I/Q -Modulator Circuit for 7-Tesla MRI Smart Power Amplifier

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Outline

- **Motivation**
  why we need smart power amplifier?
  how is the I/Q modulator constructed?

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- **Circuit Test & Analysis**
  how to verify their functionalities?

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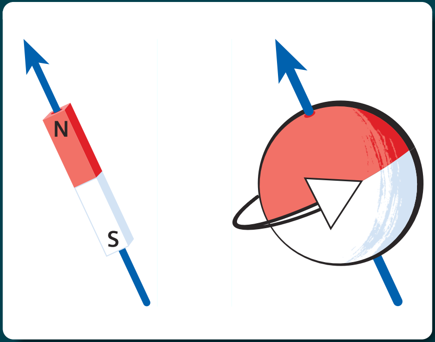
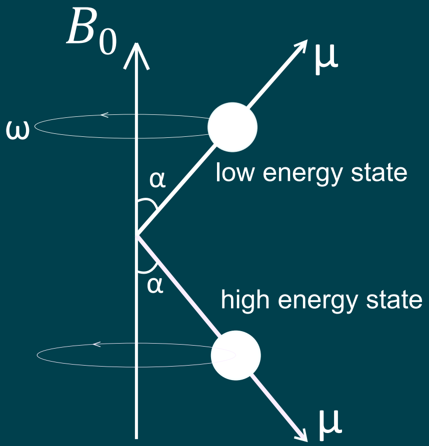
- **PCB Design & Theory**
  how to handle so many passive and active elements?
- **Circuit Test & Analysis**
  how to verify their functionalities?
- **Conclusion**

Motivation I

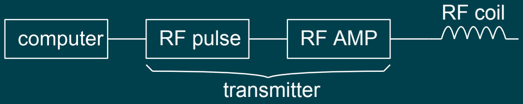
Nuclear Magnetic Resonance

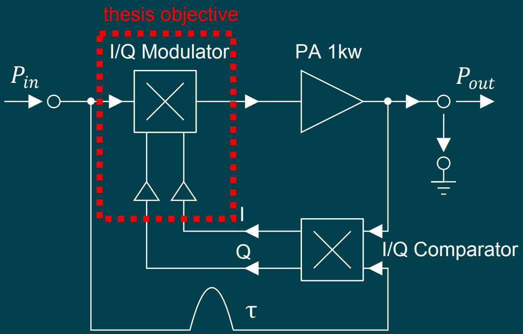




Motivation II

RF Pulse Generation





- $f_{Larmor} = \frac{\gamma}{2\pi} B_0$, e.g. $f_{Larmor} \simeq$298MHz at 7T
- RF power amplifier linearization scheme
  - cartesian feedback
  - carrier is I/Q modulated before power amplification. The distorted signal is then fed back through an I/Q demodulator. The separated I and Q components are fed back to perform the linearization.

Motivation III

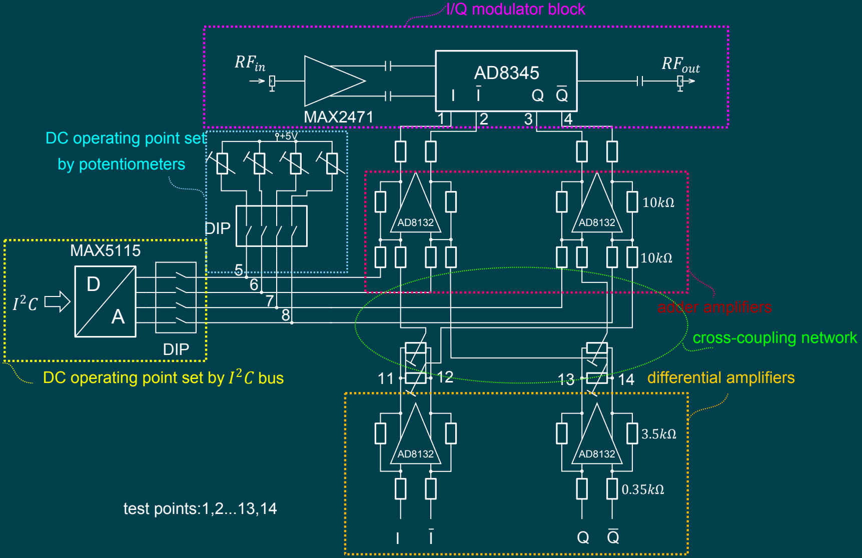
Thesis Task: I/Q Modulator Circuit

- **Functions to realise:**
  - **I/Q Modulator**
  - **amplitude/phase control of baseband signals**
  - **DC operating point set of the modulator in 2 ways**
- **How to realise?**

  Answer: circuit modularization!

Motivation IV

Thesis Task: I/Q Modulator Circuit



test points:1,2...13,14

PCB Design & Theory

Design Methodology

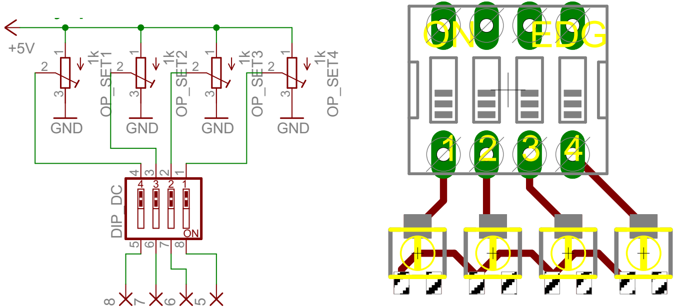
- modular design: top down, bottom up

modular programming is a programming style that breaks down program functions into independent, interchangeable modules

- circuit modularization
  - DC operating point set
    - by potentiometers
    - by DAC through I^2C control
  - Phase/amplitude adjustment
    - differential amplifier
    - adder amplifier
    - cross-coupling
  - I/Q modulator

DC Operating Point Set I

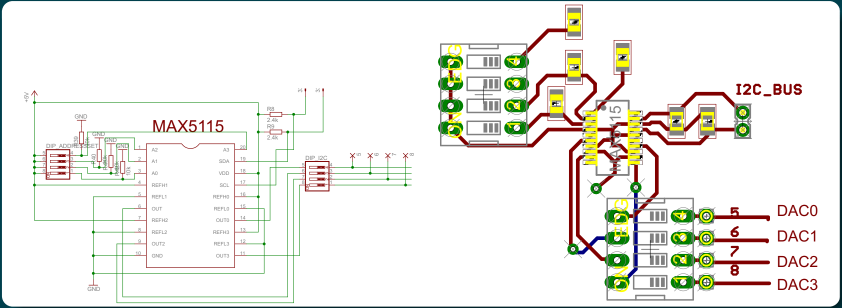
by potentiometers



- **block isolation through DIP switch**
  - advantage: isolation between function blocks
  - disadvantage: cost extra PCB area
- **4 test pins designed for test**

DC Operating Point Set II

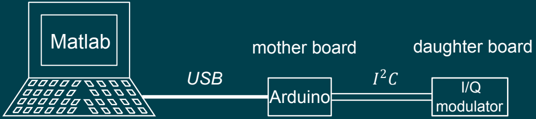
by DAC through I^2C control

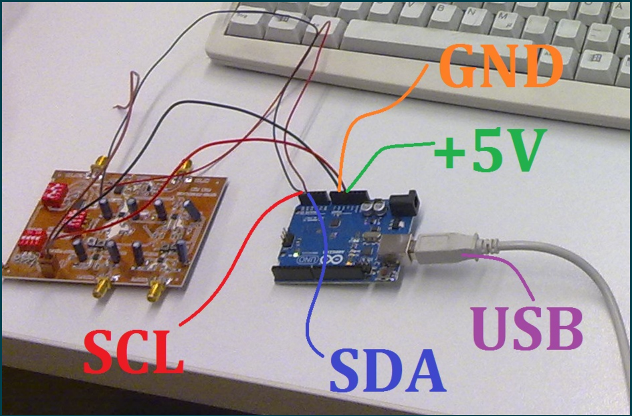


- block isolation through DIP switch
- 4 test pins designed for circuit test
- pull-up and pull-down resistors

DC Operating Point Set by I^2C

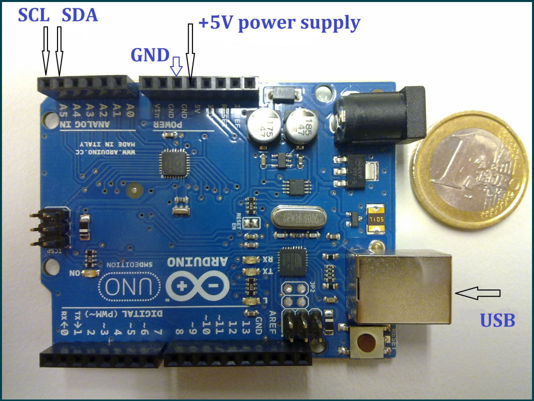
A Simple I^2C Bus Application





DC Operating Point Set by I^{2}C

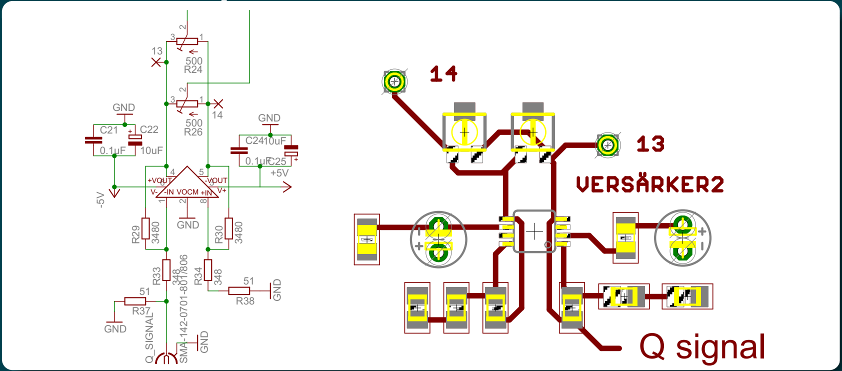
The Arduino Platform



- open-source
- simple, cheap, easy to use
- Arduino “UNO”
  - powered through USB or enternal power source
  - communication through USB
- ATTENTION: mother board and daughter board should have the same GND level!

Phase/Amplitude Adjustment I

differential amplifier

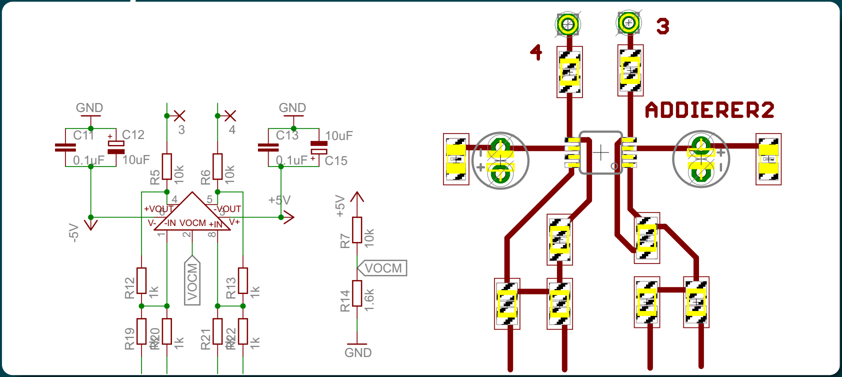


- 2 test points
- differential or single-ended input
- gain user defined

- symmetrical output
  - harmonics suppresion
  - EMI reduction

Phase/Amplitude Adjustment II

adder amplifier

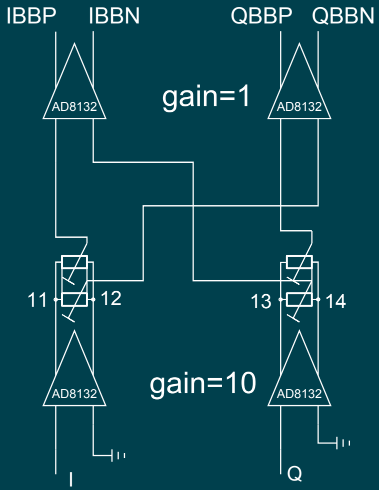


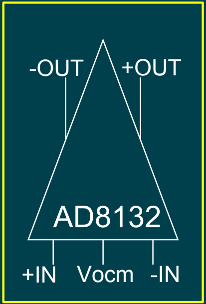
- 2 test points
- DC level controlled by V_{OCM}

- symmetrical output
  - long line signal transfer allowed
  - outputs should equal in length in PCB design

Phase/Amplitude Adjustment III

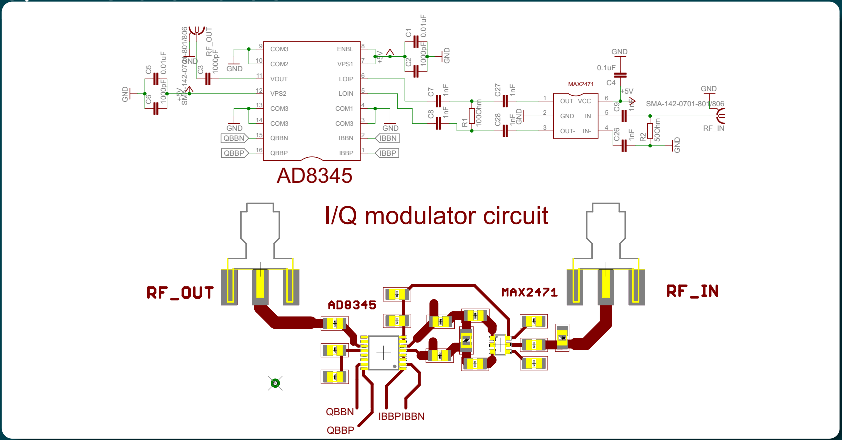
cross-coupling





- $I = \cos(t)\,, Q = \sin(t)$
- $QBBP = -[m \cdot \sin(t) - n \cdot \cos(t)] = \sqrt{m^2 + n^2} \sin(t + \varphi)$
  $m, n \in [-gain, +gain]$

I/Q Modulator I



- no test points
- inputs and outputs of AD8345 and MAX2471 are AC coupled and terminated with 50Ω resistors

- MAX2471 acts as balun
  - signal conversion from assymmetrical to symmetrical
  - immunity to external noises

I/Q Modulator II

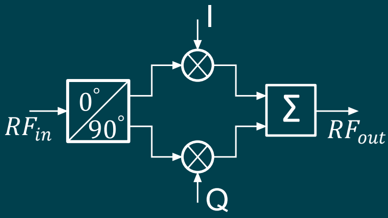
S-parameter $\underline{S}_{21}$ Measurement

- $I = V_x,\ Q = V_{const}$

  $\underline{S}_{21} = \frac{\underline{V}_2^-}{\underline{V}_1^+}\Big|_{\underline{V}_2^+=0} = \boxed{V_x e^{j0^o}} + V_{const}\, e^{j90^o}$

- $I = V_{const},\ Q = V_x$

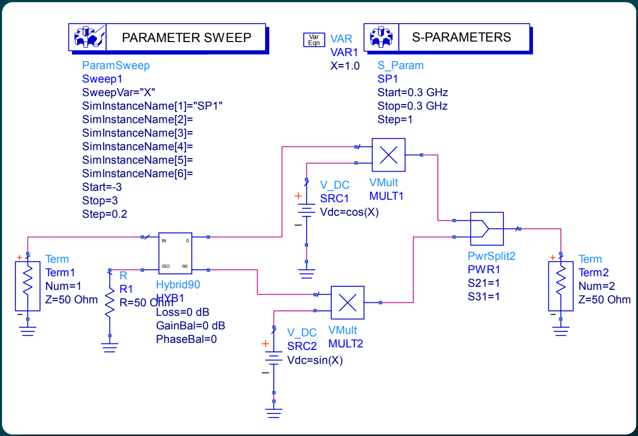
  $\underline{S}_{21} = \frac{\underline{V}_2^-}{\underline{V}_1^+}\Big|_{\underline{V}_2^+=0} = \boxed{V_x e^{j90^o}} + V_{const}\, e^{j0^o}$

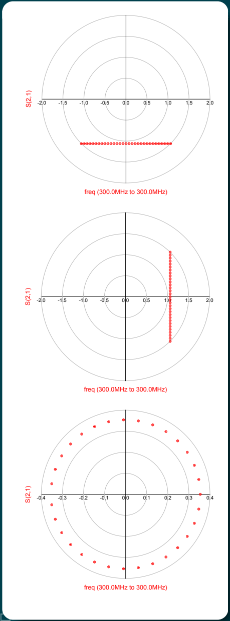


  - $I = cos(V_x),\ Q = cos(V_{DC} + 90^o) = -sin(V_x)$
    - $\underline{S}_{21} = cos(V_x)e^{j0} - sin(V_x)e^{j90^o}$
  - $I = R_e\left\{A_1 e^{j(\omega_1 t + \varphi_0)}\right\}$, and $Q = R_e\left\{A_1 e^{j(\omega_1 t + \varphi_0 + 90^o)}\right\}$
    - $\underline{S}_{21}$ doesn't exist any more because S-parameters are supposed to characterise linear networks

I/Q Modulator III

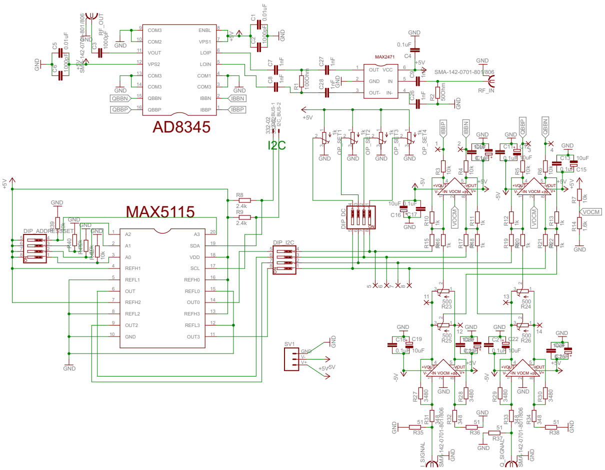
$\underline{S}_{21}$ *ADS Simulation*





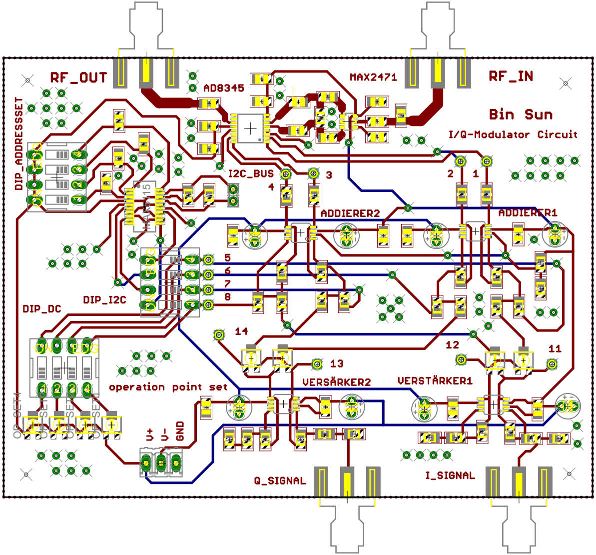
Whole I/Q Modulator Circuit I

Whole PCB Schematic



Whole I/Q Modulator Circuit II

Whole PCB Layout



PCB Assembly

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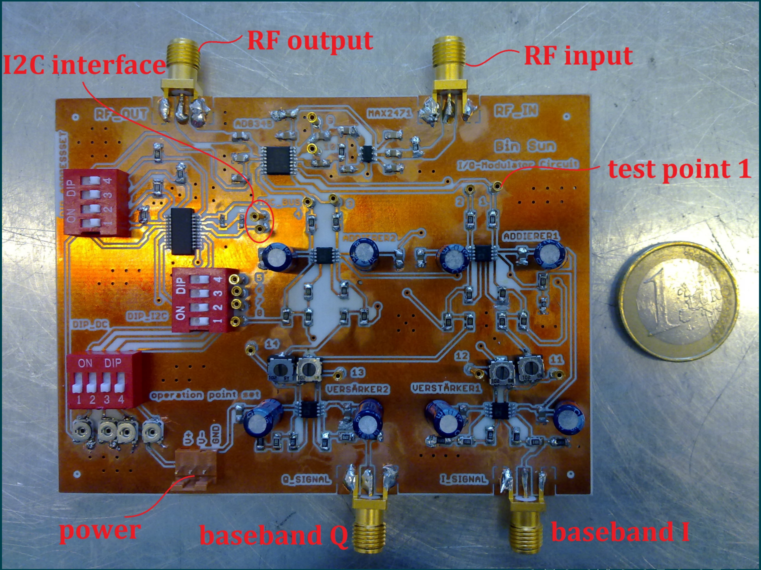


Circuit Test & Analysis I

DC current consumption of activ components

Element	DC Current Consumption	Amount	-5V Total	+5V Total
AD8345	70mA	1		
AD8132	12mA	4	48mA	123.5mA
MAX5115	200μA	1		
MAX2471	5.5mA	1		

Current consumption shown on the power suppliers:

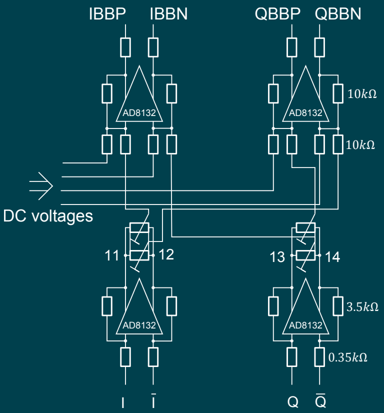
- -5V: 0.04A$\sim$0.05A
- +5V: 0.12A$\sim$0.13A

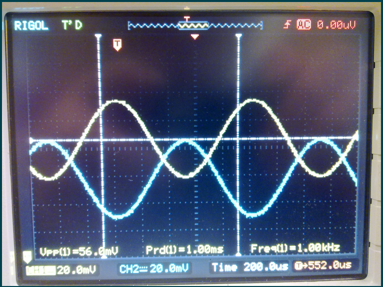
Potential problems:

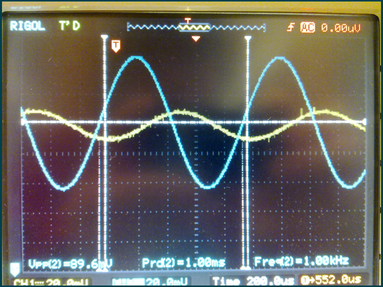
- can only roughly evaluate the components
- for example if MAX5115 is not working, the current won't change magnificently

Circuit Test & Analysis II

Functionality of the Phase/Amplitude Adjustment Circuit



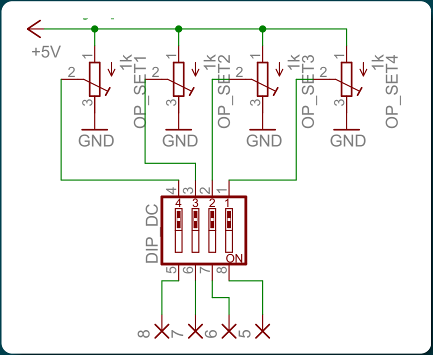


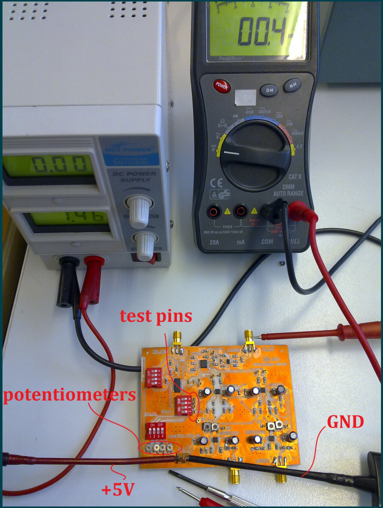


- $I = 50\text{mV} \cos(2\pi 1000\text{Hz})$
- $Q = -50\text{mV} \sin(2\pi 1000\text{Hz})$

Circuit Test & Analysis III

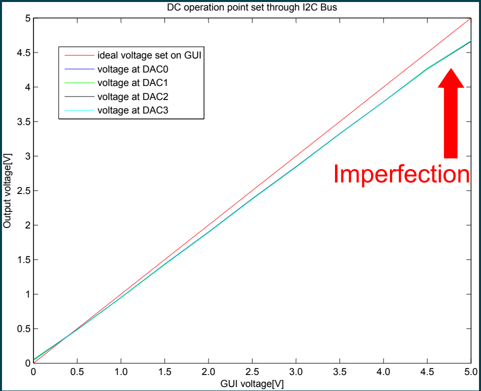
Functionality of the DC operating point set by potentiometers

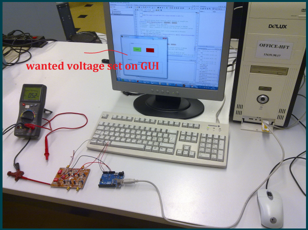




Circuit Test & Analysis IV

Functionality of the DC operating point set by DAC

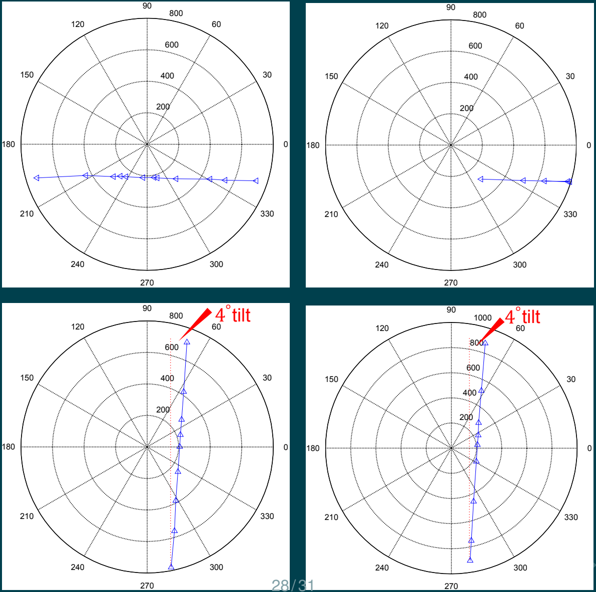




- error become larger when voltage increases
  - voltage is not exact +5V when powered by USB
  - solution: use lab power supply

Circuit Test & Analysis V

RF Functionality of the IQ Modulator



Circuit Test & Analysis VI

RF Functionality of the IQ Modulator

Conclusion

Thesis summary

- circuit modularization
  - $\surd$ simplify the routing task
  - $\surd$ provide isolation between function blocks
  - $\times$ cost extra PCB material
- future work
  - DAC output voltage imperfection
    power the Arduino board through external power source between 7V$\sim$12V instead of USB
  - I/Q modulator imperfection
    - design the microstrip lines even shorter
    - symmetrical outputs of circuits equal in length

Thank you for your attention!

Questions?