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TTT4212 RF/Microwave Design and Measurement Techniques

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Abstract

This report describes the process of designing, building and verifying an RF power amplifier for the 2.4 GHz±50MHz frequency band. The Cree CGH40010F GaN transistor is used as the active device. The circuit is built on standard FR-4 substrate. The circuit is designed and simulated in the Keysight ADS software suite, then built and measured using standard RF measurement instruments such as a network analyzer and spectrum analyzer.

The resulting amplifier was measured to have a small-signal gain of 14dB at the center frequency of 2.4 GHz, however, the gain diminished rapidly towards the lower end of the operating band at 2.35 GHz. Also the large-signal power gain and power added efficiency showed poorer performance at the lower end of the operating band. At 2.4 GHz, the large-signal gain with an input signal of 27dBm was measured to 10dB with a power-added efficiency of 35% . Third-order intermodulation distortion was measured to -22dBc at a peak output power of 38dBm with a two-tone input signal with 5Mhz spacing.

Contents

1. Introduction

In the course TTT4212 RF/Microwave design and measurement techniques at NTNU, the students are given the task of designing, building and verifying the performance parameters of an RF power amplifier. The amplifier should fulfill the following requirements and design restrictions:

- Center operating frequency of 2.4 GHz
- Based on the Cree CGH40010F GaN transistor
- Drain voltage biased at 28V
- Gate voltage biased at -3.0V or higher
- The amplifier should be unconditionally stable
- Small-signal bandwidth of at least 100 Mhz
- Small-signal gain of at least 13dB throughout the bandwidth
- Output power of at least 39dBm with a single-tone input power of 27dBm
- Some geometrical restrictions for the board layout are given to make the amplifier fit on a standardized heatsink, to avoid the added time, cost and complications of manufacturing customized heatsinks for each group of students.

The power added efficiency (with a single-tone input signal at 27dBm) and intermodulation distortion (for a two-tone signal with 5 Mhz spacing and a peak output power of 38 dBm) should also be measured, however, no requirements for these performance parameters are given, and it will be up to the group members' to decide which parameters to focus on optimizing (as long as the requirement specification is fulfilled.

The circuit shall be designed and simulated in the Keysight Advanced Design System (ADS) software suite for computer-aided design (CAD) and simulation of microwave circuits, and all performance parameters shall be verified to be within the requirement specification before proceeding to making a board layout (also in ADS), generating the Gerber production files for having the printed circuit board manufactured, and then building the amplifier and doing real world measurements at the lab.

2. Theory

2.1. Bias point and class of operation

The bias point, or working point, of an amplifier determines which class the amplifier is operating within, which in turn tells us something about the amplifiers efficiency, linearity and quiescent current. There is a wide variety of classes, the most common being class A, AB, B and C. Class A amplifiers have the highest quiescent current, the best linearity and the lowest efficiency (maximum theoretical efficiency of 50%). Class B amplifiers have no quiescent current, maximum theoretical efficiency of 78% , but will only conduct during the positive half of the signal cycle. Class AB is a hybrid between class A and B, sacrificing some of the efficiency of the class B amplifier, but gaining some of the linearity of the class A. Class C amplifiers are the most efficient of the four, having a maximum theoretical efficiency of almost 90% . But they conduct for less than 50% of the signal cycle, typically they only conduct for a third of the cycle or less. If the input signal does not exceed a certain level, one can bias the amplifier as an AB class, thus reducing quiescent current while still have class A operation in terms of linearity.

Once the amplifier class of operation has been determined, the bias point can be determined by examining the I-V characteristics of the transistor. By drawing a load line going from the drain-source voltage on the X axis, to the drain saturation current on the Y axis, we get a linear line crossing the different gate-source voltage curves. See figure 2.1. By choosing a bias point along this linear curve, we can predict both quiescent current and voltage. The bias point for a class A amplifier will approximately be at Vds/2.

2.2. Efficiency

There are several ways of expressing amplifier efficiency, the most common in the RF community being power added efficiency (PAE). PAE takes into account both the DC to RF power conversion, as well as the RF power delivered into the input of the device.

$$PAE = \frac{P_{RFout} - P_{RFin}}{P_{DC}} = \frac{P_{RFout} - P_{RFin}}{V_{DC} \times I_{DC}} \tag{2.1}$$

By subtracting the power of the input signal from the output power, we get a better indication of the actual DC to RF power conversion. For low gain amplifiers the input power can be substantial and using drain efficiency (which does not take input power into consideration), will in these cases give a falsely high efficiency.

2.3. Linearity

Linearity is an important factor to consider when designing an amplifier. A linear amplifier will amplify a small input signal and a large input signal by the same amount, meaning less distortioin of high power signals will be exhibited. To better see the linearity of a transistor one can plot the drain current as a function of the gate-source voltage. This will produce a characteristic plot which shows how linear the transistor is for certain regions of the input signal. The linearity of an amplifier is found by sweeping the input power and recording the corresponding output powers, as shown in figure B.1 in the appendix.

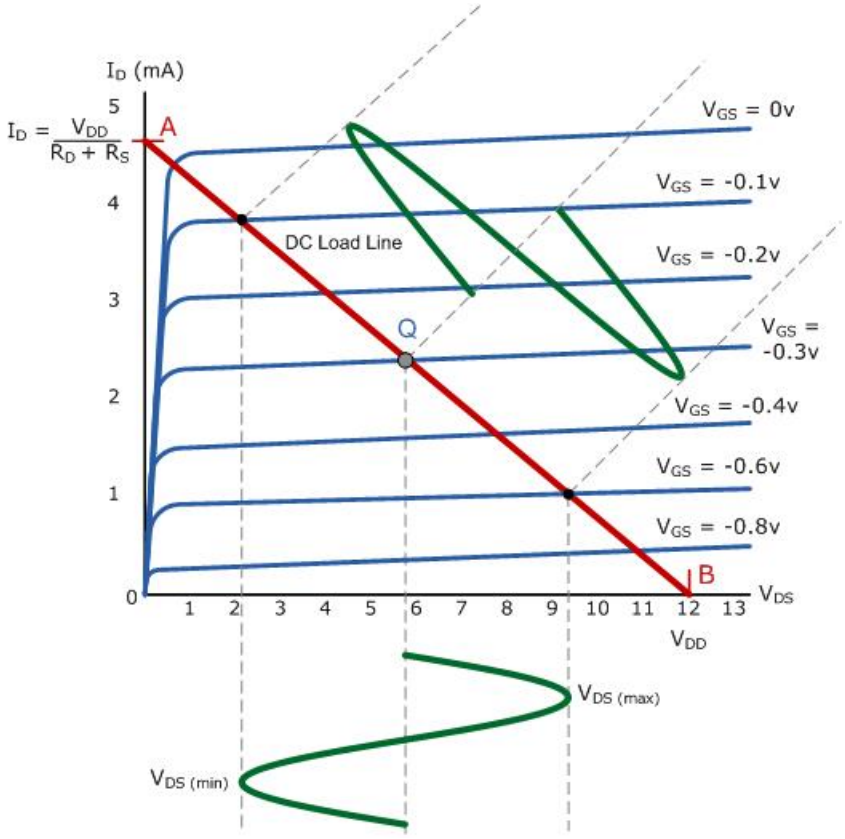

Figure 2.1.: Load line for class A amplifier

2.4. S-parameters

S-parameters, or scattering parameters, are a set of parameters which describe the reflection and transmission coefficients of each of the ports of a device. When referring to a two-port device such as an amplifier we use the parameters S_{11}, S_{12}, S_{21} and S_{22}.

S_{11} refers to the part of an incident wave in a_1, being reflected to the source through b_1, S_{12} refers to the reverse voltage gain, S_{21} refers to the forward voltage gain and S_{22} refers to the part of an incident wave being fed into a_2 being reflected back towards b_2. The relationship between incident power, reflected power and the S-parameter matrix is given by the equation:

$$\begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \times \begin{bmatrix} a_1 \\ a_2 \end{bmatrix} \tag{2.2}$$

2.5. Stability

Amplifier stability refers to the amplifiers tendency to oscillate, which is something we strive to prevent. Oscillations may occur when the reflected wave is larger than the incident wave.

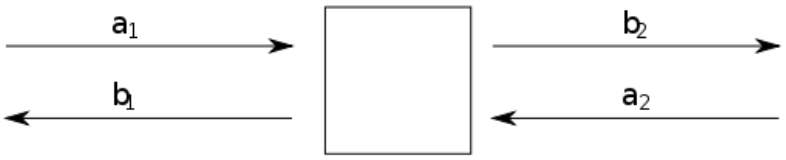

Figure 2.2.: two-port signals for s-parameters

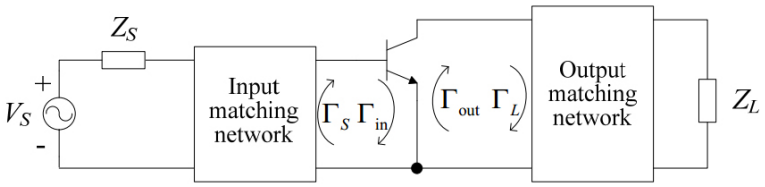

Figure 2.3.: reflections of an amplifiers circuit

In figure 2.3 the Γ values represent the reflection coefficients for each of the ports they are associated with. If the input and output matching networks are passive, then $|\Gamma_s| < 1$ and $|\Gamma_L| < 1$. The circuit can be unstable if $|\Gamma_{in}| > 1$ and $|\Gamma_{out}| > 1$.

By expressing $|\Gamma_{in}|$ and $|\Gamma_{out}|$ as functions of Γ_L and Γ_s respectively, in combination with the S-parameters, we can find an expression for a circle in the smith chart which represents the border between the region of stability and instability at input and output. These are called stability circles, and can tell us at what impedances the device is stable, or unstable.

There are two main measures of stability, the K-factor and the μ-factors. The K-factor tells us whether or not the amplifier is stable for a specific frequency, which means we need to evaluate the K-factor from 0Hz (DC) to the highest frequency the amplifier can oscillate at.

$$K = \frac{1 - |S_{11}|^2 - |S_{22}|^2 + |\nabla|^2}{2 \times |S_{21} \times S_{12}|}, \nabla = S_{11} \times S_{22} - S_{12} \times S_{21} \tag{2.3}$$

If $K > 1$ the amplifier is stable for the specific frequency. If $K > 1$ for all frequencies we say the amplifier is unconditionally stable, and if $K < 1$ for only certain frequencies, we say the amplifier is conditionally stable. The K-factor tells us if the amplifier is stable, but not by how much. A larger value of K does not indicate a more stable amplifier. When designing an amplifier it is useful to know how stable our device is, so we can take variations in the manufacturing process into consideration. For this purpose we use the μ-factors:

$$\mu = \frac{1 - |S_{11}|^2}{|S_{22} - \delta \times S_{11}^*| + |S_{12} \times S_{21}|} > 1 \tag{2.4}$$

$$\mu_{\text{prime}} = \frac{1 - |S_{22}|^2}{|S_{11} - \delta \times S_{22}^*| + |S_{12} \times S_{21}|} > 1 \tag{2.5}$$

The μ-factors tell us the distance from the center of the smith chart, to the edge of the stability circle. μ shows this distance for the output, while mu_{prime} shows the same for the input. If the

value of the factor is above 1 the device is unconditionally stable for the given frequency, and the larger the values of the factors are the more stable a device is. This way we can add some margin to our amplifier's stability, to ensure it will remain stable even with the possible variations of real components.

2.6. Quarter-wave transformer

When the wavelength of a signal is comparable to the circuit size, it is possible to manipulate the phase of the circuit's impedance by adjusting the length of the PCB traces. Adding a quarter wavelength of PCB traces equals to a 180° impedance shift in the smith chart. Such a piece of trace is called a quarter-wave transformer, as it allows to convert an open end of a microstrip trace to a short circuit to ground and vice versa. Adding two quarter-wave transformers in series transforms back to the original impedance.

2.7. Matching

To affect stability, performance and efficiency matching networks are created at the amplifier input and output to adjust the impedance "seen" by the source and load. See figure 2.3. For maximum power transfer, the output and input matching networks are matched to the characteristic impedance of the source and load, usually 50Ω for RF applications. For maximum gain or low noise the networks must be intentionally designed with mismatches compared to the characteristic impedances. By tweaking the networks matching, we can find a balance between the desired properties.

2.8. Small signal vs large signal

Small and large signal analysis is used to evaluate the amplifier design once a bias point has been chosen. When performing small signal analysis we use the chosen bias point, and look at the amplifiers response in the linear area of operation. Here we can assess the amplifiers gain, linearity and efficiency for signals well within the amplifiers capabilities. The output signal may then be described as:

$$v_{out} = a_0 + a_1 v_{in} \tag{2.6}$$

When looking at large signal analysis on the other hand we use large input signals to drive the amplifier, and a non-linearity is introduced. This non-linearity may be described as:

$$v_{out} = a_0 + a_1 v_{in} + a_2 v_{in}^2 + a_3 v_{in}^3 \dots \tag{2.7}$$

With a cosine signal on the input, the amplifiers gain may be described as:

$$G = a_1 - \frac{3}{4} a_3 |V_{in}|^2 \tag{2.8}$$

For a small v_{in}, it is shown that the gain is linear. But as v_{in} increases, the higher order output are increased enough to make decrease the output by a considerable amount. Thus we can find the 1 dB compression point, this is the v_{in} level at which the amplifiers gain is reduced by 1 dB because of the non-linearity. After this point, the gain will be decreased further.

2.9. Intermodulation distortion

Intermodulation distortion (IMD) is found when performing a two tone test on a non-linear device. Because of the same effects as shown in equation 2.7, the amplifier would create different harmonics. Since V_{in} consists of two signals of different frequencies, the output will consist of several summations and subtractions of the harmonics. See figure 2.4 for an example.

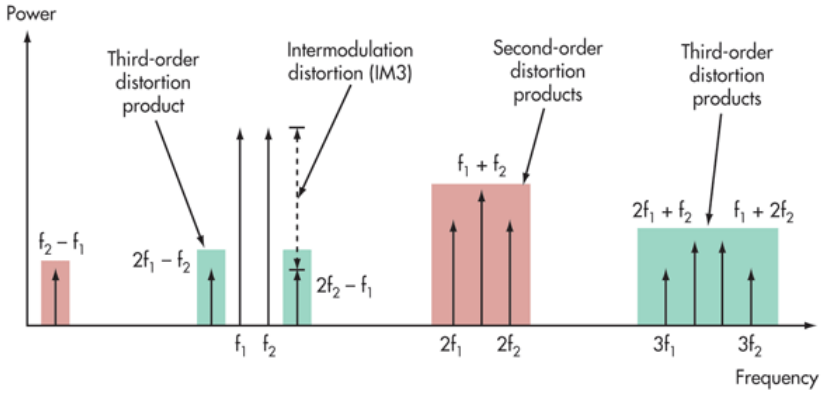

Figure 2.4.: Intermodulation distortion visualization

3. Method of design

In this chapter, the design procedure will be described, and the choices we made will be clarified. The test-measurements is then explained in detail. During the design process we will use the models given for inductors and capacitors. We will use ideal resistors from the libraries in ADS.

3.1. DC Bias point at gate

The first step in designing a power amplifier is to choose the DC bias point, which will define the amplifier's class of operation.We will be aiming for a deep AB class design because this gives a good compromise between gain, linearity and efficiency. This enables us to meet the required specifications as well as obtain good results with respect to the other performance parameters with no set requirements. We are using the ADS Design Guide called FET_IV_Gm_PowerCalcs, where we inserted the transistor as shown in figure 3.1. From the design guide we used the I/V-plot to find the gate bias voltage that gives the desired quiescent drain current of 300mA, which will be used as bias point as this will be low in the class AB range ($0 < Ids < Imax/2$). We may need to tweak the quiescent current when testing the real amplifier. The gate bias voltage that gives this quiescent current was found to be -2.6V.

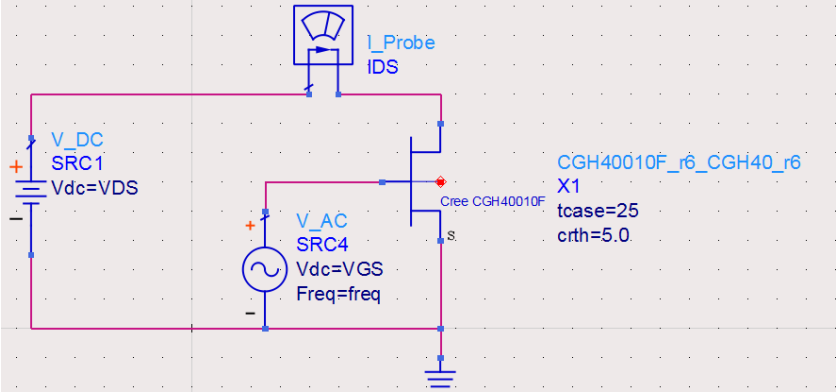

Figure 3.1.: Setup for bias-measurements

3.2. Bias network

To ensure that the RF input does not affect the DC power supply, a quarter-wave transformer was used to present an infinite impedance in the 2.4GHz band when looking towards the DC power supplies from the RF signal pathways. The values were tuned to obtain optimal ac-block as seen from the transistor gate. In addition, a bank of lumped capacitors were used to prevent noise from the DC power supplies from entering the RF signal pathway. The same DC bias network was used for both the gate and drain DC bias voltage connections.

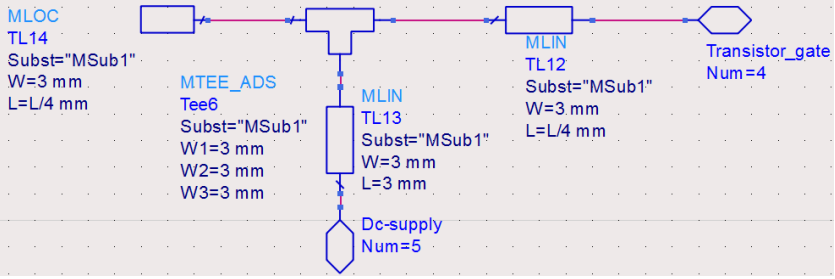

Figure 3.2.: Setup for bias-network

3.3. Stability

To check if the amplifier is stable, we used the small-signal S-parameter simulations in ADS with added blocks for measuring the stability factors (μ and μ_{prime}) on the input and output. According to the measurements, the amplifier is stable at higher frequencies, but at lower frequencies it is unstable. To remove the instabilities we will introduce losses at the lower frequencies, by adding a series RC element at the input, and a resistor at the DC bias feed point as shown in figure 3.3. The capacitor Kap4 and Resistor R3 presents a high impedance for lower frequencies,

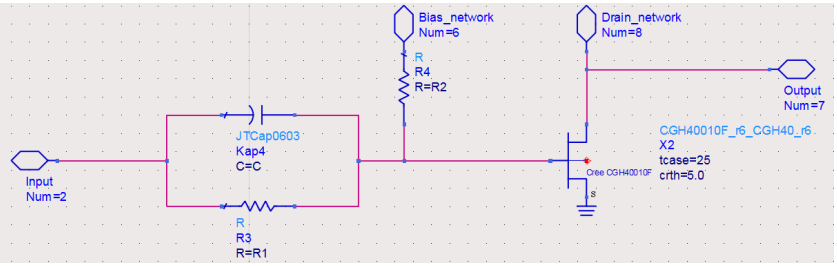

Figure 3.3.: Stability-network

but for higher the capacitor is an effective short. The resistor R4 is introduced as a loss for all frequencies.

The values C,R1 and R2 were found by using ADS' optimization feature, with optimization goals for the stability factors (μ and μ_{prime}) and the maximum available gain. The lowest value for the stability factors across the simulated frequency range from 0Hz to 6GHz was 1.05.

3.4. Matching

When stabilizing the amplifier, one of the goals for optimization was maximum available power. To achieve this power, one must match the input and output to 50 Ohm. To realise this without having to mount more components we designed a L-network consisting of an open circuit stub and a microstrip line as shown in figure 3.4. The setup was used both on the input and output of the amplifier, and optimized for max power within the band.

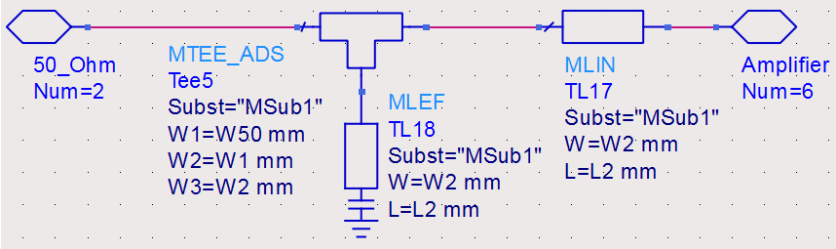

Figure 3.4.: Setup for matching the amplifier with 50Ω

3.5. Large signal simulation, one tone input signal

To run large signal simulation, a design guide called HB1TonePAE_Pswp was used. In the design guide we checked the power added efficiency, the interpolated output spectrum and fundamental output power. We saw that power added efficiency was low, so we ran an optimization with increased power added efficiency and output power with 27dBm input as goals.

3.6. Large signal simulation, two tone input signal

To run large signal simulation two tone, a design guide called HB2TonePAE_Pswp was used. In the design guide we checked the Power added efficiency, interpolated output spectrum and the output power with 27dBm as input.

3.7. Layout and conversion to real components

Now that the design is complete, all components that are related to the layout will be added. This is done to make sure that the layout will fit within the predefined board size and that there is as few as possible steep transitions between different widths of microstrip line. The transistor was placed in the center of the board for heat sink mounting. Bends were used on the microstrips to fit the geometrical restrictions. The final schematic is shown in figure A.1 and A.2. The resulting layout is shown in figure A.4.

3.8. Tests with complete layout

After all physical changes were done, the amplifier as a whole was simulated to make sure the requirements were still fulfilled. A few tweaks with respect to line geometry was needed to obtain similar responses but the design passed the requirements given by the task.

3.9. Laboratory measurements

The goal for the measurements is to determine if the amplifier (DUT) passes the requirements given by the task or not. To do this we need to perform a small signal gain test, one-tone large signal test and a two-tone large signal test.

3.9.1. Small-signal s-parameters

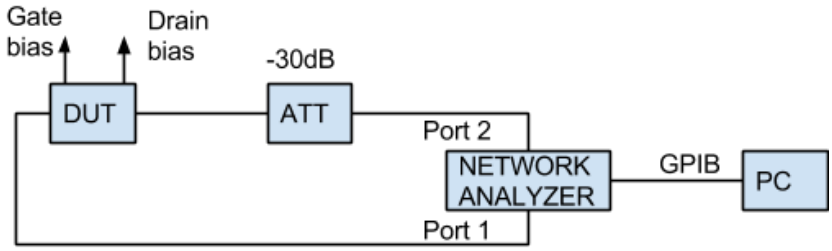

Figure 3.5.: Small-signal measurements setup

As shown in figure 3.5, an attenuator was connected to the output of the amplifier to protect the network analyzer ports from excessive input voltages that could damage the instrument. The network analyzer was calibrated using a TOLS (through-open-load-short) calibration sequence.

3.9.2. Large signal one- and two-tone

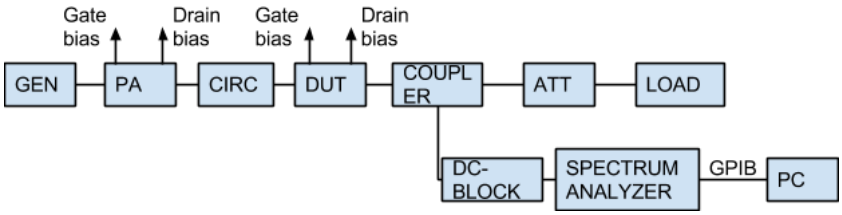

Figure 3.6.: Large-signal measurements setup

We were at liberty to choose three set frequencies to perform the large-signal testing at. We chose the frequencies 2.35 GHz, 2.40 GHz and 2.45 GHz, because testing at these frequencies would give us the best prerequisites for determining if we had met the requirement specifications within the band of operation. As shown in figure 3.6 there are several items that will introduce losses in the signal pathway, all of which must be subtracted from the measured power levels when analyzing the results in Matlab.

4. Results

4.1. Simulated results

This section lists the results from the simulation done in the Keysight Advanced Design System (ADS) software suite.

4.1.1. Transistor I-V curve

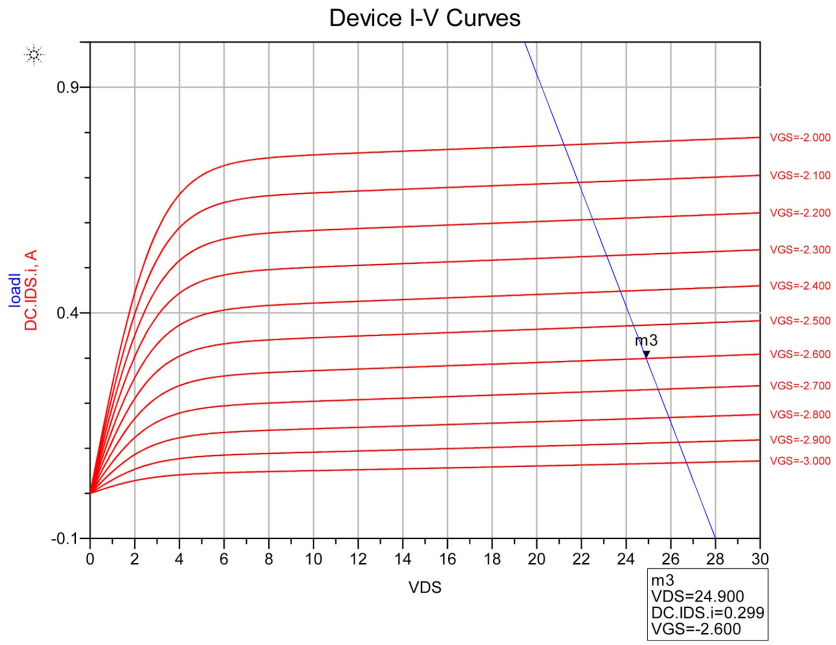

Figure 4.1.: Simulated drain current for different drain and gate bias voltages with a load-line

Note that the transistor model used is only valid for VDS voltages between 28 and 48 volts, meaning that the I-V-curves are at best approximate below 28 volts.

4.1.2. Stability simulations

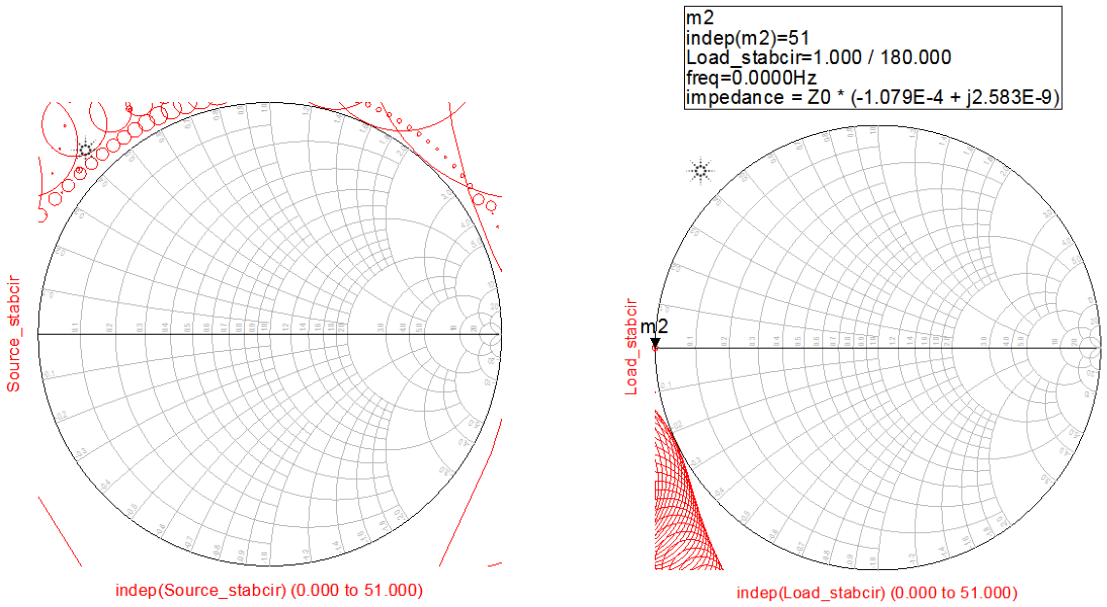

Figure 4.2.: Smith-chart representation of the stability circles for source (left) and load (right) for frequencies between 0Hz and 6GHz

4.1.3. Small-signal gain

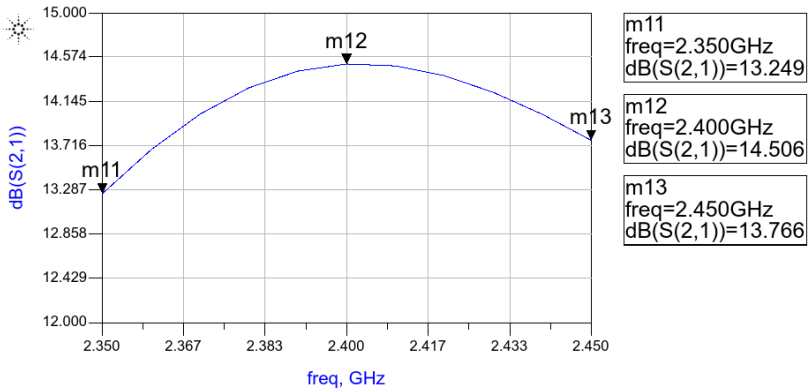

Figure 4.3.: Simulated small-signal gain within the band of operation

The small-signal gain (S_{21}) has a peak value of 14.506 dB at 2.4GHz, and a minimum value within the band of operations of 13.287 dB, giving a maximum variation of 1.257 dB within the 100MHz band of operation.

4.1.4. Large-signal gain

Frequency	Output power	gain
2.35 GHz	38.71dBm	11.71dB
2.40 GHz	39.26dBm	12.26dB
2.45 GHz	38.87dBm	11.87dB

Table 4.1.: Simulated output power with input power of 27dBm

4.1.5. Power added efficiency (PAE)

Frequency	PAE
2.35 GHz	40.30%
2.40 GHz	41.79%
2.45 GHz	42.59%

Table 4.2.: Simulated power added efficiency with output power of 38dBm

4.1.6. Third-order intermodulation distortion (TOIMD)

TOIMD high	-15.35dBc
TOIMD low	-15.62dBc

Table 4.3.: Simulated third-order intermodulation distortion with output power of 38dBm

4.2. Measured results

This section lists the results from the measurements done on the real circuit in the laboratory.

4.2.1. Small-signal gain

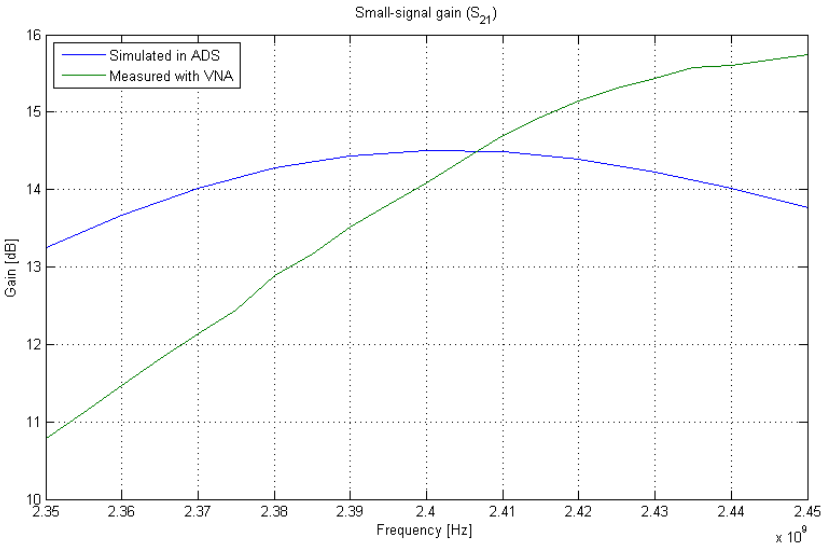

Figure 4.4.: Measured small-signal gain (green) compared to simulated small-signal gain (blue) within the band of operation

Minimum measured gain was 10.79dB at 2.35 GHz, while the maximum was measured to 15.74dB at 2.45 GHz. At the center frequency of 2.40 GHz the small-signal gain was 14.08dB

4.2.2. Large-signal gain

Frequency	Output power
2.35 GHz	34.73dBm
2.40 GHz	37.17dBm
2.45 GHz	38.37dBm

Table 4.4.: Measured power output with an input power of 27dBm

Power output for different input power levels is shown in figure B.1 in the appendix.

4.2.3. Power added efficiency (PAE)

Frequency	PAE
2.35 GHz	18.26%
2.40 GHz	35.02%
2.45 GHz	46.99%

Table 4.5.: Measured power added efficiency with output power of 38dBm

Power added efficiency for different power levels is shown in figure B.2 in the appendix.

4.2.4. Third-order intermodulation distortion

TOIMD high	-22.41dBc
TOIMD low	-22.45dBc

Table 4.6.: Measured third-order intermodulation distortion with output power of 38dBm

4.2.5. Summary of measured results

Parameter	2.35 GHz	2.40 GHz	2.45 GHz	Requirement
Small-signal gain	10.79dB	14.08dB	15.74dB	$> 13dB$
Output power with 27dBm input	34.73dBm	37.17dBm	38.37dBm	$> 39dBm$
Power added efficiency	18.26%	35.02%	46.99%	-
Third-order intermodulation distortion		high: -22.41dBc low: -22.45dBc		-

Table 4.7.: Summary of measured results

5. Discussion

5.1. Fulfillment of requirements

5.1.1. Stability

The amplifier was simulated to be unconditionally stable for all frequencies at all source and load impedances except for when the output was presented with a short-circuit to ground. In real life, it was only tested with a 50Ω termination on the input and a 50Ω dummy load, for which it proved not to oscillate at any frequency seen on the spectrum analyzer. No tendencies to start oscillating was seen when doing both small- and large-signal testing. To our best knowledge, the requirement of stability was fulfilled.

5.1.2. Small-signal gain and bandwidth

The simulated gain was within the requirement specification with a minimum value of 13.287dBm across the 100 MHz bandwidth. The measured gain was below the required minimum of 13dBm for the frequency range of 2.35 - 2.38 GHz, while it was above the 13dBm limit for the rest of the band of operation. This requirement was hence not fulfilled.

5.1.3. Large-signal gain

For an input power of 27dBm, the required output power of 39dBm was not achieved at any of the tested frequencies of 2.35 GHz, 2.40 GHz and 2.45 GHz. This requirement was then not fulfilled.

5.2. Other results

5.2.1. Power added efficiency

The power added efficiency exhibits the same shift in frequency as the gain, with the best performance at 2.45 GHz, while the results at 2.35 GHz and 2.40 GHz are below the results from the simulations in ADS.

5.2.2. Third-order intermodulation distortion

The third-order intermodulation distortion (TOIMD) was measured to be below -22dBc for all output power levels up to 38dBm. This level of TOIMD is similar to what was achieved in a comparable amplifier design described in [4], which should mean that this is an acceptable TOIMD level, again indicating that the amplifier shows good linearity.

5.3. What happened

The shape of the measured small-signal gain curve shows that the maximum gain is not at our center frequency of 2.40 GHz where it was designed to be, but probably at or above 2.45GHz. This is most probably due to incorrect matching at the input or output. Since the center frequency

was shifted upwards, this indicates that the electrical length of the matching network stubs is shorter than expected. This again leads to the observation that the propagation speed in the substrate is higher than expected, which must mean that the permittivity of the substrate is lower than expected.

Variations in the relative permittivity of the substrate is not uncommon when using standard FR-4 substrate, as this type of substrate by nature has a highly variable permittivity. If absolute control of the permittivity of the substrate is required, special, more expensive RF substrate should be used.

Since the small-signal gain at 2.45 GHz was well above the requirements, it is highly probable that the amplifier would meet the requirement specifications if some effort was put into tuning the input and output matching networks to have the input and output impedances matched as closely as possible to 50 Ohms.

5.4. What was learned

When making rf-circuit prototypes it would be wise to make stub traces longer than what is calculated. This allows for adjustments post production to compensate for variations in the substrate permittivity.

5.5. Conclusion

The project was successful in designing an RF power amplifier that is unconditionally stable, shows quite good efficiency and linearity characteristics and is functional in amplifying RF frequency signals.

The project was not able to meet all point of the requirement specifications, however, having identified the most probable reasons for not fulfilling the required performance characteristics, it is believed that only a minor redesign should be needed to be able to reach the given performance criterions.

The project was successful in teaching the students participating in the group the techniques for designing, simulating, building and measuring an RF power amplifier.

Appendix A. Schematics and layout

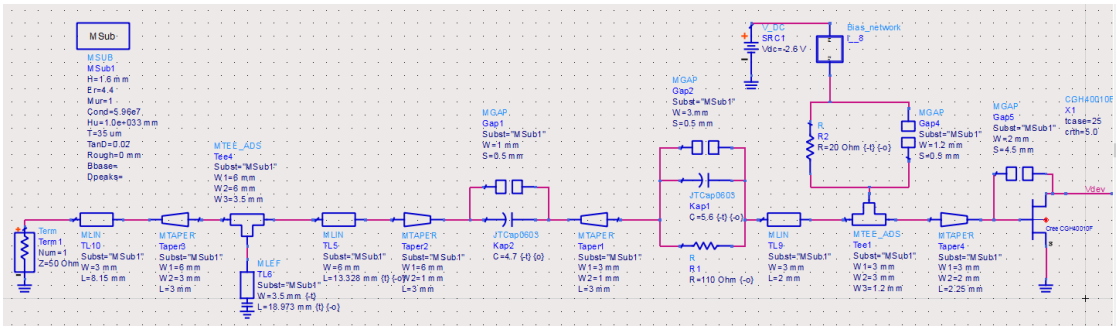

Figure A.1.: Input portion of amplifier circuit with S-parameter terminal

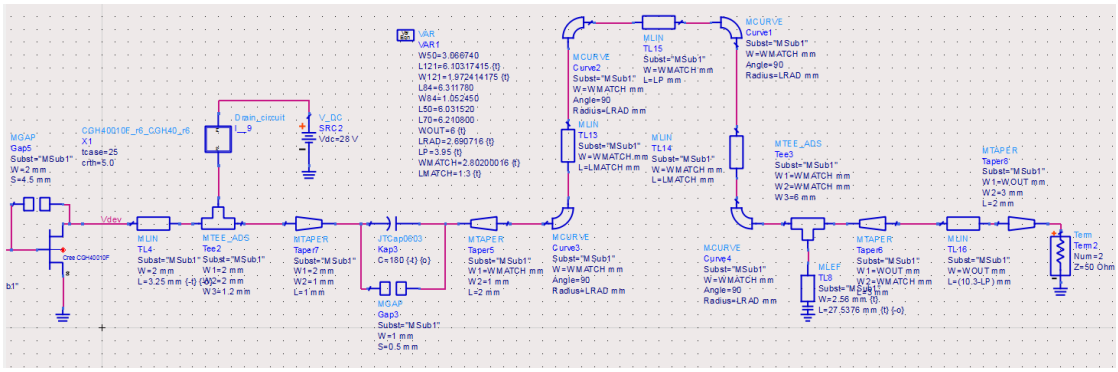

Figure A.2.: Output portion of amplifier circuit with S-parameter terminal

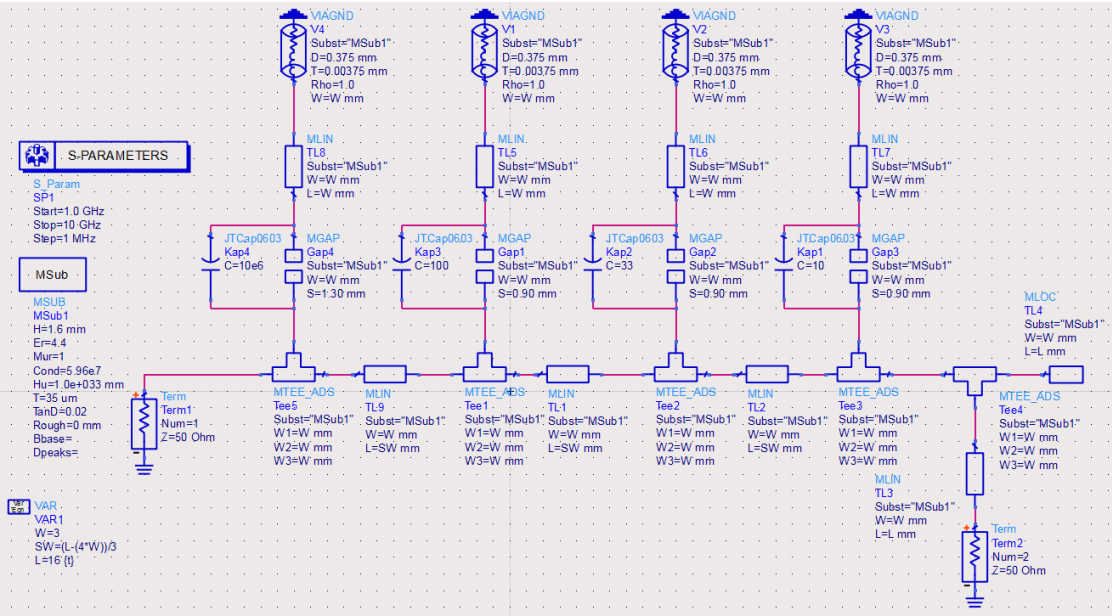

Figure A.3.: Schematics of input and output bias network

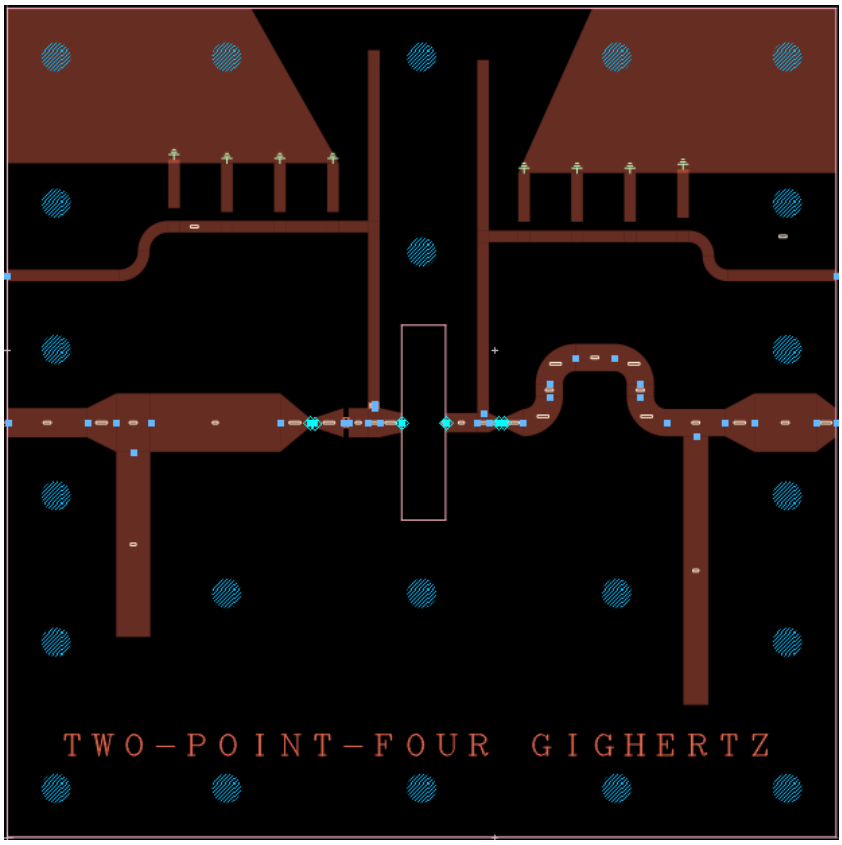

Figure A.4.: PCB layout

Appendix B. Additional graphs

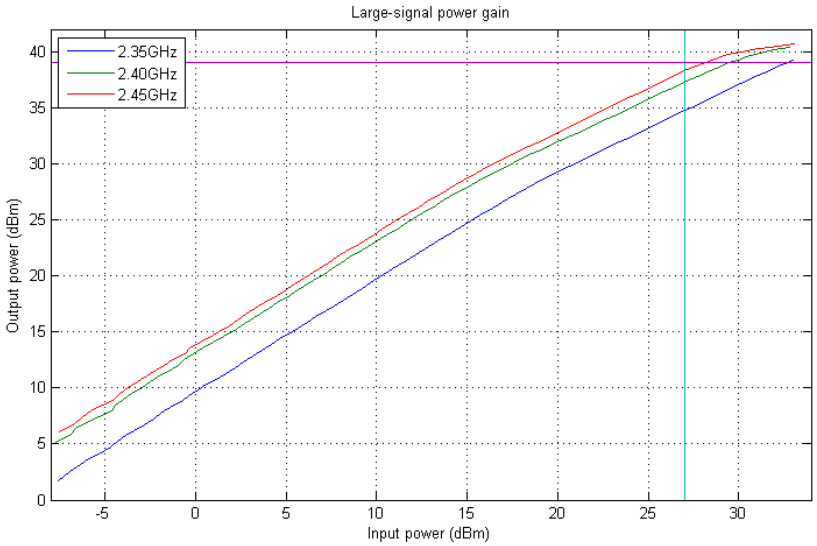

Figure B.1.: Measured output power at three different frequencies

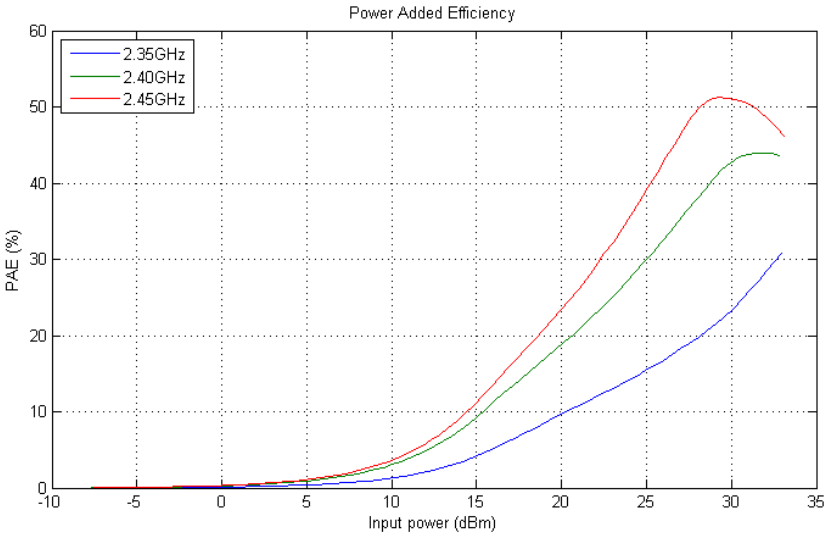

Figure B.2.: Measured power added efficiency at three different frequencies

Appendix C. Bibliography

[1] I.D. Robertson, *RFIC and MMIC Design and Technology*. The Institution of Engineering and Technology, 2nd edition, 2001

[2] i David M. Pozar, *Microwave and RF Design of Wireless Systems*. John Wiley & Sons, 1st edition, 2001

[3] *Cree CGH40010 Datasheet*. Cree, Inc. Rev 3.2, April 2012

[4] K. Niotaki, A. Collado, A. Georgiadis, J. Vardakas, *5 Watt GaN HEMT Power Amplifier for LTE*. Centre Tecnologic de Telecomunicacions de Catalunya. Research paper published in Radioengineering, Vol. 23, No. 1, April 2014. Available for download from `http://www.radioeng.cz/fulltexts/2014/14_01_0338_0344.pdf` (visited on November 19, 2014)

[5] Keith W. Whites, *Amplifier Stability*, Lecture notes from the course EE481 Microwave Engineering at South Dakota School of Mines and Technology. Available for download from `http://whites.sdsmt.edu/classes/ee481/notes/481Lecture34.pdf` (visited on November 19, 2014)

[6] *Stability Factor*, article at microwawes101.com. `http://www.microwaves101.com/encyclopedias/stability-factor` (visited on November 19, 2014)

[7] David Hall, *Understanding Intermodulation Distortion Measurements*. `http://electronicdesign.com/communications/understanding-intermodulation-distortion-measurements` (visited on November 19, 2014)

C.1. Figures from external sources

Below is a list of the sources for all figures we did not make ourselves. All sources were visited on November 19, 2014.

- Figure 2.1: `http://www.electronics-tutorials.ws/amplifier/amp16.gif`
- Figure 2.2: `http://upload.wikimedia.org/wikipedia/en/thumb/5/5c/TwoPortNetworkScatteringAmplitudes.svg/540px-TwoPortNetworkScatteringAmplitudes.svg.png`
- Figure 2.3: `http://whites.sdsmt.edu/classes/ee481/notes/481Lecture34.pdf`, page 2
- Figure 2.4: `http://electronicdesign.com/site-files/electronicdesign.com/files/uploads/2013/10/1107_MakingWaves_F1.gif`