Basic Low Noise Amplifier design and implementation

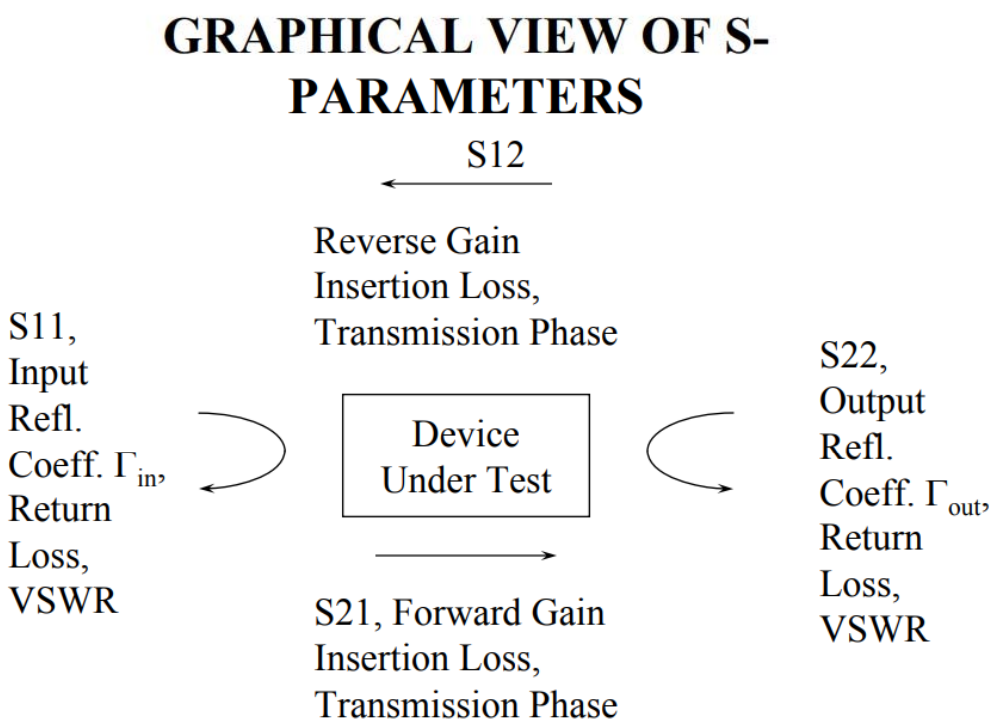
50 MHz and up, March 2020,

Goran Popovic AD6IW

Amplifiers are designed for:

- Gain
- Low noise
- Wideband
- Power
- Efficiency
- Linearity
- All above have different design procedure and requirements

Select part and start with S parameters



Touchstone s2p file, and noise parameters

```
! NEC Compound Semiconductor Devices Ltd.
! 22. July 2005
! NE3512S02
! VD = 2   ID = 10 mA
#  GHz   S   MA   R   50
!      f            S11                      S21                      S12                      S22
!     GHz      MAG      ANG           MAG      ANG           MAG      ANG           MAG      ANG
     2.000    0.972   -24.000        4.722   152.300        0.025    73.300        0.647   -17.900
     2.500    0.960   -30.200        4.685   145.500        0.031    68.900        0.638   -22.400
     3.000    0.945   -36.300        4.687   138.600        0.036    65.000        0.633   -26.600
     3.500    0.927   -42.300        4.670   131.900        0.042    60.900        0.622   -31.300
     4.000    0.907   -48.500        4.655   125.100        0.048    56.500        0.613   -35.800
     4.500    0.884   -55.300        4.624   118.000        0.053    52.800        0.601   -39.600
     5.000    0.860   -61.000        4.615   109.900        0.058    48.800        0.587   -46.000
     5.500    0.837   -68.000        4.574   104.300        0.063    44.300        0.569   -49.000
     6.000    0.808   -74.900        4.542    97.400        0.068    41.100        0.553   -52.600
     6.500    0.780   -81.900        4.506    90.500        0.073    36.600        0.535   -57.400
     7.000    0.752   -88.600        4.463    83.600        0.077    32.800        0.512   -61.600
     7.500    0.720   -95.500        4.416    76.800        0.081    29.200        0.493   -65.800
     8.000    0.687  -103.000        4.367    69.900        0.086    25.800        0.474   -70.400
     8.500    0.664  -110.600        4.315    63.000        0.089    21.600        0.448   -74.500
     9.000    0.630  -117.900        4.252    56.200        0.092    17.900        0.424   -77.700
     9.500    0.596  -126.000        4.167    49.600        0.095    14.900        0.401   -81.700
    10.000    0.573  -133.400        4.134    43.200        0.099    11.400        0.382   -86.700
    10.500    0.552  -141.900        4.078    36.400        0.102     8.300        0.355   -90.800
    11.000    0.531  -150.300        4.010    29.800        0.105     4.800        0.330   -95.500
    11.500    0.507  -158.900        3.959    23.200        0.109     1.900        0.305  -101.000
    12.000    0.495  -168.300        3.885    16.400        0.112    -1.400        0.280  -105.000
    12.500    0.475  -177.300        3.835    10.000        0.115    -4.400        0.251  -111.100
    13.000    0.469   173.600        3.763     3.800        0.117    -7.200        0.229  -116.600
    13.500    0.458   165.500        3.701    -2.600        0.121   -10.500        0.204  -123.000
    14.000    0.452   154.200        3.644    -9.300        0.124   -14.100        0.176  -130.400
    14.500    0.454   145.200        3.583   -15.600        0.128   -17.000        0.152  -140.900
    15.000    0.456   135.700        3.519   -22.200        0.131   -20.600        0.127  -152.400
    15.500    0.458   126.700        3.460   -28.600        0.134   -23.800        0.108  -168.900
    16.000    0.463   116.300        3.395   -35.200        0.137   -27.100        0.107   168.400
    16.500    0.485   107.900        3.325   -41.600        0.140   -30.400        0.099   147.400
    17.000    0.490    99.200        3.263   -48.200        0.143   -33.900        0.113   125.900
    17.500    0.507    89.900        3.199   -54.700        0.147   -37.900        0.138   109.300
    18.000    0.525    81.800        3.129   -61.300        0.149   -41.700        0.161    98.300

!      f       Fmin         Gammaopt          Rn/50
!     GHz       dB        MAG      ANG          -
     2.000    0.320      0.866    14.500      0.289
     2.500    0.320      0.838    18.800      0.276
     3.000    0.320      0.814    23.100      0.264
     3.500    0.320      0.793    27.500      0.252
     4.000    0.320      0.774    32.000      0.241
     4.500    0.320      0.758    36.600      0.229
     5.000    0.320      0.742    41.300      0.218
     5.500    0.330      0.727    46.100      0.206
     6.000    0.330      0.713    51.000      0.194
     6.500    0.340      0.699    56.200      0.182
     7.000    0.340      0.684    61.500      0.169
     7.500    0.350      0.669    67.000      0.156
     8.000    0.360      0.654    72.700      0.143
     8.500    0.360      0.637    78.700      0.130
     9.000    0.370      0.619    84.900      0.116
     9.500    0.390      0.601    91.300      0.103
    10.000    0.400      0.581    98.100      0.090
    10.500    0.410      0.561   105.100      0.078
    11.000    0.420      0.539   112.500      0.067
    11.500    0.440      0.517   120.200      0.056
    12.000    0.450      0.495   128.200      0.047
    12.500    0.470      0.472   136.600      0.040
```

Gsource_max = 1/1-[S11]^2   1.43dB

Gload max = 1/1-[S22]^2   1.22dB

Go = [S21]^2   11.54dB

Gtu max = 1.43 + 1.22 + 11.54   = 14.19dB

MSG = S21 / S12   16.01dB

Basic amplifier design steps

- Amplifier max. gain design, unilateral S12 = 0, or bilateral conjugate match
- Stability circle, amplifier must be unconditional stable.
- Find optimum impedances for desired Gain,

  Gamma opt. for low Noise Figure, and Gamma load.
- Match device with appropriate network circuits.
- Optimize LNA, it is trade off between NF, Gain, and Stability.
- Design LNA with S parameters and set of equation's, is tedious and time consuming but it is necessary to understanding design procedure.
- Computer simulation software, save time and get better results

Basic equations, conjugate gain amplifier approach

Design Equations Using S-Parameters

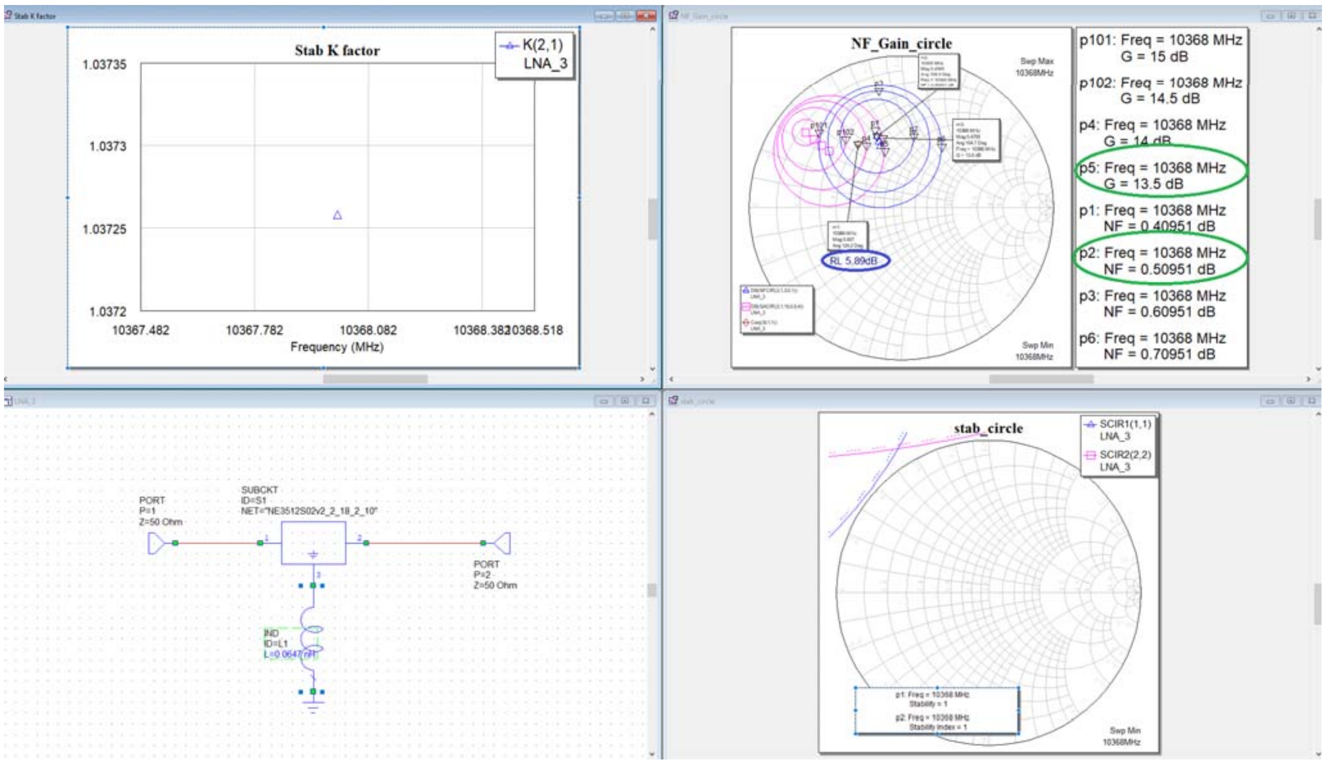
Eq		*Remarks*
(1)	$MSG_{dB} = 10 \log \left\lvert \frac{S_{21}}{S_{12}} \right\rvert$	max. stable gain
(2)	$D = (S_{11} S_{22}) - (S_{12} S_{21})$	
(3)	$K = \frac{1 + \lvert D\rvert^2 - \lvert S_{11}\rvert^2 - \lvert S_{22}\rvert^2}{2\lvert S_{12}\rvert \lvert S_{21}\rvert}$	Stability Factor
(4)	$B_1 = 1 + \lvert S_{11}\rvert^2 - \lvert S_{22}\rvert^2 - \lvert D\rvert^2$	
(5)	$MAG_{dB} = MSG_{dB} + 10 \log \left(K \pm \sqrt{K^2 - 1}\right)$	Use minus before radic positive, and plus when
(6)	$C_1 = S_{11} - (D \times S_{22}^*)$	S_{22}^* = conjugate of S_2
(7)	$\lvert\Gamma_{in}\rvert = \left[\frac{B_1 \pm \sqrt{B_1^2 - 4\lvert C_1\rvert^2}}{2\lvert C_1\rvert}\right]$	Use minus before radic positive, and plus when
(8)	$B_2 = 1 + \lvert S_{22}\rvert^2 - \lvert S_{11}\rvert^2 - \lvert D\rvert^2$	
(9)	$C_2 = S_{22} - (D \times S_{11}^*)$	S_{11}^* = conjugate of S
(10)	$\lvert\Gamma_{out}\rvert = \left[\frac{B_2 \pm \sqrt{B_2^2 - 4\lvert C_2\rvert^2}}{2\lvert C_2\rvert}\right]$	Use minus before radic positive, and plus when
(11)	$\Gamma_{in} = \lvert\Gamma_{in}\rvert \underline{/\theta\, C_1}$	
(12)	$\Gamma_{out} = \lvert\Gamma_{out}\rvert \underline{/\theta\, C_2}$	

$$\Gamma_S = \left[S_{11} + \frac{S_{12} S_{21} \Gamma_L}{1 - (\Gamma_L \cdot S_{22})}\right]^*$$

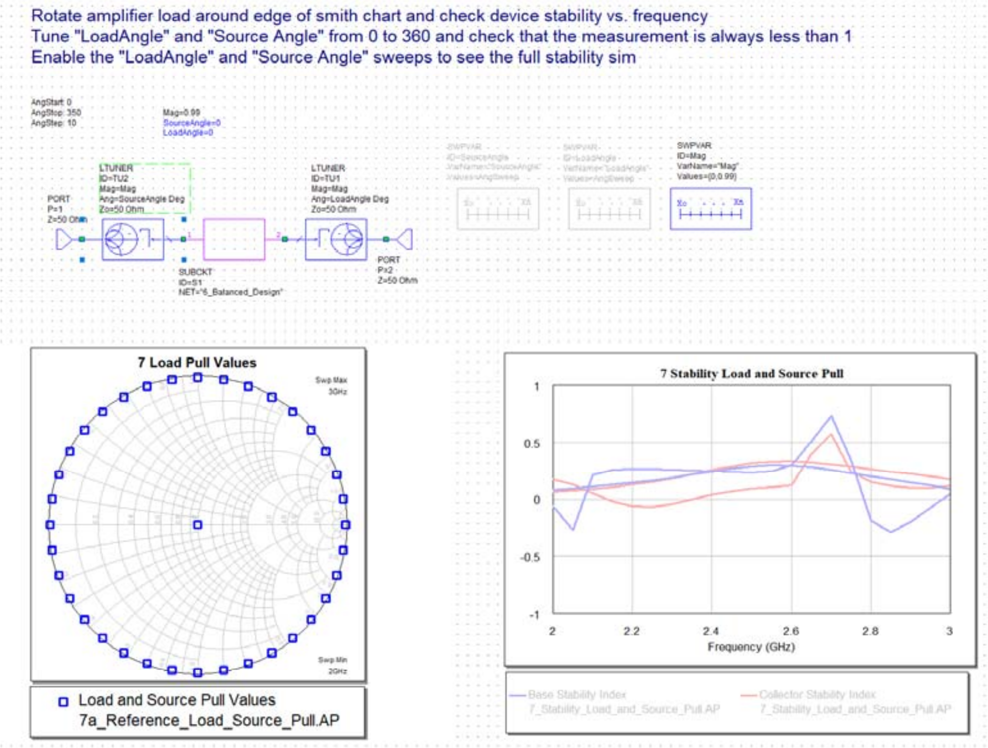
Design Te

- Change S

Stability, Gain, NF circles simulation



Load pull stability method



Using Calculator

CALCULATOR INPUTS

Zo= 50 (ohms)	F= 10368 MHz

Source and Load Impedances

Z_S= 50 j	Z_L= 50 j

Source and Load L-Matching Networks

Source: (•) Low Pass ( ) High Pass	Load: (•) Low Pass ( ) High Pass

S-Parameters (( ) Rectangular Or (•) Polar(Degrees))

S_{11}=	.5228	-130.5
S_{12}=	0.0909	26.9
S_{21}=	3.912	39.82
S_{22}=	.3959	-80.19

Starting point

Rollet Stability Factor (K)

K= 1.01

Maximum Allowable Gain

MAG= 36.7 (Gain) 15.6 (Db)

Conjugate Input and Output Reflection Coefficients

$GAMA_L$ 0.855 -249 (Polar)

$GAMA_S$ 0.888 213 (Polar)

Input and Output Impedances Looking into Amp

Z_{SM} 3.21 -14.6 j

Z_{LM} 5.75 -34.2 j

L-Network Matching Components

Source	Load
C= 1.17 pf, L= 0.411 nH	C= 0.852 pf, L= 0.770 nH
Q_s= 3.82	Q_L= 2.78
☐ Parallel leg of L-network near amp	☐ Parallel leg of L-network near amp

Equations:

$D_s=S_{11}S_{22} - S_{12}S_{21}$

$K=(1+|D_s|^2-|S_{11}|^2-|S_{22}|^2)/(2|S_{21}||S_{12}|)$

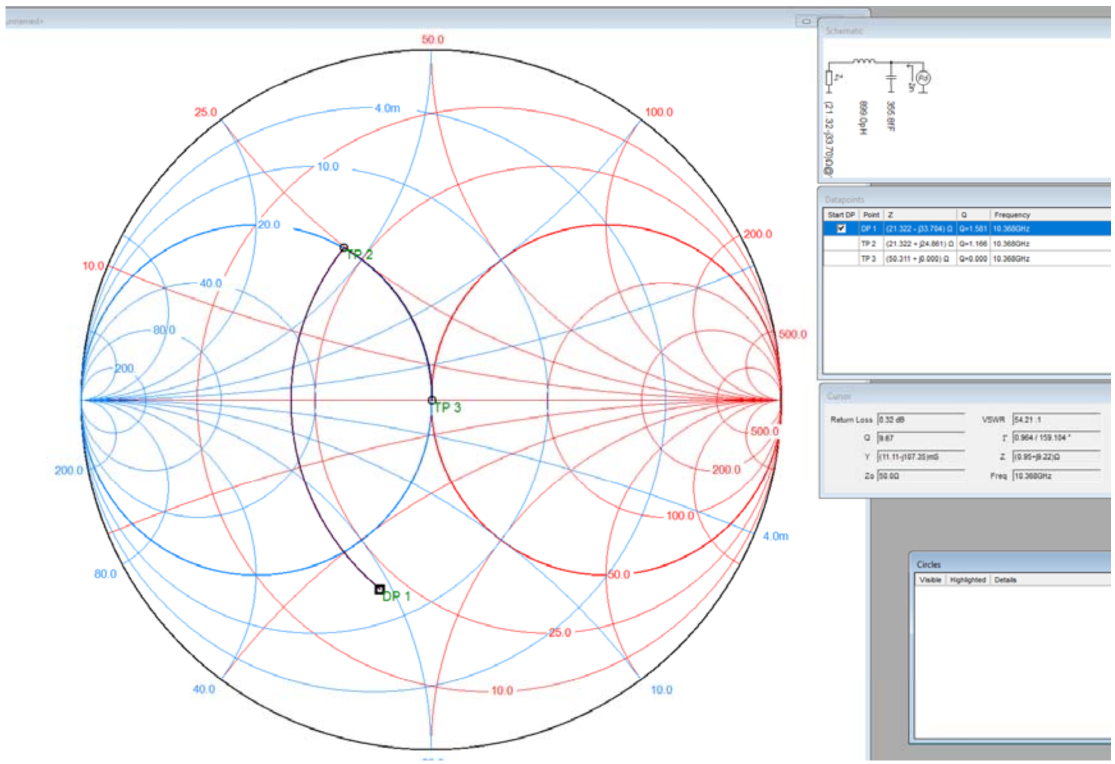
$B1=1+|S_{11}|^2 - |S_{22}|^2 - |D_s|^2$

MAG= $|S_{21}|/|S_{21}|(K\pm sqrt(K^2-1)$ -> if B is negative use +, otherwise -.

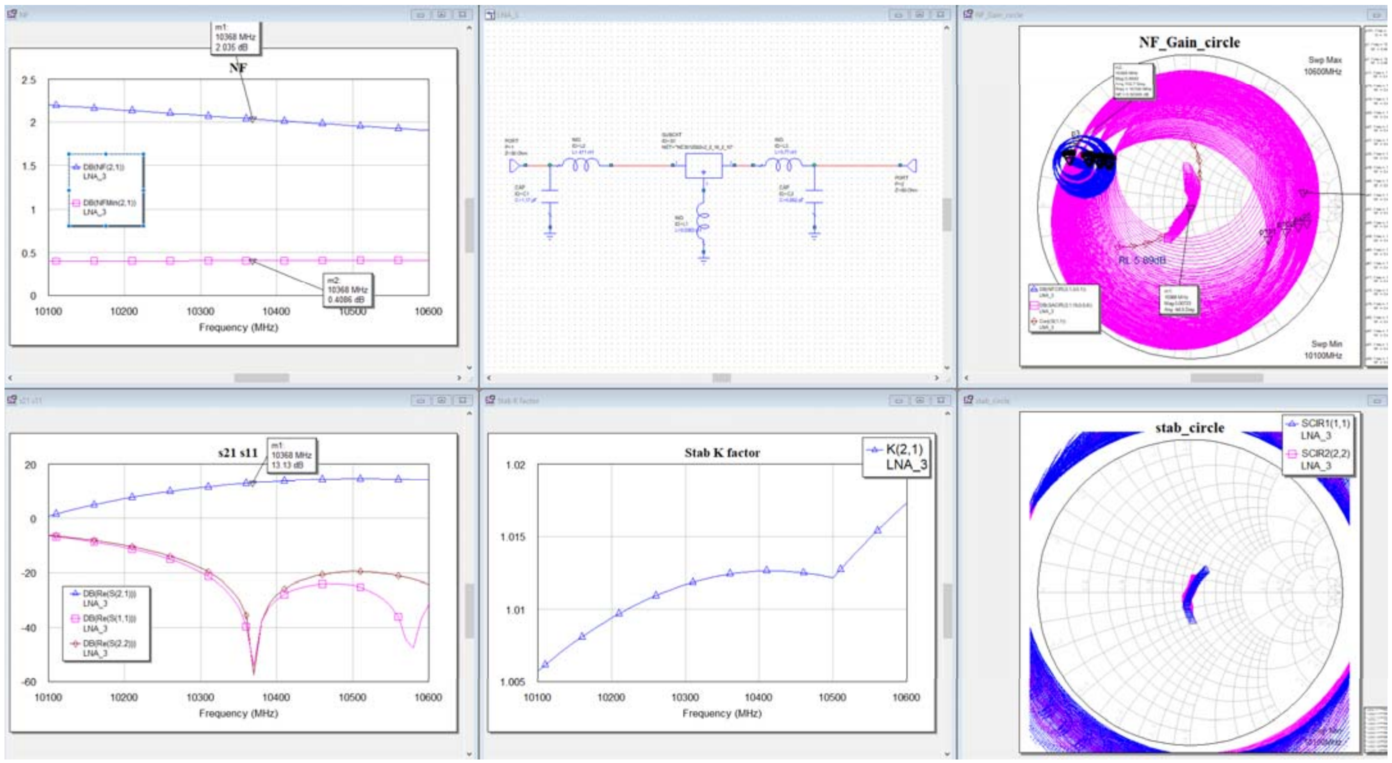
Load Reflection Coefficient:

$GAMA_L$

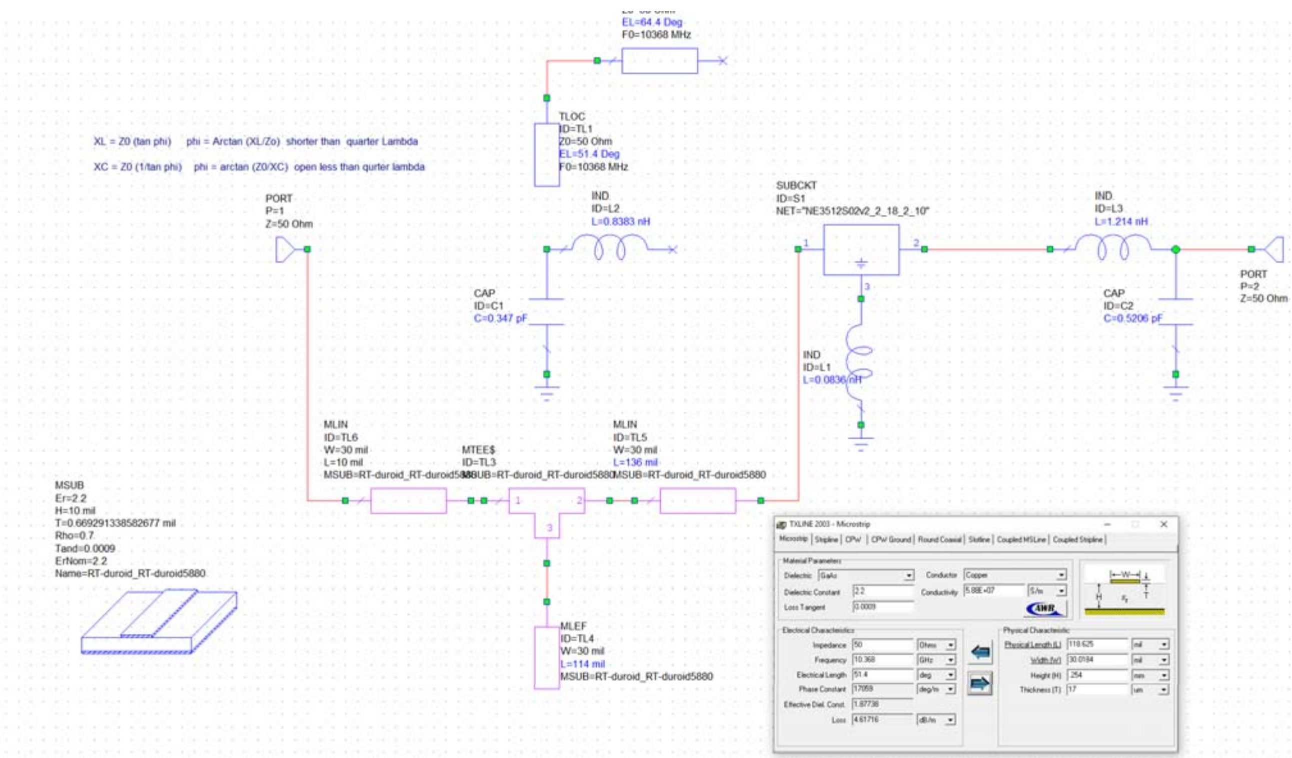
Input matching with ideal lumped elements



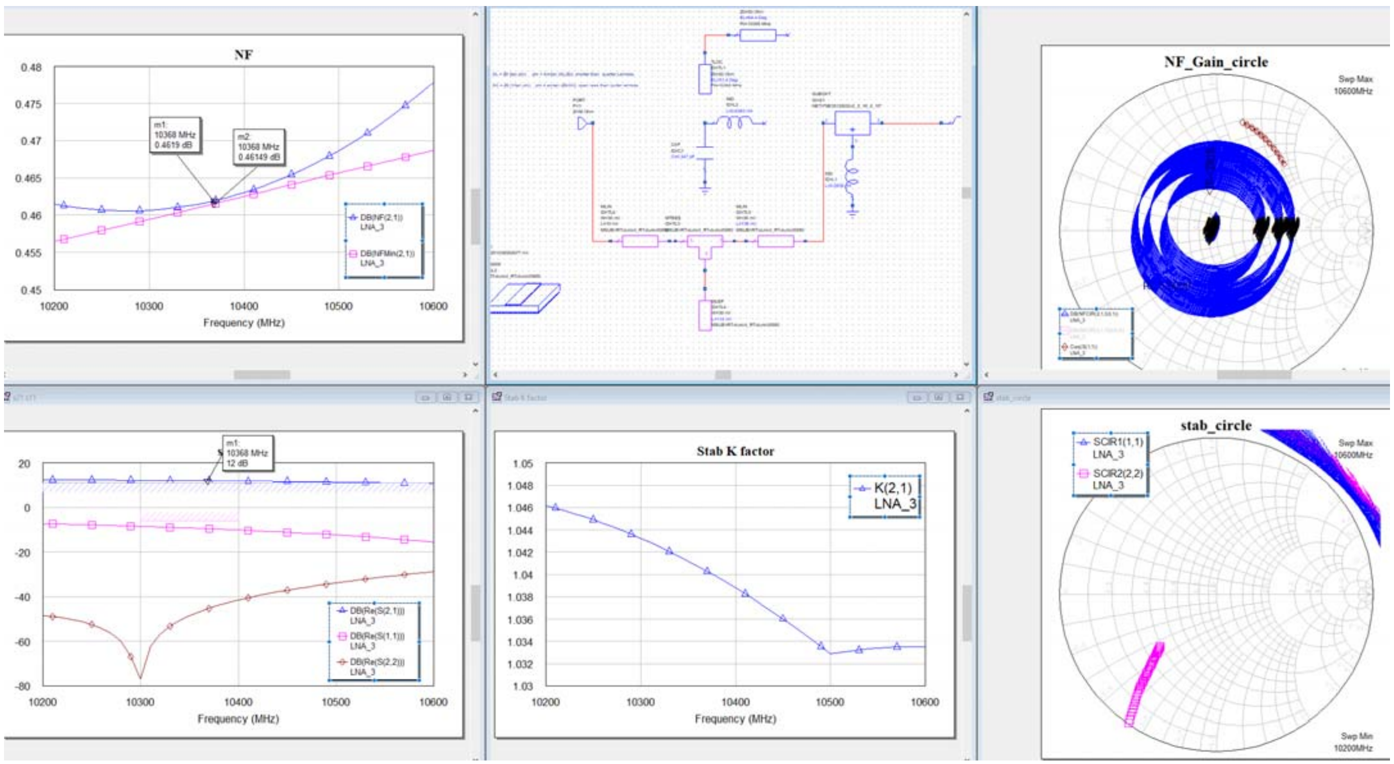
Gain amplifier simulation with ideal lumped components



Ideal components to Microstrip conversion



Microstrip input matching



Radial stub Calculator

flambda.com/stub/stub.php

Apps | WE-LQ SMT Induct... | E4402B - Keysight /... | Filter Wizard | Anal... | RF Toc

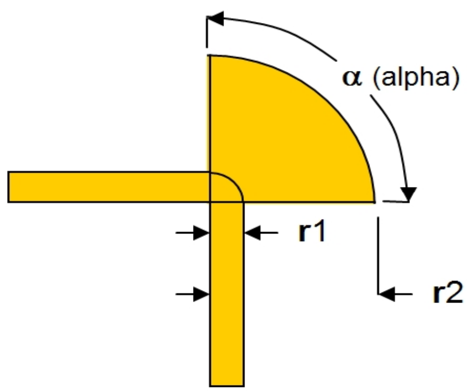


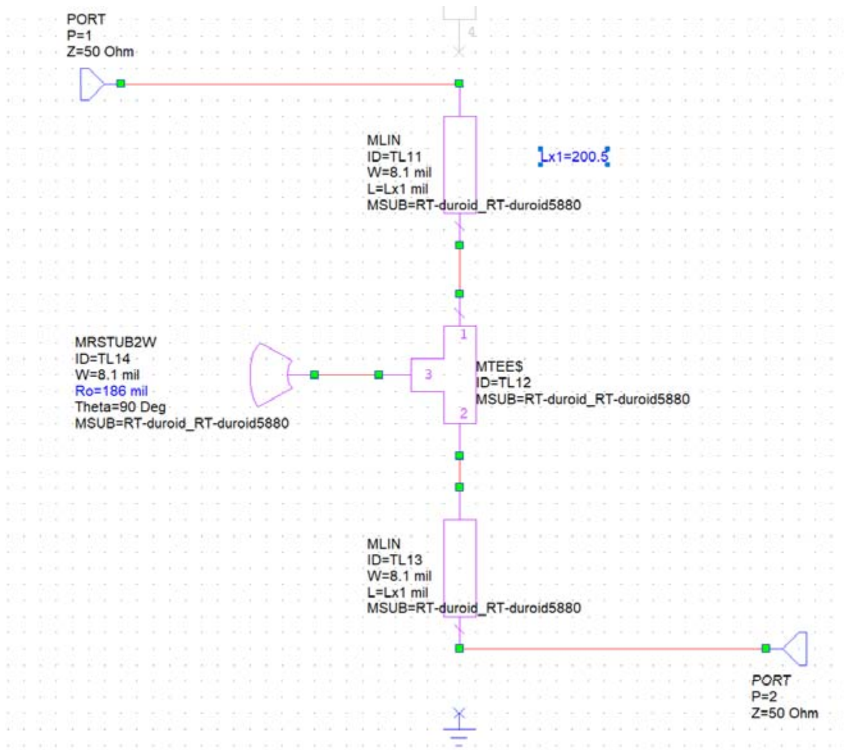
Figure 1. Microstrip Radial Stub

Use the program below to calculate dimension r2 for a radial stub.
The radial stub is used to provide a broadly resonant RF short circuit.
When cascaded with high impedance quarter-wavelength transmission lines,
the radial stub can provide an effective decoupling network for microwave
amplifiers and other active components.
The range of dielectric constant (Er) over which the results are valid is 2 to 15.
The frequency range over which the results are valid is 0.3GHz to 30GHz.
The formulas used are the work of Dr. H. A. Atwater of MIT Lincoln Labs, as published in
the November 1985 issue of Microwave Journal.

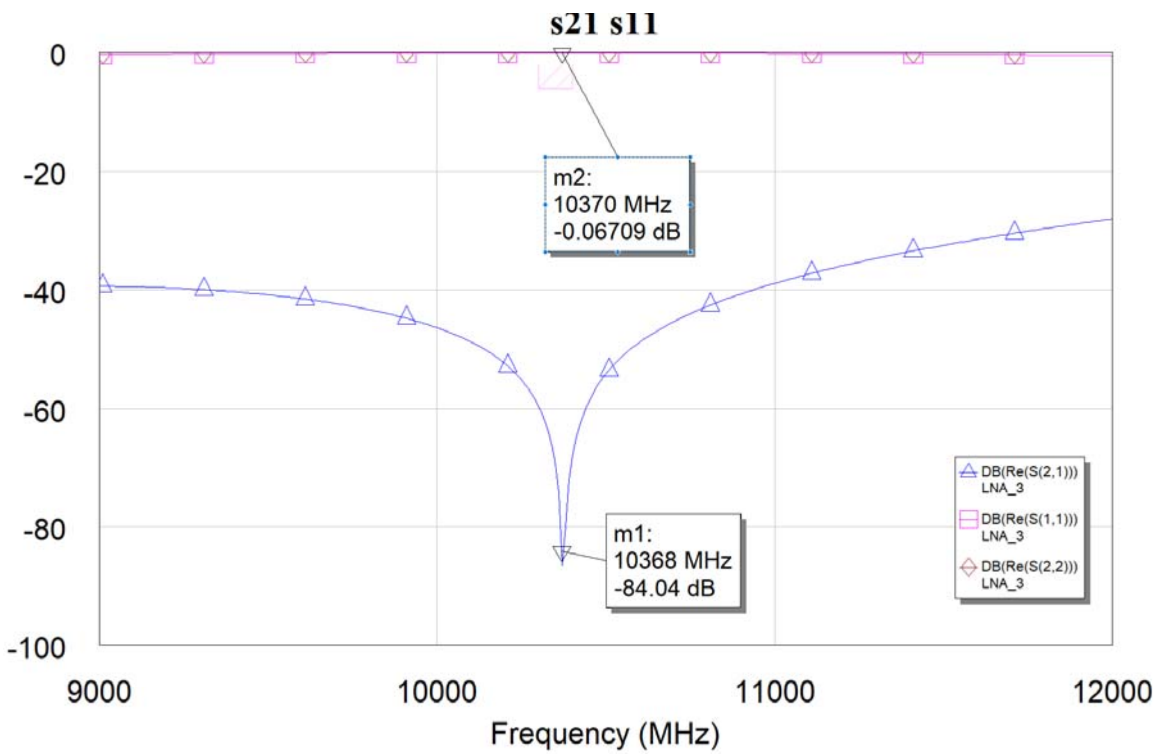
Units	◉ Inches ○ millimeters	
Angle alpha	◉ 90� ○ 60�	
Substrate Er	2.2	Dielectric Constant (range 2-15)
Frequency	10.368	GHz (range 0.3 to 30)
Substrate Height	0.01	
Radius r1	0.001	

Calculate! r2= 0.12355766847599 inches

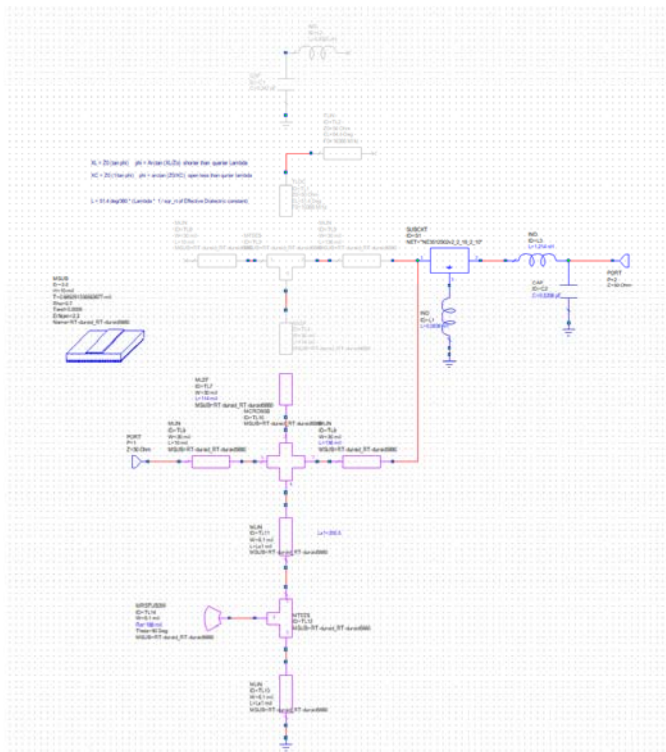
Bias circuit, quarter lambda high impedance microstrip line and radial stub -capacitor



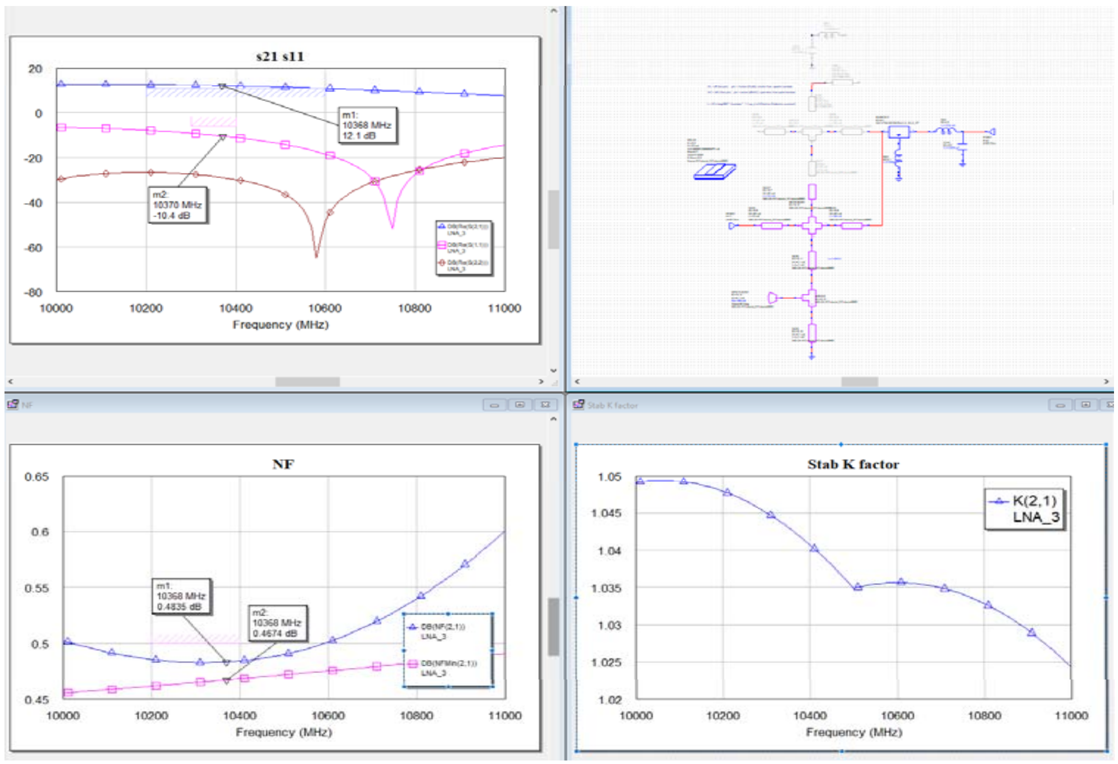
Bias simulation



Input microstrip matching, bias incorporated



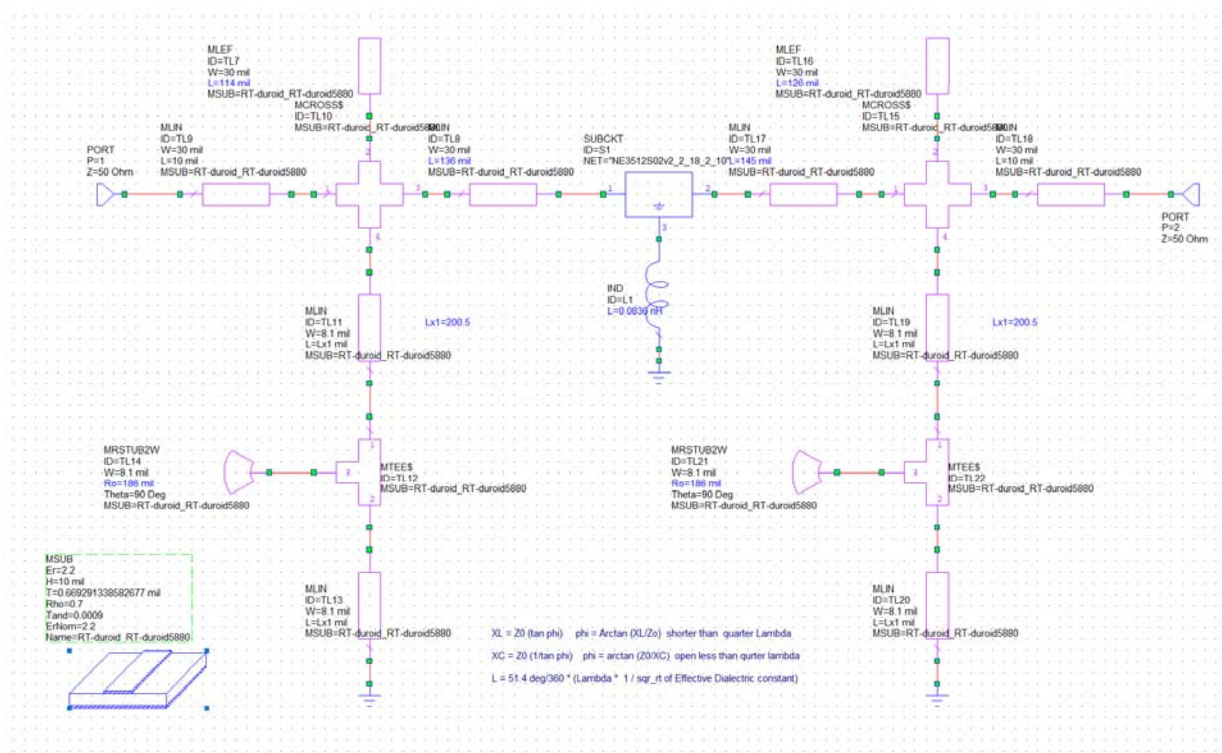
Input matching completed



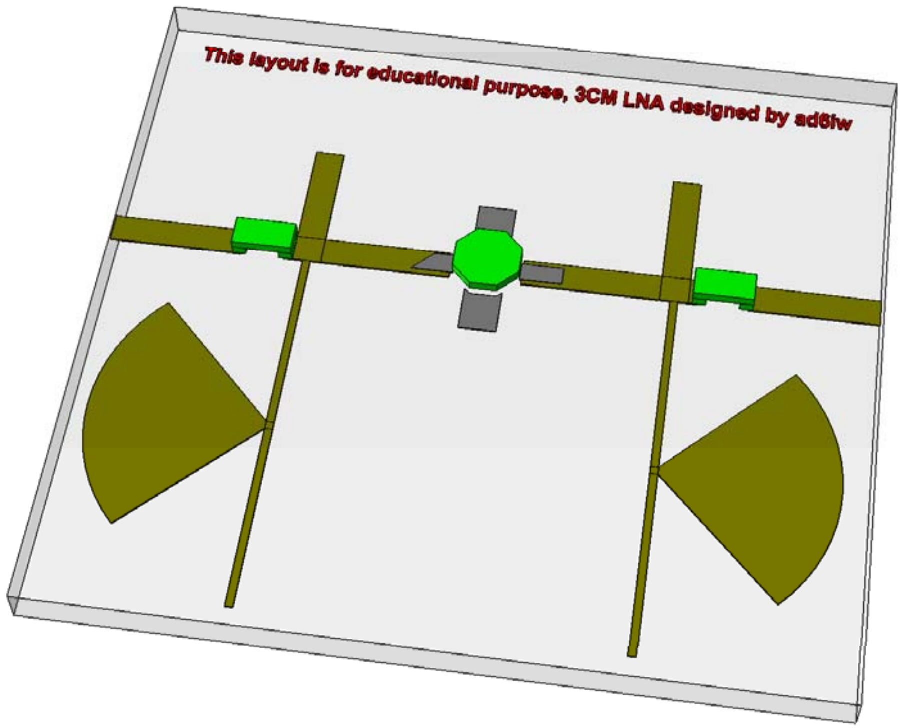
Conjunctive load matching impedance

$$\Gamma_L = \left[S_{22} + \frac{S_{21}\Gamma_s S_{12}}{1 - S_{11}\Gamma_s}\right]^*,$$

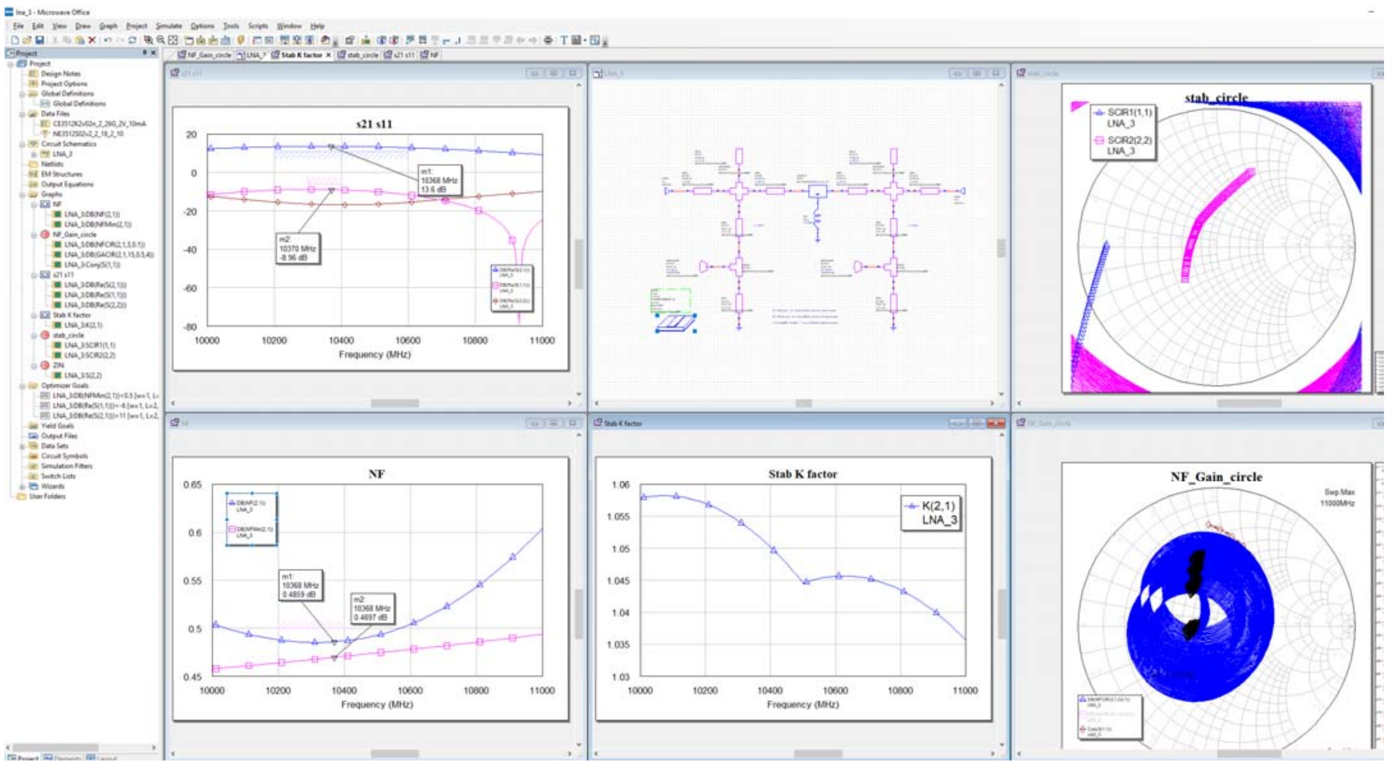
LNA final schematics



PCB LAYOUT


This layout is for educational purpose, 3CM LNA designed by ad6iw

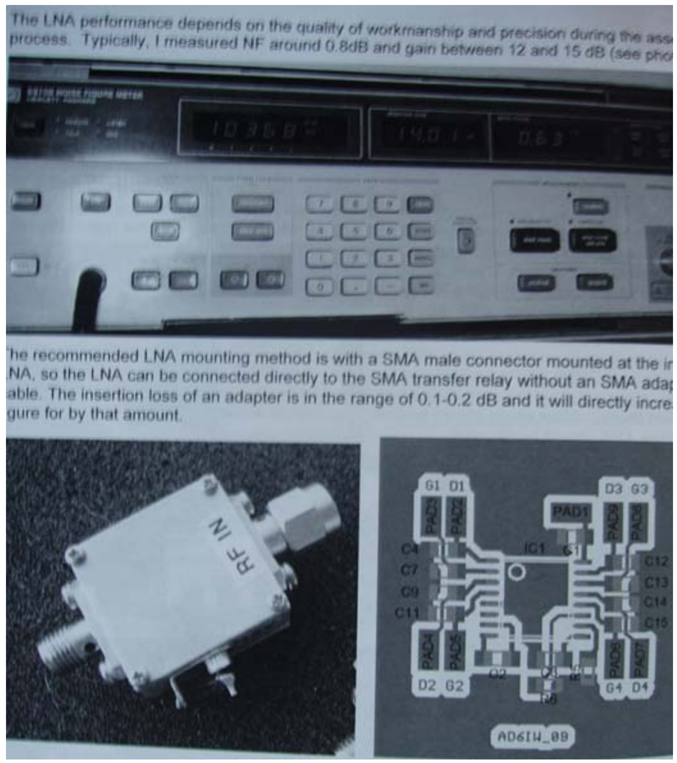
Final simulation results



Computer optimization and final steps

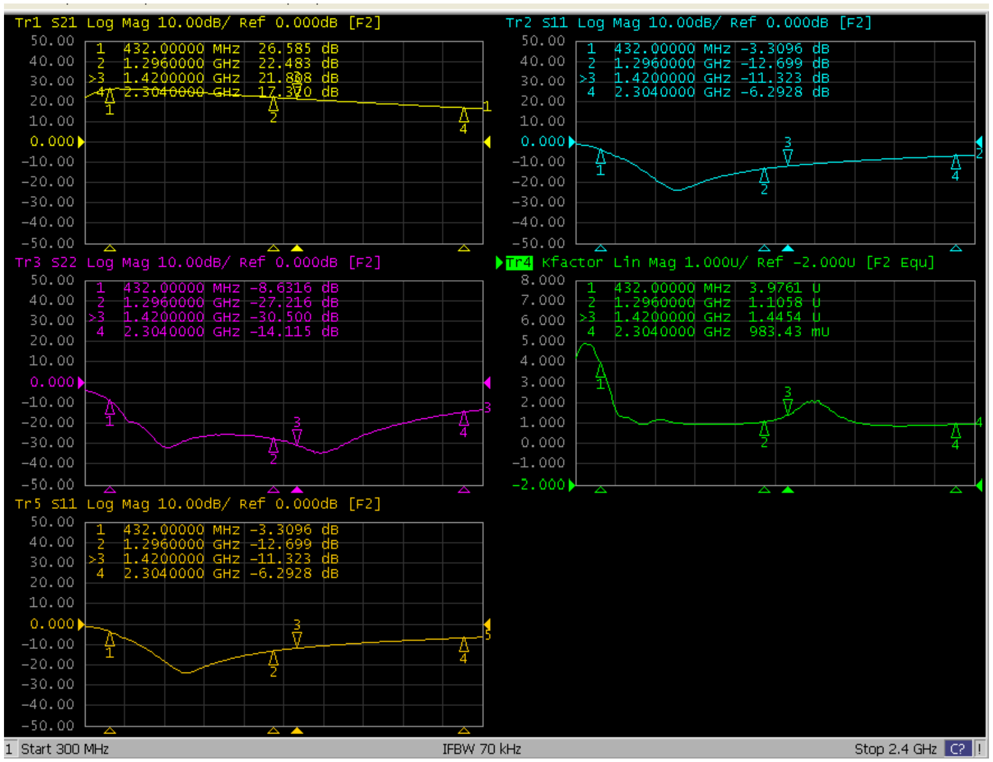
- Add coupling capacitors, connectors and optimize again
- EM test, simulate microstrip with substrate and real parts, enclosure eigenmode, cover above traces, connector transition, crosstalk
- Layout and creating Gerber file
- Prototyping
- Testing
- In reality, always lower gain and higher noise figure

LNA Testing and Construction Hints


The LNA performance depends on the quality of workmanship and precision during the ass
process. Typically, I measured NF around 0.8dB and gain between 12 and 15 dB (see pho

he recommended LNA mounting method is with a SMA male connector mounted at the ir
NA, so the LNA can be connected directly to the SMA transfer relay without an SMA adap
able. The insertion loss of an adapter is in the range of 0.1-0.2 dB and it will directly incre
gure for by that amount.

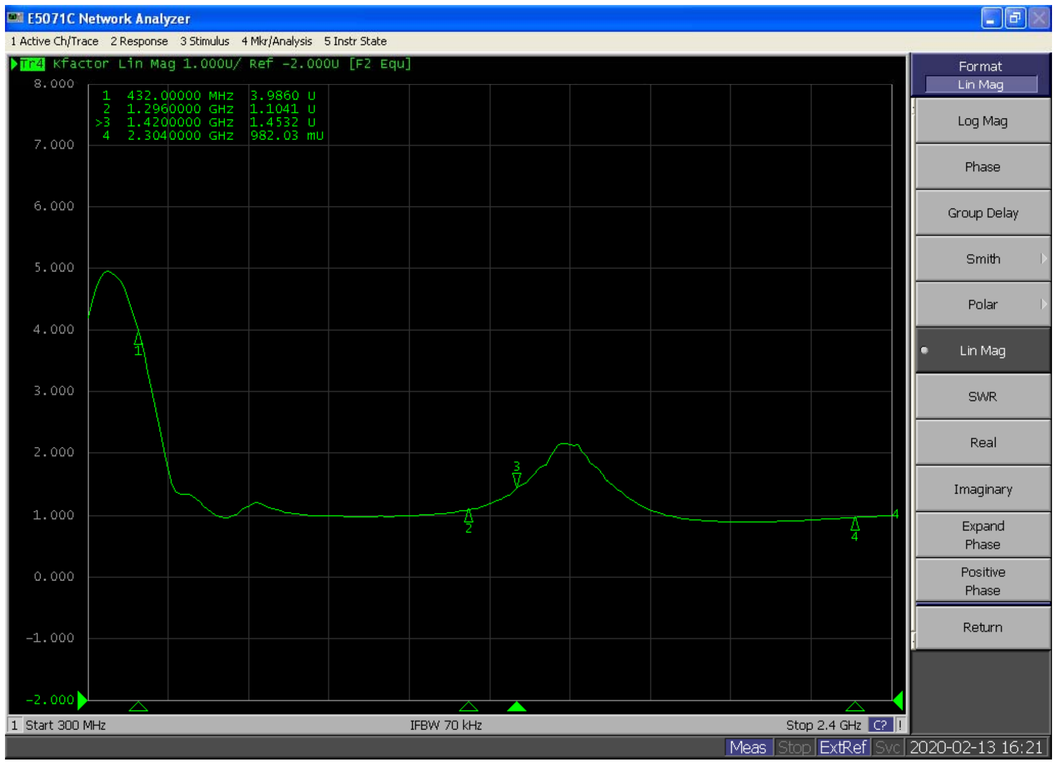
LNA test with VNA



Rollet stability factor, K-factor test with VNA. This test should be performed with any amp.

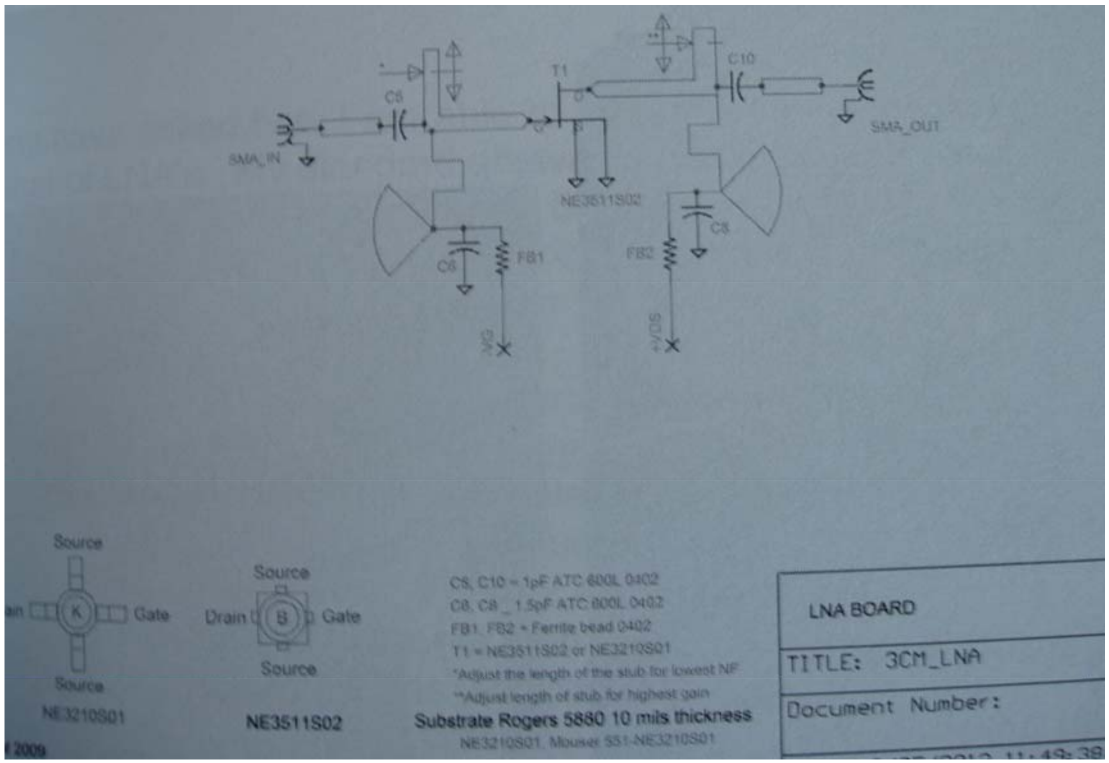
$$K = \frac{1 - |S_{11}|^2 - |S_{22}|^2 + |\Delta|^2}{2|S_{21}S_{12}|}$$

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

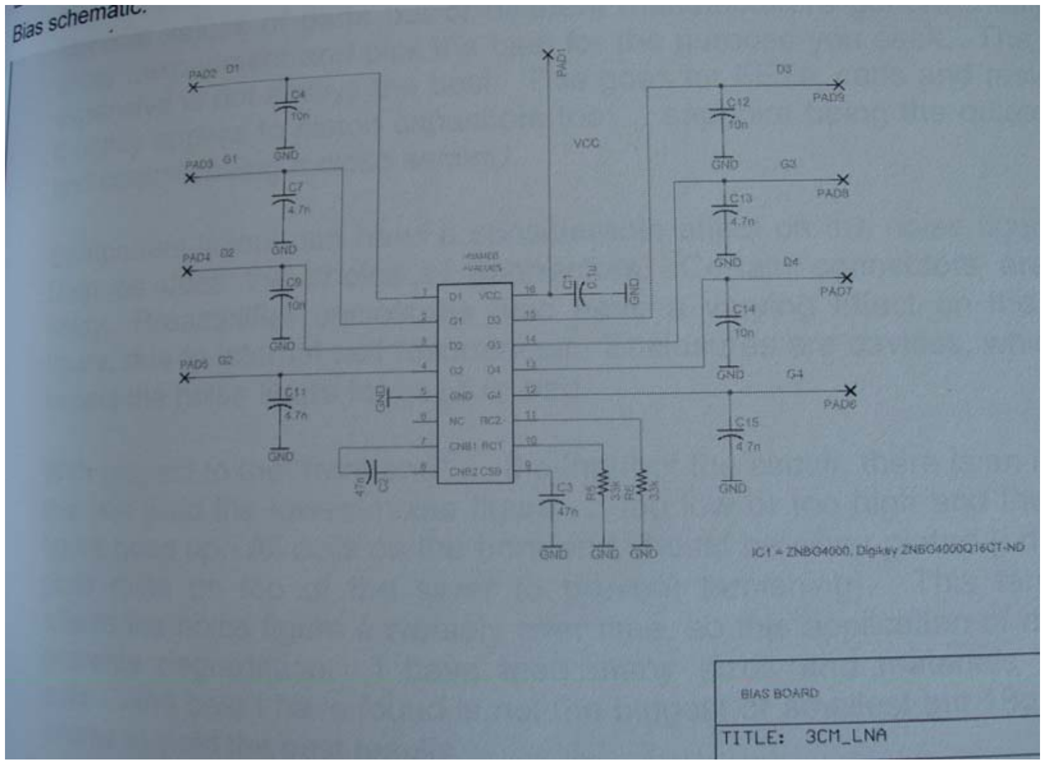


Noise Figure and Gain measurements

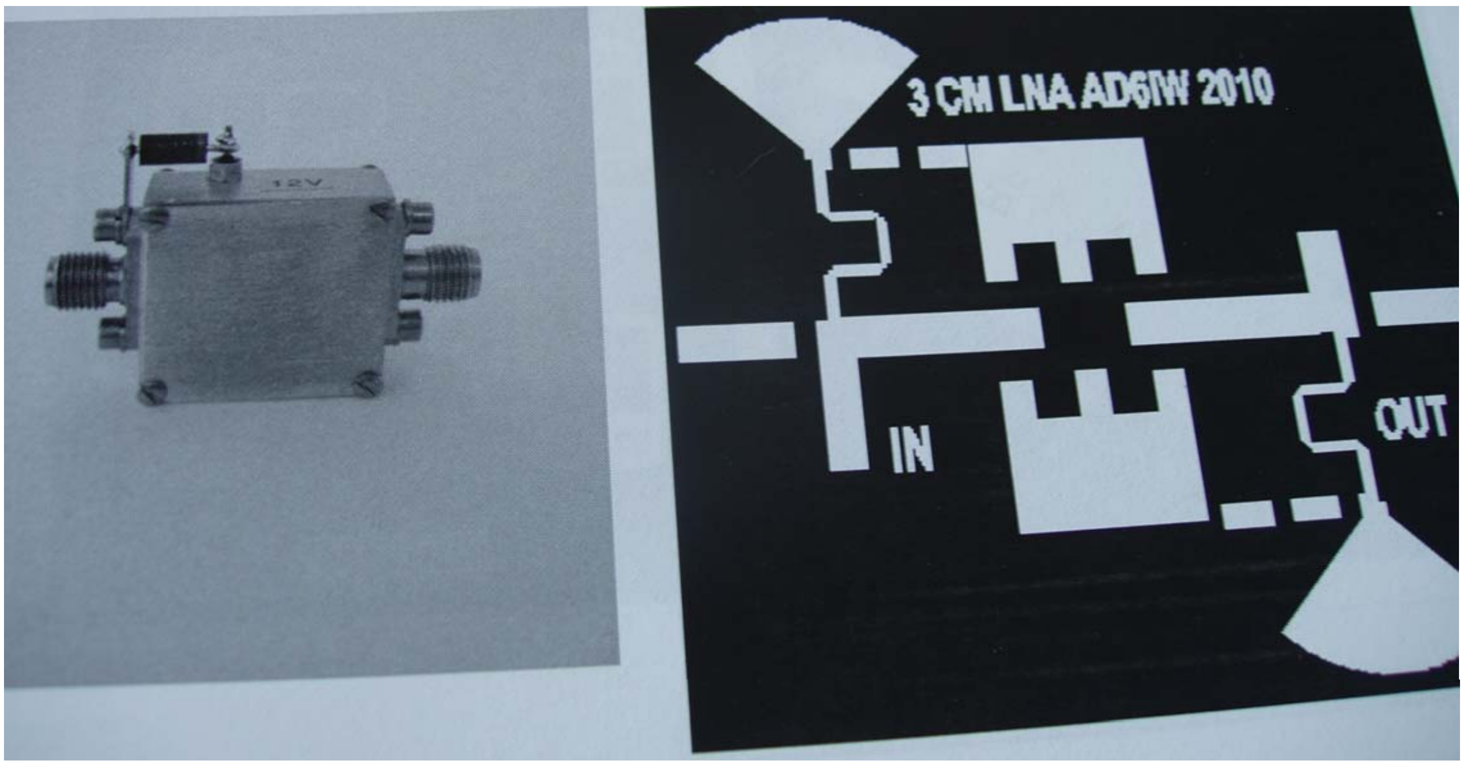
3CM LNA schematics



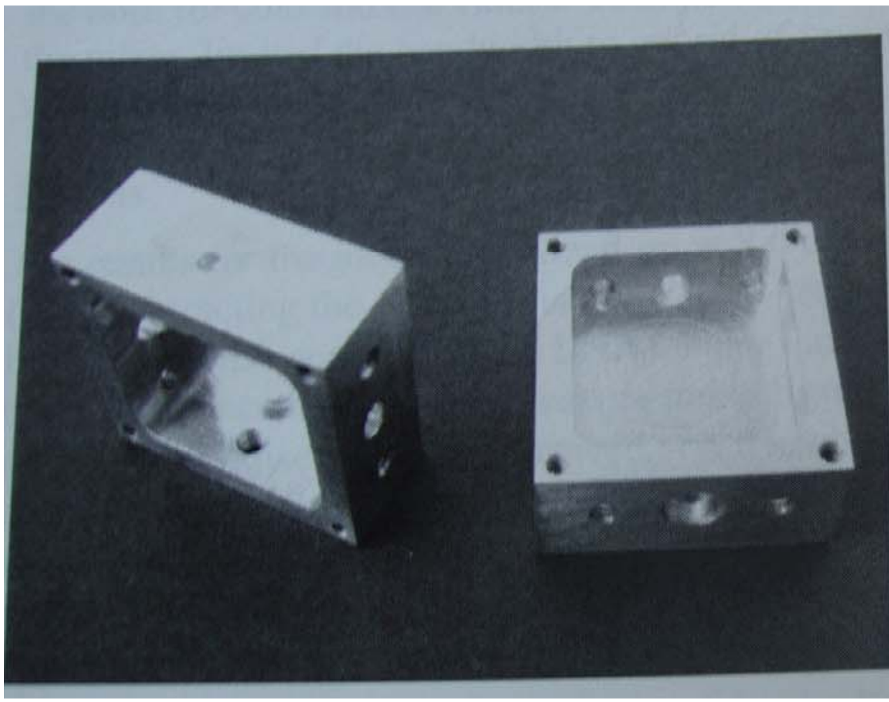
Active Bias circuit, positive and negative voltages for four GaAs Fet's

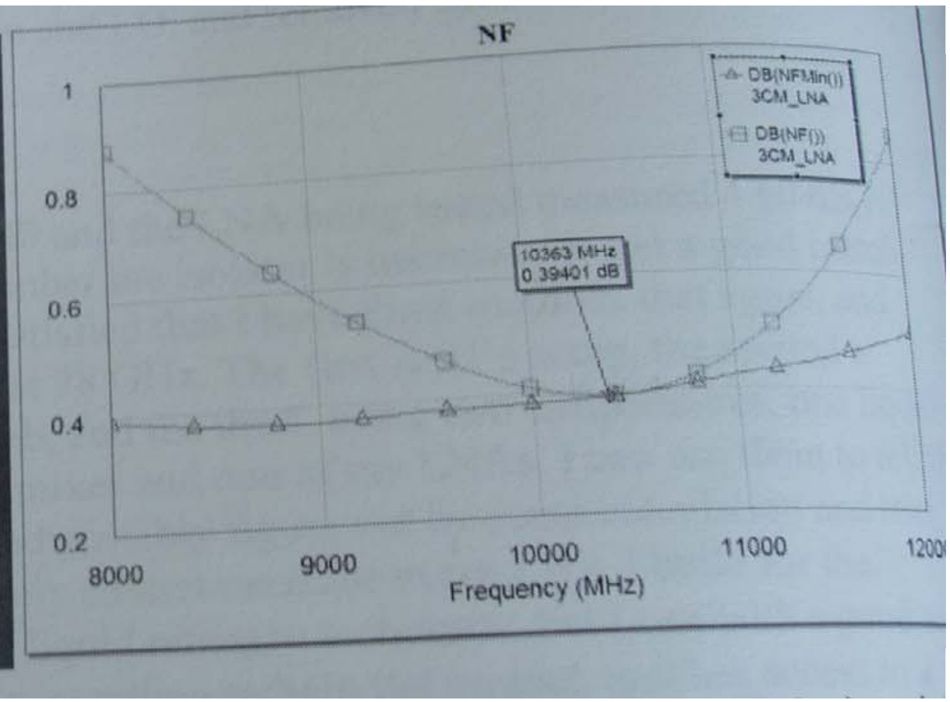


Layout and enclosure

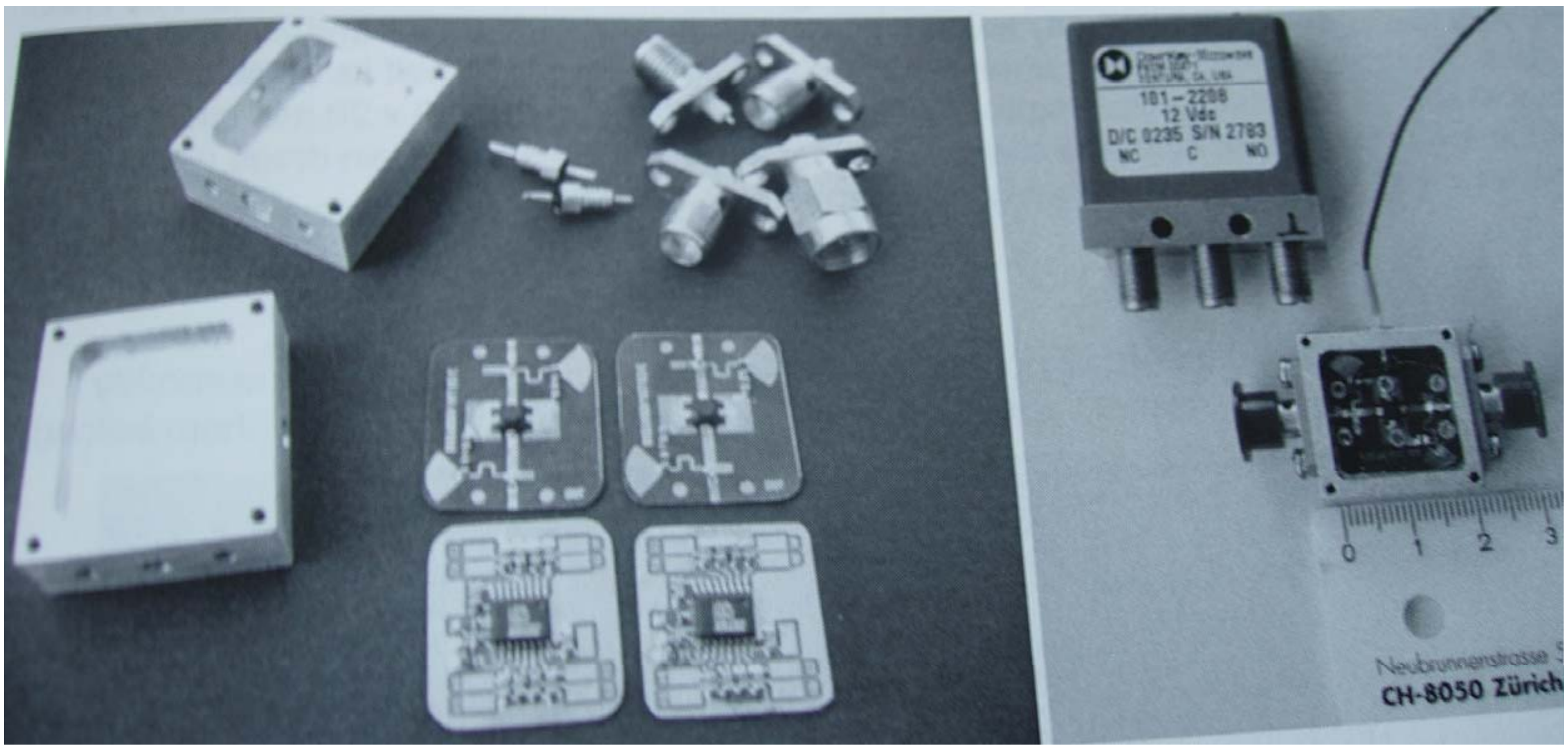


Enclosure and simulation NF

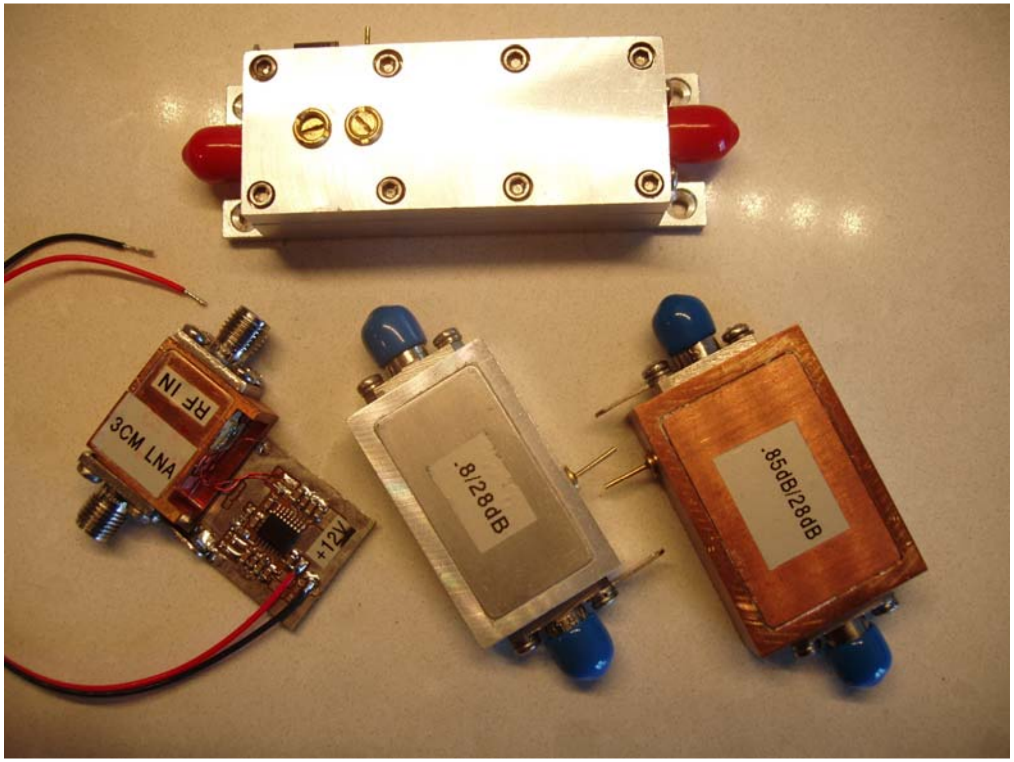




Assembling process



Homebrew LNA’s



Critical construction and design points

- Ground plane connections, especially Source leads of GaAs FET, rf connector, and pcb ground plane to enclosure connection
- Input connector transition, connector quality
- Layout
- Bias circuit implementation
- Enclosure size, metal conductivity and connector attachments
- Preferred: Al, Cooper, Silver or Gold plated metals
- Components quality and size, smaller components are preferred
- Soldering
- For high frequency amplifiers, machining is necessary

Appendix – complex mathematics

COMPLEX ADDITION

To add two complex numbers, use either rectangular form and add their real and imaginary parts together, respectively:

$$(a+jb)+(c+jd)=(a+c)+j(b+d)$$

COMPLEX SUBTRACTION

To subtract one complex number from another, use their rectangular form and subtract their real and imaginary parts, respectively:

$$(a+jb)-(c+jd)=(a-c)+j(b-d)$$

COMPLEX DIVISION

To divide two complex numbers, use polar format; then divide the magnitude of the numerator by the magnitude of the denominator and subtract the angle of the denominator from the angle of the numerator:

$$\frac{Z_1}{Z_2}=\frac{\rho_1\angle\theta_1}{\rho_2\angle\theta_2}=\frac{\rho_1}{\rho_2}\angle(\theta_1-\theta_2)$$

References

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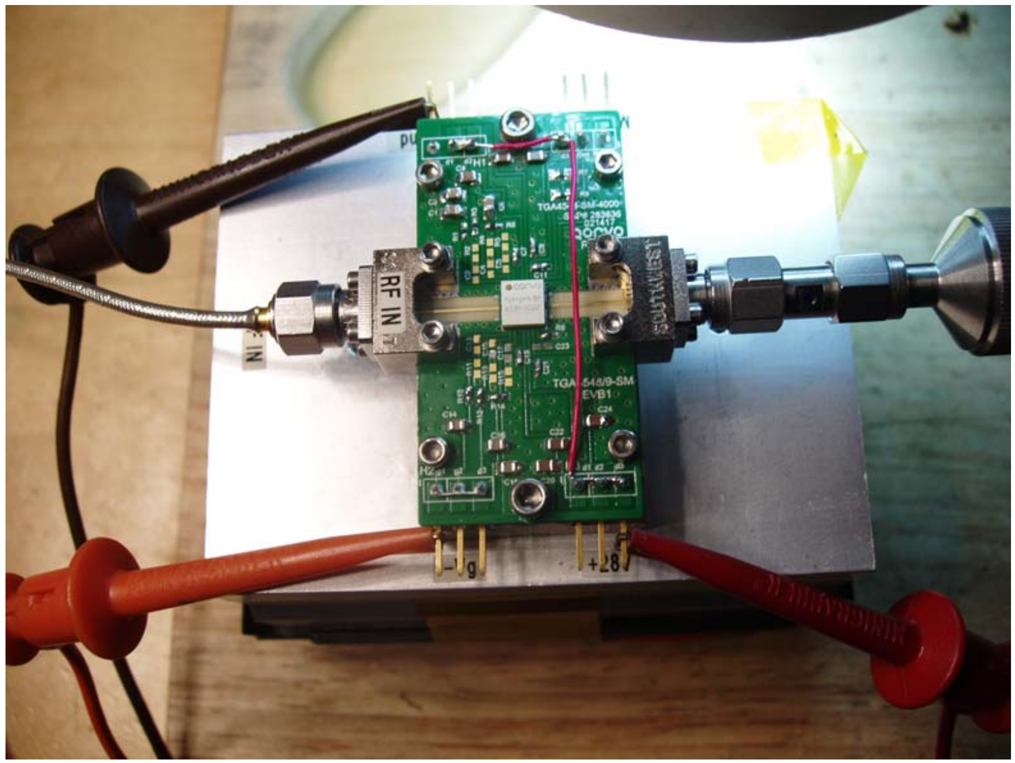
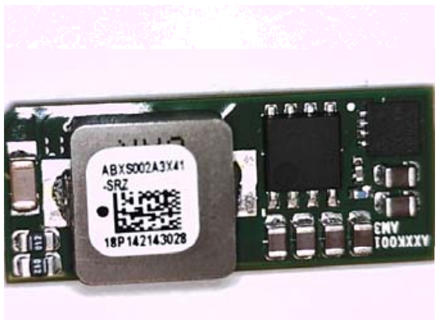
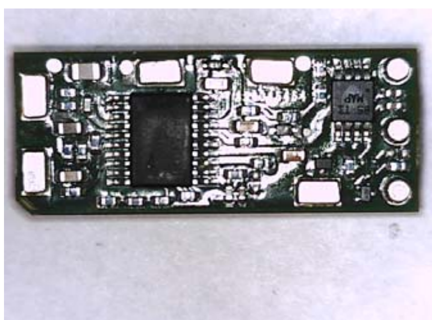
Appendix: 10W 24GHz Power Amplifier with TGA4549 report



DC converter 12 to 28V/2.3A LM5122





65W Boost Converter: Non-Isolated DC-DC Modules

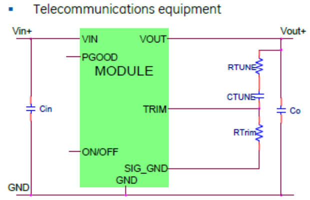
8Vdc –16Vdc input; 16Vdc to 34Vdc output; 65W Output power (max.)

TUNABLE LOOP™

RoHS Compliant

Applications

- Industrial equipment
- Distributed power architectures
- Telecommunications equipment



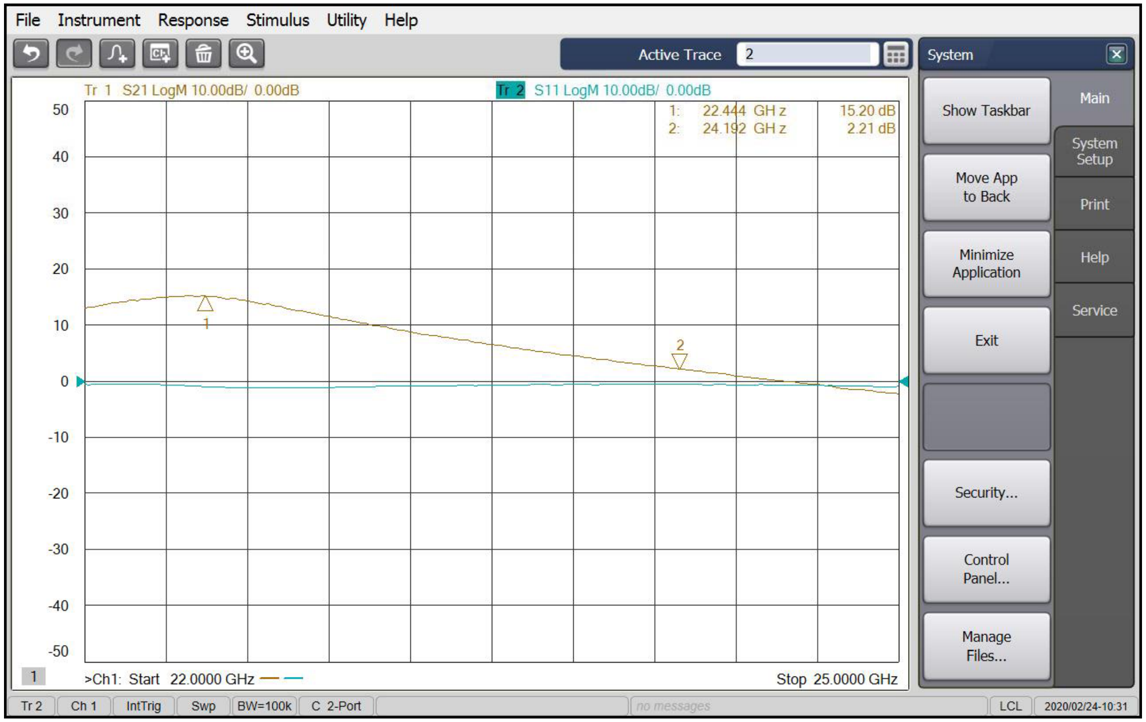
Features

- Compliant to RoHS II EU "Directive 2011/65/EU"
- Compliant to IPC-9592 (September 2008), Category 2, Class II
- Compatible in a Pb-free or SnPb reflow environment (Z versions)
- Compliant to REACH Directive (EC) No 1907/2006
- Wide Input voltage range (8Vdc-16Vdc)
- Output voltage programmable from 16 to 34Vdc via external resistor
- Tunable Loop™ to optimize dynamic output voltage response
- Power Good signal
- Output overcurrent protection (non-latching)
- Over temperature protection
- Remote On/Off
- Ability to sink and source current
- Support Pre-biased Output
- Optimized for conduction-cooled applications
- Small size: 27.9 mm x 11.4 mm x 7.5 mm(MAX) (1.1 in x 0.45 in x 0.295 in)
- Wide operating temperature range [-40°C to 85°C]
- *UL** 60950-1 2nd Ed. Recognized, CSA† C22.2 No. 60950-1-07 Certified, and *VDE*‡ (EN60950-1 2nd Ed.) Licensed
- ISO** 9001 and ISO 14001 certified manufacturing facilities

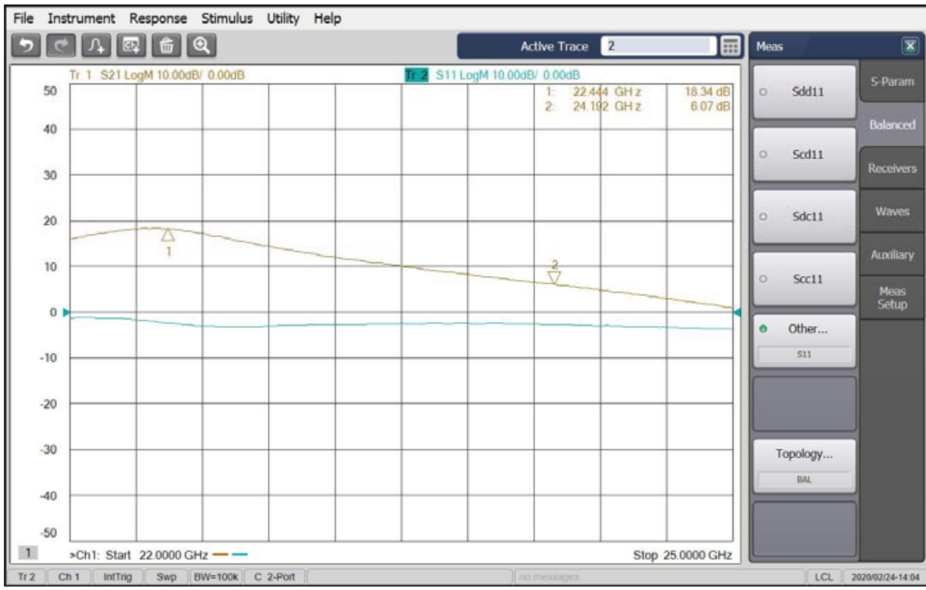
Description

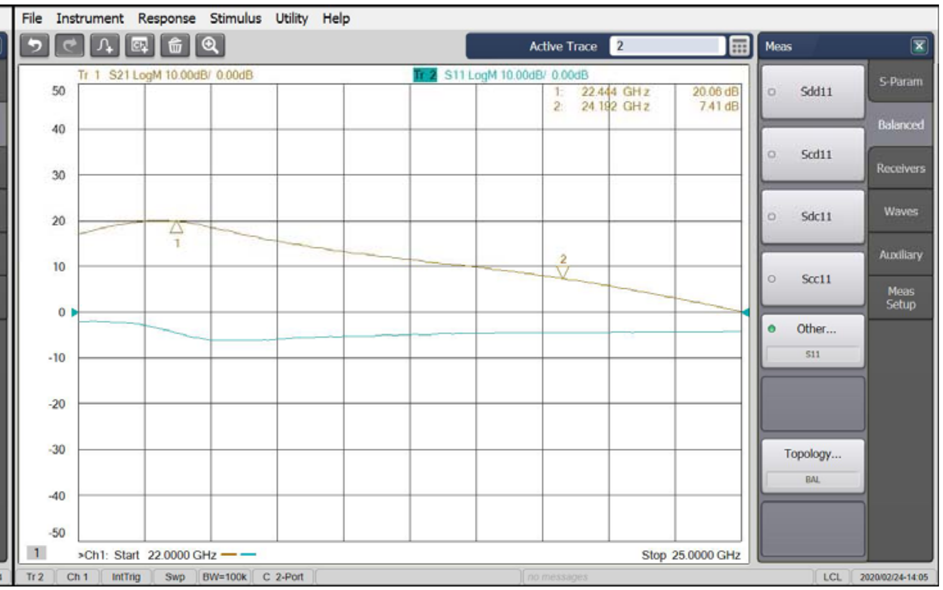
The Boost power modules are non-isolated dc-dc converters that can deliver up to 65W of output power. The module can operate over a wide range of input voltage (V_{IN} = 8Vdc-16Vdc) and provide an adjustable 16 to 34VDC output. The output voltage is programmable via an external resistor. Features include remote On/Off, over current and over temperature protection. The module also includes the Tunable Loop™ feature that allows the user to optimize the dynamic response of the converter to match the load with reduced amount of output capacitance leading to savings on cost and PWB area.

First test results ☹

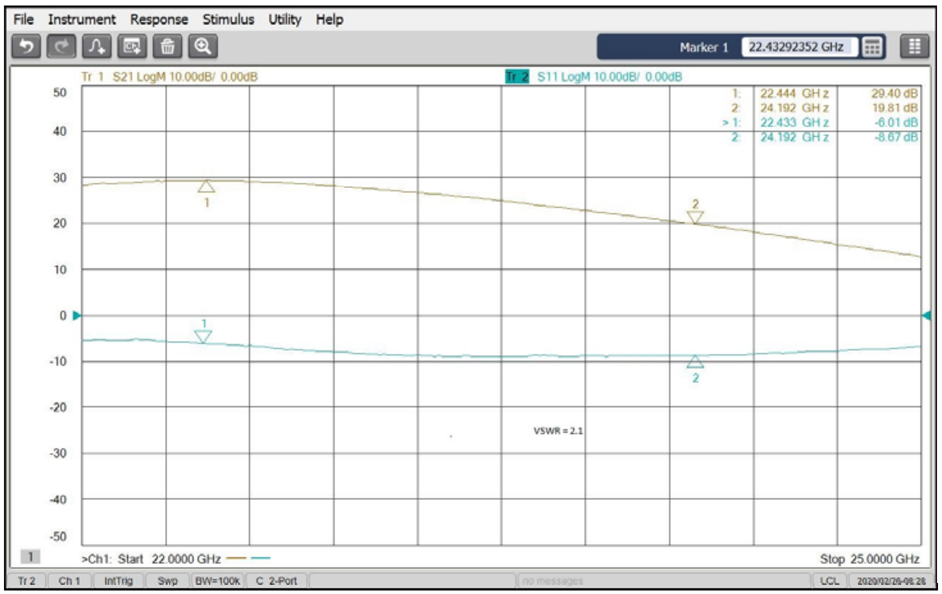


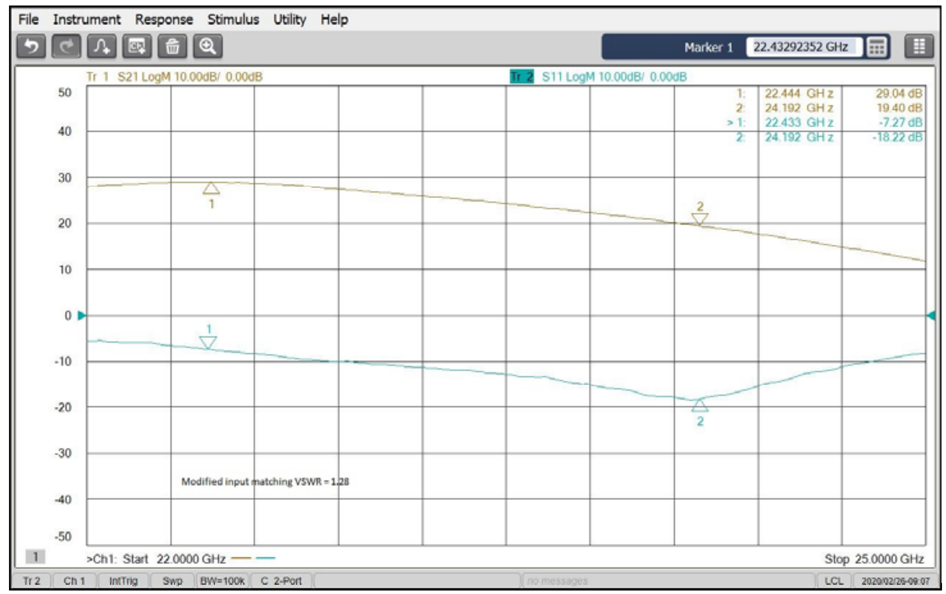
Little better, but still poor performance





Finally ☺ 100 mW in - 5.5 W out, 28V/1A
max. input power 23dBm 200mW - no smoke





24GHz Output power, 19dBm in