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DOUBLE TUNED COSINE COIL FOR NMR IMAGING/SPECTROSCOPY

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ABSTRACT

The fabrication of a cosine coil having unevenly distributed struts is detailed. Placing the struts in such a manner enables a standing wave at the desired frequency and, hence, only one resonance frequency is obtained. This study details the fabrication of a cosine coil tuned to the Li-7 frequency (77.76 MHz) and then double-tuned to the H-1 frequency (200.1 MHz) when operated at 4.7 Tesla. Double-tuning is attained by placing an LC trap in series with a capacitor used to single-tune the coil. Also, a method is suggested by which a cosine coil can be broadbanded in the lower frequency range simply by replacing a fixed capacitor.

INTRODUCTION

One goal of NMRwith *in vivo* subjects such as humans or animals is to extract biochemical information on phosphorous metabolites, carbon metabolites, or sodium distribution from local regions in the body. This generally is accomplished by obtaining a proton image and then performing ^{31}P, ^{13}C, or ^{23}Na NMR spectroscopy (or chemical shift imaging) on a localized region. When quantitative information is needed, it is of utmost importance that there is no ambiguity as to the origin of these signals. Since these nuclei are not as sensitive as ^{1}H, it makes no sense to image phosphorous and then localize for the phosphorous metabolite spectra in a particular region. It is possible to obtain a proton image of the subject first, and then very carefully reposition the subject in exactly the same position as before in another RF-coil tuned to a different frequency. This is exceedingly cumbersome and, regardless of how carefully such a procedure is employed, proper localization cannot be guaranteed, with the danger of data being contaminated by surrounding tissue signals.

Hence, it is very highly desirable to use an RF-coil that can resonate at more than one frequency. One of the frequencies that almost always is desired, when working with biological subjects, is the ^{1}H frequency, since good morphological images can be obtained in a very short time. Once an ^{1}H image is obtained, the same RF-coil should have the capability to be returned to a different frequency (such as ^{31}P) to obtain a chemical shift image or a localized spectrum of this nucleus.

One of the first body coils that was tunable to two frequencies was designed by Joseph and Fishman (1985), who were able to tune a saddle coil that contained an angular distribution of wires on a Plexiglas cylinder, to 59.1 MHz for ^{1}H and 55.6 MHz for ^{19}F. Frequency switching and matching at these frequencies was accomplished by external capacitors and varying cable lengths. Although this coil was able to double-tune between two frequencies separated by 4 MHz, considerable difficulty arises when trying to double-tune by this method to frequencies separated by greater than 10 MHz.

Schnall *et al.*, (1985a) and Schnall *et al.*, (1985b) were able to double-tune a surface coil by attaching an LC trap in series with the tuning capacitor that was used for single-tuning the surface coil. Excellent isolation is achieved between the high and the low frequencies in such an arrangement. Employing such a method to RF-coils for whole body imaging/spectroscopy has been rather slow and is still in the research stage (Isaac *et al.*, 1990.)

Birdcage coils are the most popular coils for volume imaging since they produce a highly homogeneous B_1 field (Hayes et al., 1985). The birdcage is an extension of the principle used in a saddle coil where a perfectly homogeneous transverse magnetic field in an infinitely long cylinder can be obtained by a surface current running along the path of the cylinder. This current is proportional to cosø, where ø is the azimuthal angle (Hoult and Richards, 1976). Whereas in saddle coils the current carrying wires along the length of the cylinder are spaced equally at 60°, 120°, 240°, and 300° to assume a sinusoidal distribution, in birdcage coils many parallel conductors (more than four) are placed on the cylinder and a sinusoidal distribution is imposed on these conductors by distributed capacitance. Multiple tuning such coils is quite a formidable task since these parallel conductors exhibit several modes of resonance.

Recently, it was shown that a cosine distribution could be obtained by placing discrete parallel conductors nonuniformly around the cylinder (Bollinger *et al.*, 1988). Such a system was shown to easily double-tune using the LC trap method as there is only one frequency at which it resonantes when it is singly tuned, unlike the birdcage coil which exhibits several modes of resonance (Bollinger *et al.*, 1988). The ease with which such a coil can be double-tuned is one of the attractive features of this coil. A step-by-step method of constructing such a coil is described below. The results for a coil that was double-tuned to 200 MHz for ^{1}H and 77 MHz for ^{7}Li are described.

EXPERIMENTAL

SINGLE-TUNED COSINE COIL

Fig. 1 shows a schematic drawing of a typical cosine coil. Two groups of conductors (referred to as struts) are placed on a Plexiglas

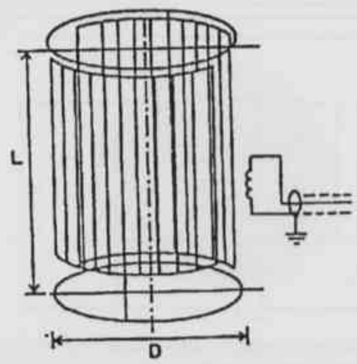

Figure 1. A typical cosine coil along with the end rings.

cylinder in a symmetrical manner opposite to each other. The way these groups of conductors are placed is shown in Fig. 2. The following steps can be followed in order to position the struts:

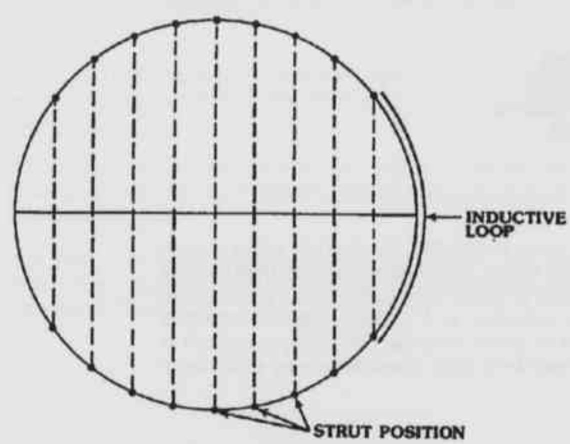

Figure 2. Cross section of cosine coil showing the points where the struts are placed. The spacing between the struts and the number of struts may be varied depending upon the desired inductance.

a) Draw a circle representing the cross section of the Plexiglass cylinder.
b) Decide on the number of struts desired and divide the diameter of this circle into that many equal segments.
c) Project these points from the diameter onto the circumference of the circle.
d) Place the group struts on the cylinder at these positions.
e) Connect each group of struts by an arc at each end of the struts.
f) Connect the center strut in each group to two end rings placed symmetrically above and below the struts. These act as the current carrying loops.

One of the gaps between the two groups of struts should be chosen to inductively feed such a coil. The inductive loop for such a coupling should have a width equal to the separation of the two groups of conductors and the length should be equal to the length of the struts to achieve maximum coupling between the loop and the coil. The inductive loop should be connected in series with a variable capacitor C_m (used for matching to the coil), the other end of which is connected to the center conductor of the transmission line as shown in Fig. 3. The other end of the loop is connected to the ground (shield of the transmission line).

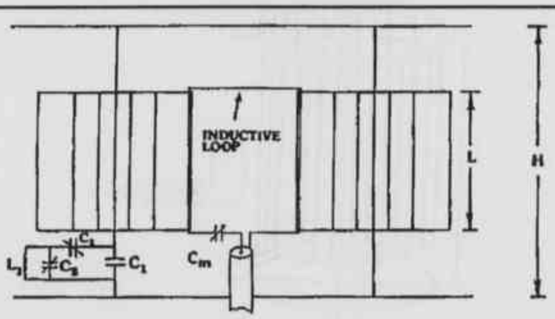

Figure 3. Schematic of a double-tuned cosine coil when cut along the length of the cylinder, showing different features and components when inductively fed.

Once the inductive feed is put into place, the following steps are followed to single-tune the cosine coil.

a) Cut the connection between one of the groups of struts and the outside ring.
b) Place a reasonable value fixed capacitance (C_1) between these two points.
c) Connect the transmission line to a network analyzer such as Wiltron model 6407 RF analyzer and look for the resonance frequency of the coil.
d) Determine the inductance of the coil using the equation $\vartheta = 1/2\pi\sqrt{L_s C_1}$ (this only will be an approximate inductance, but a good one to start with), where ϑ is the frequency of resonance, and Ls is the inductance of the cosine coil.
e) If the coil resonance is above or below the desired frequency, change the capacitor value to resonate the coil at the desired frequency since the inductance is known from the above formula.
f) Place the new capacitance (new C_1) calculated from part (e) and repeat part (c). The resonance should be very close to the desired frequency.
g) Place a variable capacitor (C_2) in parallel to this fixed capacitor which will allow fine tuning to the exact frequency, and will provide adjustment for the difference in tuning on the bench compared to in the magnet.
h) Use the capacitor C_m that is in series with the inductance loop to match the coil to 50 ohms.

A slight improvement in field homogeneity may be obtained if the fixed capacitor is distributed by placing another capacitor symmetrically across between the other group of conductors and the outer ring. Electrically, this point is in series with the first capacitor.

DOUBLE-TUNING THE COSINE COIL

When designing a double-tuned cosine coil, the coil should first be single-tuned for the lower frequency as described in the above section. Double-tuning to a higher frequency is achieved by placing a trap in series with the variable capacitor C_2 as seen in Fig. 3. The trap consists of a variable capacitor C_3 in parallel with an inductor (L_1). Appropriate turns on the inductor are determined by trial and error. Capacitor C_2 has very little reactance at higher frequencies compared to the trap circuit or the coil whereas at low frequencies C_2 is the dominant term in the reactance, since the trap looks more like an inductor, thus passing low frequencies (Schnall *et al.*, 1985a). The picture of a inductively fed cosine coil double-tuned to ^1H-^7Li is shown in Fig. 4.

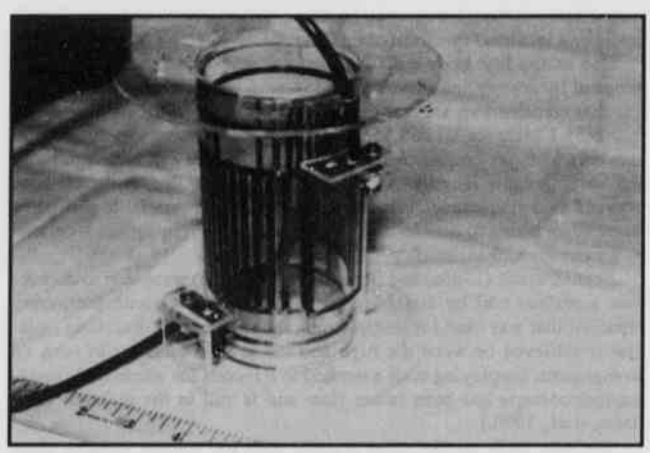

Figure 4. Photograph of an inductively fed ^1H-^7Li double-tuned cosine coil.

These coils also can be double-tuned by capacitive coupling by using the balanced matched method (Chang *et al.*, 1987). An equivalent circuit of such an arrangement is shown in Fig. 5. The capacitors C_4 and C_5 provide a balanced matching at both frequencies and also reduce the dielectric losses when the coil is loaded. The picture of a capacitively fed cosine coil double-tuned to ^1H-^{13}C is shown in Fig. 6.

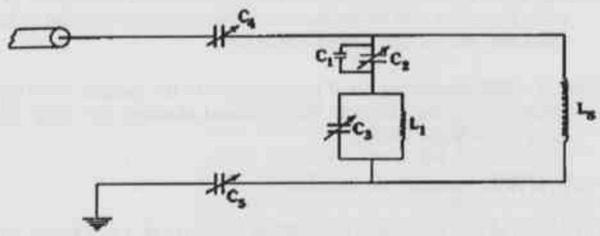

Figure 5. Schematic of a balanced matched capacitively driven, doubled-tuned cosine coil. (C_4 and C_5 are the matching capacitors).

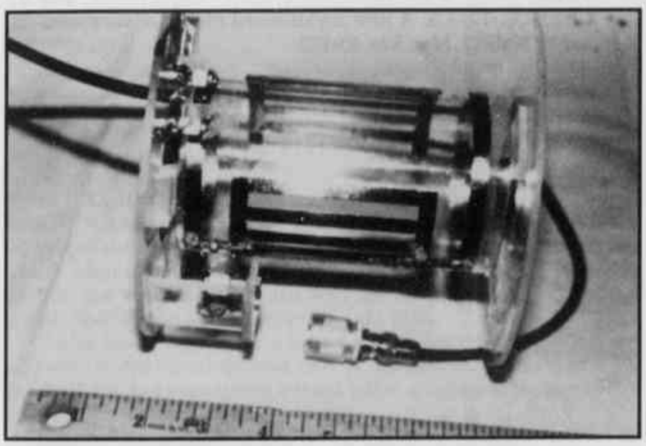

Figure 6. Photograph of a double-tune (^1H-^{13}C), balanced matched, capacitively fed cosine coil.

^1H-^7Li COIL

A double-tuned cosine coil was fabricated using 0.6 cm wide copper tape according to the above procedures to tune for ^7Li at 77.75 MHz and ^1H at 200.1 MHz. The length of the coil was 7.5 cm and the inside diameter was 7.0 cm. The two groups of conductors had seven struts placed one cm apart along the diameter of the cross section. The outer rings were placed at 1.9 cm on each side from the struts. A schematic of the coil, when cut along the length of the cylinder, is shown in Fig. 3. The coil was fed inductively. The value of capacitor C_1 was 24 pF. The values of the variable capacitors C_2, C_3, and C_m were 1-30 pF.

RESULTS AND DISCUSSION

A phantom containing 1.0 M LiCl solution which occupied 50% of the coil volume was used for testing the ^1H-^7Li coil. The unloaded and loaded Q values of the coil at 77.75 MHz were 220 and 90, respectively, whereas at 200.1 MHz, they were 180 and 83, respectively. The 90° pulse for ^7Li was 350 μs using 83 watts of power, whereas it was 480 μs for ^1H using 40 watts of power.

Figure 7a shows 128 x 128 axial and sagittal ^7Li images obtained from the phantom. The slice thickness on the sample was one cm and the field of view was 10 cm. The RF homogeneity is extremely good in these images. Fig. 7b shows a 128 x 128 axial ^1H image, from the same sample, using a one cm thick slice. The image shows some RF inhomogeneity. The variation in RF inhomogeneity was approximately 15%.

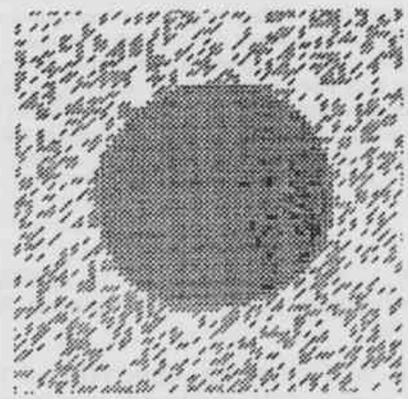

Figure 7.

(a) Axial 128 x 128 ^7Li image of a phantom containing 1M LiCl solution. (Field of view = 10 cm; slice thickness = 1 cm; scans = 4; power = 66 watts).

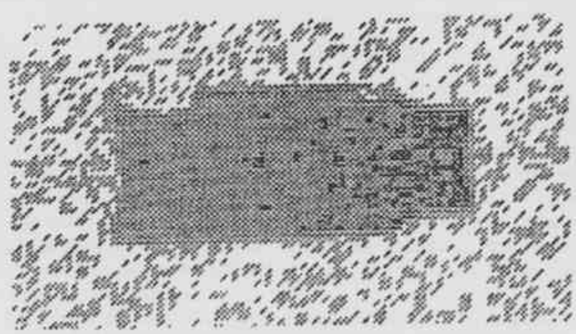

Figure 7.

(b) Sagittal 128 x 128 ^7Li image of the same phantom in (a) obtained under the same conditions.

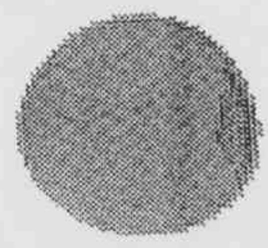

Figure 8. Axial 128 x 128 ^1H image of the same phantom used in Figure 7a obtained under the same conditions except the power used was 10 watts.

Cosine coils are relatively simple to build. Depending on the application at hand, the loss of RF homogeneity may be tolerable at the high frequency. Improvement on the RF homogeneity may be made by distributing the fixed capacitance C_1 onto the other group of conductors, as long as symmetry is maintained. Recently, a method to further improve RF homogeneity was suggested by Lowe (1990) which takes care of the slight difference in currents between the outer struts and innermost strut in the group of conductors. This method was tested only on a single-tuned coil, but also may result in improvement in homogeneity at a second higher frequency. It is observed that a length to diameter ratio of one gives a better performance compared to a 2 to 1 ratio (Lowe, 1991). Such a problem was seen when building a coil resonating at 50.3 MHz and 200.1 MHz. Double-tuning was extremely difficult when the length to diameter ratio was 1.7 and relatively easy with a ratio of one. Best results were obtained when the ratio of length to diameter was one.

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