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Dual-Tuned Removable Common-Mode Current Trap for Magnetic Resonance Imaging and Spectroscopy

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Abstract

Magnetic resonance imaging (MRI) and magnetic resonance spectroscopy (MRS) are preferred methods of gathering structural and metabolic information from the body due to their non-invasive approach to obtaining a diagnosis. Dual-tuned radiofrequency (RF) coils can detect signals produced by both hydrogen and a second atomic nuclei of interest. However, undesired electromagnetic coupling often confounds both the design and utilization of RF coils. Coaxial shield currents, also known as common-mode currents, can be induced during MR scans and cause image distortion and reduction in signal-to-noise ratio (SNR); furthermore, the energy dissipated from the cabling can create heat that poses a risk of patient burns if the routed too closely. Thus, common-mode currents must be suppressed in RF coils by employing non-magnetic current traps. In this paper, we present a novel dual-tuned current trap that is fully removable and does not require soldering directly to the cable. The design was manufactured with 3D printing to support rapid fabrication and distribution. Bench measurements at the 3T Larmor frequencies for hydrogen and phosphorous-31 demonstrate common-mode attenuation of -18 dB and -8.4 dB respectively.

I. Introduction

Magnetic resonance imaging (MRI) and spectroscopy (MRS) play unique roles toward understanding human physiology and disease, as together they offer techniques for structural imaging, functional imaging, and localized detection of chemical makeup. The majority of MRI and MRS studies utilize hydrogen nuclei (protons). However, the probing of other nuclei, such as phosphorus-31 (^{31}P) and carbon-13 (^{13}C), provides researchers the ability to study additional metabolic functions [1]. For multinuclear studies, evolution of magnetic resonance technology and advancements in higher field strengths presents the need to create dual-tuned RF coils that can provide sensitivity to non-proton nuclei while retaining their proton sensitivity and coil tuning stability [2], [3]. The signal-to-noise ratio (SNR) is a figure

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of merit that defines the image or spectral quality from an MR scan [4]. A challenge for multinuclear imaging is that nuclei other than hydrogen have lower SNR due to their low concentration in the body [1]. When designing dual-tuned RF coils for multinuclear imaging, it is of extreme importance that the coils do not experience any sort of interference and achieve the highest possible SNR [5].

RF coils are typically connected to the MR scanner by coaxial cable transmission line. The desired MR signal between the scanner and the coil propagates on coaxial cable in the differential mode—on the center conductor and the inner surface of the outer conductor. Meanwhile, especially at higher fields, the outer surface of the outer conductor may electromagnetically couple to radiated fields or the RF transmit field ($\mathbf{B}_1$), inducing undesired currents in the common mode (see Fig. 1). The inner and outer surfaces of the coaxial shield are effectively separated at RF owing to the skin effect, yet common-mode currents cause issues by coupling to nearby dielectrics (e.g., the body) and RF coils, introducing resistive loss (i.e., lowering SNR) while reducing the coil filling factor and power efficiency. Furthermore, depending on cable routing, common-mode currents have the potential to radiate and have been known to cause surface burns on the body [6], [7]. Fortunately, common-mode currents may be restricted by including trap circuits along the cabling path [8]–[10].

Two fundamental cable trap designs utilized for MRI—tank circuits and bazooka baluns—originate in the antenna literature [11], [12]; the manufacture of both cable trap designs usually involves direct soldering to the electrically-conductive outer shield conductor of the signal coaxial cable (Fig. 2). Furthermore, multinuclear MRI and MRS require multi-tuned coils, which makes the tuning process more complex and a traditional balun insufficient [13]. To address these complexities, two individual baluns can be constructed in order to facilitate the acquisition of multinuclear data. A rudimentary tank circuit trap implementation involves first winding several turns of semi-rigid coaxial cable, presenting a solenoid with inductance, L , to the common-mode current on the outer surface of the outer conductor. The terminals of the solenoid are then connected by soldering a capacitor of appropriate capacitance, C , value to resonate the LC tank at the Larmor frequency. Common-mode currents on the coaxial cable shield are consequently ‘trapped’ within the LC tank circuit and propagate no further on the cable shield. The coaxial cable winding operation adds length (and attenuation, lowering SNR) to the transmission line. The amount of current suppression of a balun can be measured using current probes connected to a network analyzer. Generally, a cable trap is considered successful if the suppression exceeds -15 dB [8].

Certain design criteria have been proposed to make cable traps without requiring direct soldering. A prominent example is known as a floating current suppression trap. It can be easily placed at critical points on a coaxial line; this is accomplished by dividing the cable trap into two halves for manufacturing [14]. These cylindrical halves are joined by a set of screws that are also spring-loaded, which allows for fine-tuning of the frequency when adjusting the separation distance. This presents a viable and efficient solution for a floating cable trap and can be modified for different frequencies by changing the values of fixed capacitors [14], but a more easily tunable, dual-tuned floating cable trap is still desired.

Dual-tuned baluns have been fabricated to achieve multinuclear common-mode current suppression [13]. The disadvantage of this current trap is that it is soldered directly onto the triaxial cable. When soldering, the thermal conductivity of the cable shield and its resulting heat-sink behavior slow the heating process and prolong contact with the soldering iron, increasing the risk of introducing a failure mode to the cable. Insufficient heat leads to intermittent solder joints, while excessive heat can quickly melt the dielectric material separating the conductors and creating a short circuit.

To address these shortcomings of existing cable trap designs, we present a fully removable, dual-tuned balun that can be clamped to the cable via screws. This eliminates the need to solder the cable trap directly to the cable and has achieved attenuation for ^1H and ^{31}P multinuclear imaging.

II. Materials and Methods

A. Cable Trap Design

The objective is to manufacture a removable cable trap that is dual-tuned to the Larmor frequencies of hydrogen and phosphorous-31 at 3 T (127.7 MHz and 51.7 MHz, respectively). To determine the approximate values needed in the cable trap for capacitance, C , and inductance, L , the following resonance equation is employed:

$$f = \frac{1}{2\pi\sqrt{LC}}, \quad (1)$$

where f is the desired resonant frequency in hertz (Hz).

The inductance and the capacitance of the cable trap can be calculated based on a quasistatic assumption using the following equations for two concentric cylinders [15]:

$$L = \frac{\mu}{2\pi} \ln \frac{b}{a} \quad (2)$$

$$C = \frac{2\pi\epsilon}{\ln(b/a)}, \quad (3)$$

where L is the inductance in henries per meter (H/m), a is the radius of the smaller cylinder, b is the radius of the larger cylinder, C is the capacitance in farads per meter (F/m), μ is the absolute permeability, and ϵ is the absolute permittivity of the material in between the two cylinders [14]. In our design, the smaller radius, a , is 9.5 mm and the larger radius, b , is 25 mm. The dielectric is acrylonitrile butadiene styrene (ABS) 3D printer filament, which has relative permittivity of 2.86. By including the length of each side of this trap, which is 5 cm, the values can be determined, resulting in an inductance of 1.93 nH/cm and a capacitance of 1.64 pF/cm.

The cylinders have a controlled separation through a spring-nut mechanism (see Fig. 3B). This allows for fine-tuning of the frequency once the capacitors are placed. The body of the removable cable trap was manufactured using ABS filament of a desktop 3D printer

(Ultimaker 3 Extended, Ultimaker, Geldermalsen, Netherlands). The design consists of two 40-mm cylindrical halves where each half is joined by a 10-mm long bridge, essentially creating two semi-cylinders for each half. This design allows for tuning each cylinder to one frequency, enabling this trap to be dual-tuned. Two semicircular printed circuit boards (PCB) were designed to connect each cylindrical half's interior and exterior surfaces: the first with a gap for adding capacitors, and the second for short-circuiting the two surfaces. The PCBs were milled (ProtoMat E44, LPKF, Garbsen, Germany) and placed at the ends of the cylinders as shown in Fig. 3A. The body was covered in copper tape, soldered at the seams and across the interfaces to the PCBs.

B. Cable Trap Testing

An RG-58 coaxial cable was routed inside two toroidal probes (as shown in Fig. 4). These probes are comprised of a semi-rigid coaxial cable pickup loop wrapped around a split toroidal ferrite core with plastic housing. Each probe was connected to an individual port of a network analyzer (E5071C, Keysight, Santa Rosa, CA, USA) and S_{21} measurements were used to assess the cable trap's ability to adequately couple to and suppress common-mode current during current-injection tests. The network analyzer measurement is performed by transmitting a broadband pulse out of port 2 onto its pickup loop, which with the ferrite core forms a 1:1 transformer to the coil cable outer conductor, consequently inducing a common-mode current on the outside of the coil cable outer conductor. This current propagates down the coaxial line and is probed on the opposite side of the cable trap, per the Reciprocity Theorem, by an identical probe connected to the port 1 input. Measuring the power transmission using a network analyzer can indicate if the cable trap has been properly tuned. The network analyzer can also provide the real and imaginary measurements of the impedance, therefore providing additional information to properly tune the circuit [8]. Capacitor adjustment sticks (TSD series, Passive Plus, Inc., Huntington, NY, USA) were placed on the circuit board to determine the value needed to suppress the currents in the intended frequency. Once the value was determined, chip capacitors (2225C series, Passive Plus, Inc., Huntington, NY, USA) were soldered to the end of the balun on the PCB.

III. Results

Each half of a prototype balun was tuned to 3T for their respective nuclei, hydrogen (127.7 MHz) and phosphorous-31 (51.7 MHz). Fig. 5 illustrates the attenuation achieved at both frequencies. Attenuation of -8.39 dB was observed for 51.7 MHz and attenuation of -17.8 dB for 127.7 MHz. Each half of the balun had an inductance of 27.5 nH and 25.5 nH, with a capacitance of 134 pF or hydrogen and 860 pF for phosphorous-31 frequencies. Anti-resonance can be observed for both frequencies of interest displaying energy loss in the tank circuit or balun.

IV. Discussion

The cable trap presented herein is removable and successfully tuned to two frequencies of interest. The device is dual-tuned and avoids the need to have two separate current traps for multinuclear MRI and MRS hardware. The trap is not directly soldered to the coaxial cable, making it easier to achieve critical placement at locations with the highest shield current [9].

The current trap has high adaptability to a variety of Larmor frequencies and cable routings. Utilizing 3D-printed ABS material as a dielectric was validated [16], and additive manufacturing allows for an intricate design customized to the project's specific needs.

A higher attenuation and reduction of anti-resonant peaks will be explored through more consistent manufacture. Instead of using copper tape the body could be copper-plated to avoid irregularities. Observed during experiments, was the possibility of obtaining higher attenuation with two traps tuned to the desired frequencies in series. The design should permit employing one cable trap for multiple cables, and validation of this case is forthcoming.

V. Conclusion

This work presents a method to manufacture a balun that can be dual-tuned and removable for multinuclear magnetic resonance studies. The current trap has high adaptability to different resonant frequencies and cable routings. The use of low-cost materials and rapid prototyping empowers any site with a benchtop 3D printer to utilize the designs to simplify RF coil deployment in both clinical and research settings, which challenges the traditional paradigm of hand-soldering trap circuits directly to the signal cable and fabricating separate in-line traps for multinuclear coils. Future work includes implementation of this dual-tuned device in multinuclear RF coil phantom studies to assess the SNR seen with the developed dual-tuned floating cable trap compared to existing baluns that must be soldered directly to the cable. Other nuclei combinations such as ^1H and ^{13}C are of interest as well as implementation at 7T.

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Figure 1.

Coaxial cable composition with direction of currents. Ideally, the currents on the outer surface of the inner conductor and the inner surface of the shield are equal amplitude and opposed direction. Common-mode current occurs when outer shield current flows in the same direction as inner conductor current.

Figure 2.

An LC balun made from semi-rigid coaxial cable, with soldering required directly to the coaxial shield at both ends of the shielded cylinder. Fixed value capacitors can be seen on the left while the inductive coaxial shield solenoid is masked by the cylindrical copper-tape cover.

Figure 3.
A) Cable trap copper-taped and tuned to both frequencies of interest. Each half before the bridge is 4-cm long and is short-circuited at the intersection of each end. B) Software rendering of exploded view.

Figure 4.

Bench test setup with two toroidal probes, coaxial line passing through, and cable trap. The toroidal probes placed on each end of the coaxial line are connected to ports 1 and 2 of the network analyzer for S_{21} measurement of the attenuation versus frequency for ^1H and ^{31}P .

Figure 5.

Attenuation vs. frequency plot of dual-tuned removable cable trap. Distinct valleys can be seen at the resonant frequency for ^{31}P and ^1H (51.7 MHz and 127.7 MHz, respectively) for the coaxial cable with the balun as compared to the coaxial cable without a balun. The overshoot apparent on one side of each valley suggests tuning should be performed deliberately to prevent gain at the Larmor frequencies.