RF Amplifier Design

Alex D. Santiago-Vargas, MSECE
Prof. Dimitrios Peroulis, Ph.D.
Purdue University

November 25, 2025

Outline

Introduction: Where are active circuits used?

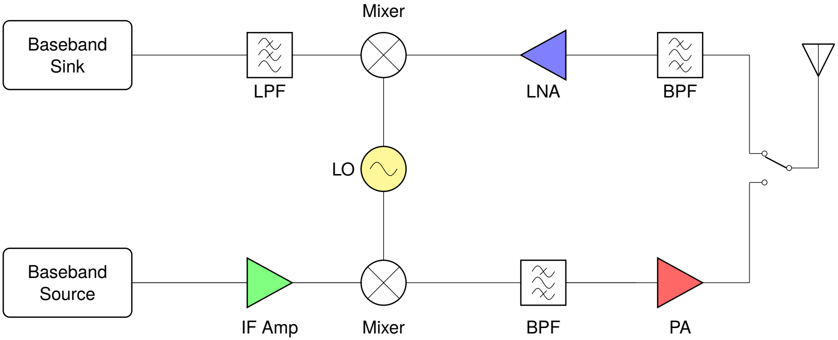


Figure 1: Heterodyne radio highlighting common active components

Introduction: Design Space

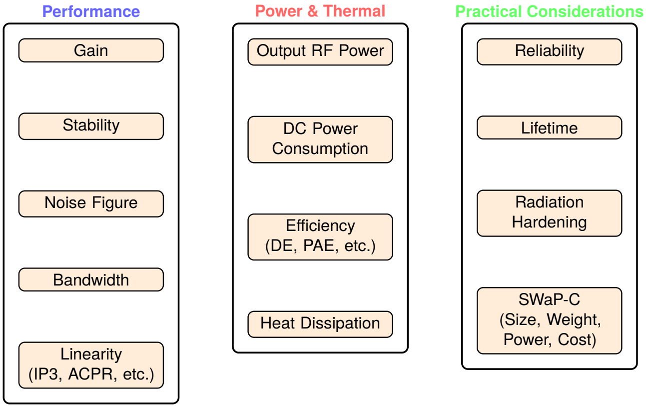


Figure 2: Active Microwave Circuits Design Space

Amplifier circuit excluding DC supply and bias

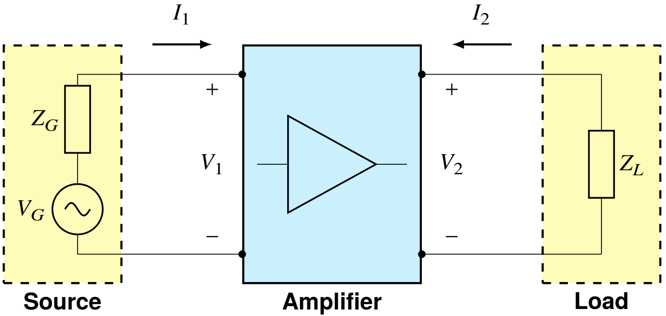


Figure 3: Amplifier circuit excluding DC supply and bias

Generic Amplifier Topology

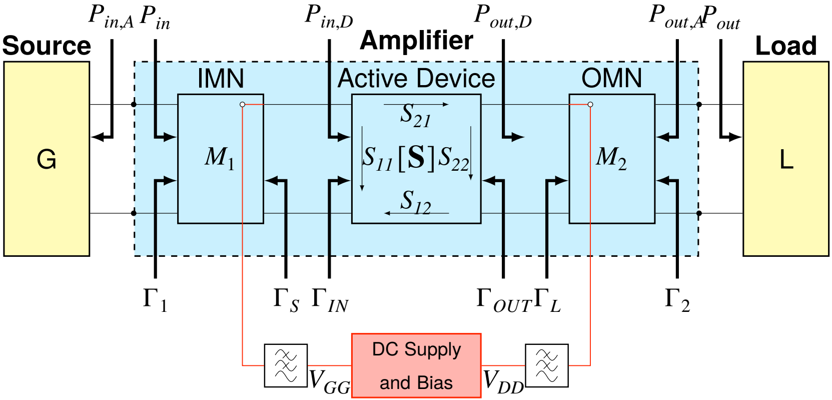


Figure 4: Generic Topology

Power Definitions

Table 1: Power parameters used in gain definitions

Power	Description
$P_{in,A}$	Available input power from the source. $P_{in} \leq P_{in,A}$.
P_{in}	Actual input power delivered to the amplifier.
$P_{in,D}$	Actual input power delivered to the device. $P_{in,D} \leq P_{in}$.
$P_{out,D}$	Available device output power of the device.
$P_{out,A}$	Available amplifier output power. $P_{out,A} \leq P_{out,D}$.
P_{out}	Actual output power delivered to load. Amplifier output power. $P_{out} \leq P_{out,A}$.

Reflection Coefficients for Two-Port Networks

Recall the input and output reflection coefficients Eqs. (1a) and (1b) of a device are calculated from the device S matrix along with the source and load (Γ_S and Γ_L).

$$\Gamma_{IN} = S_{11} + \frac{S_{21}S_{12}\Gamma_L}{1 - S_{22}\Gamma_L} \tag{1a}$$

$$\Gamma_{OUT} = S_{22} + \frac{S_{21}S_{12}\Gamma_S}{1 - S_{11}\Gamma_S} \tag{1b}$$

Power Gain

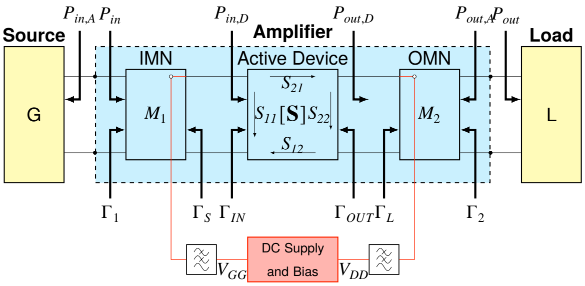
System: $$G = \frac{P_L}{P_{in}} = |S_{21}|^2 \frac{\left(1 - |\Gamma_L|^2\right)}{\left(1 - |\Gamma_{IN}|^2\right) |1 - S_{22}\Gamma_L|^2} \qquad \text{(2a)}$$

Transducer: $$G_T = \frac{P_L}{P_{in,A}} = |S_{21}|^2 \frac{\left(1 - |\Gamma_S|^2\right)\left(1 - |\Gamma_L|^2\right)}{|1 - \Gamma_{IN}\Gamma_S|^2 |1 - S_{22}\Gamma_L|^2} \qquad \text{(2b)}$$

Power: $$G_P = \frac{P_L}{P_{in,D}} = |S_{21}|^2 \frac{1 - |\Gamma_L|^2}{|1 - S_{22}\Gamma_L|^2 \left(1 - |\Gamma_{IN}|^2\right)} \qquad \text{(2c)}$$

Available: $$G_A = \frac{P_{out,A}}{P_{in,A}} = |S_{21}|^2 \frac{1 - |\Gamma_S|^2}{|1 - S_{11}\Gamma_S|^2 \left(1 - |\Gamma_{OUT}|^2\right)} \qquad \text{(2d)}$$

Why is matching needed?



$$G_T = |S_{21}|^2 \frac{\left(1 - |\Gamma_L|^2\right)}{\left(1 - |\Gamma_{IN}|^2\right) |1 - S_{22}\Gamma_L|^2}$$

$$\Gamma_S = \Gamma_L = 0 \Longrightarrow G_T = |S_{21}|^2$$

Mismatch Loss

- The source mismatch factor quantize the portion of the available power that is delivered to the device at the input.

$$M_S = \frac{P_{in,D}}{P_{in,A}} = \frac{\left(1 - |\Gamma_S|^2\right)\left(1 - |\Gamma_{IN}|^2\right)}{|1 - \Gamma_{IN}\Gamma_S|^2} \quad (3)$$

- The load mismatch factor quantize the portion of the device available output power that is delivered to the load.

$$M_L = \frac{P_L}{P_{out,A}} = \frac{\left(1 - |\Gamma_L|^2\right)\left(1 - |\Gamma_{OUT}|^2\right)}{|1 - \Gamma_{OUT}\Gamma_L|^2} \quad (4)$$

- If $\Gamma_{IN} = \Gamma_S^* \Rightarrow M_S = 1$. If $\Gamma_{OUT} = \Gamma_L^* \Rightarrow M_L = 1$.

Unifying power gains

Recall: $G_T = \frac{P_L}{P_{in,A}}, \quad G_P = \frac{P_L}{P_{in,D}}, \quad G_A = \frac{P_{out,A}}{P_{in,A}}$

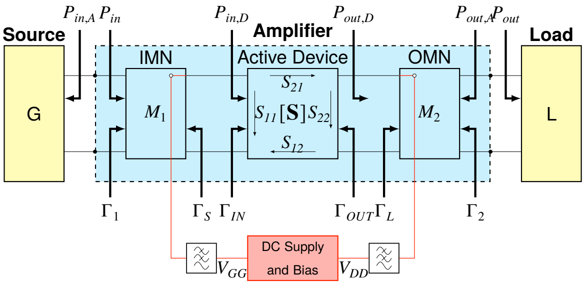
The transducer gain can be represented in terms of the power and available gain using the source and load mismatch losses.

$$G_T = \frac{P_{in,D}}{P_{in,A}} \frac{P_L}{P_{in,D}} = M_S G_P \tag{5}$$

$$G_T = \frac{P_{out,A}}{P_{in,A}} \frac{P_L}{P_{out,A}} = G_A M_L \tag{6}$$

Example on Power Gain

Calculate G_T, G_P, G_A, M_S, M_L with the following [1]:



$$\Gamma_S = 0.5\angle 120°,\quad \Gamma_L = 0.4\angle 90°$$

$$S = \begin{bmatrix} 0.6\angle -160° & 0.045\angle 16° \\ 2.5\angle 30° & 0.5\angle -90° \end{bmatrix}$$

Example on Power Gain

$$\Gamma_{IN} = S_{11} + \frac{S_{21}S_{12}\Gamma_L}{1 - S_{22}\Gamma_L}$$

$$= 0.6\angle -160^\circ + \frac{(2.5\angle 30^\circ)(0.045\angle 16^\circ)(0.4\angle 90^\circ)}{1 - (0.5\angle -90^\circ)(0.4\angle 90^\circ)}$$

$$= 0.627\angle -164.6^\circ$$

$$\Gamma_{OUT} = S_{22} + \frac{S_{21}S_{12}\Gamma_S}{1 - S_{11}\Gamma_S}$$

$$= 0.4\angle 90^\circ + \frac{(2.5\angle 30^\circ)(0.045\angle 16^\circ)(0.5\angle 120^\circ)}{1 - (0.6\angle -160^\circ)(0.5\angle 120^\circ)}$$

$$= 0.471\angle -97.63^\circ$$

Example on Power Gain

$$G_T = |S_{21}|^2 \frac{\left(1 - |\Gamma_L|^2\right)}{\left(1 - |\Gamma_{IN}|^2\right)|1 - S_{22}\Gamma_L|^2} = 9.43 = 9.75 \text{ dB}$$

$$G_P = |S_{21}|^2 \frac{1 - |\Gamma_L|^2}{|1 - S_{22}\Gamma_L|^2 \left(1 - |\Gamma_{IN}|^2\right)} = 13.51 = 11.31 \text{ dB}$$

$$G_A = |S_{21}|^2 \frac{1 - |\Gamma_S|^2}{|1 - S_{11}\Gamma_S|^2 \left(1 - |\Gamma_{OUT}|^2\right)} = 9.55 = 9.8 \text{ dB}$$

Example on Power Gain

$$M_S = \frac{\left(1 - |\Gamma_S|^2\right)\left(1 - |\Gamma_{IN}|^2\right)}{|1 - \Gamma_{IN}\Gamma_S|^2} = 0.6983 = -1.56 \text{ dB}$$

$$M_L = \frac{\left(1 - |\Gamma_L|^2\right)\left(1 - |\Gamma_{OUT}|^2\right)}{|1 - \Gamma_{OUT}\Gamma_L|^2} = 0.9874 = -0.055 \text{ dB}$$

Comparing the power gains, $G_T = 9.75$ dB, $G_P = 11.31$ dB, $G_A = 9.8$ dB. This shows that the input matching is not optimal but can provide an extra 1.5 dB of gain.

Example on Power Gain

Given a source with 0.25 W (24 dBm) of available power
The device input power:

$$P_{in,D} = P_{in,A}M_S = 24 \text{ dBm} - 1.56 \text{ dB} = 22.44 \text{ dBm}$$

The power delivered to the load:

$$P_L = G_T P_{in,A} = 9.75 \text{ dB} + 24 \text{ dBm} = 33.75 \text{ dBm}$$

The rest of the powers can be calculated similarly, using the input power, power gains, and mismatch losses.

Unilateral Transducer Gain

Unilateral device: $S_{12} = 0$.

$$G_{TU} = \left(\frac{1-|\Gamma_S|^2}{|1-\Gamma_S S_{11}|^2}\right)|S_{21}|^2\left(\frac{1-|\Gamma_L|^2}{|1-\Gamma_L S_{22}|^2}\right) = G_S G_o G_L \qquad (9)$$

Which can be decomposed into:

$$G_S = \frac{1-|\Gamma_S|^2}{|1-\Gamma_S S_{11}|^2} \qquad (10a)$$

$$G_o = |S_{21}|^2 \qquad (10b)$$

$$G_L = \frac{1-|\Gamma_L|^2}{|1-\Gamma_L S_{22}|^2} \qquad (10c)$$

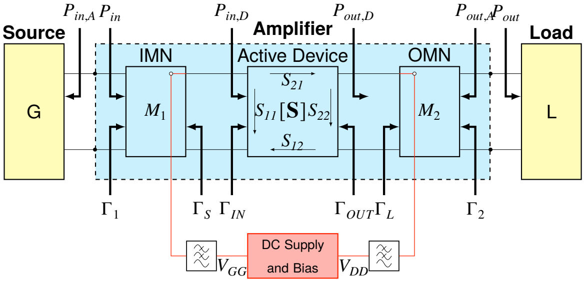
Maximum Unilateral Transducer Gain

A unilateral device can be simply conjugately matched by $\Gamma_S = S_{11}^*$ and $\Gamma_L = S_{22}^*$. In this case, the max unilateral transducer gain is

$$G_{TU,max} = |S_{21}|^2 \left(\frac{1}{1-|S_{11}|^2}\right)\left(\frac{1}{1-|S_{22}|^2}\right) \tag{11}$$

If the approximation is good enough, this can be a great figure of merit to compare devices as it is only dependent on the S parameters.

Conditions for Stability



Potentially unstable if:

$$|\Gamma_S \Gamma_{IN}| > 1 \tag{12a}$$

$$|\Gamma_L \Gamma_{OUT}| > 1 \tag{12b}$$

Conditions for Stability

Assumption: $|\Gamma_S| \leq 1$ and $|\Gamma_L| \leq 1$
In this case, stability can be ensured if

$$|\Gamma_S \Gamma_{IN}| = \left| \Gamma_S S_{11} + \frac{S_{21} S_{12} \Gamma_S \Gamma_L}{1 - S_{22} \Gamma_L} \right| < 1 \tag{13a}$$

$$|\Gamma_L \Gamma_{OUT}| = \left| \Gamma_L S_{22} + \frac{S_{21} S_{12} \Gamma_S \Gamma_L}{1 - S_{11} \Gamma_S} \right| < 1 \tag{13b}$$

for all $|\Gamma_S| \leq 1$ and $|\Gamma_L| \leq 1$.
The equations can be solved for Γ_S and Γ_L taking the form of the equation for a circle $|\Gamma - c| = |r|$.

Input Stability Circles

$$\left|\Gamma_S - \frac{\left(S_{11} - \Delta S_{22}^*\right)^*}{|S_{11}|^2 - |\Delta|^2}\right| = \left|\frac{S_{12}S_{21}}{|S_{11}|^2 - |\Delta|^2}\right| \qquad (14)$$

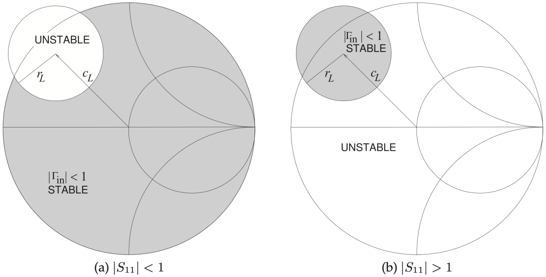


Figure 5: Input Stability Circles

Output Stability Circles

$$\left|\Gamma_L - \frac{\left(S_{22} - \Delta S_{11}^*\right)^*}{|S_{22}|^2 - |\Delta|^2}\right| = \left|\frac{S_{12}S_{21}}{|S_{22}|^2 - |\Delta|^2}\right| \tag{15}$$

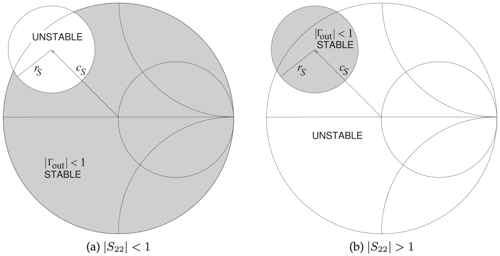


Figure 6: Output Stability Circles

Rollet's Stability Factor

$$k = \frac{1 - |S_{11}|^2 - |S_{22}|^2 + |\Delta|^2}{2|S_{12}||S_{21}|} > 1. \quad (16)$$

$$|\Delta| = |S_{11}S_{22} - S_{21}S_{12}| < 1 \quad (17)$$

.

Note this criteria is only valid within the assumption of $\Gamma_{IN} \leq 1$ and $\Gamma_{OUT} \leq 1$.

Edwards-Sinsky Stability Factor

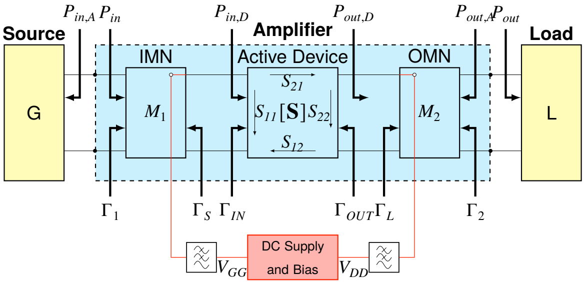
μ and μ' measure the input and output stability, respectively.

$$\mu = \frac{1 - |S_{11}|^2}{|S_{22} - S_{11}^* \Delta| + |S_{12}S_{21}|} > 1 \tag{18a}$$

$$\mu' = \frac{1 - |S_{22}|^2}{|S_{11} - S_{22}^* \Delta| + |S_{12}S_{21}|} > 1 \tag{18b}$$

Note this criteria is only valid within the assumption of $\Gamma_{IN} \leq 1$ and $\Gamma_{OUT} \leq 1$.

Example on Stability



$$S = \begin{bmatrix} 0.65\angle -95^\circ & 0.035\angle 40^\circ \\ 5\angle 115^\circ & 0.8\angle -35^\circ \end{bmatrix}$$

Example on Stability

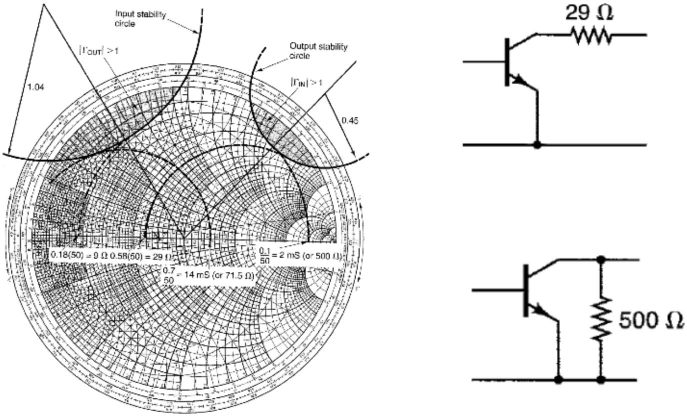
$$k = \frac{1 - |S_{11}|^2 - |S_{22}|^2 + |\Delta|^2}{2|S_{12}||S_{21}|} = 0.547$$

$$|\Delta| = |S_{11}S_{22} - S_{21}S_{12}| = 0.504$$

$$c_S = 1.79\angle 122^\circ, \quad r_S = 1.04$$

$$c_L = 1.3\angle 48^\circ, \quad r_L = 0.45$$

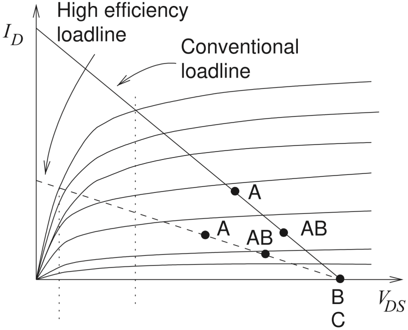
Example on Stability



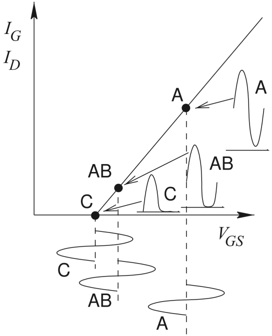
(a) Stability circles (b) Stabilization circuits

Figure 7: Example

Transistor Biasing



(a) Output transfer



(b) Input transfer

Figure 8: Current-Voltage (I-V) characteristics of a transistor.

Conduction Mode Classes of Operation

Class	Description	Conduction Angle
A	Full cycle conduction	$\theta = 360^\circ$
AB	More than half-cycle conduction	$180^\circ < \theta < 360^\circ$
B	Half cycle conduction	$\theta = 180^\circ$
C	Less than half cycle conduction	$\theta < 180^\circ$

Table 2: Conduction mode classes of operation

Efficiency

$$\eta_D = \frac{P_{RF,out}}{P_{DC}} \tag{19}$$

$$\eta_{PAE} = \frac{P_{RF,out} - P_{RF,in}}{P_{DC}} \tag{20}$$

Table 3: Efficiency in relation to gain for ideal (Class-A) linear amplifier.

Gain (dB)	η_D	η_{PAE}	η_{total}
3	40%	25%	50%
6	44%	37%	50%
10	48%	45%	50%
15	49%	48%	50%
20	50%	50%	50%

Power Amplifier Examples

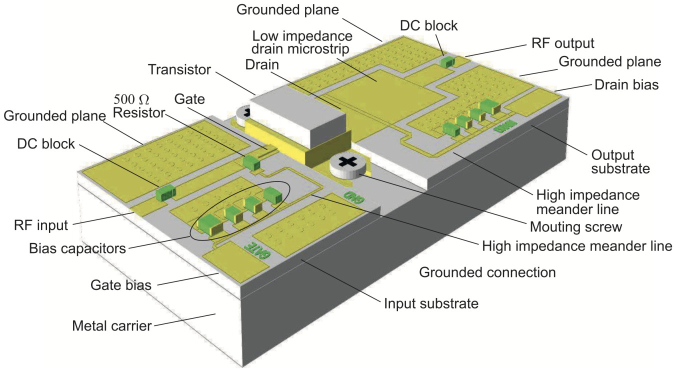
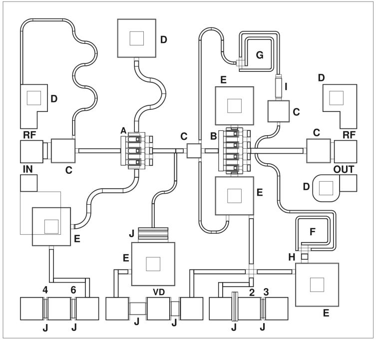
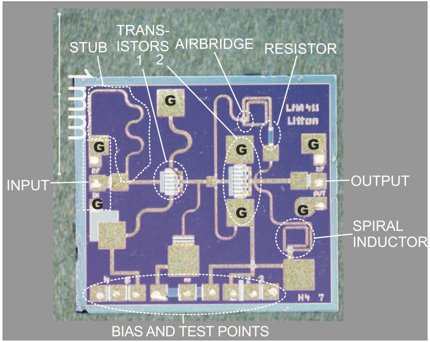


Figure 9: WiMax power amplifier for 3.4 GHz to 3.8 GHz. Taken from [2].

Power Amplifier Examples



(a) Layout



(b) Micrograph

Figure 10: X-Band (8 - 12 GHz) MMIC power amplifier. Taken from [2].

Power Amplifier Examples

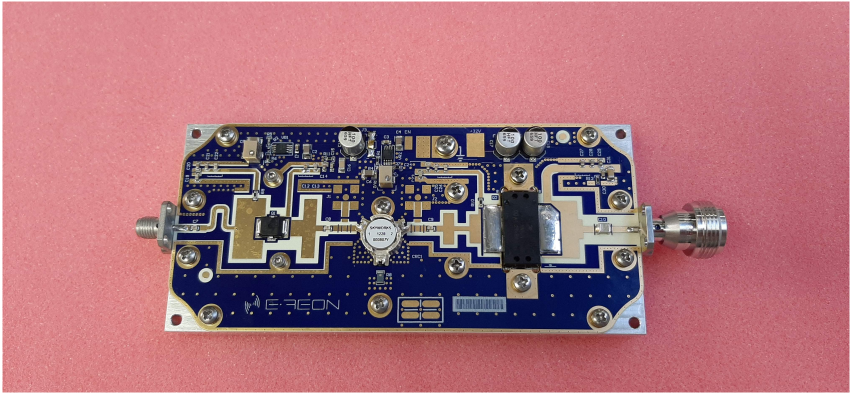


Figure 11: E-REON PowerBlast 300: 2.45 GHz ISM 250 W LDMOS amplifier with 33 dB gain and 60% efficiency [3].

Power Amplifier Examples

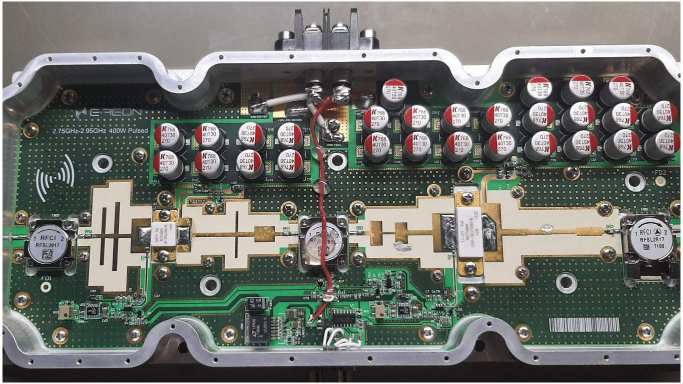


Figure 12: E-REON 2.856 GHz 400 W solid state power amplifier unit used as to drive a Klystron tube in a medical MRI [3].

References I

[1] G. Gonzalez, *Microwave transistor amplifiers: analysis and design*. Prentice hall New Jersey, 1997, vol. 2.

[2] M. Steer, *Microwave and RF Design*. NC State University: Raleigh, NC, USA, 2019.

[3] e-Reon.com, “e-reon — connecting engineers worldwide,” https://www.e-reon.com, 2025.

Thank you!