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G01N 24/04

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G1N

(54) RF Field coils for NMR apparatus

(57) An RF coil 1 or 3 and a capacitive element 9 needed to resonate the coil at a desired Larmor frequency are both fabricated, using etching techniques, on the same printed circuit board. This simplifies the construction of coil assemblies having complex conductive patterns. By utilizing a flexible printed circuit board having a substrate material characterized by high dielectric constant, low-loss and high standoff voltage properties, particularly useful constructions are obtained, e.g. for use in whole body imaging or spectroscopy. Capacitor 9 is formed by overlapping portions of the printed circuit on either side of the board. Gaps may be present in one such portion, the capacitance being adjusted by bridging the gaps. A more complex construction comprising a plurality of conductors lengthwise on the cylindrical surface, but including capacitive element in series therewith, is also disclosed. A window in the conductor pattern may enable viewing of the patient.

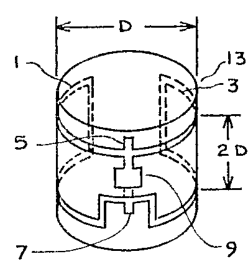

FIG. 1B

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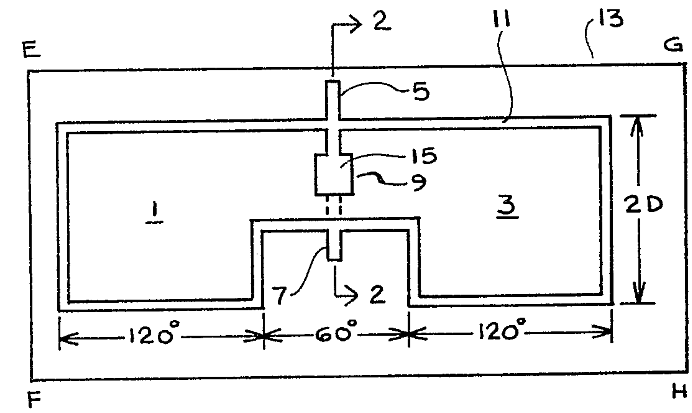


FIG. 1A

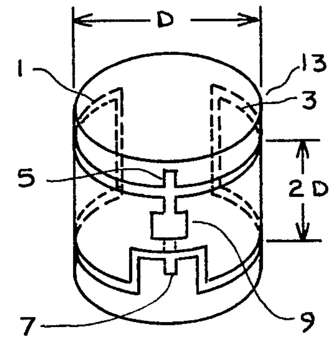


FIG. 1B

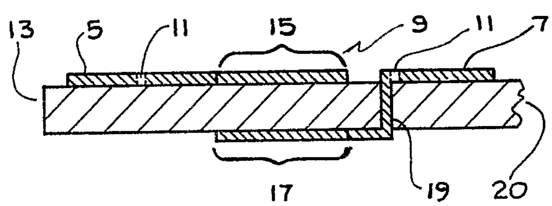


FIG. 2

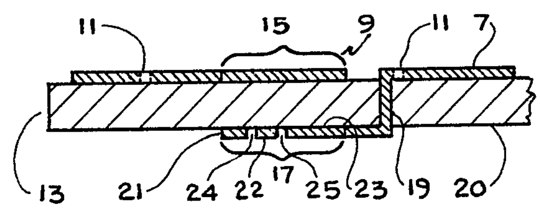


FIG. 3

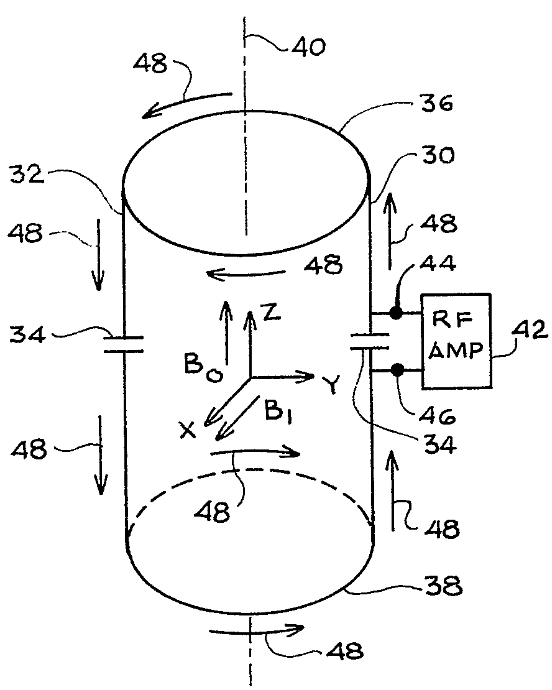


FIG. 4A

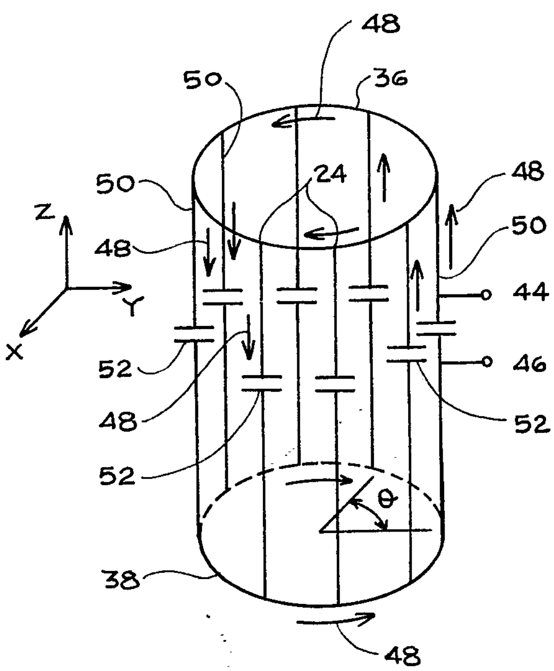
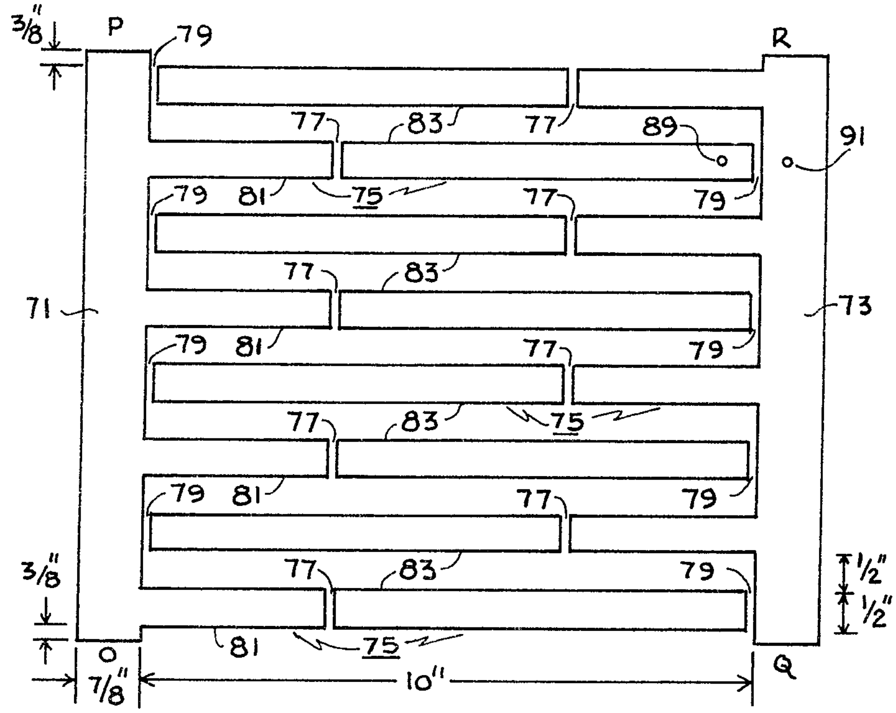


FIG. 4 B


3/8"
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83
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89
91
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81
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73
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Q
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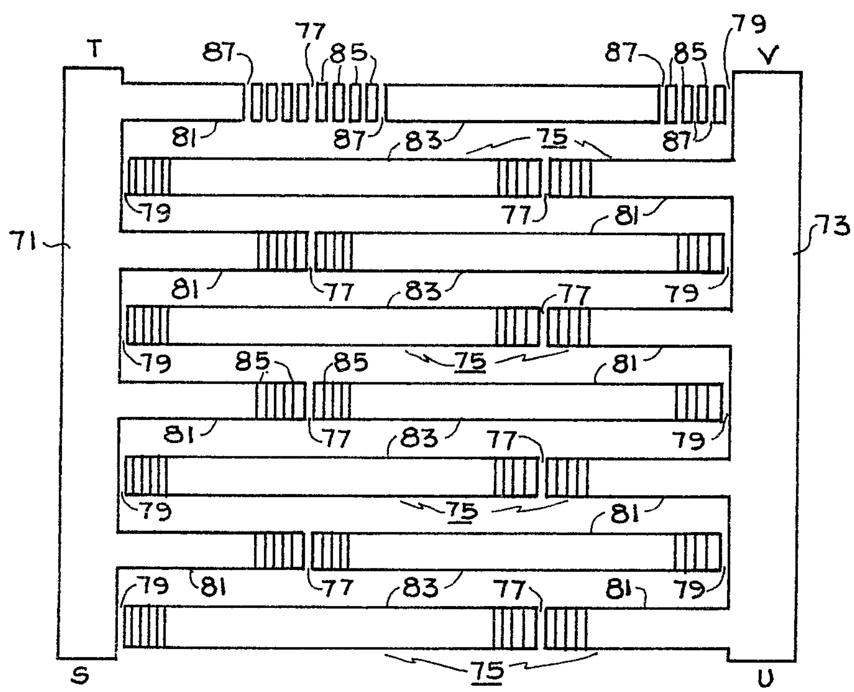
1/2"

FIG. 5A


T
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83
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FIG. 5B

SPECIFICATION

RF field coils for NMR apparatus

This invention relates to nuclear magnetic resonance (NMR) apparatus. More specifically, this invention relates to integral radio frequency (RF) coils useful with such apparatus for transmitting and/or receiving RF signals.

In the past, the NMR phenomenon has been utilized by structural chemists to study, in vitro, the molecular structure of organic molecules. Typically, NMR spectrometers utilized for this purpose were designed to accommodate relatively small samples of the substance to be studied. More recently, however, NMR has been developed into an imaging modality utilized to obtain images of anatomical features of live human subjects, for example. Such images depicting parameters associated with nuclear spins (typically hydrogen protons associated with water in tissue) may be of medical diagnostic value in determining the state of health of tissue in the region examined. NMR techniques have also been extended to in vivo spectroscopy of such elements as phosphorus and carbon, for example, providing researchers with the tools, for the first time, to study chemical processes in a living organism. The use of NMR to produce images and spectroscopic studies of the human body has necessitated the use of specifically designed system components, such as the magnet, gradient and RF coils.

By way of background, the nuclear magnetic resonance phenomenon occurs in atomic nuclei having an odd number of protons and/or neutrons. Due to the spin of the protons and neutrons, each such nucleus exhibits a magnetic moment, such that, when a sample composed of such nuclei is placed in a static, homogeneous magnetic field, B_o, a greater number of nuclear-magnetic moments align with the field to produce a net macroscopic magnetization M in the direction of the field. Under the influence of the magnetic field B_o, the magnetic moments precess about the axis of the field at a frequency which is dependent on the strength of the applied magnetic field and on the characteristics of the nuclei. The angular precession frequency, ω, also referred to as the Larmor frequency, is given by the Larmor equation $\omega = \gamma B$, in which γ is the gyronmagnetic ratio (which is constant for each NMR isotope) and wherein B is the magnetic field (B_o plus other fields) acting upon the nuclear spins. It will be thus apparent that the resonant frequency is dependent on the strength of the magnetic field in which the sample is positioned.

The orientation of magnetization M, normally directed along the magnetic field B_o, may be perturbed by the application of magnetic fields oscillating at or near the Larmor frequency. Typically, such magnetic fields designated B_1 are applied orthogonal to the direction of magnetization M by means of radio-frequency pulses through a coil connected to radio-frequency-transmitting apparatus. Magnetization M rotates about the direction of the B_1 field. In NMR, it is typically desired to apply RF pulses of sufficient magnitude and duration to rotate magnetization M into a plane perpendicular to the direction of the B_o field. This plane is commonly referred to as the transverse plane. Upon cessation of the RF excitation, the nuclear moments rotated into the transverse plane begin to realign with the B_o field by a variety of physical processes. During this realignment process, the nuclear moments emit radio-frequency signals, termed the NMR signals, which are characteristic of the magnetic field and of the particular chemical environment in which the nuclei are situated. The same or a second RF coil may be used to receive the signals emitted from the nuclei. In NMR imaging applications, the NMR signals are observed in the presence of magnetic-field gradients which are utilized to encode spatial information into the NMR signal. This information is later used to reconstruct images of the object studied in a manner well known to those skilled in the art.

In performing whole-body NMR studies, it has been found advantageous to increase the strength of the homogeneous magnetic field B_o. This is desirable in the case of proton imaging to improve the signal-to-noise ratio of the NMR signals. In the case of spectroscopy, however, this is a necessity, since some of the chemical species studied (e.g., phosphorus and carbon) are relatively scarce in the body, so that a high magnetic field is necessary in order to detect usable signals. As is evident from the Larmor equation, the increase in magnetic field B is accompanied by a corresponding increase in ω and, hence in the resonant frequency of the transmitter and receiver coils. This complicates the design of RF coils which are large enough to accomodate the human body. One source of difficulty is that the RF field generated by the coil must be homogeneous over the body region to be studied.

To produce a homogeneous RF field over the entire body portion to be studied and to achieve the desired nuclear spin excitation, the RF transmitting coil (which frequently doubles as the receiving coil) must withstand high voltages at the frequencies of interest. For example, the coil may experience voltages in excess of 5000 volts at frequencies determined by the Larmor equation. Conventional vacuum-transmitting capacitors are usually ferromagnetic and therefore are unsuitable for use in NMR apparatus. Other conventional capacitors have a quality factor Q which is too low and as a result, unacceptably degrade coil performance. The capacitors must also be flexible to conform to the shape of NMR RF head and body coils which typically have a cylindrical configuration. In accordance with the invention, it has been found advantageous to etch the RF coil conductive pattern and the capacitive elements needed to resonate the coil on a printed circuit board as an intergral assembly. This not only assures that the capacitors having the aforedescribed desirable properties are obtained, but the fabrication of coils having complex conductive pattern designs is simplified with a concomitant improvement in coil reproducibility when many coils of the same configuration are needed.

Accordingly, there is provided an NMR apparatus suitable for exciting and detecting NMR signals in an NMR sample. The apparatus includes a radio frequency coil having at least one coil turn and at least one capacitive element for resonating the coil at the Larmor frequency of the sample, wherein the coil and the capacitive element comprise a conductive pattern fabricated on the same printed circuit board.

In the accompanying drawings, by way of example only:-

Figure 1A illustrates a parallel-connected, two-turn NMR RF coil fabricated in accordance with the invention;

Figure 1B depicts the coil illustrated in Figure 1A configured as a cylinder;

Figure 2 is a cross-sectional view of the coil depicted in Figure 1A taken along line 2-2;

Figure 3 is similar to Figure 2 but illustrates an alternative embodiment;

Figures 4A and *4B* are schematic illustrations of a coil which may be fabricated in accordance with the invention; and

Figures 5A and *5B* depict conductive patterns utilized in fabricating in accordance with the invention the coil depicted in Figure 3.

Figure 1A depicts schematically a parallel-connected, two-turn NMR RF coil of conventional design but which is fabricated in accordance with the invention. The coil is made up of single turns 1 and 3 connected in parallel and driven at points 5 and 7 across a tuning capacitor 9. In coils of conventional construction, coil turns 1 and 3 are typically formed from copper tubing and mounted on a non-conductive, cylindrical coil form made of low-loss dielectric material.

The conventionally constructed coil utilizes a discrete capacitor component electrically interconnected with the copper tubing. Although such coils perform satisfactorily, they suffer from drawbacks described hereinbefore. Moreover, such conventional construction techniques do not lend themselves to use with more complex coil designs as will be disclosed with reference to Figures 4A and 4B.

In accordance with the invention, the coil and capacitor are fabricated as a single integral assembly. Referring again to Figure 1A, the coil is fabricated by etching (using conventional techniques) a conductive pattern 11, including capacitor 9, on a single, flexible printed circuit board 13. The finished coil is formed into a cylinder, as shown in Figure 1B, by fastening edge E-F to edge G-H. In general, each of the coil turns is sized to cover about 120° of the cylinder's circumference. The coil region where connections 5 and 7 are made is sized to cover approximately 60° of circumference. For maximum RF field uniformity, the side of the coils parallel to the cylindrical axis should be equal to two cylinder diameters (D). However, a coil having a side length of 2D is impractical, because RF energy is placed in regions of the patient which are not of interest. In practice, therefore, the coil side length is reduced to approximately one diameter.

Referring now to Figure 2, there is shown a cross-sectional view of the inventive NMR coil taken along line 2-2 in Figure 1A through capacitive element 9. In Figure 2 like parts are assigned the same reference numerals as in Figure 1A. Capacitor 9 is made up of a conductive region 15 etched on one side of printed circuit board 13 and a conductive region 17 disposed opposite region 15 on the other side of the printed circuit board. Region 17 is connected to lead 7 by means of a shunt 19 passing through the printed circuit. Regions 15 and 17 are separated by printed circuit substrate 20 which in the preferred embodiment comprises a low-loss dielectric material having a high voltage standoff. It has been found that commercially available double-sided printed circuit boards utilizing Teflon (R T M) synthetic resin as the substrate are particularly well suited. It should be recognized that printed circuit boards using low-loss substrate materials other than Teflon resin may be utilized in fabricating coils in accordance with the invention.

Figure 3 depicts a cross-sectional view of another embodiment of capacitive element 9 fabricated in accordance with the invention. This embodiment is substantially identical to that of Figure 2 with the notable exception that one of the conductive regions (e.g., 17) is divided into conductive pads 21-23 by means of gaps 24 and 25. Bridging one or both of gaps 24 and 25 by a conductive shunt (not shown) will increase the area of region 17 overlapping with region 15. In this manner, the capacitance of capacitor 9 can be adjusted thereby to vary the coil resonant frequency. It will be recognized that the number of gaps may be increased or decreased from two, as needed.

The manner in which relatively simople coil patterns and capacitive elements can be constructed has been disclosed hereinbefore with reference to Figures 1A-1B, 2 and 3. More complex coils, such as that depicted schematically in Figure 4B have been successfully constructed in accordance with the invention. The coil configuration depicted in Figure 4B is disclosed and claimed in commonly assigned copending Patent Application Serial No. (548,745) which is incorporated herein by reference as background material.

Referring now to Figure 4A, the single-turn saddle coil is comprised of two parallel conductive segments 30 and 32 each having a capacitor 34 connected in series therewith. The ends of conductors 30 and 32 are connected to diametrically opposed points on a pair of parallel conductive loops 36 and 38 spaced along common longitudinal axis 40. The coil could be driven by a source such as an RF amplifier generally designated 42 connected between terminals 44 and 46 in parallel with the capacitor in segment 30. Arrows 48 indicate the relevant current paths which produce a B_1 radio-frequency field perpendicular to the plane defined by conductive wire segments 30 and 32 which, for convenience, will be hereinafter referred to as being vertical. It should be noted that the direction of the B_1 field may be determined by the conventional right-hand rule. The rule states that, if the fingers of the right hand are placed around the current-carrying segment so the thumb points in the direction of current flow, the fingers will point in the direction of the magnetic field (i.e., B_1)

The complete NMR coil design is comprised in the preferred embodiment of a plurality of vertical wire segments 50 evenly spaced and connected around the upper and lower conductive circular loops 36 and 38 as shown in Figure 4B. It will be recognized that the loops need not be precisely circular but may also be elipsoidal or of some other geometrical form generally having an opening therein to accommodate the object to be examined. Each of the vertical conductive segments includes at least one capacitive element 52. The multiple current paths, each equivalent to that in Figure 2A, are indicated by arrows 48 in Figure 4B. The homogeneity of the B_1 field increases as the number of vertical conductive segments is increased. This is due to the fact that, as the number of segments is increased, the resultant field is produced by many contributions so that the effect of any one conductor is reduced. The number of conductors cannot be increased without limit since the open spaces between adjacent vertical conductors are needed to allow a path for the magnetic flux, due to current flow, to escape thereby producing a homogeneous B_1 field. Coils having 4, 8, 16, and 32 vertical conductors have been constructed. It should be noted that the vertical conductive segments need not be evenly spaced, In fact, an embodiment of the RF coil having a window formed therein to facilitate observation of the patient has been fabricated. What is needed to produce a homogeneous B_1 field is a plurality of vertical conductors distributed around the periphery of the conductive loops such that the current in the vertical conductors approximates a sinusoidal distribution. The resulting NMR coil may be thought of as a resonant cavity made up of an open-ended cylinder with an oscillating magnetic field transverse to the cylinder's axis when the coil is excited by a sinusoidal voltage or current source.

The manner in which the preferred embodiment of a coil having 32 segments and which was physically and electrically sized for NMR head studies and which was constructed in accordance with the invention will be described with reference to Figures 5A and 5B. The same construction method is utilized in the construction of body coils which are typically sized to have a larger diameter. The head coil was operable at a frequency of 21.31 MHz, which is determined by the strength of main field B_o, and the NMR isotope studied. In general, the coil is fabricated by etching (using conventional techniques) four double-sided, copper-clad Teflon resin printed circuit boards. The boards are mounted on a cylindrical support form having a 10.5 inch outside diameter. Each side of the circuit boards is etched with a different conductive pattern. Each circuit board is approximately 8 by 12 inches. It will be recognized, however, that the entire coil (including the capacitors) can be etched on a single flexible printed circuit board.

Referring now to Figure 5A, there is shown the conductive pattern utilized for etching the side of the circuit board (referred to hereinafter as the inside etched surface) which is mounted on the cylindrical form and which is closest to the NMR sample positioned in the coil. Wide strips 71 and 73, each seven-eighths inch wide, form one quarter of the length of the conductive loop elements. There are eight straight conductive elements, generally designated 75, each approximately ten inches long and one-half inch wide, extending between loop elements 71 and 73. The straight elements are separated by one-half wide blank areas where the copper is to be etched away. The straight elements are offset from the ends of loop elements 71 and 73 by approximately three-eighths inch. Adjacent ones of straight elements 75 have a gap 77 formed therein to leave, alternately, one third (designated 81) of the element connected to loop elements 71 and 73. A second gap 79 is provided in each straight element to separate the remaining two thirds (designated 83) of the straight element from the corresponding loop element. In this manner, a pattern is formed in which each straight element is made up of a connected one third of the element and an unconnected two thirds of the element. In adjacent straight conductors, the unconnected element 83 is coextensive with the connected one third and extends beyond gap 77 to be coextensive with a one third of the unconnected element in the adjacent straight conductor.

The other pattern is depicted in Figure 5B and will be referred to herein as the outside etched surface. This pattern is a mirror image of the pattern depicted in Figure 5A and is sized to have the same dimensions. The pattern of Figure 5B differs from that of Figure 5A in that straight conductor portions 81 and 83 are each provided with typically four (although more of fewer could be used) copper pads 85 by etching narrow gaps 87.

The inner and outer etched surfaces are overlayed such that points S, T, U. V (Figure 5A) lie above points O, P, Q, R (Figure 5B), respectively. In this manner, gaps 77 on each etched (inner and outer) surface are bridged by continuous portions of the unconnected two-thirds 83 of the straight elements 75 on each surface. Gaps 79 are bridged by continuous portions 81 of the straight element. The combination of copper foil segments and printed circuit dielectric form three series-connected capacitors aklong the length of each straight conductor. The number of capacitors can be varied by increasing or decreasing the number of gaps. The net capacitance in each straight conductor is typically adjusted to be approximately equal. The adjustment is accomplished by electrically connecting to conductors 81 or 83 (Figure 5B) one or more of copper pads 85 by bridging gaps 87 to change the area of overlap of the inner and outer surfaces. In the preferred embodiment, the inner and outer patterns are etched on opposite sides of a double-sided printed circuit board.

Strips 71 and 73 on each of the inner and outer etched surfaces are electrically connected together at points O and S, P and T, Q and U, and R and V to form one quarter assembly. A complete coil requires four such overlayed and interconnected assemblies. A half of the coil is made by electrically joining two quarter assemblies. Points O and Q of one quarter assembly are electrically connected to points P and R, respectively, of the second quarter assembly. The two coil halves constructed in this manner are mounted on a cylindrical coil form without electrical connections between them. The two coil halves are coupled, in operation, by the mutual inductances thereof when one of the halves is energized across one or more of the three series-connected capacitors in a straight conductor, such as, for example, at points 89 and 91 shown in Figure 5A. The drive point impedance was about 50 ohms without any adjustment with a patient's head positioned in the coil (i.e., with a loaded coil).

In the preferred embodiment, the double-sided printed circuit board dielectric (Teflon resin) thickness was about .006". Each of the three capacitors in each straight conductor was adjusted to equal approximately 133 pico farads. It should be noted that it is not important that each capacitor have equal value, but only that the net capacitances of each straight conductor are equal. The desired resonance frequency with a homogeneous RF magnetic field was at 21.31 mHz.

Another embodiment of an inventive NMR coil was constructed following the patterns disclosed with reference to Figures 5A and 5B and having 32 vertical segments. This coil was constructed on a cylindrical form having an outside diameter of 11.5 inches and a length of 16.5 inches. Strip elements 71 and 73 (Figures 5A and 5B) were .25 of an inch wide. Straight conductors 75 were .5 of an inch wide spaced at five-eighths inch interval. In this case, there were ten gaps in each straight conductor, similar to gaps 77 and 79, so that the value of each series capacitor was lower than that in the embodiment of Figures 7A and 7B. The coil resonant frequency was 63.86 mHz.

The capacitance, C, for a capacitor formed by two conductive sheets having an area A, separated by a Teflon resin substrate having a thickness d may be determined using the formula:

$$C = \frac{KA(.225pF/in}{d},$$

wherein K is the dielectric constant of the substrate material and pF designates pico farads.

For a double-sided printed circuit board utilizing a Teflon resin substrate .004 inch thick and having 1 oz. copper bonded thereto, the dielectric constant K is approximately 2.4. Suitable printed circuit boards are commercially available from 3M Company, Electronic Products Division, St. Paul, Minnesota.

While this invention has been described with reference to particular embodiments and examples, other modifications and variations will occur to those skilled in the art in view of the above teachings. Accordingly, it should be understood that within the scope of the appended claims the invention may be practiced otherwise than is specifically described.

CLAIMS

1. An NMR apparatus suitable for exciting and detecting NMR signals in an NMR sample, said apparatus including a radio frequency (RF) coil having at least one coil turn and at least one capacitive element for resonating said coil at the Larmor frequency of the sample, the improvement wherein said coil and said capacitive element comprise a conductive pattern fabricated on the same printed circuit board.

2. The NMR apparatus of Claim 1 wherein said printed circuit board includes a low-loss dielectric substrate with high-voltage standoff property, said substrate having conductive material disposed on major surfaces thereof, and wherein said capacitive element comprises overlapping conductive material areas fabricated on opposite sides of the substrate.

3. The NMR apparatus of Claim 2 wherein at least one of the overlapping conductive areas comprises a plurality of electrically insulated conductive pads, which pads are electrically interconnectable to vary the area of overlap between the conductive material areas forming said capacitive element thereby to vary the capacitance thereof.

4. The NMR apparatus of Claim 1 wherein said coil includes a conductive portion made up of first and second conductive segments, each segment having at least one non-conductive gap formed therein, said first and second segments being fabricated on opposite sides of said printed circuit board such that the gap in one conductive segment is bridged by a continuous region of the other conductive segment, thereby to form at least one capacitive element in series with said conductive coil portion.

5. The NMR apparatus of Claim 4 wherein at least one of said conductive segments includes an electrically insulated conductive pad in the region of the non-conductive gap, said pad being electrically connectable to the remainder of the conductive segment to vary the area of overlap of said first and second segments so as to adjust the capacitance of said capacitive element.

6. The NMR apparatus of Claim 4 wherein said first and second segments are fabricated on opposite sides of a single printed circuit board.

7. The NMR apparatus of Claim 4 wherein said conductive coil portion includes a plurality of series-connected capacitive elements, said coil being energizable across a plurality of combinations of said series-connected capacitive elements such that different combinations thereof provide different coil impedances.

8. A NMR apparatus substantially as herein described with reference to the accompanying drawings.

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