T/R switches, baluns, and detuning elements are three major devices to reduce RF/EM couplings among receive RF coils, transmit RF coils and MRI system environment around RF coils in MRI system. Inadequate designs on these parts often lead to unnecessary high transmit power consumption, noisy NMR signal and the RF heating issues. In this paper we discuss the basic functions, theories and commonly used types of these three devices. Figure 1 shows a diagram of typical transmit/receive coil with these devices.

Figure 1 A diagram of a typical transmit/receive coil

Introduction

Several concepts need to be introduced before the discussion of these devices. These concepts are very helpful to understand the functions and theories of the devices.

1. LC resonant circuit: LC circuit is widely used in MRI RF coils. In fact the RF coil itself is an LC resonant circuit. In general the dominant loss of LC circuit in the devices is from resistance of inductor, and capacitors may be regarded as low loss or lossless. The loss can be thought as a resistor $R_s$ in series with the inductor $L_s$. The blocking impedance of LC resonant circuit at the working frequency is very important for design considerations. It is easier in practice to transform serial resistance of inductor into parallel resistance which is shown in Figure 2. If the quality factor $Q$ of LC circuit is known, then $R_p = X_{L_p}Q = X_{C}Q$. $R_p$ is the main parameter for calculating temperature rise of the LC circuit.

Figure 2. LC resonant circuit

2. Transmission line: Transmission line is also frequently used in MRI coils. It is characterized by its intrinsic impedance. The industry standard is 50 Ohms. One
of the best and commonly used transmission lines is coax type line. Since its forward and backward currents cancel each other, there is no radiation from coax cable theoretically. Considering a piece of lossless transmission line shown in Figure 3, when the right side is shorted (cable center connected to the cable shield), the impedance seen from the left hand side can be written as $Z = iZ_0 \tan\left(\frac{2\pi l}{\lambda}\right)$, where $Z_0$ is the intrinsic impedance of the transmission line, $\lambda$ is the wavelength of transmission line at the working frequency and $l$ is the length of the transmission line. The impedance is like an inductor when $l$ is less than quarter wave length. When the right side is open, $Z = -iZ_0 \cot\left(\frac{2\pi l}{\lambda}\right)$. This is like capacitor for $l<\lambda/4$. These two properties are often used in baluns, detuning elements and T/R switches design. Transmission line can be simulated by lumped elements, such as $T$ or $\pi$ network. Both of the networks also have high pass and low pass types [2]. Lumped-element transmission line is very attractive in lower frequency due to the space saving.

3. Switching diode: Switching diode is a high speed non-linear device. When the forward voltage is greater than its ON voltage, it becomes short. When the voltage's less, it becomes open. It is frequently used in RF coils to provide protection and detuning purpose. However, since its RF impedance in short still has about 2 or 3 Ohms, the power handling of the diode is limited. Usually it takes $rm$ power less than 0.5W. When it is OPEN, it still has 2 to 3 pF capacitance with dozens of k$\Omega$ resistance in parallel.

4. Pin diode: Pin diode is made of P-region silicon, pure silicon and N-region silicon [3]. Its performance mainly depends on its geometry and the material. When forward DC is applied to the PIN diode, it allows RF signal to go through. The forwarded RF resistance can reach less than 0.5 Ohm. Thus, PIN diode can handle more RF power. When DC is disconnected, the RF signal can still pass for a short period of time if no reverse DC is applied. This is called carrier life time. This property is utilized in one of the detuning elements later.

**T/R switch**

The purpose of T/R switch is to protect receiver (preamplifier) from the damage due to high RF power of transmit mode in MRI system. In most time diodes are put into the path between transmit port and preamplifier so that no noise is coupled from transmit port to preamplifier in receive mode. It is known that transmit coil can be driven in quadrature mode or linear mode. Therefore there are two types of T/R switches. One is for linear mode; the other is for quadrature mode.

Figure 4 shows a T/R switch in linear mode [4]. D1 and D2 are PIN diodes. In transmit mode both diodes are applied forward DC bias. Both are ON. D1 allows RF power from transmit port TX to go to coil. Since transmission line between coil and receiver port RX is quarter wavelength, the coax cable impedance seen from coil side is open. While this protects preamplifier, the matching of the coil remains unchanged. When the coil is in receive mode, both diodes are applied reverse bias, then the coil just connects to RX port directly through a transmission line.
A quadrature hybrid is required to drive a quadrature coil. Figure 5 shows the geometry of the hybrid. Even-Odd mode analysis can be used to understand the function of this device [5]. The device is very symmetrical. Any port can be used as input port. When all ports are matched to $Z_0$, the power of input port equally splits into output ports 2 and 3. The phase difference between ports 2 and 3 is $90^\circ$. Port 4 is completely isolated from port 1. Since most MRI coils work at low frequency (<130MHz), the transmission lines are often simulated by the lumped elements.

It is known that T and $\pi$ network can be used, which both have high pass and low pass types. Thus, there are many circuits available to build quadrature hybrid using lumped elements. Considering hybrid loss and manufacturability, the least number of inductors and components are used mostly. Figure 6 shows a simple quadrature hybrid using lumped elements. Since the current phases in two inductors have $90^\circ$ difference, the two inductors may be wound as twisted pair for same inductance consideration. Since coils are tuned and matched to a standard phantom in practice, it is not feasible that coils have excellent matching for all patients. When a pair of quadrature coils is connected to the hybrid, the perfect matching condition is not always met for quadrature hybrid. In fact, the reflected powers from two quadrature coils are mostly absorbed by port 4. The matching seen by port 1 is the isolation between two quadrature coils. Preamplifier at the isolated port needs additional protection. Similar concept of T/R switch in linear mode can be applied for this purpose. Figure 7 shows an example of T/R switch circuit.
Balun

Balun is the common-mode choke in RF coils. It presents low impedance to the signal current which is in differential mode and allows DC coupling. To the common-mode current it presents itself as a high impedance choke. The functional diagram of balun is shown in Figure 8. Mostly balun is placed in coil cables to reduce common mode RF current of cable shield. The common mode current generates unnecessary coupling and heating of the RF coils and cables. Properly choosing the right baluns and putting them at the right places are very important, and failure to do so becomes a safety issue in most time. Since RF coils generate (receive) RF power (signal), RF coils are common mode devices. Balun clearly defines the boundary between the RF coil and coax cable connecting to the coil. An RF coil without balun/ inadequate balun or putting in the wrong place is equivalent to extending the RF coil, thereby becoming to the undesired devices. As a result this increases the coil loss. This means extra RF power for transmit coil and low SNR for receive coil.

Balun has two functions in MRI receive coils. One function is for transmit state. As mentioned before, baluns are put on the cables to stop RF current on the shield. This is to prevent RF energy getting away from the body coil area. The magnitude of this effect is a strong and complicated function of the insertion depth of the antenna (coax cable) as well as the antenna impedance (environment) [6]. Inadequate balun design leads to excessive RF current on the coax cable, causes the burning of the balun and generates RF burning if a patient is very close to the cable. In most time multiple baluns are required to put on the coax cables to further reduce the coupling from the dipole mode to the multi-pole mode coupling as well as increase the total impedance of the baluns. The second function of balun is to reduce the RF noise coupling from other noise sources in the receive mode [4].

To design an RF coil successfully following questions have to be addressed: where the baluns should be, how many baluns are required and what kind of baluns should be used. There are several rules may need to be followed. First it is important to know the transmit coil electric field (E field) distribution. Second the coax cable routing should be chosen carefully to avoid the high E field region. Third the balun should be put at the high E field areas of the chosen cable route. Last but not the least, the baluns have to be evaluated to see whether they can stand the heating of the high E field. If not, either stronger bigger baluns need to be applied or multiple baluns can be used to reduce the coupling.

There are several baluns widely used in RF coils. The first one is the solenoid balun. Its drawing and equivalent circuit are shown in Figure 9. This balun has very high blocking impedance and probably is the strongest balun available. One drawback of this balun is that the capacitor has to be soldered / connected to the cables. The second type is the transformer-like balun [7]. Its drawing is shown in Figure 10. To make this balun work an independent LC circuit is built first. Then the RF cables are wound around the LC circuit so that the windings strongly couple to the LC circuit through the mutual inductance. Last the LC circuit is tuned to the working frequency. This is also a strong balun with the advantage of no soldering on the RF cable. However, this requires additional mechanical device to hold the LC circuit and cable winding. The third one is so called “bazooka balun” which is a transmission line balun. The best way to implement this balun is to use tri-axial cable. However, due to its size and cost tri-axial
cable is not always used in RF coils. Alternatively a short cylindrical mechanical former is designed to simulate the tri-axial line. The blocking impedance is almost proportional to the length of the former and \( \log(R/r) \), where \( R \) and \( r \) are the radii of the former and the cable, respectively. The disadvantage of this balun is its low blocking impedance. However, since this balun is very big, it partially compensates this disadvantage. The last one is the lattice balun shown in Figure 12 [4]. This is a four-component device and very symmetrical. Compared to other baluns, this balun has too many components, therefore it is very difficult to tune. The baluns discussed above are all 1:1 baluns, i.e., 50 Ohms to 50 Ohms. It may be possible to use non 1:1 baluns at lower frequency when the Q factor of RF coil is high.

**Detuning element**

Since receive coil and transmit coil are working at the same frequency, they need to decouple to each other in transmit and receive mode, respectively. The decoupling is mostly realized by diode controlled detuning elements.

For transmit coil the detuning elements are simply PIN diodes which are put in the coil path. For receive coil the detuning process is more complicated. The receive coil is put into the transmit field \( B_1 \). Since \( B_1 \) is alternative magnetic field, it generates
induced E field in the coil loop. The detuning element has to provide high impedance in
the coil loop to reduce the RF current from the induced E field. It doesn’t matter where
the detuning elements are placed in the coil path. The first question is about how many
detuning elements are required on the coil. One of the criterions is

\[ \frac{(\omega_0 B A)^2}{NR} R_{\text{thermal}} < \Delta T, \]

where \( N \) is the total number of the detuning elements, \( A \) is the coil area, \( R \) is the
blocking resistance of the detuning element, \( R_{\text{thermal}} \) is the thermal resistance of detuning
element and \( \Delta T \) is the temperature rise limit. However, the induced E field is just one
part of the detuning purpose. The other part is from leaking capacitance of the transmit
coil, which is supposed to stay inside the transmit coil. However, the leakage may
interact with the receive coil region in most time. This leaking capacitance is part of the
transmit coil and consume RF power from RF power amplifier directly. The RF current
from this effect is quite significant. The detuning elements equal to baluns in this
situation. As a result the rules of balun need to be followed. The right positions of the
detuning elements are difficult to be determined. Generally FDTD method is employed
to calculate E field distribution, and the detuning elements are put at the highest E field
point of the coil path to stop RF current.

There are several types of detuning elements for receive coil. The first type is the
passive detuning element shown in Figure 12. The advantage of this circuit is that no
DC power is required. However, since switching diode has larger resistance, its power
rating is limited. The second one is the active detuning element which uses PIN diode
(Figure 13). This circuit can take much more power but requires DC bias. The last one
is self-biased detuning circuit. The idea is to extract small amount of RF power from
transmit field and use that power to bias the PIN diode. Therefore it also handles more
RF power. Figure 14 shows an example of this type.

![Passive detuning](image1)
![Active detuning](image2)
![Self-biased detuning](image3)

**Summary**

This paper briefly introduces the functions, properties and commonly used types
of T/R switches, baluns and detuning elements. All these devices are the different
applications of an LC resonant circuit.

**Reference:**

8. US Patent 6850067, Feb 1th 2005, Burl et al,