Construction of Receive Arrays: A Four-Channel Rat Coil for 9.4 T

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This course will focus on the construction of a four-channel receive array intended for proton imaging of small animals (in particular, rats) at 9.4 T (400.2 MHz). Although this demonstration is geared toward a specific application, the construction methods presented here are applicable to receive arrays for both humans and animals, and with any number of elements. The demonstration will cover the basic steps of constructing a receive array: the design of a former, tuning and matching, preamplifier decoupling, active detuning, geometric decoupling, and cable management. This course is intended for the student, technician, or researcher who wants to learn the basic steps on how to build a receive array. The steps below are intended only to be a general guide, as each coil designer may have a different approach depending on the particular application and their personal style. There are a number of great resources available to the novice coil builder, including past ISMRM educational presentations, several books (1-3), and many papers—including the classic paper by Roemer et al. (4).

The construction of radiofrequency arrays consists of the fabrication of hundreds to thousands of components. The coil builder needs to be both careful and patient, since it only takes one bad component or connection to cause a severe degradation in performance that can render the coil unusable. To this end, care needs to be taken at every stage of coil design, fabrication, and testing, to avoid large headaches in the future.

1. Coil former and geometrical layout

Often one of the most under-appreciated aspects of coil building is the design and construction of the former. The mechanicals of a project can often be the most time consuming of all stages. When designing the former, it is important to keep in mind a number of questions, such as, but not limited to:

- What is the size and shape of the anatomy that I want to image?
- How will the person/animal be placed in the coil?
- What coil will be used for transmission?
- Is there physiological monitoring equipment that requires placement near the anatomy?
- Is the coil comfortable for the subject?
- Does there need to be a mirror with line-of-sight to a projector?

- If it is an animal, how will it be restrained/motion-stabilized?
- How will the coil be fixed in place inside the scanner?
- How will the coil be connected to the scanner?
- Where will preamplifiers, cables, etc., be located?

For the purposes of this demonstration, we have developed a receive array for rat imaging on a 9.4-T scanner. For simplicity of demonstration, we have limited the coil to four channels placed on a cylindrical former that circumscribes approximately 2/3 of the head (Fig. 1). The diameter of the former was chosen to accommodate a rat head and to provide complete coverage of the brain, as determined previously through MRI scans. This former has openings to allow for ear bars to be used for immobilizing the head. Other groups have designed formers that stabilize the animal by sandwiching the animal's head between two halves contoured to the head (5).

Our coil consists of a linear array of four coils, with the overlap chosen to be about 15% of the coil width (slightly higher than the 10% suggested by (4)). Grooves are placed

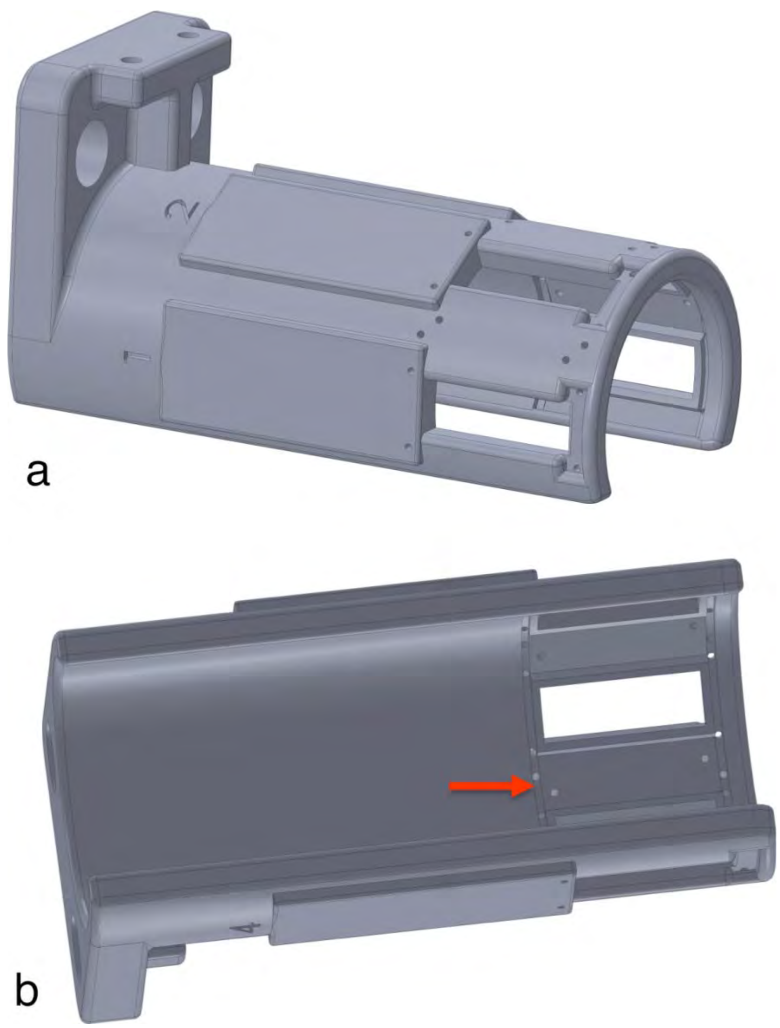

Figure 1. The coil former as viewed from the (a) top and (b) bottom. Recessed grooves (indicated by the arrow) are placed in the interior of the coil for placement of the coil conductors.

on the inside of the former for the coil conductors. The conductors are fed through holes in the former to variable capacitors mounted on the outside of the former to facilitate tuning and matching. The wires are also fed through the former to permit coil elements to be overlapped while maintaining sufficient space between overlapped conductors at the crossing point. It is important to have the conductors as close as possible to the brain, as this is the most efficient means to increase SNR, and is especially important when dealing with small animals, where the width of the former can place the coil at a significant distance from the anatomy of interest.

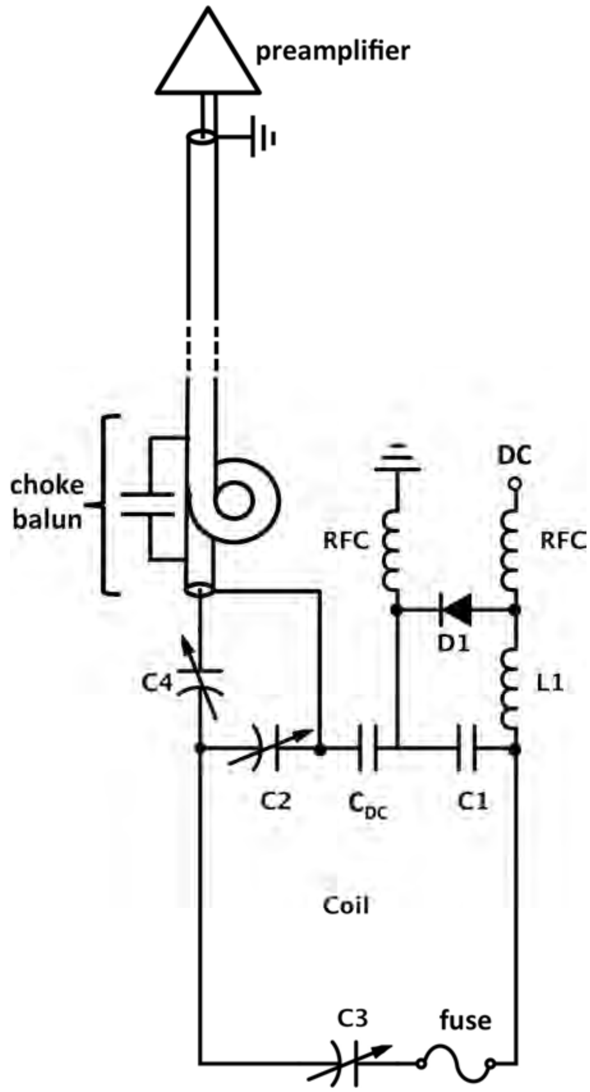

Figure 2. A schematic of a single receive element in the array. Capacitors C1 and C2 create a voltage divider at the output of the coil. A parallel-resonant, active-detuning circuit is formed about C1 (5.6 pF) using L1 (a handwound inductor) and a PIN diode (D1). RF chokes (RFC) create a high impedance to RF on the DC bias lines. A 470-pF capacitor (C_{DC}) is used as a DC block. A 3-10 pF variable capacitor, C3, fine tunes the coil resonance to 400.2 MHz. C2 (8-30 pF) and C4 (3-10 pF) are used to match the coil impedance to the optimal noise match of the preamplifier, in this case 50 Ω. The coaxial cable, including the choke balun, and C4 transform the preamplifier impedance to a parallel inductance across C2 for preamplifier decoupling. A fuse is placed in the coil loop as a safety precaution in case there is a failure in the active-detuning circuit during transmit.

It is important to construct the former from materials that do not produce an NMR signal. This former was designed using CAD software and constructed out of polycarbonate on a 3D printer. As seen in Fig. 1, flat surfaces were created where components will be mounted, such as capacitors and baluns. Furthermore, thought was given as to how the cables will be routed to the preamplifiers (through strain reliefs), and how the former and preamplifiers will be mounted inside the scanner. Regions of the coil former within coil elements have been removed to allow visual access to the animal and for the potential use of ears bars to restrict motion. Since there are numerous applications for small-animal imaging, there are a wide variety of formers and setups that can be created. The amount of planning and thought that is given at this stage of the design can have a large effect on the ease of construction and more importantly, the practicality of the coil for the end-user.

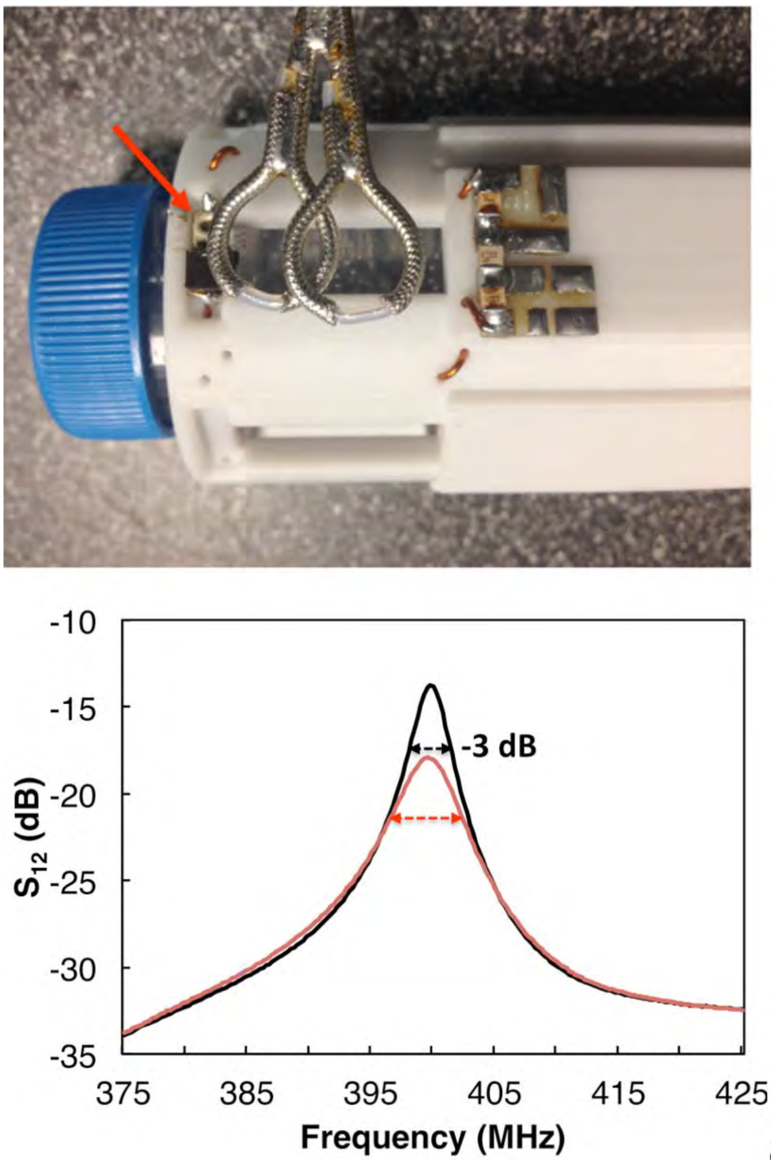

Figure 3. A double-probe measurement of a single receive element resonating at 400.2 MHz. The red arrow indicates the tuning capacitor that is adjusted to tune the resonance to 400.2 MHz. The *Q* of the coil can be measured by the ratio of the resonant frequency over the bandwidth at -3 dB of the maximum transmission. The ratio of the *Q* measured when the coil is unloaded (black line) versus loaded (red line) provides a relative measure of losses attributable to the sample versus the coil.

2. Coil tuning

When constructing an RF array, it is helpful to start by fully constructing a single coil, including the tuning, matching, preamplifier decoupling, and active detuning. The complete circuit schematic for the coil we will be constructing is provided in Fig. 2.

This circuit differs slightly from that originally described by Roemer et al. (4); however, it is still widely used, including in animal coils (6), and offers certain advantages for our particular application. To begin, we assemble the conductors of a single coil element and populate the element with fixed-value, surface-mount capacitors at C1, C2, and C3 (in this case, 5.6 pF). Using two decoupled probes loosely coupled to the element (a description of the probes is provided at the end of this document), we measure S_{12} on a network analyzer (Fig. 3). The maximum transmission will occur at the coil's resonant frequency. The fixed capacitors should be adjusted to tune the coil close to the frequency of interest. The resonance need only be close to the desired frequency, as C3 is then replaced by a variable capacitor to allow fine-tuning of the resonant frequency.

At this point it can be helpful to measure the *Q*-ratio of the coil (i.e., the ratio of unloaded to loaded *Q*). This ratio provides an estimate of the amount of sample losses relative to coil losses. A *Q* ratio of 2 indicates equal contributions to the noise from the sample and the coil; the achievable *Q* ratio will be dependent on the coil size, load, etc., but the desire is to produce as high a *Q* ratio as possible. We measure the *Q* of the coil by measuring S_{12} with the loosely coupled double-probe. The *Q* of the spectrum is calculated as the ratio of the centre frequency to the bandwidth at the full-width half-maximum (i.e., -3 dB from the maximum S_{12}). The *Q*-value can be calculated automatically on most current network analyzers. The *Q*-ratio will then be determined by measuring the *Q* with and without sample loading. The choice of sample will greatly affect the *Q*, and ideally should be the intended sample/animal of interest. The *Q*-ratio can be measured at different stages of coil construction to determine if significant losses are being introduced, such as by the active detuning circuit or the presence of surrounding conductors. The *Q*-ratio of an isolated element in this coil was approximately 2 (=150/75) when loaded with a 50-mM NaCl solution.

3. Active detuning

Now that we have tuned the coil, an active-detuning circuit can be constructed around C1. The active detuning circuit should present a high-impedance to the receive coil during transmit, thus preventing damage to the receive circuitry and possible harm to the subject. Using a wire-wound inductor and a PIN diode, a parallel-resonant circuit can be created with C1 when the PIN diode is forward biased (~100 mA forward-bias current for this particular PIN diode). This circuit can be constructed on a separate board in isolation and then integrated into the circuit. RF chokes (inductors with a self-resonance slightly above the frequency of interest, in our case 470-nH inductors) are incorporated into the detuning circuit to prevent RF on the DC bias lines. Additional RF chokes are placed on the bias lines to prevent RF coupling to the lines from the transmit coil. DC cables should be twisted pairs or coaxial cables to minimize Lorentz forces on the cables during switching of the current within a magnetic field as well as minimize noise pickup. These cables should be affixed to the former, as repeated movement has the potential to cause the cables to break. In this design, the twisted pair of DC wires was wrapped around the coaxial cable to provide structural support.

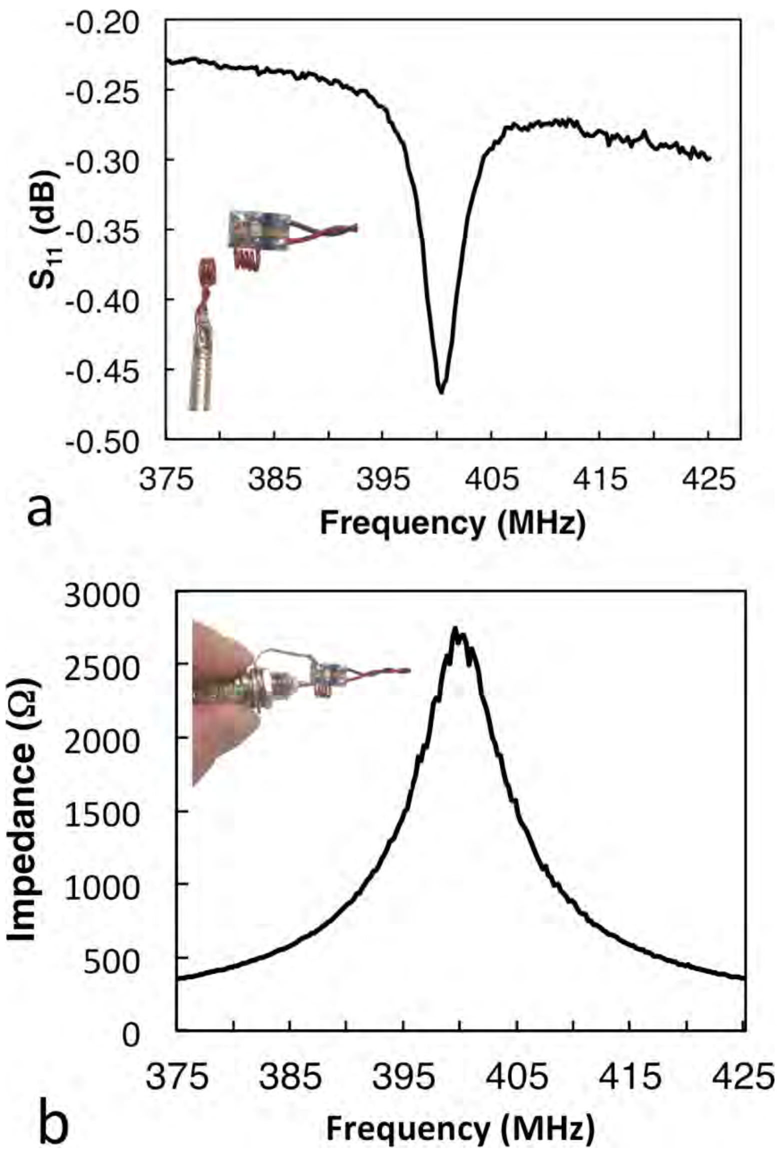

Figure 4. (a) An S_{11} measurement of the biased active-detuning network using a sniffer probe lightly coupled to the inductor. The inductor wires can be bent to fine-tune the resonance to the desired frequency. (b) A direct impedance measurement of the active-detuning circuit shows an impedance of 2.7 kΩ across the capacitor.

The active detuning circuit can be tuned with the diode forward biased. Using a small sniffer probe lightly coupled to the wire-wound inductor, the reflection coefficient, S_{11}, can be measured (Fig. 4); alternatively, a direct measurement of the impedance across the capacitor can be made using an impedance analyzer. The wire on the inductor can be squeezed or separated to fine-tune the resonance of the circuit. The detuning circuit can then be soldered into the loop element. To measure the effectiveness of the detuning circuit, an S_{12} measurement with the double-probe can be made over the element, with the detuning circuit being biased on and off (Fig. 5). The difference between the maximum S_{12} when tuned and the minimum S_{12} when detuned provides the degree of isolation during transmit. This value should be at least -35 dB. If insufficient detuning is attained, an additional detuning circuit can be added to the loop. The coil under investigation here achieved detuning of at least -40 dB on each channel.

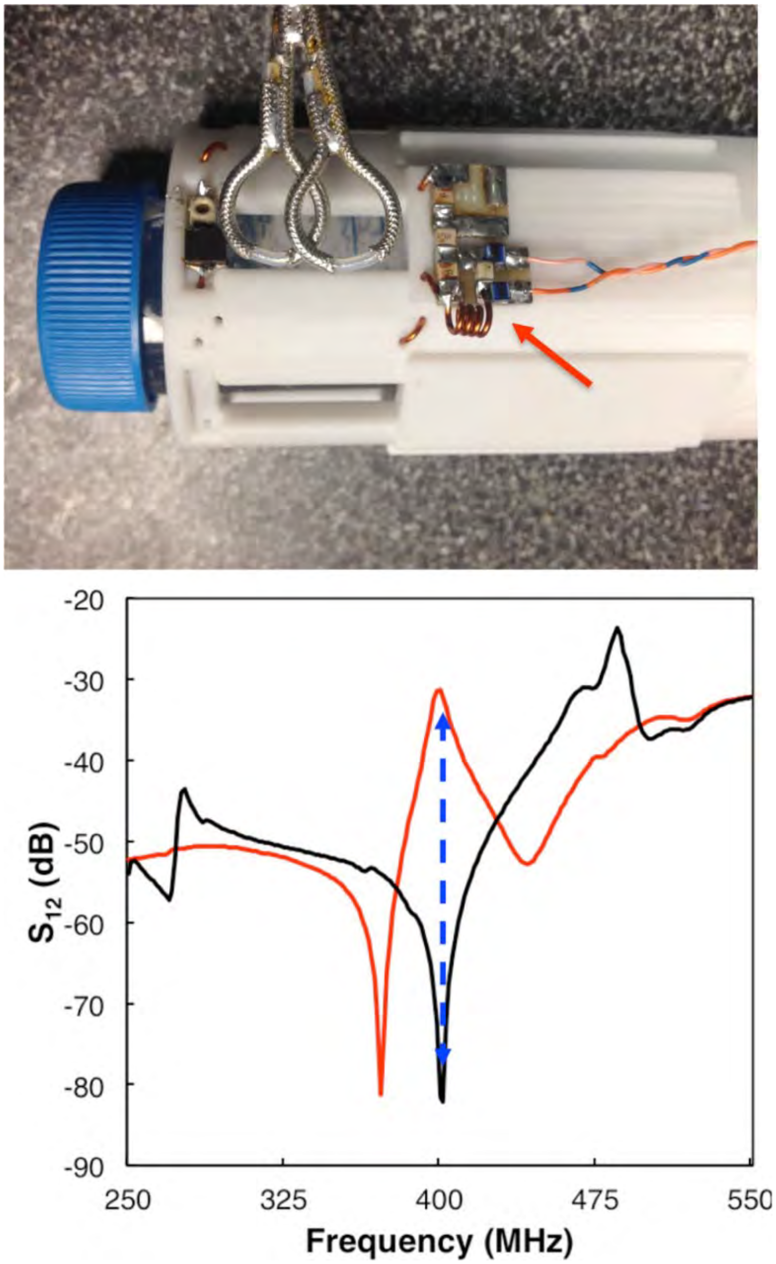

Figure 5. A double-probe measurement of the coil element with the integrated active-detuning network (as indicated by the arrow). The difference in S_{12} between the tuned (PIN diode reverse biased - red line) and detuned (PIN diode forward biased - black line) provides a measure of the degree of isolation during transmission (blue arrow).

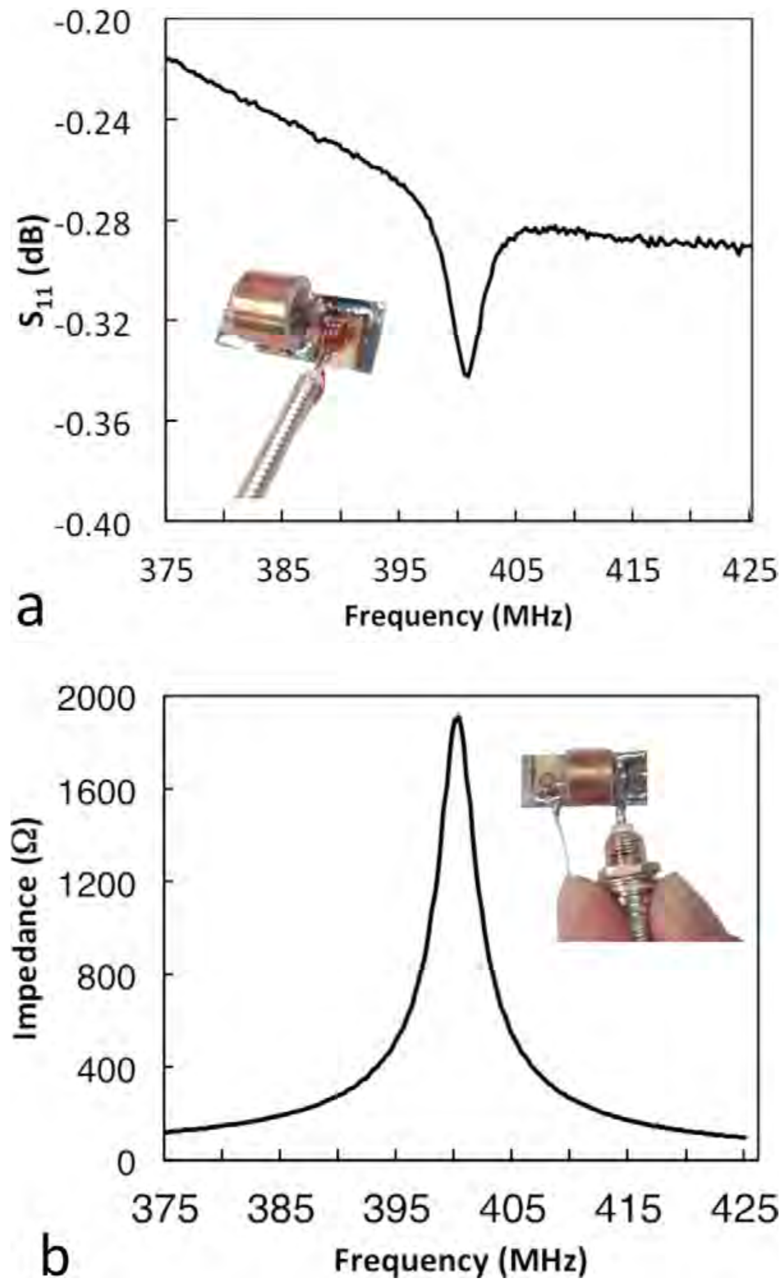

Figure 6. (a) An S_{11} measurement of the balun resonance using a sniffer probe. The resonant frequency can be fine-tuned by bending the inductor's wires within the shield. (b) A direct measurement of the impedance across the capacitor indicates an approximate impedance to common-mode currents of 1.9 kΩ.

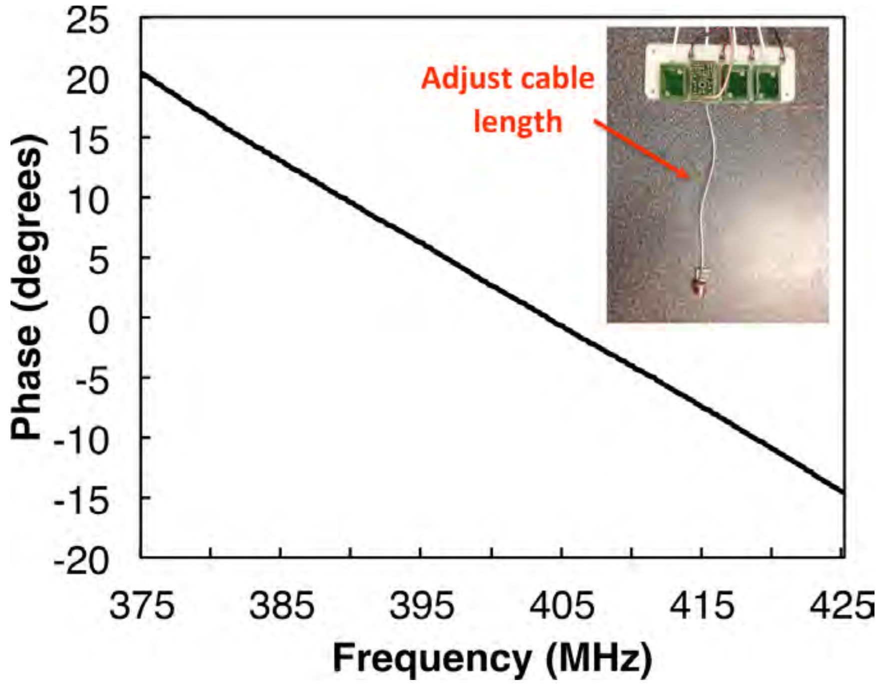

Figure 7. The phase of the cable plus balun (approximately 3° at 400.2 MHz) is measured by plugging directly into the preamplifier socket using a dummy preamplifier and measuring S_{11}. The actual phase will be half of the measured value, since this is a measurement of the reflection coefficient. The phase can be adjusted by changing the length of the coaxial cable.

4. Coil noise matching

The impedance of the single element is now ready to be matched to 50 Ω to minimize the noise figure of the preamplifier. Before this can be carried out, we need to connect the coil element to the preamplifier, since all cable lengths between the coil and the preamplifier will cause an impedance transformation and must be taken into account. The coil is connected to the preamplifier with a coaxial cable and a choke balun placed at the output of the coil. The choke balun serves two purposes: (1) to convert the balanced signal induced in the coil to an unbalanced signal as required by this particular preamplifier, and (2) to reduce common-mode currents on the coaxial cable induced by the transmit coil or surrounding receive elements.

The choke balun can be constructed by looping a coaxial cable inside a shielded tube and bridging the inductor with a capacitor. Using an S_{11} measurement acquired with a sniffer probe, or a direct impedance measurement acquired with an impedance analyzer, the resonant frequency can be fine-tuned by bending the inductor's wires (Fig. 6). These baluns can be made in isolation and soldered into the circuit.

The choice in cable length will depend on the application and the desired distance between the preamplifier and the coil. In some circuit designs, the length of the coaxial cable will be used to tune the preamplifier decoupling, thereby requiring a careful choice of cable length. In the circuit described here, the coaxial cable length (including the balun) and C4 will transform the preamplifier input impedance to a parallel-inductance across C2 for preamplifier decoupling. Since the preamplifier decoupling can be "fine-tuned" using C4, there is a range in cable lengths that can be used. We chose to make the coaxial cable, plus balun, a length that provided a λ/2 (180º) phase shift. The phase of the cable can be measured on the network analyzer by soldering the cable to the preamplifier socket and measuring the phase of S_{11} using a dummy preamplifier (see Fig. 7). Since this is a reflection measurement, the actual phase of the cable is half of the phase measured using S_{11}. It is important to use a port extension on the network analyzer to properly calibrate any measurement acquired with this probe, since the phase length of the probe will otherwise alter the measurement. We plug directly into the preamplifier socket, since even small cable lengths at 400.2 MHz will cause a phase change and impedance transformation.

With the coaxial cable and balun in place, and C4 temporarily shorted, the coil can be tuned and matched using an S_{11} measurement directly from the preamplifier input using the dummy preamplifier (Fig. 8). With the coil loaded with an appropriate sample, the tuning capacitor (C3) and matching capacitor (C2) can be varied to tune the coil to 400.2 MHz and match the coil to the optimal noise-match of the preamplifier, which is 50 Ω. This will minimize the noise figure of the preamplifier. Matching the impedance of the coil is accomplished by either minimizing S_{11} at the frequency of interest on a log scale, or by matching to 50 Ω on a Smith chart. Matching the coil impedance beyond an S_{11} of -20 dB has diminishing returns.

5. Preamplifier decoupling

Now that we have tuned and matched a single coil, we need to tune the preamplifier decoupling. The low impedance of the preamplifier is transformed to an inductance across C2 that forms a parallel-resonant circuit. This creates a high impedance in the coil loop to minimize the current and consequently the coupling to other elements. At this point, if we use the double-probe to measure the S_{12} of the loop element with a powered preamplifier in place, we will notice that the minimum S_{12} is not at our desired frequency. To fine-tune the preamplifier decoupling, we will add C4 to the circuit. We can now vary C4 to adjust the minimum S_{12} to 400.2 MHz (Fig. 9). If C4 does not have sufficient range to tune the preamplifier decoupling to the correct frequency, then the coaxial cable length can be adjusted as well.

The addition/modification of C4 has an effect on the noise-match of the coil; therefore, we need to repeat the matching and tuning procedure as described above. This, in turn, will affect the preamplifier decoupling, which will need to be fine-tuned. However, since C4 has only a small effect on the match of the coil, typically only a couple of iterations are required to achieve both optimal preamplifier decoupling and an optimal noise match.

To quantify the effectiveness of preamplifier decoupling, the double-probe can be used to make an S_{12} measurement of the loop when the powered preamplifier is present versus when the preamplifier is replaced by a 50-Ω load (Fig. 9). The difference between the maximum S_{12} when the 50-Ω load is used, and the minimum S_{12} when the low-impedance preamplifier is used, provides the degree of preamplifier decoupling. The degree of preamplifier decoupling will be dependent on a number of factors, including the size of the coil, frequency of interest, the input impedance of the preamplifier, and the loss in cable/components between the preamplifier and the coil. Typically, preamplifier decoupling should be better than -15 dB. In this coil, the mean preamplifier decoupling was -20 dB.

It is important to note that preamplifiers should be mounted to the former in a manner that ensures their correct orientation with respect to the main magnetic field to minimize the Hall effect and any associated frequency shifts.

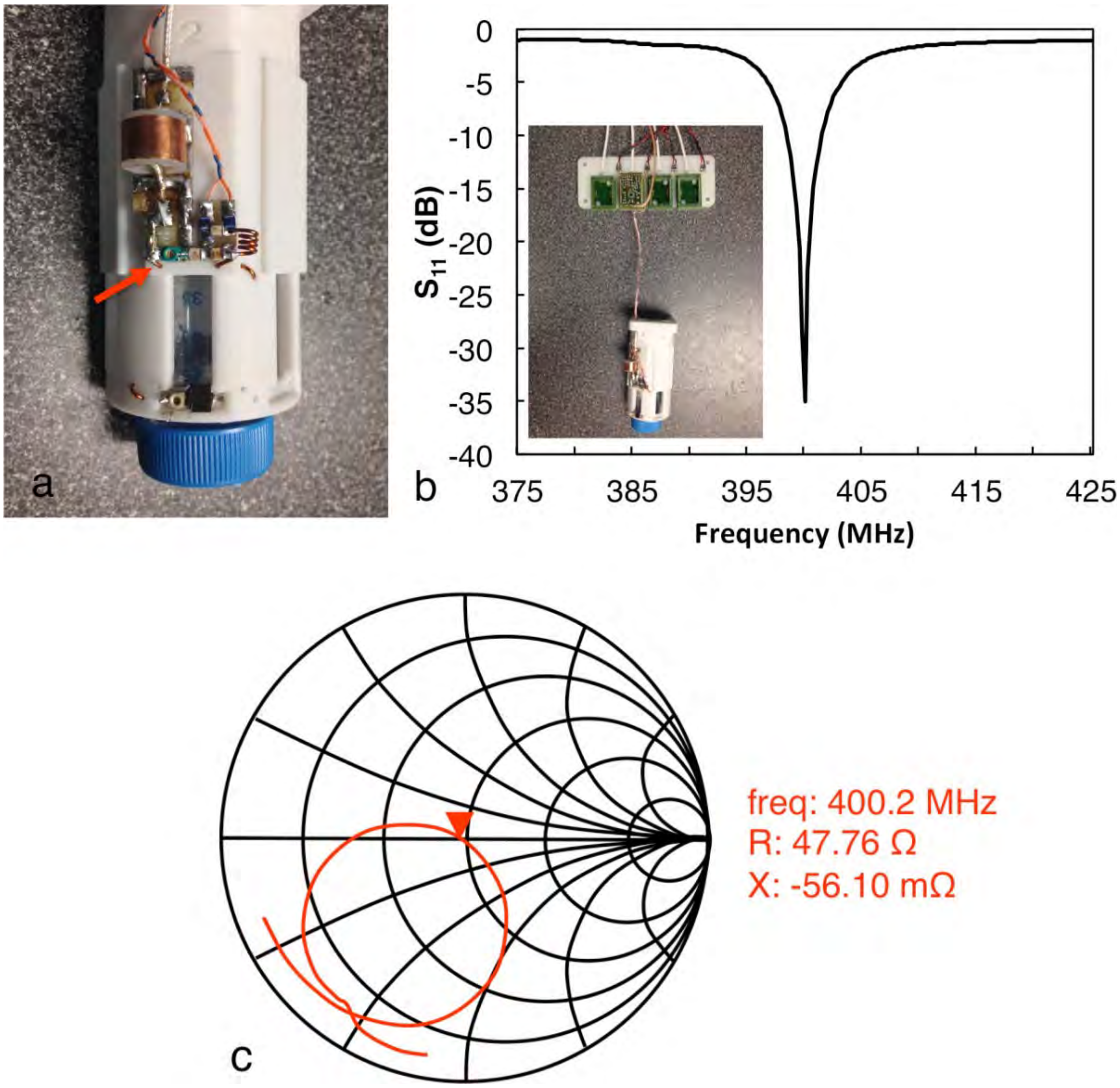

Figure 8. (a) A variable capacitor is placed at the drive port of the coil (as indicated by the arrow) to match the coil to the optimal noise-impedance of the preamplifier (50 Ω). (b) By measuring S_{11} of the loaded coil directly at the preamplifier socket, the matching and tuning capacitors can be adjusted to provide a minimum S_{11} at the resonant frequency. (c) This correlates to a 50-Ω real impedance, with minimal reactance, at the resonance frequency, as indicated on the Smith chart.

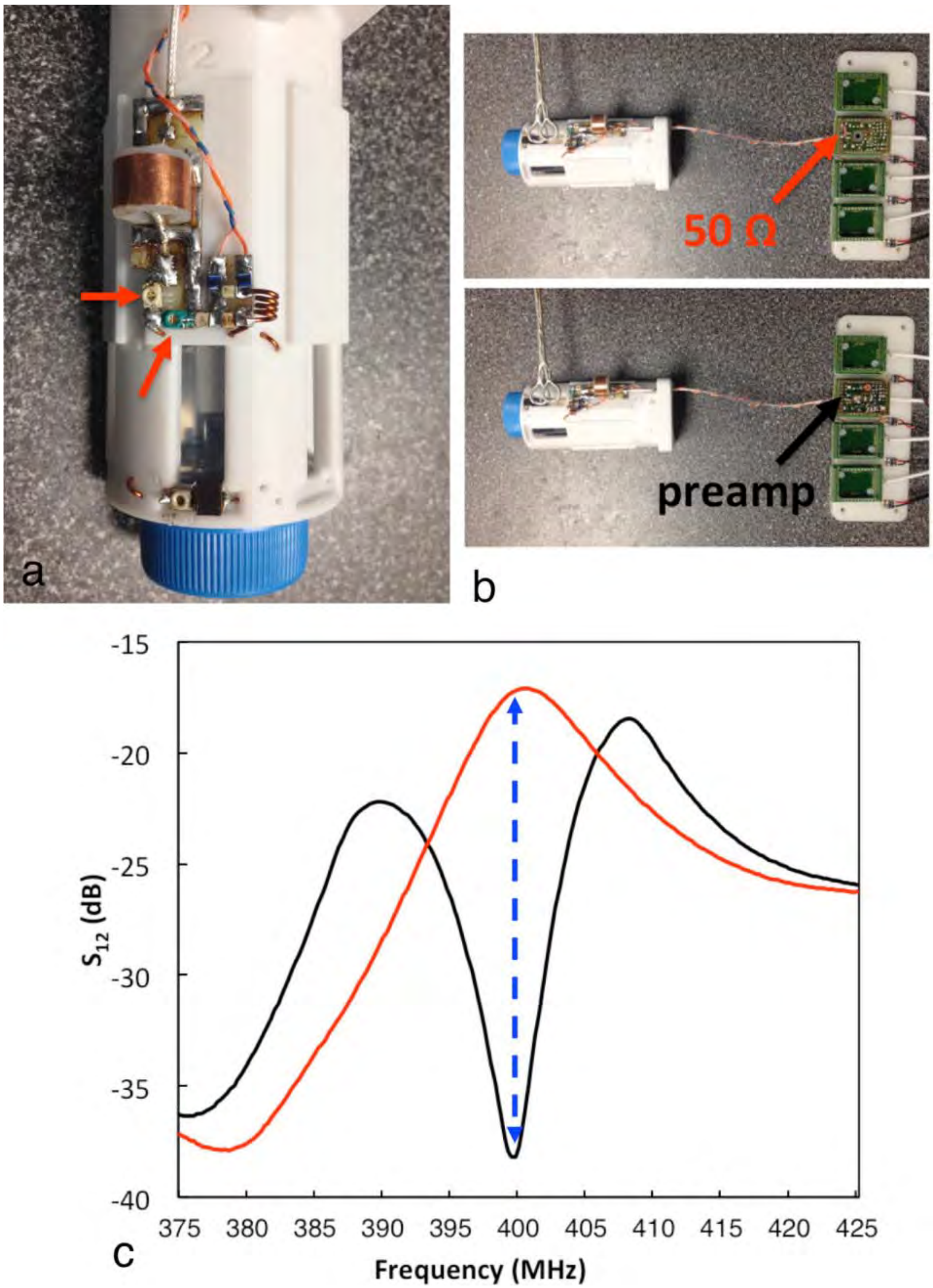

Figure 9. Preamplifier decoupling is accomplished by adjusting the series variable capacitor, C4, and the matching capacitor, C2. (b) Using a double-probe to measure S_{12} with the preamplifier present, the minimum transmission should be adjusted to occur at the resonant frequency (c, black line). The low-impedance preamplifier can be replaced by a 50-Ω load (b), creating a peak in S_{12} (c, red line), with the difference between S_{12} measurements (blue arrow) being the degree of preamplifier decoupling.

Geometric decoupling

Now that we have completed a single coil, including preamplifier decoupling and active detuning, we can fully assemble the coil. We attach all the coil conductors, tuning circuits, pre-made active-detuning circuits, pre-made choke baluns, coaxial cables, etc. By using an interface box (described at the end of this document) that can provide 10 V to the preamps and provide control over the current supplied to each active-detuning circuit, we can investigate each coil element in isolation.

Once the array is populated, with all coil elements detuned, a double-probe should be placed near each coil element to ensure the active-detuning circuits are working and there is an S_{12} minimum at the frequency of interest. With all other elements detuned, each element can then be tuned and matched, and preamplifier decoupling adjusted, as described in the procedure above.

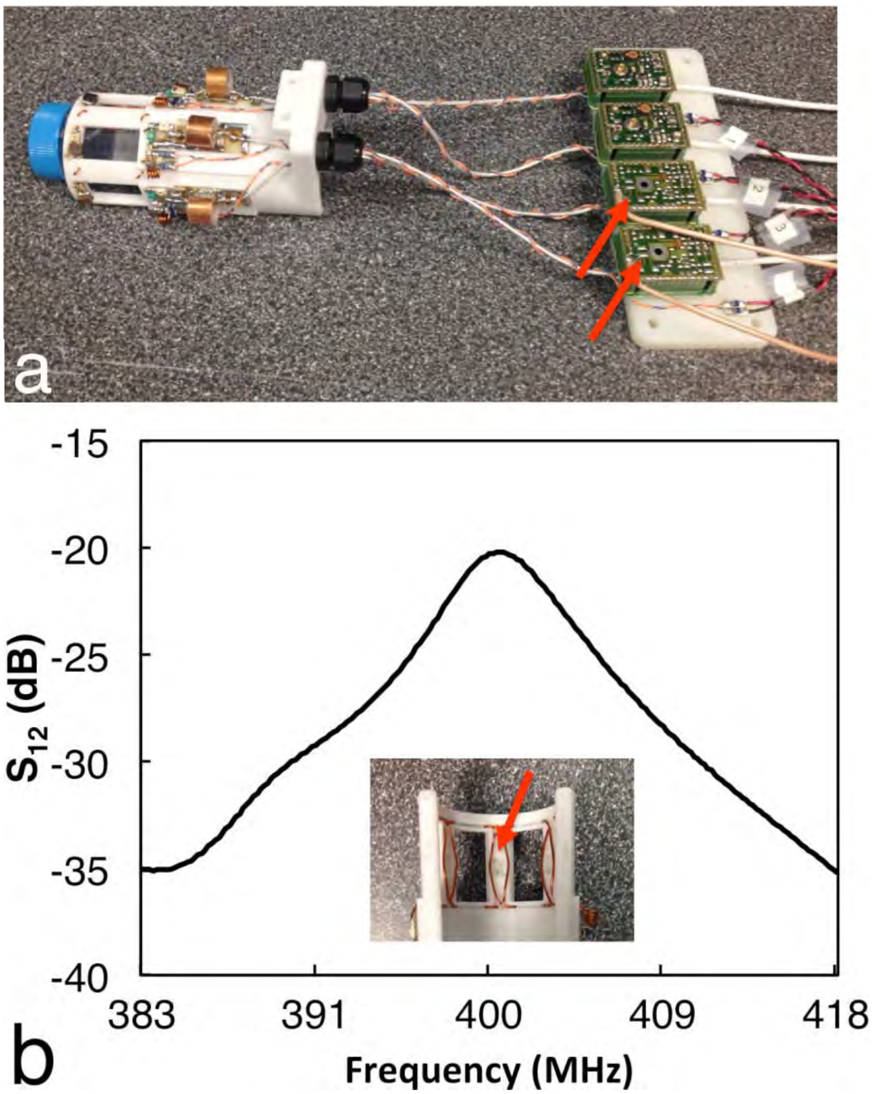

Figure 10. (a) The optimal overlap between adjacent elements can be determined through an S_{12} measurement when plugging directly into the preamplifier sockets (indicated by arrows) of the elements under investigation. (b) The overlap between elements should be mechanically adjusted to minimize S_{12} at the frequency of interest.

At this point, inductive coupling between adjacent elements can be investigated, and the critical overlap between adjacent elements can be adjusted to minimize inductive coupling. With all other elements detuned, aside from the two elements under investigation, the S_{11} of each coil can be measured either with a single probe or directly form the preamplifier socket. If there is peak splitting due to coupling, the overlap between the two coils can be adjusted by bending the wires slightly. Once there is only one resonant peak in the S_{11} spectrum of each coil, an S_{12} measurement between the two preamplifier-sockets can be performed to quantitatively assess the degree of coupling (Fig. 10). The overlap can once again be adjusted to minimize S_{12}. Attaining an S_{12} of better than -12 dB is a reasonable target value. For this particular coil, the mean S_{12} between adjacent elements was -20 dB.

Once the wires are bent, it is important to once again match and tune the coil to the original values. It may also be necessary to adjust the preamplifier decoupling if C2 was adjusted. This procedure can then be carried out for each pair of overlapping coils in the array. It is typically a good idea to do this twice for the entire array, each time making sure the tune, match, and preamplifier decoupling are restored for any coils in which the conductors were modified. A final check of the tuning, matching, preamplifier decoupling, and active detuning is always a good idea before testing the completed array (Fig. 11) in the scanner.

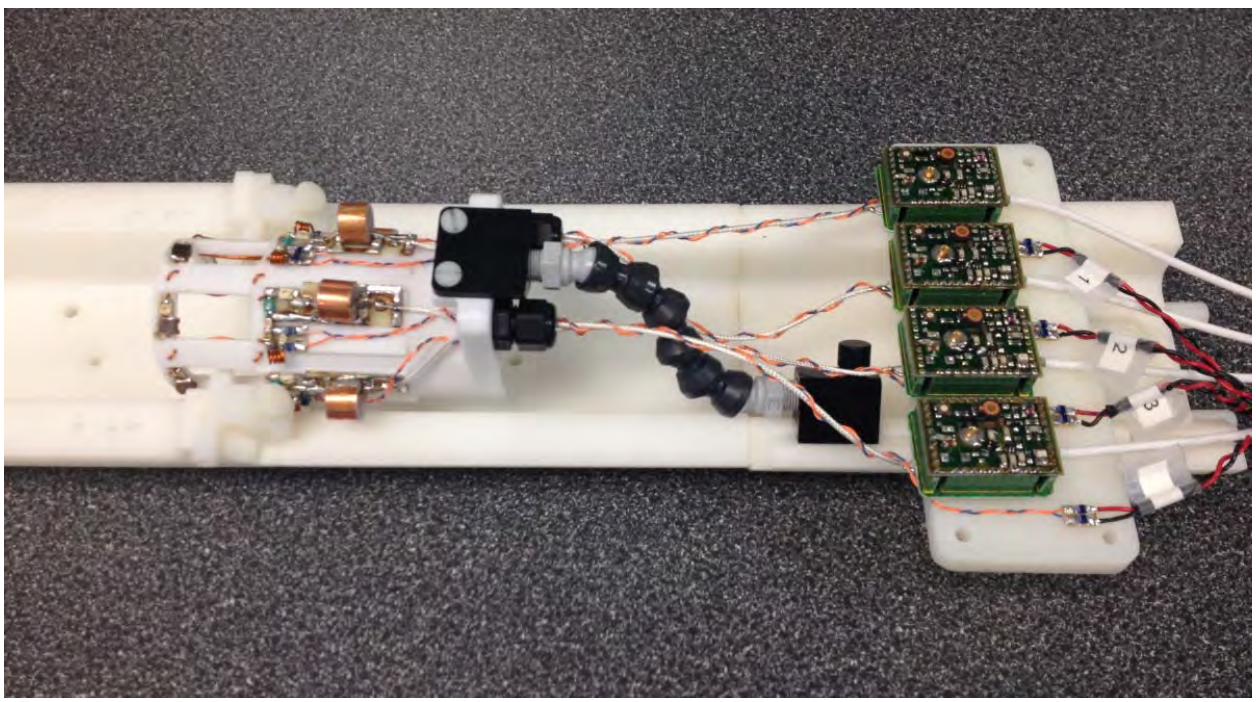

Figure 11. A photograph of the completed coil attached to the "rat tray" with ear bars attached for immobilization. Covers can be made to surround the coil and preamplifiers to prevent damage.

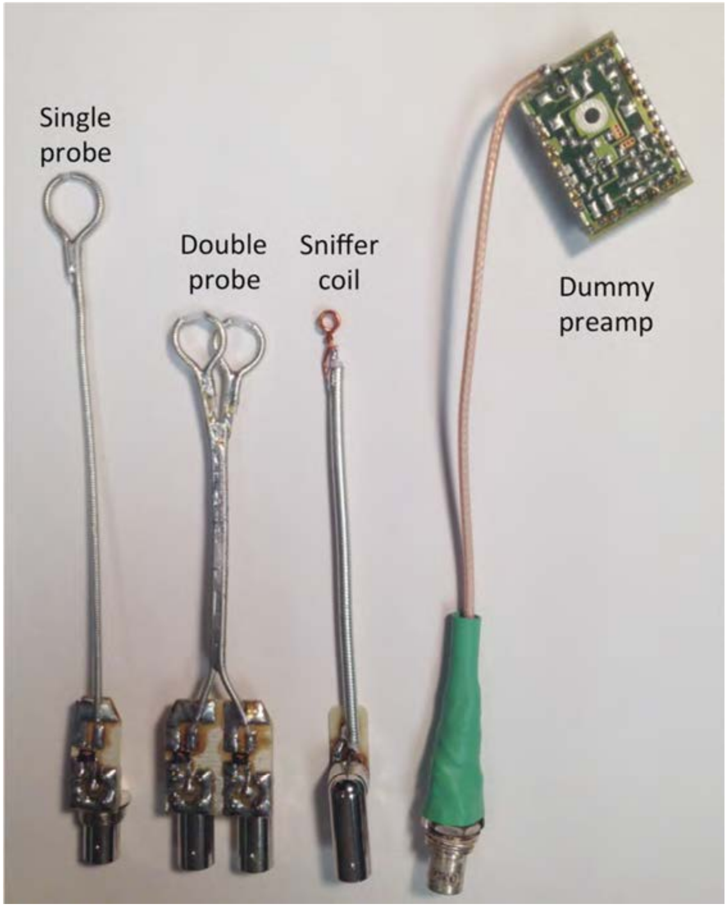

Figure 12. Here are the homemade probes that are used extensively in the construction of a receive array. A single probe can be used to measure the S_{11} response of an element. The double-probe consists of two single probes overlapped to increase isolation between the probes at the frequency of interest. This probe is used to measure the S_{12} response of an element. The sniffer probe can be used to measure S_{11} of a small circuit and to identify "leakage fields". The "dummy preamplifier" can be plugged directly into the preamplifier socket to account for all impedance transformations between the preamplifier and the coil element.

Homemade probes

There are several homemade probes (Fig. 12) that every coil builder requires in their "toolbox." The first is a probe that consists of a loop of semi-rigid coaxial cable with a gap in the middle of the loop's shield. The centre conductor of the cable is soldered to the shield to complete the loop. These single loops can be made with or without broadband baluns placed on the input of the loop. The second kind of probe takes two of these loops and overlaps them to minimize the coupling at the frequency of interest—this is often referred to as a double-probe. The shields of the coaxial cables can be soldered together. The third probe is a "sniffer probe", which consists of a small solenoid soldered onto the end of a semi-rigid coaxial cable. The final probe is a "dummy preamplifier" that has all the components removed and can fit into the preamplifier socket. This can be used to make direct measurements at the preamplifier socket.

Interface box

It is important to have an interface box that connects to your receive array (Fig. 13). This interface box can vary in complexity, but typically contains bias-T's to supply the required voltage to the preamplifiers (in our case 10 V) and to be able to look at the output of each preamplifier. It also contains switches on the DC lines supplying each coil's active-detuning circuit to allow for the bias to be turned on and off. The interface to the coil will differ depending on the scanner's vendor and may require special high-density connectors.

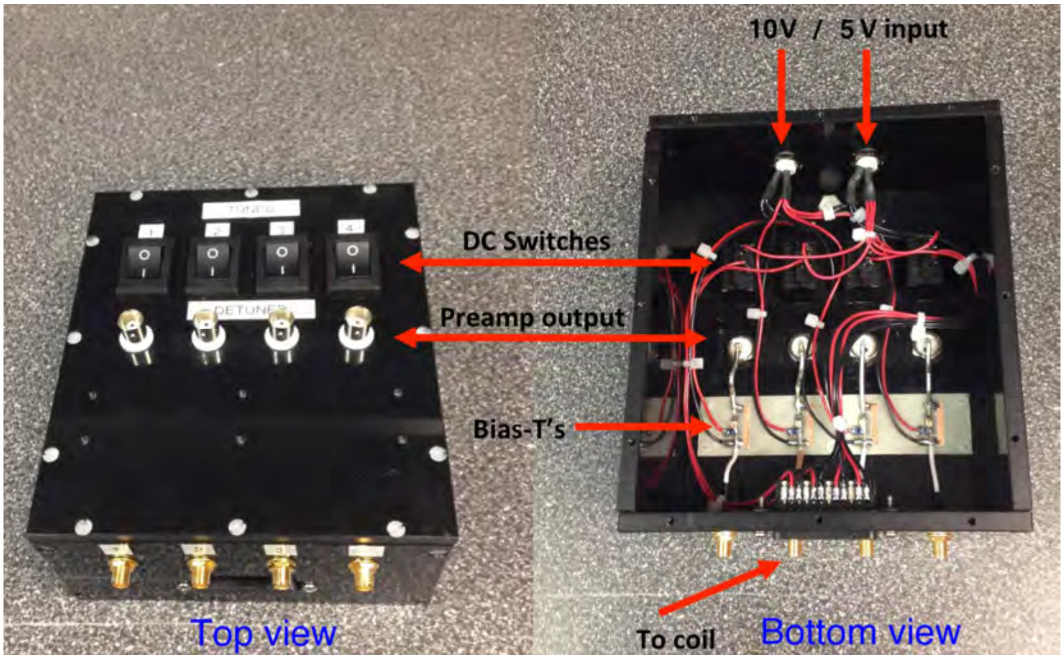

Figure 13. The interface box that allows independent control of the bias voltages supplied to coil elements. This interface box also includes bias-T's to supply 10 V to the preamplifiers. A scaled-up version of such an interface box is crucial for the development of receive arrays with high channel counts. The interface to this box should match the coil interface on the scanner, which will differ depending on the vendor of the scanner.

Materials

Description	Model/Series	Company
Surface-mount capacitors	100B	ATC
Variable capacitors	SGC3S	Sprague-Goodman
PIN diodes	MA4P505-1072T	M/A-Com Technology Solutions
RF chokes (inductors)	AISC-1008	Abracon Corporation
Semi-rigid coaxial cable	UT-085C-FORM UT-141C-FORM	Micro-coax
Non-magnetic coaxial cable	RG178	Coast Wire
Broadband balun	CX2156NL	Pulse Electronics Corporation

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