A 500 W, Broadband, Non-Magnetic RF MOSFET Amplifier for MRI Use

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Introduction

The Cartesian feedback method of transceiver operation, used for effective (40 dB) blocking of phased-array coil interactions during transmission and reception, demands that signal propagation delays be minimal. Thus the authors have developed a versatile non-magnetic 10-1000 MHz transceiver[1] that functions at the magnet bore entrance. An important component is the power amplifier, and modern metal oxide field effect transistors (MOSFET's) hold the promise of delivering hundreds of watts of radio frequency (RF) power while functioning in magnetic fields. Thus we report here their use in producing up to 500 W in a push-pull class AB configuration over a bandwidth of 100 to 300 MHz.

Operating Conditions

***Thermal considerations*:** If conventional test equipment (e.g. a spectrum analyser) is to be usable, the amplifier must be able to run continuously, producing > 1 kW of heat. While forced-air cooling is viable, the use of liquid cooled "cold plates" (e.g. D6 Industries, Lawrence, MA, USA) is a compact and elegant alternative. Even with a cold plate, however, heat must diffuse more rapidly from the transistors, so they are best bolted to an intermediate, thick (~8 mm) copper slab. The slab's surfaces should be flat to ~ 20 μm to give excellent thermal contact; a smear of silicone grease is also useful. Components and printed circuit board traces may have to pass up to 25 A DC or 12 A RF, and a weak link here is solder, with its low melting point and significant resistivity. Resistance is greatly increased by skin effect, and so an adequate solder surface area is essential, which sets in turn a lower limit on component size. Extra high-current trace thickness is advisable too. Failure to observe these precautions can result in a highly destructive arc discharge as solder melts and then vaporises.

***Component stress*:** Components must be able to handle repeatedly peak voltages and currents without breakdown. 500 W at 50 Ω implies a peak voltage of 224 V and this may be added to the power supply voltage V_{dd} – say 44 V. Thus 500 V DC working voltage capacitors are essential. If they are also handing large RF currents (500 W at 50 Ω = 4.5 A peak), high Q-factors are vital and low-inductance, ceramic-chip transmitter capacitors are the components of choice. V_{dd} should be no more than about 40% of the maximum transistor voltage for safety and obviously, the transistors must be able to pass the required current.

Transistor specifications: RF power MOSFET transistors are low impedance, high current devices of limited voltage (e.g. 110 V) with substantial drain-source capacitance C_{ds} and a small drain-gate capacitance C_{dg}. In parallel with C_{ds} is the MOSFET's dynamic resistance $R_d = dV_d/dI_d$. Both C_{ds} and R_d vary with drain voltage V_d, current I_d and frequency. A direct measure of them can be made by placing a known inductor L between the drains of a push-pull transistor pair with decoupled voltage V_{dd} applied at a centre-tap. L then resonates with $C_{ds}/2$ in parallel with $2R_d$. With the transistors gates grounded, no current flows and a high Q-factor Q_0 is obtained. However, with 1 A flowing in each transistor (gate voltages 2.7 V, decoupled), the Q-factor Q_1 drops precipitately. With our transistor of choice (MRF6V2300N, Freescale Semiconductor, Tempe, AZ, USA) and L = 25 nH, Q_0 = 77.4 at 121.2 MHz giving C_{ds} == 138 pF while Q_1 = 3.0 at 108 MHz. C_{ds} was then calculated (from full network theory as the Q-factor is low) to be 182 pF with Rd = 27 Ω. Note the increase in capacitance as the MOSFET conductance channel opens.

Loading theory for MOSFET's is as for vacuum tubes – they are *not* power-matched. For a class AB push-pull amplifier, Terman[2] teaches that the required inter-drain load for optimum RF power output W is given by $R_{ld} = 2(V_{dd} - V_{sat})/W$ where V_{sat} is the transistor saturation voltage. With V_{dd} = 44 V, V_{sat} = 2 V and W = 500 W, R_{ld} = 7.1 Ω. This value should be compared with the dynamic source resistance of two transistors in series; i.e. $2R_d$ = 54 Ω. The ratio η of the two values is a measure of the ability of MOSFET transistors to block current in coupled phased-array coils, the blocking factor being 1 + η, i.e. 18.7 dB at 1 A per transistor. This may be compared with a value of 16 dB (dropping to 10 dB at 250 W output) found earlier[1] for a commercial, single-ended MRF6V2300N 300 W amplifier.

***Circuit design*:** The push-pull design in Fig. 1 was chosen to minimise power line decoupling, while balanced 50 Ω outputs reduce the cable interactions present with multiple transmitting coils. The design task may then be summarised as requiring a balanced 7.1 Ω resistance in parallel with $C_{ds}/2$ to be transformed to a balanced 100 Ω load over as wide a frequency range as possible. A Guanella 4:1 50 Ω coaxial line transformer reduces a 100 Ω load to 25 Ω over a large frequency range. However, such transformers are usually wound on ferrites to extend their low-frequency range. Instead, we wound the transformer on a high-density polyethylene toroid and it covered the frequency range 60 to 500 MHz. We then searched for a critically coupled, doubly-resonant circuit technique to cope with capacitance $C_{ds}/2$ while transforming from 25 Ω to 7.1 Ω. Only one suitable circuit was found – a tuned autotransformer with primary inductance ~ 20 nH. To give the large magnetic coupling required, the inductor was wound in pancake form, as shown. This resulted in coupling factors in excess of 0.8. However, with such a small primary inductance L, lead inductance enhanced L considerably, thereby suitably diminishing the maximum coupling constant. Passive testing without transistors was in accord with simulation.

Measuring the *in-situ* characteristics of the load circuit is difficult and potentially destructive. We cannot simply drive the transistors' gates as the devices inflict their own transfer function on the measurement. Rather, a network analyser must be connected *via a balun* directly to the drain circuit with power on and gates decoupled. However, oscillation, whether balanced or common mode, could then destroy the network analyser. We therefore employed on both transmit and receive ports homemade 20 dB T-section attenuators with leg crossed diodes. The 1/8 W T-arms were designed to burn to open circuit in the presence of high voltages.

Results

The basic, broadband (100 – 300 MHz) class AB design (~20 dB gain) of Fig. 1 has been validated, though optimal operation has not yet been achieved, thanks to the variation of C_{ds} with output power. Direct evidence has been obtained that for coupled array coils, high power MOSFET's of themselves provide only mediocre blocking ability (18.7 dB maximum, whereas 40 dB is ideal). Nevertheless, the blocking they *can* give is a useful enhancement to that provided by Cartesian feedback. We are confident that it is possible to attain full 500 W output between 100 and 300 MHz with only two transistors and continue to research the design.

References

1. D.I. Hoult *et al*, MAGMA, In press, 2008. 2. F. E. Terman, *Electronic and Radio Engineering* (4th ed.), McGraw-Hill, New York, 1955, p. 354.

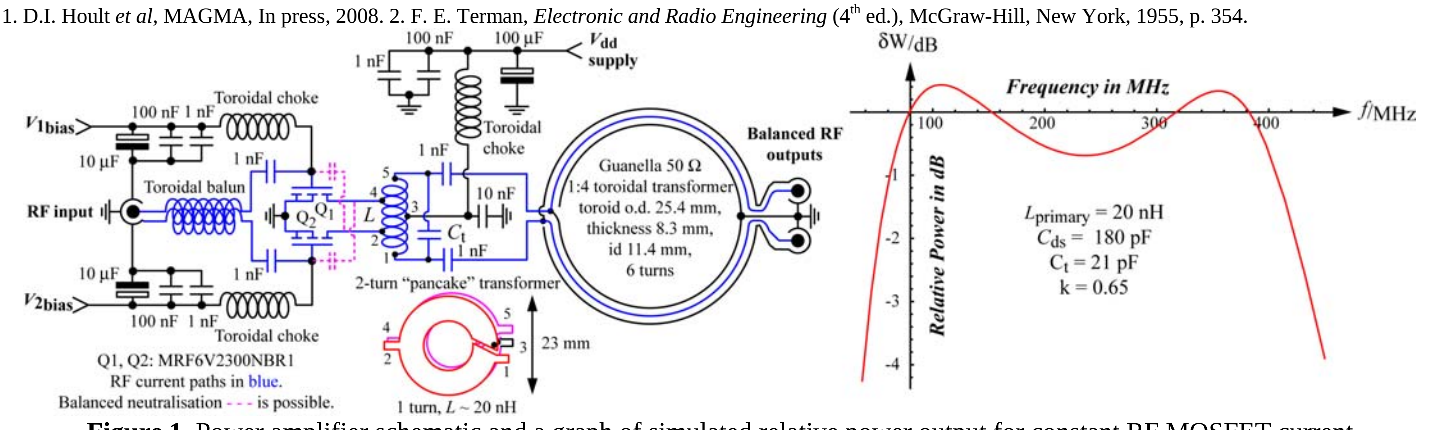

Figure 1. Power amplifier schematic and a graph of simulated relative power output for constant RF MOSFET current.