Circuit and Transmission Lines – Scott B. King

Outline – For MRI RF Technology Students
- Overview of transmission lines, differential mode, common-mode blocking, phase shifting, and impedance matching
- Basic network theory, lumped element equivalent model of transmission line
- Phase shifter and matching RF networks
- RF networks: baluns, splitters/combiners, hybrids, preamp decoupling, transmit decoupling

Audience Objectives
- To understand some of the typical RF circuits used in MRI
- To be able to go back to the lab and build them

Transmission lines, such as a co-axial cable, stripline, or optical fibre, are used to propagate electromagnetic waves between the output and input of electrical devices. In an ideal electrical transmission line such as a co-axial cable, the MRI signal is propagated as differential-mode TEM fields that are fully contained between equal and opposite currents flowing in the two conductors (Fig.1). Unwanted, are common-mode RF propagation (equal currents flowing in same direction) due to an unbalanced (voltage not equal and opposite) connection-interface or coupling to unbalanced external fields (body transmit coil, or other Rx-cables).

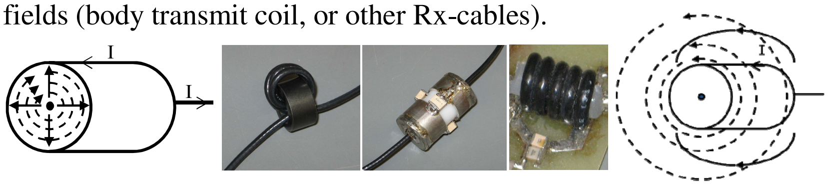


Fig.1: (Left) Differential-mode fields of a co-axial transmission line, showing TEM fields (E-solid, B-dash) and equal and opposite currents. (Middle) ferrite, tuned Bazooka balun, and tuned solenoid cable traps used to suppress common-mode currents/fields (Right).

Phase Shifting and Impedance Matching using Transmission Lines

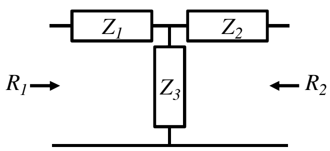
It is important to understand how such a transmission line affects the phase of the propagating wave or signal, as well as how it transforms a load impedance. A lossless transmission line of length, l, and characteristic impedance $Z_C = Z_0$ (which is the ratio of the complex voltage to the complex current of the propagating wave at the same time point), with output terminated by an impedance Z_L (Fig.2), has an input impedance given by [1],

$$Z_{in} = Z_0 \frac{jZ_0 \tan(\theta) + Z_L}{jZ_L \tan(\theta) + Z_0}$$

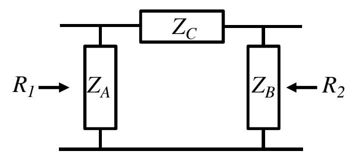
where the phase shift, $\theta = 2\pi l/\lambda$ and λ (= $k\,\lambda_{vaccuum}$, k = velocity factor) is the characteristic line wavelength.

For a transmission line with a fixed characteristic impedance $Z_C = Z_0 = 50$ ohms, since θ is frequency dependent, so is the transformed impedance. If the line length is a multiple of $\lambda/4$ (n*90°), then $Z_{in} = Z_0^2/Z_L$, meaning that a n*90° line transforms a open to a short and a short to an open, the latter being extremely useful in creating high impedance for blocking RF current or signal propagation!

It is much more common to use discrete components rather than transmission lines to produce phase shifts and impedance transformations, so it is extremely useful to model an electrical transmission line as a linear two-port network shown in Fig. 2, with characteristic impedance Z_C (typically = Z_0 = 50 ohms). The general solutions that allow matching R_1 to R_2, with a particular phase shift θ, are given by [2],



$$Z_1 = -j\frac{R_1\cos\theta - \sqrt{R_1R_2}}{\sin\theta}$$
$$Z_2 = -j\frac{R_2\cos\theta - \sqrt{R_1R_2}}{\sin\theta}$$
$$Z_3 = -j\frac{\sqrt{R_1R_2}}{\sin\theta}$$



$$Z_A = j\frac{R_1R_2\sin\theta}{R_2\cos\theta - \sqrt{R_1R_2}}$$
$$Z_B = j\frac{R_1R_2\sin\theta}{R_1\cos\theta - \sqrt{R_1R_2}}$$
$$Z_C = j\sqrt{R_1R_2}\sin\theta$$

Fig. 2: Two-port complex-impedance lumped element representations of a transmission line; T-network (*Left*), and π-network (*Right*), and corresponding component formulas for characteristic impedances R_1 and R_2, and phase shift θ.

PHASE SHIFTERS

Following this, one can design a simple phase shifter that does not transform impedance ($R_1 = R_2 = Z_0$) using any variant of the T- or π-networks shown below, although generally the first two are preferred because they contain only one inductor, which generally has a lower Q than a capacitor.

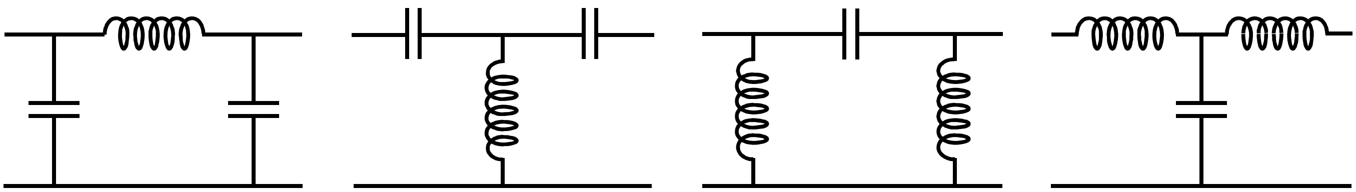


Fig. 4: Phase shifter networks

Quadrature Hybrid (Splitter/Combiner) Design

A common design for a quadrature hybrid [1] is shown in Fig. 5 below, made from two -45° phase shifters and two 50 Ohm capacitors. The Tx and Rx ports are very well isolated, and the two outputs achieve equal amplitude and a 90° phase shift necessary for quadrature combination of two orthogonal fields to produce a circularly polarized (CP) field, common in all quadrature (CP) birdcage coils.

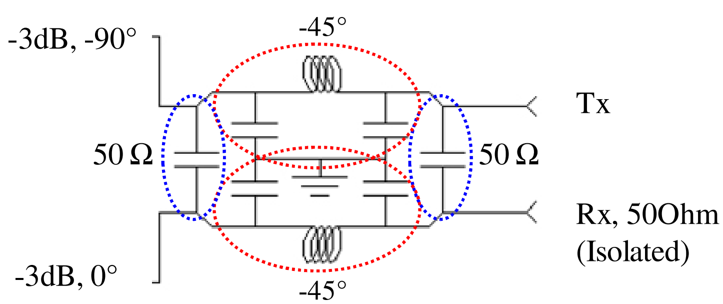


Fig. 5: Common quadrature hybrid design

Tx/Rx Switching

The most common method of providing transmit/receive switching is to use the following circuit, which incorporates a 90° phase shifter and a shunt pin diode to provide a short (when forward biased) on the Rx side that is transformed to an open on the Tx side during the transmission stage, blocking transmit voltage from the receiver.

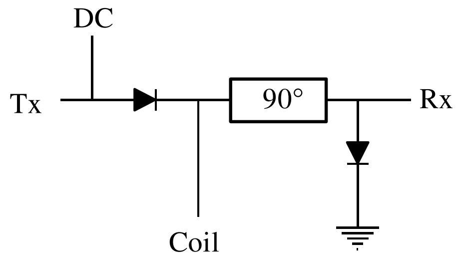


Fig. 7: Typical active Tx/Rx switch used in MRI applications

In this talk, network analysis will be described to allow one to determine the above sets of lumped element phase shifter and impedance matching RF networks, and then real examples of the design and construction of various MRI RF networks will be shown, such as; phase shifters, RF coil input matching baluns, quadrature hybrid (splitter/combiner) designs, Tx/Rx switches, phased array Rx-coil active/passive decoupling, and phased array preamplifier decoupling

References

[1] Mispelter J, Lupu M, Briguet A. NMR Probeheads for Biophysical and Biomedical Experiments: Theoretical Principles & Practical Guidelines. Imperial College Press, London, 2006.

[2] Fredrick E. Terman, *Electronic and Radio Engineering*, McGraw-Hill 4th Ed. 1955.

[3] Chen C-N, Hoult DI. Biomedical Magnetic Resonance Technology. Bristol: Adam Hilger; 1989.