Improving UHF Transmit Efficiency with Voltage Baluns

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Introduction: Common-mode currents due to voltage imbalances contribute to radiation loss, and thereby reduce the effective power (percentage of total power delivered to the load). As radiation losses increase with the fourth power of the frequency, the losses are more dramatic at 7T. Maximizing the power efficiency is of particular importance for parallel transmit arrays due to the limited power available per channel of commercial systems. Common-mode currents can be reduced by 90° baluns (e.g., 90° lattice baluns, can baluns, and bazooka baluns), which present a high impedance on the coax shield. However, only a 180° balun can provide a balanced feed [1]. The capacitances and inductances required for lumped element baluns decrease with increasing frequency, and thus unpredictable parasitic inductances, asymmetries of leads, and stray capacitances, play a larger role and can seriously impair balun tuning. Due to the increased importance of robust baluns for high field MR, simple tests of touching a cable to determine balun efficiency are no longer sufficient, and thus quantitative methods are necessary. We investigate the performance of a wide-band and a narrow-band 180° balun for use at 7T, and present simple quantitative methods.

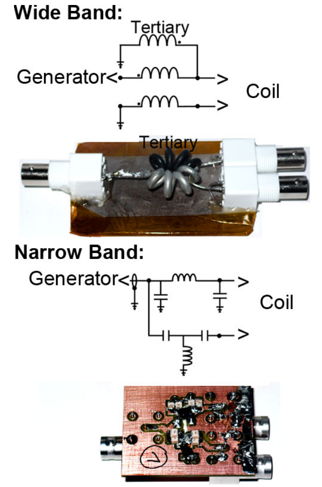

Figure 1 Wide-band balun: Tertiary winding connects inner conductor at the balanced port to the outer shield at the generator side. Narrow-band balun with all reactances equal to +/- 50 ohms. Photos show mounting for vector network analyzer measurements.

Methods: Fabrication: 1) A wide-band 1:1 180° balun [2] was fabricated by winding coaxial cable as half of a toroid. A tertiary winding with identical inductance was connected between the shield on the generator side of the balun and the inner conductor on coil side (balanced port) (Fig. 1). Short leads were attached to the balanced port of the balun to enable connection to the coil, and coaxial connectors for measurements. The spacing and length of the leads were constructed to match the dimensions of the high power capacitor to which they were eventually attached. A capacitor of known value was temporarily added in parallel to the windings before joining them together to measure resonance frequency, in order to ensure that the inductances were equal. 2) A narrow-band 1:1 180° balun as described in [1] with Pi and T quarter-wave sections [3], with reactances equal to +/- 50 ohms (Fig. 1).

Balance Performance: Amplitude and phase balance of the voltage at the balanced port was measured with a network analyzer. Ports 1 and 2 of the network analyzer were calibrated (open, short, 50 ohm, and through port). The baluns were mounted onto a board with three coaxial connectors with common ground (Fig. 1). Port 1 was connected by a cable to the generator side of the balun. The coil feed ports were connected one at a time to the network analyzer, with the other side terminated by a 50-ohm load (Fig. 2). Measurements of complex S_{21} were repeated 10 times for each arm of the coil feed port (reconnecting each time).

Calculation: A relative common mode rejection ratio (*rCMRR*) was calculated to combine effects of phase and amplitude match. The *rCMRR* is the ratio of the differential and common mode transmission coefficients. The ratio of these transmission coefficients used a transformation from conventional to mixed-mode scattering parameters [4] as $rCMRR = |(S_{41} - S_{21})/(S_{41}+S_{21})|$. The amplitude balance *AB* and phase balance *PB* were calculated from S_{41} and S_{21} measurements of the balun as $AB = 20\cdot \log |(S_{41}/S_{21})|$, and $PB = \mathrm{ang}(S_{41}/S_{21})$.

Common-mode Current: A home-built current probe was used to assess whether baluns provided a decrease in common-mode currents, using methods similar to previous studies [5]. Measurements were conducted with no balun, a wide-band balun, and a narrow-band balun feeding a loaded transmit coil. The transmit coil (80 mm by 100 mm rectangle, 8 distributed capacitors) was tuned and matched for each case ($|S_{11}|$= -30 dB).

MR Scanner Transmit Efficiency: As a final comparison, the transmit efficiency of the balanced transmit coil was characterized in the MR scanner to determine if the reduction of radiated cable losses provided increased efficiency despite the added insertion loss of a balun. An 8-channel receive array was used for acquiring flip-angle maps [6]. The required voltage for a 90°-deflection pulse for each case was compared in the same spatial location within the phantom. The cylindrical phantom contained 7.3 L of a solution with 1.24g $NiSO_4 \times 6H_20$ and 2.62 g NaCl per L. The shield was that of the gradient coil (diameter = 640 mm).

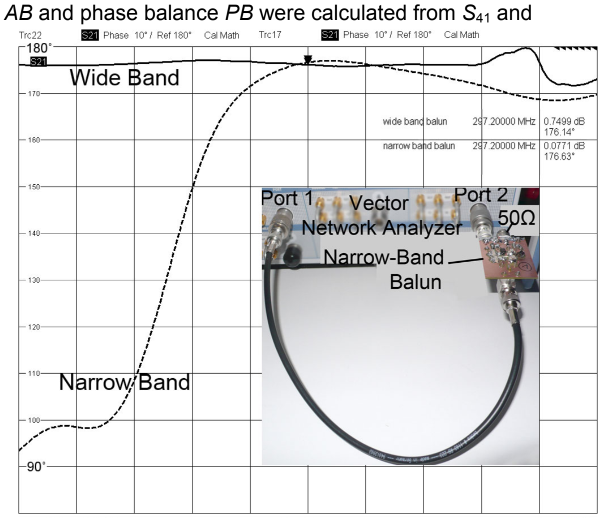

Figure 2 Phase balance measurements for wide and narrow band baluns. Inset shows vector network analyzer with ports 1 and 2. Unused branch of balun terminated with 50 ohm. Center 297.2 MHz, span 300 MHz.

Results: The *rCMRR* at 297.2 MHz was 27 dB for the wide-band balun and 24 dB for the narrow-band balun. Fine-tuning of the narrow-band balun, employing phase and amplitude balance measurements, led to an improved *rCMRR* of 30 dB at 297.2 MHz. The tuned narrow-band balun had a balance of 0.1 dB and 176° at 297.2 MHz. The wide-band balun had a balance of 0.7 dB and 177° at 297.2 MHz, and better than 1 dB and 170° over the 300-MHz-bandwidth surrounding the operating frequency. Repeated measures gave standard deviations of 0.5 dB for *rCMRR*, 0.01 dB for *AB*, and 0.04° for *PB*. Current-meter measurements indicated that the addition of baluns reduced the common-mode currents by more than -15 dB (-40 dB for both baluns and -25 dB in absence of balun, consistent with [5]). Transmit power efficiency improved due to the addition of a 180° balun. The improvement was inhomogeneous, with an average of over 10% and a maximum exceeding 50%.

Discussion: Wide-band and narrow-band baluns provide practical means for reducing common-mode radiation losses at 7T. In the event that the coil and surround are not sufficiently symmetric for use with a 180° balun, a 90° balun can be used to feed the 180° balun, creating a hybrid balun. The 1:1 baluns have 50-ohm differential impedances, and therefore each branch presents only 25 ohms. For reliable balance measurements the conditions for analyzing each branch of the balun must be identical. For this reason, each branch was analyzed one at a time. *CMRR* in the case of the impedance mismatch present are only relative measures, hence *rCMRR*. Simulation of CMRR in the presence and absence of mismatch (balun branches terminated with 50 or 25 ohms) suggests that the present mismatch degrades *rCMRR* by less than 2dB. Insertion loss measurements require a test configuration that either corrects for, or eliminates the impedance mismatch, and therefore requires further consideration. In the absence of direct insertion loss measurement we therefore assessed the transmit efficiency of a transmit coil in the scanner. Although wideband baluns have higher insertion losses than lumped baluns, there may be added benefit to baluns that do not require fine-tuning, and are less susceptible to stray capacitances [2]. Due to the increase of radiation loss with frequency, balanced feed is crucial at UHF. The network analyzer methods presented are simple and effective, and can be used to evaluate and improve balun performance, and thereby contribute to improved power efficiency of transmit coils and arrays at 7T.

References: [1] Peterson et al, ISMRM 2002; [2] Ruthroff Proc. of IRE 1959, p 1337-1342; [3] Brennecke, Proc. IRE 1944, p 15-17; [4] Bockelman et al, IEEE Trans. Microwave Theory and Techniques, Vol 43, p1530-1539, 1995; [5] Peterson et al, Concepts in Magnetic Resonance Engineering, Vol 19, p 1-8, 2003; [6] Amadon et al, ISMRM 2008.

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