Driver Amplifier for 7–Tesla MRI
Smart Power Amplifier

presented by
Kevin Kolpatzeck

supervised by
Prof. Dr.-Ing. Klaus Solbach

Institute of Microwave and RF Technology
University of Duisburg Essen
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7–Tesla MRI system employs 32 channels, each of which can produce 1 kW of pulsed power at 300 MHz.

Each channel consists of an RF power amplifier and a cartesian feedback loop.
1 kW – power amplifier:

- Driver Amplifier will be used to evaluate some concepts for the driver and high-power stage, e.g.
  - Temperature Compensation
  - Power Monitor
Driver Amplifier can be divided into five sub-circuits:

- Operating Point Stabilization
- Class A / Class AB Switching
- Temperature Compensation
- On / Off Switching
- Drain – Source Voltage Stabilization
- Load Regulation
- Easy & precise monitoring of
  - pulse power
  - momentary power
Power Amplifier
Power Amplifier Concept

- Power amplifier is built around a Freescale MRF6V2010N
  - RF power MOSFET
  - n-channel
  - enhancement mode

![Diagram of Power Amplifier](image)
Input circuit provides d.c. – feed and matching of the 50 Ω – source to the input of the MOSFET.

- **d.c. – block**
  - 1 nF
  - 12 nH

- **second stage of matching**
  - 32 nH
  - 1 nF
  - 3 pF...10 pF set to 6.1 pF

- **MRF6V2010N**
Best match has been achieved with the two-stage matching network, that is however quite different from the manufacturer’s recommendation.

Input reflection coefficient $S_{11}$ has been measured with a vector network analyzer (VNA) for a Class A and a Class AB operating point.
Small signal ($P_{in} = 0$ dBm) input reflection coefficient $S_{11}$ as measured with VNA.
Output circuit provides d.c. – feed and matching of the output of the MOSFET to the 50 Ω – load.

- d.c. – feed and first stage of matching
- Second stage of matching

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Power Amplifier
Power Gain

- Power gain (forward transmission coefficient $S_{21}$) is determined by
  - operating point
  - input power
  - quality of the input and output matching networks

- Power gain has been measured with
  - vector network analyzer (VNA)
  - RF signal generator and power meter
  - (RF signal generator and spectrum analyzer)
- Small signal ($P_{in} = 0 \text{ dBm}$) power gain $S_{21}$ as measured with VNA
Power gain and $P_{1\text{dB}}$ as measured with RF signal generator and power meter.
Third – order intermodulation products are not affected by output filter, so they can be used to quantify the harmonic distortion caused by the MOSFET.

Third – order intercept point has been measured with a two-tone measurement:

![Diagram of RF signal generator, power amplifier, and spectrum analyzer](image)
## Power Amplifier

### Summarized Data

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<th>VNA</th>
<th>Power Meter</th>
<th>Spectrum Analyzer</th>
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</table>
| **Input Reflection Coefficient $S_{11}$**  
($P_{in} = 1$ mW / 0 dBm) | – 33 dB |             |                   | **These values need some discussion!** |
| **Small signal power gain**  
($P_{in} = 1$ mW / 0 dBm) | 27.5 dB | 27.1 dB     |                   | ca. 24 dB          |
| $P_{1dB}$               |         | 15.2 dBm    |                   | ca. 17.3 dBm       |
| **Maximum Output Power**  
($P_{in} = 100$ mW / 20 dBm) | 19.1 W / 42.8 dBm |             |                   | 12.6 W / 41 dBm    |
| $IIP_3$                 |         |             | 23.2 dBm          |                   |
| $OIP_3$                 |         |             | 49.5 dBm          |                   |
Small signal power gain and maximum output power strongly exceed the values to be expected from the datasheet.

Explanations:

- Measurements have been performed with three different principles, leading to similar results → plausible
- Measurements at $V_{GS} = 3.4$ V (Class A); datasheet values at $I_{DQ} = 30$ mA (corresponding to $V_{GS} \approx 2.6$ V; close to Class B)
- Measured input return loss $S_{11}$ is approx. $-33$ dB; datasheet values are between $-14$ and $-9$ dB
- Input and output matching networks are quite different from the networks in the datasheet, both in architecture and component values → realized matching networks are supposedly better than the manufacturer’s
Gate Bias Circuit
Concept

- Operating Point Stabilization
- Choosing a Class A and a Class AB operating point
- Switching between these two points

0 V: Class A
5 V: Class AB

Operating Point Selection

Temperature Compensation

Temperature stabilization of the quiescent current

On-Off Switching

0 V: On
5 V: Off

Fast switching between the designated gate bias voltage and $V_{GS} = 0$ V

Gate d.c. feed

+ 5 V
- Input voltage is stabilized against ripple and noise on the power supply rail with low-pass filter and Zener diode.

- One potentiometer ($R_3$) allows the selection of the Class A operating point.

- A portion of a second potentiometer ($R_5$) is bypassed by a logic-level MOSFET T1 when a voltage of 5 V is applied at its gate.

- This potentiometer determines the distance between the Class A and the Class AB operating point.
Only certain pairs of operating points can be reached with this circuit.
The threshold voltage of a MOSFET decreases with increasing temperature → the quiescent drain current increases.

\[ \frac{dV_{th}}{dT} = \left( 1 + \frac{\gamma}{2\sqrt{V_{\text{inv}}}} \right) \cdot \frac{dV_{\text{inv}}}{dT} \]

with \[ \frac{dV_{\text{inv}}}{dT} = -2.3 \ldots -1.7 \ \text{mV/K} \]

The operating point shifts as the device heats up.
The forward voltage $V_D$ of a silicon pn–diode follows a similar law as the threshold voltage of a MOSFET: \[
\frac{dV_D}{dT} \approx -1.7 \text{ mV/K}
\]

**Compensation principle:**

- one pn–diode is placed far away from the MOSFET (approximately ambient temperature)
- one pn–diode is placed close to the MOSFET (approximately junction temperature)
- The difference between the forward voltages is amplified and added to the selected gate bias voltage by a differential amplifier with common mode offset input of type AD8137
Sensor diode is placed next to the MOSFET, not on top because diode picks up electromagnetic field radiated by the MOSFET.
Gate Bias Circuit
Temperature Compensation

\[ V'_{\text{Bias}} = V_{\text{Bias}} + \frac{R_5}{R_3} \cdot (V_{D1} - V_{D2}) \]

**Common-mode offset**

**Differential amplifier with feedback potentiometers**

**Temperature sensing diode**

**Reference diode**

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The feedback potentiometers around the differential amplifier must be set to the same value for the common mode offset to work properly.

A procedure for adjusting the feedback resistors for optimum temperature compensation has been developed.

The quiescent drain current is held constant to within about 10 mA.

Problem: In an enclosure the reference diode will eventually heat up, too.
Pulsed operation: amplifier does not need to be in its operating point when no pulse is present at the RF input.

Power dissipated in the MOSFET can be reduced by switching $V_{GS}$ to 0 V between the pulses.
- Power amplifier needs stable drain–source voltage, especially during the RF pulses
- Little current flowing into the drain between the pulses
- Significant current flowing into the drain during the pulses
  - Large transients
  - Power supply regulator is under stress
  - Power line inductance hinders transients
  - Power supply might not be able to provide the required drain current

→ **Solution:** charging capacitors and discrete voltage regulator close to the amplifier
Static line regulation: dependence of the output of a regulator on the input in the static case.

- Slope 0.4, i.e. line regulation ca. 4 dB
- Slope 1
- Regulation threshold
Load regulation: dependence of the output of a regulator on the load

\[ \Delta V \approx 66 \text{ mV}, \text{ i.e. load regulation ca. } 28.7 \text{ dB} \]
- Necessity to measure the output power of the amplifier during operation
- Difficult because of high frequency and large dynamic range
- Solution: AD8307 logarithmic amplifier
  - converts RF voltage to d.c. voltage (envelope)
  - outputs a voltage that is proportional to the logarithm of the input voltage
- Theoretically output power can be measured with a multimeter this way
Output voltage of the driver amplifier needs to be reduced to within the input range of the AD8307 with a probe circuit.

- Probe resistor with frequency compensation
- a.c. coupling
- 50 Ω termination

Input equivalent circuit of the AD8307
Low frequency roll-off suppresses LF hum and d.c. offset

High frequency roll-off attenuates HF noise and harmonics
Power Monitor
Pulsed Operation

RF in:

Gate ON:

RF out:

Logarithm of pulse output power

AD8307 out:

Logarithm of noise power

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- Consequence for measurement of output power:
  - Analog multimeter: approx. measures average power
  - Oscilloscope: measures pulse and noise power
  - Digital multimeter: does not allow any sensible measurement

- Solution: Sample–and–hold circuit based on an LF398 that holds the output voltage of the AD8307 between the pulses

- S/H circuit can be controlled by “Gate ON” voltage because it is supposed to be high only during the RF pulses
Power Monitor
Complete Circuit

S/H Circuit

Probe

Logarithmic amplifier IC

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- Relationship between d.c. output voltage and output power must be established

→ Calibration against a reference power meter
Linear law between d.c. output voltage and power in dBm:

\[ P_{\text{Pulse}} = \left( 39.73 \frac{V_{\text{Pulse}}}{V} - 54.79 \right) \text{dBm} \]
Assembly
Circuit Board Layout

Voltage Regulator
Power Amplifier
Gate Bias
Power Monitor
Good source–ground connection (low resistance, low inductance) and low thermal resistance is important

Glue–on mounting on a self–built brass heatsink
Assembly
Power MOSFET Mounting

- Soldered Connection
- Top Ground Plane
- Substrate
- Lower Ground Plane
- Brass Heatsink
- Electrically Conductive Epoxy
- Electrically Conductive Silver
- Current Path

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Assembly

Housing
Assembly
Additional Circuitry

- Signaling LEDs
- Inverter for the Gate ON voltage
- Polarity protection
- Placed on a perfboard underneath the lid of the box
Conclusion

- Complete, conveniently usable amplifier for amplification from 100 mW to 10 W
- Amplification and maximum output power higher than expected
- Relatively poor distortion figures
- Concepts for use in driver and high power amplifier have been tested and proven functional and useful
  - Operating point flexibility
  - Temperature compensation
  - Gate shutdown
  - Power Monitor
Thank you for your interest!