(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
4 September 2008 (04.09.2008)

PCT

(10) International Publication Number
WO 2008/104895 A1

(51) International Patent Classification:
G01R 33/341 (2006.01) *G01R 33/422* (2006.01)
G01R 33/36 (2006.01)

(21) International Application Number:
PCT/IB2008/050328

(22) International Filing Date: 30 January 2008 (30.01.2008)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
60/891,539 26 February 2007 (26.02.2007) US

(71) Applicant *(for all designated States except US)*: **KONINKLIJKE PHILIPS ELECTRONICS, N.V.** [NL/NL]; Groenewoudseweg 1, NL-5621 BA Eindhoven (NL).

(72) Inventors; and
(75) Inventors/Applicants *(for US only)*: **ZHAI, Zhiyong** [CN/US]; 6809 Mayfield Road, Apt. 571, Mayfield Heights, Ohio 44124 (US). **MORICH, Michael, A.** [US/US]; 7580 Jeremy Avenue, Mentor, Ohio 44060 (US). **DEMEESTER, Gordon, D.** [US/US]; 30175 Overlook Drive, Wickliffe, Ohio 44092 (US).

(74) Agent: **DAMEN, Daniel, M.**; Philips Intellectual Property & Standards, High Tech Campus 44, P.O. Box 220, NL-5600 AE Eindhoven (NL).

(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BR, BW, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PG, PH, PL, PT, RO, RS, RU, SC, SD, SE, SG, SK, SL, SM, SV, SY, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MT, NL, NO, PL, PT, RO, SE, SI, SK, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Declaration under Rule 4.17:
— *as to applicant's entitlement to apply for and be granted a patent (Rule 4.17(ii))*

Published:
— *with international search report*
— *before the expiration of the time limit for amending the claims and to be republished in the event of receipt of amendments*

(54) Title: DOUBLY RESONANT HIGH FIELD RADIO FREQUENCY SURFACE COILS FOR MAGNETIC RESONANCE

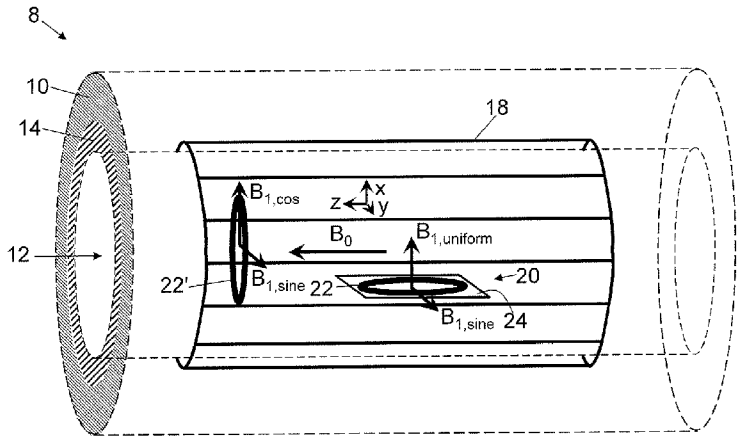


Fig. 1

(57) Abstract: A radio frequency coil comprises an annular conductor or parallel annular conductors (22, 22c, 22d) configured to support: (i) a uniform electrical current distribution generating a first B_1 field ($B_{1,uniform}$) at a first magnetic resonance frequency directed out of a plane of the annular conductor or conductors; and (ii) a sinusoidal electrical current distribution generating a second B_1 field ($B_{1,sine}$) at a second magnetic resonance frequency directed parallel with the plane of the annular conductor or conductors. A magnetic resonance scanner comprises: a magnet (10) generating a static magnetic field (B_0); a magnetic field gradient system (14) configured to superimpose selected magnetic field gradients on the static magnetic field; and said radio frequency coil including said annular conductor or parallel annular conductors (22, 22c, 22d).

WO 2008/104895 A1

DOUBLY RESONANT HIGH FIELD RADIO FREQUENCY SURFACE COILS FOR MAGNETIC RESONANCE

DESCRIPTION

The following relates to the magnetic resonance arts. It finds particular application in magnetic resonance imaging at high magnetic fields (e.g., about 3 Tesla or higher), and is described with particular reference thereto. However, the following finds more general application in magnetic resonance imaging, magnetic resonance spectroscopy, and the like performed at substantially any magnetic field.

Surface coils are known and used in the magnetic resonance arts to excite or detect magnetic resonance in a localized region of a subject. Surface coils typically include a single annular conductive loop or an array of planar conductive loops positioned close to the region of interest of a subject. An electric current driven through the single annular conductive loop or loops arrangement generates a B_1 field oriented transverse to B_0 field and the plane of the coil loop or loops. Conversely, in a readout mode a B_1 field oriented transverse to the B_0 field and the plane of the coil loop or loops induces an electric current in the coil loop or loops that can be used to detect magnetic resonance. The butterfly or figure-eight surface coil is also known. This coil produces a B_1 field oriented transverse to B_0 field and parallel to the plane of the surface coil. In application, one or more such surface coils are placed close to or on a patient or other subject, such that the close proximity of the surface coil or coils enhances radio frequency coupling and magnetic resonance signal strength.

In spite of these advantages of existing surface coils, some problems remain. One difficulty is that the number of surface coils used in a given study can become problematic. Each surface coil operates at a single magnetic resonance frequency, and so multi-nuclear studies require use of multiple surface coils tuned to the magnetic resonance frequencies of different nuclear species of interest. Since the coils are in close proximity to or contact or rest upon the patient, a large number of surface coils can be uncomfortable and intimidating to the patient. The number of surface coils installed at any given time can be reduced by swapping surface coils in and out as needed; however, this is done at the expense of increased imaging session duration and increased risk of positioning errors in the placement of the surface coils.

Another difficulty with existing loop surface coils is that they operate in a uniform resonance mode in which the B_1 field is oriented transverse to the coil plane. Such a loop coil is most effective when oriented such that the static B_0 magnetic field is in the plane of the surface coil, so as to maximize the angle between the B_0 and B_1 fields. In contrast, birdcage and TEM coils are generally cylindrical volume coils that couple with an interior region surrounded by the birdcage or TEM coil and are oriented with their axis generally aligned with the $\mathbf{B_0}$ field. Hence, these coils are not suitable for use as surface coils.

The following provides new and improved apparatuses and methods which overcome the above-referenced problems and others.

In accordance with one aspect, a generally planar surface coil is disclosed, comprising one or two annular conductors arranged generally parallel with a coil plane of the generally planar radio frequency coil and configured to support (i) a uniform electrical current distribution generating a first B_1 field at a first magnetic resonance frequency directed out of the coil plane, and (ii) a sinusoidal electrical current distribution generating a second B_1 field at a second magnetic resonance frequency directed parallel with the coil plane.

In accordance with another aspect, a radio frequency coil is disclosed, comprising an annular conductor configured to support: (i) a uniform electrical current distribution generating a first B_1 field at a first magnetic resonance frequency directed out of a plane of the annular conductor; and (ii) a sinusoidal electrical current distribution generating a second B_1 field at a second magnetic resonance frequency directed parallel with the plane of the annular conductor.

In accordance with another aspect, a magnetic resonance scanner is disclosed, comprising: a magnet generating a static magnetic field; a magnetic field gradient system configured to superimpose selected magnetic field gradients on the static magnetic field; and an annular conductor configured to support a sinusoidal electrical current distribution generating or induced by a B_1 field at a magnetic resonance frequency directed parallel with the plane of the annular conductor.

One advantage resides in obtaining a dual resonance from a single surface coil.

Another advantage resides in facilitating the use of fewer surface coils during magnetic resonance data acquisition.

Another advantage resides in providing a quadrature surface coil.

Another advantage resides in providing a doubly-tuned surface coil for multi-nuclear magnetic resonance data acquisitions.

Still further advantages of the present invention will be appreciated to those of ordinary skill in the art upon reading and understand the following detailed description.

FIGURE 1 diagrammatically shows a magnetic resonance scanner including a surface coil configured to support both uniform and sinusoid resonances at the same or at different magnetic resonance frequencies.

FIGURE 2 plots sinusoidal resonance frequency for a continuous unshielded circular annular conductor without intervening capacitance or inductance elements, as a function of radius of the circular annular conductor.

FIGURE 3 diagrammatically shows the uniform resonance mode of the annular conductor of the surface coil of FIGURE 1.

FIGURE 4 diagrammatically shows the sinusoidal resonance mode of the annular conductor of the surface coil of FIGURE 1.

FIGURE 5 diagrammatically shows a side sectional view of one embodiment of the surface coil of FIGURE 1.

FIGURE 6 diagrammatically shows a plan view of an embodiment of the surface coil of FIGURE 1 that includes a continuous closed-loop microstrip transmission line annular conductor.

FIGURE 7 diagrammatically shows a plan view of an embodiment of the surface coil of FIGURE 1 that includes a segmented closed-loop microstrip transmission line annular conductor having gaps defining discrete capacitance elements.

FIGURE 8 diagrammatically shows a plan view of an embodiment of the surface coil of FIGURE 1 that includes a segmented closed-loop microstrip transmission line annular conductor having gaps defining capacitance elements, further including series inductor elements.

FIGURE 9 diagrammatically shows a plan view of a generally planar radio frequency coil that includes two parallel segmented closed-loop microstrip transmission

line annular conductors each having gaps defining capacitance elements, one of which further includes series inductor elements.

FIGURES 10 and 11 diagrammatically show side sectional and perspective views, respectively, of an embodiment of the surface coil of FIGURE 1 that includes an annular conductor shielded by both a planar radio frequency shield and by a transverse annular shield portion.

FIGURE 12 plots calculated transverse B_1 field versus frequency at a point 10 centimeters above a 15-centimeter radius circular annular conductor for (i) an unshielded annular conductor ("ring-only"); (ii) an annular conductor shielded by a planar radio frequency shield ("ring+planar shield"); and (iii) an annular conductor shielded by both a planar radio frequency shield and by a transverse annular shield portion ("ring+planar shield+transverse annular shield portion").

FIGURES 13-16 plot calculated parameters for uniform and sinusoidal resonance modes, respectively, for a circular annular conductor similar to that of FIGURE 8 having a diameter of 14 centimeters, annular conductor width of 1 centimeter, and a dielectric substrate having thickness of 1.5 centimeters and dielectric constant ε_r=2.1, having eight capacitance elements in series with inductive elements tuned to support a uniform current density at a magnetic resonance frequency of 120.7 MHz (corresponding to ^{31}P in a 7 Tesla static B_0 magnetic field) and tuned to support a sinusoidal current density at a magnetic resonance frequency of 298 MHz (corresponding to ^{1}H in a 7 Tesla static B_0 magnetic field). More particularly:

FIGURES 13 and 14 plot calculated current distribution along an annular conductor for the uniform and sinusoidal resonance modes, respectively;

FIGURE 15 plots calculated S_{11} versus frequency; and

FIGURE 16 plots calculated $|B_1^+|(x)$ normalized to the value of $|B_1^+|(x=1 \text{ centimeter})$ versus position along the coil axis direction in an average brain tissue.

With reference to FIGURE 1, an illustrative bore-type magnetic resonance scanner **8** includes a magnet **10** generating a static magnetic field $\mathbf{B_0}$ oriented parallel with a bore opening **12** of the scanner **8**. The magnet **10** can be a superconducting or resistive

magnet. Other geometries besides the illustrated horizontal bore geometry can be implemented. The magnetic resonance scanner **8** further includes a magnetic field gradient system **14** configured to superimpose selected magnetic field gradients on the static magnetic field $\mathbf{B_0}$. In some embodiments, the magnetic field gradient system **14** includes windings for selectively generating three orthogonal magnetic field gradients, for example along orthogonal designated x-, y-, and z-directions. Typically, the magnetic field gradient system is disposed inside of the magnet, as the illustrated magnetic field gradient system **14** is disposed inside of the illustrated magnet **10**; however, other configurations are also contemplated, such as an arrangement disclosed in Overweg, Int'l Appl. No. WO 2005/124381 in which the gradient coil windings are disposed outside of the magnet and the generated magnetic field gradients are coupled into the bore opening by a ferromagnetic yoke. In FIGURE 1, the magnet **10** and magnetic field gradient system **14** are diagrammatically shown as transparent to reveal the interior of the bore opening **12**.

In operation, one or more radio frequency coils, such as an illustrative birdcage-type whole-body coil **18** integrated into the scanner **8**, or a transverse electromagnetic (TEM) coil (not shown), or a surface coil **20**, or the like, is energized by a suitable radio frequency signal at one or more magnetic resonance frequencies to excite magnetic resonance in one or more nuclear species, such as the ^{1}H, ^{13}C, ^{31}P, ^{23}Na, ^{19}F, or other nuclear species. One or more magnetic field gradients are typically applied by the magnetic field gradient system **14** to spatially limit and/or encode the excited magnetic resonance or resonances. The excited magnetic resonances are read out by one or more of the radio frequency coils **18**, **20**. The readout or receive coil may be the same or different from the radio frequency coil used for excitation.

The surface coil **20** includes an annular conductor **22** configured to support: (i) a uniform electrical current distribution generating a first, $\mathbf{B_{1,uniform}}$ field at a first magnetic resonance frequency directed out of a plane of the annular conductor **22**; and (ii) a sinusoidal electrical current distribution generating a second, $\mathbf{B_{1,sine}}$ magnetic field at a second magnetic resonance frequency directed parallel with the plane of the annular conductor **22**. This dual-mode configuration advantageously allows the surface coil **20** to be used as a doubly-tuned surface coil if the first and second magnetic resonance frequencies are different. An example of an application of such a doubly-tuned surface coil is multi-nuclear magnetic resonance imaging or spectroscopy, in which the first and second

magnetic resonance frequencies are suitably magnetic resonance frequencies of different nuclear species in a given static magnetic field $\mathbf{B_0}$.

FIGURE 1 also diagrammatically shows an annular conductor **22'** that is similar to the annular conductor **20**, but is oriented with the axis of the annular conductor **22'** parallel with the static magnetic field $\mathbf{B_0}$. In other words, the direction of the $\mathbf{B_0}$ field is transverse to the plane of the annular conductor **22'**. In this arrangement, the annular conductor **22'** can be used as a quadrature transmit/receive coil by exciting it using two sinusoidal modes that are phase-shifted by 90° at the same magnetic resonance frequency. For example, the illustrated annular conductor **22'** suitably supports $\mathbf{B_{1,sine}}$ and $\mathbf{B_{1,cos}}$ fields. This dual-mode configuration advantageously allows the surface coil **20** to be used as a quadrature surface coil.

With reference to FIGURE 2, heretofore the sinusoidal mode of a continuous unshielded annular conductor has not been considered to be of value for magnetic resonance imaging or spectroscopy, because the resonance frequency was deemed to be too high and the generated B_1 field was deemed to be too non-uniform. However, the inventors have recognized that for high-field magnetic resonance and for an annular conductor of sufficiently large radius, the sinusoidal mode oscillates at a useful frequency range matching certain magnetic resonance frequencies of interest. For instance, the ^{1}H magnetic resonance frequency is 298 MHz in a static magnetic field $\mathbf{B_0}$ of 7 Tesla. As indicated in FIGURE 2, the sinusoidal resonance of a circular annular conductor having a reasonable diameter of about 32 centimeters (c/298MHz/π) closely matches this ^{1}H magnetic resonance frequency. Moreover, the inventors have recognized that at higher magnetic field, the spatial uniformity is largely determined by the dielectric and conductive characteristics of the patient or other subject loading the coil; hence, at static $\mathbf{B_0}$ magnetic field values greater than 3 Tesla, the relatively large unloaded non-uniformity of the $B_{1,sine}$ field is acceptable.

With reference to FIGURE 3, the uniform oscillation mode of the annular conductor **22** of the surface coil **20** of FIGURE 1 is illustrated. In the uniform mode the current distribution is uniform around the annular conductor **22**. This mode does not require a circular annulus, and is typically tuned using capacitance elements in the conductor. The $\mathbf{B_1}$ field generated by the current depends on position with respect to the loop. In FIGURE 3, the reference direction is counterclockwise; however, the uniform

current distribution oscillates temporally between clockwise and counterclockwise at the first magnetic resonance frequency of the uniform oscillation. The uniform current distribution produces a $B_{1,uniform}$ field directed transverse to or out of the plane of the annular conductor **22**. At the point of time illustrated in FIGURE 3, the illustrated $B_{1,uniform}$ field is directed out of the page of the paper corresponding to the counterclockwise reference direction of the uniform current distribution.

FIGURE 4 shows the sinusoidal oscillation mode of the annular conductor **22** of the surface coil **20** of FIGURE 1. The current distribution around the circular annular conductor **22** is sinusoidal with a spatial period equal to the circumference of the annular conductor **22**. Accordingly, at the resonance frequency where the current distribution wavelength coincides with the ring circumference there are two current distribution nulls, one maximum positive current amplitude point, and one maximum negative current amplitude point. At the time instant illustrated in FIGURE 4, the two current distribution nulls are positioned at points designated as 0^o and 180^o, the maximum positive current amplitude ($+I_{max}$) point is at 90^o, and the maximum negative current amplitude point ($-I_{max}$) is at 270^o. The resulting $\mathbf{B_{1,sine}}$ field is directed parallel with the plane of the annular conductor **22**.

The configuration of the annular conductor **22** of the surface coil **20** is such as to support both the uniform and sinusoidal oscillations current modes and their associated magnetic fields simultaneously. Thus, the same surface coil **20** can be used to simultaneously generate or detect B_1 fields at both the first and second magnetic resonance frequencies. If the first and second magnetic resonance frequencies are different, the surface coil **20** can be used to excite or acquire multi-nuclear magnetic resonance simultaneously.

FIGURE 5 shows one suitable implementation of the surface coil **20**, in which the annular conductor **22** is configured as an annular microstrip transmission line on a generally planar dielectric substrate **24**. A ground plane **26** or other planar radio frequency shield is arranged parallel with the annular conductor **22** disposed on a side of the dielectric substrate **24** opposite the annular conductor **22**. The presence of the shield **26** advantageously boosts the Q factor of the coil. In these embodiments, the annular conductor **22** and the ground plane **26** are suitably lithographically or otherwise patterned or selectively deposited conductive films.

In the illustrated configuration of FIGURE 5, the ground plane **26** is an annular ground plane; however, a disk-shaped or other larger-area ground plane or radio frequency shield can be used instead. For example, a ground plane can be used that covers the backside of the dielectric substrate **24** but is suitably segmented to reduce gradient induced eddy currents, yet appears continuous at radio frequency via capacitive connections. FIGURE 5 also indicates certain geometrical parameters that affect the tuning of the coil, such as the annular conductor diameter **D**, the thickness **H** of the dielectric substrate **24**, and the width **W** of the annular conductor **22**. The designation of diameter **D** for the annular conductor **22** assumes a circular configuration for the annular conductor. In some embodiments, the annular conductor is contemplated to deviate somewhat from perfect circularity, and may for example be somewhat elliptical or so forth. However, substantial deviation from circularity is generally disadvantageous in that it can adversely affect uniformity of the $\mathbf{B}_{1,\text{sine}}$ field. It should also be noted that the diameter **D** corresponds to twice the radius, i.e. 2**R**, as also indicated in FIGURE 5.

With reference to FIGURES 6-8, the annular conductor **22** can have various configurations with differing degrees of freedom for tuning. FIGURES 6-8 show plan views of various surface coil embodiments each employing the cross-sectional configuration of FIGURE 5. In the plan views of FIGURES 6-8, the dielectric substrate **24** is not shown, so that the annular conductor is seen on top of the ground plane **26**. In practice, the dielectric substrate **24** may be opaque, transparent, or translucent.

In the configuration of FIGURE 6, the annular conductor is a continuous closed annular conductor **22a**. In this arrangement, the first uniform mode is absent and only the second sinusoidal mode is useable. The tuning of the sinusoidal mode is through the parameters **D**, **W**, and **H**. This makes it difficult to fine-tune the sinusoidal mode; however, in some cases a suitable geometry can be obtained to achieve a specific selected magnetic resonance frequency value. Although the annular conductor **22a** is referred to herein as a closed annular conductor, it is to be appreciated that the closed annular conductor **22a** may include a gap (not shown) in the annular conductor in order to feed the coil with a suitably-coupled source such as a capacitively coupled source.

In the configuration of FIGURE 7, the annular conductor is a broken annular conductor **22b**, having (in the illustrated example) eight gaps **30**. The gaps **30** define capacitive elements that affect the first magnetic resonance frequency of the uniform

mode more than the second magnetic resonance frequency of the sinusoidal mode. Accordingly, in this arrangement, the second magnetic resonance frequency corresponding to the sinusoidal mode is suitably selected by designing the parameters **D**, **W**, dielectric constant ε_r and thickness **H**, and the capacitance elements **30** are selected to adjust the first magnetic resonance frequency corresponding to the uniform mode. While gaps **30** in a microstrip transmission line conductor **22b** define the capacitance values of the capacitance elements in the embodiment of FIGURE 7, in other embodiments discrete capacitors may be used. Accordingly, in this arrangement, geometric design parameters **D**, **W**, ε_r and **H**. affect both the first magnetic resonance frequency of the uniform mode and the second magnetic resonance frequency of the sinusoidal mode. The tuning design is suitably performed in conjunction with an electromagnetic simulator, by iteratively adjusting the capacitance values and one or more parameters of **D**, **W**, ε_r and **H** until the desired first and second magnetic resonance frequencies are achieved.

In the configuration of FIGURE 8, the annular conductor is again a broken annular conductor **22c**, having (in the illustrated example) eight gaps **30** defining capacitive elements that affect the first magnetic resonance frequency of the uniform mode more than the second magnetic resonance frequency of the sinusoidal mode. Additionally, series inductive elements **32**, such as discrete inductors, are included. The inductive elements **32** affect the second magnetic resonance frequency of the sinusoidal mode more than the first magnetic resonance frequency of the uniform mode. Accordingly, in this arrangement, the geometric design parameters **D**, **W**, ε_r and **H** can be first determined for best fit to a loading subject. The tuning design is then suitably performed in conjunction with an electromagnetic simulator, by iteratively adjusting the inductance and capacitance values until the desired first and second magnetic resonance frequencies are achieved.

With reference to FIGURE 9, a surface coil similar to that shown in FIGURE 8 is described. The surface coil of FIGURE 9 includes the annular conductor **22c** and also includes an additional concentric and co-planar annular conductor **22d**. In FIGURE 9, annular conductor **22d** is of a slightly smaller radius than the annular conductor **22c**. The annular conductors **22c**, **22d** have similar topologies including eight gaps in each annular conductor, and the ground plane **26** provides shielding for both annular conductors **22c**, **22d**. Capacitive elements are used to tune one annular conductor to a first magnetic resonance frequency of the uniform mode. Series inductive elements,

such as discrete inductors, are used to tune the other annular conductor to a second magnetic resonance frequency of the sinusoidal mode. In a multi-nuclear imaging or spectroscopy application of the surface coil of FIGURE 9, the uniform mode is used for one of the loops at a lower multi-nuclear frequency and a sinusoidal mode is used for the other loop at a higher frequency, such as the ^{1}H frequency. In other contemplated applications, the surface coil of FIGURE 9 is driven in quadrature with both annular conductors **22c**, **22d** resonating at the same frequency. In a suitable approach, the inner annular conductor **22d** is driven via a port **P1** while the outer annular conductor is driven via a port **P2** with a 90^{o} phase shift.

The two illustrated annular conductors **22c**, **22d** are co-planar (making them equidistant from the subject) and concentrically arranged. However, the disclosed operational modes, such as quadrature or multi-nuclear resonance modes, are also achievable using annular conductors arranged in spaced apart parallel planes, arranged non-concentrically, or arranged both in spaced apart parallel planes and non-concentrically. In one contemplated embodiment, a generally planar radio frequency coil includes two annular conductors supporting the uniform and sinusoidal current distributions, respectively. In such a radio frequency coil, it is contemplated for the two annular conductors to have the same radius, but to be arranged in spaced apart parallel planes. Such annular conductors may be either concentric or non-concentric.

With reference to FIGURES 10 and 11, further improved resonance quality (i.e., higher resonance Q) can be obtained by having a more enclosing dielectric substrate **34** supporting a more enclosing a radio frequency shield **36** that includes a planar radio frequency shield **36a**, similar to the ground plane **26**, that is disk shaped (as shown) or annular (similar to the ground plane **26**), and that further includes a transverse annular (short cylinder) radio frequency shield portion **36b** extending transverse to the planar radio frequency shield **36a** and surrounding at least an outer perimeter of the annular conductor **22**. Improvements in the Q are higher when the shield **36b** extends to the upper plane of the annular conductor **22** or further. The conductive loop portion **22** can also be attached to the short cylinder **36b** as opposed to the backing disk **36a**. Alternatively, the more enclosing dielectric substrate **34** can be omitted, and a self-supporting annular shield portion can be used.

With reference to FIGURE 12, the calculated effect of increasing shielding on the resonance quality Q is illustrated. FIGURE 12 plots calculated transverse B_1 field versus frequency at a point 10 centimeters above a 15-centimeter radius circular annular conductor for (i) an unshielded annular conductor ("ring-only"); (ii) an annular conductor shielded by a planar radio frequency shield ("ring+planar shield"); and (iii) an annular conductor shielded by both a planar radio frequency shield and by a transverse annular or short cylindrical shield portion ("ring+planar shield+transverse annular shield portion"). A substantial narrowing of the resonant peak is obtained for each increase in shielding, i.e. between the unshielded annular conductor and the annular conductor with ground plane, and between the annular conductor with ground plane and the addition of the transverse annular shield portion. Simulations indicate that most of the improvement through addition of the transverse annular shield portion are obtained when the added transverse shield portion extends a distance equal to or slightly greater than the height of the annular conductor **22**.

A doubly resonant single loop surface coil as described was modeled using electromagnetic modeling software. The modeled surface coil included a circular annular conductor similar to that of FIGURE 8 and having the cross-section shown in FIGURE 5. The modeled coil had a diameter **D**=28 centimeters (radius **R**=14 centimeters), a width **W**=1 centimeter for the annular conductor, and a dielectric substrate having thickness **H**=1.5 centimeters (see FIGURE 5 for dimensional definitions) and dielectric constant ε_r=2.1. The modeled coil had eight capacitance elements **30** in series with inductive elements **32** tuned to support a uniform current density at a first magnetic resonance frequency of 120.7 MHz (corresponding to ^{31}P in a 7 Tesla static B_0 magnetic field) and tuned to support a sinusoidal current density at a second magnetic resonance frequency of 298 MHz (corresponding to ^{1}H in a 7 Tesla static B_0 magnetic field).

FIGURES 13 and 14 plot the current distribution magnitude for the uniform mode (FIGURE 13) and for the sinusoidal mode (FIGURE 14). In FIGURES 13 and 14, a higher current density magnitude is indicated by a whiter area. The uniform mode shows a uniform annular current distribution as expected. The sinusoidal mode shows the expected two current distribution nulls, and two current distribution maxima corresponding to $+I_{max}$ and $-I_{max}$, again as expected.

FIGURE 15 plots calculated S_{11} (that is, reflected power) versus frequency. The uniform and sinusoidal modes are clearly seen as sharp negative valleys in the S_{11} plot at 120.7 MHz and 298 MHz, respectively.

FIGURE 16 plots calculated $|B_1^+|(x)$ normalized to the value of $|B_1^+|(x=1$ centimeter) versus position along the loop axis direction in an average brain tissue ($\sigma = 0.55$S/m, $\varepsilon_r = 52$) which is placed 1 centimeter above the annular conductor. Note that in FIGURE 16, the filled circles corresponding to the plot for the sinusoidal mode are merely differentiating indicators, and do not indicate individual calculated points. The plot of FIGURE 16 shows a typical ring $|B_1^+|$-field profile where the $|B_1^+|$-field decreases with the depth. This doubly-tuned coil is suitable for near surface multi-nuclear imaging and spectroscopy.

A conventional, uniform current, multi-nuclear surface coil is constructed by combining two or more separate loops resonating at different frequencies. In such an arrangement, the two separate loops can couple with each other unless appropriately trapped and/or geometrically configured to reduce coupling. An advantage of the doubly-tuned single loop coil disclosed herein is that since both uniform and sinusoidal modes are supported by the same annular conductor, coil-coil coupling is not a concern. Indeed, the uniform and sinusoidal modes are operatively independent.

Additionally, the single doubly-tuned annular conductor is simpler to construct, and includes fewer parts, than a dual coil having separate resonating loops. Yet a further advantage is that the sinusoidal mode can be fed in quadrature to increase transmit and receive efficiency for ^{1}H imaging, while the uniform current mode used for the ^{31}P or other nuclear species is driven linearly. The usefulness of the sinusoidal quadrature drive will depend on the orientation of the coil with respect to the $\mathbf{B_0}$ field.

With reference back to FIGURE 1, the B_1 fields should be generally transverse to the static magnetic field $\mathbf{B_0}$ to maximize the excited or detected magnetic resonance. Accordingly, as shown in FIGURE 1, the annular conductor **22** should be arranged such that $\mathbf{B_{1,uniform}}$ is generally transverse to the static magnetic field $\mathbf{B_0}$. This is suitably achieved by arranging the surface coil **20** such that the static magnetic field $\mathbf{B_0}$ is generally parallel with the plane of the annular conductor **22**. The sinusoidal $\mathbf{B_{1,sine}}$ field will substantially be in a plane that includes the z axis aligned with the $\mathbf{B_0}$ field. Each of $\mathbf{B_{1,uniform}}$ and $\mathbf{B_{1,sine}}$ will function as a linear coil for nuclear magnetic resonance (NMR),

rather than as a rotating field quadrature coil. Alternatively, quadrature operation can be achieved by using two co-planar loops as described with reference to FIGURE 9. In another described approach, the loop plane is oriented generally orthogonal to the z axis as is the case for annular loop 22' of FIGURE 1. This orientation also assures that the sinusoidal $\mathbf{B}_{1,sine}$ field is generally transverse to the static magnetic field $\mathbf{B}_0$. In this orientation a loop $\mathbf{B}_{1,uniform}$ mode is not useful for NMR. It is envisioned that various loop orientations and combinations of modes may be used.

If the first and second magnetic resonance frequencies are the same, for example using two co-planar loops, then a total transverse B_1 field is generated which results from the vector sum of the $\mathbf{B}_{1,sine}$ and $\mathbf{B}_{1,uniform}$ fields. This transverse field advantageously has less orientation-dependence than does the transverse B_1 field of a conventional surface coil operating only in the uniform mode.

Although surface coils are illustrated herein, the disclosed generally planar radio frequency coils can also be used in other applications, such as coil elements of a SENSE coil array or phased coil array, or as a local coil fixed to the bore, or so forth. In a coil array configuration, each coil element may be a generally planar annular conductor, such as the illustrated annular conductors **22**, **22a**, **22b**, **22c**, **22d**, but the coil array made up of a plurality of such generally planar annular conductor elements may have a non-planar shape, such as a body-fitting shape, a cylindrical shape, or so forth. Moreover, the term "generally planar" as used herein is intended to encompass generally planar annular conductors that have some bowing or curvature, for example to facilitate arrangement of an array of such generally planar annular conductor elements in a desired torso-fitting, cylindrical, or other non-planar shape.

The invention has been described with reference to the preferred embodiments. Modifications and alterations may occur to others upon reading and understanding the preceding detailed description. It is intended that the invention be construed as including all such modifications and alterations insofar as they come within the scope of the appended claims or the equivalents thereof.

CLAIMS

Having thus described the preferred embodiments, the invention is now claimed to be:

1. A generally planar radio frequency coil comprising:

one or two annular conductors **(22, 22c, 22d)** arranged generally parallel with a coil plane of the generally planar radio frequency coil and configured to support (i) a uniform electrical current distribution generating a first B_1 field **($B_{1,uniform}$)** at a first magnetic resonance frequency directed out of the coil plane and (ii) a sinusoidal electrical current distribution generating a second B_1 field **($B_{1,sine}$)** at a second magnetic resonance frequency directed parallel with the coil plane.

2. The radio frequency coil as set forth in claim **1**, wherein the one or two annular conductors comprise a single annular conductor **(22)** configured to support both the uniform current distribution and the sinusoidal current distribution, and second magnetic resonance frequency is higher than the first magnetic resonance frequency.

3. The radio frequency coil as set forth in claim **1**, wherein the one or two annular conductors include two annular conductors **(22c, 22d)**, one of which is configured to support the uniform current distribution and the other of which is configured to support the sinusoidal current distribution.

4. The radio frequency coil as set forth in claim **3**, wherein the second magnetic resonance frequency is higher than the first magnetic resonance frequency.

5. The radio frequency coil as set forth in claim **3**, wherein the first magnetic resonance frequency and the second magnetic frequency are the same, and the two annual conductors **(22c, 22d)** define a quadrature surface coil.

6. The radio frequency coil as set forth in claim **3**, wherein the two annular conductors **(22c, 22d)** are concentric and co-planar.

7. The radio frequency coil as set forth in claim **1**, further including:

a generally planar radio frequency shield **(26, 36a)** arranged parallel with the one or two annular conductors **(22, 22c, 22d)**.

8. The radio frequency coil as set forth in claim **7**, wherein the generally planar radio frequency shield **(26, 36a)** is one of disk-shaped and annular.

9. The radio frequency coil as set forth in claim **7**, further including:

a transverse annular radio frequency shield portion **(36b)** extending transverse to the generally planar radio frequency shield **(36a)** and surrounding at least an outer perimeter of the one or two annular conductors **(22, 22c, 22d)**.

10. A magnetic resonance scanner incorporating at least one generally planar radio frequency coil set forth in claim **1**.

11. A radio frequency coil comprising:

an annular conductor **(22)** configured to support:

(i) a uniform electrical current distribution generating a first B_1 field **($B_{1,uniform}$)** at a first magnetic resonance frequency directed out of a plane of the annular conductor, and

(ii) a sinusoidal electrical current distribution generating a second B_1 field **($B_{1,sine}$)** at a second magnetic resonance frequency directed parallel with the plane of the annular conductor.

12. The radio frequency coil as set forth in claim **11**, wherein the second magnetic resonance frequency is higher than the first magnetic resonance frequency.

13. The radio frequency coil as set forth in claim **12**, wherein the first magnetic resonance frequency corresponds to magnetic resonance of a first nuclear species in a selected static magnetic field **(B_0)**, and the second magnetic resonance frequency corresponds to magnetic resonance of a second nuclear species in the selected static magnetic field **(B_0)**.

14. The radio frequency coil as set forth in claim **13**, wherein the second magnetic resonance frequency corresponds to the ^{1}H magnetic resonance in the selected static magnetic field ($\mathbf{B_0}$).

15. The radio frequency coil as set forth in claim **14**, wherein the first magnetic resonance frequency corresponds to the magnetic resonance of a nuclear species selected from the group consisting of ^{19}F, ^{13}C, ^{23}Na, and ^{31}P in the selected static magnetic field ($\mathbf{B_0}$).

16. The radio frequency coil as set forth in claim **13**, wherein the selected static magnetic field ($\mathbf{B_0}$) is greater than 3 Tesla.

17. The radio frequency coil as set forth in claim **11**, wherein the annular conductor **(22)** includes:

one or more elements **(30)** having capacitance effective to tune the annular conductor **(22b, 22c)** to support a uniform electrical current distribution generating a first B_1 field ($\mathbf{B_{1,uniform}}$) at the first magnetic resonance frequency directed out of the plane of the annular conductor; and

one or more elements **(32)** having inductance effective to tune the annular conductor **(22c)** to support a sinusoidal electrical current distribution generating a second B_1 field ($\mathbf{B_{1,sine}}$) at the second magnetic resonance frequency directed parallel with the plane of the annular conductor.

18. The radio frequency coil as set forth in claim **11**, wherein the annular conductor **(22)** has a width and annular diameter and is spaced apart from a ground plane by a dielectric layer of dielectric width and dielectric constant, and further includes one or more capacitive elements **(30)**, wherein the width, annular diameter, dielectric width, dielectric constant, and capacitive elements are effective to tune the annular conductor **(22)** to support the uniform and sinusoidal electrical current distributions at selected respective first and second magnetic resonance frequencies.

19. The radio frequency coil as set forth in claim **11**, wherein the annular conductor **(22)** includes an annular microstrip transmission line.

20. The radio frequency coil as set forth in claim **19**, wherein the microstrip annular microstrip transmission line includes one or more gaps **(30)** defining capacitances effective to tune the annular conductor **(22b, 22c)** to support a uniform electrical current distribution generating a first B_1 field **($B_{1,uniform}$)** at the first magnetic resonance frequency directed out of the plane of the annular conductor.

21. The radio frequency coil as set forth in claim **11**, further including:

a dielectric substrate **(24, 34)** on which the annular conductor **(22)** is disposed; and

a ground plane **(26, 36a)** disposed on a side of the dielectric substrate **(24, 34)** opposite the annular conductor **(22)**.

22. A magnetic resonance scanner incorporating the radio frequency coil set forth in claim **11**.

23. A magnetic resonance scanner comprising:

a magnet **(10)** generating a static magnetic field **(B_0)**;

a magnetic field gradient system **(14)** configured to superimpose selected magnetic field gradients on the static magnetic field; and

an annular conductor **(22)** configured to support a sinusoidal electrical current distribution generating or induced by a B_1 field **($B_{1,sine}$)** at a magnetic resonance frequency directed parallel with the plane of the annular conductor.

24. The magnetic resonance scanner as set forth in claim **23**, wherein the annular conductor **(22)** is further configured to support a uniform electrical current distribution generating or induced by a B_1 field **($B_{1,uniform}$)** at a magnetic resonance frequency directed out of a plane of the annular conductor.

25. The magnetic resonance scanner as set forth in claim **24**, wherein a plane of the annular conductor **(22)** is arranged generally parallel with the static magnetic field **(B_0)**.

26. The magnetic resonance scanner as set forth in claim **23**, wherein the annular conductor includes:

two parallel annular conductors **(22c, 22d)** one of which is configured to support the sinusoidal electrical current distribution directed parallel with the two parallel planar annular conductors and the other of which is configured to support a uniform electrical current distribution generating or induced by a B_1 field **($\mathbf{B_{1,uniform}}$)** at a magnetic resonance frequency directed transverse to the two parallel planar annular conductors.

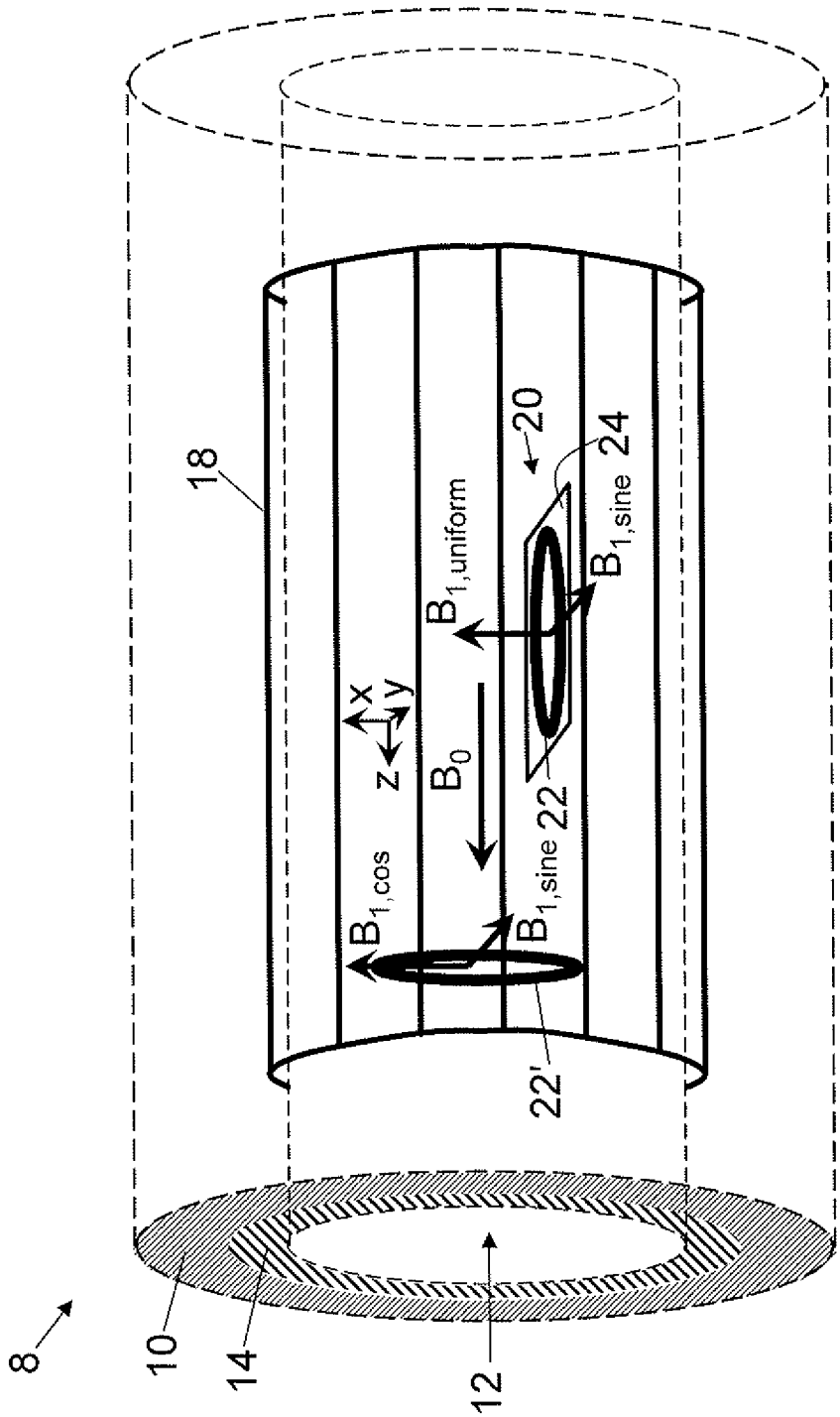


Fig. 1

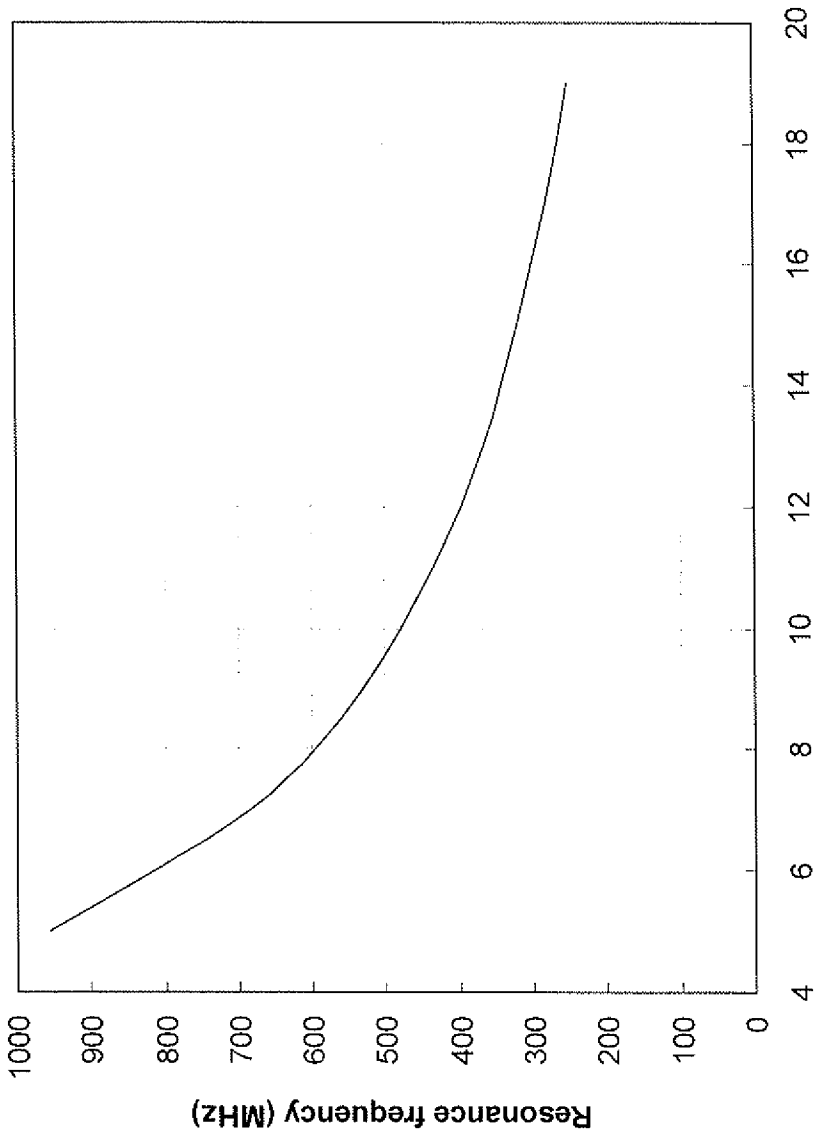

Resonance frequency (MHz)
1000
900
800
700
600
500
400
300
200
100
0
4
6
8
10
12
14
16
18
20
Ring radius (cm)

Fig. 2

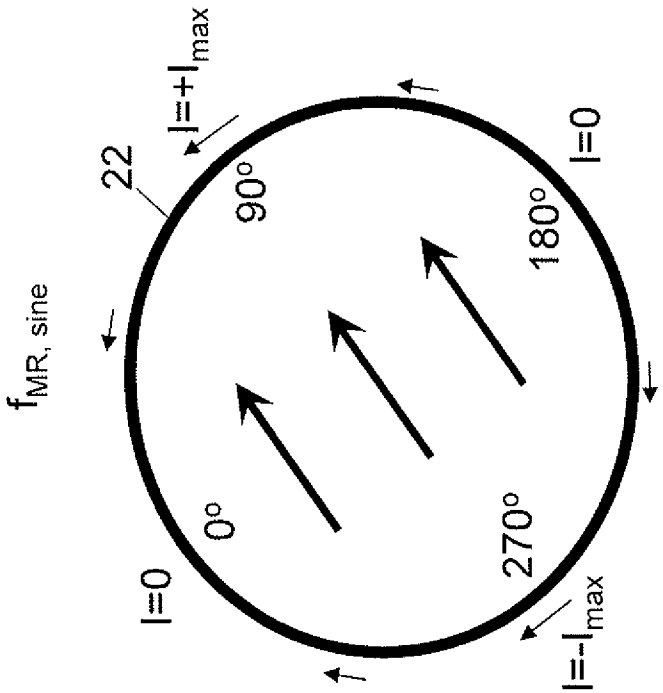


Fig. 4

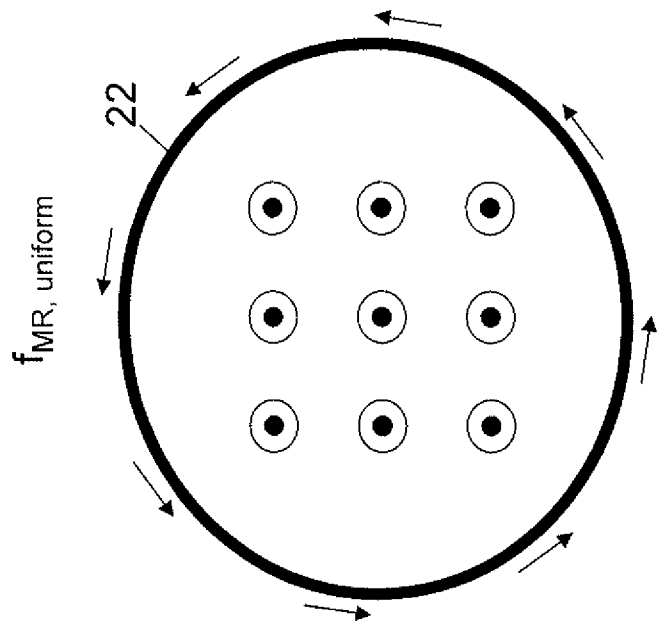


Fig. 3

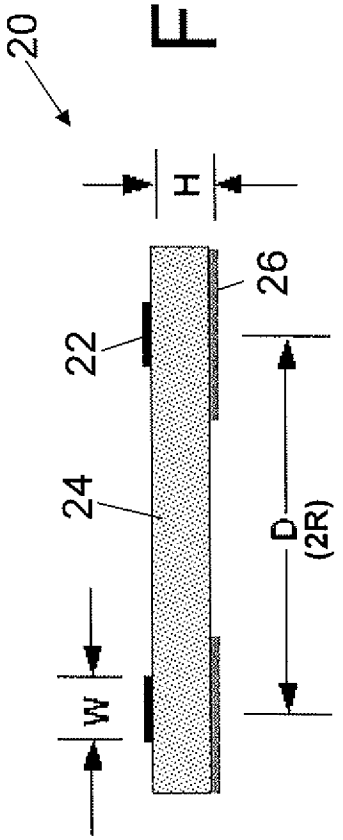


Fig. 5

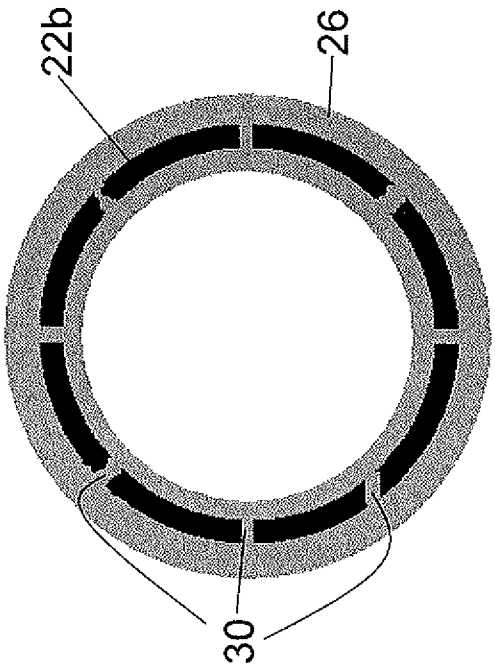


Fig. 7

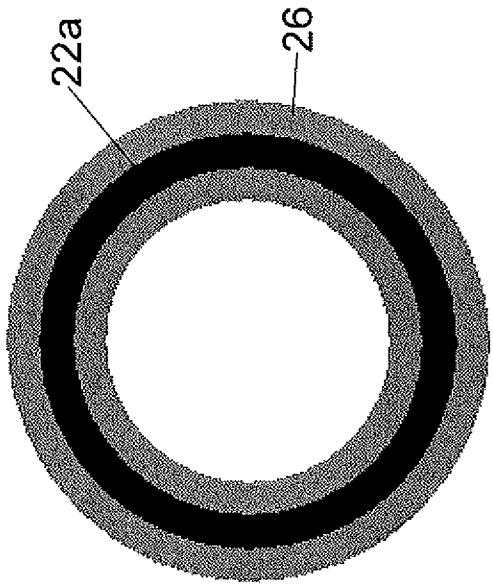


Fig. 6

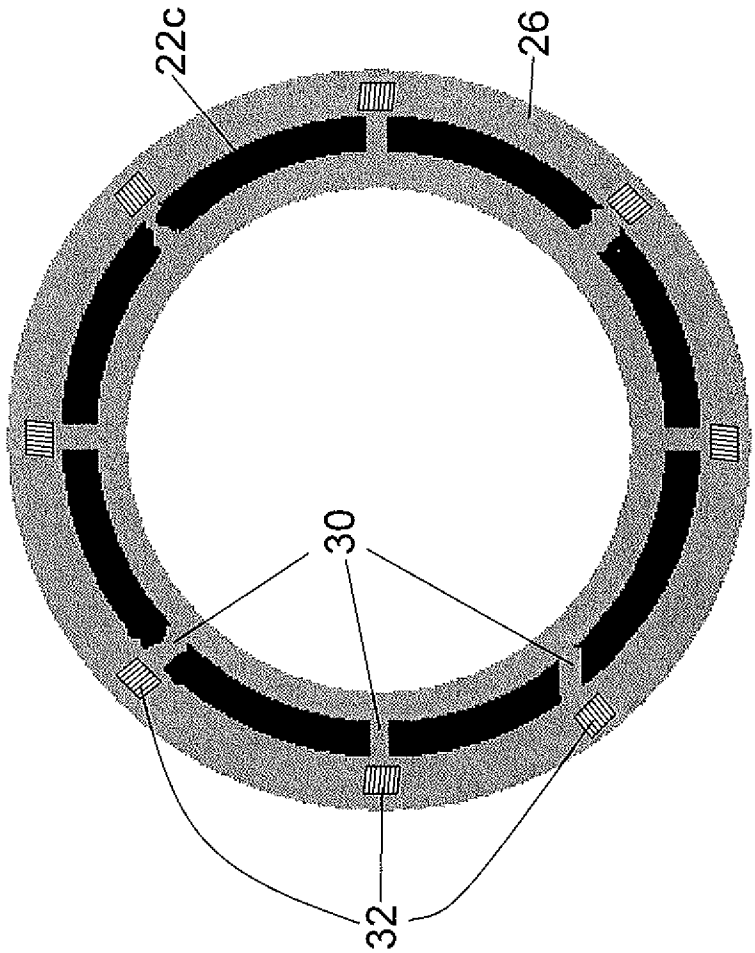


Fig. 8

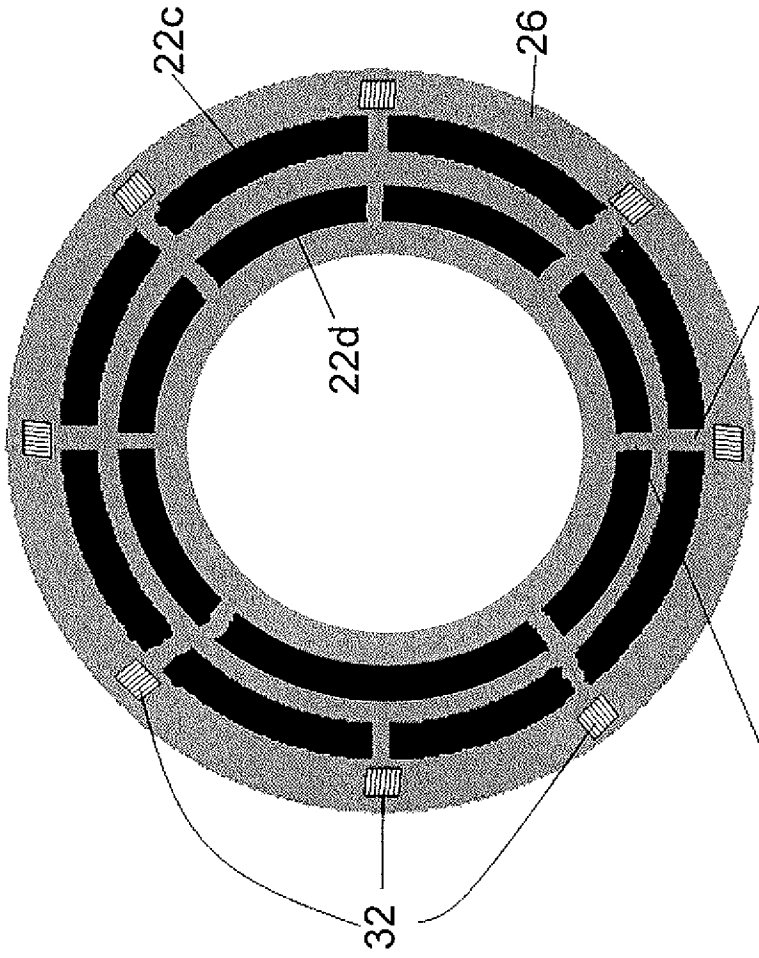


Fig. 9

Fig. 10

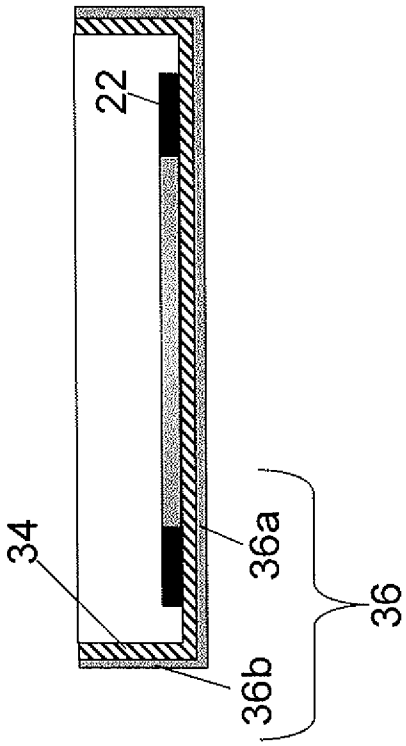
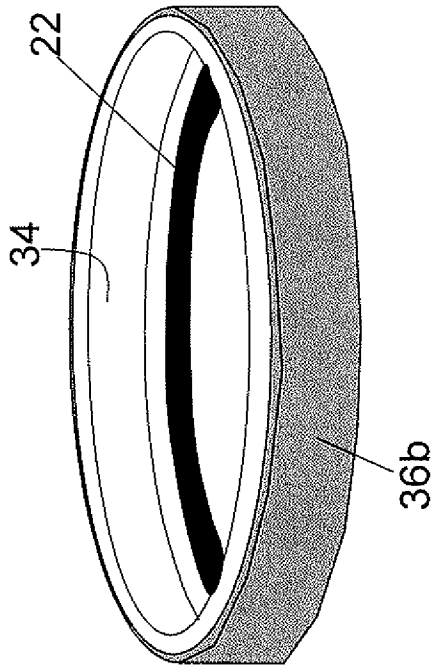


Fig. 11



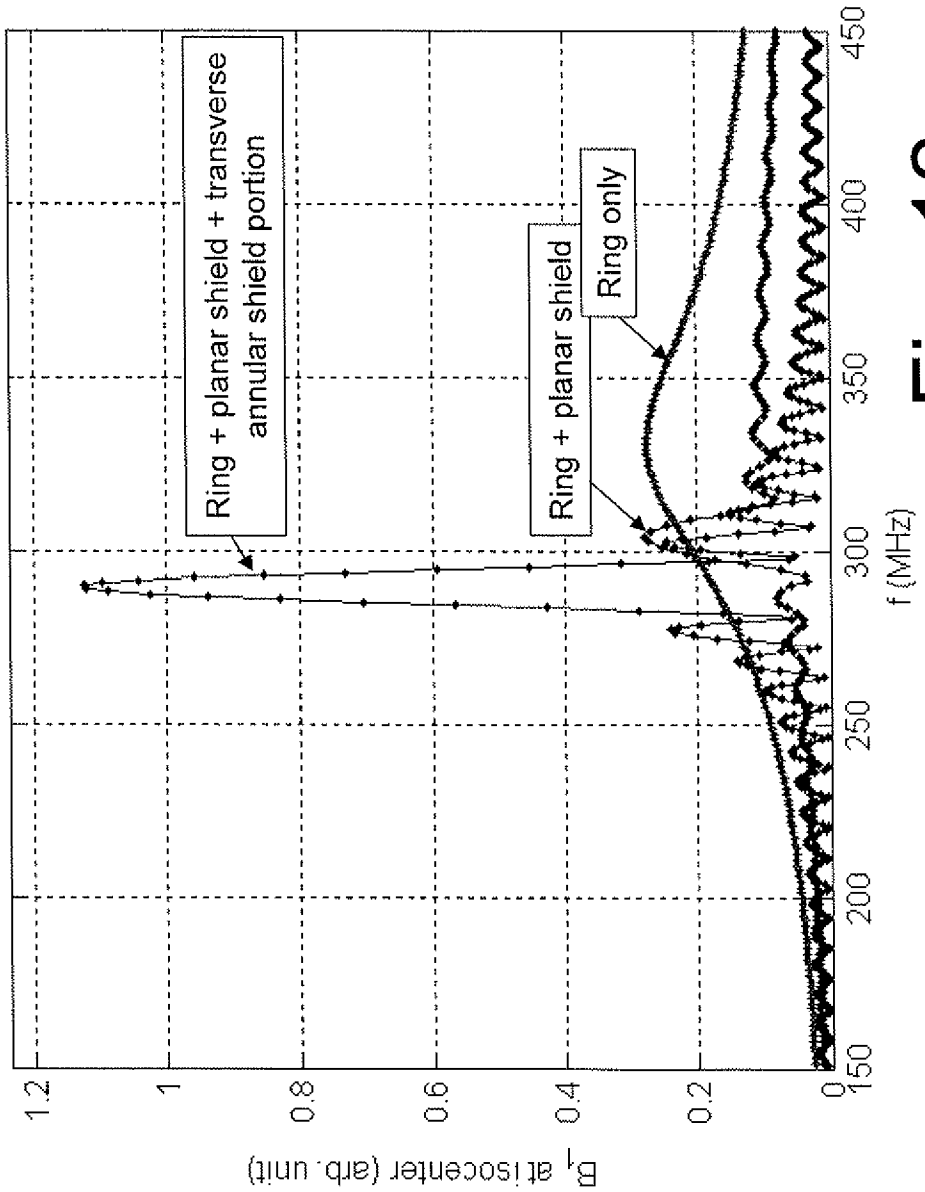

Ring + planar shield + transverse annular shield portion
Ring + planar shield
Ring only
B1 at isocenter (arb. unit)
f (MHz)
0
0.2
0.4
0.6
0.8
1
1.2
150
200
250
300
350
400
450

Fig. 12

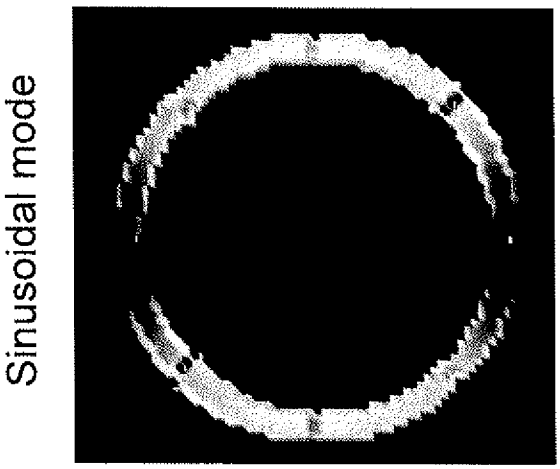


Fig. 14

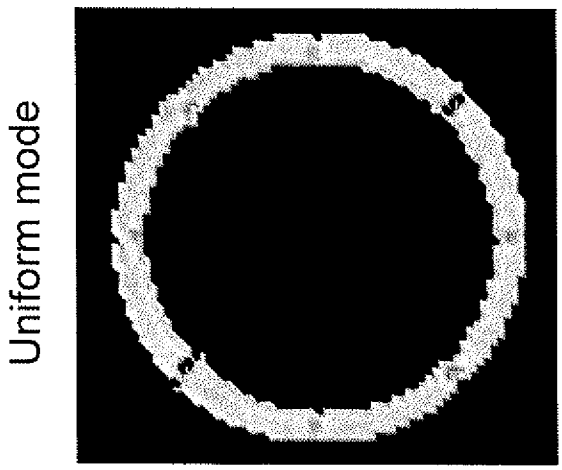


Fig. 13

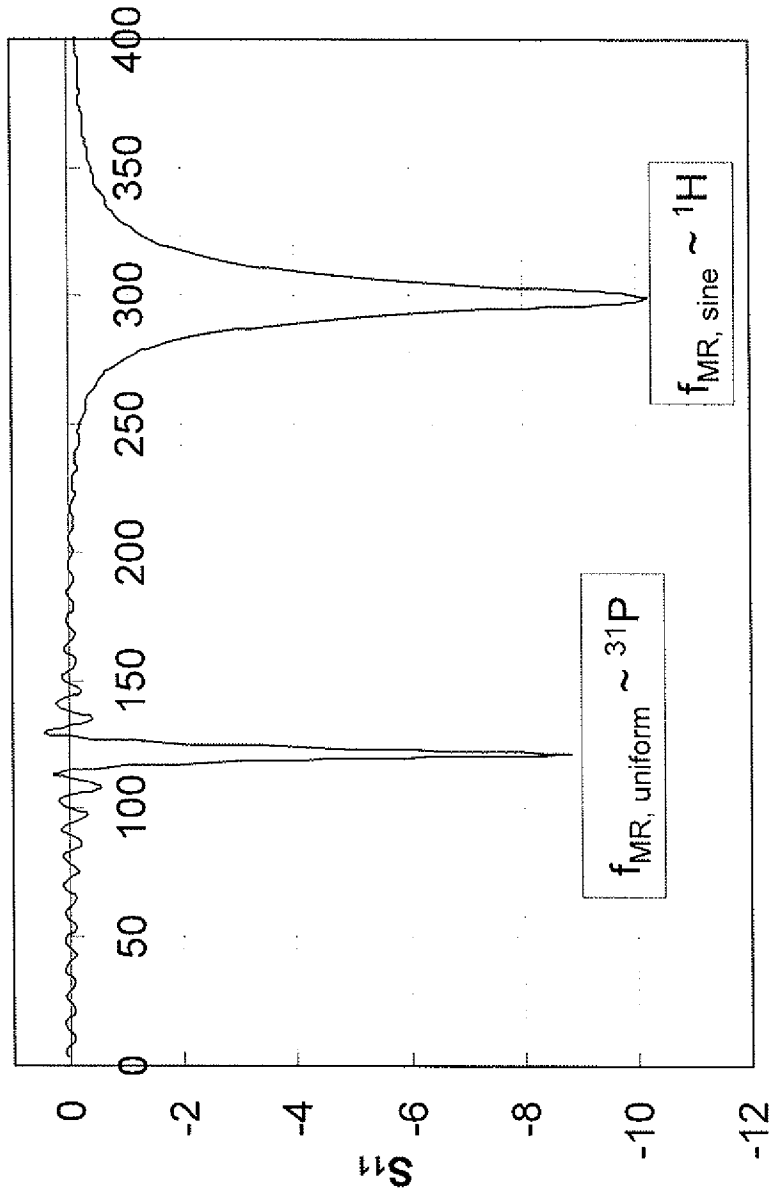

0
-2
-4
-6
-8
-10
-12
S11
0
50
100
150
200
250
300
350
400
f (MHz)
f_MR, uniform ~ 31P
f_MR, sine ~ 1H

Fig. 15

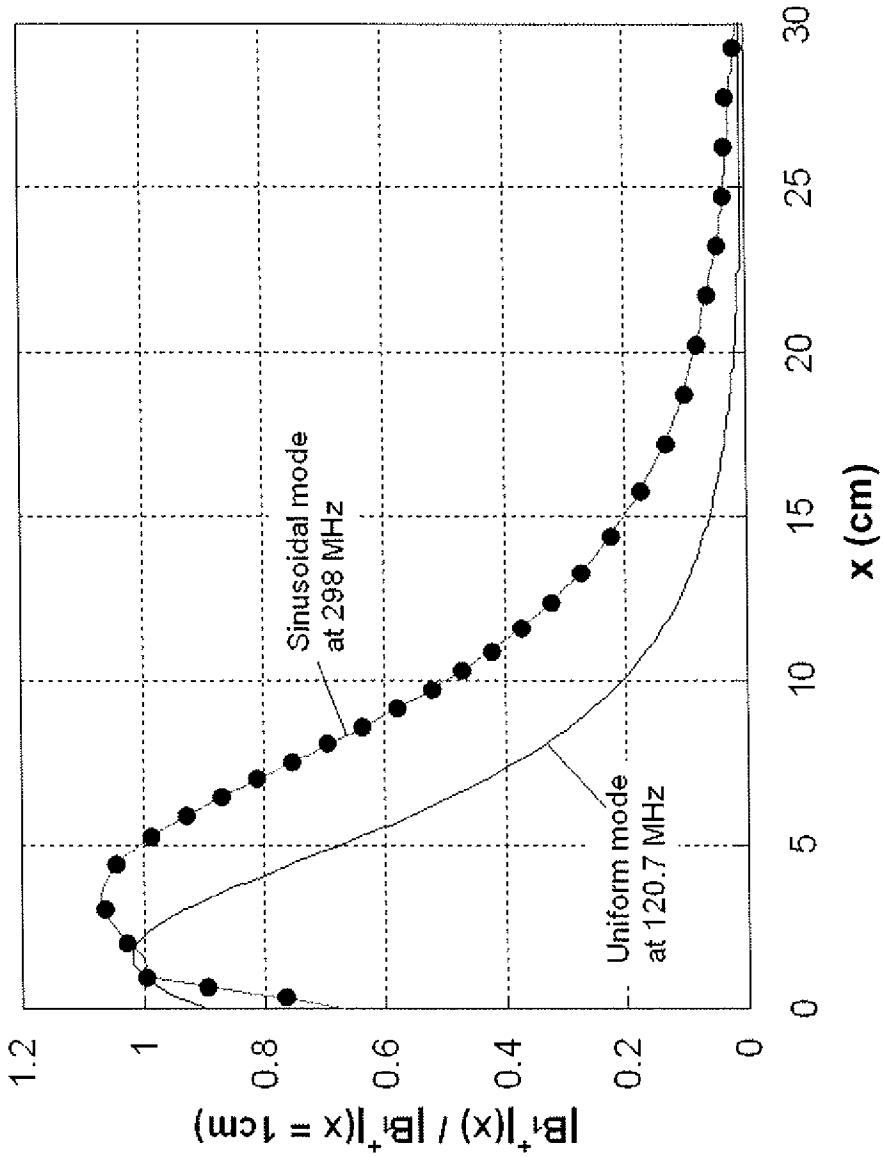

Sinusoidal mode
at 298 MHz
Uniform mode
at 120.7 MHz
x (cm)
0
5
10
15
20
25
30
0
0.2
0.4
0.6
0.8
1
1.2

Fig. 16

INTERNATIONAL SEARCH REPORT

International application No
PCT/IB2008/050328

A. CLASSIFICATION OF SUBJECT MATTER
INV. G01R33/341 G01R33/36 G01R33/422

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)
G01R

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

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	JP 07 303623 A (GE YOKOGAWA MED SYST LTD) 21 November 1995 (1995-11-21) the whole document	1-26
X	US 4 928 064 A (KEREN HANAN [IL]) 22 May 1990 (1990-05-22) column 2, line 17 - column 2, line 52 column 3, line 47 - column 5, line 54; figures 1-3	1,2, 10-17, 22-25

-/--

[X] Further documents are listed in the continuation of Box C.

[X] 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

"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	Date of mailing of the international search report
1 July 2008	15/07/2008

Name and mailing address of the ISA/	Authorized officer
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	Lersch, Wilhelm

INTERNATIONAL SEARCH REPORT

International application No
PCT/IB2008/050328

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	PESHKOVSKY ET AL: "Sensitivity enhancement and compensation of RF penetration artifact with planar actively detunable quadrature surface coil" MAGNETIC RESONANCE IMAGING, TARRYTOWN, NY, US, vol. 24, no. 1, 1 January 2006 (2006-01-01), pages 81-87, XP005239435 ISSN: 0730-725X see the chapters 1., 2. and 4.	1,2, 7-11,17, 18,22-25
X	US 5 898 306 A (LIU HAIYING [US] ET AL) 27 April 1999 (1999-04-27) column 3, line 61 - column 5, line 19 column 7, line 38 - column 8, line 27; figures 1,2	1,2, 10-17, 22-25
P,X	Z.ZHAI ET AL.: "Ring Structured RF Coils for Ultra-High Field MRI" PROC.INTL.SOC.MAG.RESON.MED. 15, 2007, page 3276, XP002486310 conference abstract	23
A	K.C.ONG ET AL.: "Radiofrequency Shielding of Surface Coils at 4.0 T" JMRI, vol. 5, 1995, pages 773-777, XP002486311 the whole document	7-9,18, 21
A	WO 2005/076029 A (RAPID BIOMEDIZINISCHE GERAETE [DE]; LANZ TITUS [DE]; GRISWOLD MARK [DE) 18 August 2005 (2005-08-18) page 2, line 24 - page 5, line 27 page 7, line 9 - page 7, line 30 page 9, line 26 - page 11, line 3 page 11, line 30 - page 12, line 7; figures 1,2,7	7-9, 18-21
A	EP 1 122 549 A (YOKOGAWA MEDICAL SYST [JP]) 8 August 2001 (2001-08-08) paragraphs [0029] - [0054], [0060]; figures 2-8,10,13	7,8, 18-21
A	ZHANG X ET AL: "MICROSTRIP RF SURFACE COIL DESIGN FOR EXTREMELY HIGH-FIELD MRI AND SPECTROSCOPY" MAGNETIC RESONANCE IN MEDICINE, ACADEMIC PRESS, DULUTH, MN, US, vol. 46, no. 3, 1 September 2001 (2001-09-01), pages 443-450, XP001096736 ISSN: 0740-3194 the whole document	19-21

-/--

INTERNATIONAL SEARCH REPORT

International application No
PCT/IB2008/050328

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	X.ZHANG ET AL.: "Higher-Order Harmonic Transmission-Line RF Coil Design for MR Applications" MAGNETIC RESONANCE IN MEDICINE, vol. 53, 2005, pages 1234-1239, XP002486312 see pages 1234-1236 -----	19-21

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/IB2008/050328

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
JP 7303623 A	21-11-1995	JP 3422559 B2	30-06-2003
US 4928064 A	22-05-1990	IL 85786 A	10-06-1991
US 5898306 A	27-04-1999	NONE	
WO 2005076029 A	18-08-2005	DE 102004006322 A1 EP 1714162 A1 US 2007159176 A1	10-11-2005 25-10-2006 12-07-2007
EP 1122549 A	08-08-2001	US 6320383 B1	20-11-2001