**Multi-tuned Radiofrequency Coil using MicrofluidicallyTunable Capacitor for**

**Magnetic Resonance Imaging/Spectroscopy at 7-Tesla**

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**Abstract** – *Multi-nuclear magnetic resonance imaging and spectroscopy are considered valuable tools due to their capability of diagnosis and monitoring of several diseases. They require multi-nuclear Radiofrequency coils to interrogate the proton (1H) and other nuclei (X-nuclei) in the human body. Such coils provide anatomical images by acquiring (1H) spectra and metabolites information by acquiring spectra of X-nuclei. In addition, the high signal received from proton (1H) is used for B0 shimming purposes. However, the signal strength for these X-nuclei is too low. Hence, the signal-to-noise-ratio is low. The main advantages of using multinuclear Radiofrequency coils are that they speed up the imaging process and reduce the spatial positioning error that might arise when replacing the Radiofrequency coil in order to perform imaging of different nuclei. In addition, comfortable environment will be provided for patients by avoiding any inconvenience of moving out and asking to replace the coils. In this paper, a multi-tunablemicrostrip transmission lineRadiofrequency coil has been designed by using microfluidicallytunableRadiofrequency capacitor. This capacitor offers a wide range of capacitance tuning which extends between Cmin=1.76 pF and Cmax=48.7 pF. Hence, a wide range of resonant frequencies (fmin=75 MHz - fmax=298 MHz) can be offered by this coil to excite several nuclei at a field strength of 7-Tesla.*

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***Keywords****:Magnetic Resonance Imaging (MRI),Magnetic Resonance Spectroscopy (MRS), Microstrip Transmission Line RF coil, Double-tuned (DT),Microfluidically Tuned Capacitor (µTC)*

# **Nomenclature**

|  |  |  |
| --- | --- | --- |
|  | *Description* | *Unit of measure* |
| aBR33C13CDIFR41HL7LiMRMRIMRSMEMSµTCn23Na31PPINRFSNRSU-8Tvivo | Length of unfilled channelBorosilicate glassCapacitorCarbonDeionizedFiberglass cloth with an epoxyHydrogenInductorLithiumMagnetic ResonanceMagnetic Resonance ImagingMagnetic Resonance SpectroscopyMicroelectromechanical systemMicrofluidically tunable capacitorNumber of interleaved platesSodium PhosphorusP-type, intrinsic, and N-type RadiofrequencySignal-to-Noise ratioPhotodefinable epoxyTeslaLiving organism | mmFHF[Hz][kg⋅s−2⋅A−1] |
| *Greek Notations* |
| δ | Loss angle | [°] |
| εγλσ | PermittivityGyromagnetic RatioWavelengthConductivity | [F/m](Hz/Tesla)[m][S/m] |
| *Subscripts* |
| max | Maximum |
| min | Minimum |

# **Introduction**

Magnetic resonance imaging and spectroscopy (MRI/S) are known as valuable and promising diagnostic tools because of their ability to investigate the metabolism in the human body such as 31P, 7Li, 23Na, 13C, etc., which are called ”x-nuclei”. For example, 23Na MRI is used to quantify the glycosaminoglycan content in cartilage and therefore can detect and assess the biochemical degradation of cartilage in osteoarthritis. In addition, 23Na MRI can be also used to detect brain tumours by showing the increase of sodium concentration in patient’s brain relative to the structure of normal one [1]. Recently, 23Na MRI has demonstrated diagnostic importance in benign and malignant breast tumors [2], acute and subacute stroke [3], detection of mild Alzheimer disease [4], and functional imaging of the human kidney [5]. Meanwhile, 31P MRS can provide information on muscle function [6], therefore patients who suffer from muscular disorder can perform clinical follow-up. 13C MRS is used in metabolic studies such as measuring the rate of net hepatic glycogenolysis in humans [7].

Several techniques have been used to design and construct dual-tuned RF coils such as trap circuits [8] and PIN diodes [9]. These techniques employ lossy components which might lead to degrade the image quality.

In [10], a multi-tuned RF coil using variable capacitance diode (varactor) has been proposed. However, varactors have relatively high noise and low quality factor. An alternative variable capacitor which can be used is microelectromechanical system (MEMS) tunable capacitor. However, these capacitors suffer from low capacitance tuning range [11].

In this paper, a wide range of frequency tuning has been achieved by designing microfluidically tuned capacitors for meandered microstrip line RF coil at 7T.

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The work presented in this paper is organized as follows: Section 2 presents the literature review of successful double-tuned RF coils for several applications, Section 3 presents two types and common used double-tuned RF coils, Section 4 presents the simulation of the proposed double-tuned RF coil along with analysis and discussion of results, the conclusion of the proposed coil is presented in section 5.

# **Literature Review**

Despite the low concentration of these nuclei in the body which leads to low signal strength (typically less than 1/1000 of 1H) [12], several multinuclear MR applications have been demonstrated to provide biomedical information such as 1H/23Na [13–15], 1H/13C [16, 17] and 1H/31P [6, 18] spectroscopic imaging. Table 1 summarizes the gyromagnetic ratio and the resonant frequencies for 1H and common.

Zhang and his research group have acquired high-resolution head image by using a double-tuned, circular-polarized TEM coil. This coil has been designed for human head proton and 31P MRI/MRSstudies at 7T. It consists of an 8-channel 1H arrayand an 8-channel 31P array alternatively positioned in a cylindrical cavity. High isolation between the 1H channel and 31P channel has been obtained which was greater than -30 dB. Excellent SNR with superior sensitivity have been achieved within 18 minutes in vivo [19].

An 8-channel RF coil consists of 4 loop- and 4 dipole-elements have been designed and constructed for 19F and 1H lung imaging at 7T [20]. It consists of two sections: a planar posterior section and a curved anterior section to conform to an average chest. This coil supports anatomical 1H imaging as well as functional 19F MRI of the lung in clinically acceptable scan times.

In vivo 1H-decoupled 13C MRS in the human calves has been performed at 7T by using double tuned 13C-1H transceiver array coils. A 4 channel 13C -4 channel 1H transceiver phased-array coil has been designed and built to achieve high sensitivity over a large field-of-view. Moreover, a strong sensitivity at the C frequency and hightransmit efficiency at the H frequency have been obtained as well.These results enhance the potential of array coils to perform more 13C MRS in humans, especially where the concentration of metabolite are low (i.e. brain) [21].

A double resonant solenoid coil for imaging chlorine (35C) and sodium (23Na) in the rat brain has been designed. Each end of the solenoid is connected to a matching network where the other end was shorted to ground using two designs: Design with traps or Design with PIN diodes. The SNR of the design with traps was higher than that of the design with PIN diodes. Images of a rat brain have been acquired with a reasonably high resolution and in an acceptable total acquisition time. Anatomical details of the brain can be distinguished [22].

A double-layered dual-tuned RF coil for signal acquisition of 1H and 23Na at 7T MRI system has been designed and fabricated [9]. This coil composes of 8-pair double-layered dual-tuned transmit/receive coil array. Each pair consists of two loops in the same plane: The outer loop is tuned to the1H resonant frequency whereas the inner loop is tuned to the 23Na resonant frequency. Capacitive decoupling method has been used to decouple the 1H coil elements. A single RF port is used to feed both loops with the corresponding resonant frequency. Selection of resonant frequency for each loop is achieved by a PIN diode. A verification of the RF coil performance has been done not only through bench tests but also by acquisition of MR imaging. This coil can be exploited for studing various diseases as well as obtaining metabolic information. As a volume structure, it can be applied to the head and knees. As a planar structure, it can be applied to other parts of the human body.

In [23], a double-resonant 13C/1H surface coil system for in *vivo* application has been developed and implemented. In this design, specific filters have been implemented to decouple both channels. The double-tuned RF coil method has been applied for designing double tuning volume coil as well. For example, a low-pass birdcage coil has been designed for simultaneous acquisition of signal at two-frequencies (1H and 31P frequencies) by inserting trap circuits into its rungs [24]. Another demonstration of a double tuned birdcage RF coil using trap circuits has been presented in [25]. This coil has been designed for 23Na and 1H imaging at 1.5 Tesla. Another option to design a double tuned birdcage RF coil has been demonstrated in [17]. The designer has used variable capacitor (varactor) instead of trap circuit to tune between two-nucleiresonant frequencies at 3 Tesla for 19F and 1H imaging.

In [26], a novel dual-tuned quadrature volume RF coil has proposed. This coil uses eight elements of half-wavelength (λ/2) microstrip RF coils for 1H channel and eight elements of quarter-wavelength (λ/4) for 13C channel. The elements from the two types of RF coils have been arranged alternately along the circumference of a cylindrical volume. A homogeneous B1 field at both resonant frequencies have been generated by the proposed design and high isolation between the two channels has been achieved. In [27], a hybrid technique of designing double-tuned RF coil at 7T has been proposed and investigated. This design combines a microstrip transmission line RF coil and a lumped-element LC loop coil. The microstrip transmission line RF coil has been tuned to 1H frequency whereas the lumped element loop coil has been tuned to 13C frequency. This coil provides intrinsic decoupling between both coils due to the orthogonality of the magnetic fields from both coils.

In [28], 2 nested coaxial birdcage coil has been presented. This coil has been constructed by putting one of the birdcages inside the other. The inner birdcage (low-pass) has been tuned to the lower frequency and the outer birdcage (high-pass) has been tuned to the higher frequency. Alternatively, a folded four-ring quadrature birdcage coil has been designed as a double-tuned coil at 9.4T [29]. The outer coil (High-pass) has been tuned to 1H frequency and the inner coil (low-pass) has been tuned to 23Na frequency. This coil has demonstrated higher 23Na image quality in comparison to the nested birdcage RF coils due to the improvement obtained in the SNR.

TABLE I

Gyromagnetic ratio and resonant frequency at 7T for common nuclei.

In [30],an 8-rung, highpass, 31Pbirdcage has been designed and fabricated as an insert for 8-channel, multi-transmit, 1H coil at 7T. In order to decrease coupling between both coils, a tank circuit tuned to 297 MHz has been placed at both ends of each rung in the birdcage. To assess the functionality of both coils (1H multi-transmit capabilities &31P + enhancement) we examined both calf muscles of a single volunteer simultaneously. Outstanding anatomical muscle delineation has been. As homogeneous excitation has been achieved with the 31P birdcage, differences in phosphocreatine between separate calf muscles could be visualized.

Helmet coil is widely used in MRI due to it’s capability of increasing the SNR. Recently, because this coil has been re-designed based on the wheel-and –spoke coil, the geometry of it has been modified by adding additional shared ring in order to achieve a dual resonant frequencies at 3T MRI (1H and 31P frequencies). MR measurements have been carried out on Siemens Trio 3T MRI which show 24 % higher sensitivity can be provided by using dual-tuned helmet coil in comparison with the dual-tuned birdcage. Moreover, the SNR of 31P spectra acquired by helmet coil was 20% higher than that acquired by birdcage [31].

An open self-resonant periodic design based dual-tuned 1H/31P coil with no need of variable lumped elements for tuning and matching has been presented in [32]. This coil has been proposed for studing energetics in human forearm muscles at 4.7T.It is made up of a parallel- wire resonator based on an open self-resonator periodic structure. The geometry has been designed by employing two rows of seven parallel subwavelength wires each. The coil is operated by exciting two mutually orthogonal eigenmodes: The surface mode for 1H frequency and the volumetric mode for 31P frequency.

A dual-tuned coil consists of two bentdipoles (1H) and 4-loop array (31P)has been designed for 1H/31P brain application at 3T [33]. A good isolation has be achieved because the dipole antenna is located over the center of a loop coil.A comparison between the bent dipole antenna and the birdcage has been done by measurements. The results show highest magnetic field strength at the center brain is provided by birdcage. In contrast, highest magnetic field at the top of the head has been provided by using the bent dipole antenna. Moreover, highest sensitivity at the center of the coil has been obtained by birdcage coil, whereas focused sensitivity at the top of the phantom has been obtained by bent dipole antenna.

A multi-nuclear lung MRI using 19F gas and 1H has been achieved by using MEMS in a quadrature transmit/receive RF coil at 1.5T. The MEMS is used to switch the coil between the two resonant frequencies (1H and 19F). This study has been accomplished by designing two surface-coil loops isolated by using a capacitive decoupling network. The results show that the power consumption of MEMS is much lower than that for PIN diodes [34].

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Nucleus** | **1H** | **31P** | **7Li** | **23Na** | **13C** |
| Gyromagnetic Ratio (γ/2π) in MHz/Tesla | 42.6 | 17.2 | 16.5 | 11.3 | 10.7 |
| Frequency @ 7T in MHz | 298.0 | 120.6 | 115.8 | 78.8 | 75.0 |

# **Dual-nucleiCoilMethods**

* 1. *Double-Tuned RF Coil*

This coil is designed to have capability of tuning at two-different frequencies: the proton frequency and the x-nuclei frequency. In [8], a double-tuned two-port surface RF coil for both 1H- and 23Na-MRI has been demonstrated. To achieve inter-channel decoupling, the designer has used trap circuit. A significant improvementin SNR has been achieved by this coil as well as optimal decoupling between both channels.

A wider frequency-switchable range technique has been proposed in [35]. This technique enable switching between 5different frequencies by employing PIN diodes.A comparison between employing PIN diodes and trap circuits in designing dual-tuned RF coil has been intensivelystudied and presented in [36]. This study concludes that designing dual-tuned RF coil using PIN diodes offers lowerlosses and better tuning efficiency in comparison to trap circuits. However, a proposed solution to reduce the lossesassociated with trap circuits has been presented in [37] by improving the trap design.

* 1. *Two separate RF Coils*

This method requires two separate RF coils; one coil is tuned to the 1H frequency and the other one is tunedto x-nuclei frequency. In order to obtain 1H and x-nuclei images, either both coils are being used simultaneously or

theimaging process is divided into two-phases; by obtaining each image individually. Coil exchange requiredextra scanning time in addition to the potential error which might arise due to repositioning the patient within thescanner. However, designers who use both coils simultaneously are required to suppress the interactions between coils.

Recently, several double-tuned RF coil designs that use two separate coils have been proposed. For example, in [38]a double-tuned RF surface coil to obtain 1H and 23Na images has been demonstrated. This double-tuned coil iscomprised of a large square loop which has been tuned to 1H frequency and a small square loop which has been tunedto 23Na frequency. In order to suppress the interaction between the two loops, a trap circuit has been inserted in thesmall loop.

# **Resultsand Discussion**

* 1. *A Simulation Study*

In recent years, the demand of using ultra-high magnetic field MRI scanners has been increased for bothclinical imaging and research studies. This is due to the achievements that have been obtained by these scanners interms of high image quality and higher SNR [39–41]. In contrast, these scanners demand higherresonant frequency due to the increased operating magnetic field. The higher frequency requirement will increasethe radiation losses as a consequence. To overcome this, challenge microstrip transmission line RF coilshave been proposed such as surface coils [42], volume coils [43, 44], and microstrip arrays [45].

In [46], a centrally-fed microstrip line RF coil utilizes capacitive termination has been proposed. This RF coilhas demonstrated high quality factor as well as SNR. Meanders at both ends of this RF coil havebeen added to improve the penetration characteristic and to enhance decoupling [47]. In order to reduce the specificabsorption ratio (SAR), the meanders have been loaded by dielectric materials [48]. More properties concerning thisRF coil have been reported in [49].

In this work, the proposed multi-tunable microstrip transmission line RF coil is shown in Figure 1(a). This RF coilhas been upgraded from the one that already has been used in several applications, which concentrate only on 1H MR imaging [50, 51]. It consists of two conductors printed on FR-4 substrate (εr= 4.4, tan δ=0.02) of 0.5 mm thickness,with dimensions 250 × 100 mm2. A ground plane is placed behind the conductors with 20 mm air gap separation.The width of each conductor is 15 mm and for the copper lines within the meanders at both ends of the coil is 2 mm. Ahomogeneous phantom (εr=45.3, σ=0.8 S/m) with dimensions 600×90×370 mm3 is located at a distance of 200 mmabove the coil. The proposed RF coil makes use of a microfluidically tunable RF capacitor (µTC) to tune between the resonant frequencies of X-nuclei shown in Table 1. Two capacitors have been used to terminateboth ends of the RF coil. This capacitor has been designed to have 23 interleaved plates with long microfluidicchannel as shown in Figure 1(b). A prototype of such a coil is shown in Figure 1(c). A large tuning range of capacitance has been obtained by inserting fluid with highdielectric constant in these channels and precise control of capacitance has been achieved bycontrolling the positionof this fluid between the metallic plates.



(a)



(b)



(c)

Fig.1. Multi-tunablemicrostrip transmission line RF coil. (a) Geometry of the meander RF coil.(b) The structure of microfluidically tuned capacitor, (c) RF coil prototype.

The SU-8 cover layer, which support some microwave properties [52], hasbeen used with very small thickness(0.02mm). The BR33 substrate has been used as mechanical/electrical support.

A parallel plate capacitor is discussed in [53], and the capacitance can be calculated by the following equation:

$$C =(n-1) ×capacitanceof one pair of plates$$

$=\left(n-1\right)×ε\_{0}ε\_{r}\frac{A}{d}$(1)

where ”εo” is the absolute permittivity of free space, ”εr” is the relative permittivity of dielectric medium, ”A” is thearea of each plate in m2, ”*d*” is the distance between two adjacent parallel plates and ”*n*” is the number of interleavedplates. However, we can’t rely on this formula for accurate calculation of capacitance since our capacitor has a coverlayer and a substrate which leadsto a shifting in capacitance. Accurate capacitance values have been obtained by usingCST Microwave Studio (CST AG, Darmstadt, Germany) and the calculation method that has been followed can besummarized as follows: the RF coil has been terminated with (µTC) filled totally with deionized (DI) water (εr = 80)and the obtained resonant frequency has been compared with the same RF coil terminated with lumped elementcapacitor instead. By tuning this capacitor to reach the same resonant frequency, the capacitance of (µTC) will beknown. The similar procedure has been done by filling the channel of (µTC) with vacuum. Once we have these twocapacitance values, we can calculate the total capacitance of the capacitor for any fluid position inside the channel bymaking use of the following equation:

$$C\_{t}=C\_{vacuum}+C\_{DI-water}$$

$=\frac{1.575×a}{4.4}+\frac{48.7×(4.4-a)}{4.4}$ (2)

where ”*a*” is the length of unfilled channel as shown in Figure 1(b). The light color in the channelrepresents the vacuum whereas the dark color represents the fluid. The capacitance of the capacitor in vacuum is equal to 1.575 pF whereas the value is equal to 48.7 pF when it is fully filled with DI-water. This capacitorcan be modelled as two capacitors connected in series: capacitor filled with vacuum and capacitor filled with fluid.The next step is to calculate the values of ”*a*” for all x-nuclei frequencies. This has been done by calculating thecapacitance of the lumped capacitor for each frequency using CST and then substitute this value in Equation 2. The values of ”a” for all x-nuclei frequencies have been calculated and registered in Table 2. We note that the capacitorvalue increases as the fluid starts to fill the capacitor channel gradually. Furthermore, the capacitor offers a widerange of capacitance tuning which extends between Cmin=1.76 pF and Cmax=48.7 pF.

Figure 2 shows five µTCs withdifferent fluid positions in channel for all x-nuclei frequencies.

TABLE II

The corresponding capacitances for different x-nuclei frequencies.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Nucleus** | **1H** | **31P** | **7Li** | **23Na** | **13C** |
| Ct(pF) | 1.76 | 18.40 | 20.10 | 45.00 | 48.70 |
| Cvacuum (pF) | 1.57 | 1.00 | 0.96 | 0.13 | 0.00 |
| CDI-water (pF) | 0.19 | 17.40 | 19.10 | 44.90 | 48.70 |
| a (mm) | 4.38 | 2.83 | 2.67 | 0.35 | 0.00 |



(a)



(b)





(c)



(d)



(e)

Fig. 2. Fluid positions in channel. (a) 1H, (b) 31P, (c) 7Li, (d) 23 Na, (e) 13C.

* 1. *Analysis of the Results and Discusion*

Figure 3 shows the obtained return loss (dB) for different positions of the fluid in the µTC channel. Weobserve that the maximum resonant frequency (298 MHz) occurs once the capacitance channel is almost empty. When the DI-water starts to be inserted in the capacitor channel, the resonant frequency decreases untilit has fully filled and the resonant frequency reaches the lowest value (75 MHz).

The shifting in resonant frequencyis not only the resulting effect of inserting the DI-water in the capacitor channel. Indeed, the Q-factor of the RFcoil is also degraded as shown in Table 3. The Q-factor has been calculated from the -3dB points of the S11 curveafter a matching network. This degradation of Q-factor is affected by the performance of the capacitor.

Introducing different amounts of deionized water to achieve “variable capacitance” will introduce additional losses that increase proportionally with the amount of deionized water. For example, in the case of 13C the Q-factor decreases by about 33 % with respect to the 1H coil, and this will have a direct effect on the X-nuclei SNR.

Fig. 3. S11 parameter for different x-nuclei frequencies.

 In [54] adetailed study has been done to analyze the performance of microfluidically tuned capacitor. This study demonstratesa degradation of Q-factor of the capacitor with DI-water penetration in capacitor channel.

Figure 4(a) shows themagnitude of H-field in a mid-sagittal section for 0.5W input power after tuning to 1H frequency. We notice that theH-field distribution is focused in the direction of the phantom and decays at the ends of the RF coil. This leads toless radiation loss and increases the transmit sensitivity of the coil on the near side of the phantom. Figure 4(b) showshomogeneous distribution of magnetic field 20mm inside the phantom along the longitudinal distance of the coil. Asimilar magnetic field distributions have been obtained in-terms of homogeneity for all other x-nuclei frequencies as seen in Figure 5. However, the magnitude of magnetic field decreases for lower resonant frequencies. This can bejustified by comparing the physical length of the RF coil that has been already used in our simulation design andthe physical length that should be used to design the RF coil without using additional reactive elements for adjustingthe electrical length. This effect is found in dipole antenna. If the gain is calculated at resonant frequency using thecorresponding physical length without using reactive load and at lower resonant frequency by using reactive load, thedegradation in gain will be observed. One solution to compensate for this degradation is to drive the RF coil by higherexcitation signal.



1. Simulated |H| field in a mid-saggital section.



(b) Simulated |H| field, 20mm above the bottom of the phantom.

Fig. 4. Simulated |H| field by using µTC after tuning to 1H frequency.



Fig. 5. Simulated |H| field, 20mm above the bottom of the phantom for different x-nuclei frequencies.

TABLE III

RF coil Q-factor for different x-nuclei.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Nucleus** | **1H** | **31P** | **7Li** | **23Na** | **13C** |
| 3dB Bandwidth (MHz) | 4.5 | 1.9 | 1.8 | 1.6 | 1.7 |
| Q-factor | 66 | 63 | 63 | 46 | 45 |

# **Conclusion**

A new RF coil tuning method using microfluidically tunable RF capacitor has been investigated to design amulti-tunable microstrip transmission line RF coil. By this capacitor, a range of 47 pF capacitance can be achieved such as to be useful for the most important X-nuclei at 7T (from fmin=75 MHz to fmax=298 MHz). Precise tuning of frequency can be accomplished by using a microfluidic network having integrated pneumatic valves.

In vivo X-nuclei images can be acquired by using this coil with a reasonably high resolution and in an acceptable total acquisition time. Such a coil provide anatomical images by acquiring (1H) spectra and metabolities information by acquiring spectra of X-nuclei. It is considered valuable tool due to its capability of diagnosis and monitoring of several diseases. Meanwhile, this coil provides comfortable environment for patients by avoiding any inconvenience of moving out and asking to replace the coils.

This method can beused for other RF functions, for example,to match the RF coil input impedance to 50 ohm. In order to utilize and integrate this coil to the MRI scanner hardware, a transmit-receive (TR)switch compatible for multi-tuned RF-coil has to be developed, and this is the potential future work.

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