Ultra-low Output Impedance RF Power Amplifier Array

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INTRODUCTION: Mutual coupling between the transmit elements is one of the challenges when practicing parallel excitation [1,2]. One class of approaches has been recently proposed to improve the isolation between transmit elements, in which a RF power MOSFET is used to drive each element directly and configured to function approximately as a current source [3,4]. However, the series resonant element in this class of approaches also acts as a severely mismatched load to the MOSFET, and thus significantly degrades its maximum output power [5]. In this work, as analogous to the popular configuration in the receiver case [6], an ultra-low output impedance RF power amplifier was developed for simultaneously achieving maximum output power and inter-element isolation.

THEORY: As shown in Fig. 1, two identical transmit coils driven by two independent RF power amplifiers are considered. These two coils are coupled with each other through mutual inductance *M*. Each power amplifier is modeled as a voltage source with a source resistance r_s. Generally, the matching network in Fig. 1 not only transforms the low impedance of the series resonant coil into an expected value, but also amplifies the input current by *x/r* times. The current *I* running in coil 1 consists of two components, the desired one $I^{(S)}$ that is due to V_1 and the undesired one $I^{(M)}$ that is due to V_2, as calculated by Eqn. 1. The ratio of $I^{(M)}$ to $I^{(S)}$, which represents the severity of corruption due to the coupling effect, is expressed as Eqn. 2, which clearly indicates that minimizing source impedance will improve isolation.

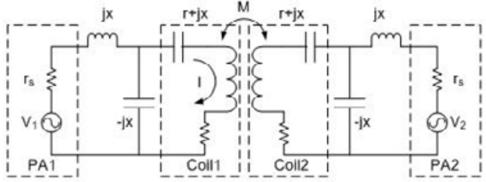


Fig. 1. Equivalent circuit model of coupled transmit coils

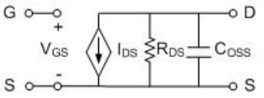


Fig. 2. Equivalent circuit model of MOSFET

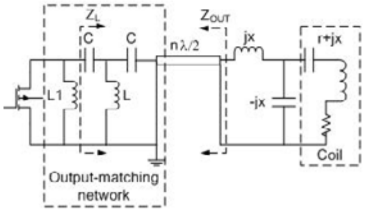


Fig. 3. The output-matching network in the ultra-low output impedance RF power amplifier

$$\begin{cases} I^{(S)} = \dfrac{-jxV_1}{rr_S + \omega^2 M^2 r_S^2/(rr_S + x^2) + x^2} \\ I^{(M)} = \dfrac{jxV_2}{rr_S + \omega^2 M^2 r_S^2/(rr_S + x^2) + x^2} \cdot \dfrac{j\omega M}{r + x^2/r_s} \end{cases} \quad (1)$$

$$\frac{\left|I^{(M)}\right|}{\left|I^{(S)}\right|} = \frac{\omega M}{r + x^2/r_s} \quad (2)$$

$$Z_L = \omega^2 L^2/50 = 1/(50\omega^2 C^2) \quad (3)$$

Fig. 2 illustrates the equivalent circuit model of a MOSFET. To maximize inter-element isolation by taking advantage the low source-impedance idea above and to simultaneously maximize the available output power, a new matching network is introduced. As shown in Fig. 3, the matching network uses an inductor *L1* to resonate C_{OSS}, and *C* and *L*, chosen to be series resonant at the working frequency, to further transform the drain-source resistance R_{DS} into $Z_{OUT}=\omega^2L^2/R_{DS}$. R_{DS} is usually very high, the output impedance Z_{OUT} can thus be made very low as it is primarily determined by the series resonant circuit, which is nearly a short circuit at the resonant frequency. Meanwhile, the same matching network transforms the input impedance of the coil into Z_L, the optimum load at which the output power of the MOSFET can reach its maximum rated value. Generally, the input impedance of the coil is matched to 50 Ω to minimize reflected power, in which case Eqn. 3 defines the impedance transformation. Setting Z_L in Eqn. 3 to the optimum load value specified for the MOSFET then ensures that highest output power can be achieved.

METHOD & RESULTS: Based on the configuration shown in Fig. 3, two ultra-low output impedance RF power amplifiers were built with high power MOSFET (ARF475FL, 900 W peak, Advanced Power Technology) to work at 128 MHz. The device was set to Class AB operation, the bias current was set to 200 mA, and the drain voltage was set to 150V.The optimum load of the MOSFET at this voltage is 25 Ω, while the R_{DS} is measured to be about 2 kΩ. *C* was accordingly selected to be 35 pF and *L* was adjusted to resonate with it at 128 MHz. When a 50 Ω load was connected, the gain was measured to be 17 dB.

To evaluate the isolation performance, two 8x8 cm^2 coils that were tuned and matched to 50 Ω independently were placed on a phantom (1.33g/L NaCl, 0.66g/L CuSO4), as illustrated in Fig. 4. The under-lapped placement of the two coils gave rise to significant inductive coupling in this setup. Coil 1 was driven by amplifier 1 (PA1), which was in turn driven by a pre-amplifier to obtain 40 W output power. A small circular coil with 0.8 cm diameter was used as a current probe and placed beside coil 2 to sense the current flowing in coil 2. The probe was connected to the receiver of the network analyzer (Agilent 4395A) through a coaxial cable. In a first study, coil 2 was connected with amplifier 2 (PA2), which had no driving current. Both amplifiers were gated on simultaneously, and S21 was measured versus the output power of PA1. Fig. 5 shows the isolation improvements, quantified by normalizing the S21 measurements with the corresponding ones that were obtained with coil 2 terminated with a 50 Ω resistor instead of PA2. The results indicate that the isolation was improved by at least -25 dB compared to that of the 50 Ω case.

A further study was conducted to compare the isolation performance of the new approach with that associated with the use of a commercial RF power amplifier (HD20310, HD Communications, 25W). The experiment setup was similar to that shown in Fig. 4, but coil 2 was actively driven by hard pulses amplified by PA2 in Case 1 and same hard pulses amplified by the commercial RF amplifier in Case 2. In both cases a 30W constant RF waveform was output by PA1. An oscilloscope was used to monitor, through the current probe, the waveform of the current flowing in coil 2. Fig. 6 summarizes the experimental results, which show that the current component due to coupling was dramatically reduced when the ultra-low output impedance power amplifier was applied.

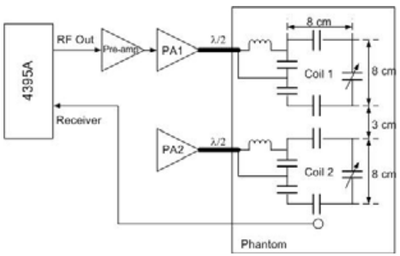


Fig. 4. Experiment setup

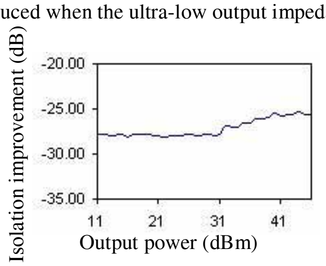
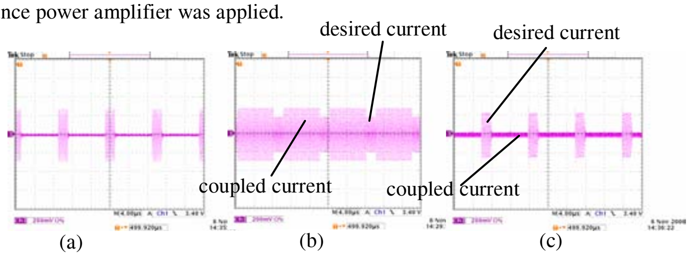


Fig. 5. Isolation improvement v.s. output power of PA1



(a) (b) (c)

Fig. 6. Waveforms of the current in coil 2
(a) The hard pulses used in the Case 1&2 (b) Case 2: PA1 and the commercial power amplifier output power (c) Case 1: PA1 and PA2 output power

CONCLUSION: The theoretical and experimental results suggest that ultra-low output impedance RF power amplifier can be realized by introducing a proper matching network, which is able to achieve, simultaneously, a) considerable reduction of coupling effect between parallel transmit coils by suppressing inductively induced currents, and b) maximum output power for a given MOSFET by establishing an optimal load.

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