The IAF mHEMT Low-Noise Technology and its Extension to Cryogenic Applications

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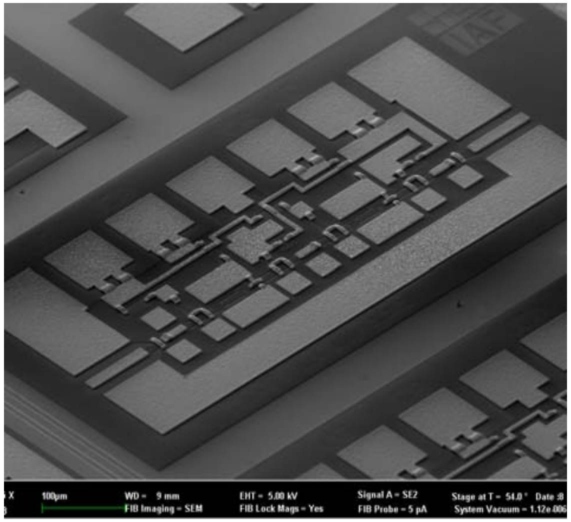
Outline

- IAF Microwave Competences
- IAF mHEMT Technologies
- MMICs
- Noise Peformance
- IAF SS mHEMT Model
- Extension of mHEMT Model
- Technology Improvements?
- Effect of Gate Leakage
- Summary



IAF Competences in Millimeterwave-Technology

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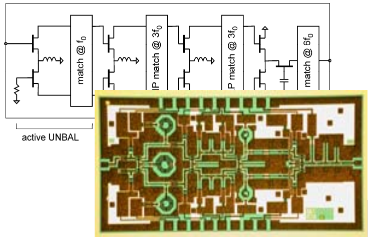
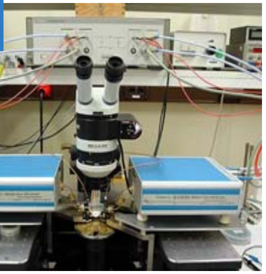


Circuit Design
Simulation
Modelling
Layout

Technology
Epitaxy
MMIC Processing

Packaging
Module-Design und -manufacturing
Bonding, waveguide transitions
Hybride development



Charakterisation
S-Parameter up to 500 GHz
Power and Noise up to 210 GHz
Life-time measurements etc.

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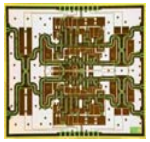
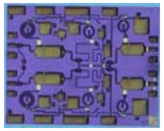
Cooperations in mm-Wave Technology

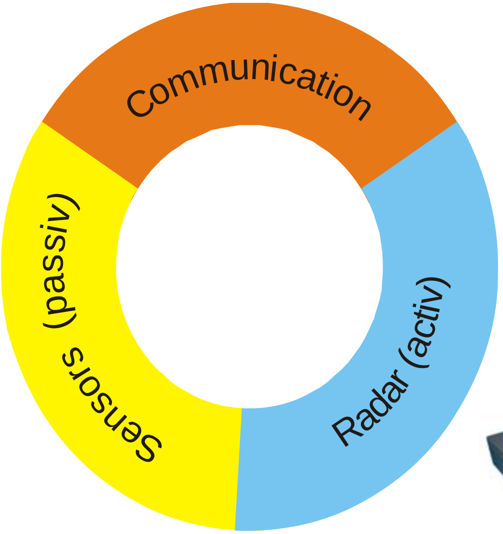


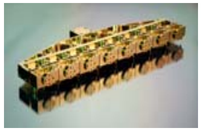
Sony
Wireless Communication at 60 GHz

MPIfR/CAY/IRAM/SETI / Chalmers
UltraLow-Noise
Amplifiers in cryo-operation



FGAN/FHR
Radiometers at 220 GHz





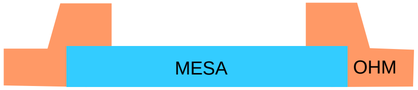
FGAN/FHR
Imaging Radar at 94 GHz

FGAN/FHR
SAR Radar at 94 and 220 GHz

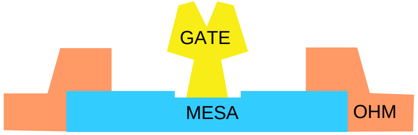
Radiometer Physics/ESA
Radiometry at 60/94/150/183/230 GHz

IAF mHEMT-Technology: Processing

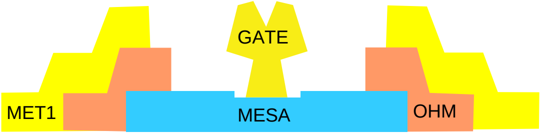
wet etched MESA



GeAu Ohmic contacts

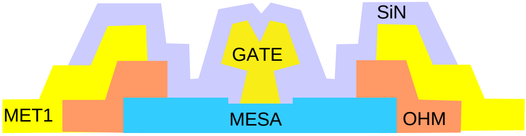


PtTiPtAu e-beam gate



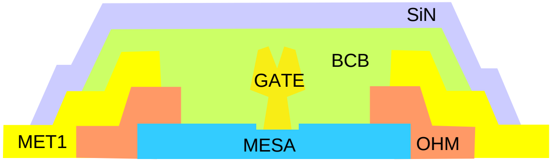
1. Metall

100 nm technology



250 nm SiN passivation

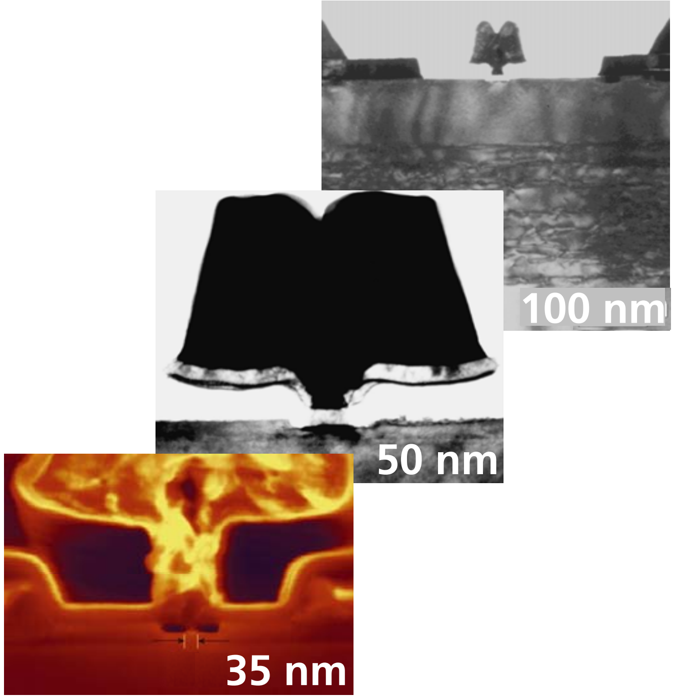
50/35 nm technology



250 nm SiN passivation on BCB

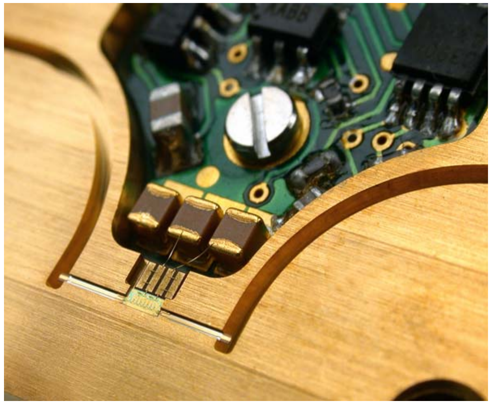
IAF m-HEMT Technology: Electrical Parameters

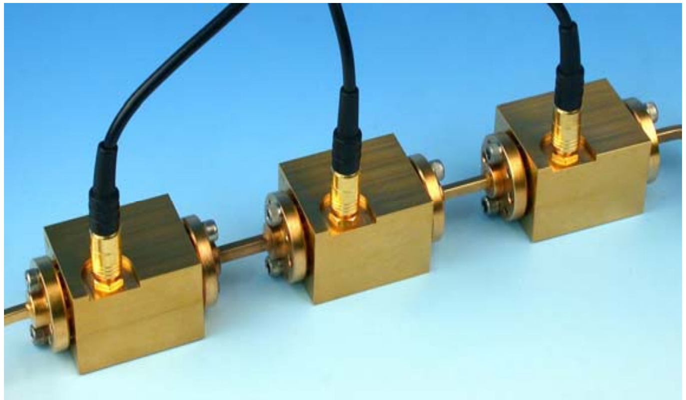
$In_xGa_{1-x}As$ Channel /metamorphic buffer/ GaAs



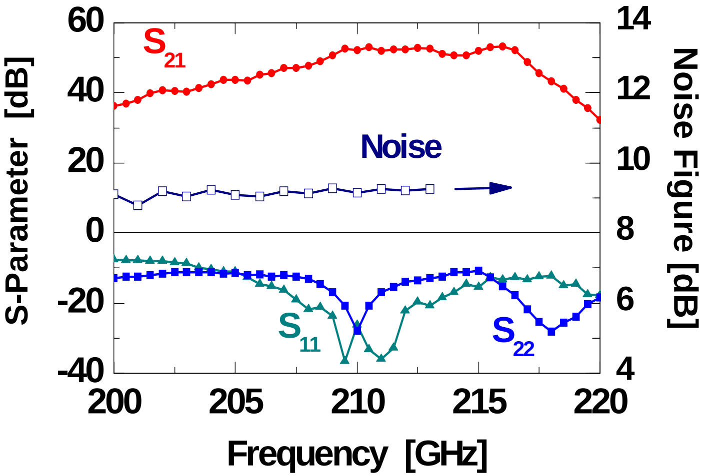
	35 nm	50 nm	100 nm
x (%)	80	80	65
R_C (Ωmm)	0.03	0.05	0.07
R_S (Ωmm)	0.10	0.15	0.23
R_g (Ω/mm)	250	250	400
$I_{D,max}$ (mA/mm)	1600	1200	900
V_{BD} (V)	1.5	2.5	4
$g_{m,max}$ (mS/mm)	2500	1800	1300
f_T (GHz)	550	380	220
f_{max} (GHz)	~700	~500	300

220 GHz Low-noise Amplifier Modules (2006)

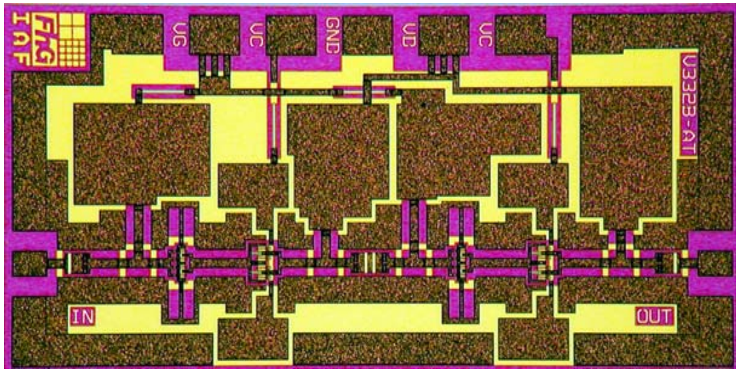


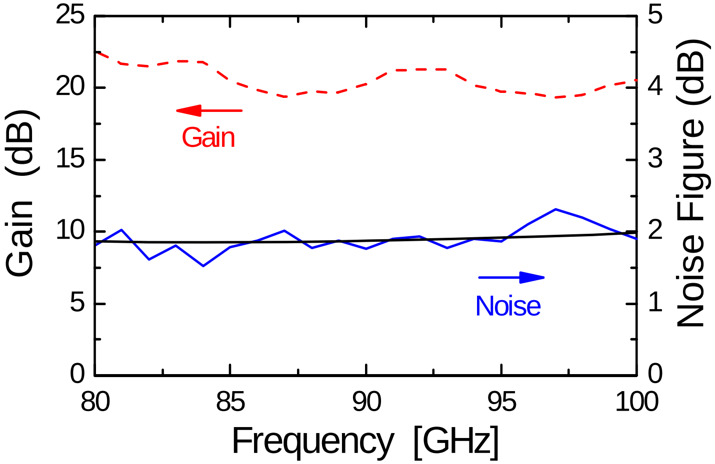


- the first 220 GHz LNA modules
- gain (1 module): 18 dB
- gain (3 module): 53 dB
- noise: 9 dB @ 200..213 GHz



50 nm W-band Low-noise Amplifier





- two-stage cascode LNA
- grounded coplanar waveguide (GCPW)
- 50 nm gate length mHEMT
- 0.75 x 1.5 mm^2 chip size

- 20 dB gain (80 - 100 GHz)
- 1.9 dB noise figure

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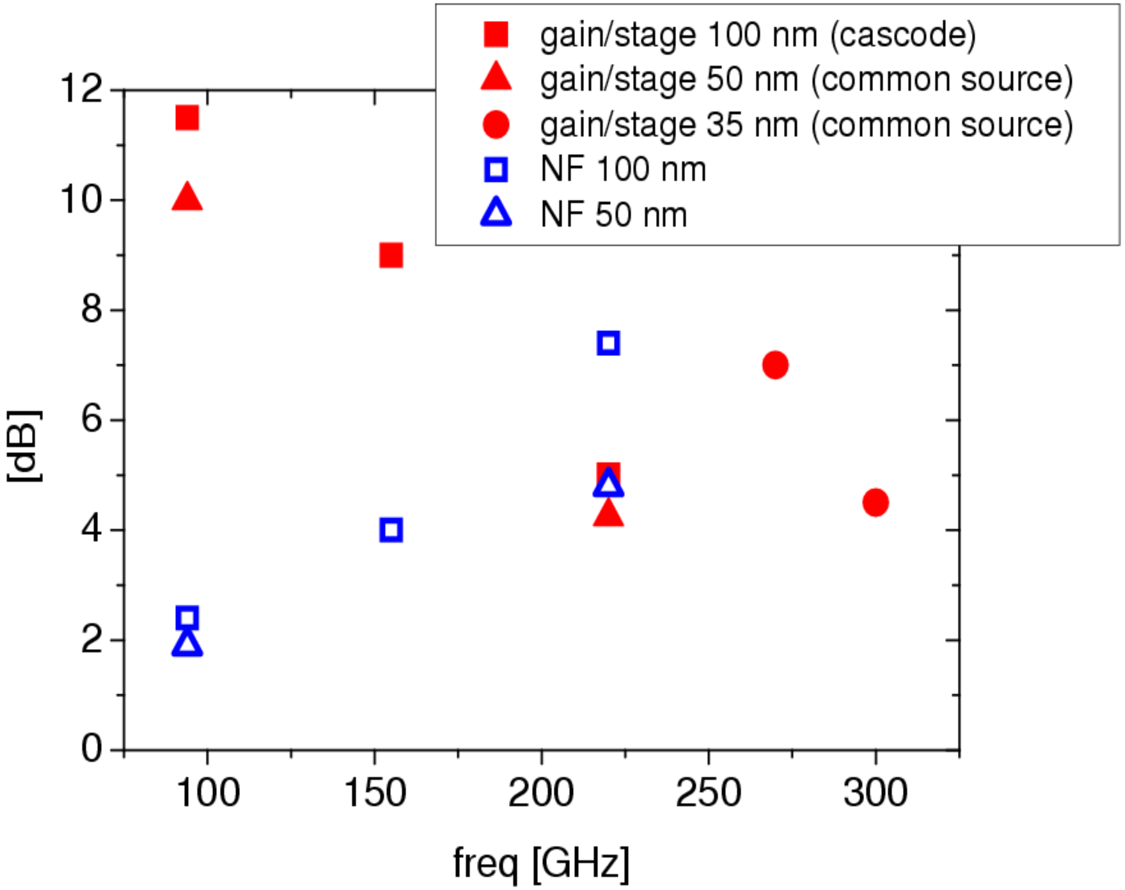
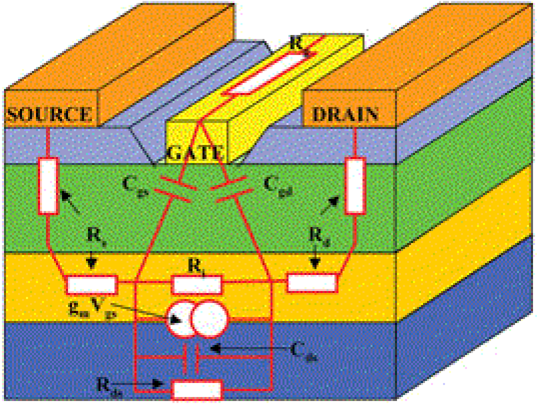
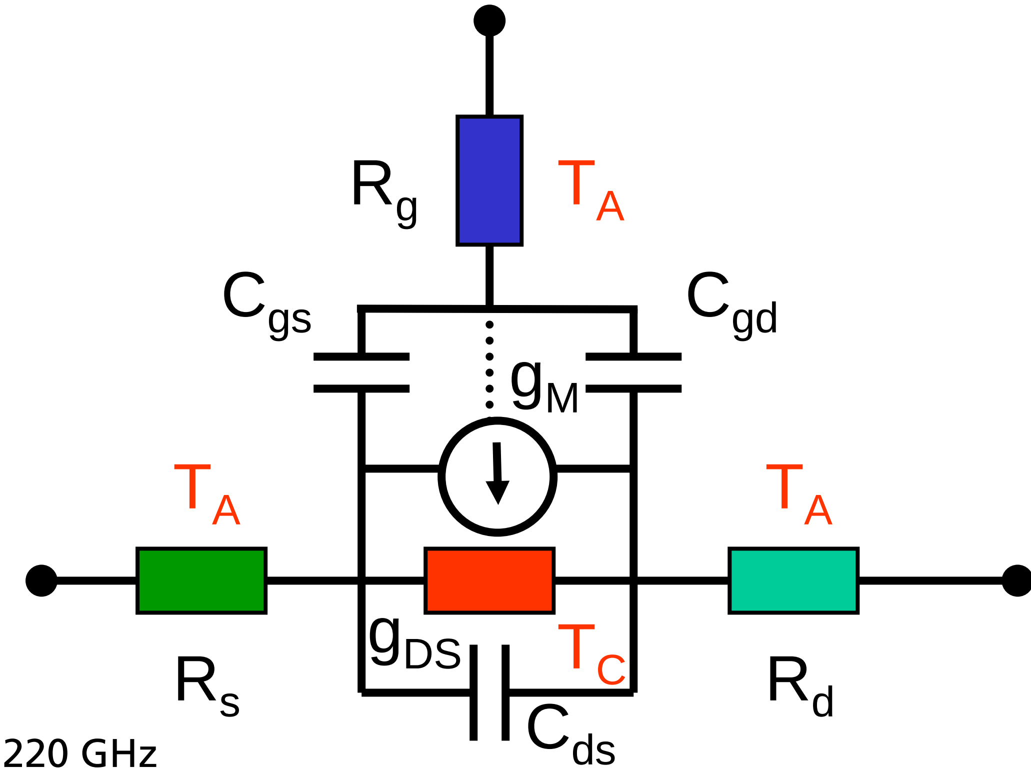
Small-Signal Amplifier Performance Summary



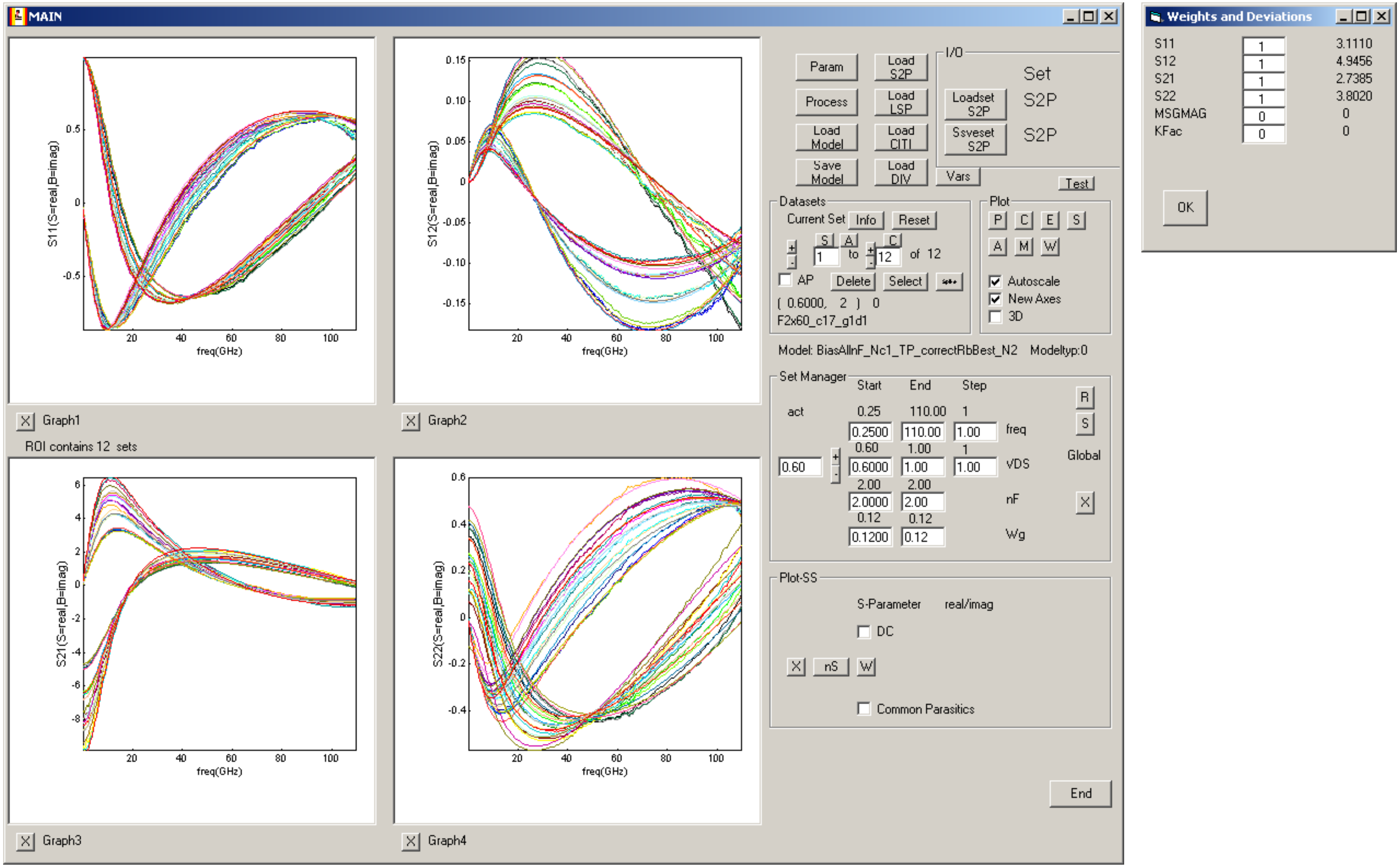
IAF Lumped Element mHEMT-Model





- ⇒ covers wide bias range
- ⇒ covers frequency range from 0.3 to 220 GHz
- ⇒ scalable from 10 µm to 120 µm
- ⇒ variable finger number
- ⇒ proper noise description
- ⇒ T=300 K

Extraction Tool LARA



ROI contains 12 sets

Current Set 1 to 12 of 12

☐ AP

(0.6000, 2) 0

F2x60_c17_g1d1

☑ Autoscale
☑ New Axes
☐ 3D

Model: BiasAlInF_Nc1_TP_correctRbBest_N2 Modeltyp:0

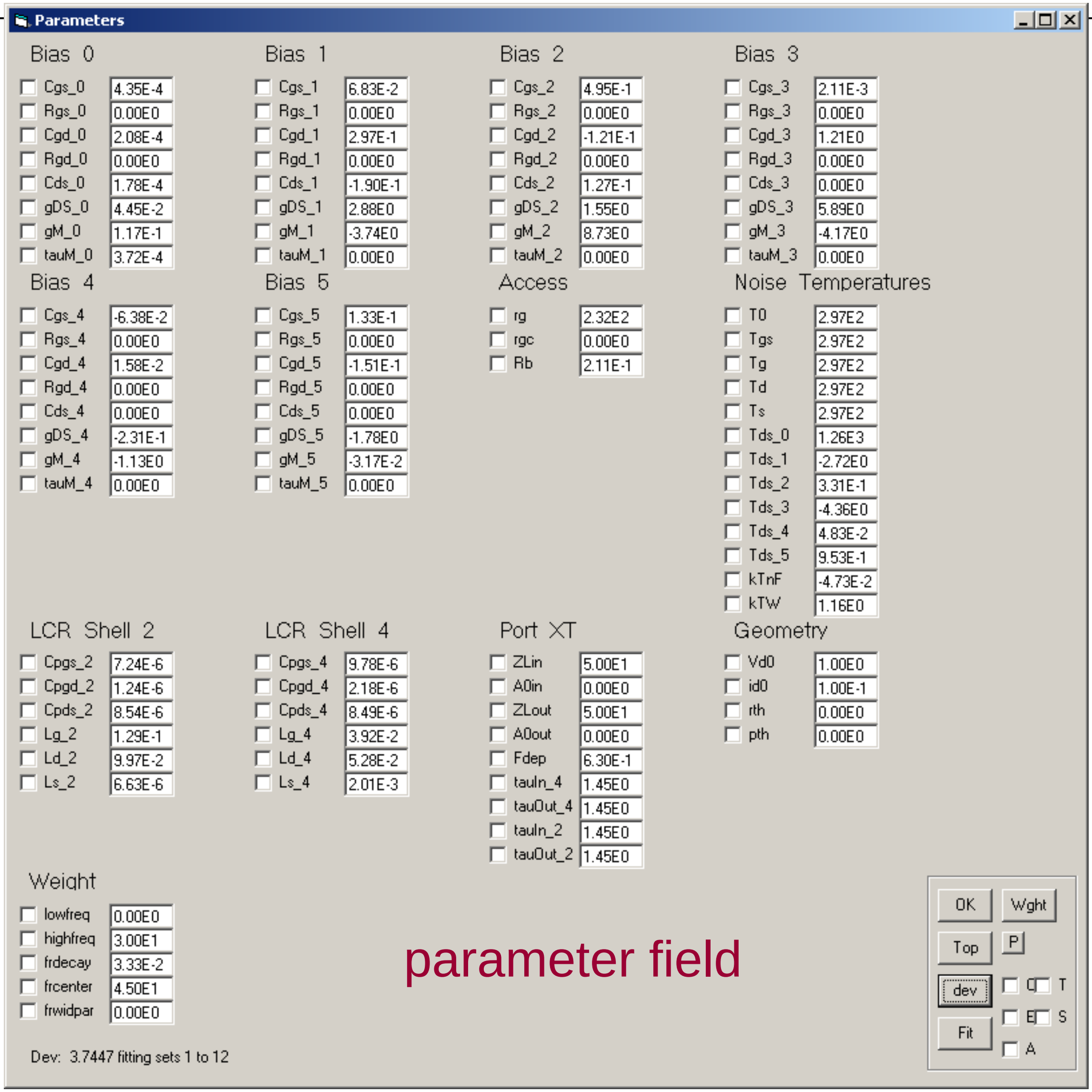
	Start	End	Step	
act	0.25	110.00	1	
	0.2500	110.00	1.00	freq
	0.60	1.00	1	
0.60	0.6000	1.00	1.00	VDS
	2.00	2.00		
	2.0000	2.00		nF
	0.12	0.12		
	0.1200	0.12		Wg

☐ DC

☐ Common Parasitics

S11	1	3.1110
S12	1	4.9456
S21	1	2.7385
S22	1	3.8020
MSGMAG	0	0
KFac	0	0

LARA Model Scripts



Bias 0		Bias 1		Bias 2		Bias 3	
☐ Cgs_0	4.35E-4	☐ Cgs_1	6.83E-2	☐ Cgs_2	4.95E-1	☐ Cgs_3	2.11E-3
☐ Rgs_0	0.00E0	☐ Rgs_1	0.00E0	☐ Rgs_2	0.00E0	☐ Rgs_3	0.00E0
☐ Cgd_0	2.08E-4	☐ Cgd_1	2.97E-1	☐ Cgd_2	-1.21E-1	☐ Cgd_3	1.21E0
☐ Rgd_0	0.00E0	☐ Rgd_1	0.00E0	☐ Rgd_2	0.00E0	☐ Rgd_3	0.00E0
☐ Cds_0	1.78E-4	☐ Cds_1	-1.90E-1	☐ Cds_2	1.27E-1	☐ Cds_3	0.00E0
☐ gDS_0	4.45E-2	☐ gDS_1	2.88E0	☐ gDS_2	1.55E0	☐ gDS_3	5.89E0
☐ gM_0	1.17E-1	☐ gM_1	-3.74E0	☐ gM_2	8.73E0	☐ gM_3	-4.17E0
☐ tauM_0	3.72E-4	☐ tauM_1	0.00E0	☐ tauM_2	0.00E0	☐ tauM_3	0.00E0

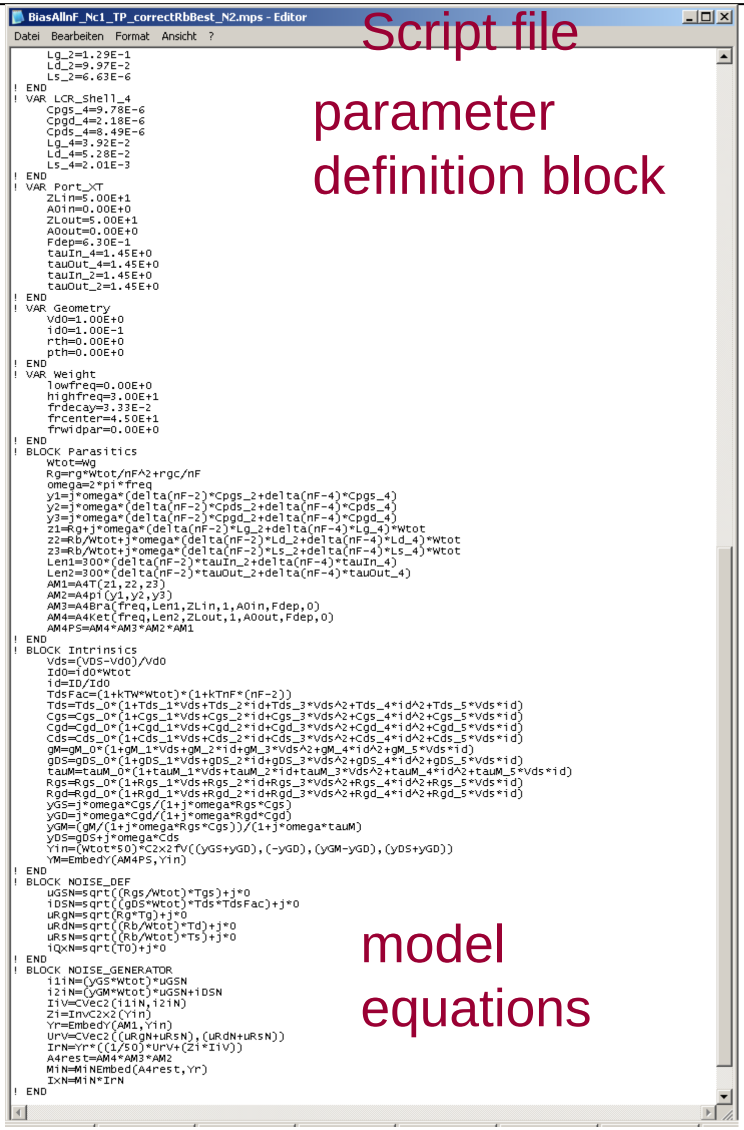
Bias 4		Bias 5		Access		Noise Temperatures	
☐ Cgs_4	-6.38E-2	☐ Cgs_5	1.33E-1	☐ rg	2.32E2	☐ T0	2.97E2
☐ Rgs_4	0.00E0	☐ Rgs_5	0.00E0	☐ rgc	0.00E0	☐ Tgs	2.97E2
☐ Cgd_4	1.58E-2	☐ Cgd_5	-1.51E-1	☐ Rb	2.11E-1	☐ Tg	2.97E2
☐ Rgd_4	0.00E0	☐ Rgd_5	0.00E0			☐ Td	2.97E2
☐ Cds_4	0.00E0	☐ Cds_5	0.00E0			☐ Ts	2.97E2
☐ gDS_4	-2.31E-1	☐ gDS_5	-1.78E0			☐ Tds_0	1.26E3
☐ gM_4	-1.13E0	☐ gM_5	-3.17E-2			☐ Tds_1	-2.72E0
☐ tauM_4	0.00E0	☐ tauM_5	0.00E0			☐ Tds_2	3.31E-1
						☐ Tds_3	-4.36E0
						☐ Tds_4	4.83E-2
						☐ Tds_5	9.53E-1
						☐ kTnF	-4.73E-2
						☐ kTW	1.16E0

LCR Shell 2		LCR Shell 4		Port XT		Geometry	
☐ Cpgs_2	7.24E-6	☐ Cpgs_4	9.78E-6	☐ ZLin	5.00E1	☐ Vd0	1.00E0
☐ Cpgd_2	1.24E-6	☐ Cpgd_4	2.18E-6	☐ A0in	0.00E0	☐ id0	1.00E-1
☐ Cpds_2	8.54E-6	☐ Cpds_4	8.49E-6	☐ ZLout	5.00E1	☐ rth	0.00E0
☐ Lg_2	1.29E-1	☐ Lg_4	3.92E-2	☐ A0out	0.00E0	☐ pth	0.00E0
☐ Ld_2	9.97E-2	☐ Ld_4	5.28E-2	☐ Fdep	6.30E-1		
☐ Ls_2	6.63E-6	☐ Ls_4	2.01E-3	☐ tauIn_4	1.45E0		
				☐ tauOut_4	1.45E0		
				☐ tauIn_2	1.45E0		
				☐ tauOut_2	1.45E0		

Weight	
☐ lowfreq	0.00E0
☐ highfreq	3.00E1
☐ frdecay	3.33E-2
☐ frcenter	4.50E1
☐ frwidpar	0.00E0

Dev: 3.7447 fitting sets 1 to 12

parameter field



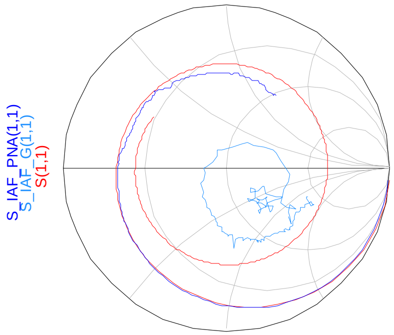
Script file

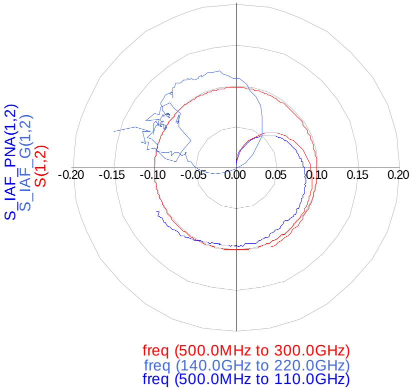
parameter definition block

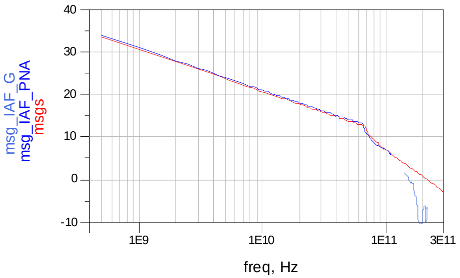
model equations

```
    Lg_2=1.29E-1
    Ld_2=9.97E-2
    Ls_2=6.63E-6
! END
! VAR LCR_Shell_4
    Cpgs_4=9.78E-6
    Cpgd_4=2.18E-6
    Cpds_4=8.49E-6
    Lg_4=3.92E-2
    Ld_4=5.28E-2
    Ls_4=2.01E-3
! END
! VAR Port_XT
    ZLin=5.00E+1
    A0in=0.00E+0
    ZLout=5.00E+1
    A0out=0.00E+0
    Fdep=6.30E-1
    tauIn_4=1.45E+0
    tauOut_4=1.45E+0
    tauIn_2=1.45E+0
    tauOut_2=1.45E+0
! END
! VAR Geometry
    Vd0=1.00E+0
    id0=1.00E-1
    rth=0.00E+0
    pth=0.00E+0
! END
! VAR Weight
    lowfreq=0.00E+0
    highfreq=3.00E+1
    frdecay=3.33E-2
    frcenter=4.50E+1
    frwidpar=0.00E+0
! END
! BLOCK Parasitics
    Wtot=Wg
    Rg=rg*Wtot/nF^2+rgc/nF
    omega=2*pi*freq
    y1=j*omega*(delta(nF-2)*Cpgs_2+delta(nF-4)*Cpgs_4)
    y2=j*omega*(delta(nF-2)*Cpds_2+delta(nF-4)*Cpds_4)
    y3=j*omega*(delta(nF-2)*Cpgd_2+delta(nF-4)*Cpgd_4)
    z1=Rg+j*omega*(delta(nF-2)*Lg_2+delta(nF-4)*Lg_4)*Wtot
    z2=Rb/Wtot+j*omega*(delta(nF-2)*Ld_2+delta(nF-4)*Ld_4)*Wtot
    z3=Rb/Wtot+j*omega*(delta(nF-2)*Ls_2+delta(nF-4)*Ls_4)*Wtot
    Len1=300*(delta(nF-2)*tauIn_2+delta(nF-4)*tauIn_4)
    Len2=300*(delta(nF-2)*tauOut_2+delta(nF-4)*tauOut_4)
    AM1=A4T(z1,z2,z3)
    AM2=A4pi(y1,y2,y3)
    AM3=A4Bra(freq,Len1,ZLin,1,A0in,Fdep,0)
    AM4=A4Ket(freq,Len2,ZLout,1,A0out,Fdep,0)
    AM4PS=AM4*AM3*AM2*AM1
! END
! BLOCK Intrinsics
    Vds=(VDS-Vd0)/Vd0
    Id0=id0*Wtot
    id=ID/Id0
    TdsFac=(1+kTW*Wtot)*(1+kTnF*(nF-2))
    Tds=Tds_0*(1+Tds_1*Vds+Tds_2*id+Tds_3*Vds^2+Tds_4*id^2+Tds_5*Vds*id)
    Cgs=Cgs_0*(1+Cgs_1*Vds+Cgs_2*id+Cgs_3*Vds^2+Cgs_4*id^2+Cgs_5*Vds*id)
    Cgd=Cgd_0*(1+Cgd_1*Vds+Cgd_2*id+Cgd_3*Vds^2+Cgd_4*id^2+Cgd_5*Vds*id)
    Cds=Cds_0*(1+Cds_1*Vds+Cds_2*id+Cds_3*Vds^2+Cds_4*id^2+Cds_5*Vds*id)
    gM=gM_0*(1+gM_1*Vds+gM_2*id+gM_3*Vds^2+gM_4*id^2+gM_5*Vds*id)
    gDS=gDS_0*(1+gDS_1*Vds+gDS_2*id+gDS_3*Vds^2+gDS_4*id^2+gDS_5*Vds*id)
    tauM=tauM_0*(1+tauM_1*Vds+tauM_2*id+tauM_3*Vds^2+tauM_4*id^2+tauM_5*Vds*id)
    Rgs=Rgs_0*(1+Rgs_1*Vds+Rgs_2*id+Rgs_3*Vds^2+Rgs_4*id^2+Rgs_5*Vds*id)
    Rgd=Rgd_0*(1+Rgd_1*Vds+Rgd_2*id+Rgd_3*Vds^2+Rgd_4*id^2+Rgd_5*Vds*id)
    yGS=j*omega*Cgs/(1+j*omega*Rgs*Cgs)
    yGD=j*omega*Cgd/(1+j*omega*Rgd*Cgd)
    yGM=(gM/(1+j*omega*Rgs*Cgs))/(1+j*omega*tauM)
    yDS=gDS+j*omega*Cds
    Yin=(Wtot*50)*C2x2fV((yGS+yGD),(-yGD),(yGM-yGD),(yDS+yGD))
    YM=EmbedY(AM4PS,Yin)
! END
! BLOCK NOISE_DEF
    uGSN=sqrt((Rgs/Wtot)*Tgs)+j*0
    iDSN=sqrt((gDS*Wtot)*Tds*TdsFac)+j*0
    uRgN=sqrt(Rg*Tg)+j*0
    uRdN=sqrt((Rb/Wtot)*Td)+j*0
    uRsN=sqrt((Rb/Wtot)*Ts)+j*0
    iQxN=sqrt(T0)+j*0
! END
! BLOCK NOISE_GENERATOR
    i1iN=(yGS*Wtot)*uGSN
    i2iN=(yGM*Wtot)*uGSN+iDSN
    IiV=CVec2(i1iN,i2iN)
    Zi=InvC2x2(Yin)
    Yr=EmbedY(AM1,Yin)
    UrV=CVec2((uRgN+uRsN),(uRdN+uRsN))
    IrN=Yr*((1/50)*UrV+(Zi*IiV))
    A4rest=AM4*AM3*AM2
    MiN=MiNEmbed(A4rest,Yr)
    IxN=MiN*IrN
! END
```

ADS Model Verification



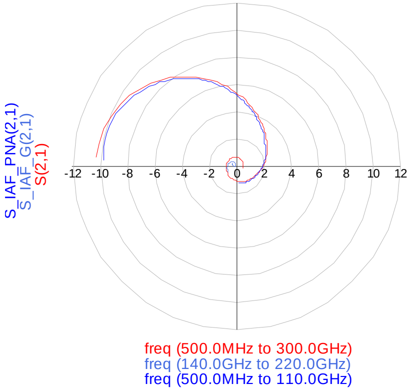


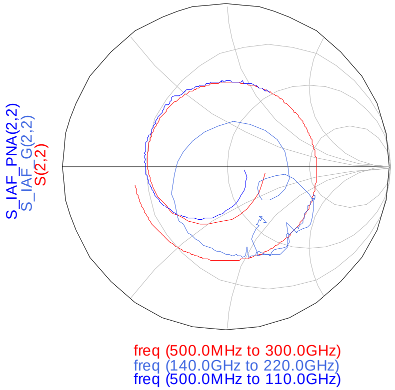


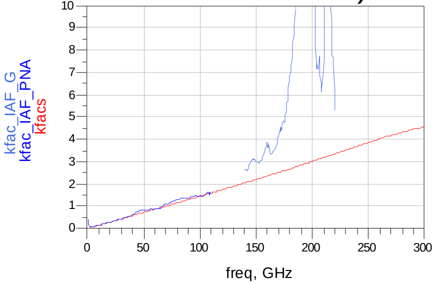
F2x60 id=400 Vd=1 LG=100

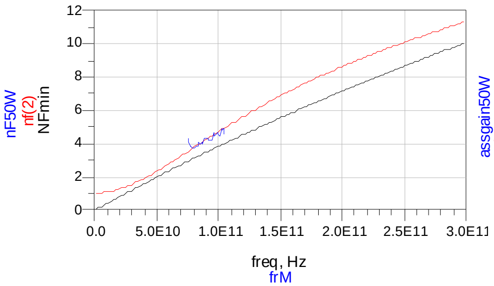
On-wafer probing

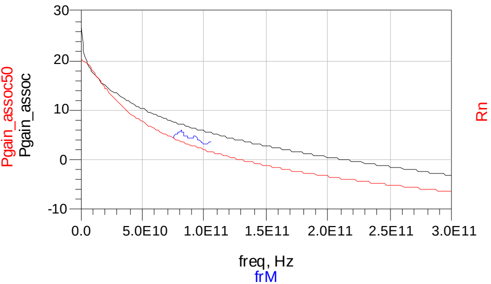
(Large Systematic measurement errors in G-Band)

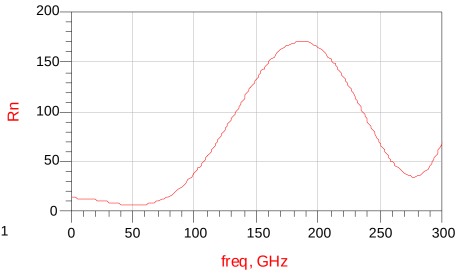


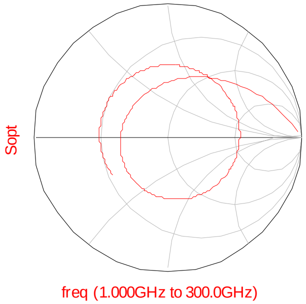












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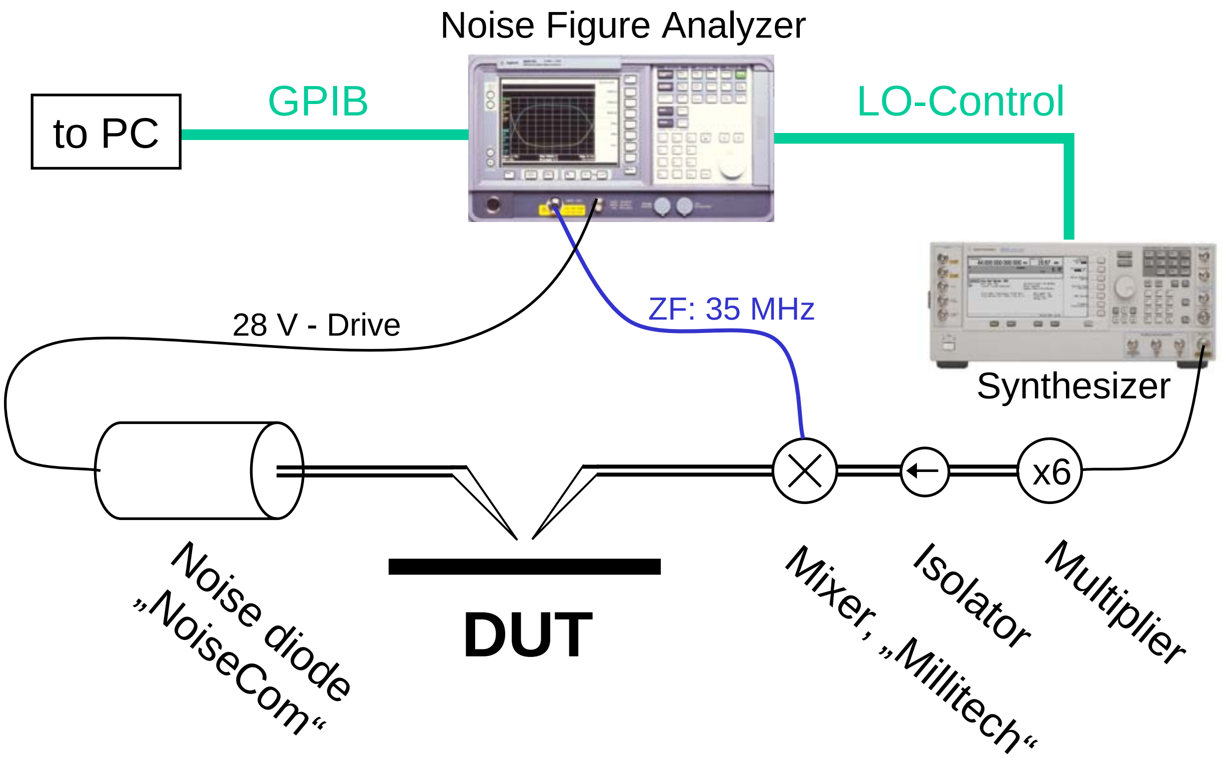
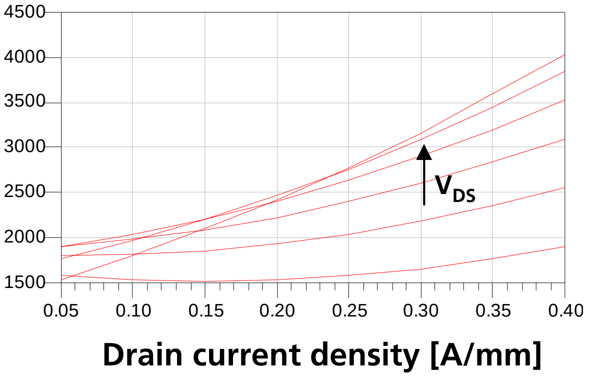
NF50 Measurement at W-Band

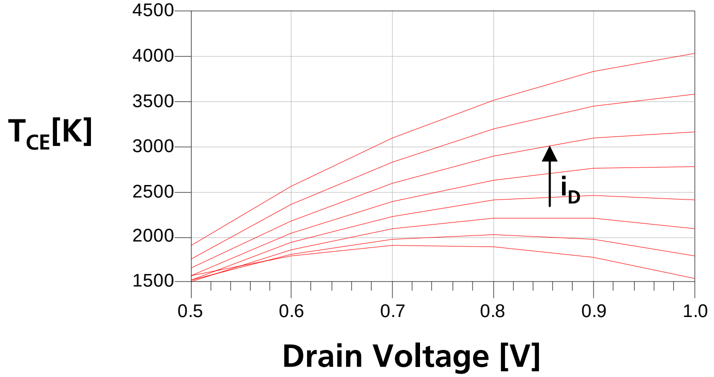


Electron Temperature vs Bias (T=300K)

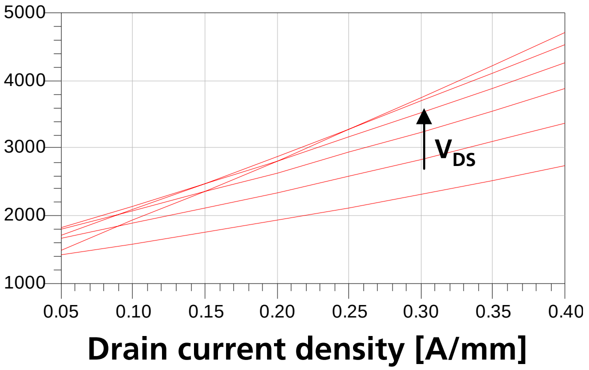
IAF mHEMT

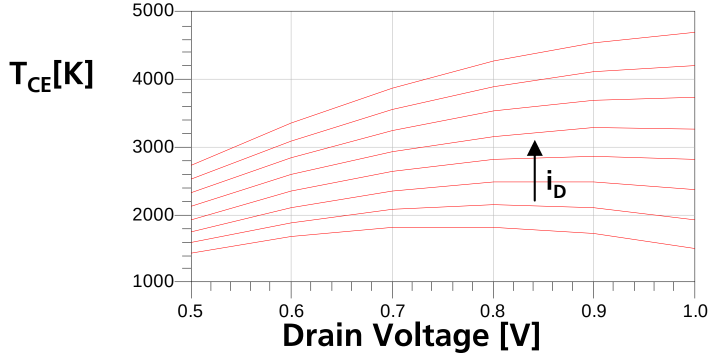
L_G=100 nm





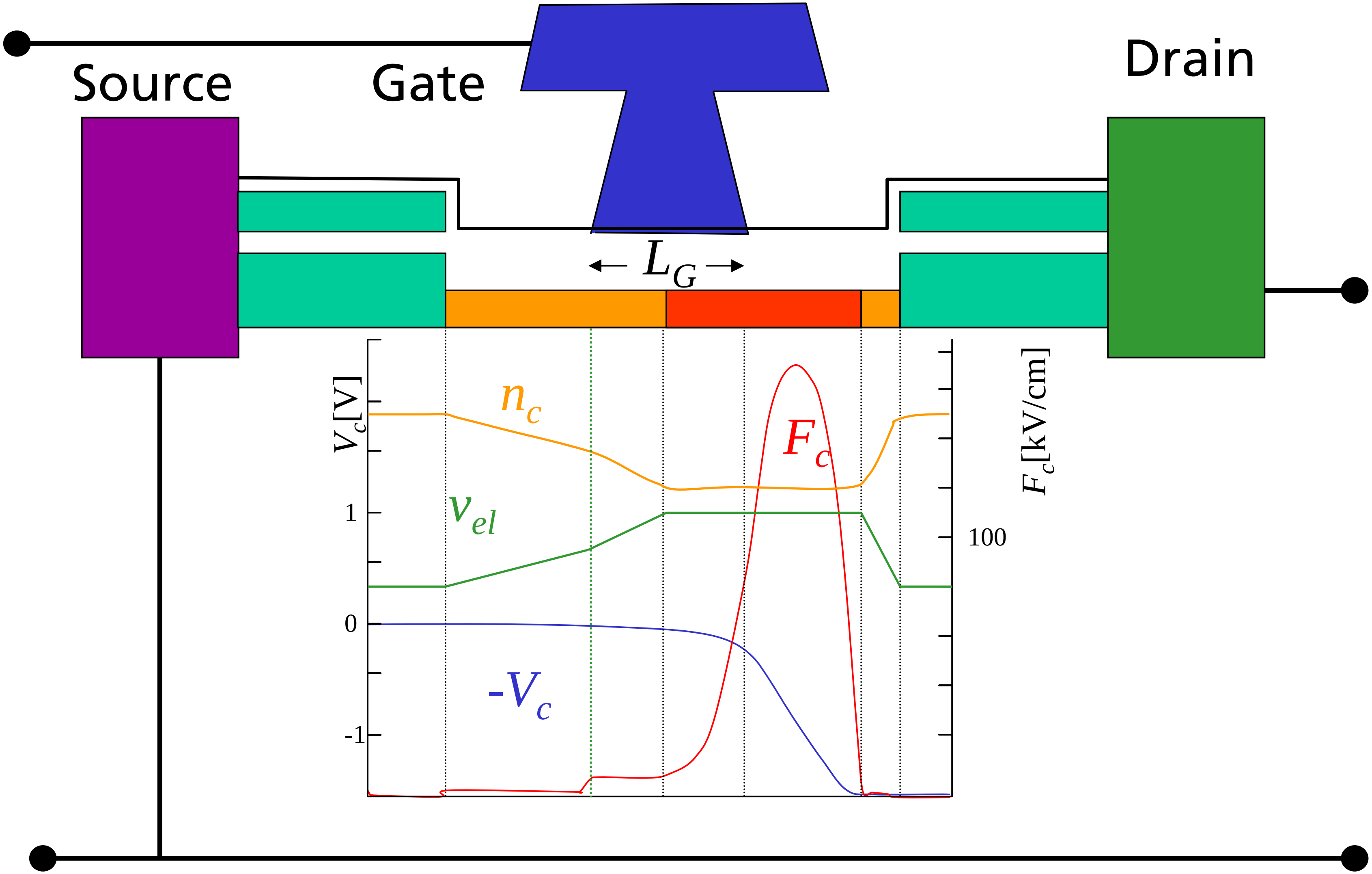
L_G=50 nm





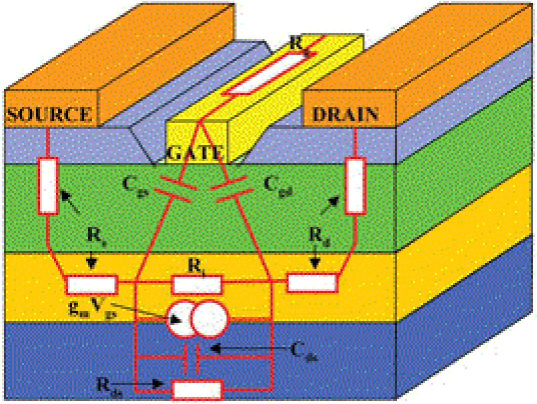
Hot electrons in high field region of transistor

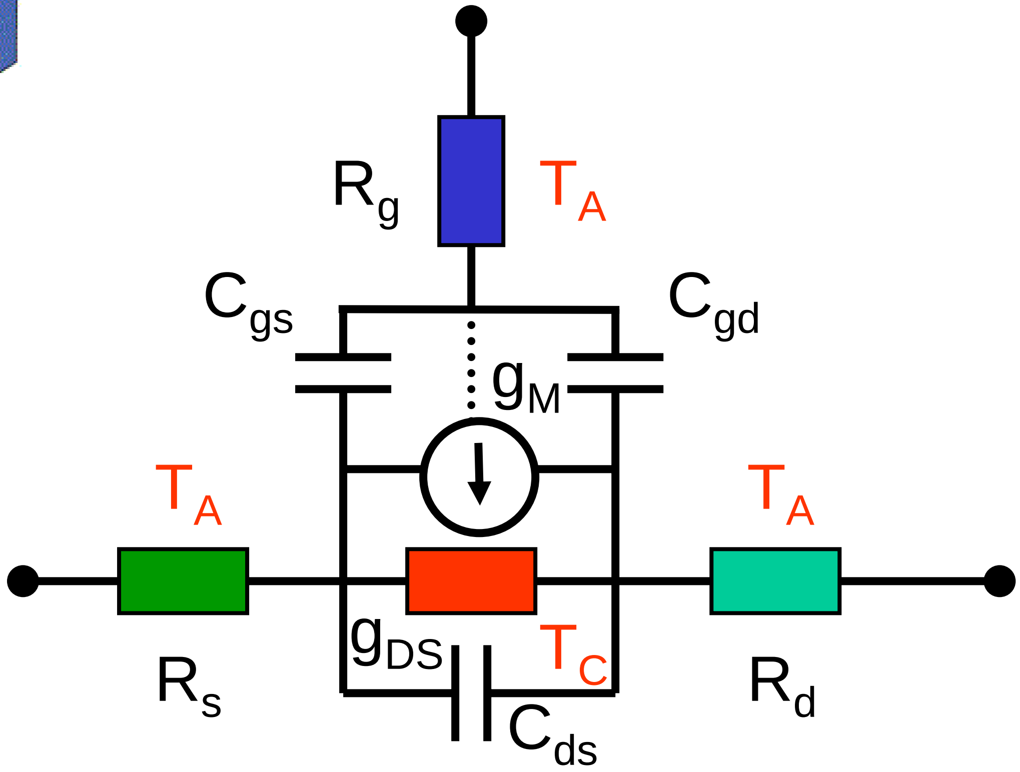
Short Channel HEMT



Fraunhofer IAF

Lumped Element mHEMT-Model and Low Noise Technology Criteria



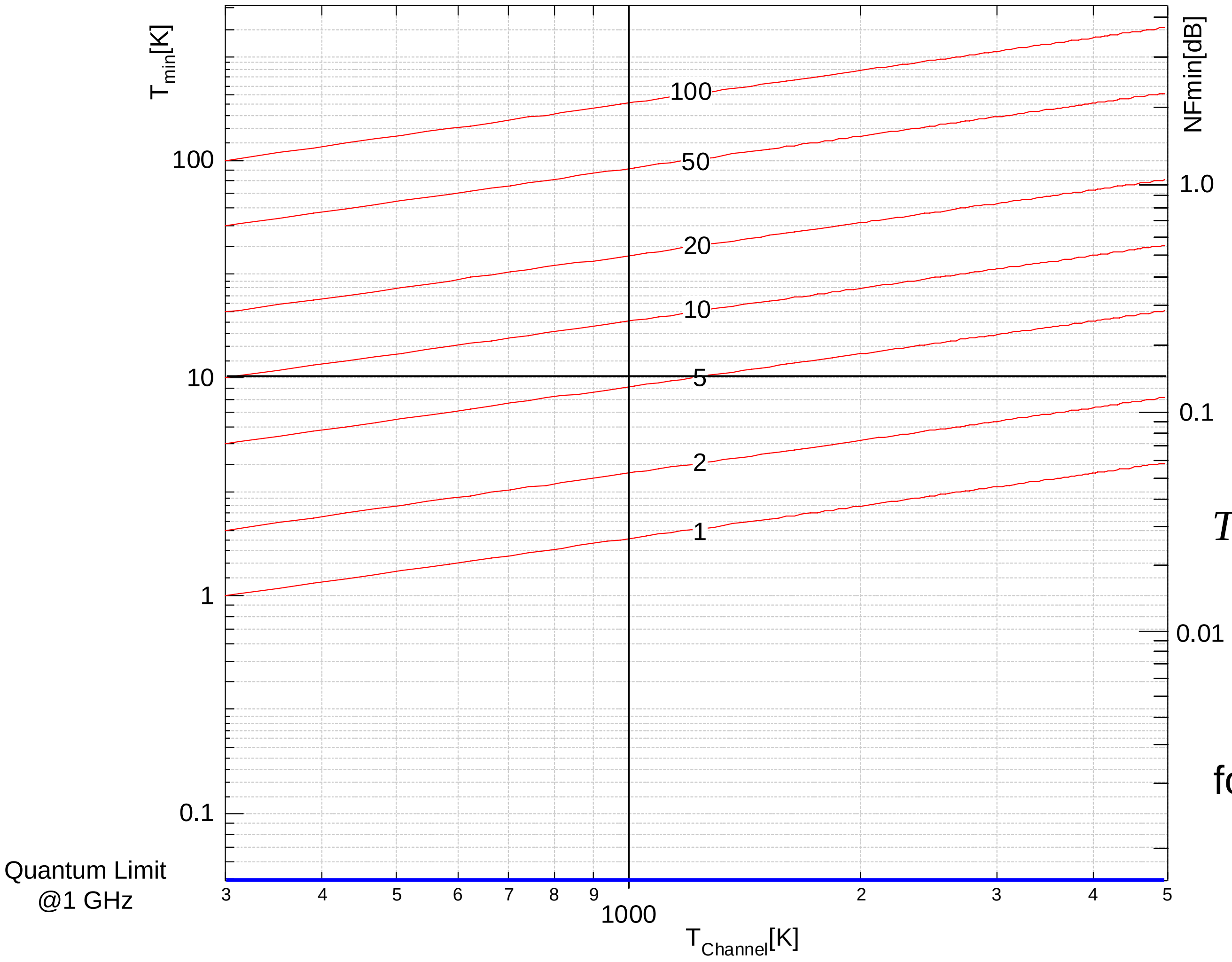


Technological Low Noise Criteria

- ⇒ high electron mobility (g_{DS}, g_M)
- ⇒ low sheet resistance (R_s,R_d)
- ⇒ low contact resistance (R_s,R_d)
- ⇒ low gate line resistance (R_g)
- ⇒ High Gain (small channel distance)
- ⇒ Temperature??

$$T_{\min} = \sqrt{T_{Ambient} T_{Channel}}\, f / f_{\max}$$

Assessment of Minimum Noise Temperature for mHEMT



L_G=100 nm
f_{max}=300 GHz
T_{amb}=300 K

$$T_{\min} = \sqrt{T_{Ambient} T_{Channel}}\, f \,/\, f_{\max}$$

for $f \ll f_{\max}$

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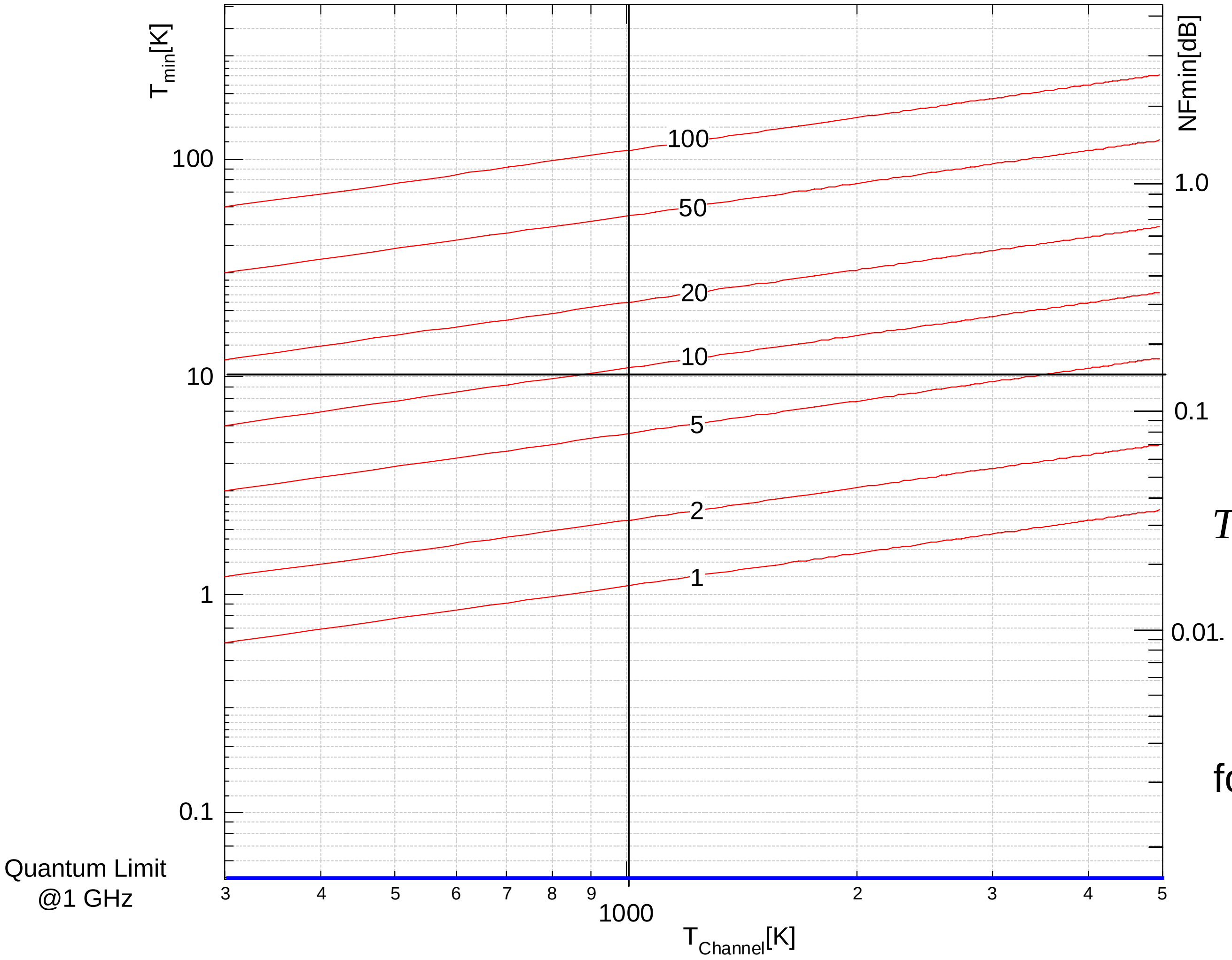
Assessment of Minimum Noise Temperature for mHEMT



L_G=50 nm

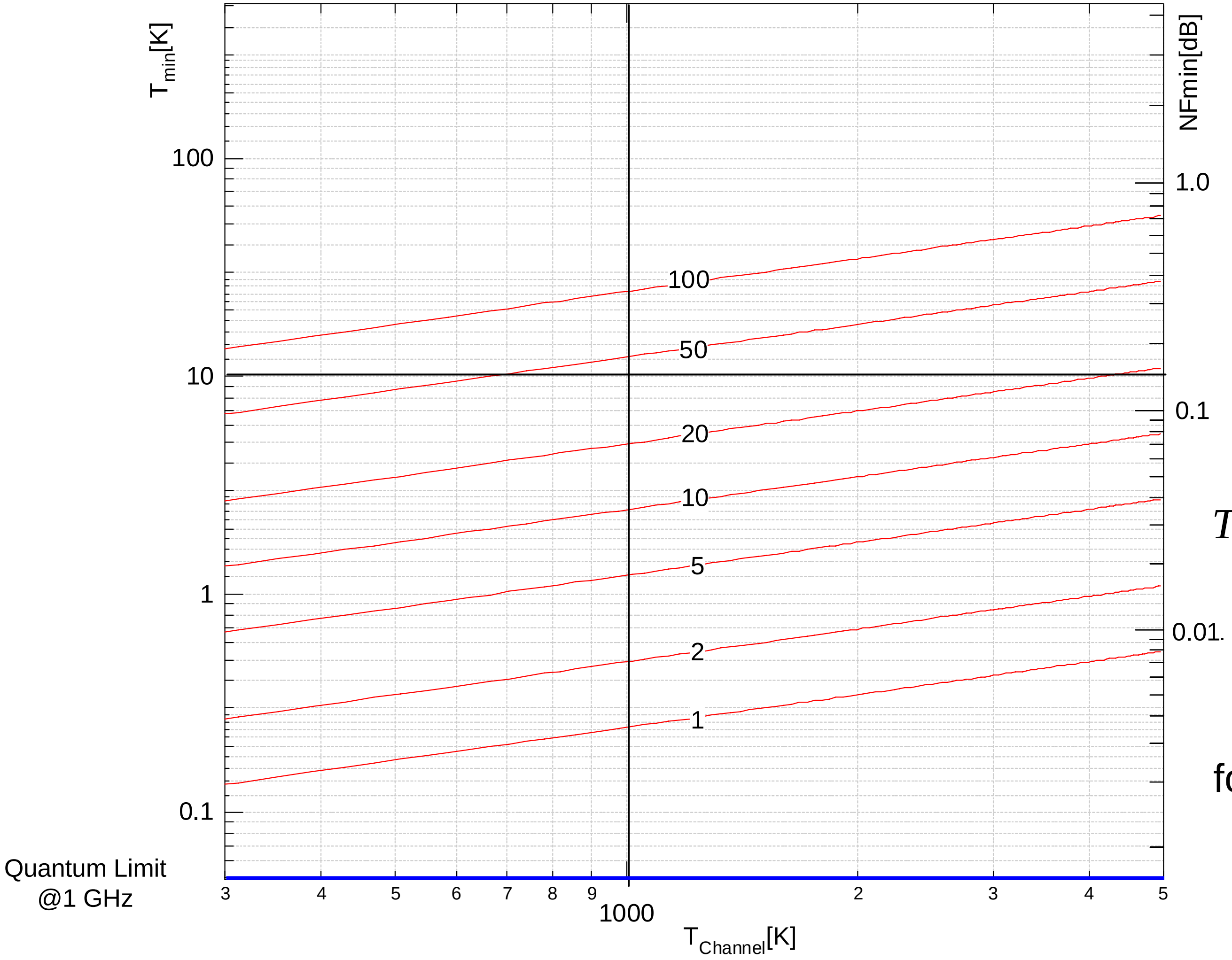
f_{max}=500 GHz

T_{amb}=300 K

$$T_{\min} = \sqrt{T_{Ambient} T_{Channel}}\, f / f_{\max}$$

for $f \ll f_{\max}$

Assessment of Minimum Noise Temperature for mHEMT

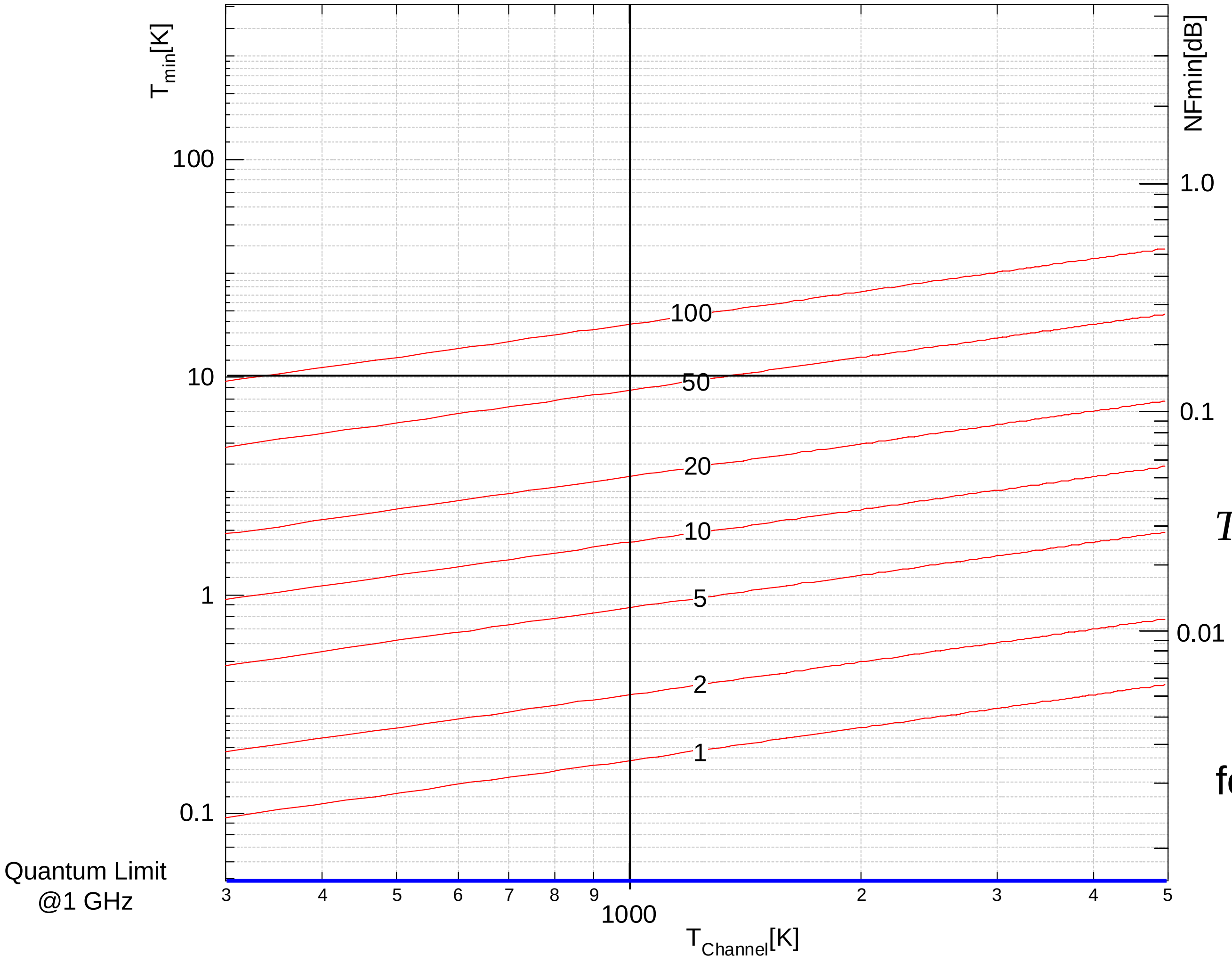


L_G=50 nm
f_{max}=500 GHz
T_{amb}=15 K

$$T_{\min} = \sqrt{T_{Ambient} T_{Channel}}\, f \,/\, f_{\max}$$

for $f \ll f_{\max}$

Assessment of Minimum Noise Temperature for mHEMT

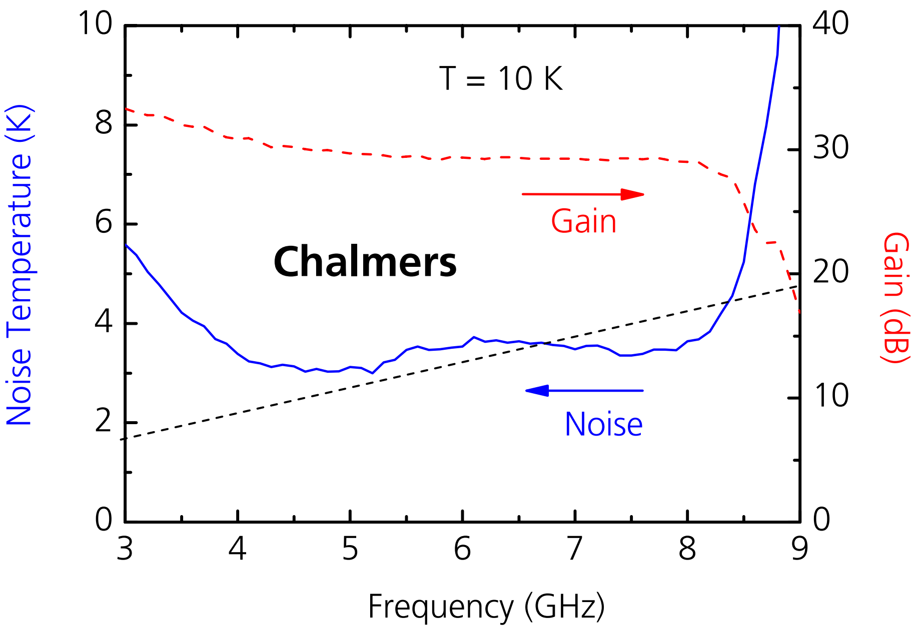


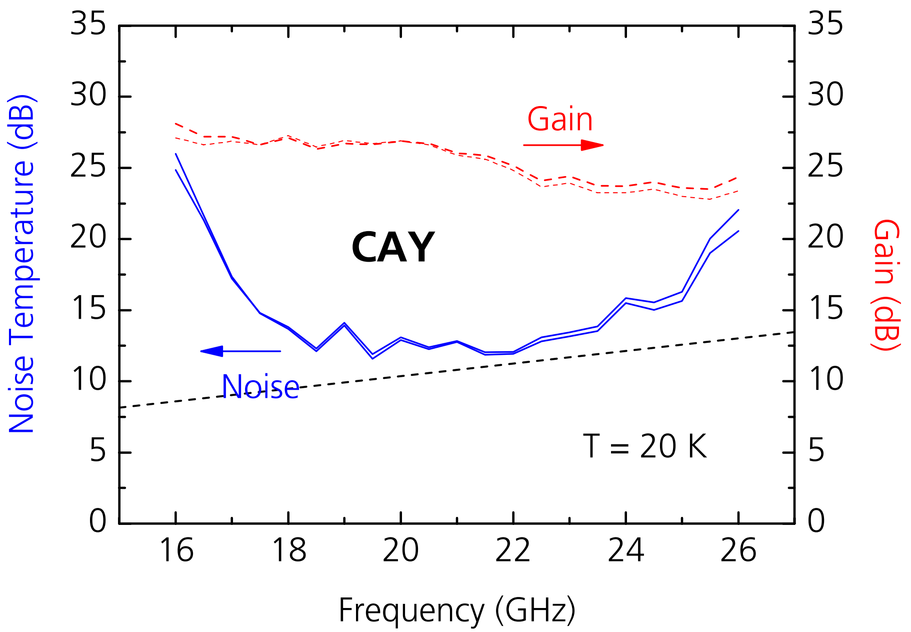
L_G=35 nm
f_{max}=700 GHz
T_{amb}=15 K

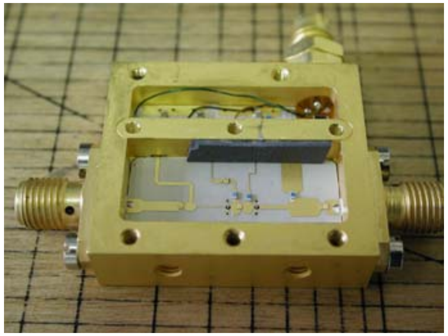
$$T_{\min} = \sqrt{T_{Ambient} T_{Channel}}\, f / f_{\max}$$

for $f \ll f_{\max}$

mHEMT-Performance at Cryogenic Temperatures

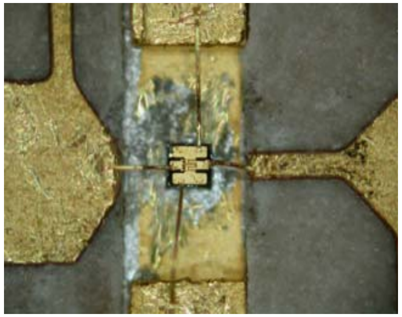




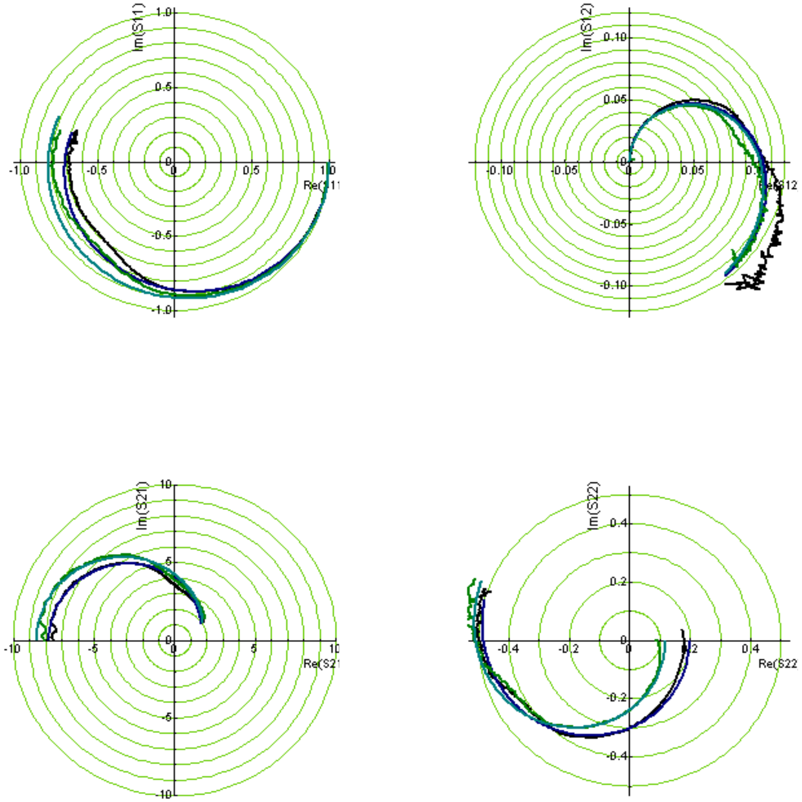


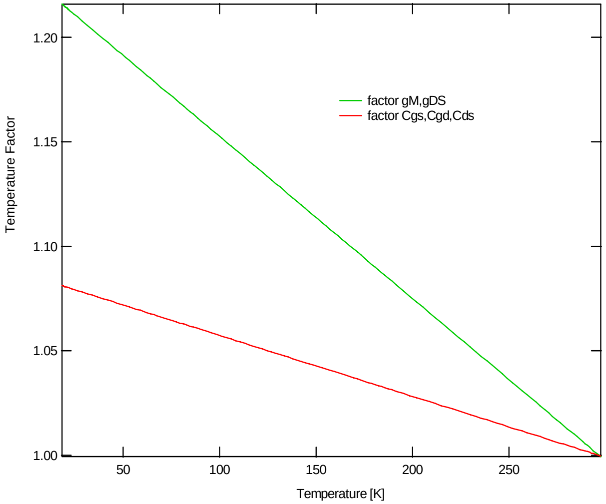
Test in Hybrid Amplifiers
- First stage : 4x40 mHEMT
- Gate Length 100 nm

Close to Best InP-HEMT performance
T_N~f/2



Temperature Dependence S-Parameters





small signal elements:

- g_M,g_{DS} increase by 20% (vsat)
- C_{gs},Cgd,Cds increase by 8% (dielectric)

MAX-PLANCK-GESELLSCHAFT

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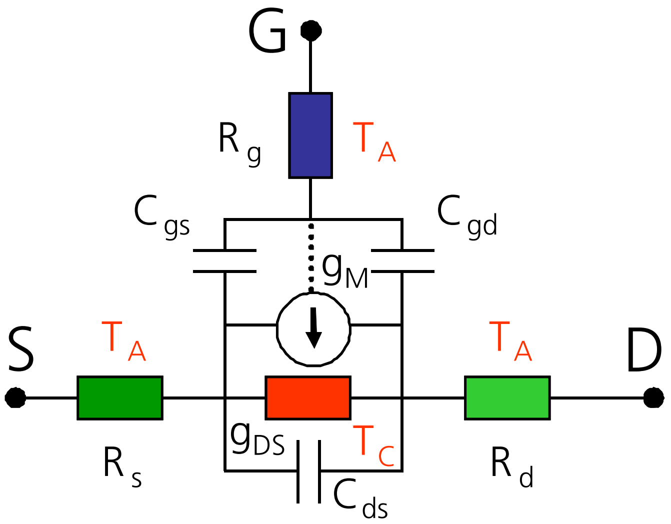
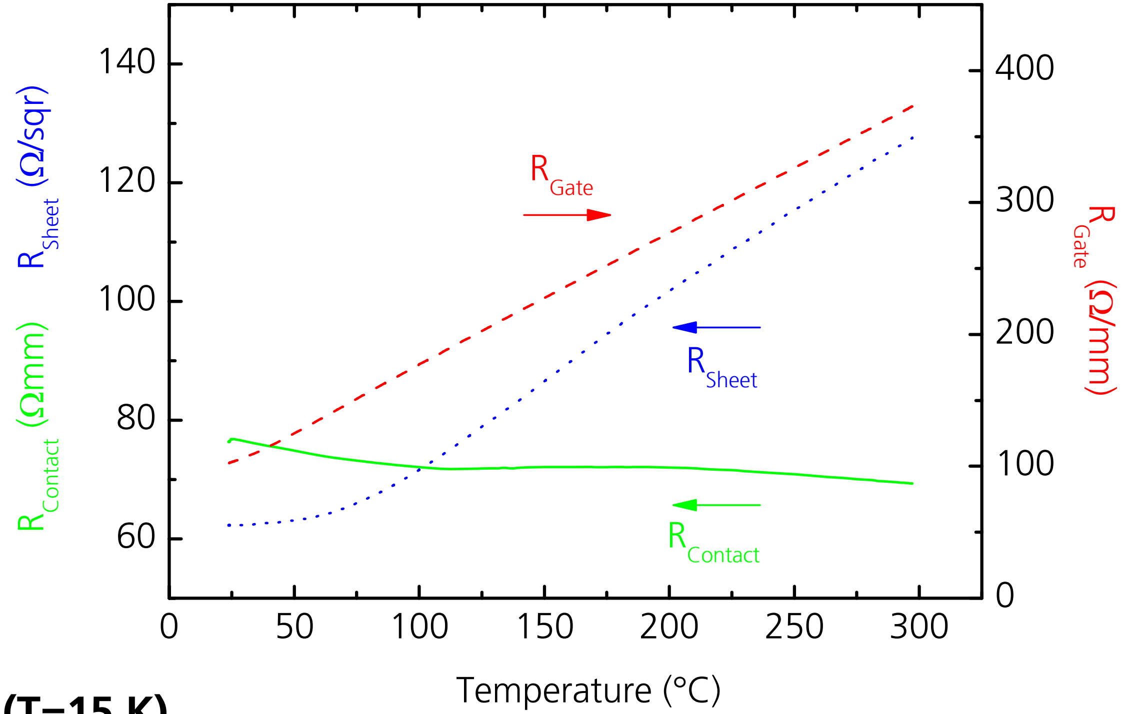
Max-Planck-Institut
für Radioastronomie

mHEMT Small Signal Model and T-Dependence of Noise Sources

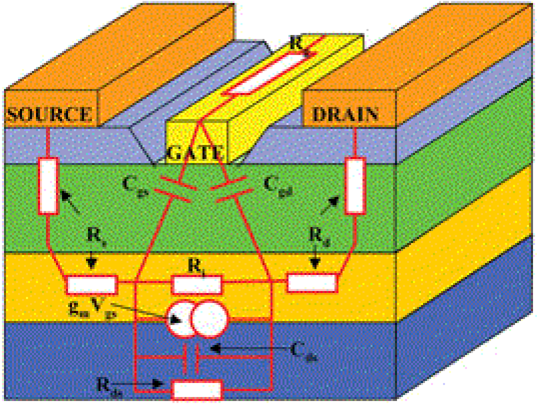


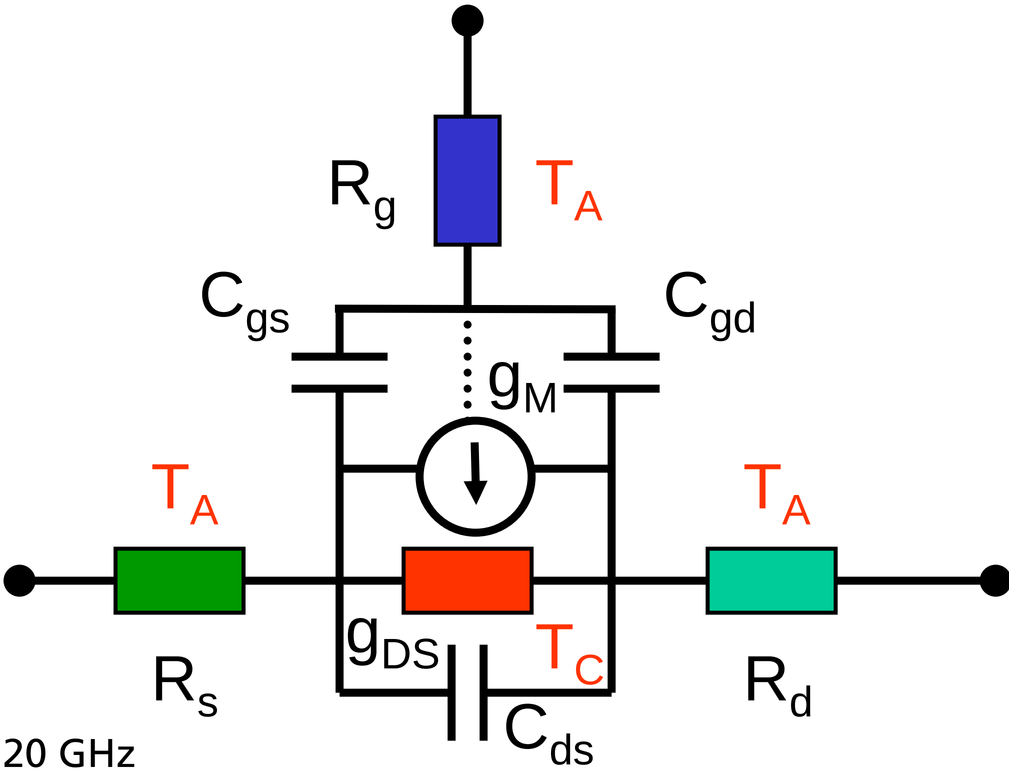


Changes RT-performance vs Cryo (T=15 K)

- **R_{sheet} decreases (-55%)**
- **R_c increases (+10%)**
- **R_g decreases (-66%)**

Extended IAF Lumped Element mHEMT-Model





⇒ covers wide bias range

⇒ covers frequency range from 0.3 to 220 GHz

⇒ scalable from 10 µm to 120 µm

⇒ variable finger number

⇒ proper noise description

⇒ 15 K < T < 300 K

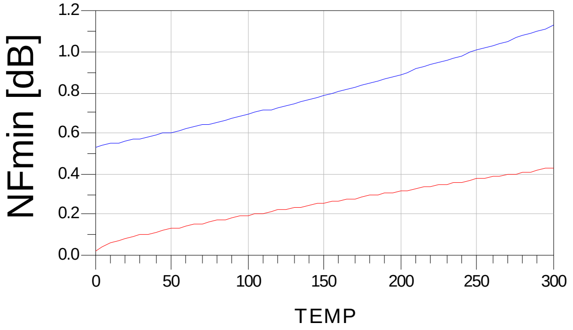
Assumptions Noise

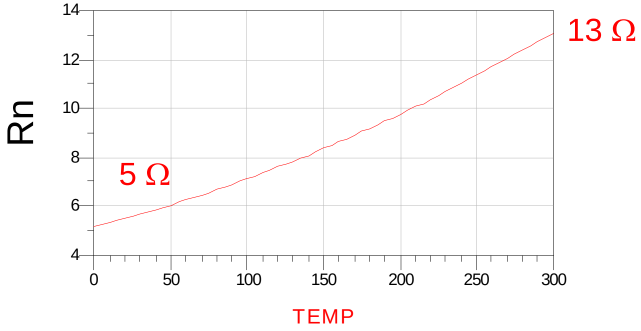
- Noise Temperature R_s,R_d,R_g ambient

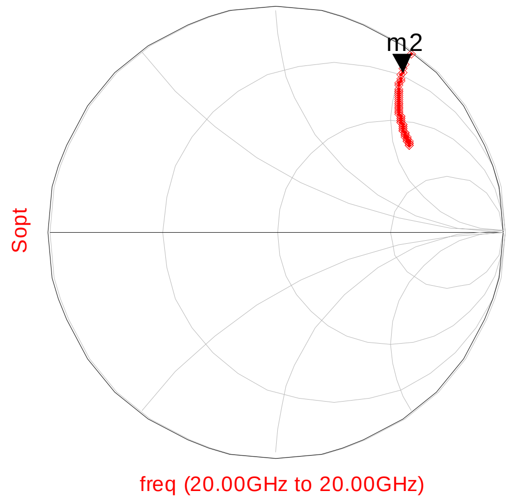
- Electron Temperature T_C not affected

Model: Noise Performance vs. Temperature

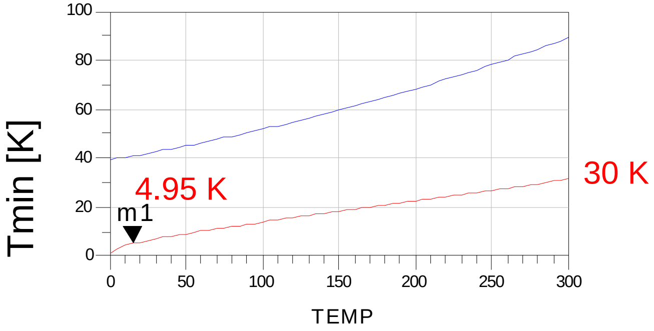
F2x40: LG=50 nm; id=150 mA/mm;Vd=1 V; f=20 GHz

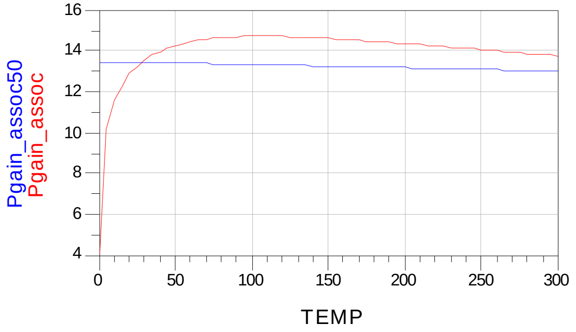


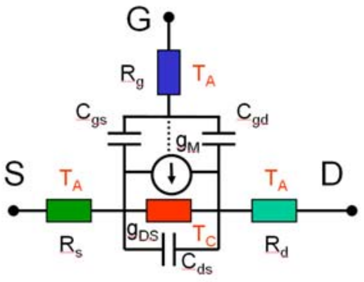




m2
freq=20.00GHz
Sopt=0.898 / 51.870
TEMP=15.000000
impedance = Z0 * (0.278 + j2.026)







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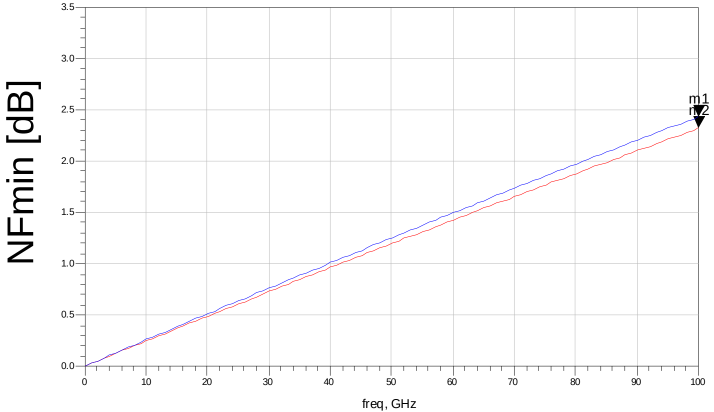
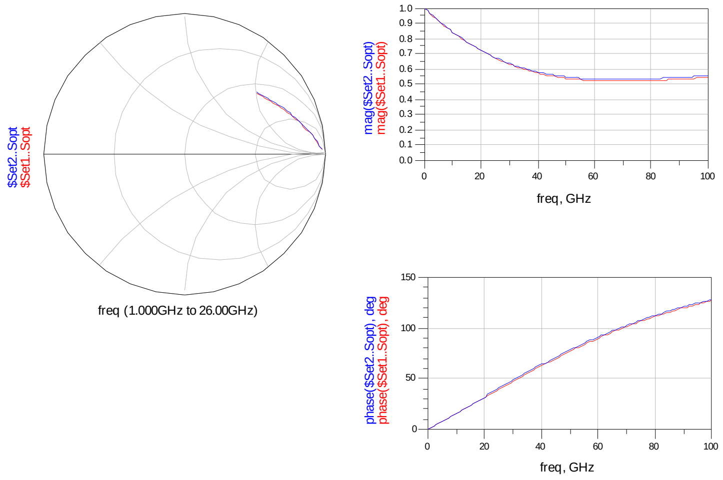
Influence of Output Conductance on Noise

F2x30
LG=100 nm
T=300K
i_D=150 mA/mm
V_{ds}=1 V



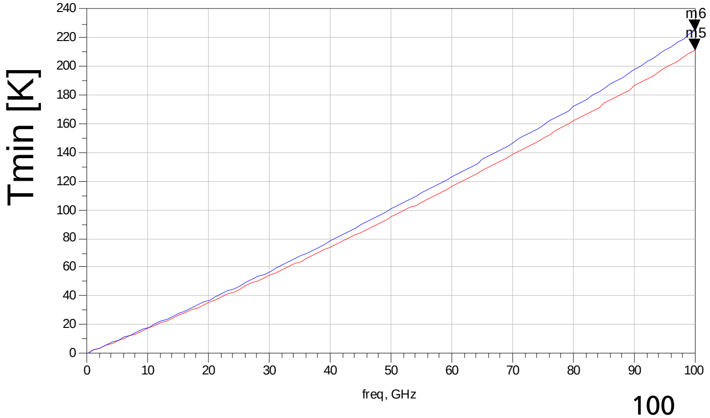
Sopt



Red: model
Blue: gDS plus 10%
Fmin:+5.0%; Rn:+5.5%

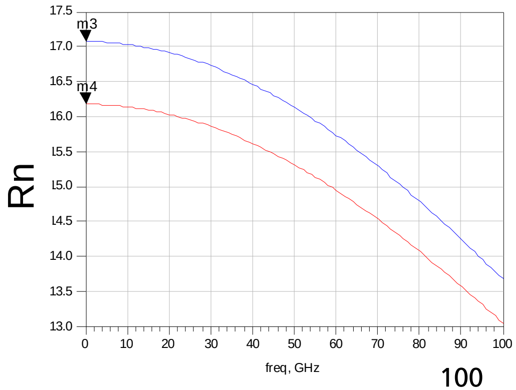
Freq[GHz] 100

2.317 2.430



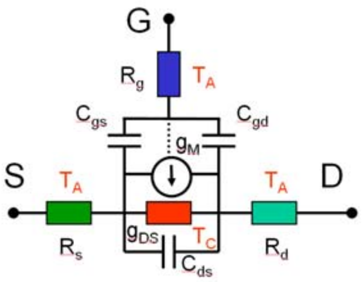
100

211 K 224 K

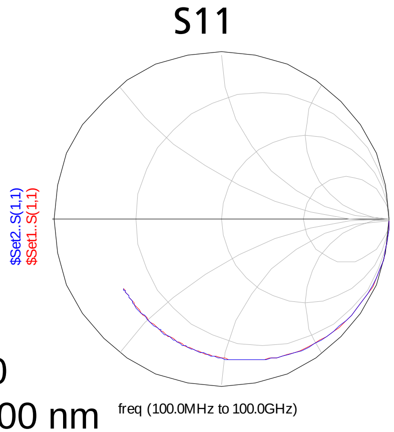


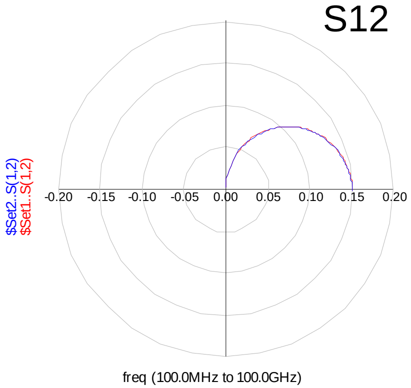
100

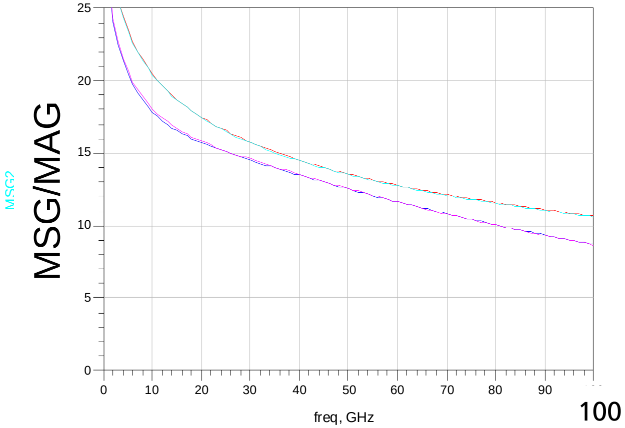
16.18 17.07



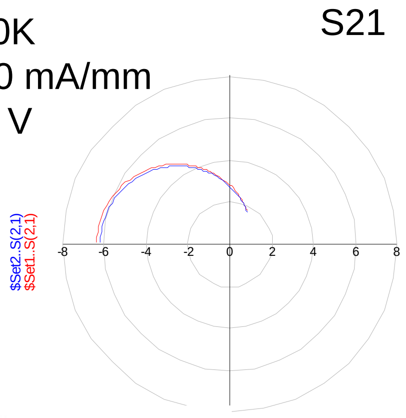
Influence of Output Cond. on SS-Performance

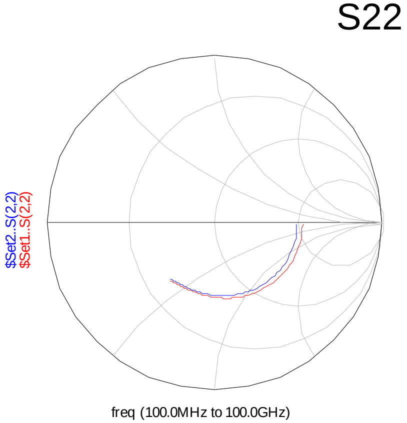


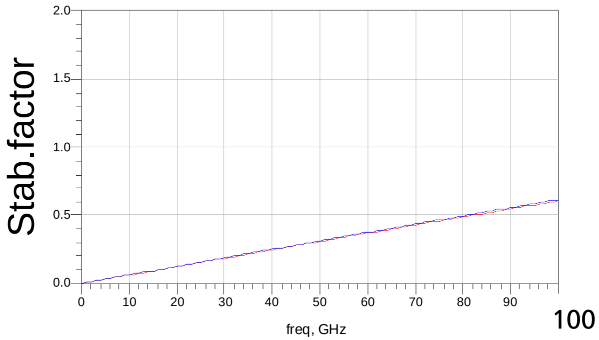


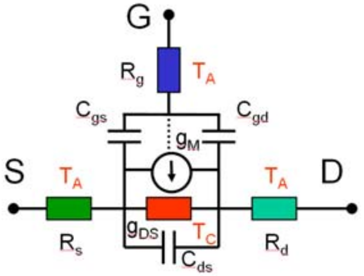


F2x30
LG=100 nm
T=300K
i_D=150 mA/mm
V_{ds}=1 V





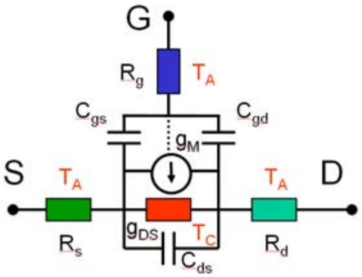




Red: model
Blue: gDS plus 10%
Fmin:+5.0%; Rn:+5.5%

Technological Improvements?

Idea for Sensitivity Test:
- Increase Contribution of Noise Sources by 10%
- Use model to calculate noise parameters

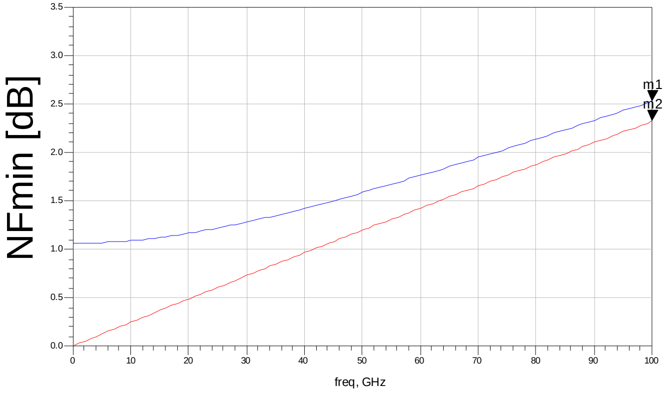


	ΔNF_{min}[%]	ΔR_n[%]
R_g	+2.8	+2.2
R_s	+1.6	+2.6
R_d	+0.3	+0.0
g_{DS}	+4.9	+5.5

F2x30
LG=100 nm
T=300K
i_D=150 mA/mm
V_{ds}=1 V

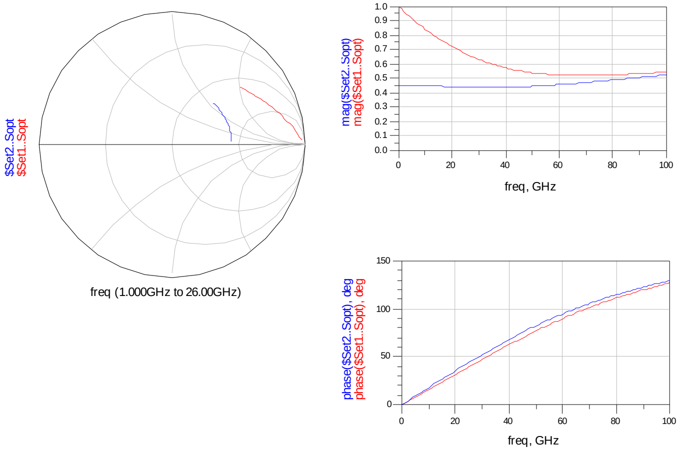
Influence of Gate Leakage on Noise

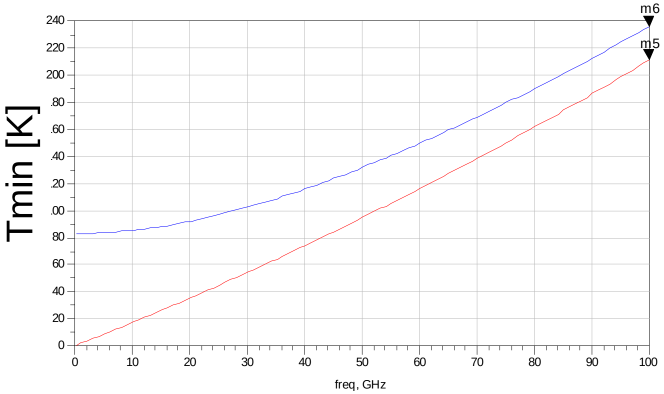
F2x30
LG=100 nm
T=300K
i_D=150 mA/mm
V_{ds}=1 V



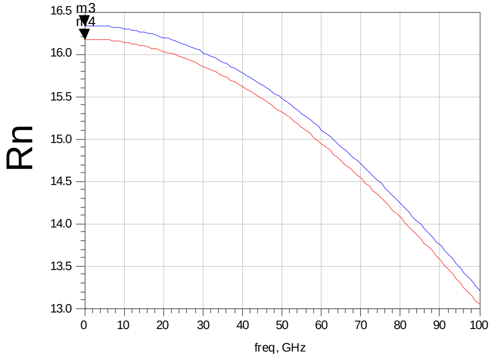
2.317 2.542

Sopt





211 K 236 K



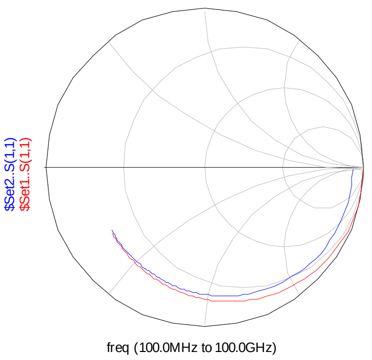
m4
freq=100.0MHz
$Set1..Rn=16.176

m3
freq=100.0MHz
$Set2..Rn=16.339

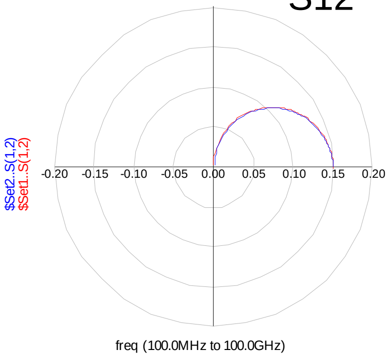
Gate Leakage : gGS=15 mΩ/mm (i_{GS}≈0.5 mA/mm)

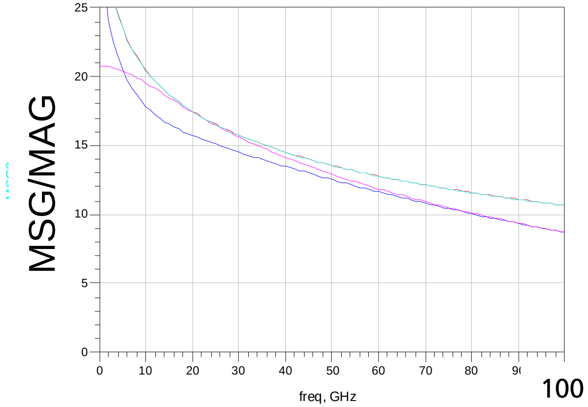
Influence of Gate Leakage on SS-Performance

S11

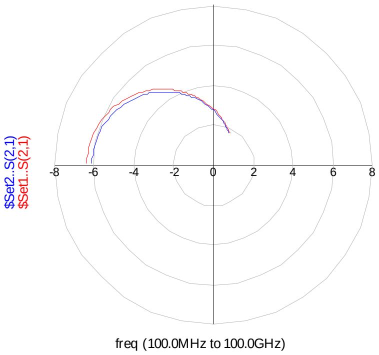


S12

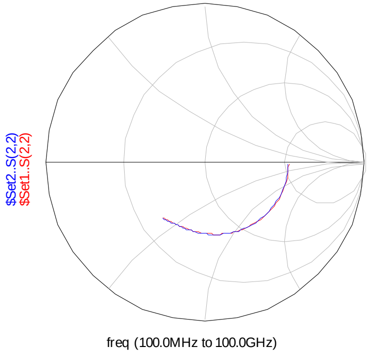


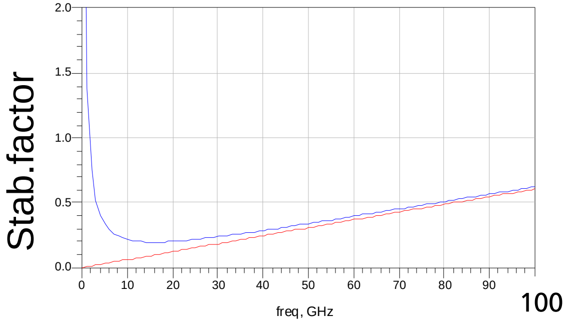


S21



S22

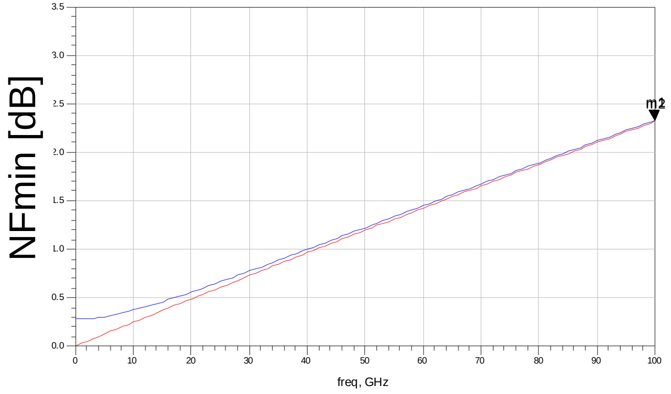




Gate Leakage : gGS=15 mΩ/mm (i_{GS}≈0.5 mA/mm)

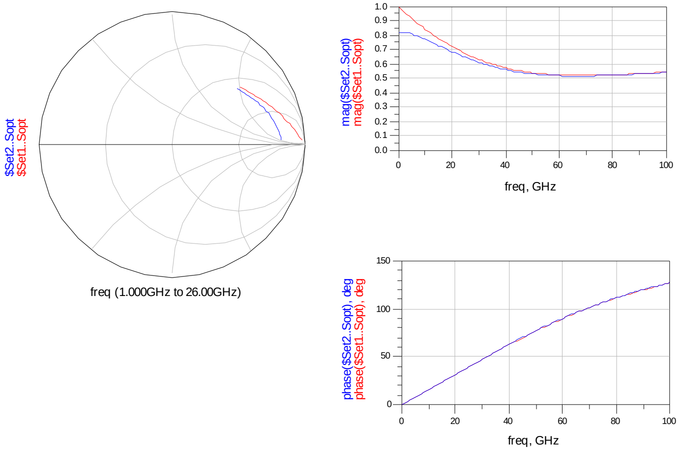
F2x30
LG=100 nm
T=300K
i_D=150 mA/mm
V_{ds}=1 V

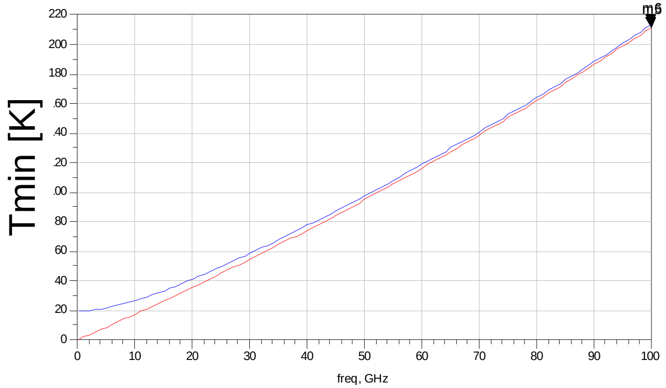
Influence of Gate Leakage on Noise

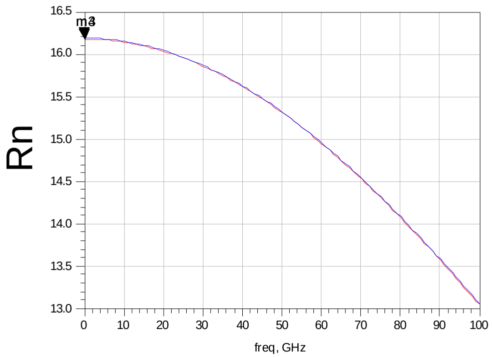


n
f
$
2.317
7
2.331
31

Sopt







211 K

213 K

m4
freq=100.0MHz
$Set1..Rn=16.176

m3
freq=100.0MHz
$Set2..Rn=16.186

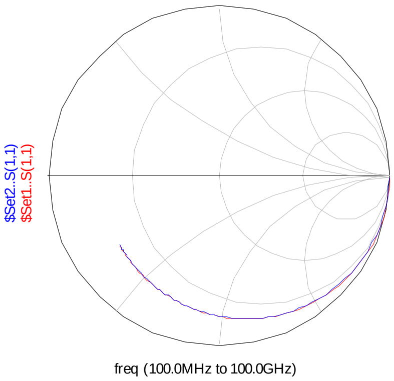
F2x30
LG=100 nm
T=300K
i_D=150 mA/mm
V_{ds}=1 V

Gate Leakage : gGS=1 mΩ/mm (i_{GS}≈40 µA/mm)

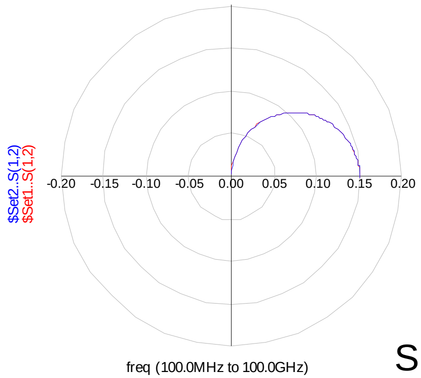
Fraunhofer
IAF

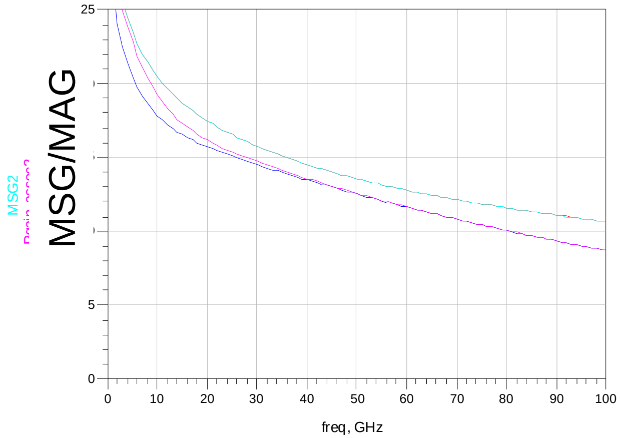
Influence of Gate Leakage on SS-Performance

S11

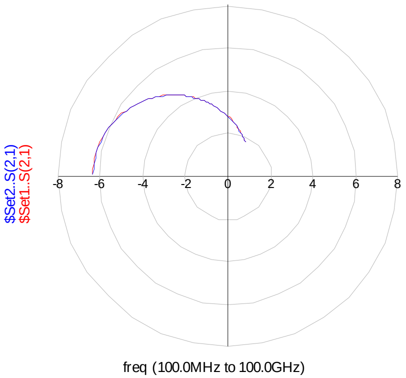


S12

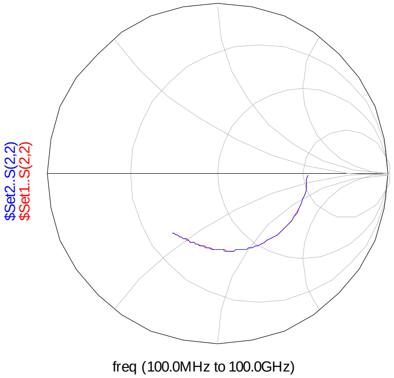


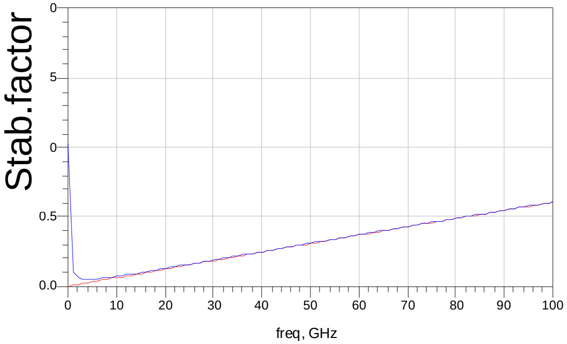


S21



S22



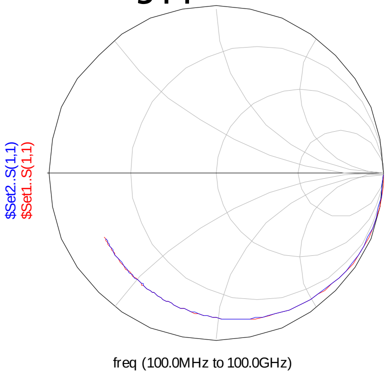


F2x30
LG=100 nm
T=300K
i_D=150 mA/mm
V_{ds}=1 V

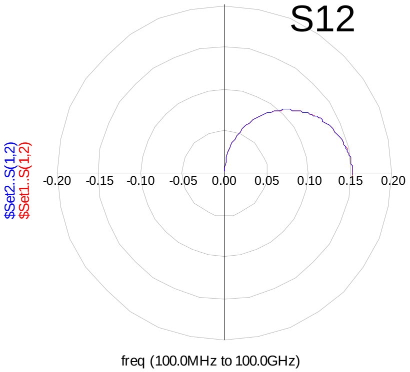
Gate Leakage : gGS=1 mΩ/mm (i_{GS}≈40 µA/mm)

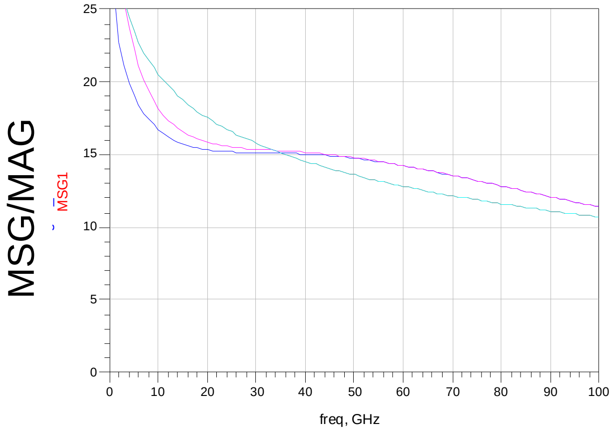
Influence of Gate Leakage on SS-Performance

S11

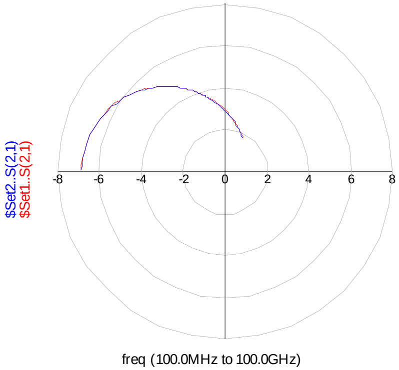


S12

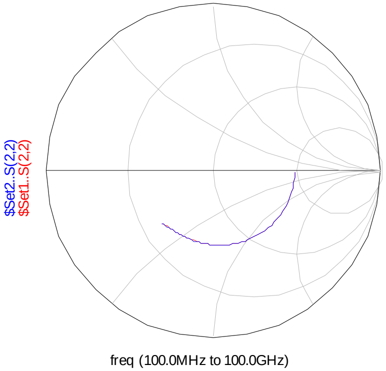


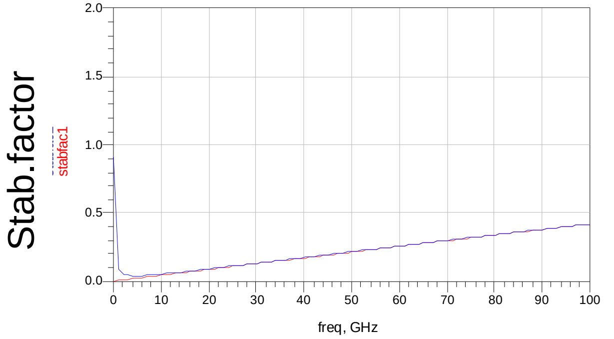


S21



S22



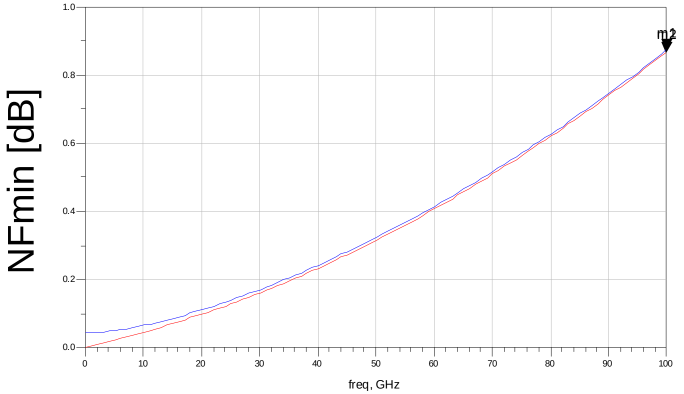


F2x30
LG=100 nm
T=15K
i_D=150 mA/mm
V_{ds}=1 V

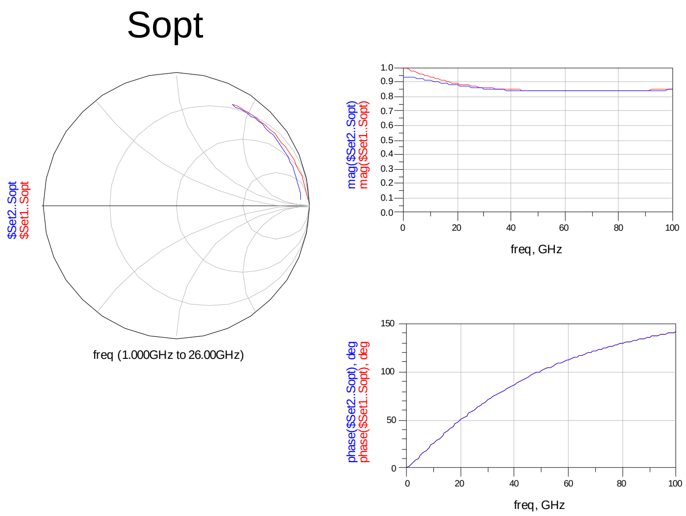
Gate Leakage : gGS=1 mΩ/mm (i_{GS}≈0.5 mA/mm)

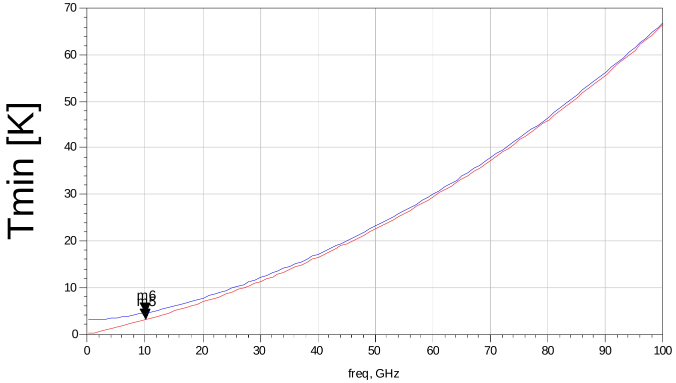
Fraunhofer
IAF

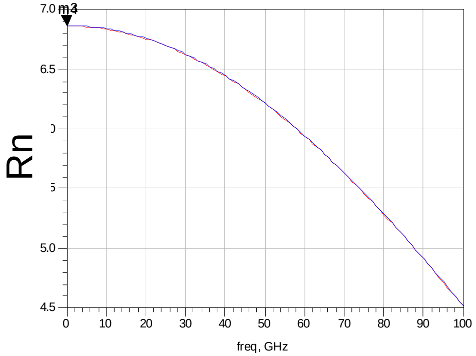
Influence of Gate Leakage on Noise



0.867 0.873







F2x30
LG=100 nm
T=15K
i_D=150 mA/mm
V_{ds}=1 V

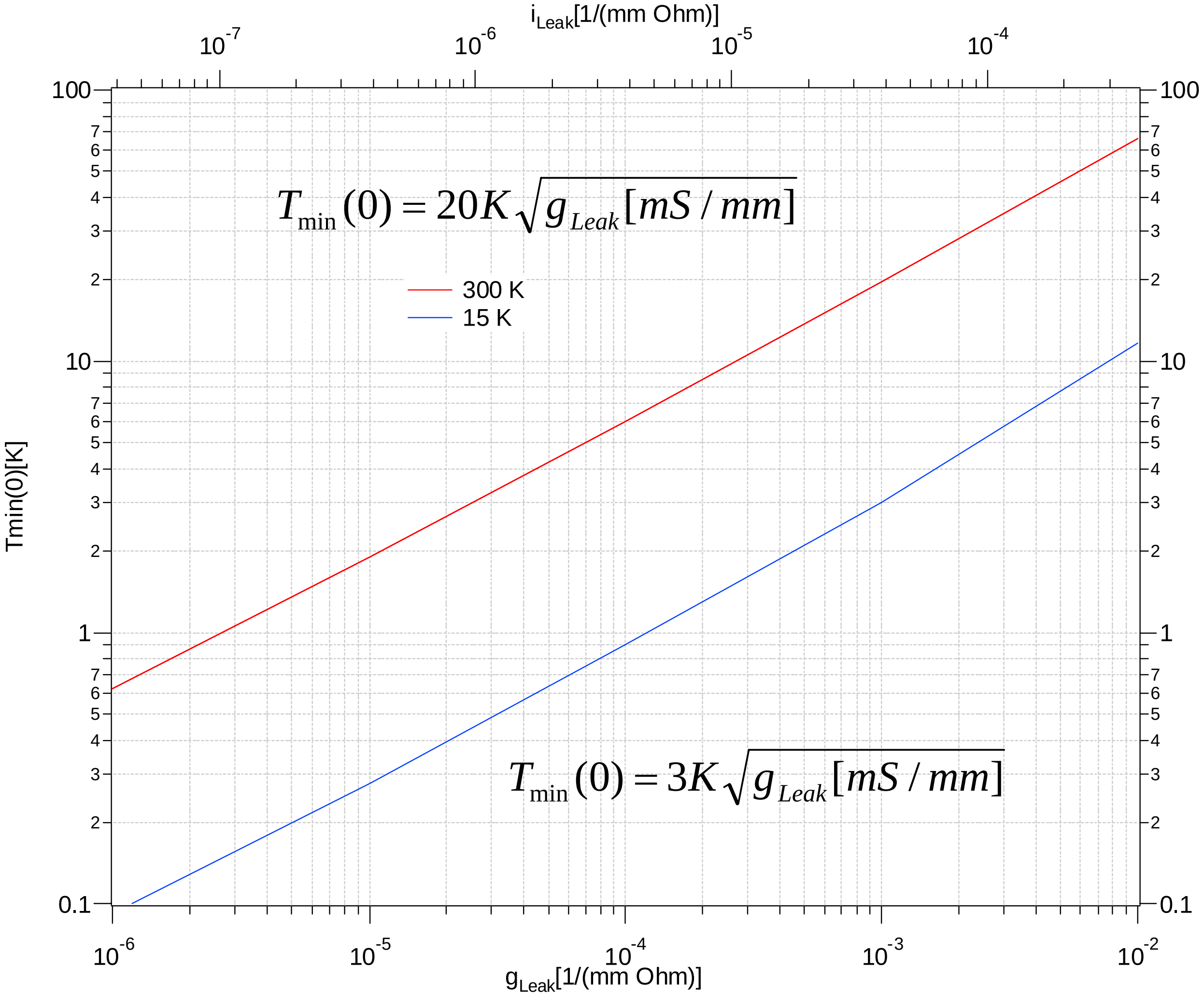
3.13 K 4.53 K

m4
freq=100.0MHz
$Set1..Rn=6.862

m3
freq=100.0MHz
$Set2..Rn=6.866

Gate Leakage : gGS=1 mΩ/mm (i_{GS}≈40 µA/mm)

T_{min} with Gate-Leakage



Similar effect for g_{GS} and g_{GD}

F2x30(LG=100)

Conclusions

- Scalable/bias-dependent cryo-model
  - Large temperature variations for access resistances
  - Slight increase of intrinsic conductances/capacitiies
- Gate Leakage
  - affects T_{Nmin} and S_{opt}
  - critical for C- and X-band LNAs
  - Little effect in W-band
- Potential for Cryo-Optimization ?
  - Large Decrease of R_g,R_s,g_{DS} necessary to achieve small decrease in T_{min}
  - R_d can be significantly increased without noise deterioration