An automatic antenna matching method for monostatic FMCW radars

Professor: Prof. Dr.-Ing. Klaus Solbach

Supervisor: Dipl. -Ing. Michael Thiel

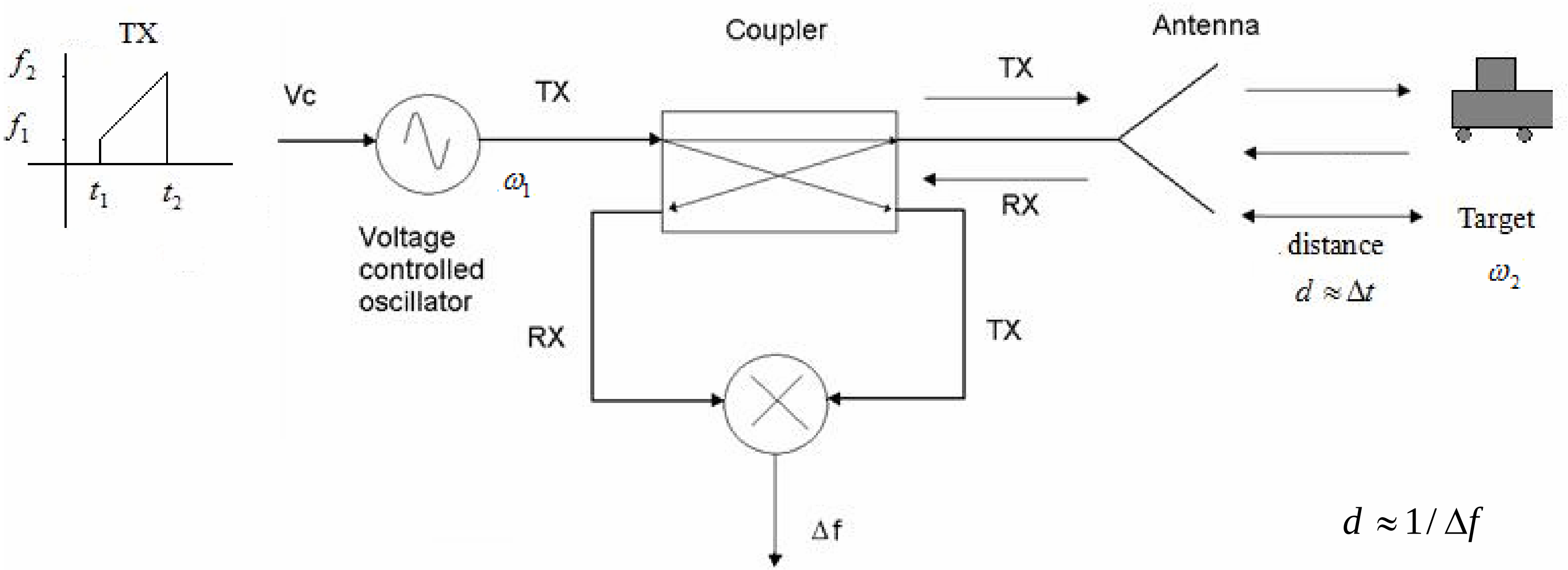
Student: Yan Shen

Outline

- Introduction
- System Development and Design
- Impedance Tuner Design
- Test Results
- Controller Algorithm
- Conclusions and Further Work

Introduction

Hardware Realization of the FMCW Monostatic Radar



$$d \approx 1/\Delta f$$

$$TX \times RX = [A1\cos(\omega_1)][A2\cos(\omega_2)] = A1A2[\cos(\omega_1 - \omega_2) + \cos(\omega_1 + \omega_2)] = \frac{A1A2}{2}[\cos(\Delta\omega) + \cos(\Delta\omega + 2\omega_1)]$$

If RX and TX are not well decoupled:

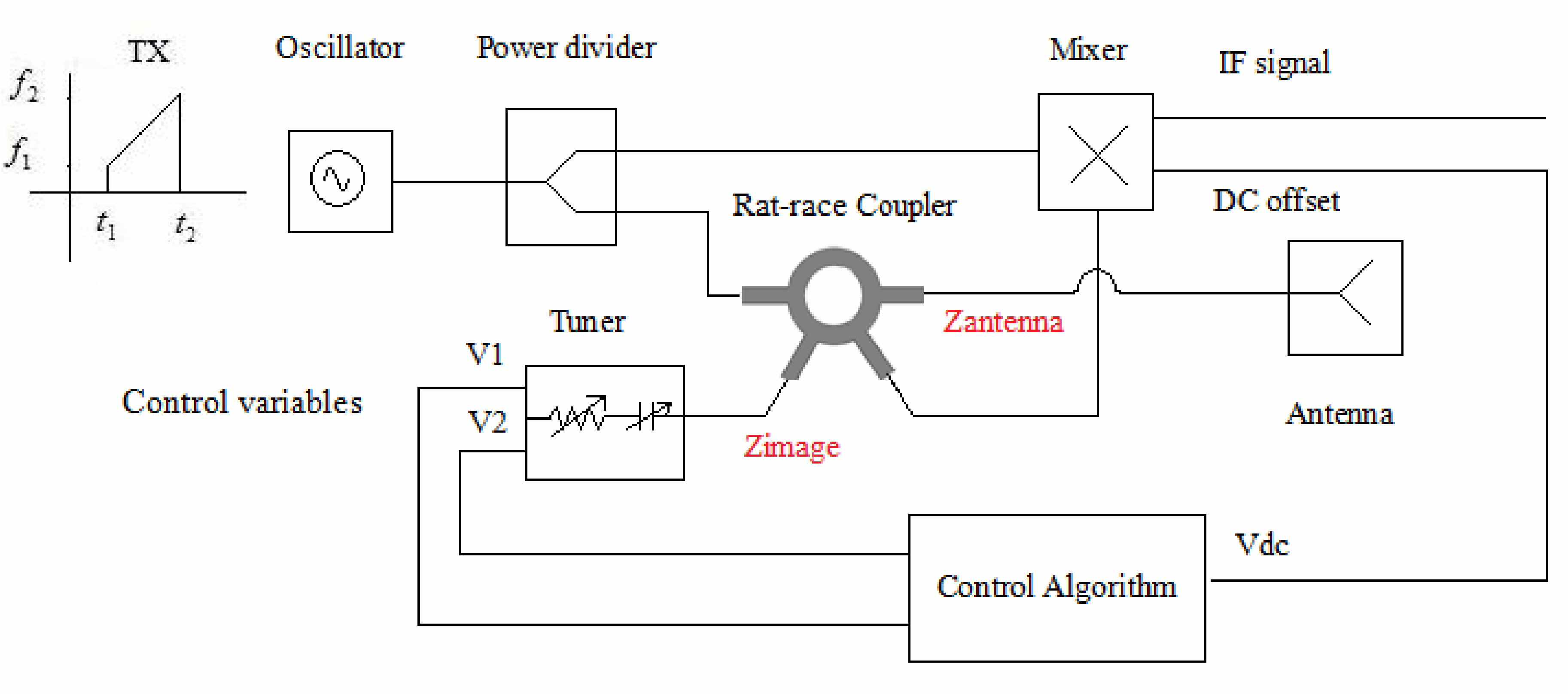
$$RX \times (TX + n \times RX) = RX \times TX + n \times RX \times RX$$

→ DC offset → Reduced performance of the mixer due to changed DC operation.

Decoupling → Diplexers → Rat-race coupler

if Zimage(V1,V2) = Zantenna, RX and TX are well decoupled.

Antenna impedance changes —Temperatures, radiation environments→ Impedance tuner

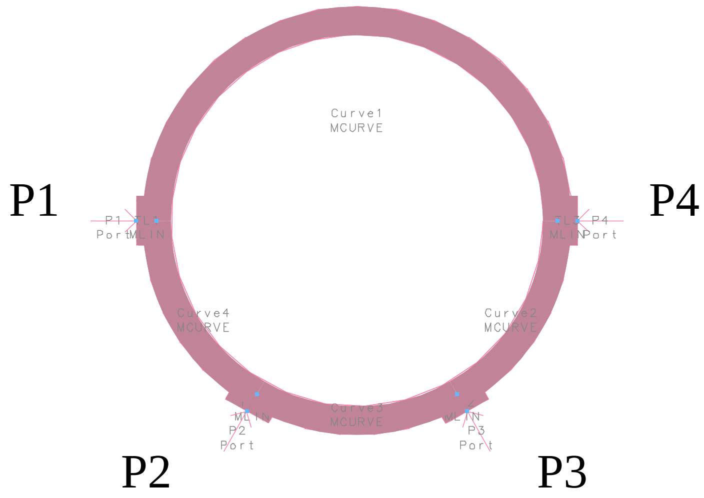


System Design and Development

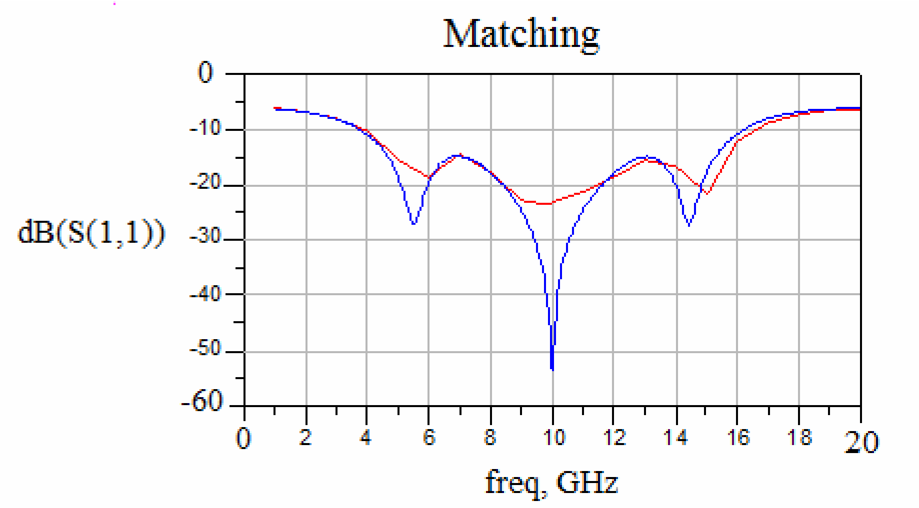
- Rat-race Coupler
- Wilkinson Power Divider
- Gilbert Cell Mixer
- Patch Antenna
- System Modelling and Development

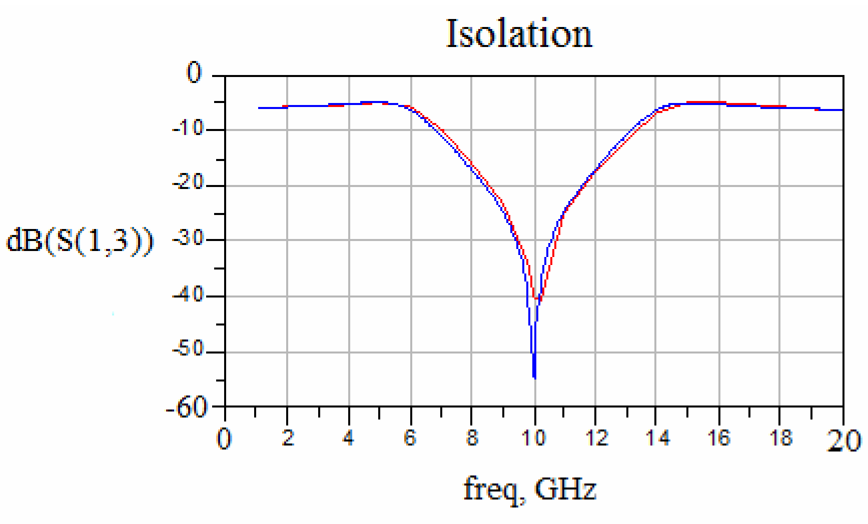
Rat-race Coupler

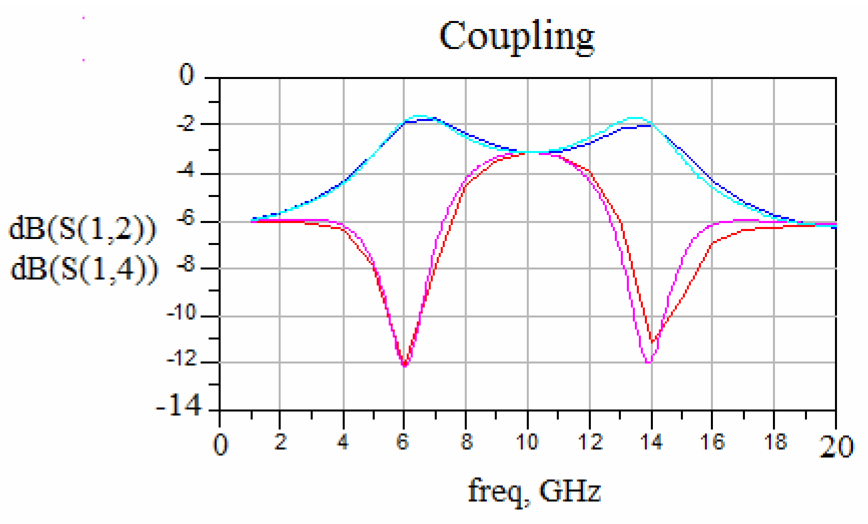
ADS layout



Schematic VS Momentum

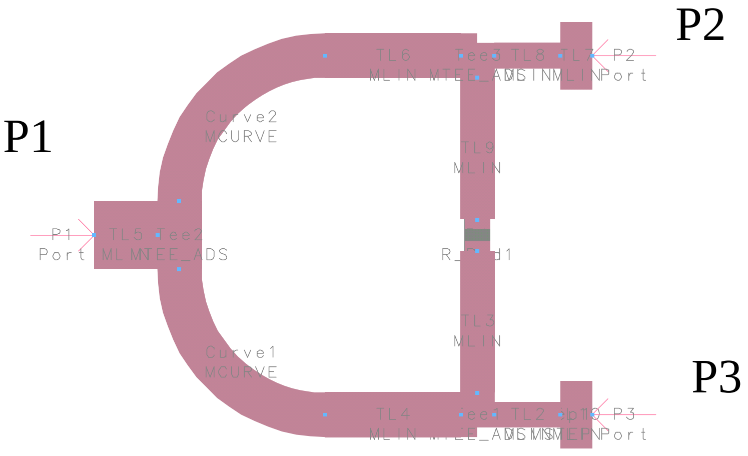




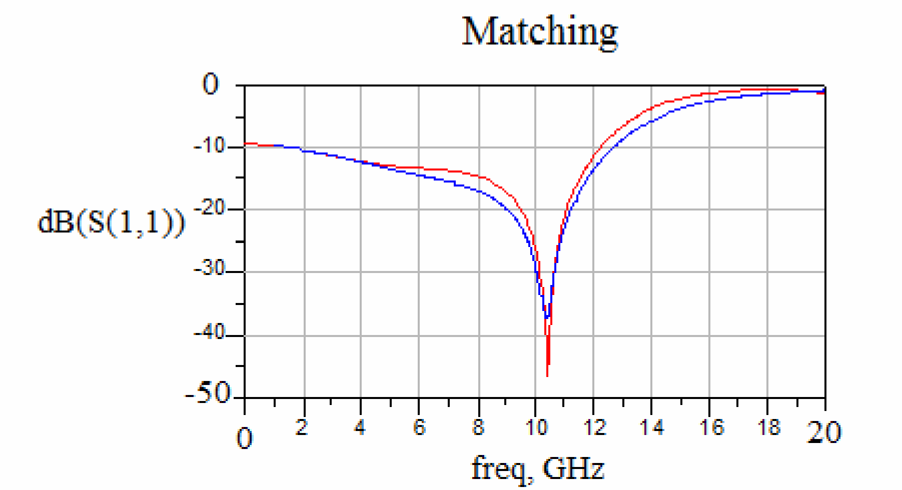


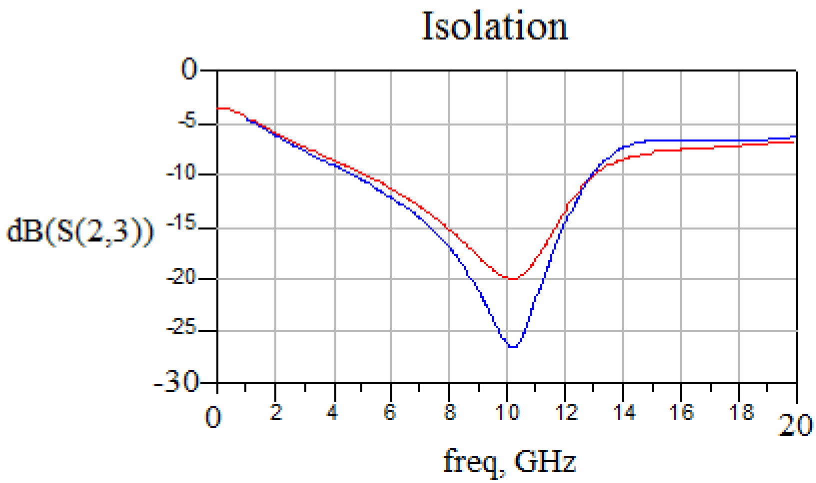
Wilkinson Power Divider

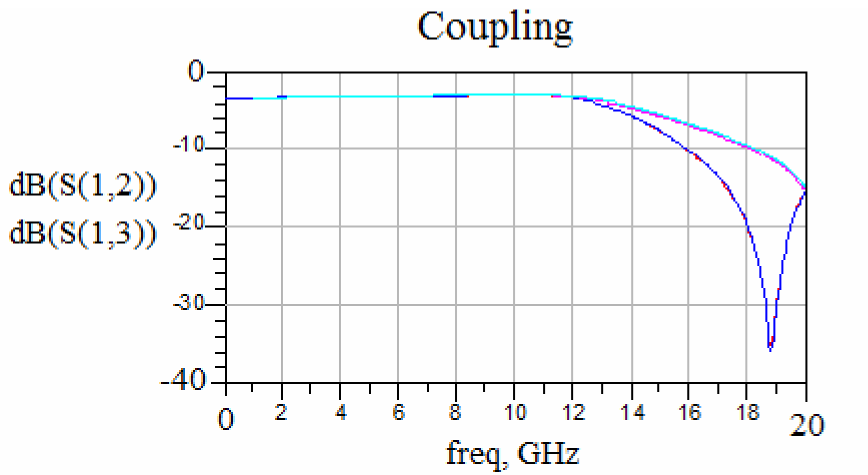
ADS layout



Schematic VS Momentum

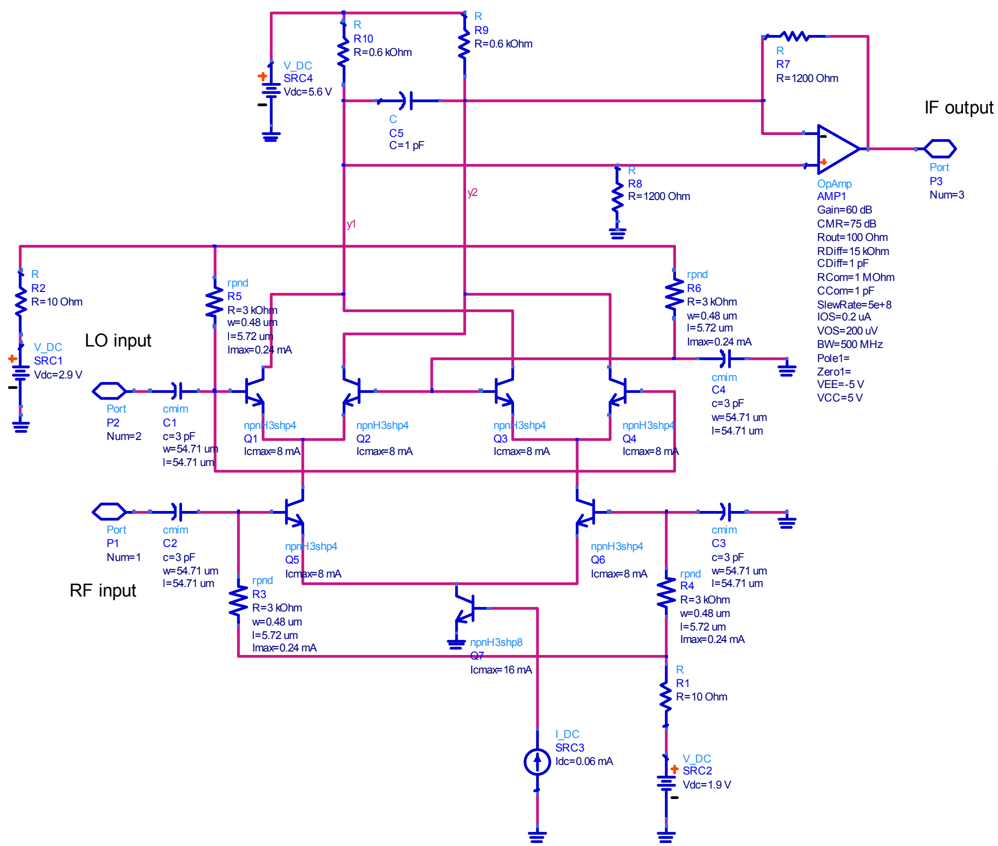




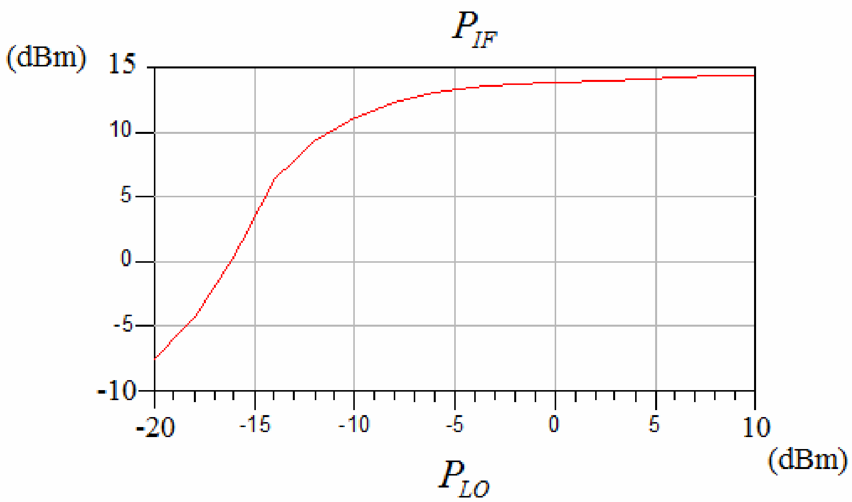


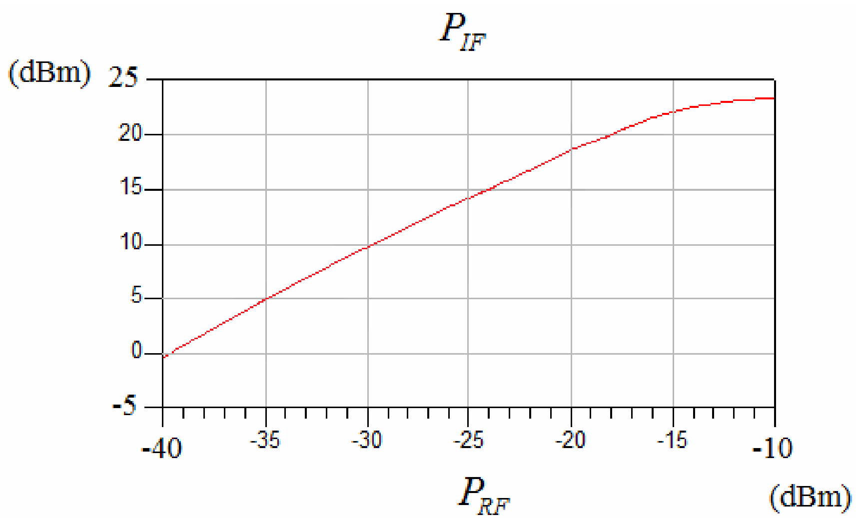
Gilbert Cell Mixer

Mixer schematic



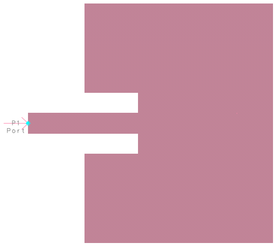
Power level test

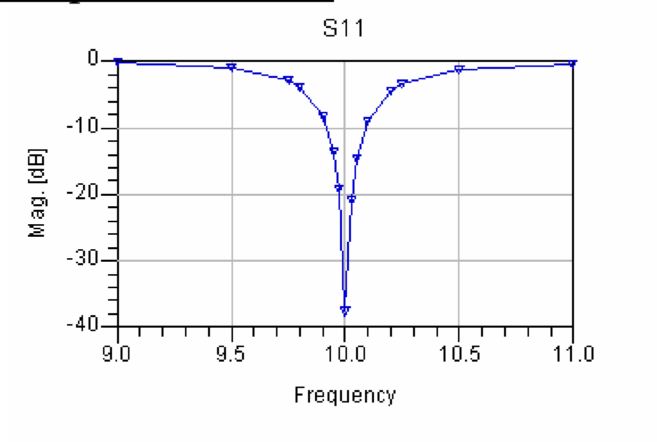




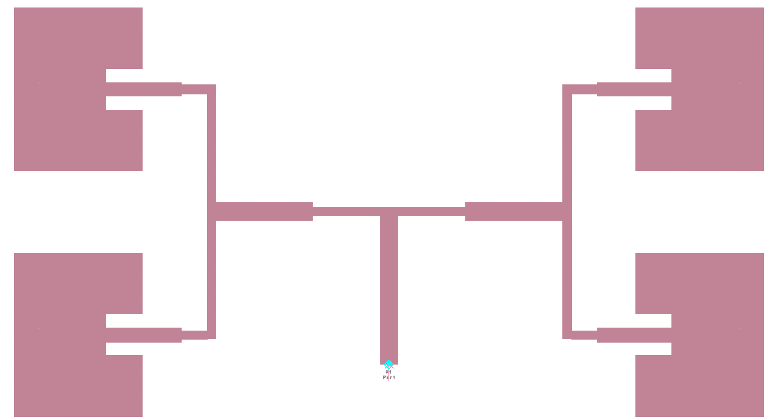
Patch Antenna

Single inset-fed patch antenna



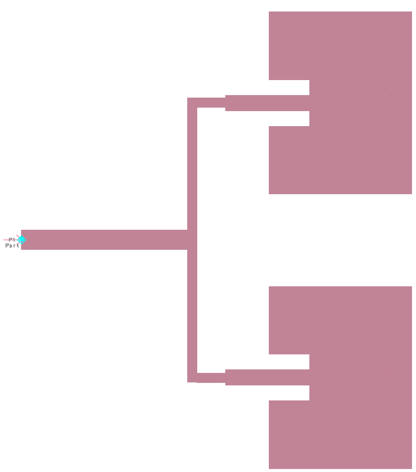


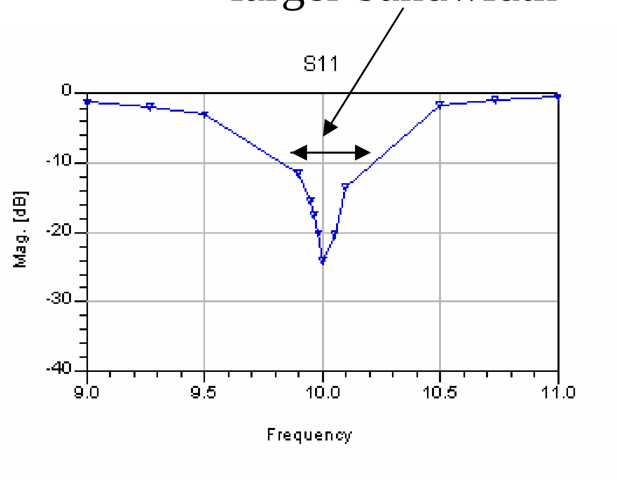
Quad inset-fed patch antenna



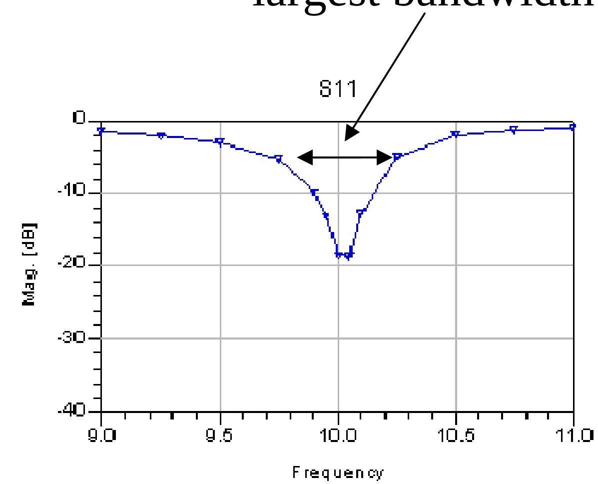
Twin inset-fed patch antenna

larger bandwidth

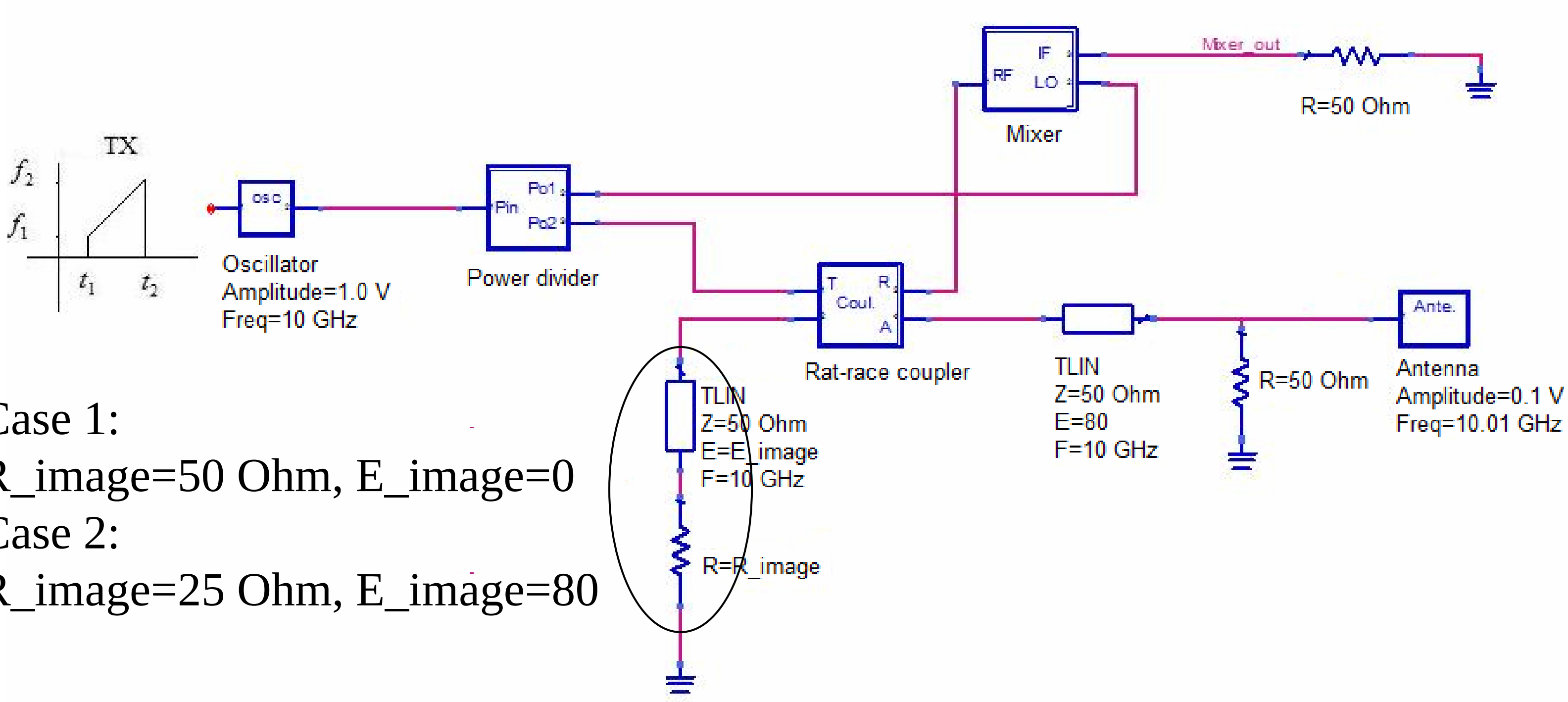




largest bandwidth

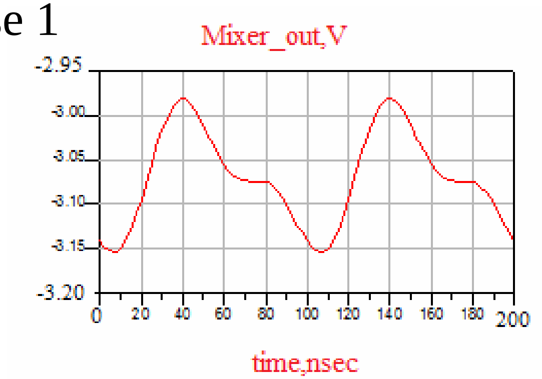


System Modelling



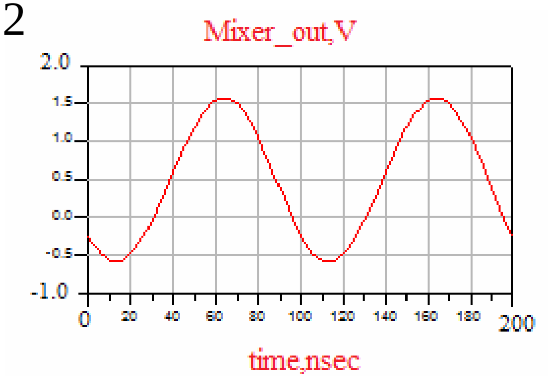
Case 1:
R_image=50 Ohm, E_image=0
Case 2:
R_image=25 Ohm, E_image=80

Case 1



0.000Hz: 3.069/180.000
10.00MHz: 0.066/-171.451

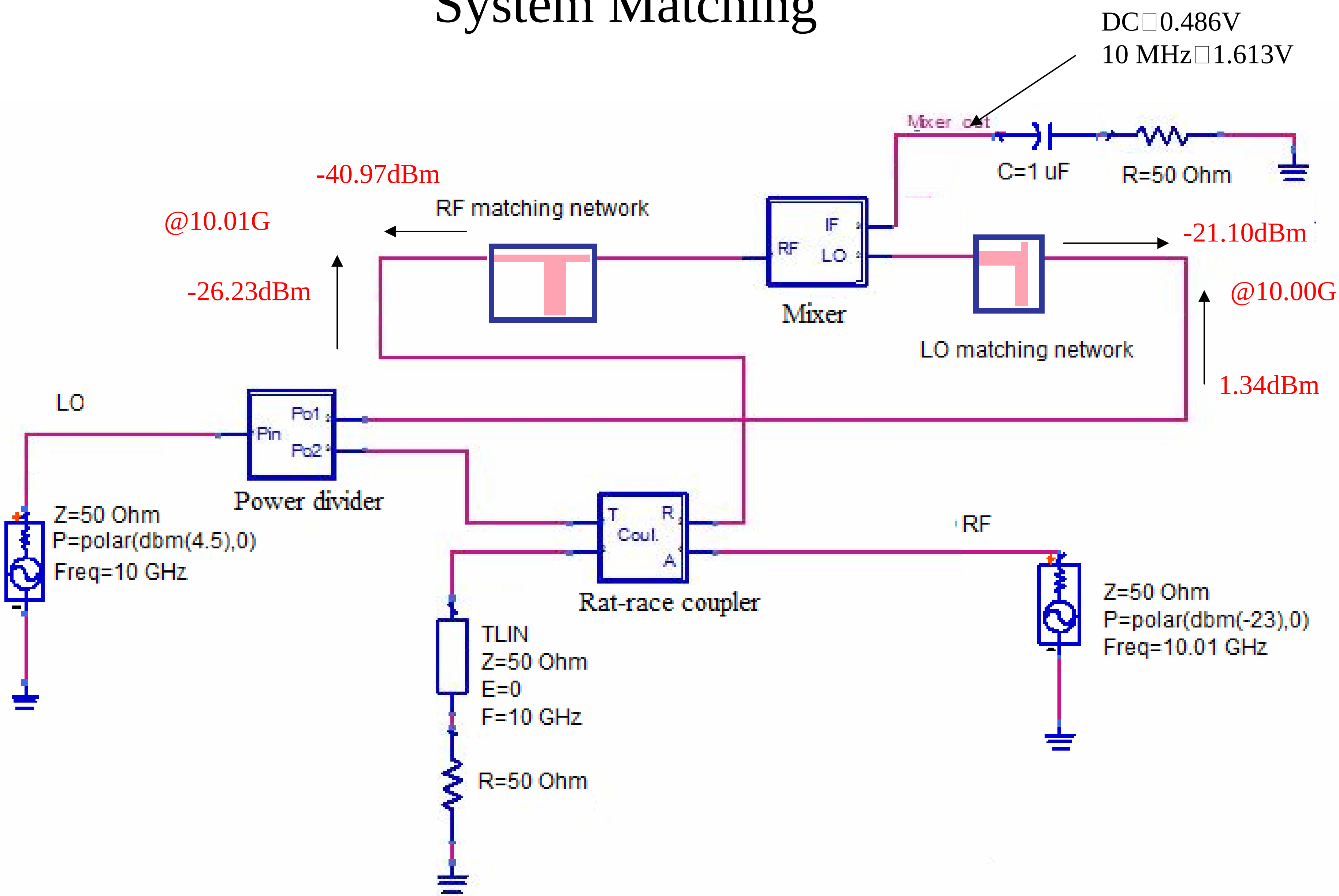
Case 2



0.000Hz: 0.490/0.000
10.00MHz: 1.075/131.432

IF_gain
=20log(1.015/0.066)
=24dB!

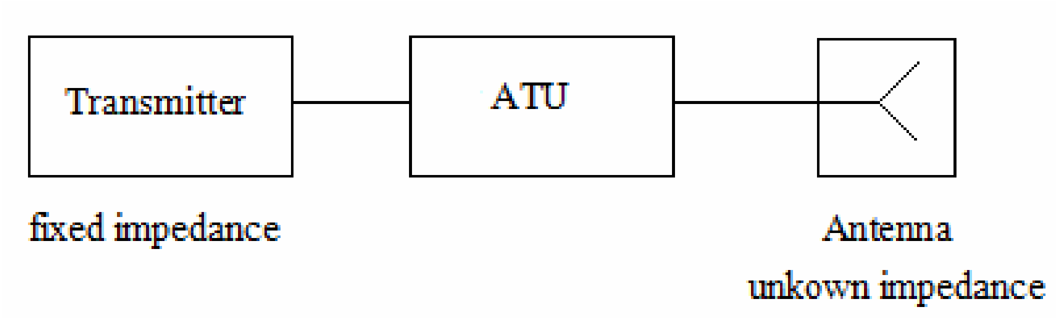
System Matching



Tuner Design

The traditional transmission tuner:

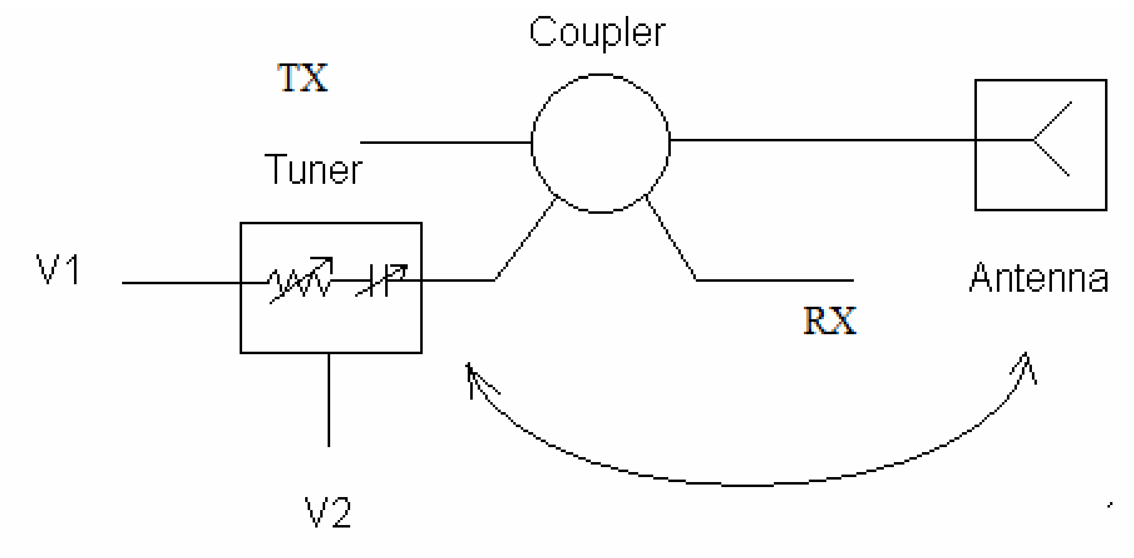
Additional induced losses on the feed line due to multiple reflections and losses in the ATU itself:



Transmission Tuner

The reflection tuner:

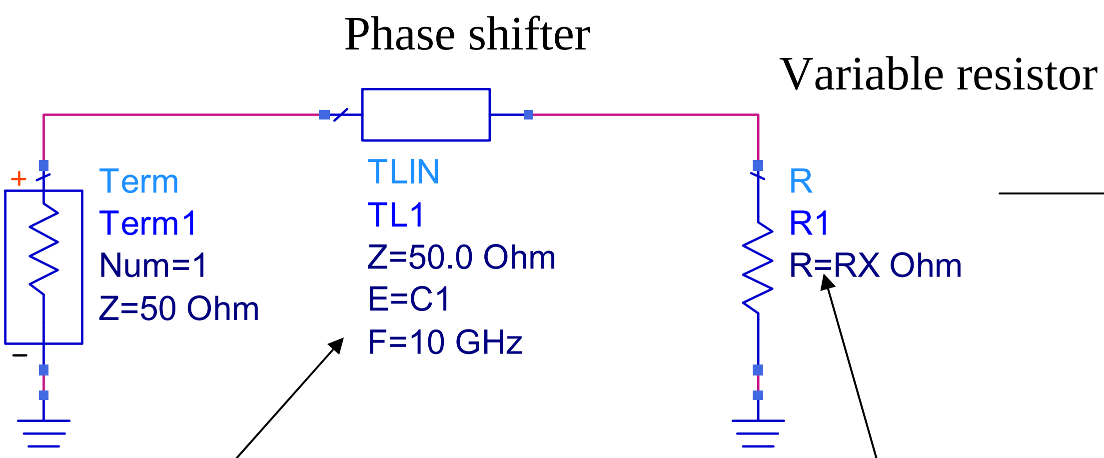
Losses on the tuner has no influence to the system.

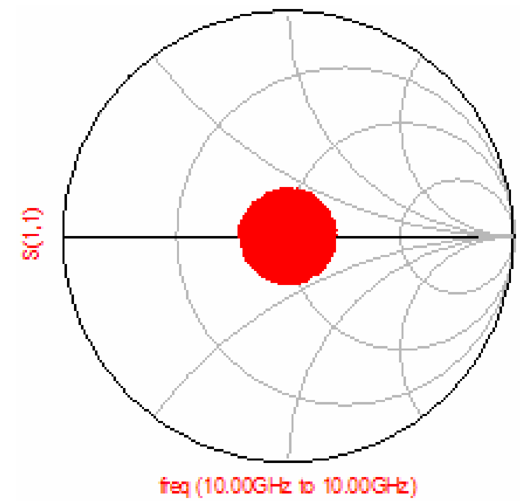


Reflection Tuner

Principle of our tuner

<u>Tuner schematic:</u> <u>Simulation result:</u>



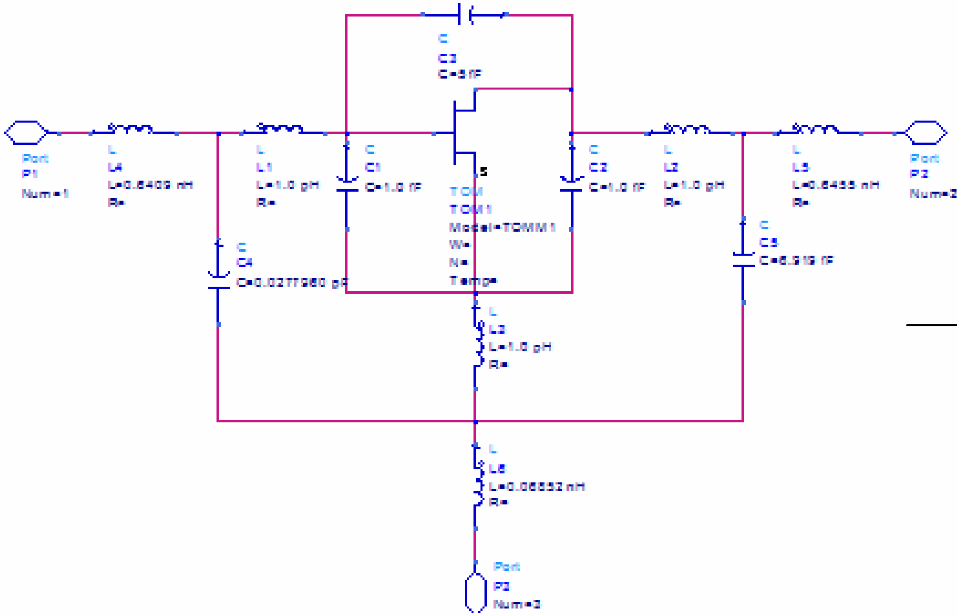


C1: 0~90°
tune the phase

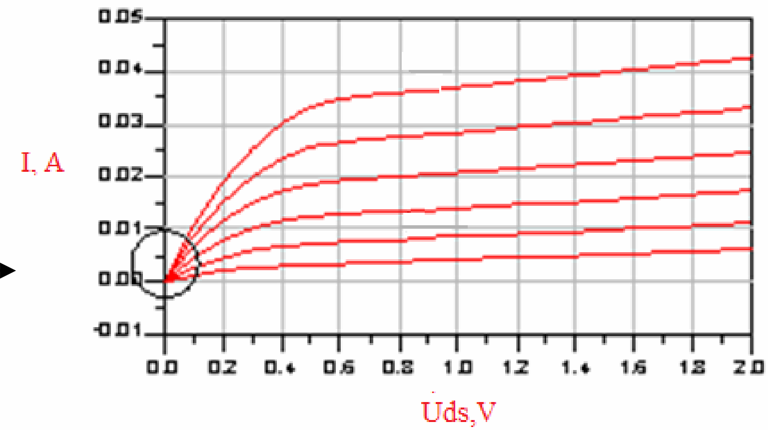
RX: 33.3~75 Ohm
tune the amplitude

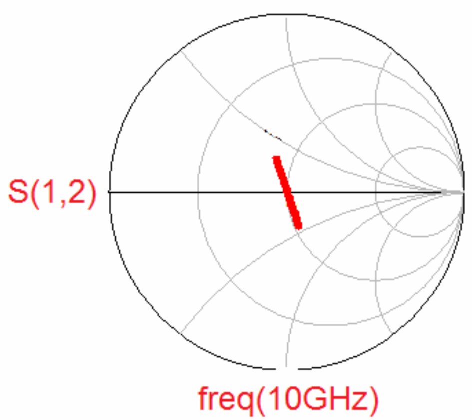
FET as Voltage-controlled Resistors

nonlinear Triquint MGF1402 package.

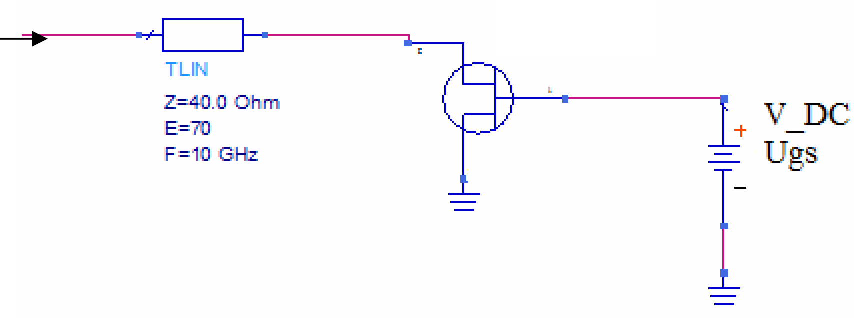


Rds~Ugs





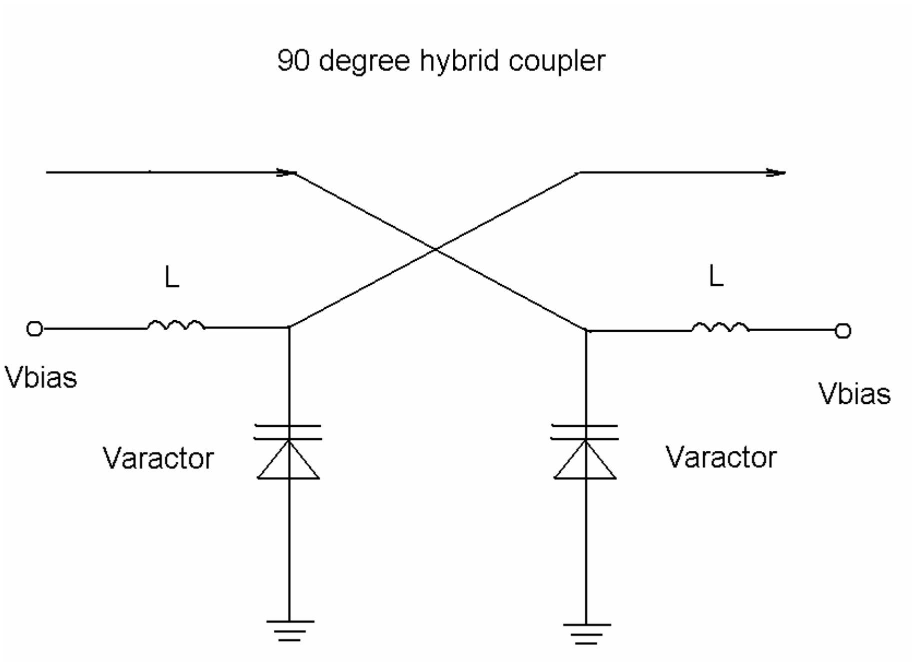
MGF1402



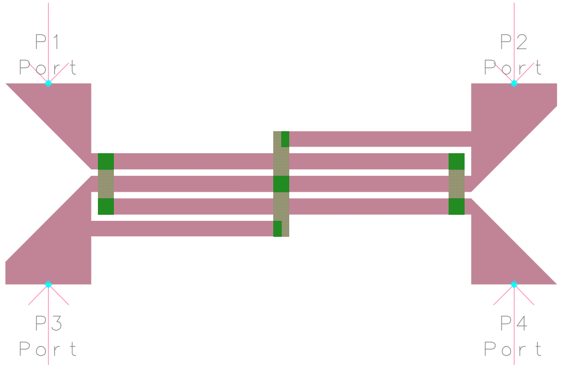
Ugs:-0.5913 ~ -0.5101 V

Phase Shifter Design

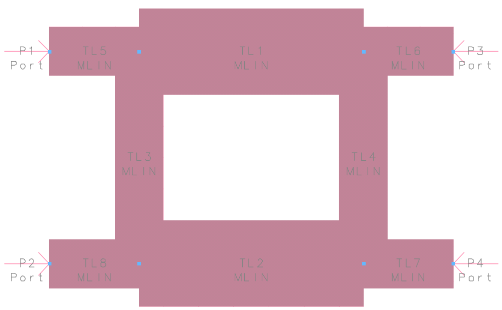
Variable reactance reflection phase shifter



90°hybrid coupler:



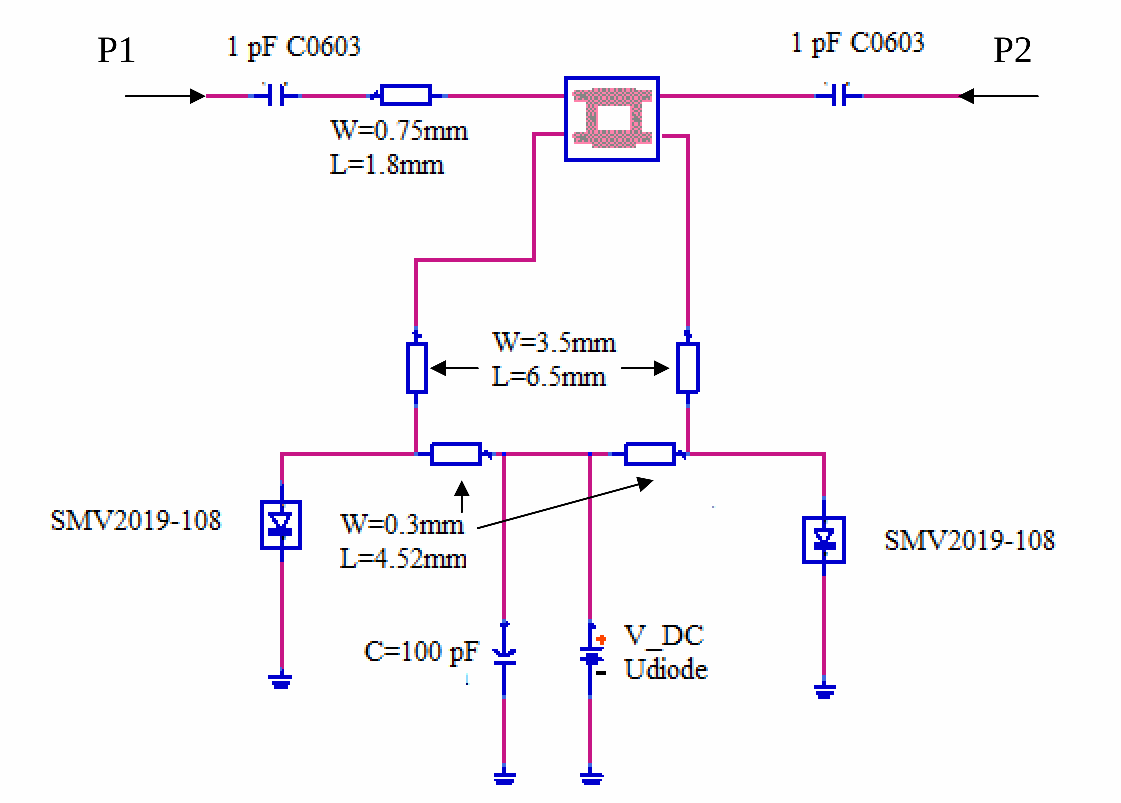
Lange coupler



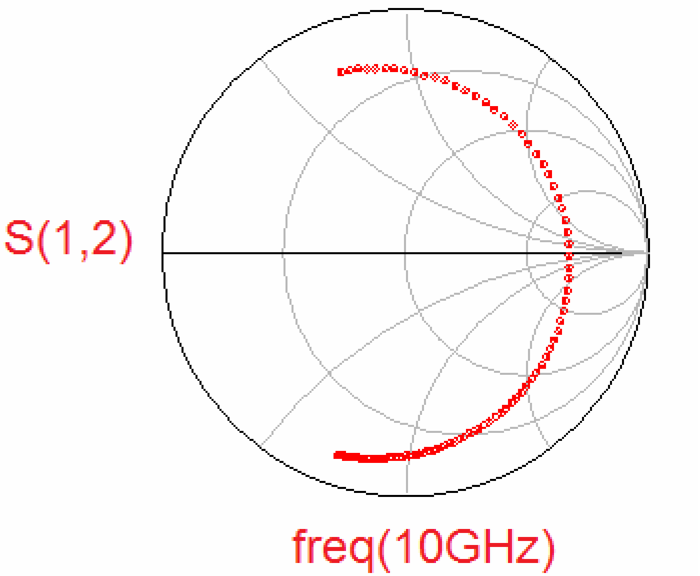
Branch-line coupler

Phase shifter schematic:

Branch-line coupler and Silicon tunning Varactor SMV 2019-108



Simulation result:

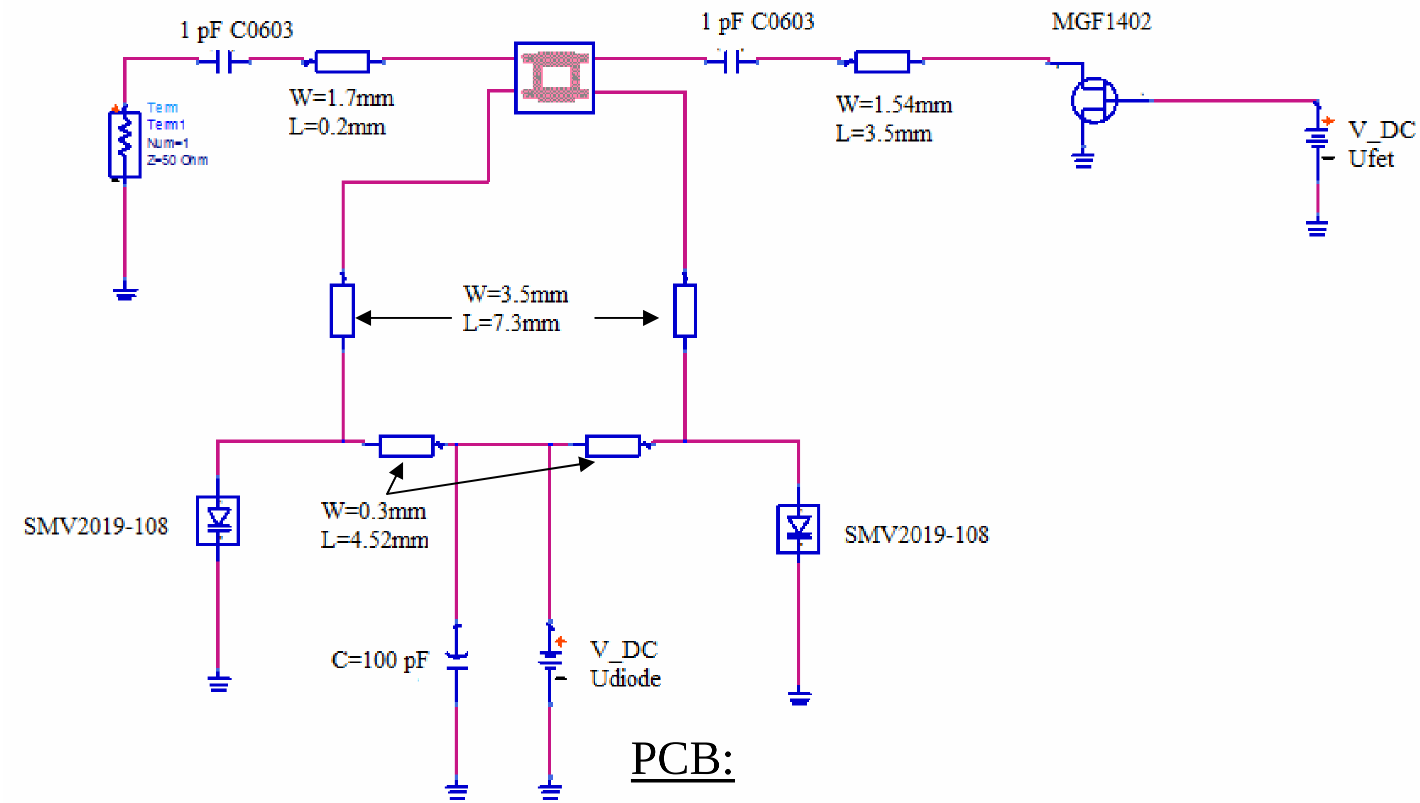


Udiode: 0~20 V → Phase shift: 218°

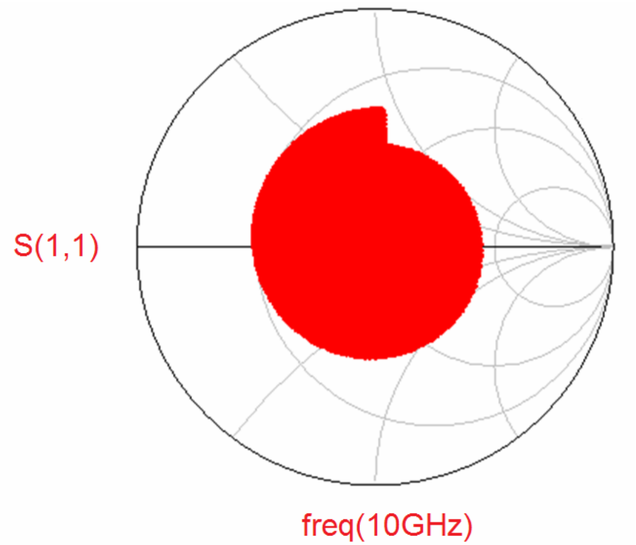
Tuner Schematic:

Udiode: 0~20V

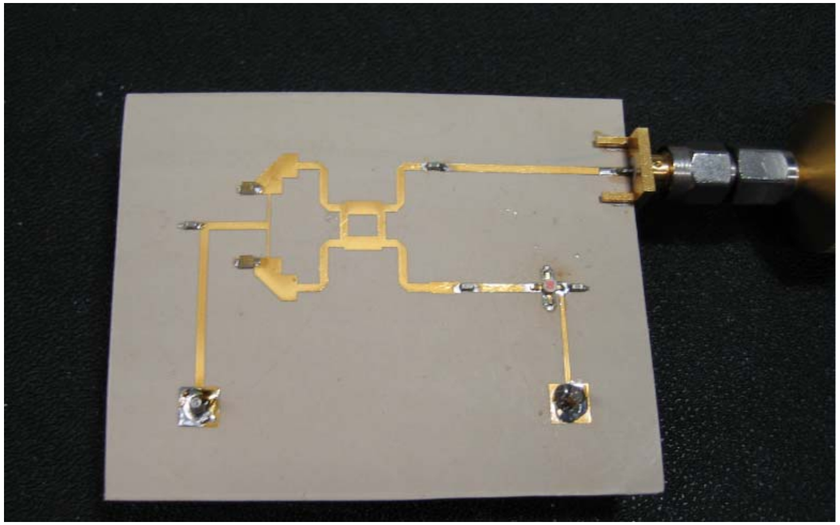
Ufet: -0.6~0V



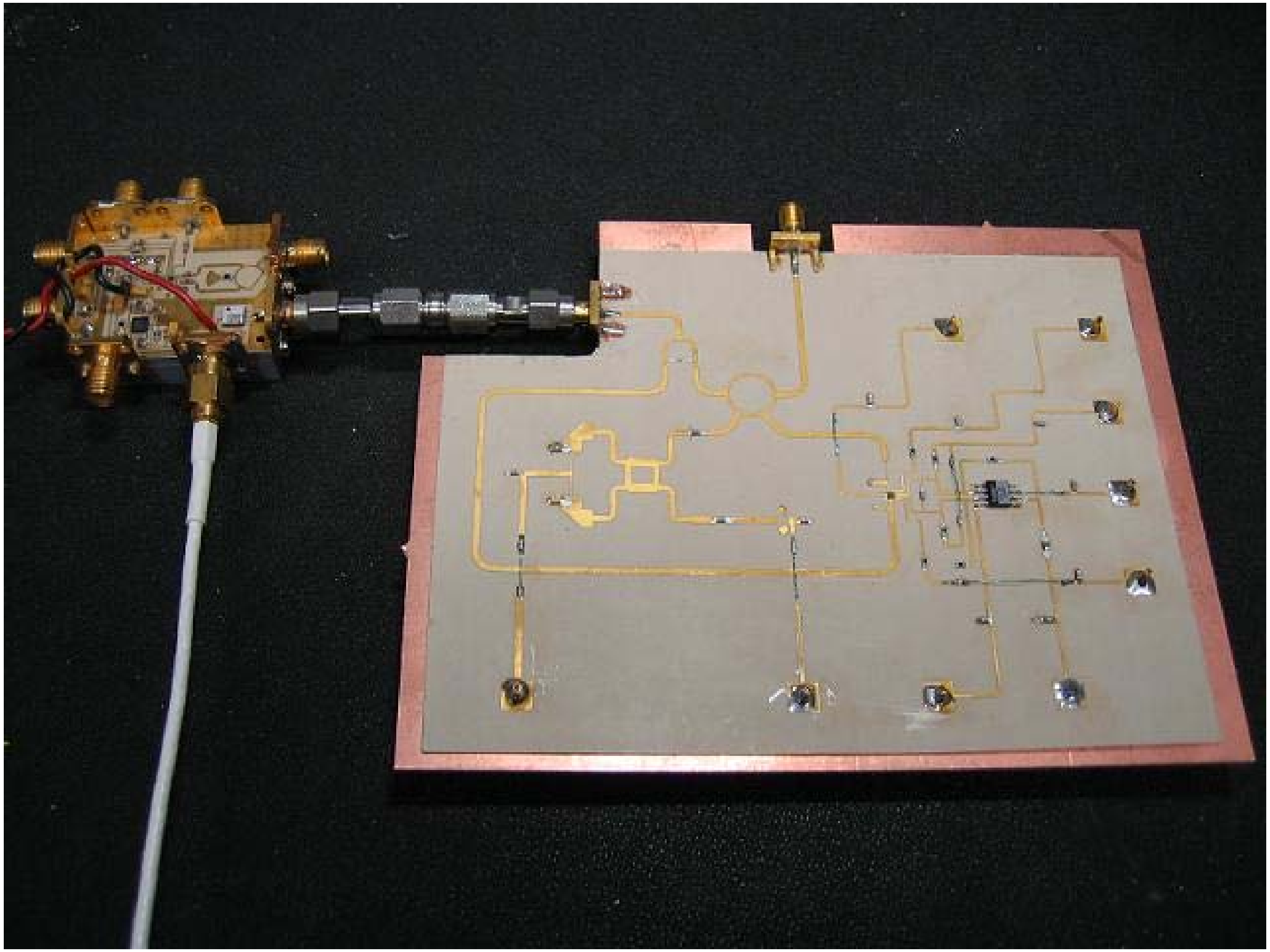
Simulation result:



PCB:



PCB of the Final Radar System

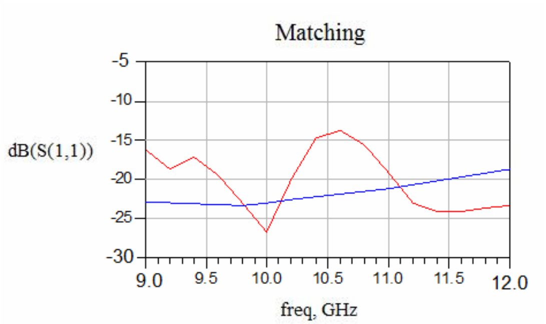


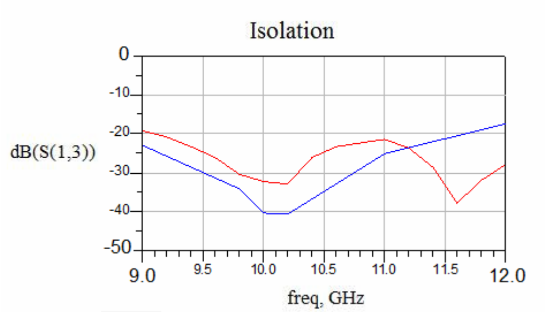
Test Results

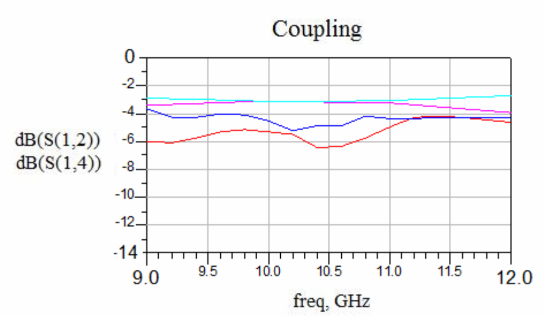
PCB VS Momentum

NWA

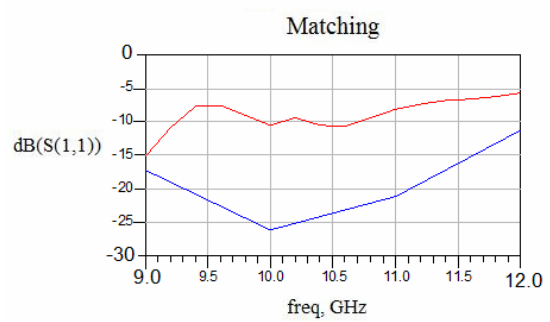
Rat-race coupler

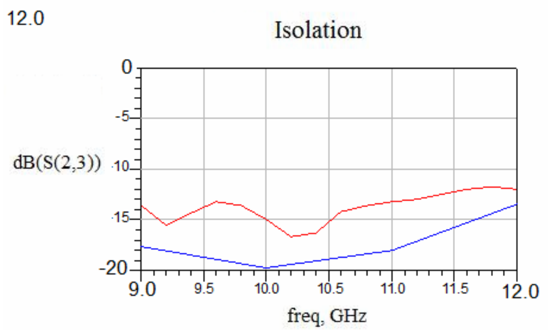


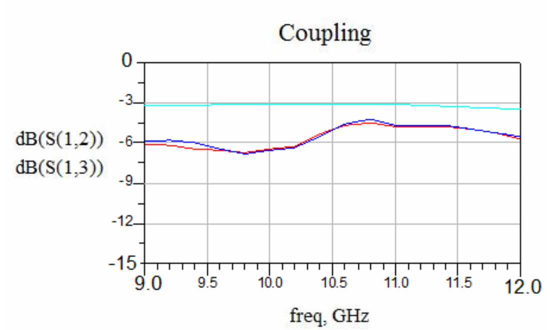




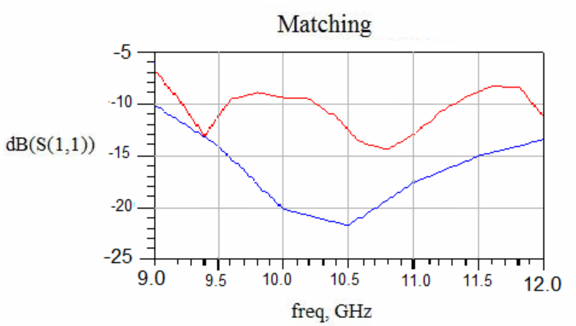
Power divider

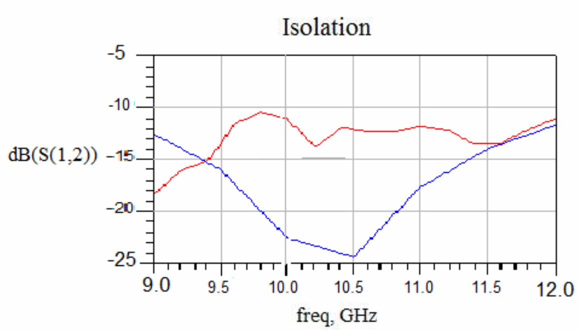


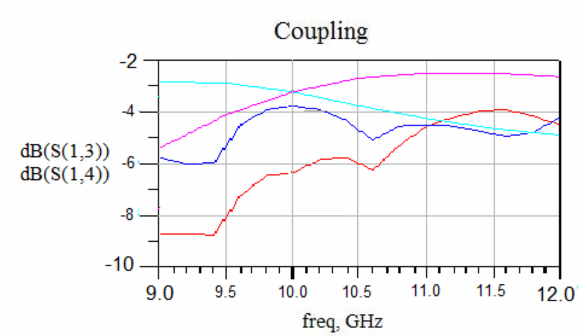




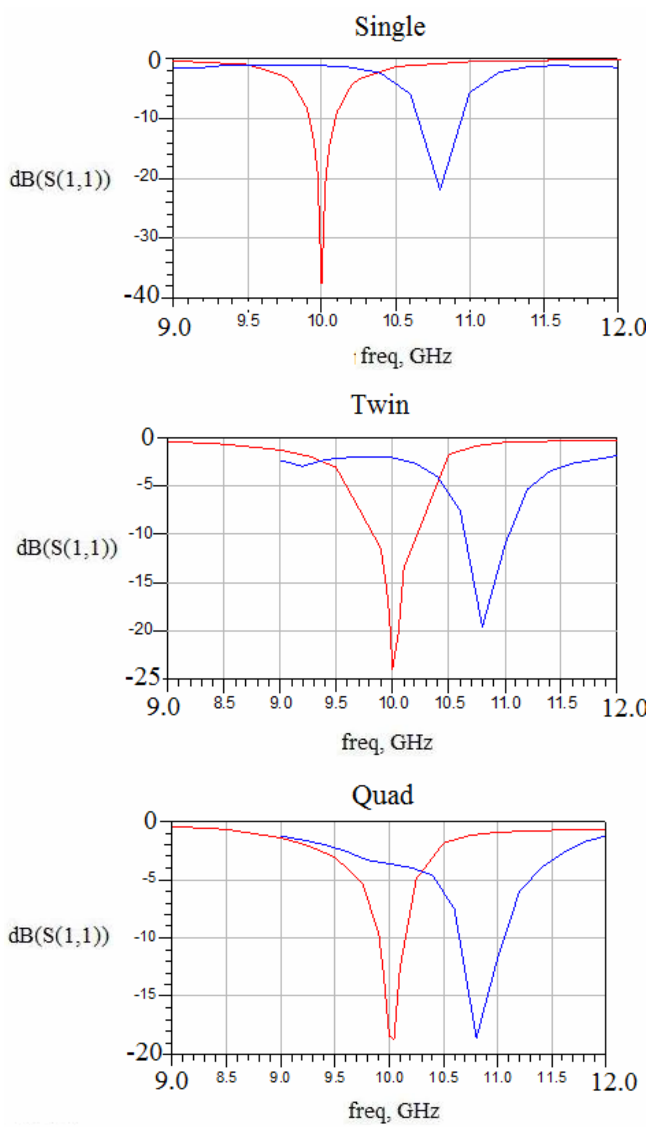
Branch-line coupler



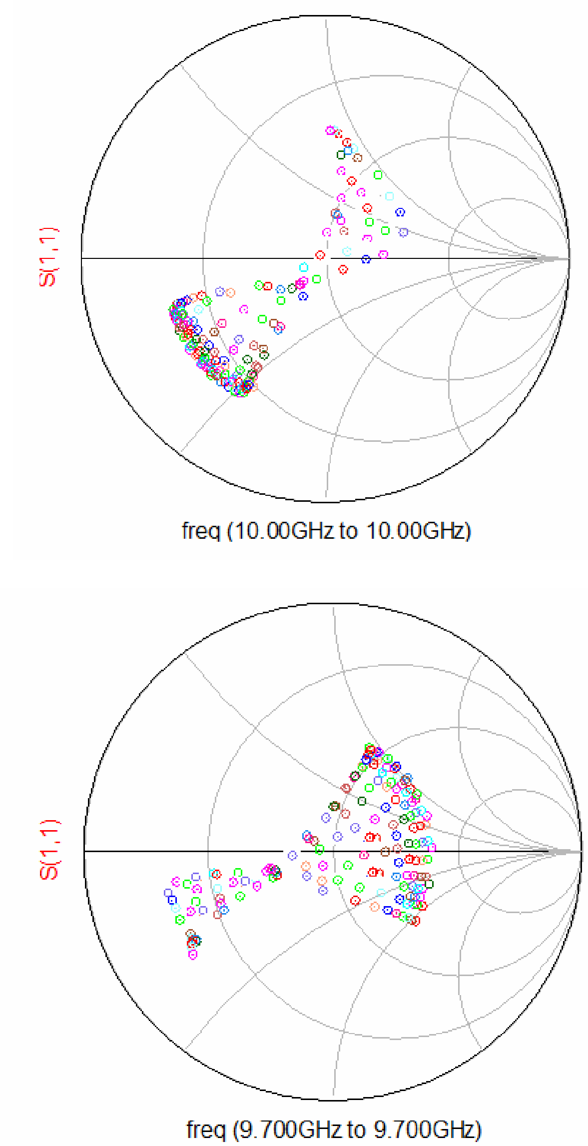




Antenna PCB VS Momentum



Tuner



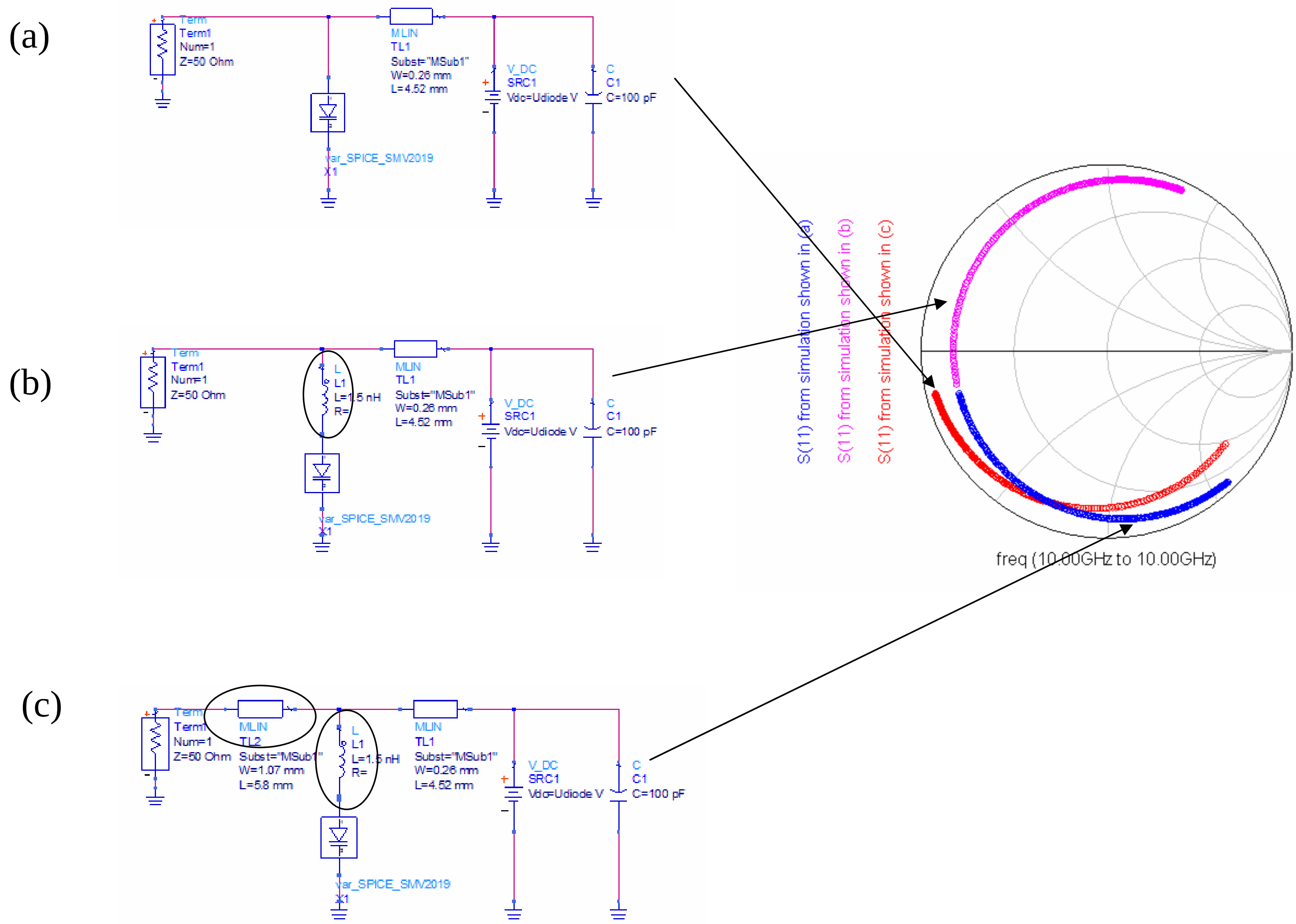
→ Phase shift is not enough;
FET works good.

↓

Too high series inductance

↓

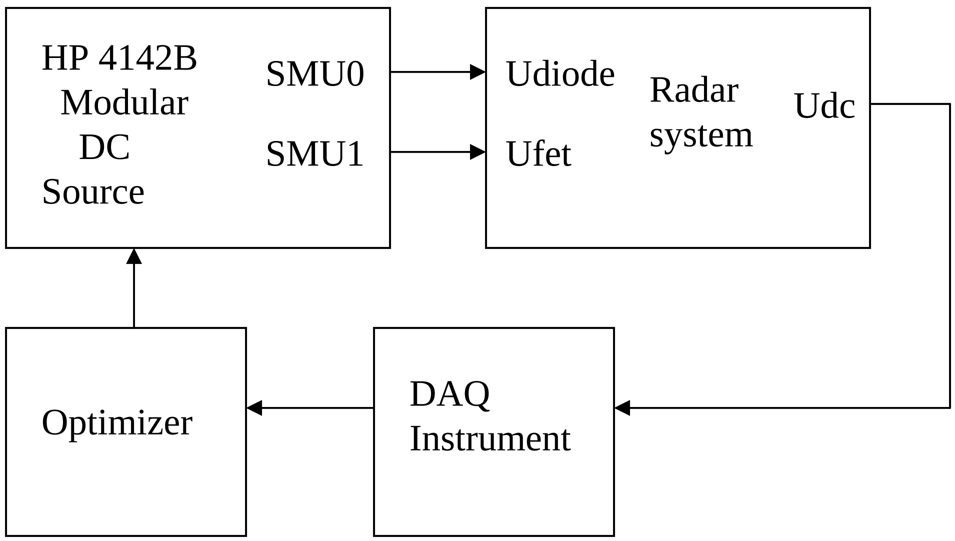
Two ways to improve



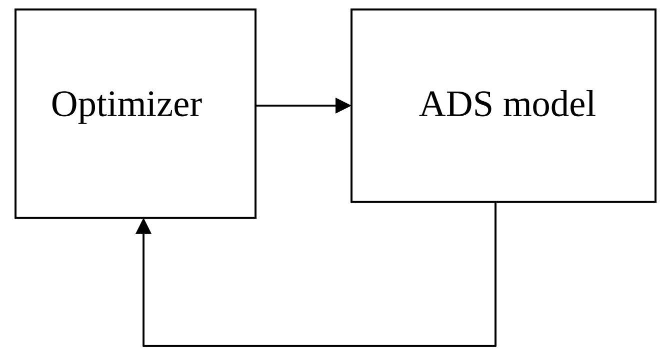
(a)
Term
Term1
Num=1
Z=50 Ohm
MLIN
TL1
Subst="MSub1"
W=0.26 mm
L=4.52 mm
V_DC
SRC1
Vdc=Udiode V
C
C1
C=100 pF
var_SPICE_SMV2019
X1
(b)
Term
Term1
Num=1
Z=50 Ohm
L
L1
L=1.5 nH
R=
MLIN
TL1
Subst="MSub1"
W=0.26 mm
L=4.52 mm
V_DC
SRC1
Vdc=Udiode V
C
C1
C=100 pF
var_SPICE_SMV2019
X1
(c)
Term
Term1
Num=1
Z=50 Ohm
MLIN
TL2
Subst="MSub1"
W=1.07 mm
L=5.8 mm
L
L1
L=1.5 nH
R=
MLIN
TL1
Subst="MSub1"
W=0.26 mm
L=4.52 mm
V_DC
SRC1
Vdc=Udiode V
C
C1
C=100 pF
var_SPICE_SMV2019
X1
S(11) from simulation shown in (a)
S(11) from simulation shown in (b)
S(11) from simulation shown in (c)
freq (10.00GHz to 10.00GHz)

Controller System

Real control system



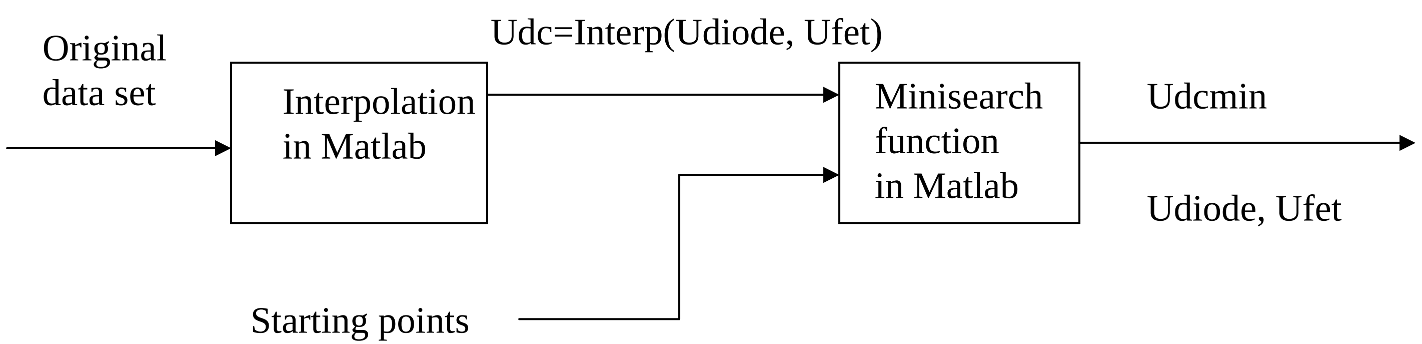
Simulated control system



Control algorithm

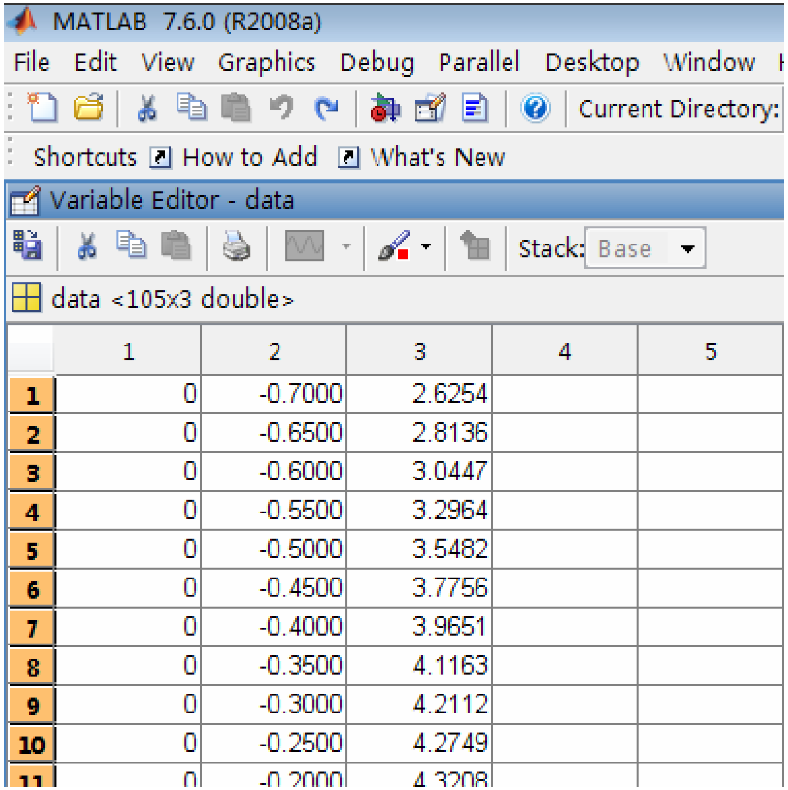
Aim:
Minimize Udc

$$Udc = f(Ufet, Udiode)$$

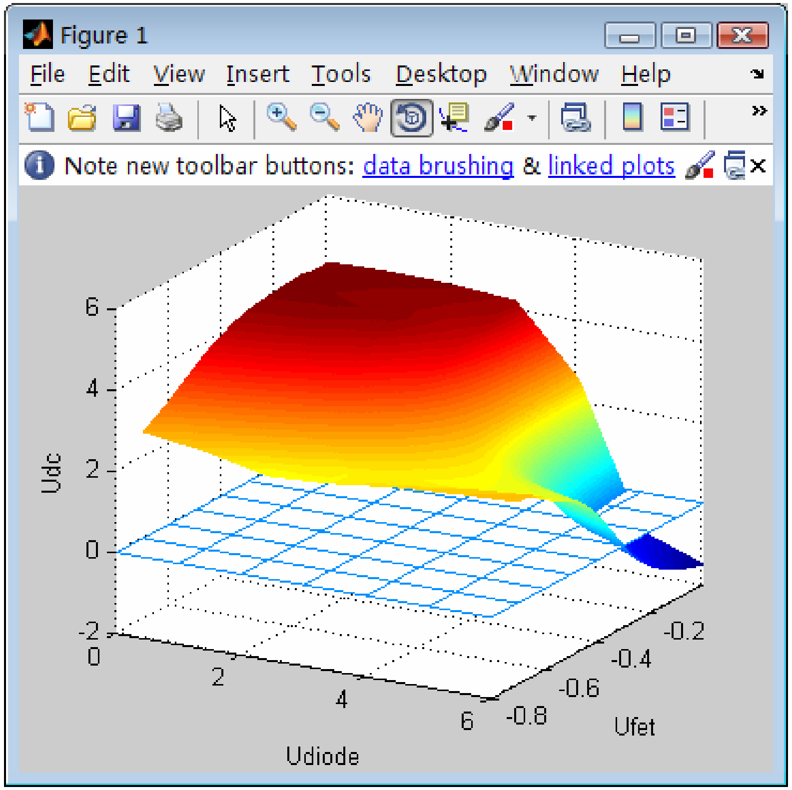


Original data set, Column 1 is Udiode and Column 2 is Ufet. Column 3 is Udc.

Three dimentional plotted graph



	1	2	3	4	5
1	0	-0.7000	2.6254		
2	0	-0.6500	2.8136		
3	0	-0.6000	3.0447		
4	0	-0.5500	3.2964		
5	0	-0.5000	3.5482		
6	0	-0.4500	3.7756		
7	0	-0.4000	3.9651		
8	0	-0.3500	4.1163		
9	0	-0.3000	4.2112		
10	0	-0.2500	4.2749		
11	0	-0.2000	4.3208		

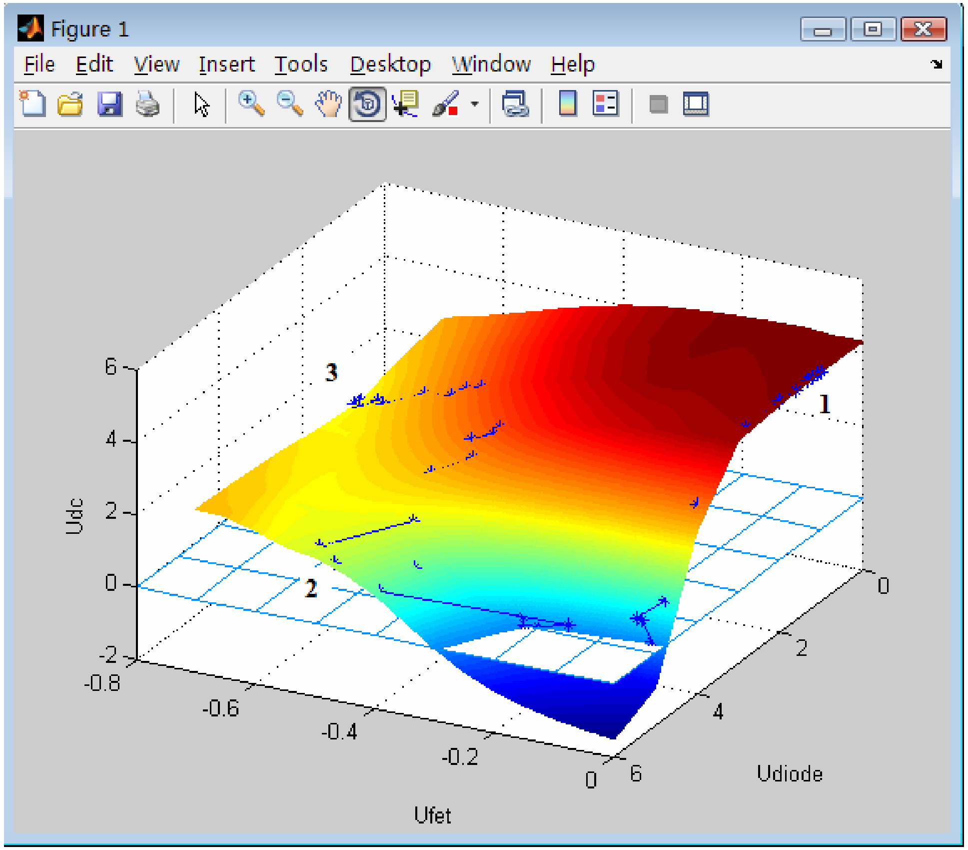


Examples

1. [x, fval, history, DC] = func2 ([1, 0])
   Result: x = 4.7380 -0.0219
   fval = 2.5215e-005

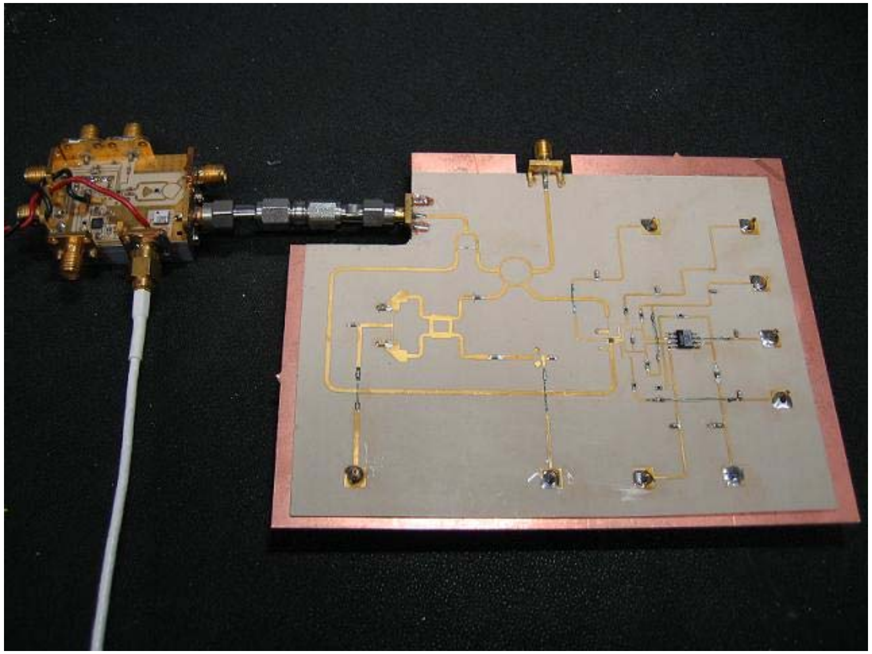
2. [x,fval,history,DC]=func2([3,-0.4])
   Result: x = 4.9778 -0.2191
   fval = 5.0413e-010

3. [x,fval,history,DC]=func2([2,-0.5])
   Result: x = 2.0001 -0.7000
   fval = 2.0723



Conclusions

This master thesis developed a dynamic method to minimize the DC offset at the output of the mixer. A demonstrator was built on an RF grade circuit board (PCB) working at an RF of 10 GHz and consisting of a voltage controlled oscillator (VCO), a Rat- race coupler, a power divider, a tunable impedance network, a Gilbert cell mixer. The hardware is shown below.

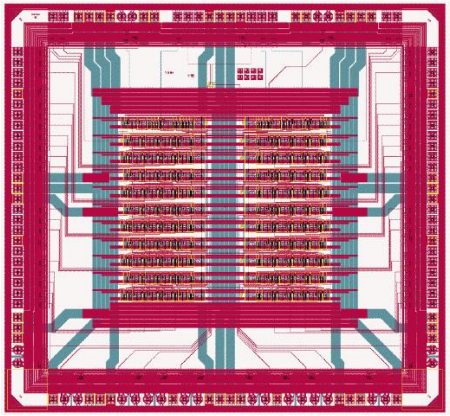


Further Work

- There is a large space for the optimization of the tuner. Some methods can be found out to reduce the series inductance in order to increase the phase shift, which will lead to a larger range of realizable impedance values as shown in the ADS simulation.

- The performance of the dynamic method to minimize the DC offset can be improved by using an I/Q mixer. An IQ-mixer consists of two balanced mixers and two hybrids. It provides two IF signals with equal amplitudes which are in phase quadrature. Two outputs provide two DC values which can be used better to control the two control voltages for the tuner.

- In the future, this work can be transferred into an integrated circuit solution working at much higher frequencies (e.g. 77) based on CMOS or BICMOS technology, where resistors, capacitors, diodes, transistors and multi level metals conductors are available.



A 10-bit data multiplexor manufactured in a SiGe BiCMOS process.

Appendix A

Patch Antenna

- Let the substrate dielectric constant, thickness, patch length, patch width, be denoted by ε_r, h, L, W respectively.
- In this experiment the patch will be fed by a microstrip transmission line, which usually has a 50 Ohm impedance. The antenna is usually fed at the radiating edge along the width (W) as it gives good polarisation, however the disadvantages are the spurious radiation and the need for impedance matching.
- Here, an inset feed is used to match the antenna, because the resistance varies as a cosine squared function along the length of the patch. A 50 Ohm can be found in a distance from the edge of the patch. This distance is called the inset distance.

1) Width of the patch

$$W = \frac{c}{2f_0\sqrt{\frac{\varepsilon_r + 1}{2}}}$$

Where c = the velocity of light

f_0 = operating frequency

2) Because the electric field lines reside in the substrate and parts of some lines in air. This transmission line cannot support pure transverse-electric-magnetic (TEM) mode of transmission, since the phase velocities would be different in the air and the substrate, an effective dielectric constant must be obtained in order to account for the fringing and the wave propagation in the line.

Effective dielectric constant:

$$\varepsilon_{reff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}(1 + 12\frac{h}{W})^{-\frac{1}{2}}$$

3) The length may also be specified by calculating the half-wavelength value and then subtracting a small length to take into account the fringing fields as:

$$L = L_{eff} - 2\Delta L$$

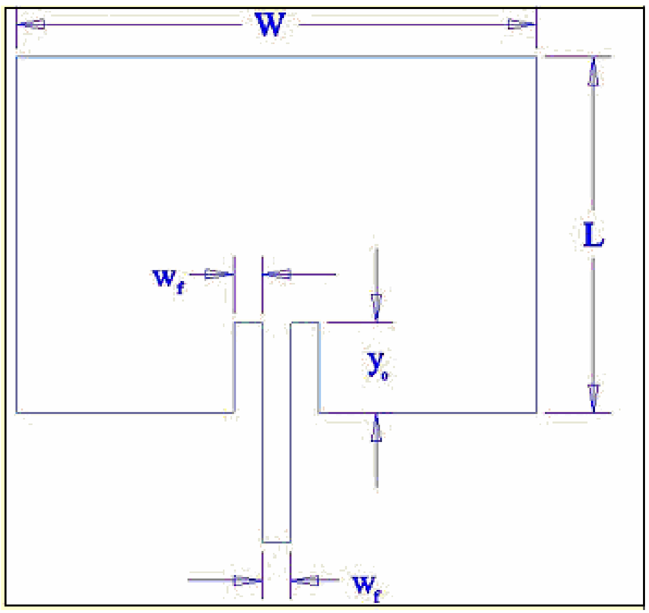
$$\Delta L = 0.412h \frac{(\varepsilon_{reff} + 0.3)(\frac{W}{h} + 0.264)}{(\varepsilon_{reff} - 0.258)(\frac{W}{h} + 0.8)}$$

4) For a given resonance frequency, the effective length is given as:

$$L_{eff} = \frac{c}{2 f_0 \sqrt{\varepsilon_{reff}}}$$

We get:

W=9.945mm, L=7.801mm



We use the curve fit formula to find the exact inset length to achieve 50 Ohm input impedance for the commonly used thin dielectric substrates.

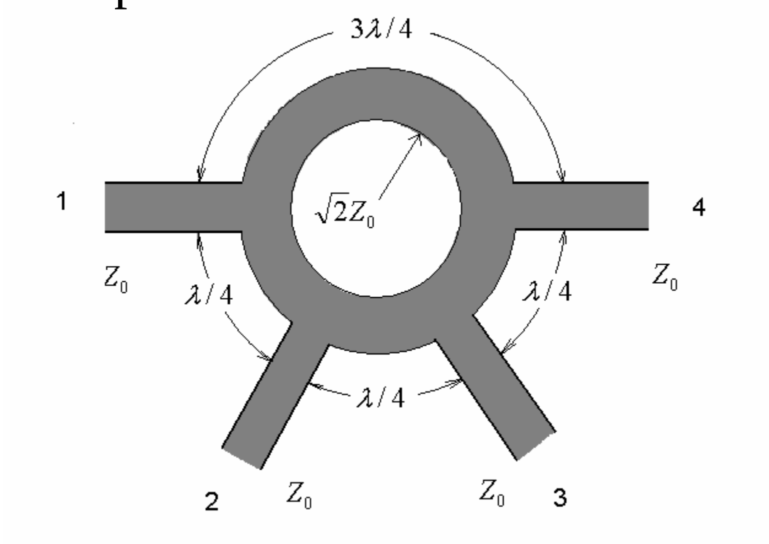
$$y_0 = 10^{-4}\left\{\begin{array}{l} 0.001669\varepsilon_r^{\,7} + 0.1376\varepsilon_r^{\,6} - 6.1783\varepsilon_r^{\,5} + 93.187\varepsilon_r^{\,4} - 682.69\varepsilon_r^{\,3} \\ + 2561.9\varepsilon_r^{\,2} - 4043\varepsilon_r + 6697 \end{array}\right\} \times \frac{L}{2}$$

we get:

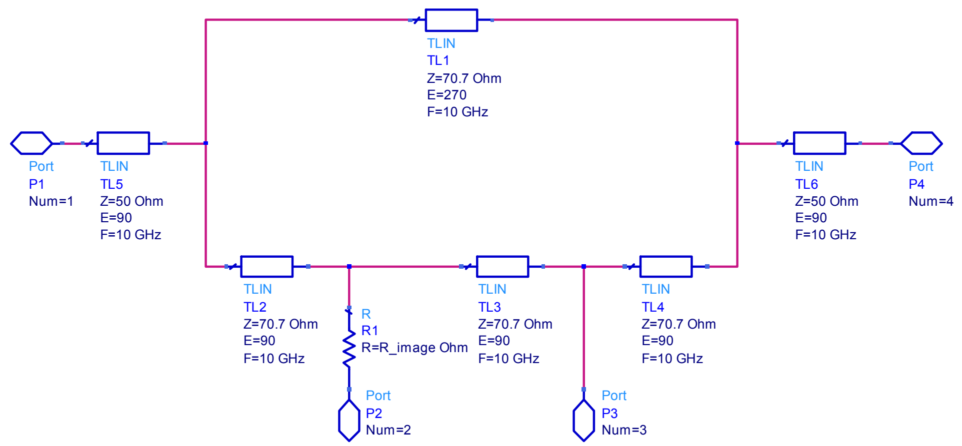
$$y_0 = 2.22$$

Rat-race Coupler

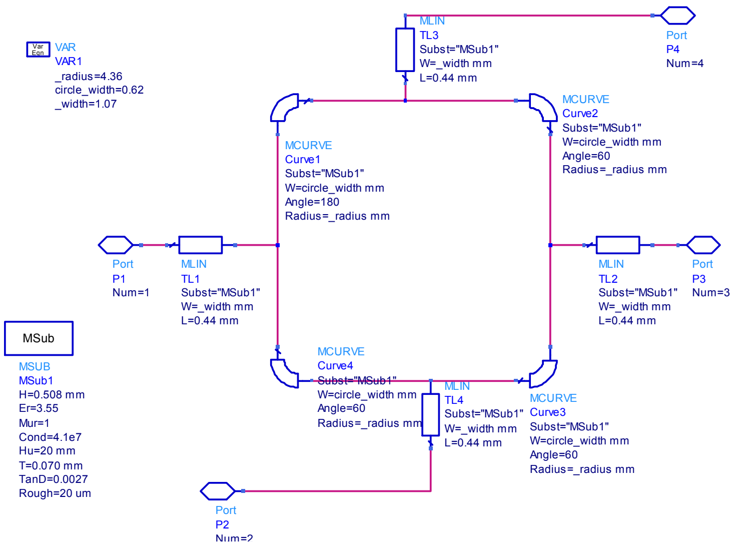
Principle



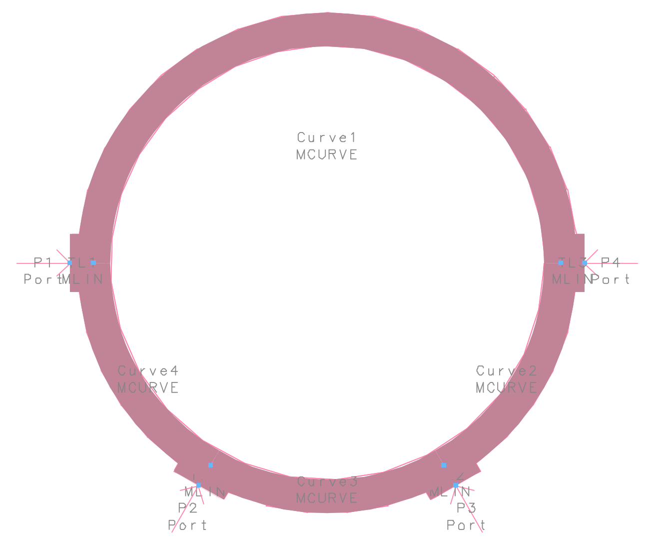
Basic circuit



Real circuit schematic

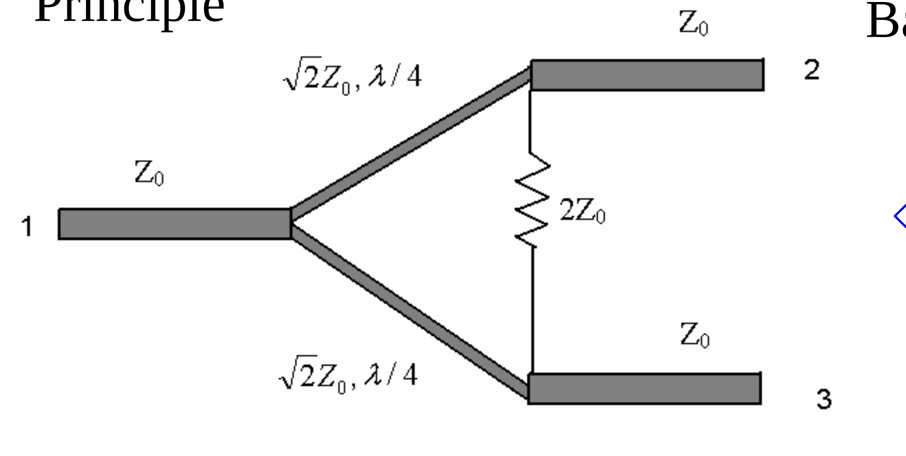


ADS Layout

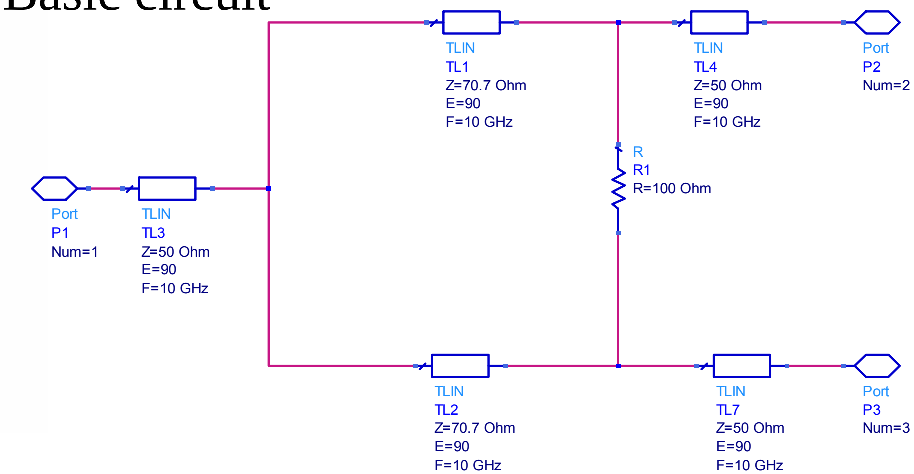


Wilkinson power divider

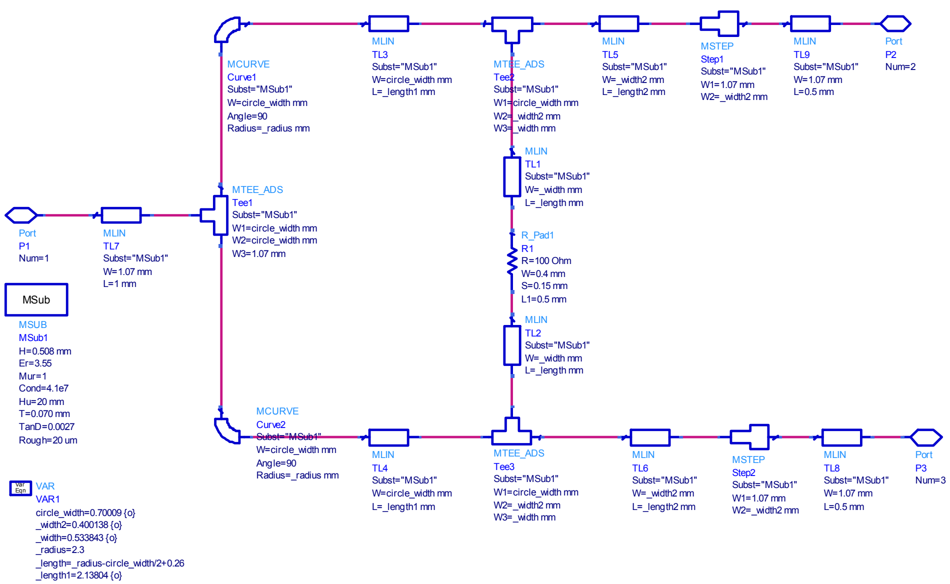
Principle



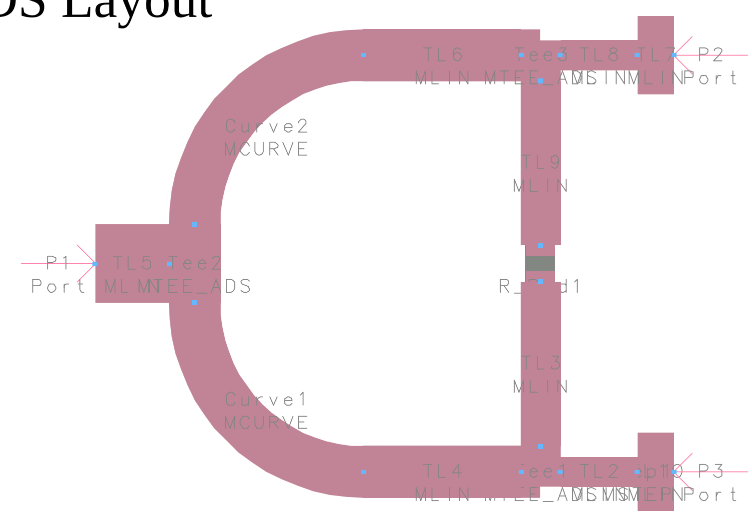
Basic circuit



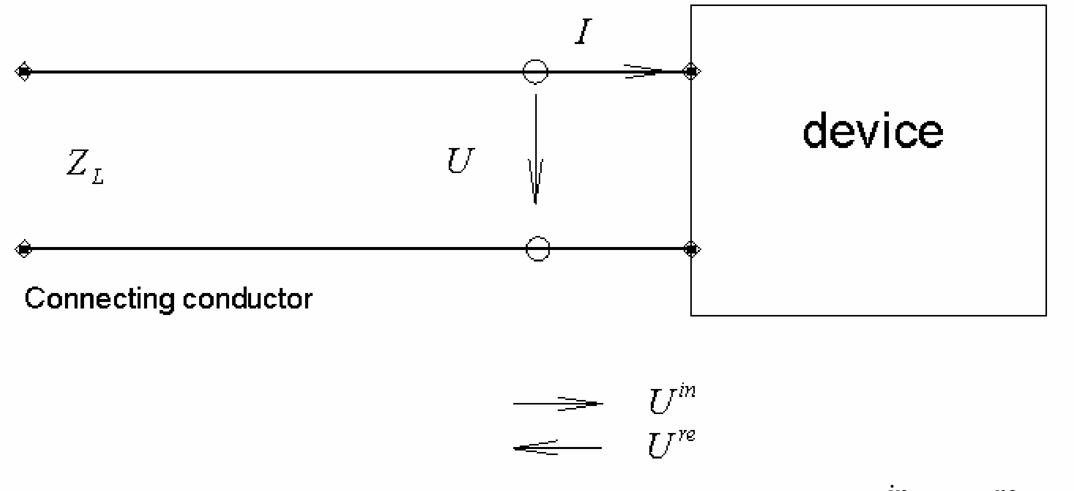
Real circuit schematic



ADS Layout



wave variable



$$U = U^{in} + U^{re}$$

$$I = (U^{in} - U^{re}) / Z_L$$

Relative voltage and current: $u = \frac{U}{\sqrt{Z_L}}; [u] = \sqrt{W}$ $i = I \times \sqrt{Z_L}; [i] = \sqrt{W}$

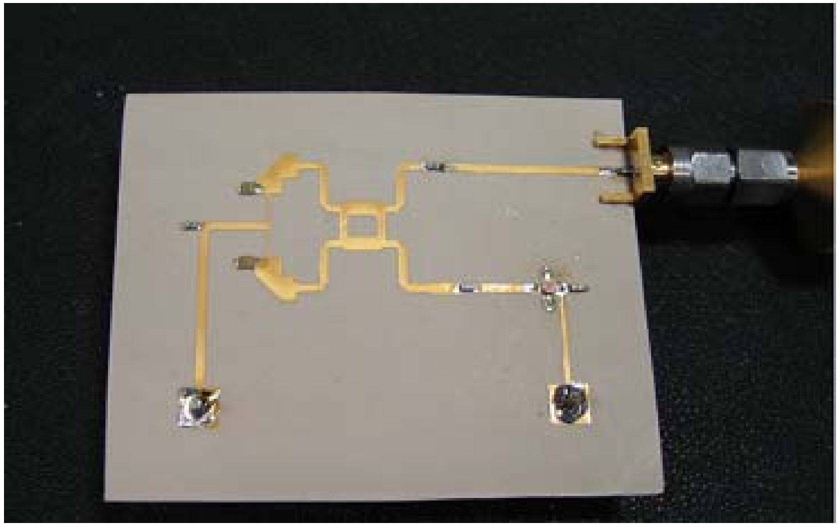
Wave variables: $a = \frac{U^{in}}{\sqrt{Z_L}}, b = \frac{U^{re}}{\sqrt{Z_L}}$

So $u = a + b; i = a - b$ $a = \frac{(u+i)}{2} = (\frac{U}{\sqrt{Z_L}} + I \times \sqrt{Z_L}) / 2$ $b = \frac{(u-i)}{2} = (\frac{U}{\sqrt{Z_L}} - I \times \sqrt{Z_L}) / 2$

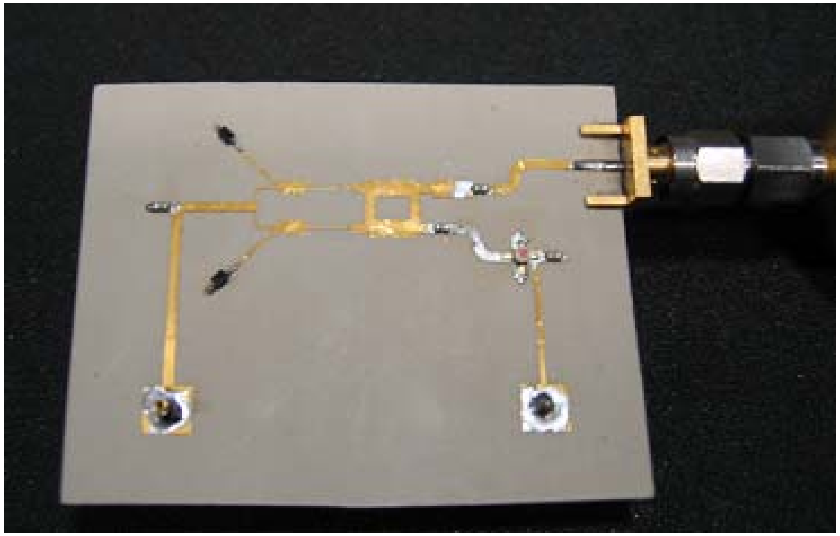
Power: $P^{in} = \frac{1}{2}|a|^2; P^{re} = \frac{1}{2}|b|^2$

Appendix B

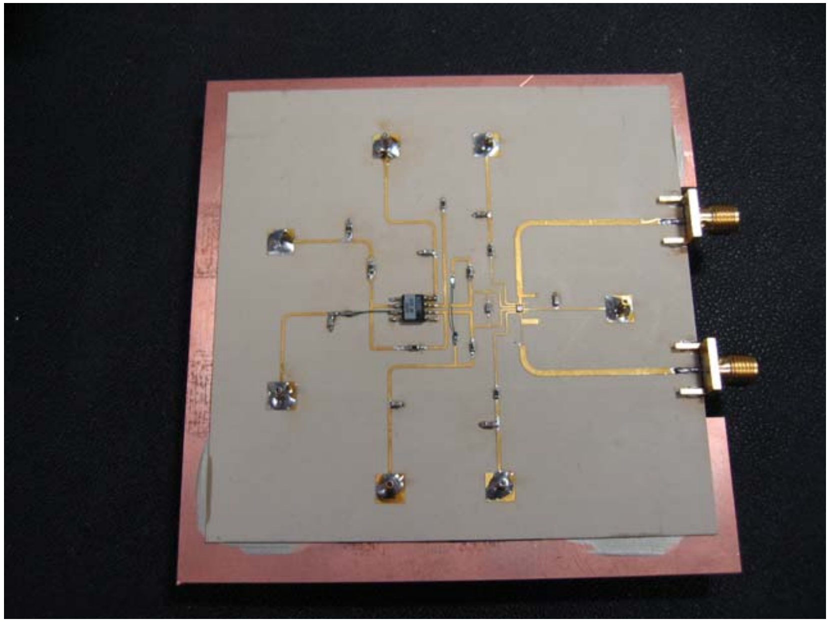
Tuner with Branchline coupler and SMV 2019-108

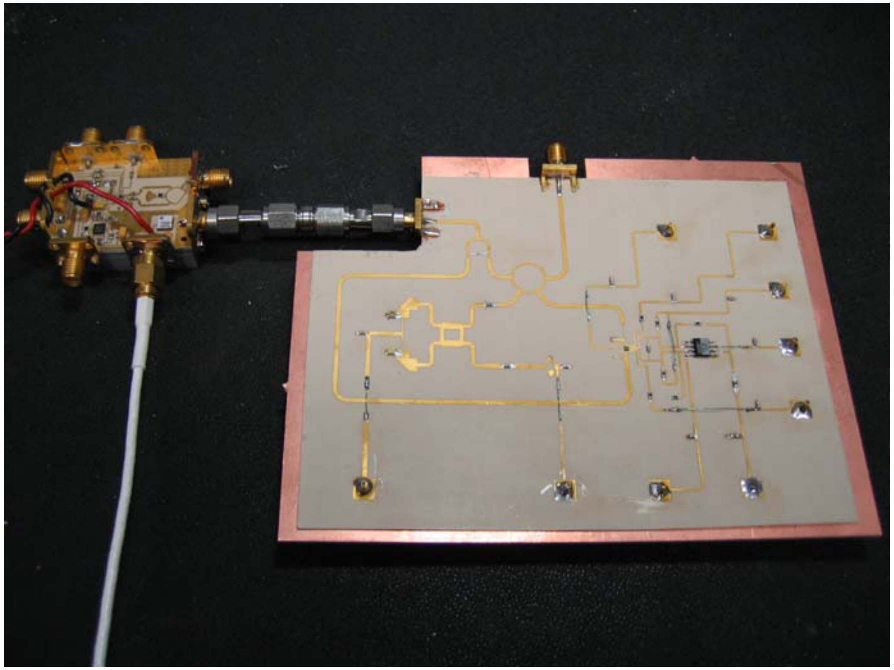


Tuner with Branchline coupler and SMV 1245-011



Mixer testing circuit board

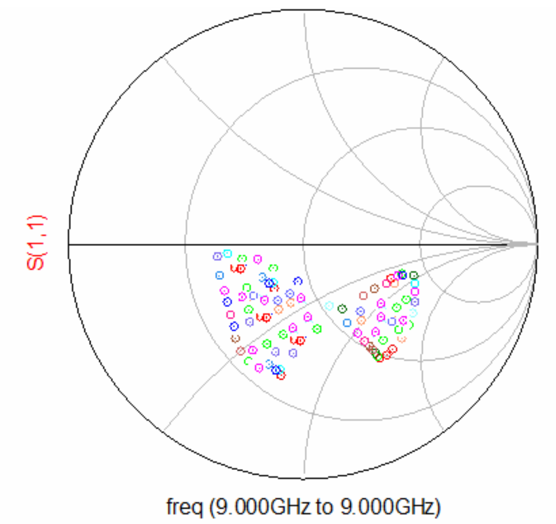


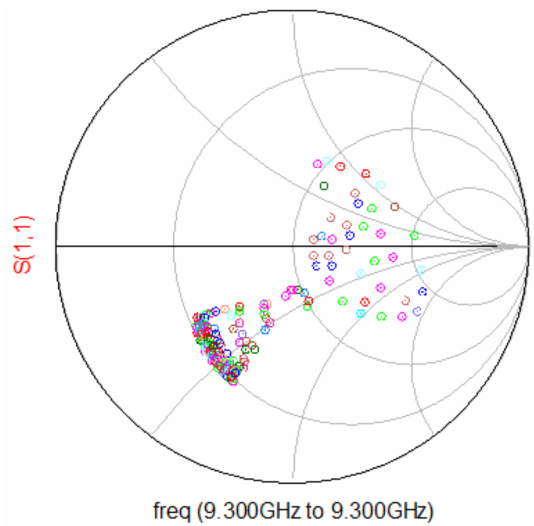


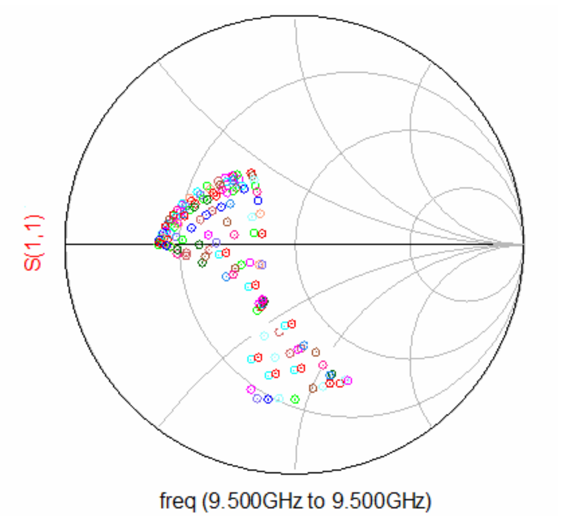
System circuit board

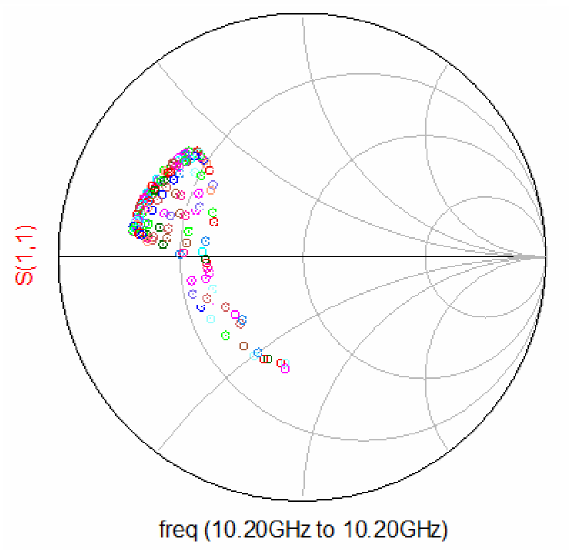
Appendix C

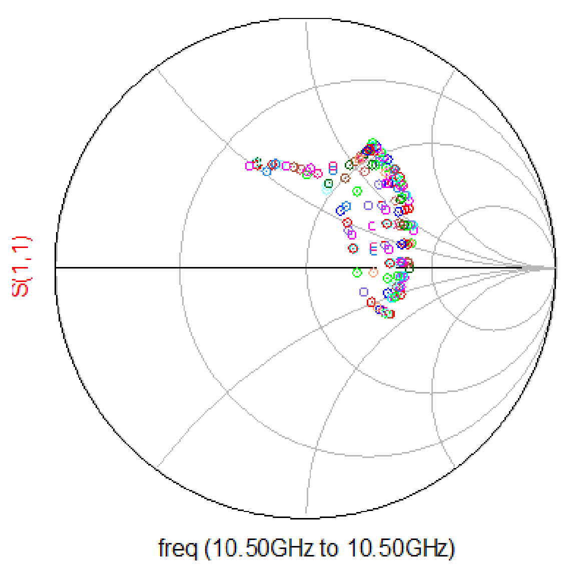
Tuner test results

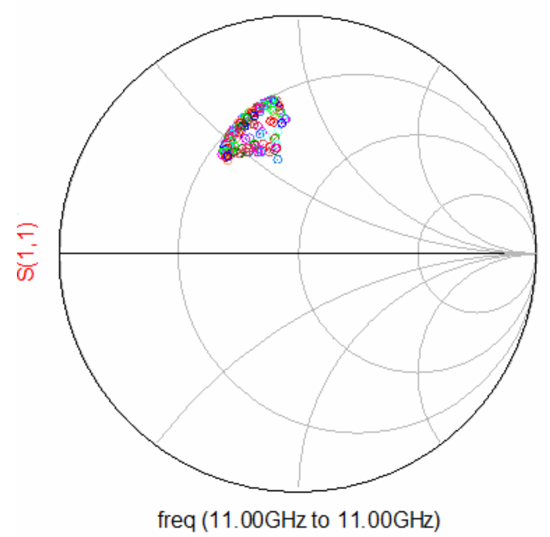












Appendix D

Interpolation

```
• function v3=interpolation(v1,v2)
• userdata = importdata('final.txt');
• data = userdata.data;
• Ufet=-0.7:0.05:0;
• Udiode=0:1:6;
• Udc1=data(1:15,3)';
• Udc2=data(16:30,3)';
• Udc3=data(31:45,3)';
• Udc4=data(46:60,3)';
• Udc5=data(61:75,3)';
• Udc6=data(76:90,3)';
• Udc7=data(91:105,3)';
• Udc=[Udc1;Udc2;Udc3;Udc4;Udc5;Udc6;Udc7];
• v3=interp2(Ufet,Udiode,Udc,v2,v1);
• v3=abs(v3);
```

Optimization

```
• function [x fval history DC] = func2(x0)
•    history = [];
•    options = optimset('OutputFcn', @myoutput);
•    [x fval] = fminsearch(@(x)
  interpolation(x(1),x(2)),x0,options);
•    function stop = myoutput(x,optimvalues,state);
•        stop = false;
•        if state == 'iter'
•          history = [history; x];
•        end
•    end
• DC=interpolation(history(:,1),history(:,2));
• plot3(history(:,1),history(:,2),DC,'-*')
• xlabel('Udiode'),ylabel('Ufet'),zlabel('Udc');
• grid on
• axis ([0 6 -0.8 0  -2 6])
• end
```