrite. A coil 44 is wound about, but spaced away from, core 38. The core sections 37 and 38 have complementary threads 39 and 40 allowing the air gap 41 to be adjusted to a desired spacing. A tuning slug 42 formed of high permeability material is moveable along bore 43 to effect tuning by introducing high permeability material to bridge the flux between core sections 37 and 38. This arrangement allows tuning by variation of the air gap spacing and the position of the tuning slug 42.

Referring now to Figure 14 a coil arrangement according to another embodiment is shown including a core section 46 formed of a high permeability material, such as ferrite. A coil 50 is wound about core 46. An air gap 47 is provided in core 46 – in this case it is internal but it may also be external to bore 49. A tuning slug

48 formed of high permeability material is moveable along bore 49 to effect tuning by introducing high permeability material to bridge the flux between core sections adjacent the air gap 47.

5 Referring now to Figure 15 the core consists of a lower core section 51 joined to an upper core section 52, all formed of a high permeability material. An air gap 53 is defined between core sections 51 and 52. In this case an external slug 54 formed of a high permeability material is provided about core section 52 and may be raised and lowered with respect thereto to facilitate tuning. Various  
10 other arrangements in which the tuning slug is located and moveable about an air gap at an edge of a core are also contemplated. Such arrangements do not require the slug to move within a bore of the core.

Figure 16 shows an IPT transmitter coil 56 and an IPT receiver coil 55 of the type  
15 shown in Figure 14 in which the cores form a magnetic path indicated by flux lines 57 in one direction passing between outer edges of the cores and flux lines 58 in the other direction passing between central regions of the cores. The direction of the flux will oscillate rapidly during power transfer. It will be appreciated that adjustment of the position of a tuning slug alters the inductance  
20 of a coil and the reluctance of the main magnetic circuit between the coils.

It will be appreciated that in all the above embodiments a coil will be provided about the core, complementary threads provided in the slug and core may be used for adjustment or the slug may be freely moveable and then secured in  
25 place by gluing etc. The aspect ratio of the tip of the tuning slug should also be greater than 1:1 to assist in fine tuning.

It will also be appreciated that the tuning slug has an “effective permeability” that varies along its length – that is to say for a cylindrical bore for example that

the effective permeability at a cross-section along the axis of the bore the effective permeability is permeability for the entire cross section. Thus for a cross section where half the volume of the bore is occupied by a slug formed of a material of constant permeability the effective permeability will be half that  
5 where the entire slug occupies the bore. Alternatively, the effective permeability may vary if the slug is of constant cross-section (e.g. a cylinder) but the permeability of the material forming the slug varies progressively along the axis of the slug.

10 There is thus provided coil arrangements enabling precise fine tuning of inductance without the need for fine threads. Embodiments avoid the large fluctuations of inductance that are characteristic of the use of known tuning slug configurations in which the sudden introduction of a high permeability material into the flux path way affects the inductance in a non-linear or “binary” manner,  
15 making fine tuning difficult.

Where reference is made to any integer it will be appreciated that such integer may be a discrete integer or a number of integers performing the required function. Likewise, where reference is made to a number of discrete integers it  
20 will be appreciated that they may be integrated into a single unified integer. While the present invention has been illustrated by the description of the embodiments thereof, and while the embodiments have been described in detail, it is not the intention of the applicant to restrict or in any way limit the scope of the appended claims to such detail. Additional advantages and  
25 modifications will readily appear to those skilled in the art. Therefore, the invention in its broader aspects is not limited to the specific details, representative apparatus and method, and illustrative examples shown and described. Accordingly, departures may be made from such details without departure from the spirit or scope of the applicant’s general inventive concept.

**CLAIMS:**

1. A coil arrangement for an inductive power transfer system comprising:
  - a. a core having a region of decreased permeability,
  - 5 b. a coil associated with the core, and
  - c. a tuning slug which is moveable along an axis adjacent the region of decreased permeability in order to adjust the inductance of the coil arrangement, the tuning slug having an effective permeability which varies along said axis.
- 10 2. A coil arrangement for an inductive power transfer system comprising:
  - a. a core having a region of decreased permeability and a bore passing through the region of decreased permeability;
  - b. a coil associated with the core, and
  - 15 c. a tuning slug which tapers at one end and is movable along the bore into the region of decreased permeability to adjust the inductance of the coil arrangement.
- 20 3. A coil arrangement for an inductive power transfer system comprising:
  - a. a core having a region of decreased permeability and a bore passing through the region of decreased permeability;
  - b. a coil associated with the core, and
  - c. a tuning slug having progressively increasing effective permeability from one end thereof and being movable along the
  - 25 bore into the region of decreased permeability to adjust the inductance of the coil arrangement.
4. A coil arrangement as claimed in any one of the preceding claims wherein the region of decreased permeability is created by an air gap in the core.

5. A coil arrangement as claimed in claim 4 wherein the air gap is in the form of a slot.
- 5 6. A coil arrangement as claimed in any one of claims 1 to 3 wherein the region of decreased permeability is due to variation of permeability of material forming the core.
7. A coil arrangement as claimed in any one of the preceding claims in which the one end of the tuning slug has angled faces.
- 10 8. A coil arrangement as claimed in claim 7 wherein the one end is conical.
9. A coil arrangement as claimed in claim 7 wherein the one end is in the form of a wedge.
- 15 10. A coil arrangement as claimed in any one of claims 1 to 6 in which the one end of the tuning slug has a convex taper.
11. A coil arrangement as claimed in claim 10 wherein the one end on the tuning slug has a generally elliptical cross-section along its axis.
- 20 12. A coil arrangement as claimed in any one of claims 1 to 6 in which the one end of the tuning slug is stepped along its axis.
- 25 13. A coil arrangement as claimed in any one of the preceding claims in which the one end of the tuning slug has a convex taper.

14. A coil arrangement as claimed in any one of the preceding claims in which the tuning slug is a two part slug having a first section that is movable relative to the second section.
- 5 15. A coil arrangement as claimed in any one of the preceding claims in which the tuning slug has an aspect ratio greater than 1:1.
16. A coil arrangement as claimed in any one of claims 1 to 6 wherein the permeability of the slug material varies along its length.
- 10 17. A coil arrangement as claimed in claim 16 wherein the tuning slug is of generally cylindrical form.
18. A coil arrangement as claimed in claim 1 wherein a cavity is formed in one end of the tuning slug so as to provide gradually increasing effective permeability from one end.
- 15 19. A coil arrangement as claimed in any one of the preceding claims in which the tuning slug is threaded and engages with a complementary thread in the core.
- 20 20. A coil arrangement as claimed in any one of the preceding claims wherein the core is formed in two parts having adjustable spacing to adjust the size of an air gap between them.
- 25 21. A coil arrangement as claimed in claim 20 wherein the two core parts are connected by complementary threads.
- 30 22. A coil arrangement as claimed in claim 1 wherein the core has an external air gap and a tuning slug is moveable adjacent to the air gap.

23. A coil arrangement as claimed in claim 22 wherein the core includes a cylindrical section having a circumferential slot defining an air gap and the tuning slug is in the form of a ring moveable along the cylindrical section adjacent the air gap.

5

24. A coil arrangement as claimed in any one of the preceding claims including an actuator which moves the tuning slug relative to the core.

10

25. A coil arrangement as claimed in claim 24 wherein the actuator is controlled by a control circuit to maintain the frequency of operation of the coil arrangement within a desired frequency range.

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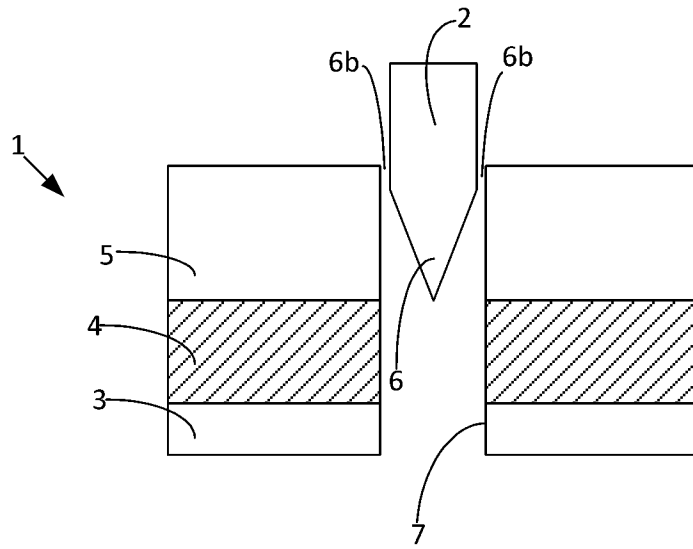


Figure 1a

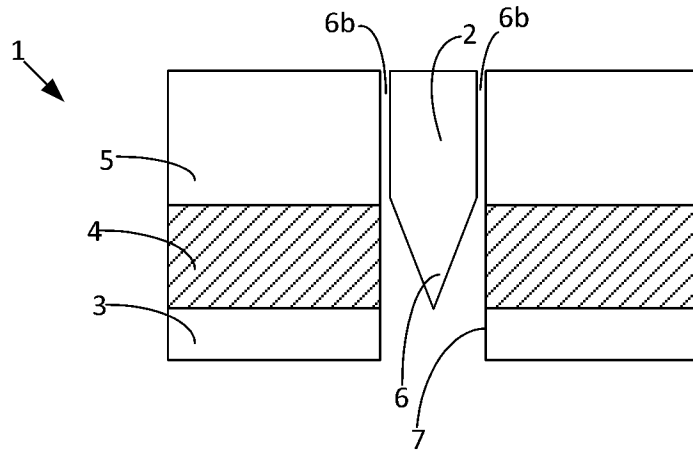


Figure 1b

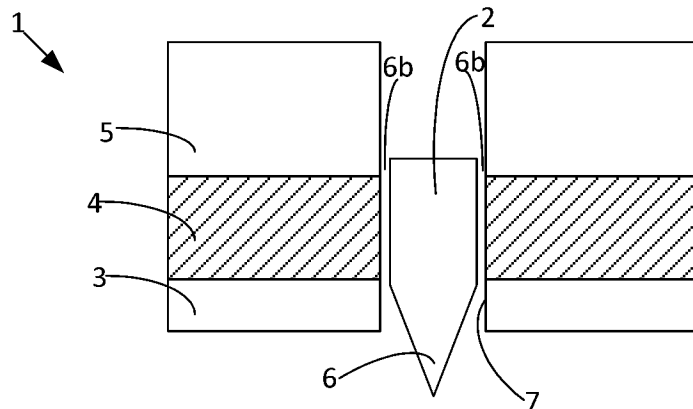


Figure 1c

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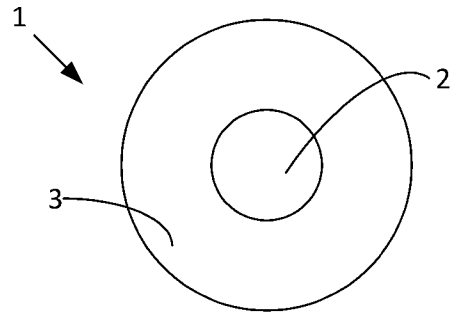


Figure 2

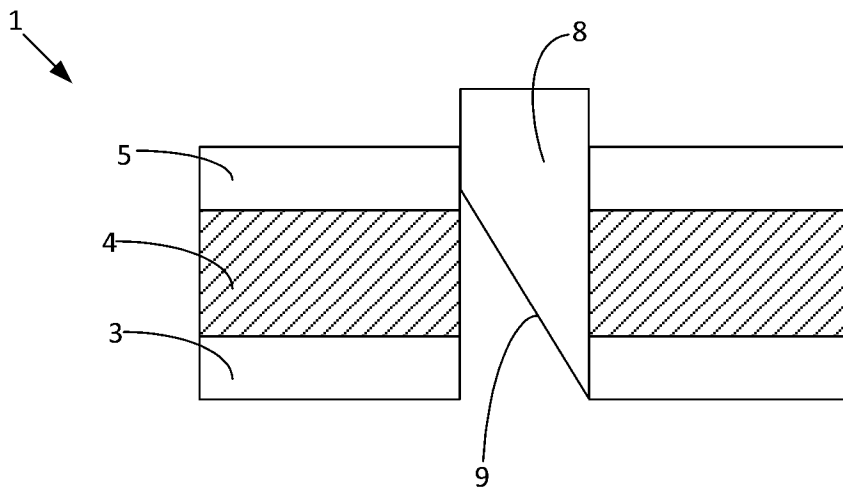


Figure 3

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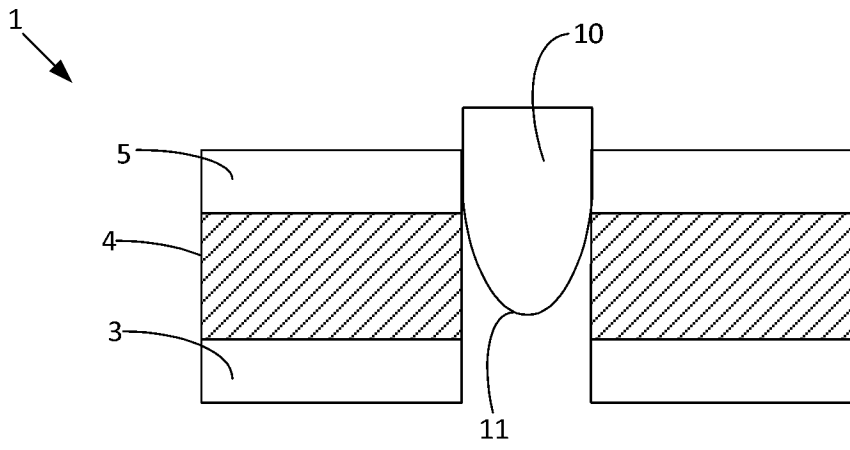


Figure 4

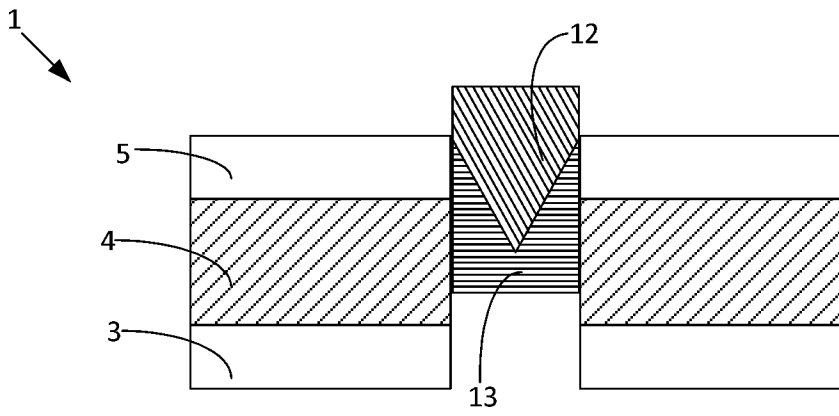


Figure 5

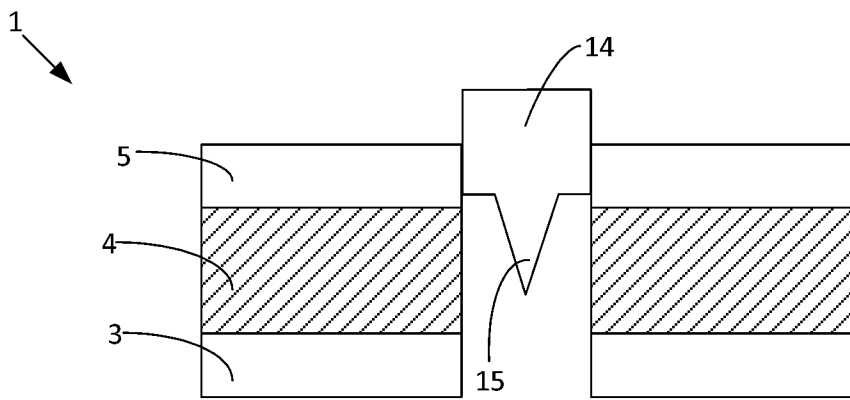


Figure 6

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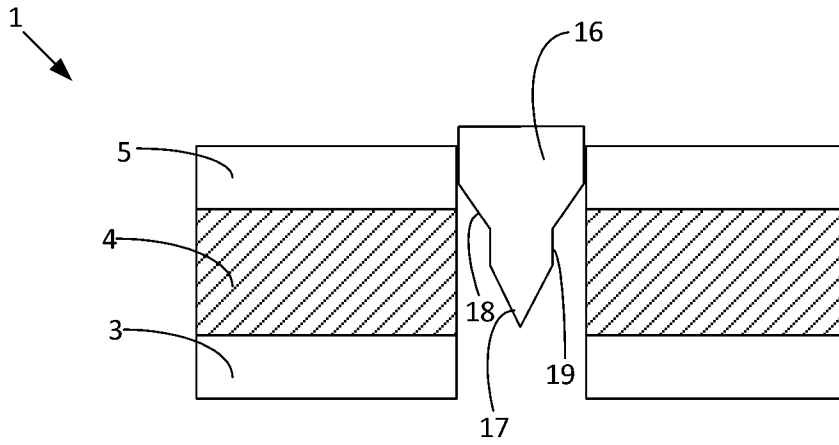


Figure 7

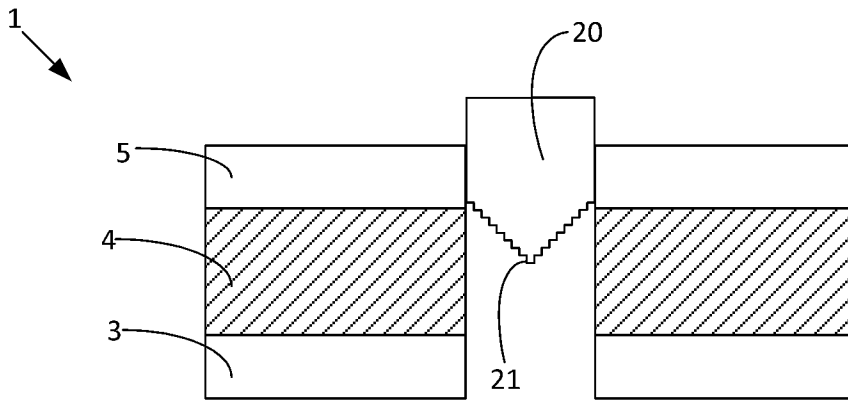


Figure 8

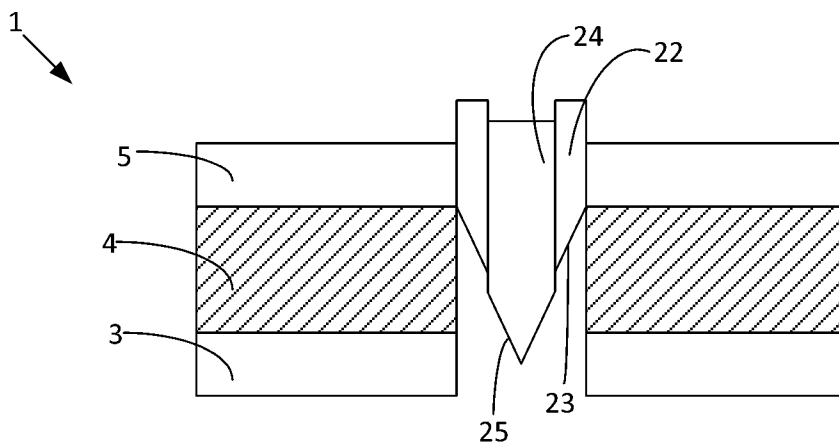


Figure 9

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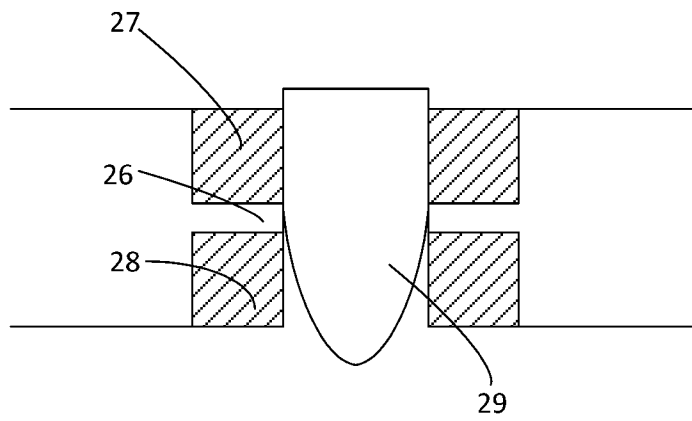


Figure 10

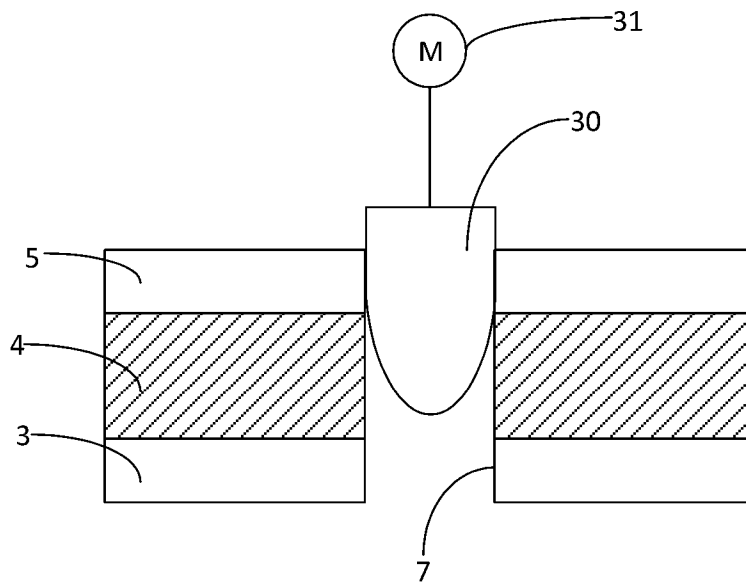


Figure 11

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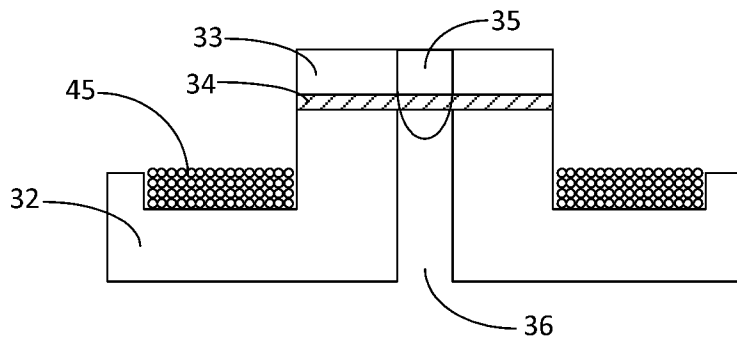


Figure 12

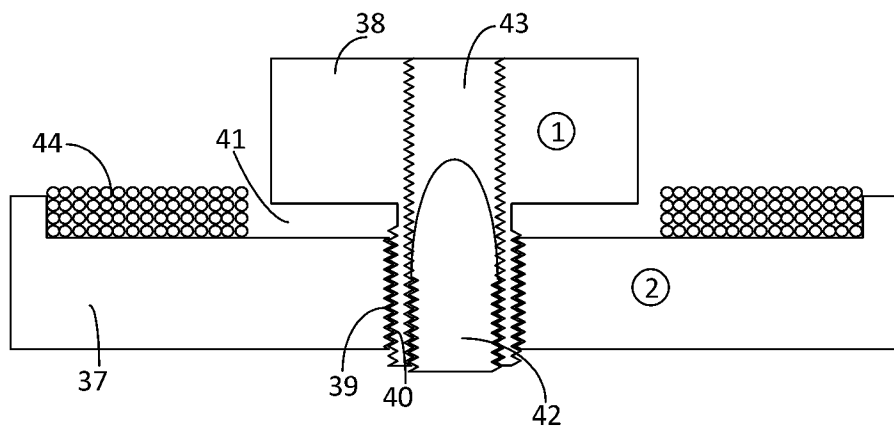


Figure 13

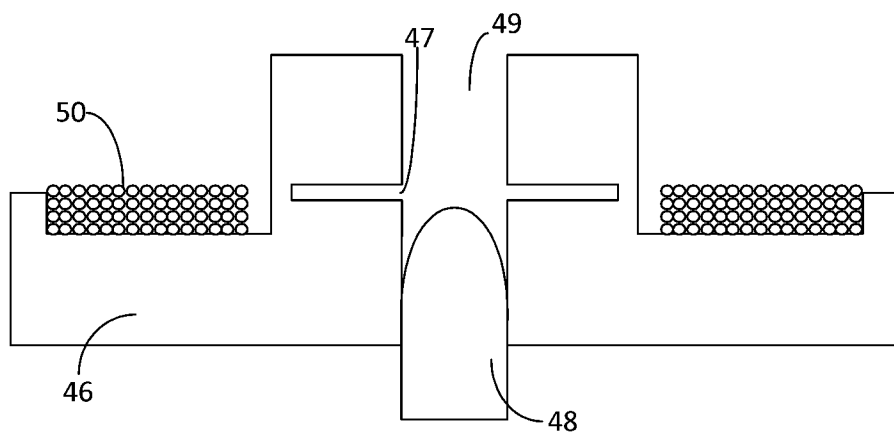


Figure 14

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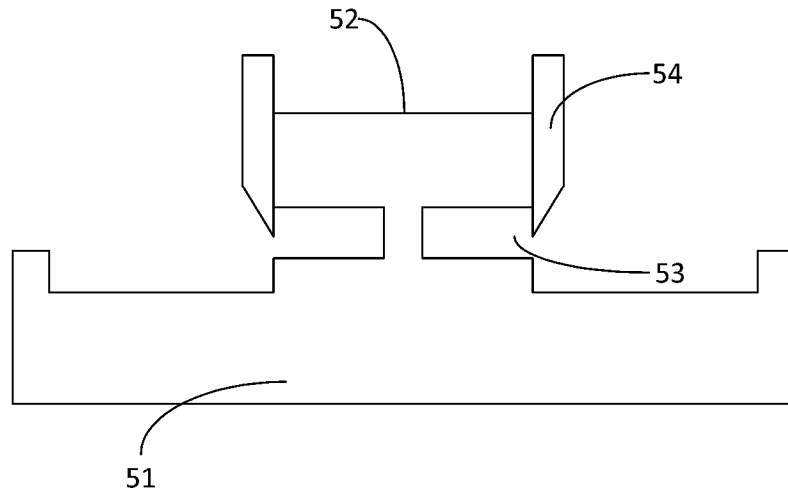


Figure 15

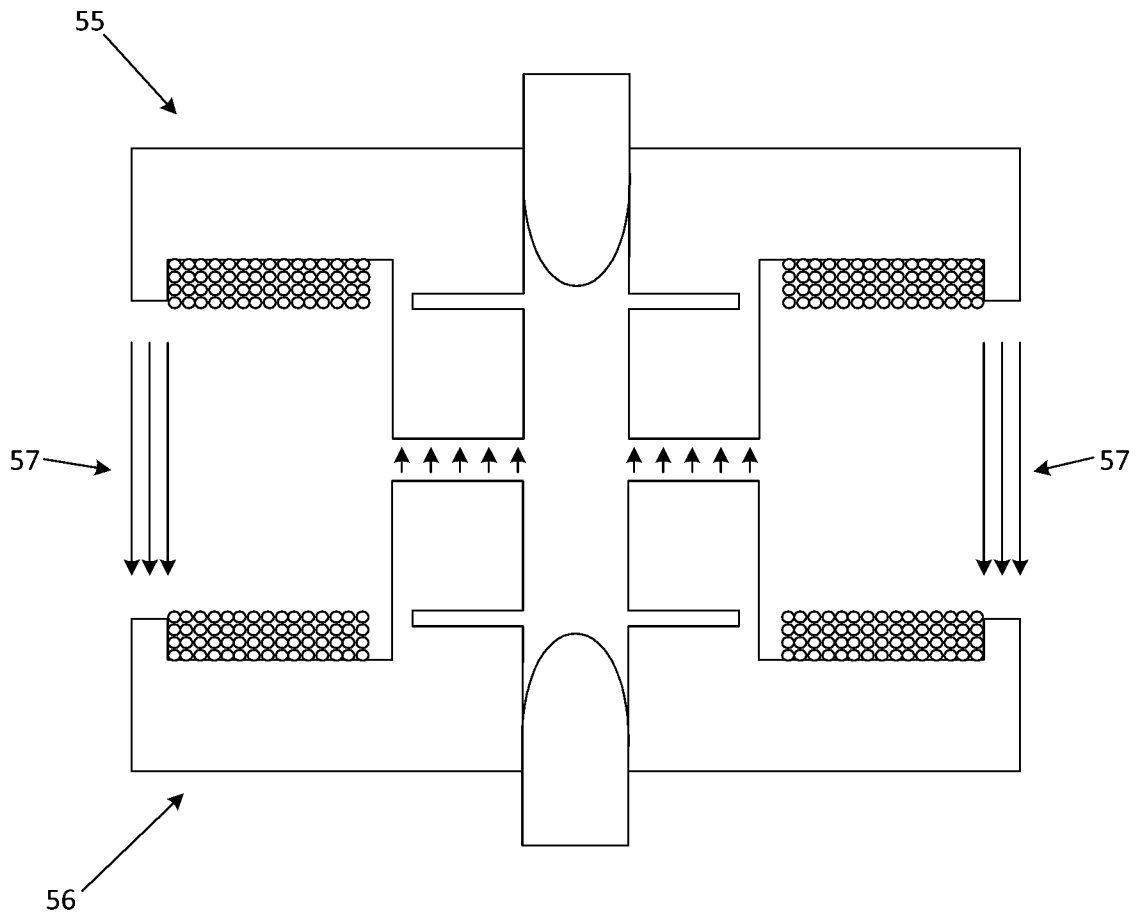


Figure 16

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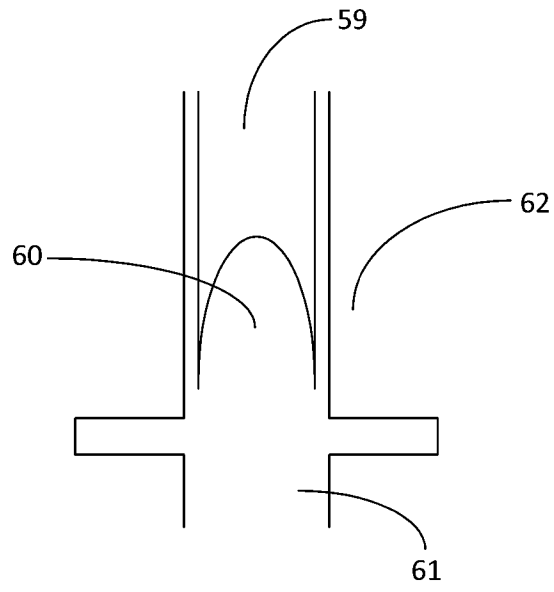


Figure 17

## INTERNATIONAL SEARCH REPORT

International application No.

PCT/NZ2017/050068

## A. CLASSIFICATION OF SUBJECT MATTER

**H02J 50/10 (2016.01) H01F 38/14 (2006.01) H01F 21/02 (2006.01) H02J 5/00 (2016.01)**

According to International Patent Classification (IPC) or to both national classification and IPC

## B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

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 practicable, search terms used)

Databases: PATENW (EPODOC, WPIAP and TXTE), Espacenet, Google Patents and Google; CPC/IPC Symbols: H02J17/-, H02J5/-, H02J7/-, H01F21/-, H02J50/-, H01F38/14, H01F2003/103;

keywords: wireless, inductive, charging, power, core, tune, slug, ferrite, magnet, permeability, inductance, moveable, air gap, gapped core, actuator, two part slug, taper, narrow, conical, angle, stepped and like terms.

Applicant/Inventor names were searched in internal databases provided by IP Australia, Espacenet and AusPat. Inventor/Applicant 'John Talbot Boys' or 'Auckland Uniservices Limited' were also searched in Google.

## C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Documents are listed in the continuation of Box C		

 Further documents are listed in the continuation of Box C See patent family annex

* Special categories of cited documents:		
"A" document defining the general state of the art which is not considered to be of particular relevance	"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	
"E" earlier application or patent but published on or after the international filing date	"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	
"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)	"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	
"O" document referring to an oral disclosure, use, exhibition or other means	"&" document member of the same patent family	
"P" document published prior to the international filing date but later than the priority date claimed		

Date of the actual completion of the international search

24 August 2017

Date of mailing of the international search report

24 August 2017

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**INTERNATIONAL SEARCH REPORT**

International application No.

C (Continuation).

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**PCT/NZ2017/050068**

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X	US 2015/0302982 A1 (U.S. Army Research Laboratory) 22 October 2015 figs. 1 & 2, paras [0005-0011], [0021-0023], [0029]	1-25
A	US 6483202 B1 (BOYS) 19 November 2002 see whole document especially figs 1-4 and corresponding columns in the description.	1-25
A	US 2011/0304220 A1 (WHITEHEAD) 15 December 2011 see whole document especially abstract, figs. 4 & 5, para [0027-0028], [0037].	1-25
A	US 4511872 A (OLMSTED et al.) 16 April 1985 see whole document especially figs. 1-3 & 7.	1-25
A	US 2012/0235567 A1 (KARALIS et al.) 20 September 2012 see whole document especially figs. 11-16.	1-25

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