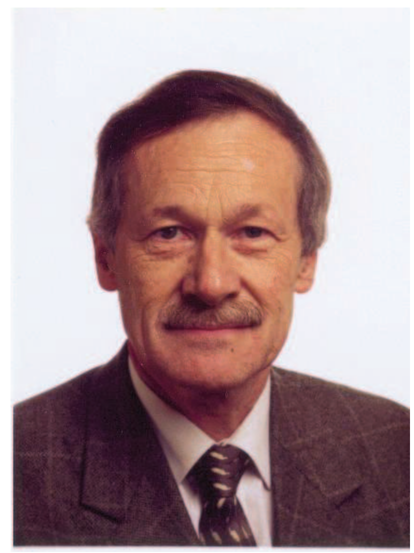
Low-Noise Amplifiers

Willy Sansen

KULeuven, ESAT-MICAS

Leuven, Belgium

willy.sansen@esat.kuleuven.be



Receiver Topology

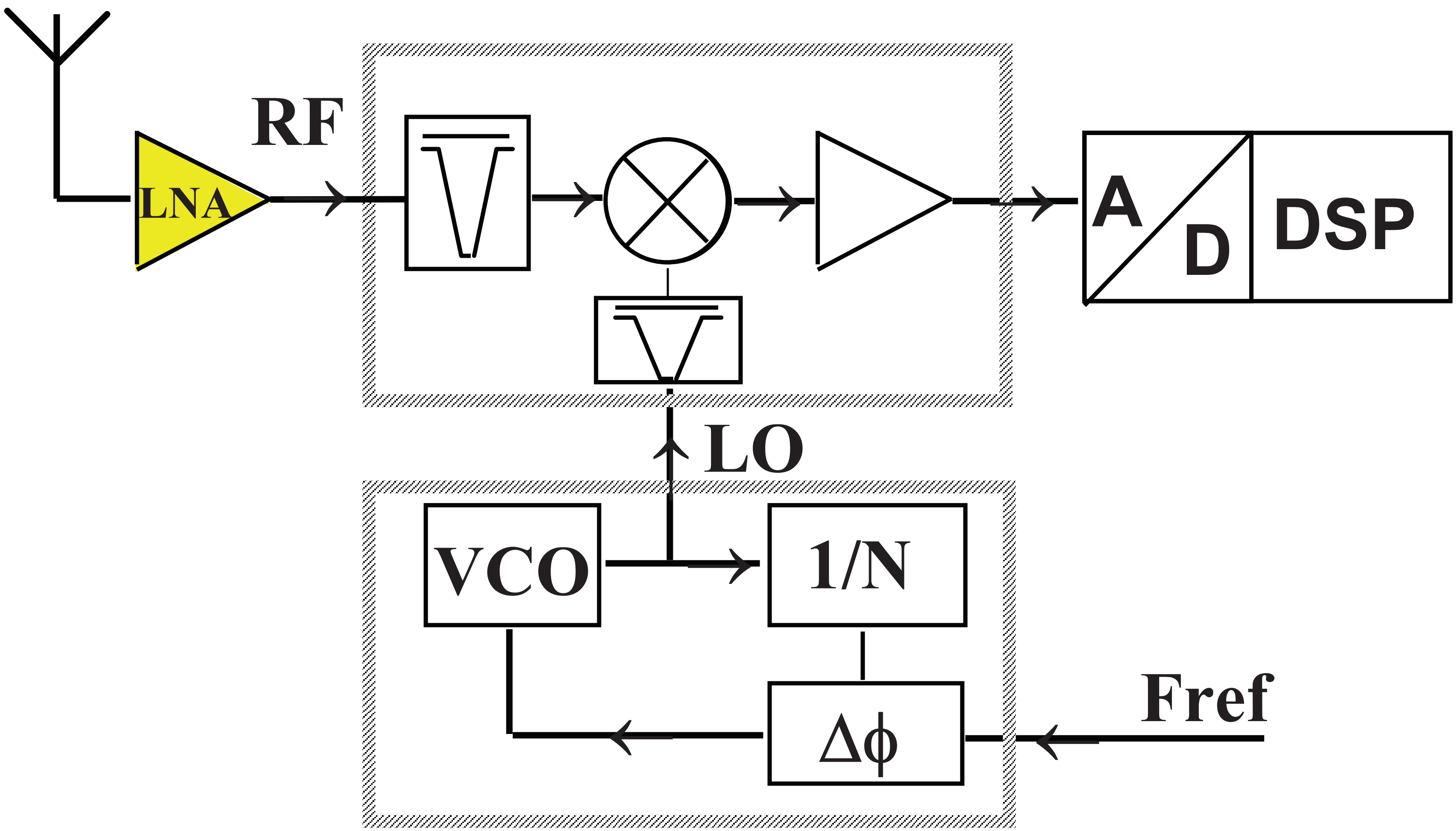
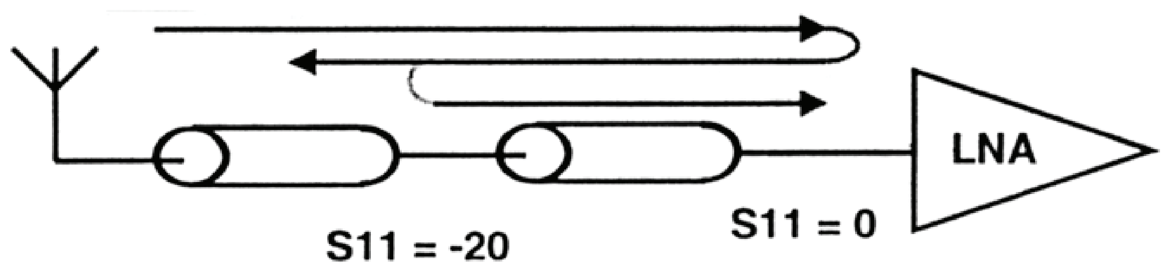
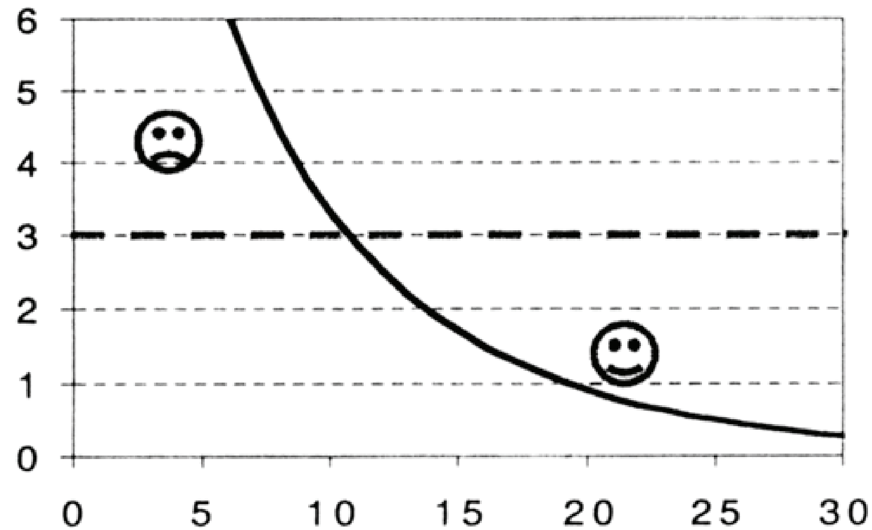


Table of contents

Transmission line effects



Unwanted Signal over Signal in -dB

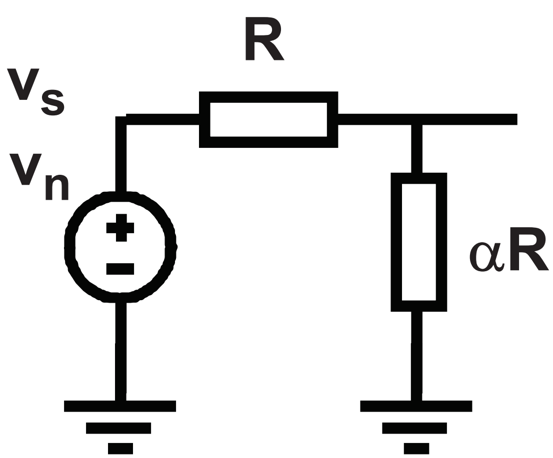


- S11 dB

Noise Figure

$$Vn = \sqrt{4RkTB}$$

$$Vs = \sqrt{4R.S}$$



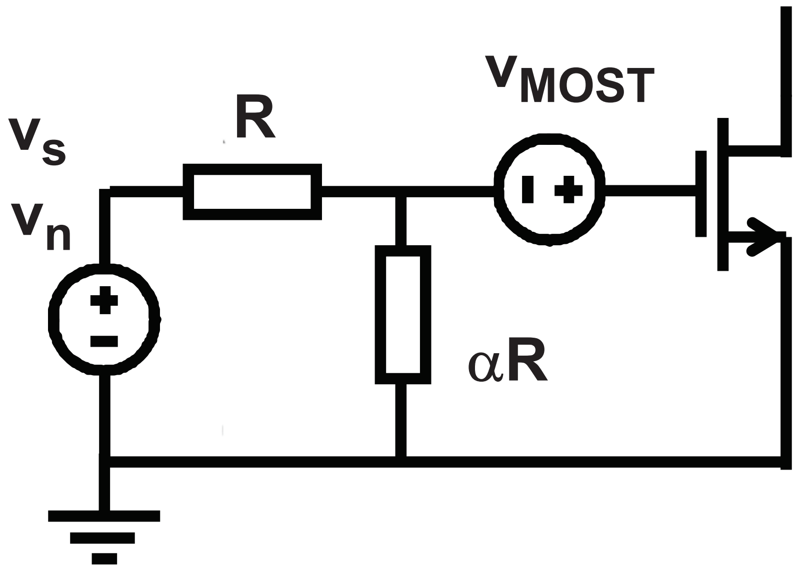
$$NF = \frac{\textit{total output noise power}}{\textit{output noise due to input source}}$$

$$NF = \frac{4kTB[\frac{\alpha}{(1+\alpha)^2} + \frac{1}{(1+\alpha)^2}]}{4kTB\frac{\alpha}{(1+\alpha)^2}}$$

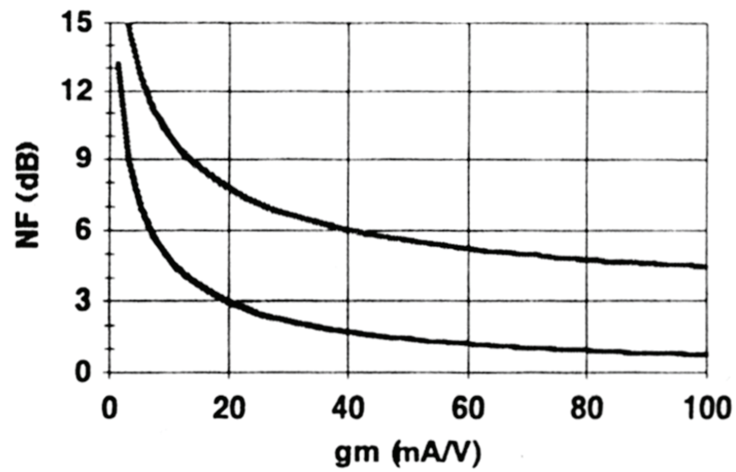
$$NF = \frac{1+\alpha}{\alpha}$$

Resistive match : $\alpha = 1$: NF = 3 dB

MOST amplifier with Resistive termination



$$v_{MOST} = 4kT\,\frac{2}{3\,g_m}$$



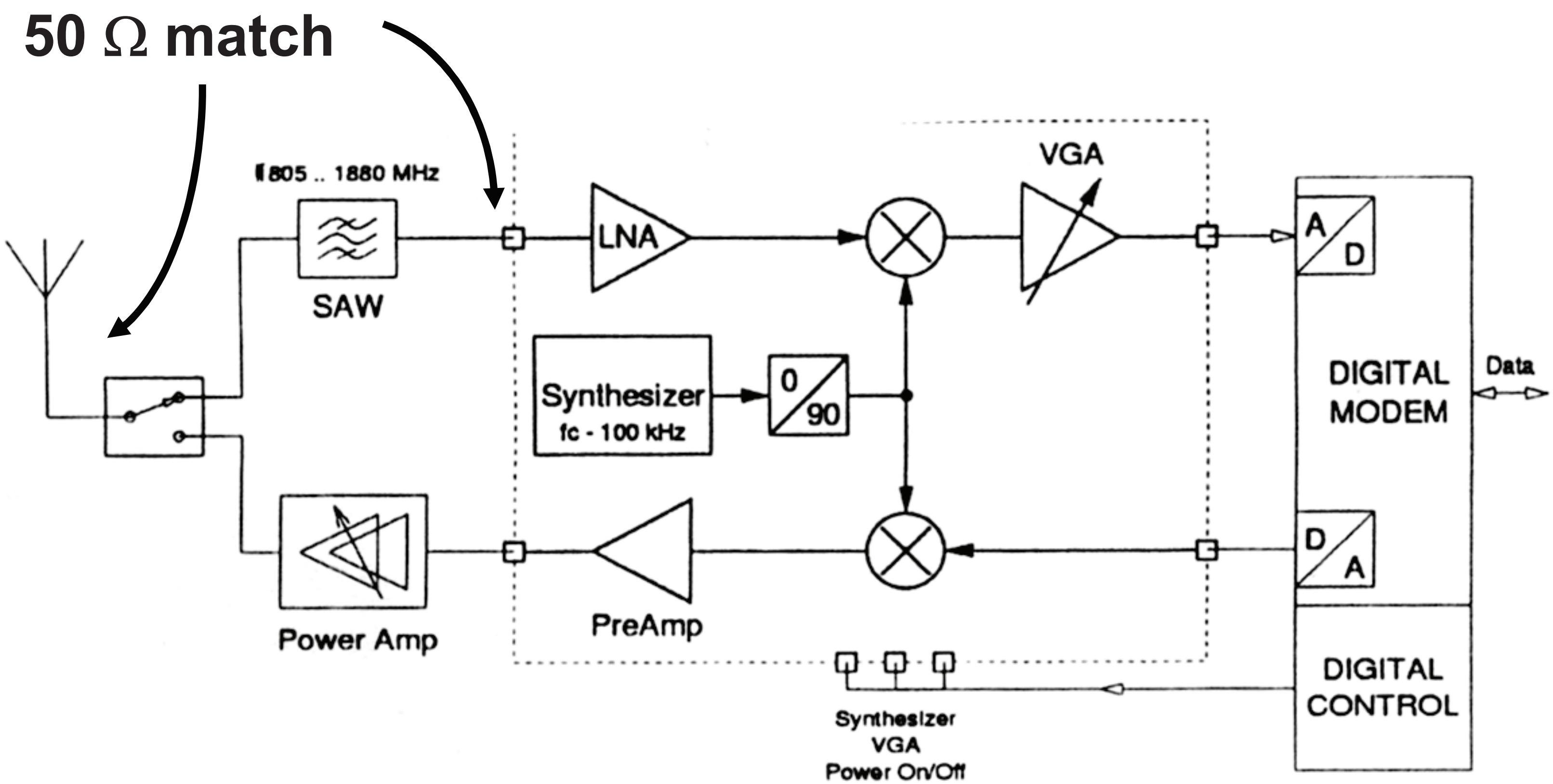
$$NF = \frac{1+\alpha}{\alpha} + \left(\frac{1+\alpha}{\alpha}\right)^2 \frac{1}{gm.R}$$

α = 1 (Matched): $\boxed{NF = 2 + \frac{4}{gm.R}}$

$\alpha = \infty$ (Open circuit): $\boxed{NF = 1 + \frac{1}{gm.R}}$

Table of contents

Transceiver



Minimum NF and IIP3 for DCS-1800

Sensitivity	-100 dBm
SNR	9 dB
Input noise	-109 dBm
kT =	-174 dBm
Bandwidth (200 kHz)	+ 53 dB
NF : -109 - (-174+53) =	12 dB
Attenuating blocking filter : 3 dB	NF < 9 dB
+ 3 dB Sensitivity	-97 dBm
SNR (-49 dBm sine)	9 dB
IIP3 = -49 + (-49- (-106/2)) =	-20.5 dBm
With attenuating blocking filter : 3 dB	IIP3 < -23.5 dBm

Linearity CMOS amplifier

Velocity saturation

$v_{max} \approx 10^7$ cm/s

$\Theta L \approx 0.2\ \mu m/V$

$$I_{ds} = \frac{\mu_0 C_{ox}}{2n} \cdot \frac{W}{L} \cdot \frac{(V_{GS} - V_T)^2}{1 + \Theta \cdot (V_{GS} - V_T)}$$

$$\Theta = \theta + \frac{\mu_0}{L_{eff} \cdot v_{max} \cdot n}$$

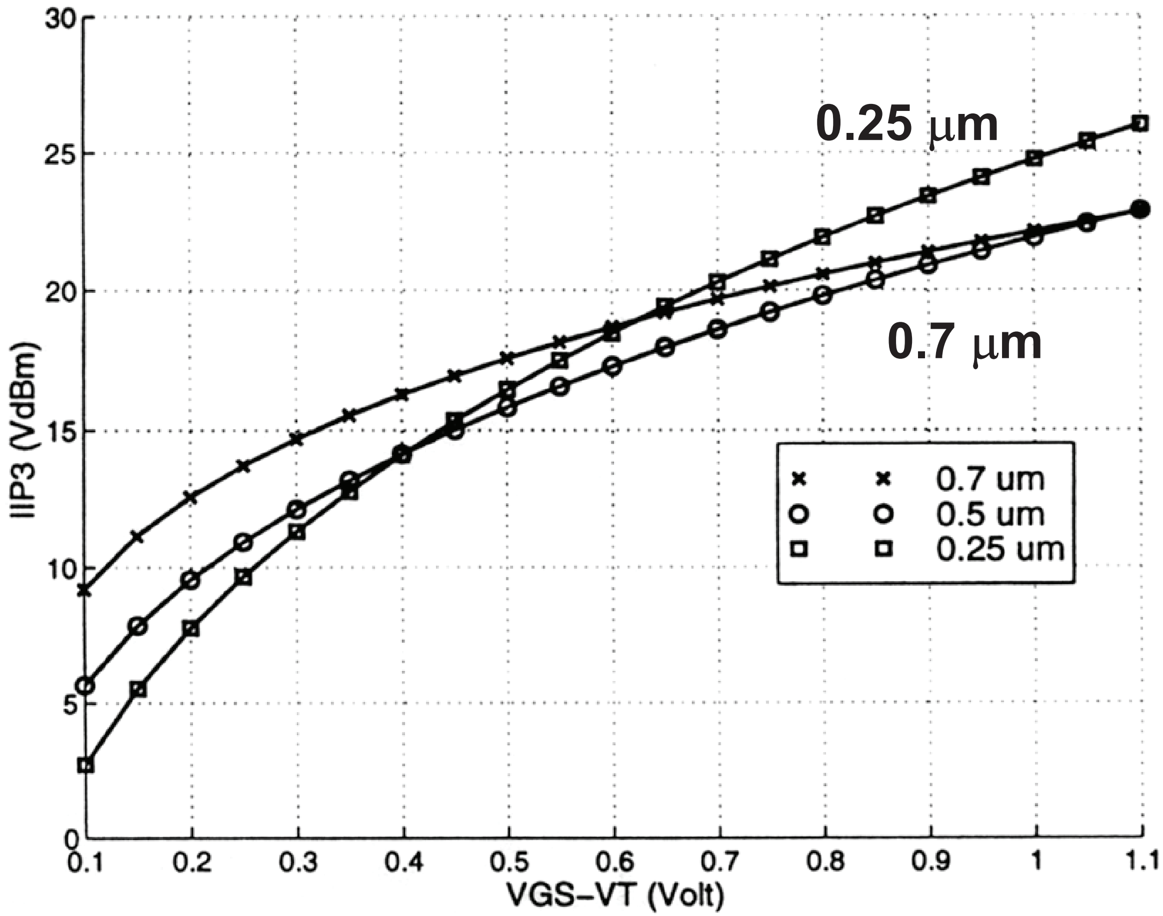
$$IM2 = \frac{v}{V_{GS} - V_T} \cdot \frac{1}{(1+r)\cdot(2+r)}$$

$$r = \Theta \cdot (V_{GS} - V_T)$$

$$IM3 = \frac{3}{4} \frac{v^2}{(V_{GS} - V_T)} \cdot \frac{\Theta}{(1+r)^2 \cdot (2+r)}$$

$$IIP3 \cong 11.25 + 10 \cdot Log_{10}\Big((V_{GS} - V_T) \cdot (1+r)^2 \cdot (2+r)/\Theta\Big)$$

IIP3 for different CMOS technologies



Velocity saturation

$v_{max} \approx 10^7$ cm/s

$\Theta L \approx 0.2$ μm/V

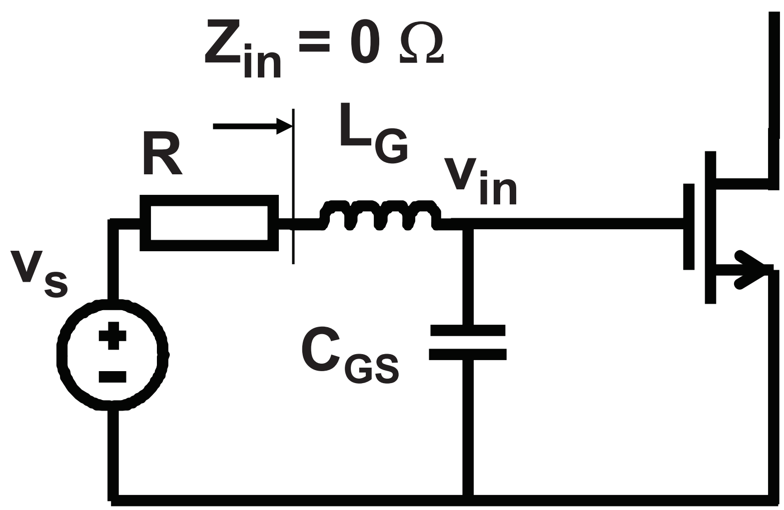
L = 0.7 μm $\Theta \approx 0.5\ V^{-1}$

L = 0.25 μm $\Theta \approx 1.2\ V^{-1}$

Table of contents

- Noise Figure and Impedance Matching
- LNA specifications and linearity
- Input amplifier or cascode
- Non-quasi-static MOST model
- More realizations
- Inductive ESD protection

Inductive input : gain



$$Z_{in} = \frac{1}{j\omega C_{GS}} + j\omega L_G$$

1 $$L_G = \frac{1}{C_{GS}\,\omega_{in}^2}$$

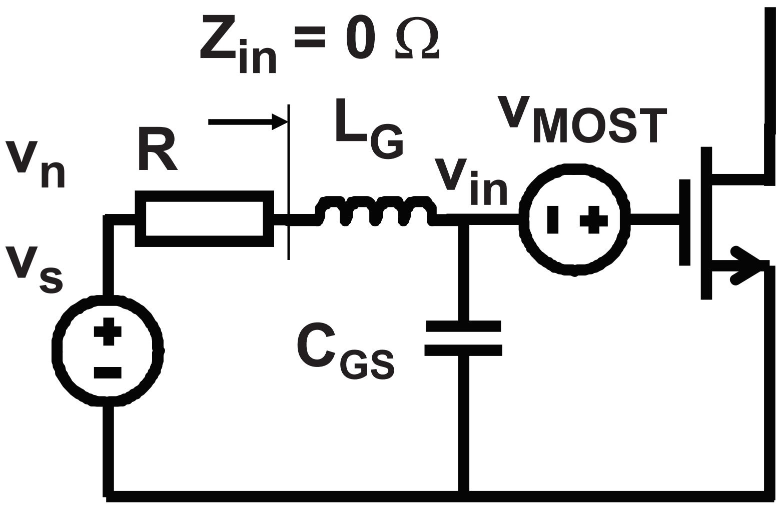
At $$f_{in} = \frac{1}{2\pi\sqrt{L_G C_{GS}}}$$

2 $$\frac{v_{in}}{v_s} = \frac{1}{R\sqrt{C_{GS}/L_G}} = \frac{1}{2\pi\, R C_{GS}\,\omega_{in}}$$

Extra Gain ≈ 10 dB

L_G = 15 nH; C_{GS} = 0.5 pF; fin = 1.8 GHz ; R = 50 Ω;

Inductive input : noise



$$v_{MOST} = 4kT\,\frac{2}{3\,g_m}$$

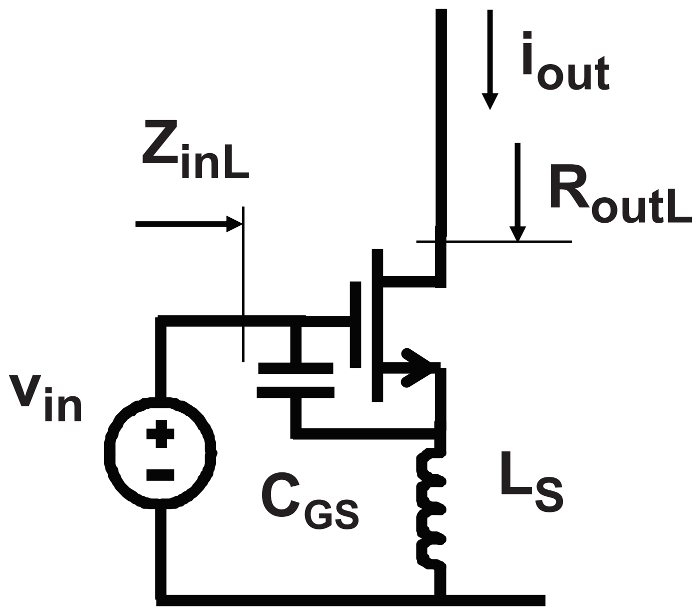
$$\frac{v_{in}}{v_s} = \frac{1}{R\sqrt{C_{GS}/L_G}}$$

$$NF = 1 + \frac{\left(R\sqrt{C_{GS}/L_G}\right)^2}{g_m R} = 1 + \frac{R\,C_{GS}}{g_m\,L_G} = 1 + g_m R\left(\frac{\omega_{in}}{\omega_T}\right)^2$$

$$NF_{gmR=1} \approx 0.4 \text{ dB}$$

L_G = 15 nH; C_{GS} = 0.5 pF; fin = 1.8 GHz

Inductive degeneration in the Source



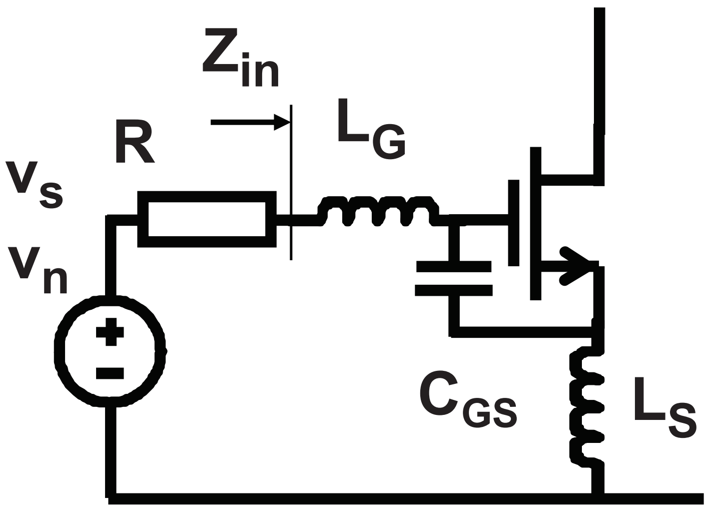
$$g_{mL} = \frac{g_m}{1 + g_m L_S s}$$

$$R_{outL} = r_{DS}\,(1 + g_m L_S s)$$

$$Z_{inL} = g_m \frac{L_S}{C_{GS}} + \frac{1 + L_S C_{GS}\, s^2}{s\, C_{GS}}$$

$$Z_{inL} = L_S\,\omega_T + L_S s + \frac{1}{s\, C_{GS}}$$

Inductive degeneration in Source and Gate



$$Z_{in} = \frac{1}{j\omega C_{GS}} + j\omega\,(L_G + L_S) + \omega_T L_S$$

① $$L_G + L_S = \frac{1}{C_{GS}\,\omega_{in}^2}$$

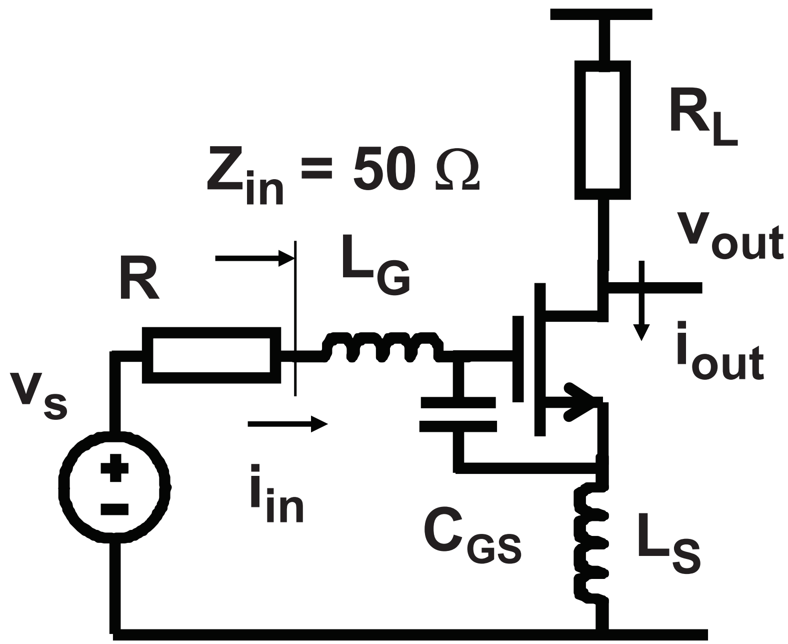
② $$L_S = \frac{R\,C_{GS}}{g_m} = \frac{R}{\omega_T}$$

Impedance Match :

$Re\,(Z_{in}) = R_{in} = R$ at ω_{in}

$Im\,(Z_{in}) = 0$

Inductive degeneration : gain



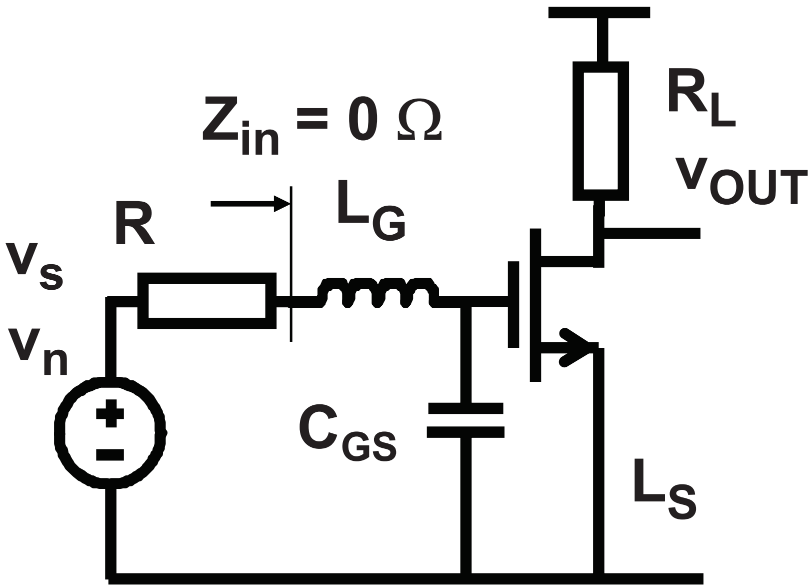
Under matching :

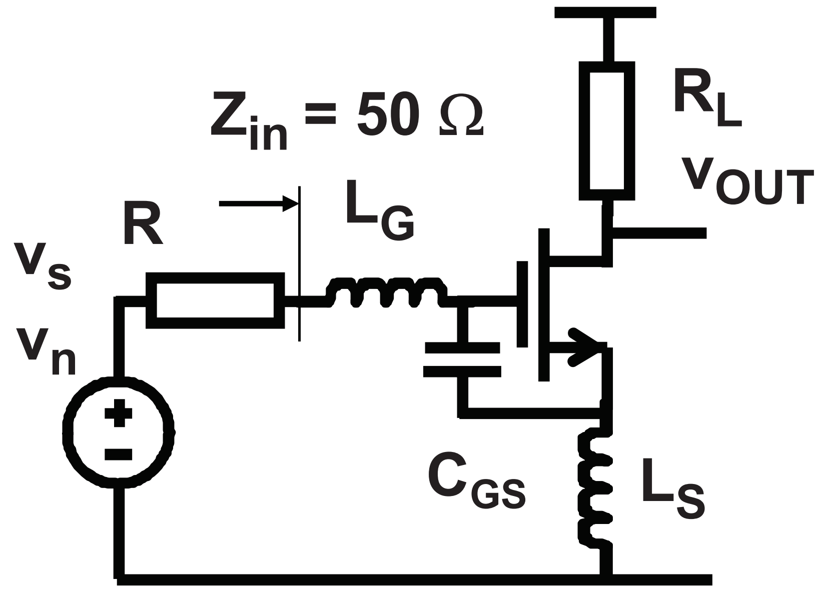
$$\frac{i_{out}}{i_{in}} = \frac{\omega_T}{\omega_{in}}$$

$$\frac{v_{out}}{v_{in}} = \frac{i_{out}}{i_{in}} \frac{R_L}{2R}$$

$$G_P = \frac{P_{out}}{P_{in}} = \left(\frac{\omega_T}{\omega_{in}}\right)^2 \frac{R_L}{2R}$$

Inductive degeneration : gain





$$G_v = \frac{g_m}{\sqrt{C_{GS} / L_G}} \frac{R_L}{R}$$

$$G_v = \frac{g_m}{\sqrt{C_{GS} / (L_G + L_S)}} \frac{R_L}{2R}$$

$$G_v \ / \ G_{v,R=50\Omega} = 2x$$

Inductive degeneration : Noise Figure

$$NF = 1 + \frac{dv_{in}^2}{dv_R^2} = 1 + \frac{R\,C_{GS}}{g_m\,(L_G+L_S)}$$

$$dv_{in}^2 = 4kT\,\frac{2/3}{g_m}\,df \approx 4kT\,\frac{1}{g_m}\,df$$

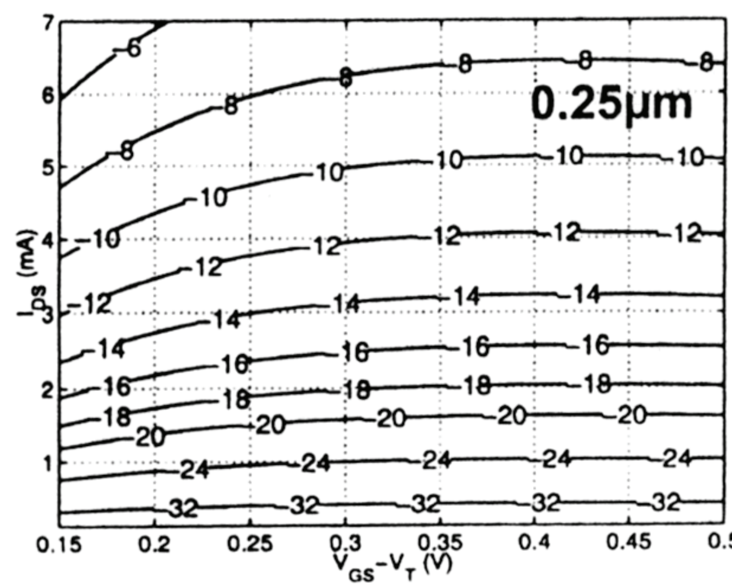
$$dv_R^2 = 4kT\,R\,df$$

$$NF = 1 + g_m\,R\,\left(\frac{\omega_{in}}{\omega_T}\right)^2$$

Inductive degeneration : IIP3 vs IDS

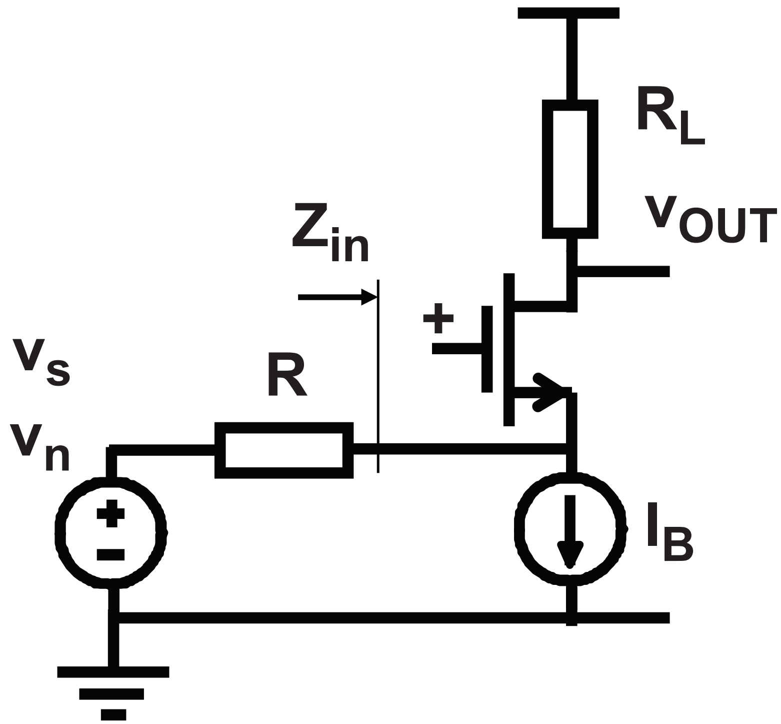
$$IIP3 \approx 11.25 + 20\log_{10}(\underbrace{\sqrt{\frac{Vgst(2+r)^2(1+r)}{\Theta}}\frac{1+\Theta Vgst}{Vgst^2}}_{\approx \mathbf{Cst}}.\omega_{in}\frac{100}{\mu_0}I_D L^2)$$

$$IIP3 \approx Cst + 20\log_{10}(\frac{\omega_{in} I_D L^2}{\mu_0})$$



r = Θ V_{gst} = Θ (V_{GS}-V_T)

Cascode or current input : Z_{in}



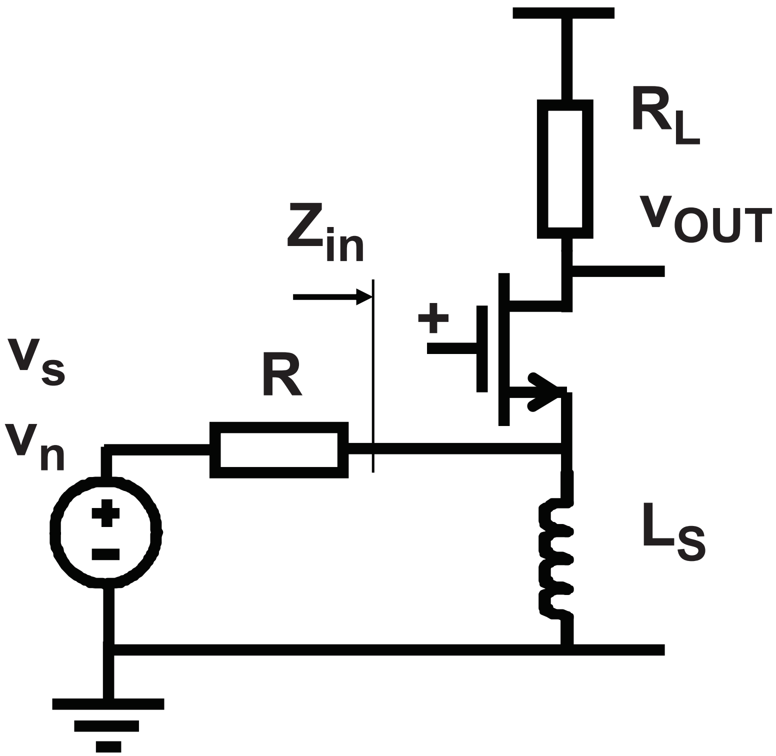
$$R_{in} = \frac{1}{g_m}$$

$$= 50\ \Omega \text{ at } 20\text{ mS}$$

$$R_{in} = \frac{1}{g_m}\frac{1}{n}\left(1 - \frac{R_L}{2r_{DS}}\right)$$

Depends on r_{DS} !

Cascode or current input : Gain & NF



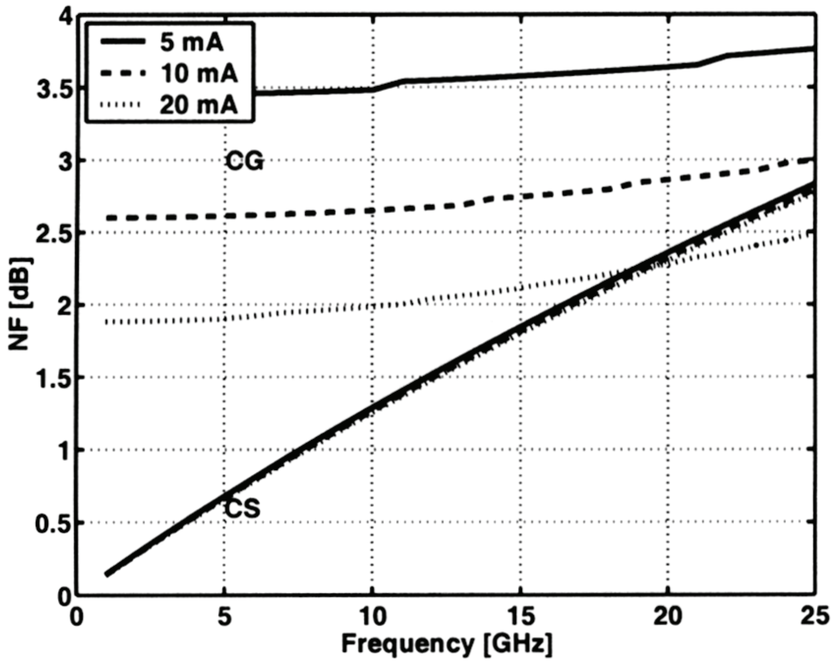
$$\frac{i_{out}}{i_{in}} = 1$$

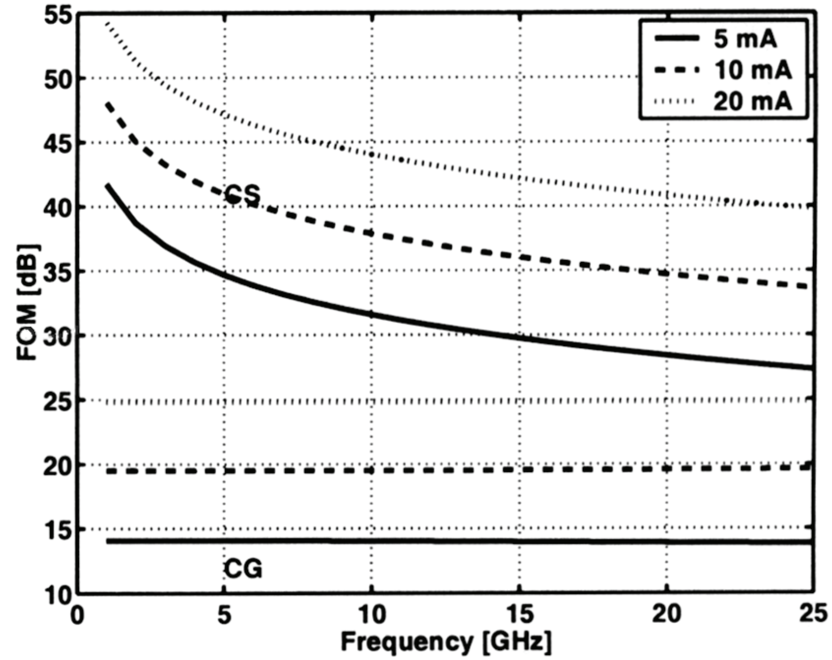
$$G_P = \frac{P_{out}}{P_{in}} = \frac{R_L}{4R}$$

$$NF = 1 + \frac{1}{g_m R}$$

Match : NF = 3 dB

LNA : amplifier versus cascode

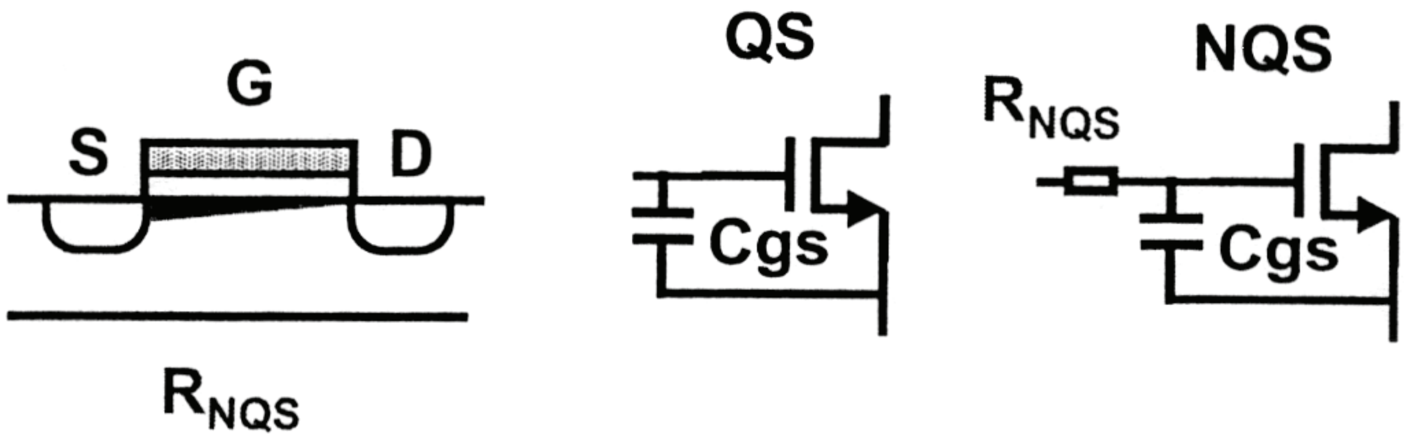




$$\mathrm{FOM} = \frac{G_P \, \mathrm{IIP3}}{\mathrm{NF} - 1}$$

Table of contents

Non-quasi static MOST model



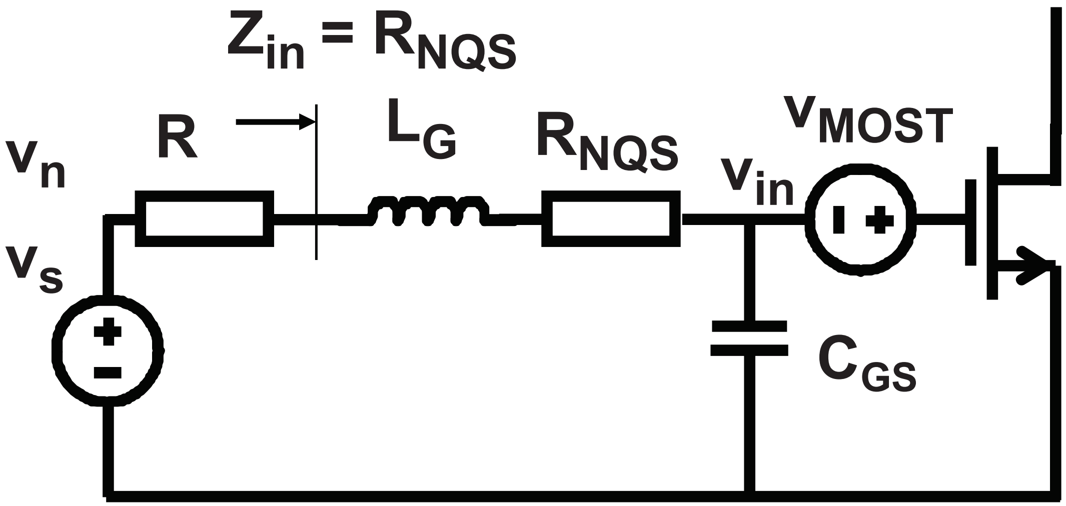
$$R_{NQS} = \frac{1}{5\,g_m}$$

Normally important for $f > f_T / 5$

C_{GS} is tuned out by L_G !!

Ref.Janssens, ACD 1998

Inductor in input

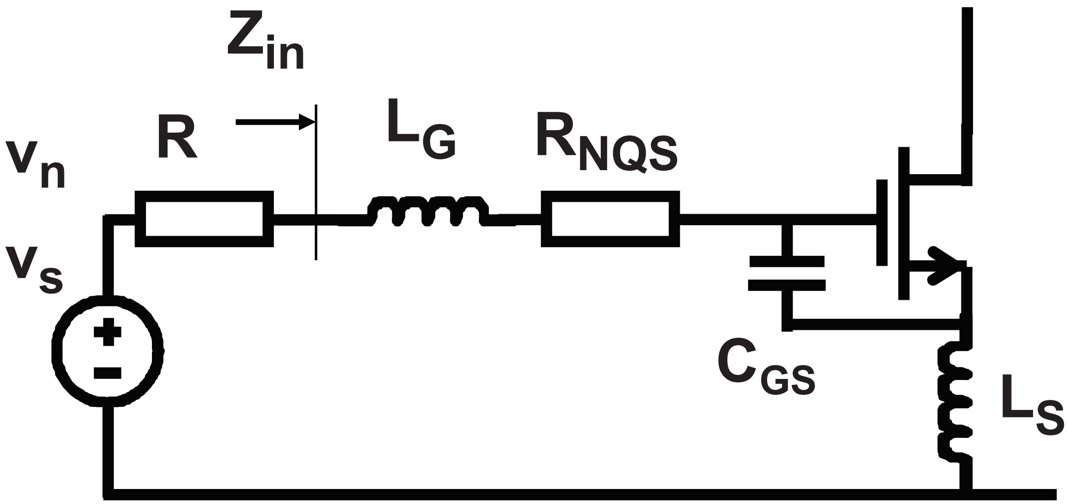


$$NF = 1 + \frac{R.Cgs}{gm.Lg}\left(1 + \frac{R_{NQS}}{R}\right)^2 + \frac{R_{NQS}}{R}$$

$$NF = 1 + \frac{R.Cgs}{gm.Lg}\left(1 + \frac{1}{5gmR}\right)^2 + \frac{1}{5gmR}$$

$NF_{gm=20mS} = 1.2\ dB$

Inductive degeneration with NQS model



$$\omega^2 Cgs(Lg + Ls) = 1$$

$$Ls = \frac{(R - R_{NQS})Cgs}{gm}$$

$$NF = 1 + \frac{R.Cgs}{gm(Lg + Ls)}\left(1 + \frac{R_{NQS}}{R}\right)^2 + \frac{R_{NQS}}{R}$$

$NF_{gm=20mS}$ = 1.2 dB

Noise matching

$$NF = 1 + \frac{R.Cgs}{gm.(Lg + Ls)}(1 + \frac{1}{5gmR})^2 + \frac{1}{5gmR}$$

Optimum $$R = \frac{1}{5gm}.\sqrt{1 + \frac{5.(Lg + Ls)gm^2}{Cgs}} = 80\Omega$$

NF ≈ 1 dB (g_m = 20 mS)

L_G+L_S = 15 nH; C_{GS} = 0.5 pF; f = 1.8 GHz

Noise matching (Optimum design)

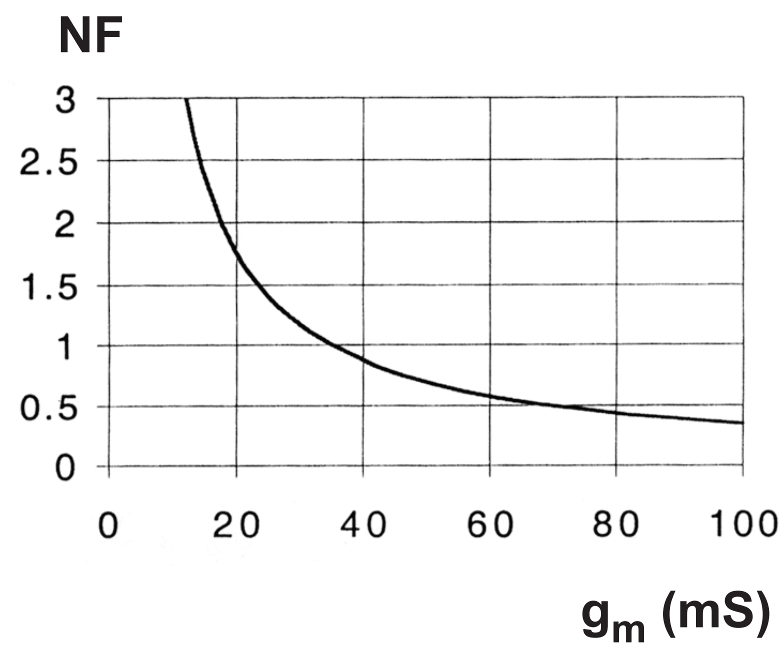
$$NF = 1 + \frac{R.Cgs}{gm.(Lg + Ls)}(1 + \frac{1}{5gmR})^2 + \frac{1}{5gmR}$$

Opt. $$Cgs = \frac{5.(Lg + Ls)gm^2}{(5.Rgm)^2 - 1}$$

$$NF = 1 + \frac{5gmR.}{(5gmR)^2 - 1}(1 + \frac{1}{5gmR})^2 + \frac{1}{5gmR}$$

$$NF \approx 1 + \frac{2}{5gmR}$$

$g_m R > 1$



Lower NF requires more power !

Gain vs Rin for optimal NF

$$G = \frac{gm}{\sqrt{\frac{5gm^2}{(5gmR)^2 - 1}}} \cdot \frac{R_L}{(R + Rin)}$$

Gain + 2dB

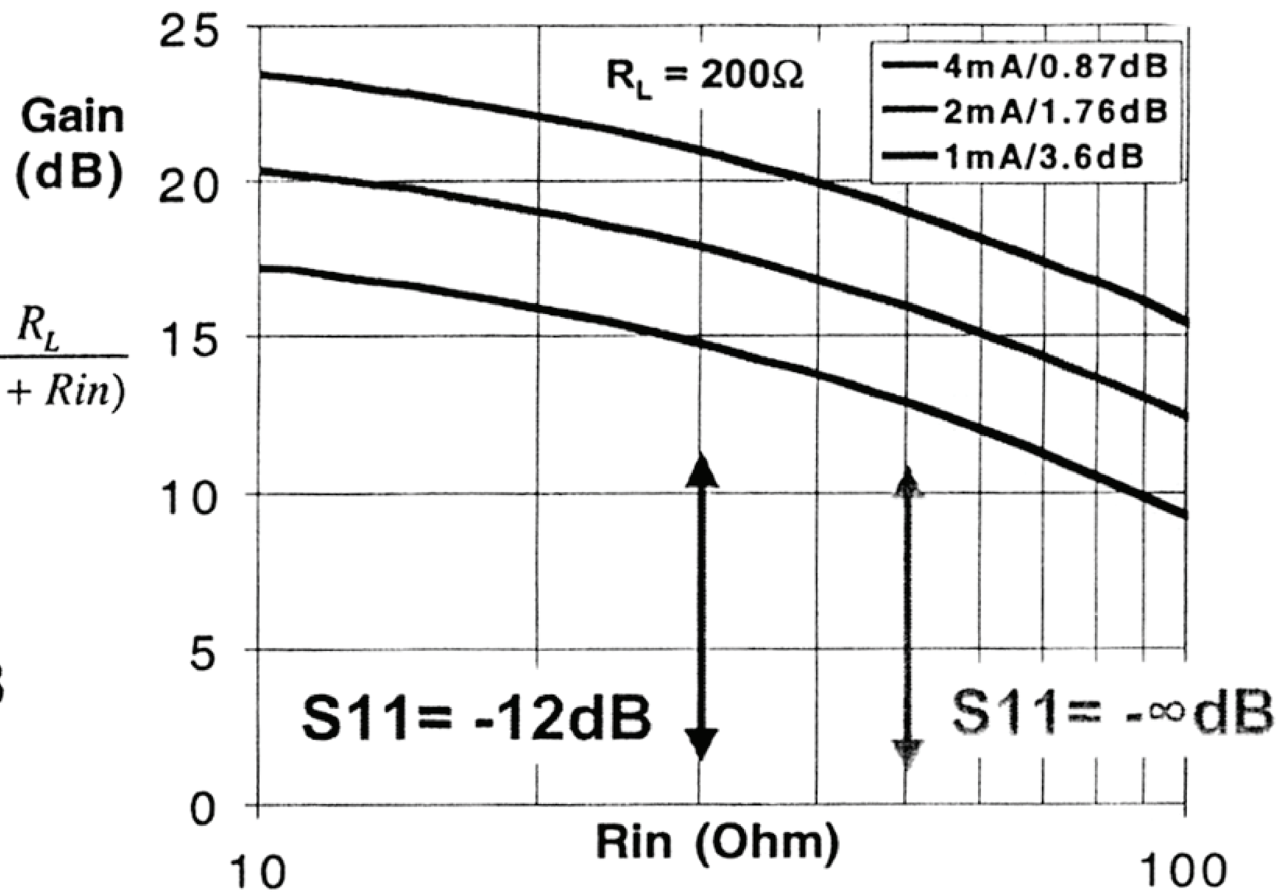
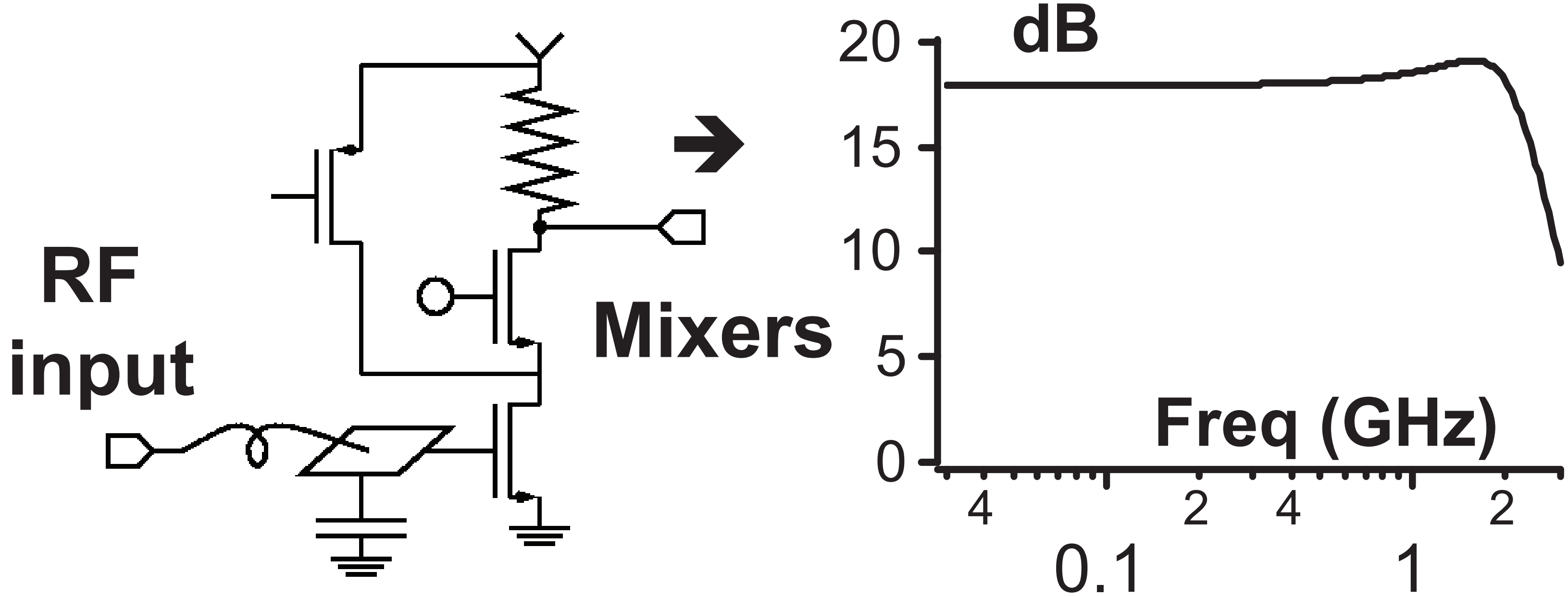


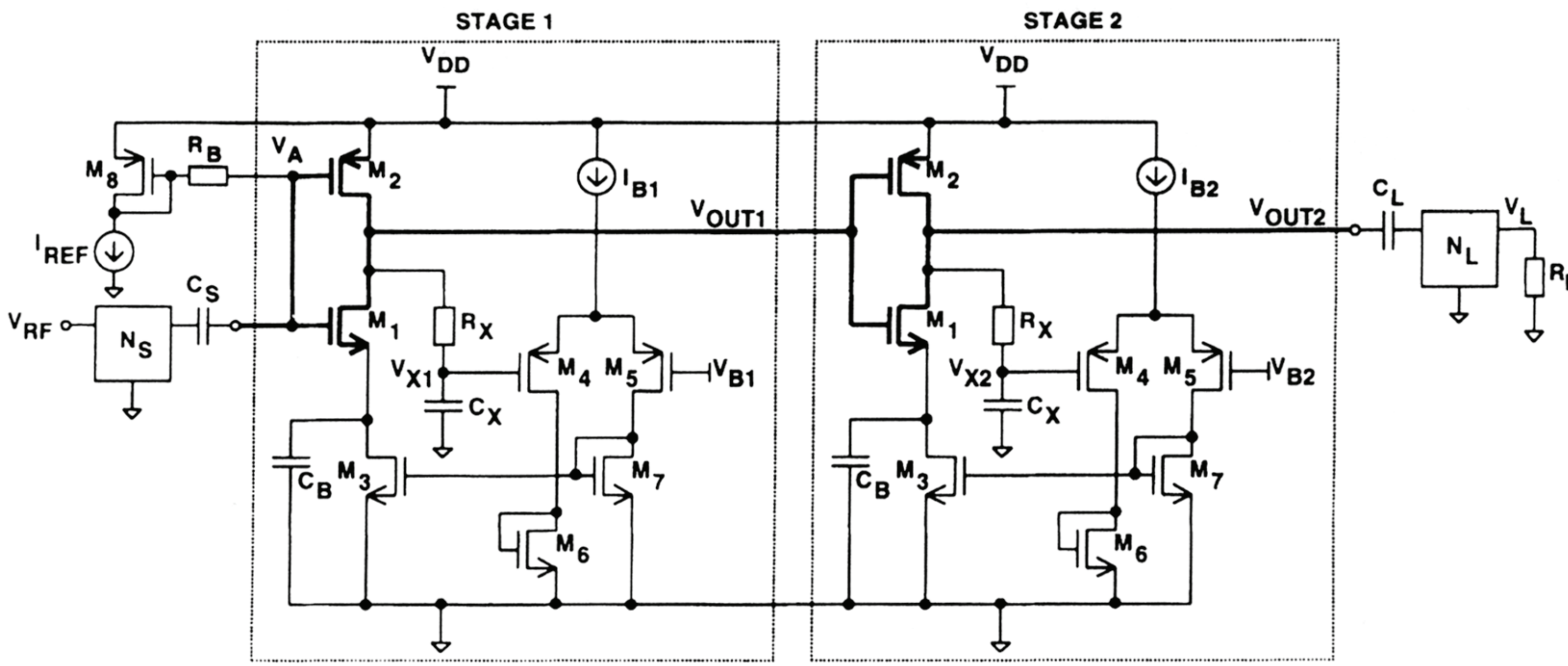
Table of contents

Low-noise amplifier



Broad-Band Topology : multi-mode possible

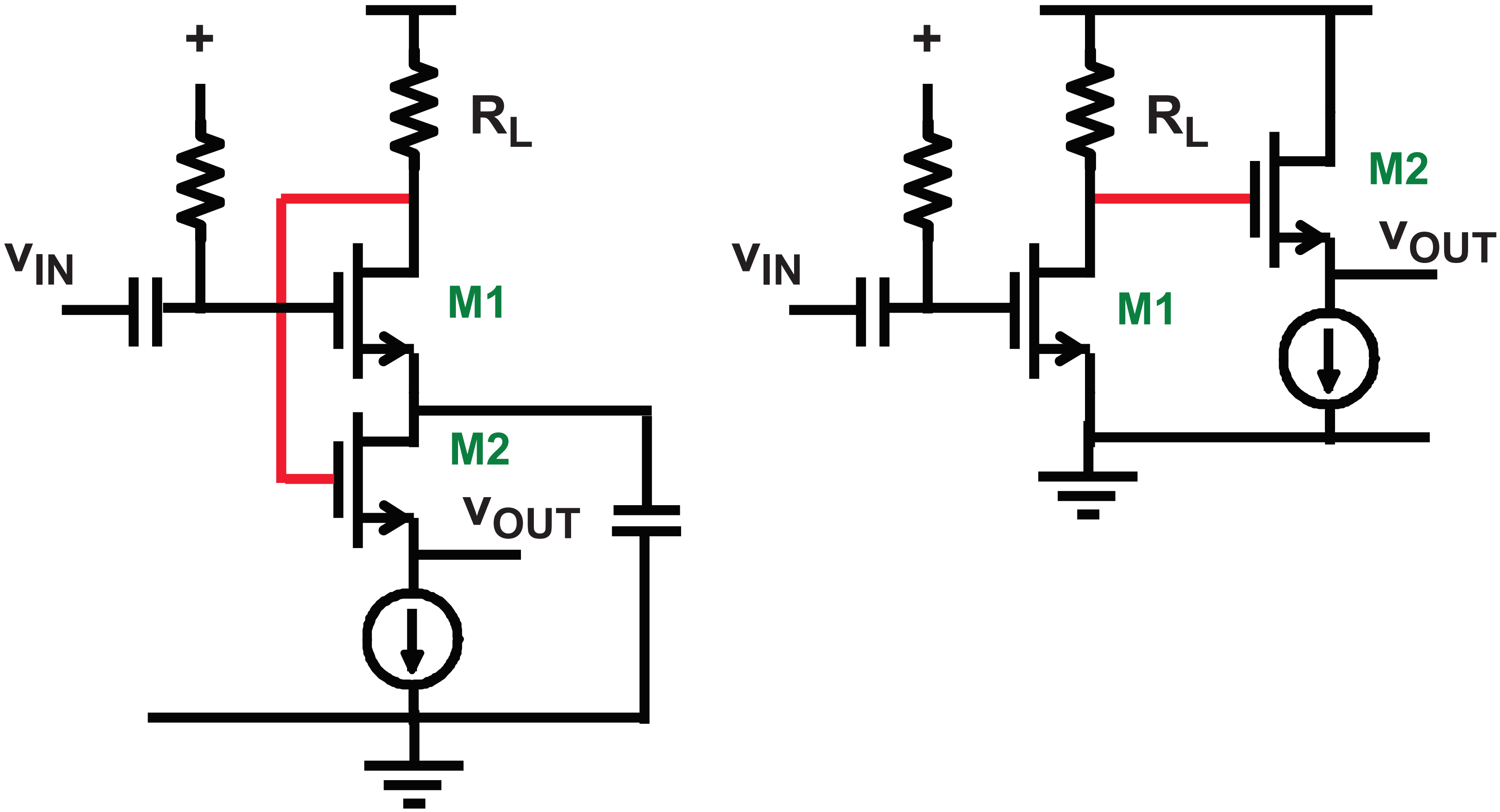
LNA 900 MHz with reuse



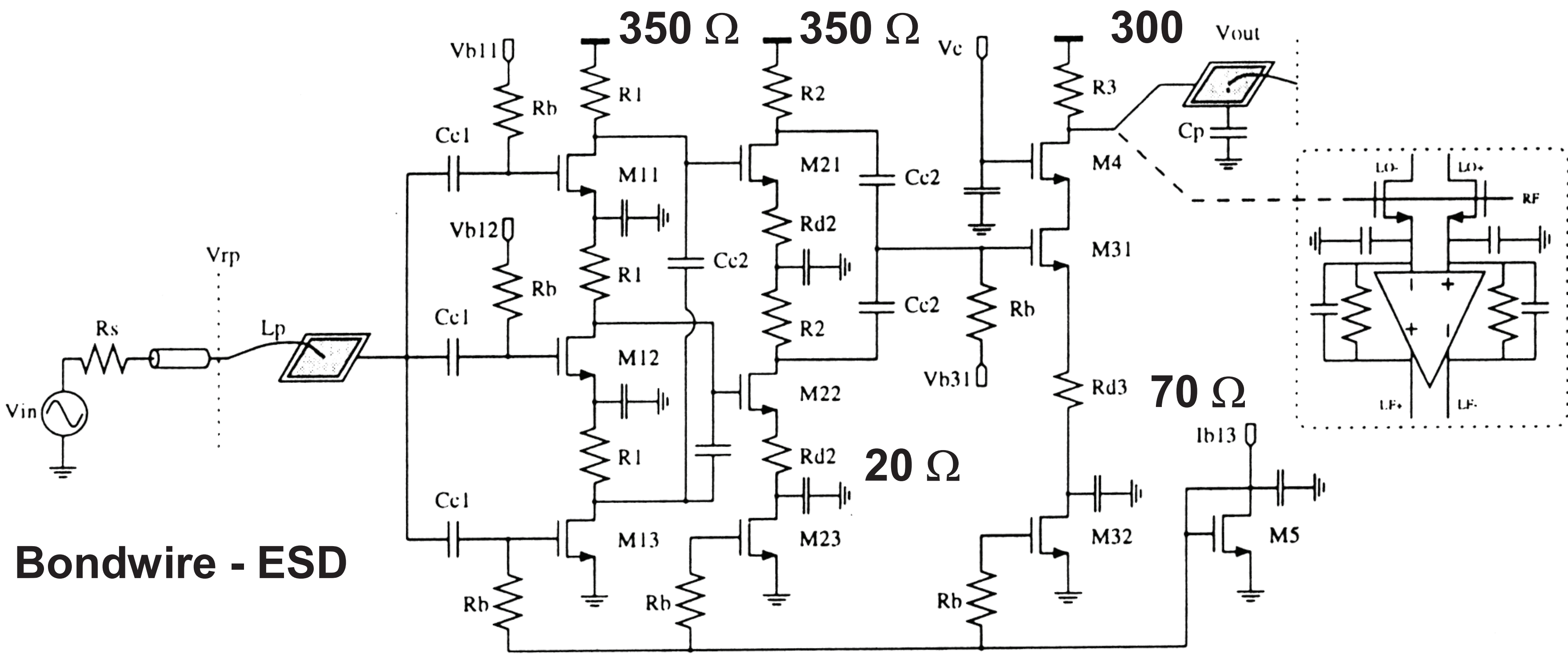
NF = 2.2 dB **G = 15.6 dB** **P = 20 mW (2.7 V)**

Karanicolas, JSSC Dec 96, 1939-1944

LNA with reuse



LNA with reuse : realization



Bondwire - ESD

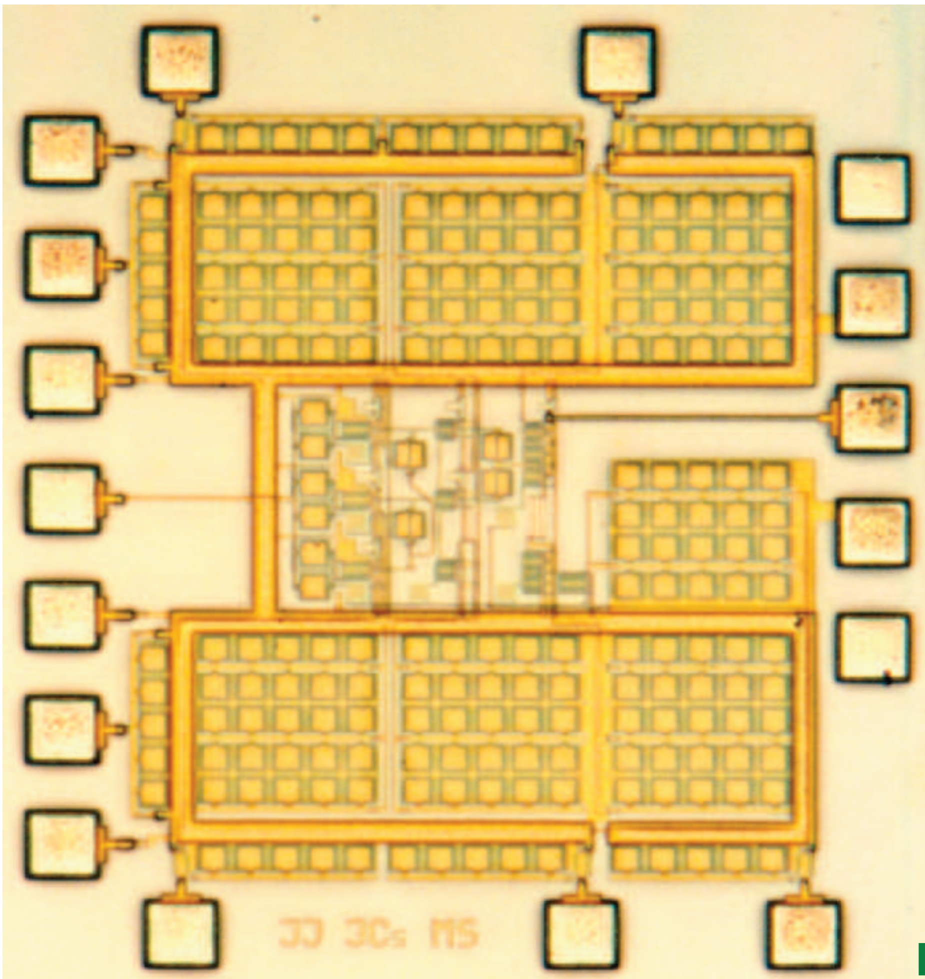
160/0.5	100/0.5	200/0.5
1.2 mA	0.7 mA	1.5 mA

$V_{GS} - V_T = 0.22$ V

Coupling capacitance $C_{c2} \approx 2$ pF

Ref.Janssens, ACD 1998, Kluwer 98

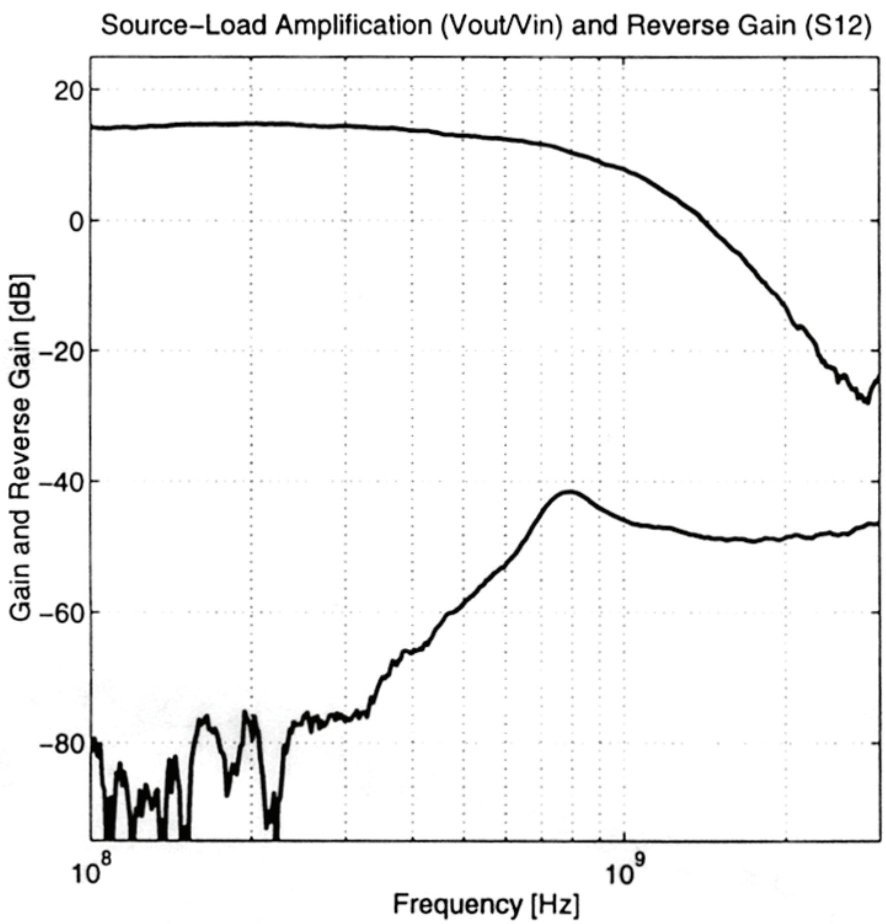
CMOS LNA with reuse



Fin	900 MHz
Power	10 mW
NF	2.3-3.3 dB
Gain	14.8 dB
IIP3	-4.7 VdBm
S11	-7 dB
Area	0.12 mm^2

Ref.Janssens, M.Steyaert, CICC'98

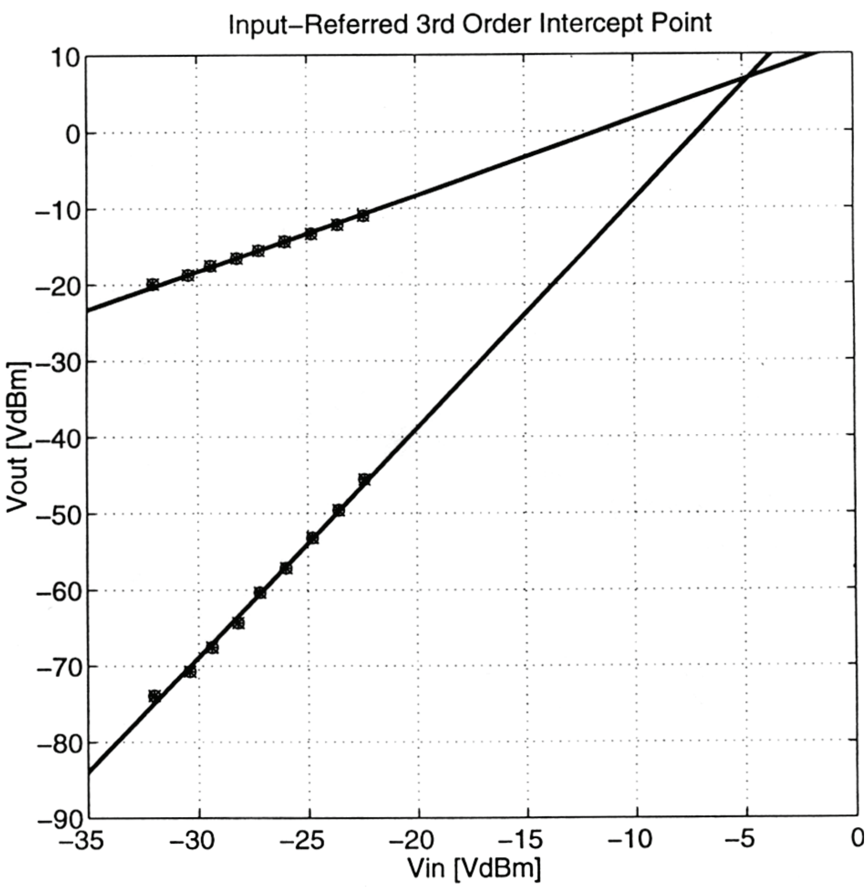
Measurements - 1

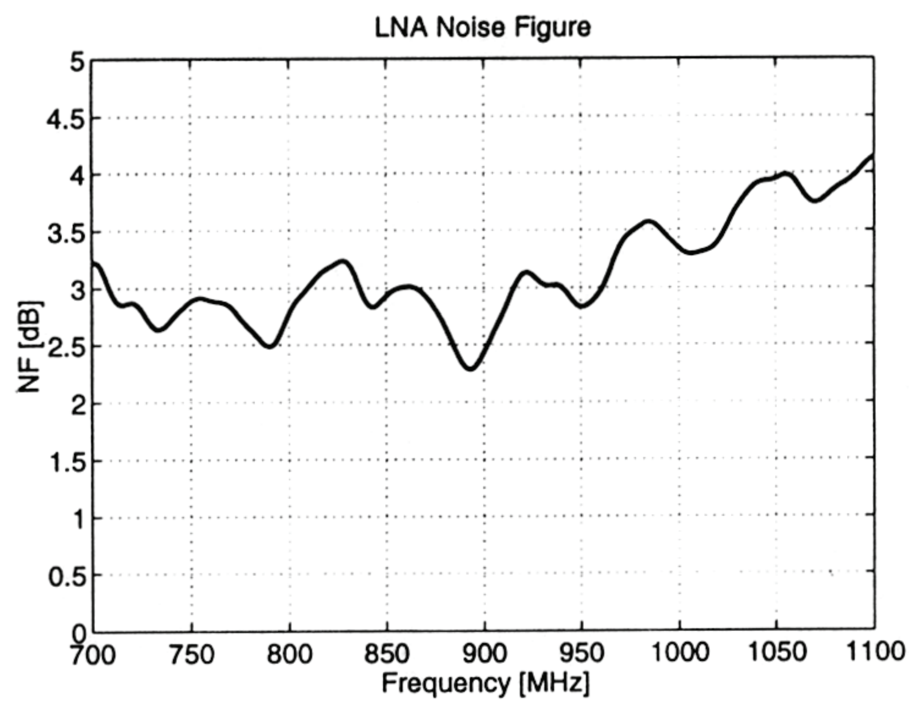


Forward & Reverse gain

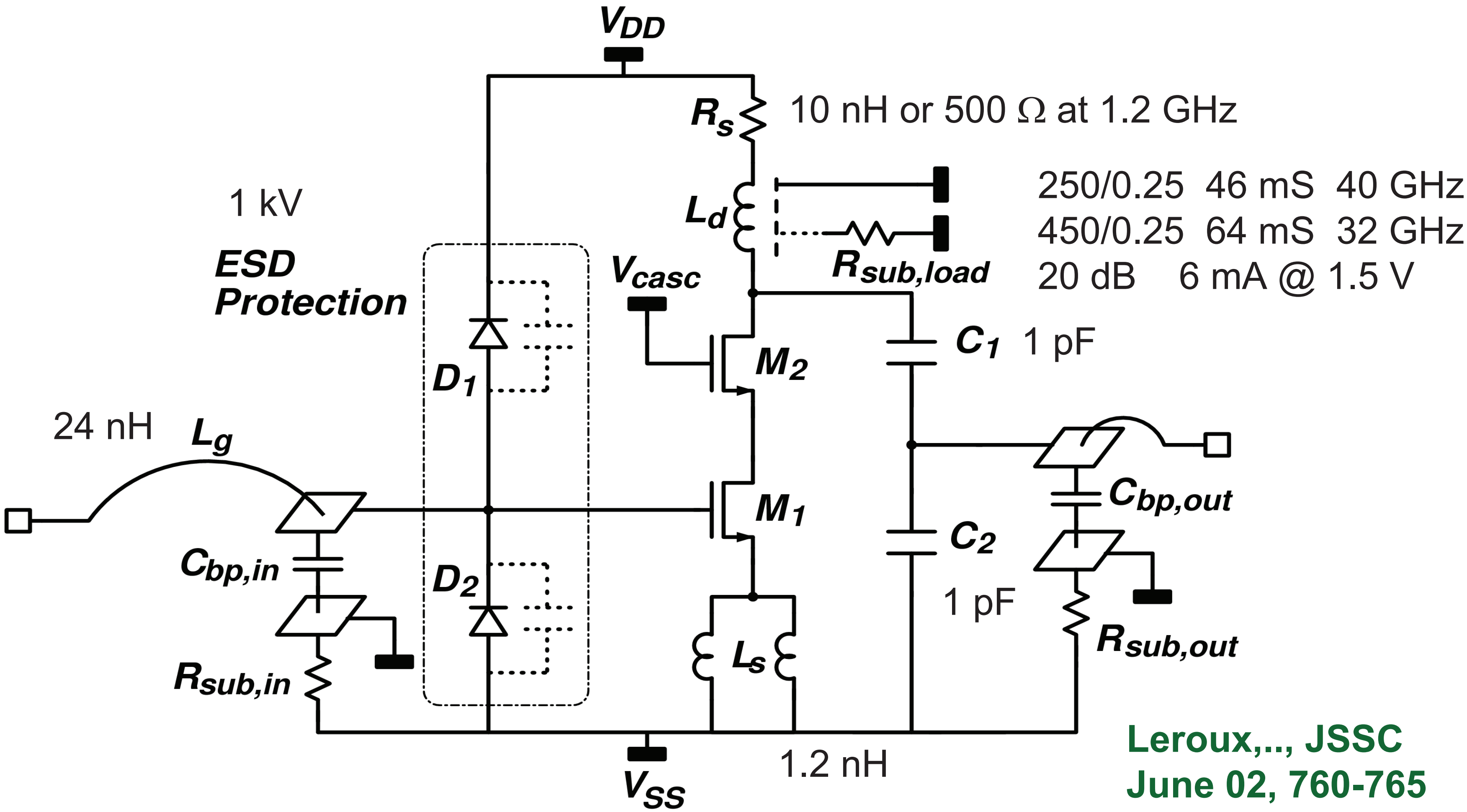
Parameter	Value
Supply voltage	3.0 *Volt*
Power dissipation	10 *mW*
-3dB band	50 - 700 *MHz*
Noise figure	2.3 - 3.3 *dB*
In-band gain Gain at 900 MHz	14.8 *dB* 9 *dB*
Reverse isolation	> 41 *dB*
Input IP3	-4.7 *VdBm*
Die area	1.0 x 1.2 mm^2

Measurements - 2



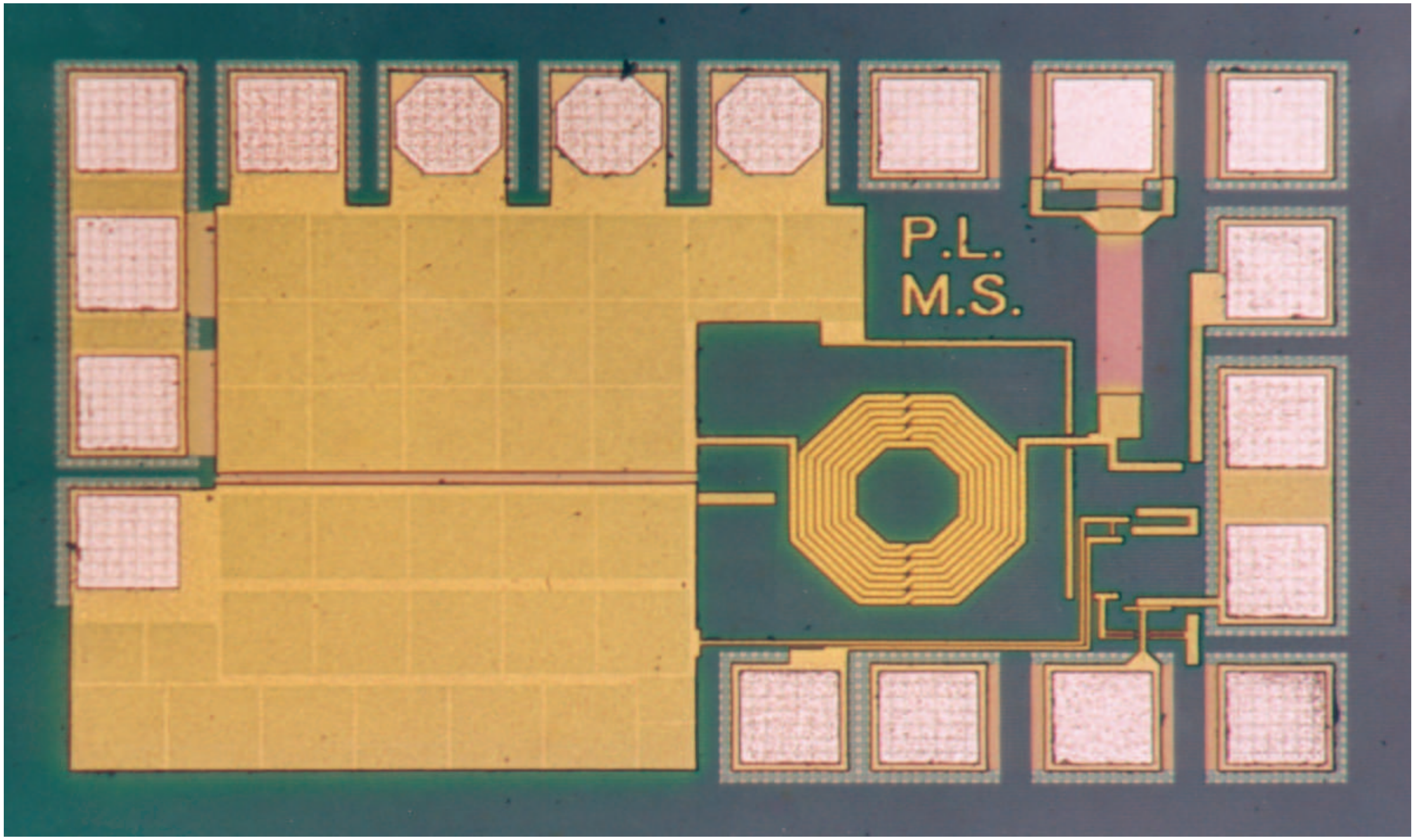


1.2 GHz LNA with C-ESD protection



Leroux,.., JSSC
June 02, 760-765

LNA Micrograph



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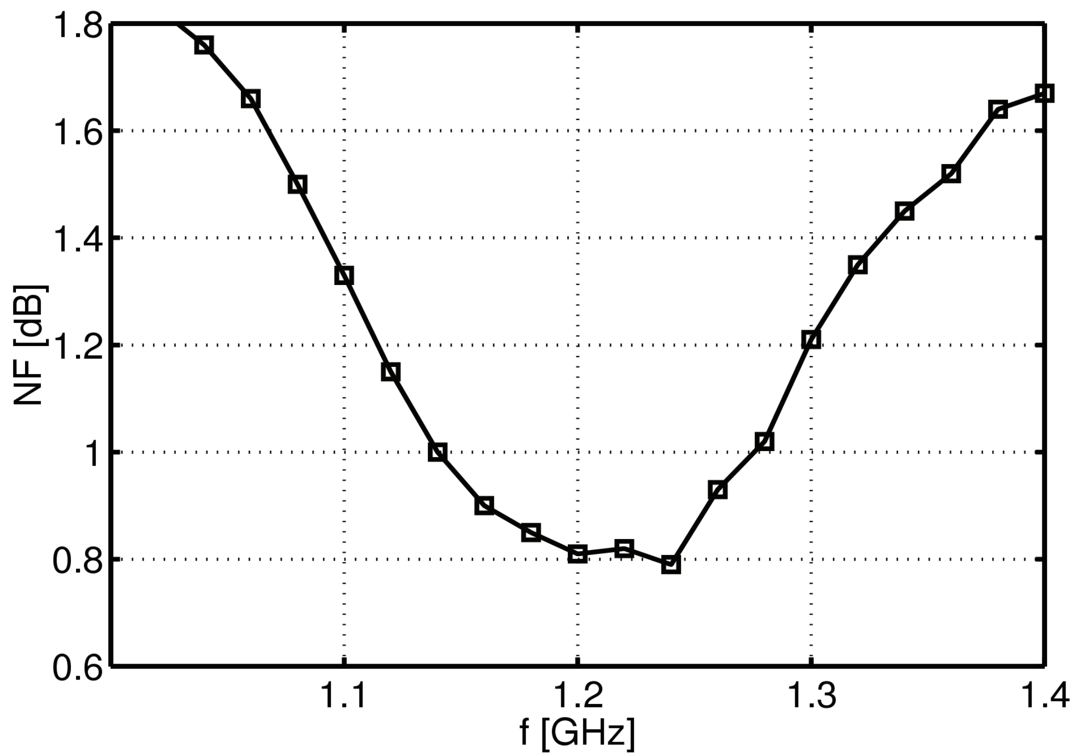
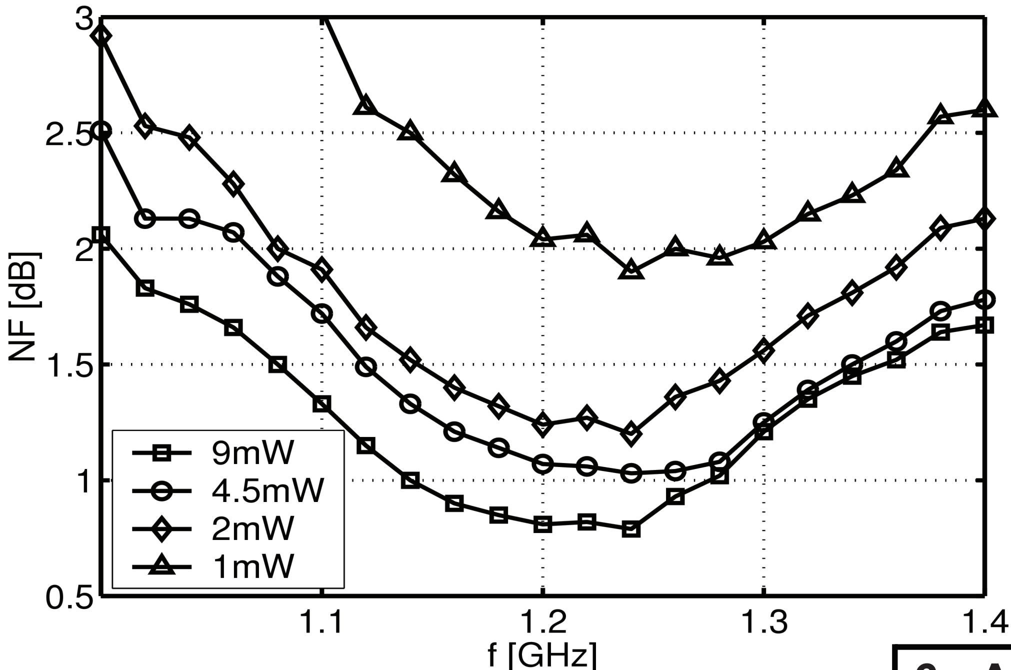
Noise Figure

- **Min. NF = 0.8 dB**
- **BW (NF<1dB) = 130 MHz**



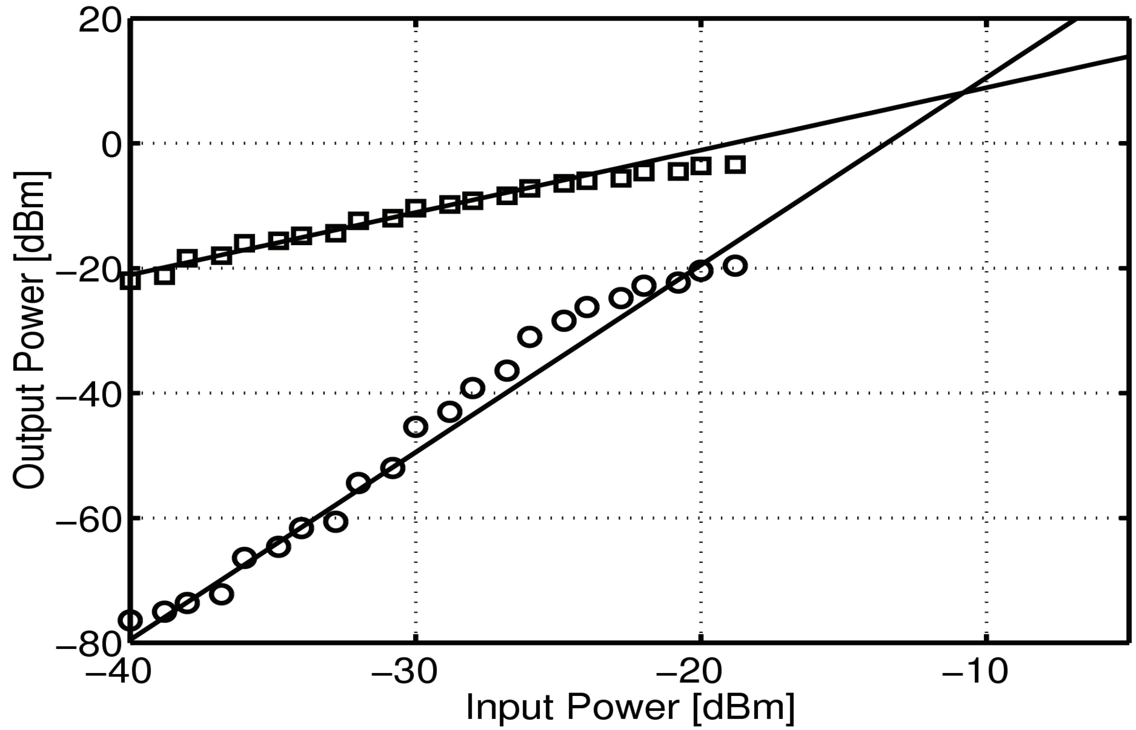
Noise Figure



	NF @ min
6mA @ 1.5V	0.8dB
3mA @ 1.5V	1 dB
2mA @ 1V	1.2dB
1mA @ 1V	1.9dB

Linearity performance

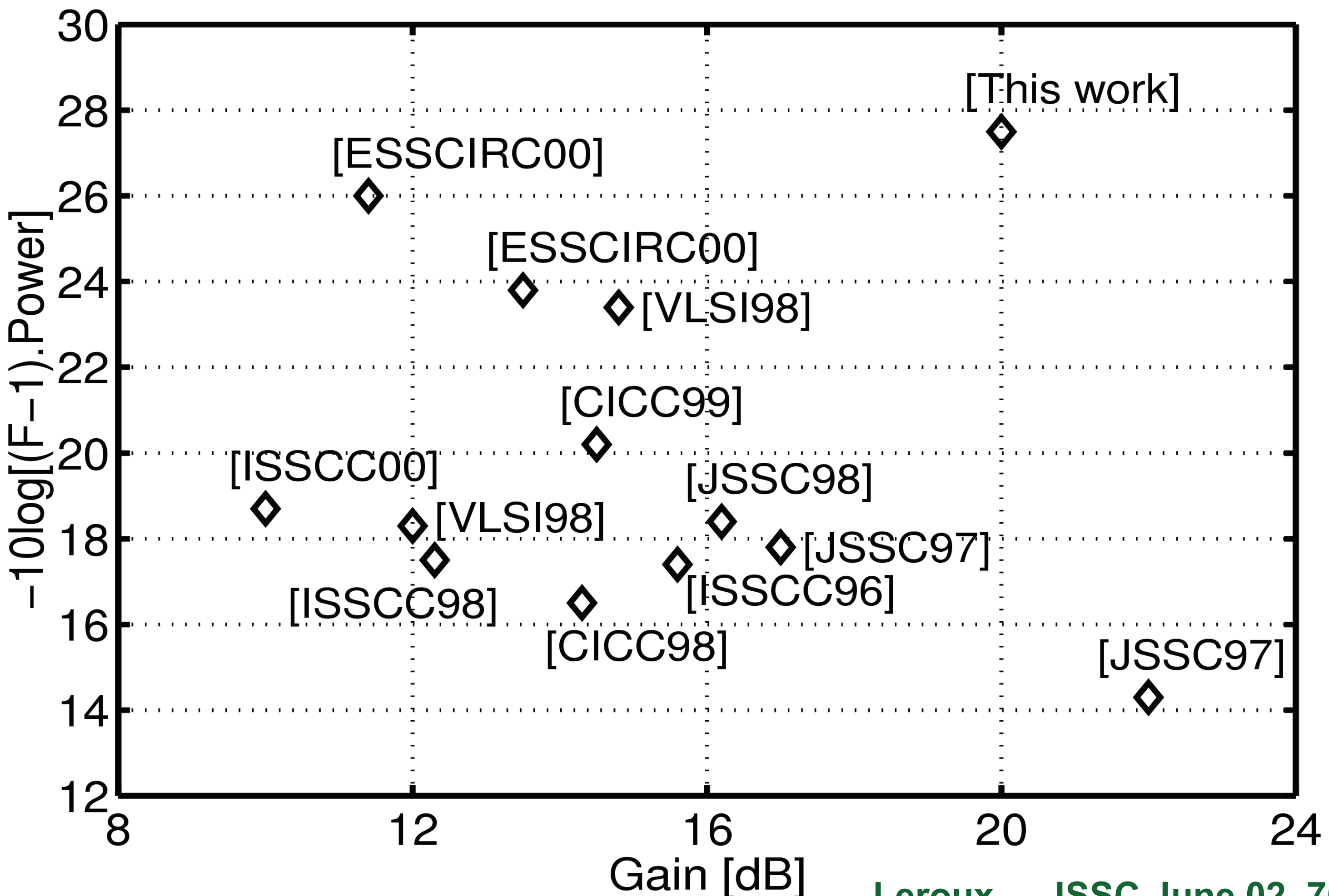
- Input IP3 = -10.8 dBm
- Input 1dBCp = -24 dBm



Performance summary

Parameter	*Specification*	*Measurement*
Supply voltage	1.5 *Volt*	1.5 *Volt*
Power dissipation	10 *mW*	9 *mW*
Noise figure	1 *dB*	0.79 *dB*
Power gain @ 1.23 GHz	*Max.*	20 *dB*
S11 at 1.23 GHz	-10 *dB*	-11 *dB*
S22 at 1.23 GHz	-10 *dB*	-11 *dB*
Reverse isolation	30 *dB*	31 *dB*
Input IP3	-20 *dBm*	-10.8 *dBm*
HBM ESD-protection	0.5 *kV*	0.6 *kV* / -1.4 *kV*
Die area	-	0.6 x 1.1 mm^2

Performance comparison



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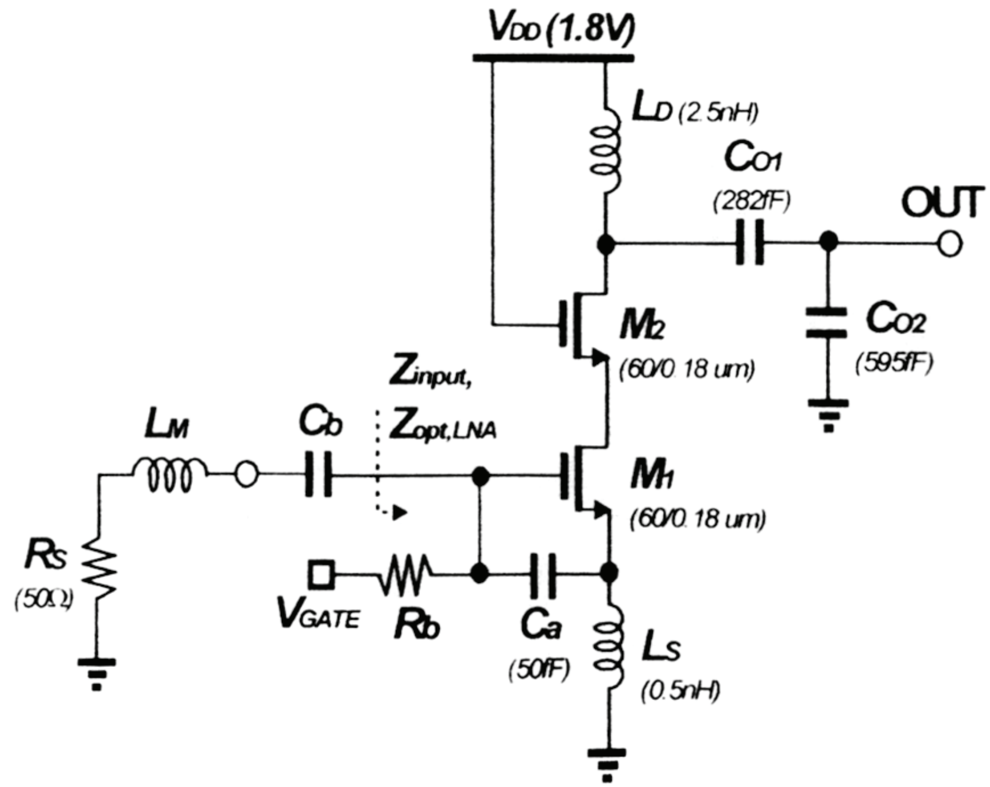
5.2 GHz LNA

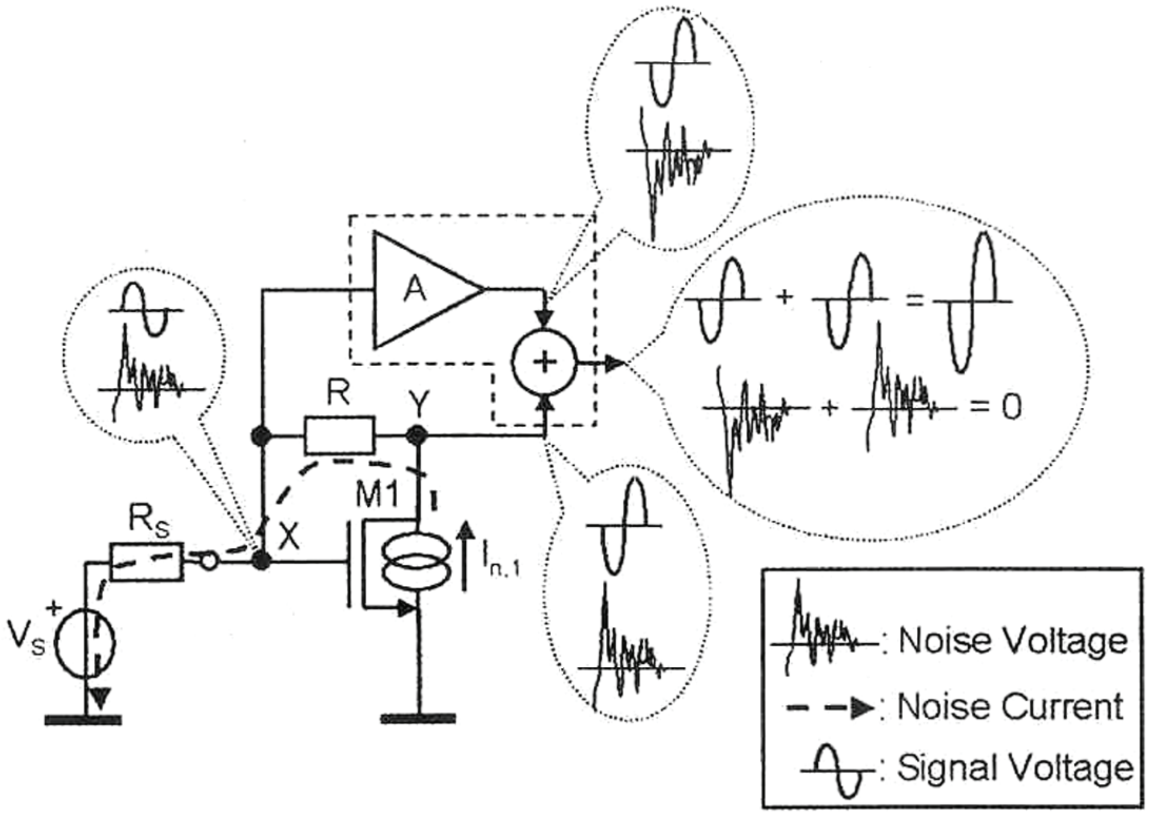


5.2 GHz
Gain 16 dB
NF 1.1 dB

1.8 V
12.4 mW

Han,.., JSSC March 05, 726-735

Noise-cancellation principle



$$v_X = \frac{R_S\, I_{n,1}}{1 + g_{m1} R_S}$$

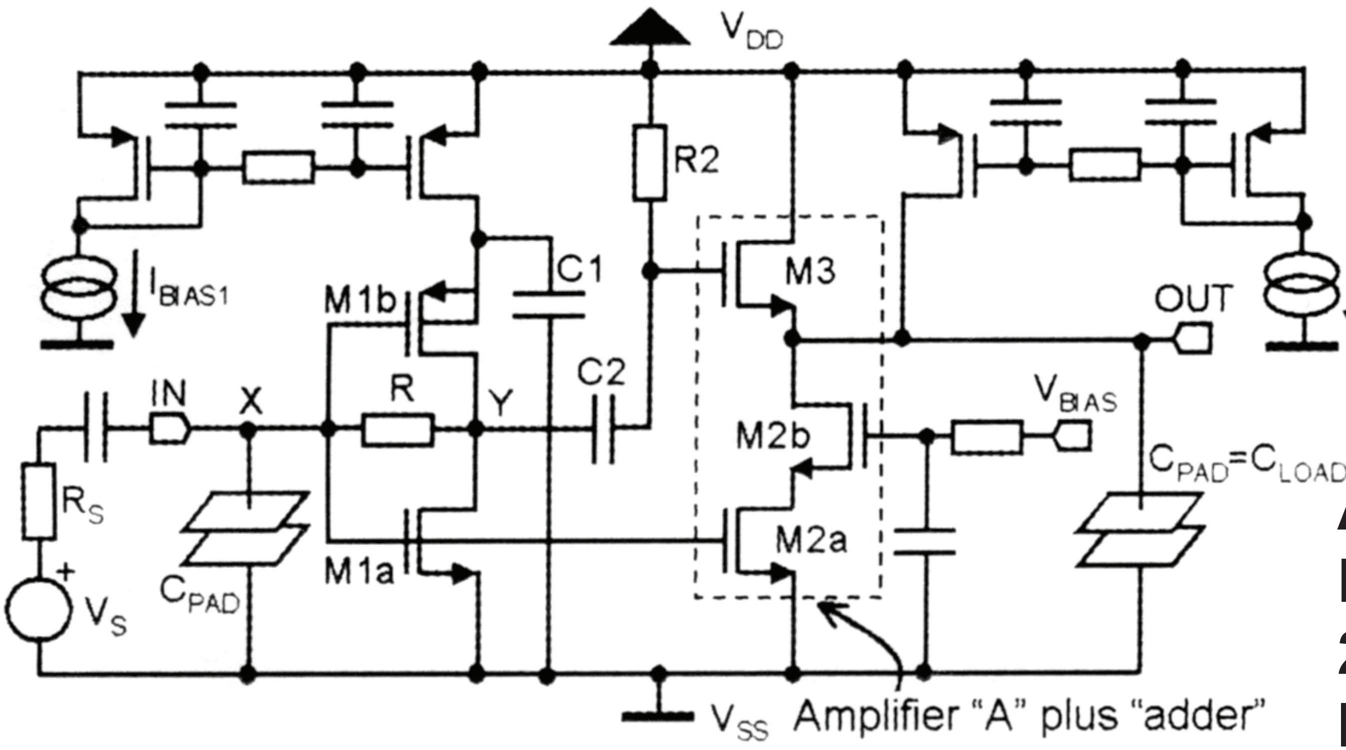
$$v_Y = \frac{(R + R_S)\, I_{n,1}}{1 + g_{m1} R_S}$$

$$v_{OUT} = A v_X + v_Y$$

cancels the noise

Bruccoleri,.., JSSC Febr.04, 275-282

Noise-cancelling LNA

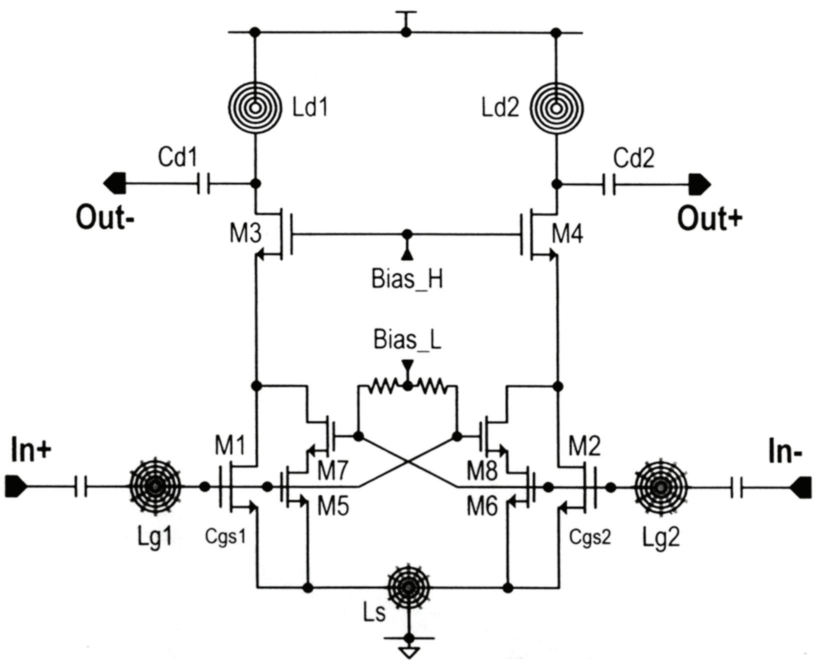


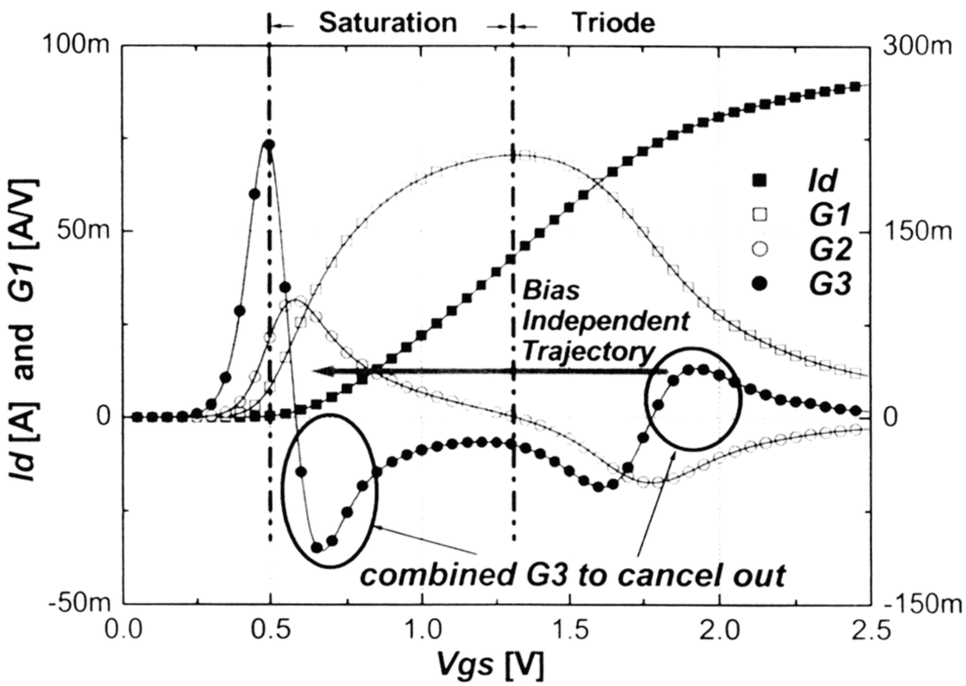
A_v = 14 dB
NF < 2.4 dB
2 GHz
IIP3 0 dBm
14 mA 2.5 V

Noise cancelling condition : $$\frac{g_{m2}}{g_{m3}} = \frac{R + R_S}{R_S}$$

Bruccoleri,Nauta,
JSSC Febr.04,
275-282

Differential LNA in 0.25 μm CMOS : 2.4 GHz



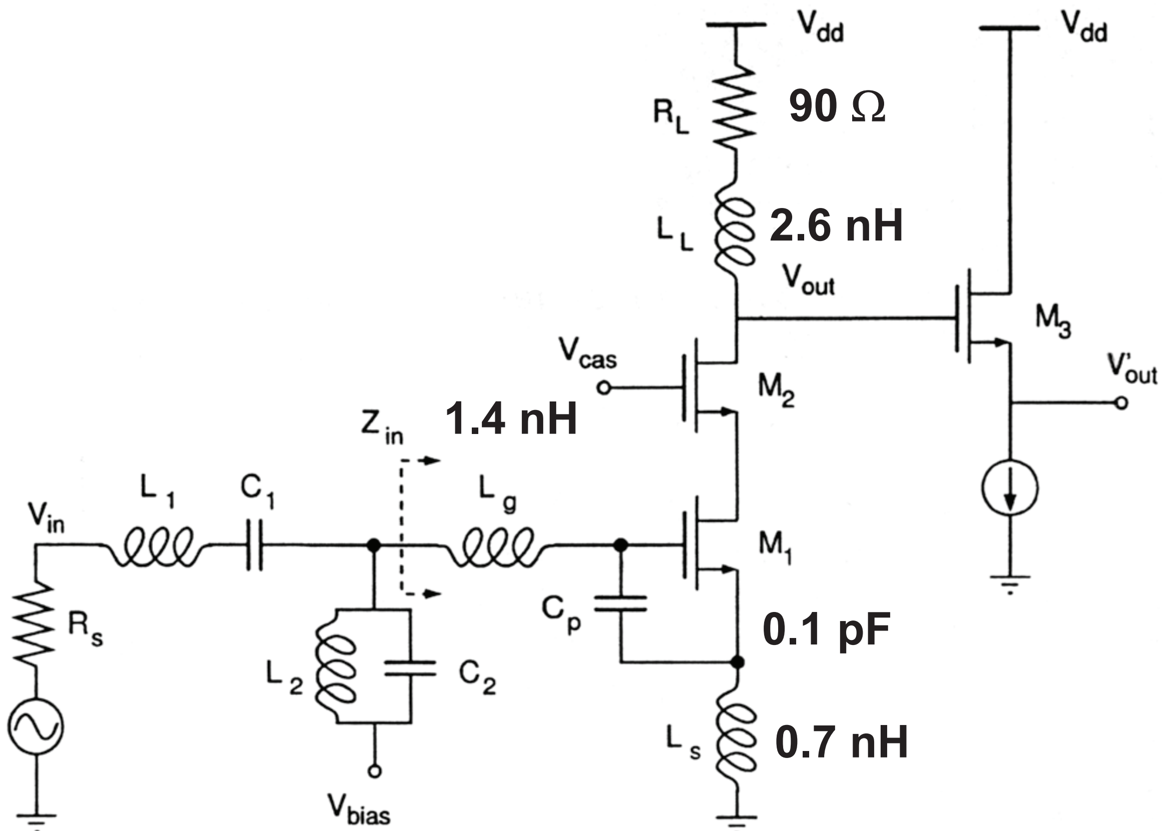


17 % More output power : 23.5 mW or +16 dBm

For same P_{-1dB} = -5 dBm

Youn,.., ISSCC 03, 406-407

LNA for UWB (3 - 10 GHz)



A_v = 9.3 dB

NF < 4 dB

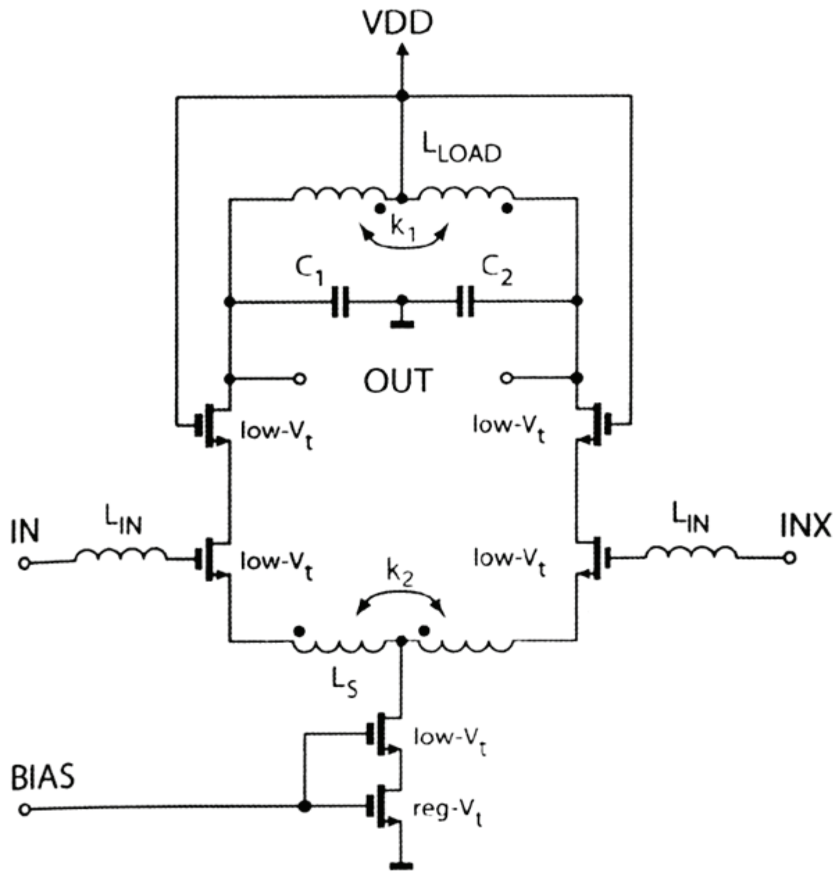
IIP3 = 6.7 dBm

1.5 V 5 mA

0.18μm CMOS

Bevilacqua,.., JSSC Dec.01, 2259-2268

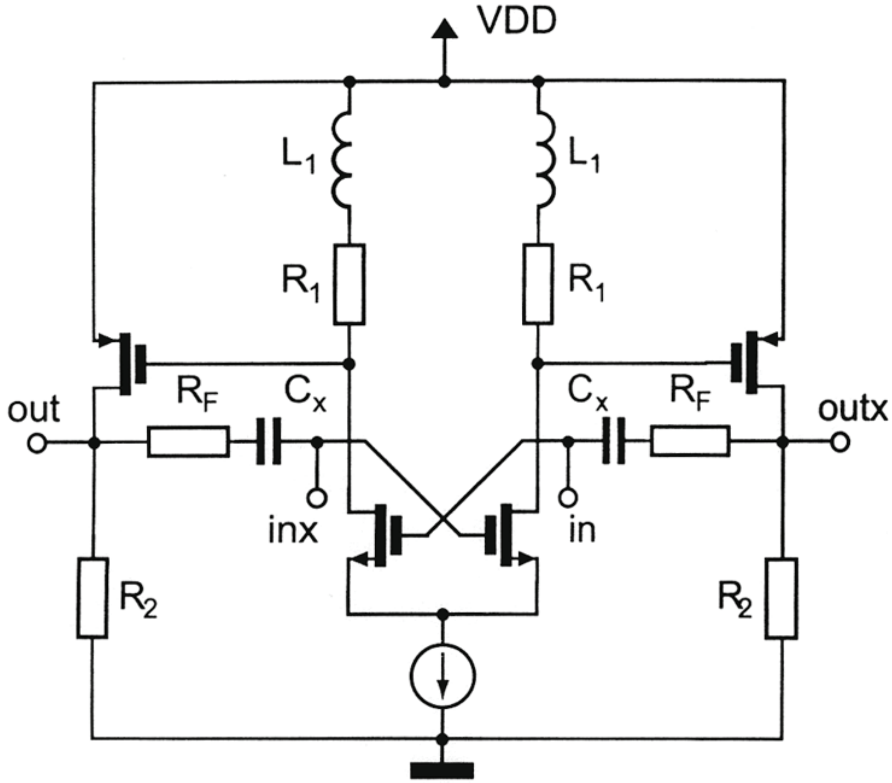
Differential LNA at 17 GHz



WLAN ISM 17 GHz
A_v = 25.8 dB
NF < 10 dB
IIP3 = -40 dBm
1.5 V
0.13μm CMOS

Kienmayer,.., ESSCIRC 2005, 133-136

Differential LNA at 5 GHz



UWB 3 - 5 GHz

A_v = 25.8 dB

NF < 3.6 dB

IIP3 = -22.7 dBm

1.5 V 45 mW

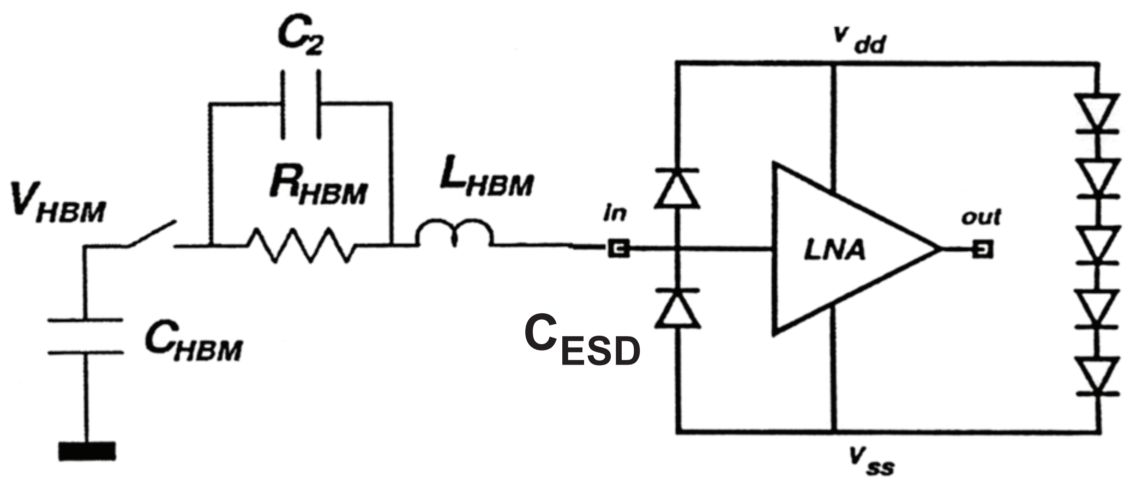
HBM ESD 1.5 kV

Salerno,.., ESSCIRC 2005, 219-222

Table of contents

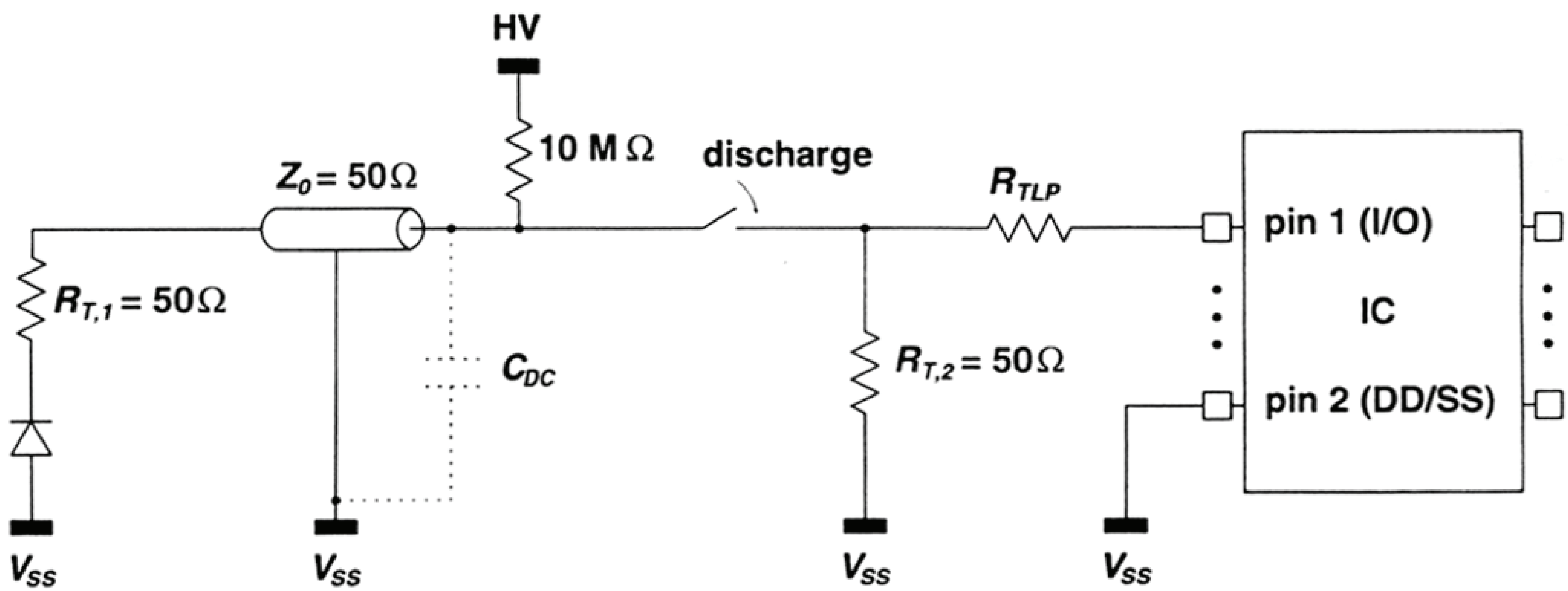
ESD protection : Human Body model

- CMOS requires ESD protection
- Protection network deteriorates RF performance
- Standards for testing : Human Body Model
  Transmission Line Pulse …
- Human Body Model :



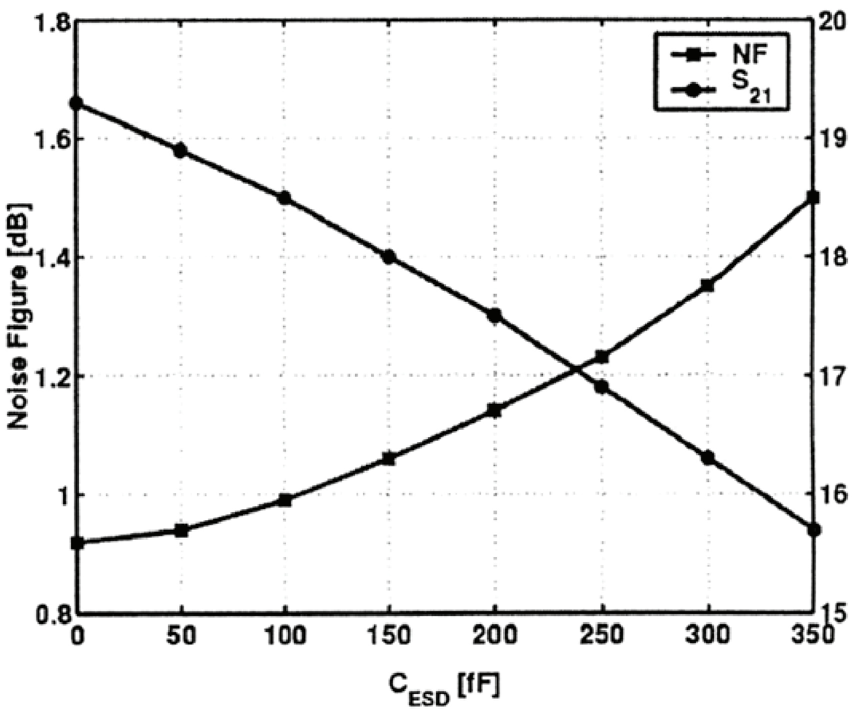
C_{HBM} = 100 pF
R_{HBM} = 1.5 kΩ
V_{HBM} =
I_{max} = 0.67 A / kV
Required 2 kV !!

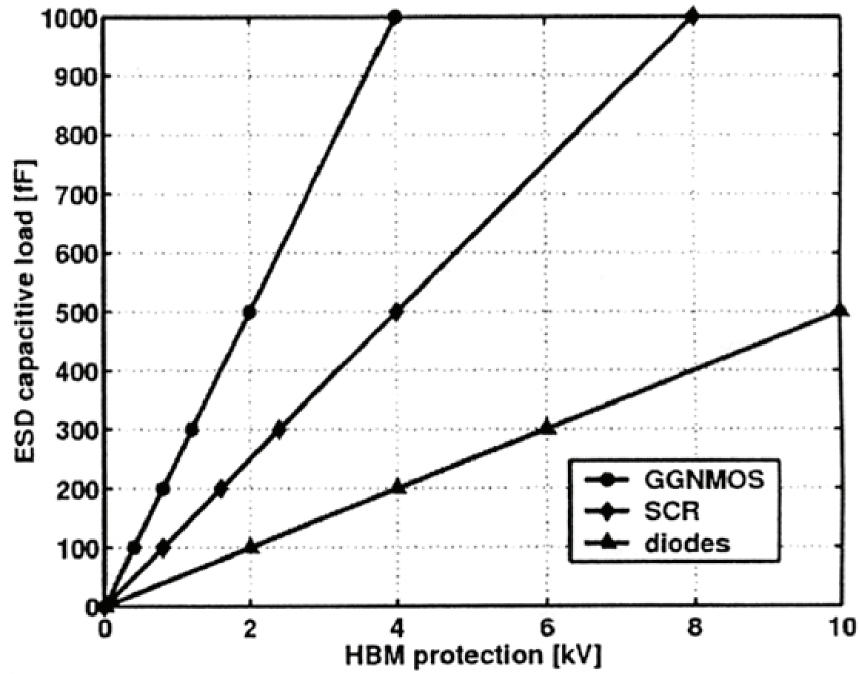
ESD protection : Transmission Line Pulse



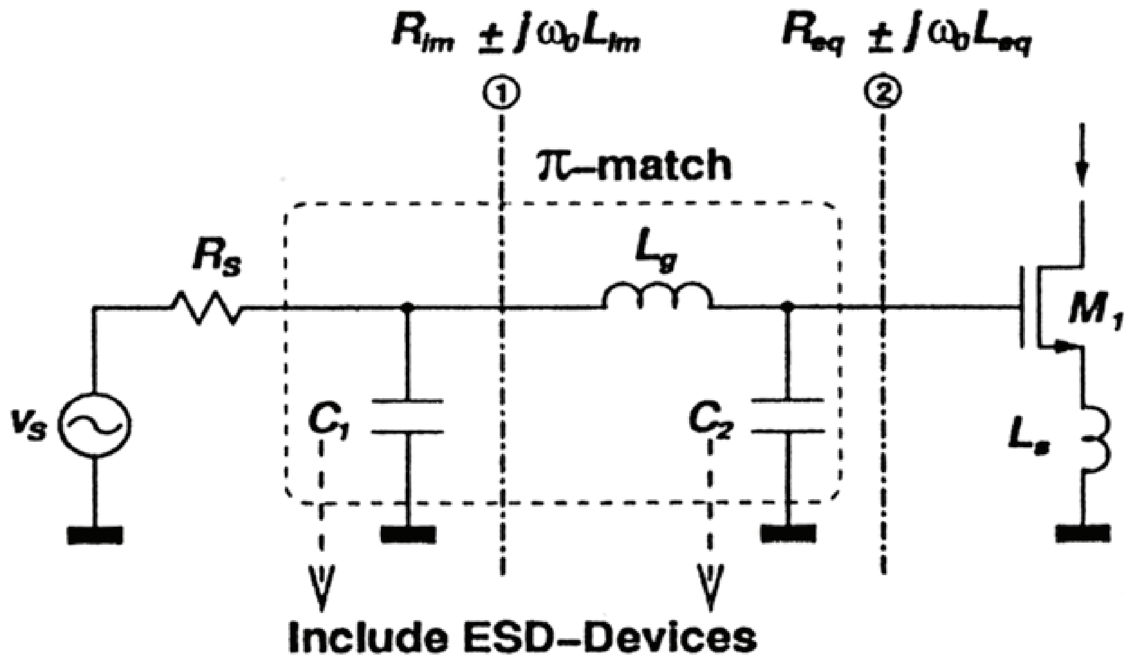
HV : High Voltage : kV's

Simulated deterioration by ESD diodes





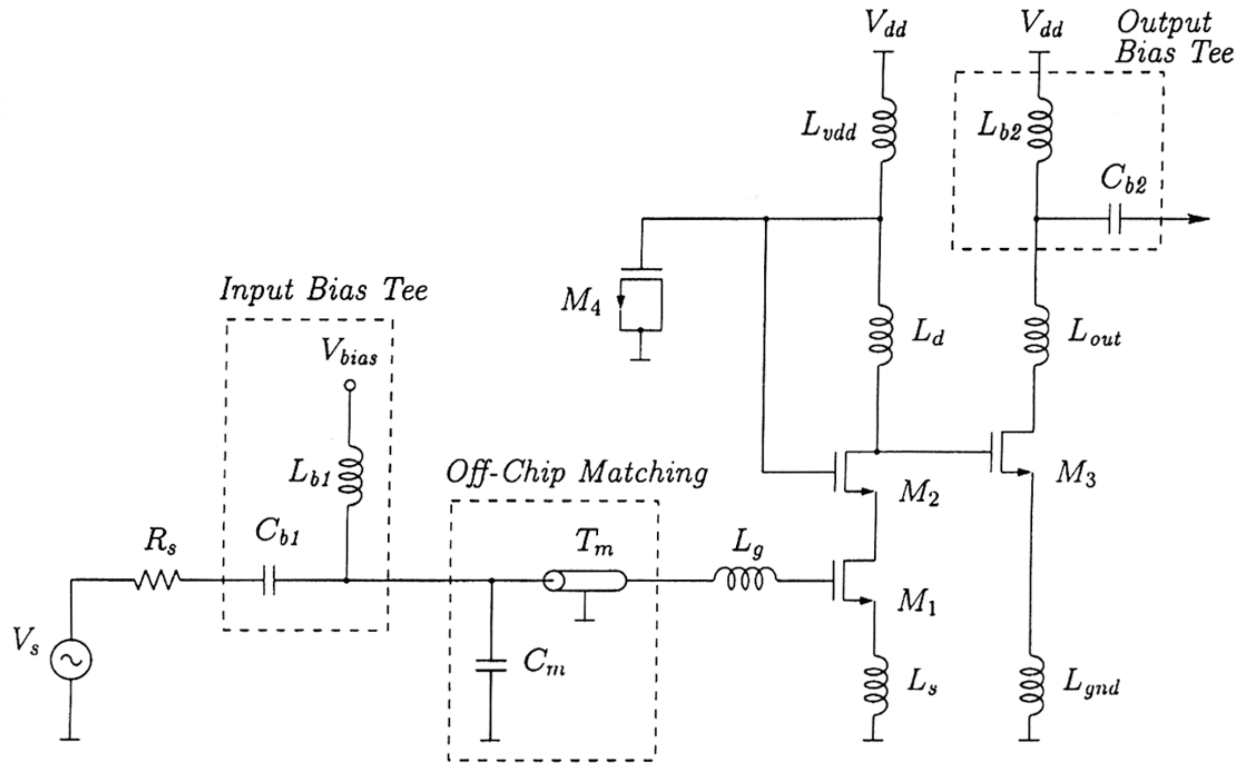
Π-network with Capacitive ESD protection



Requires on-chip inductor !

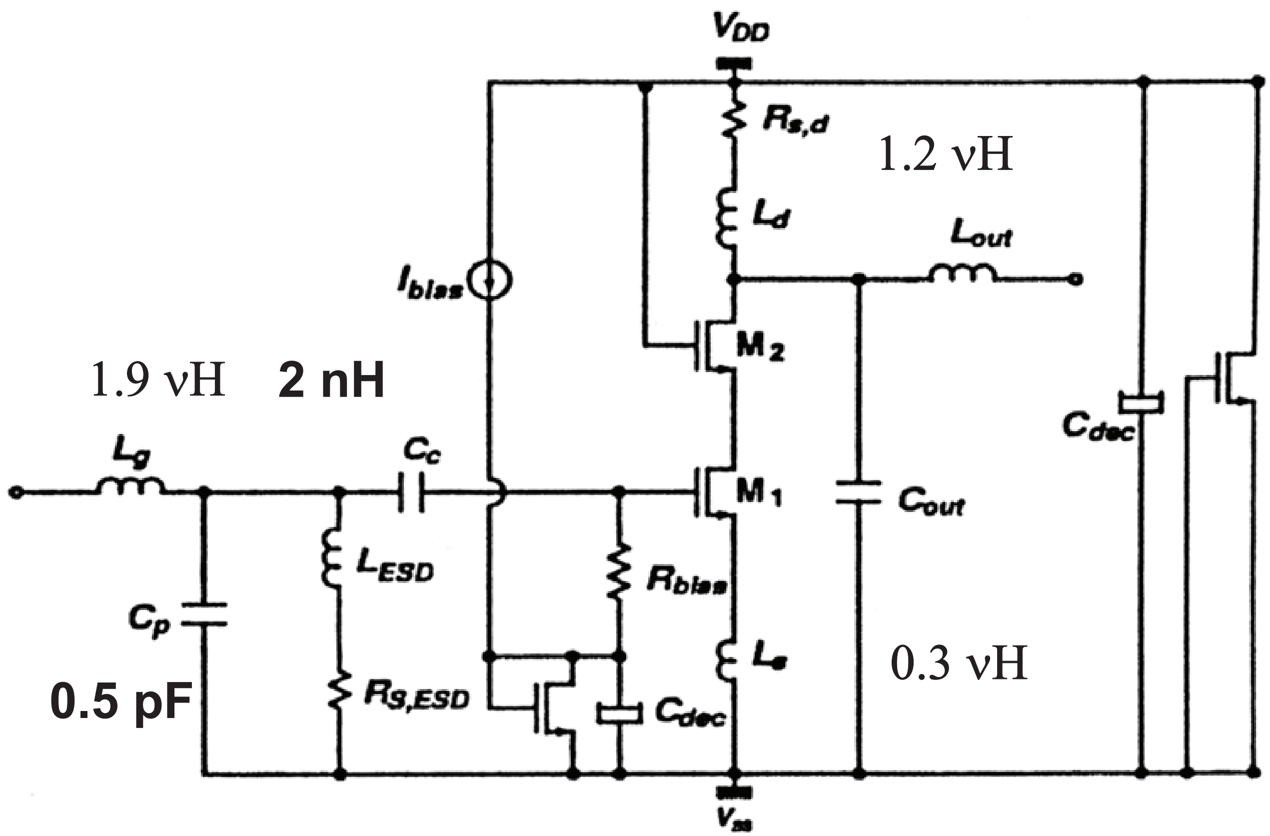
Leroux,.., Kluwer 2005

1.5 V 1.5 GHz LNA



Schaeffer,.. JSSC May 97, 745-759

LNA with L-ESD protection for 5 GHz LNA

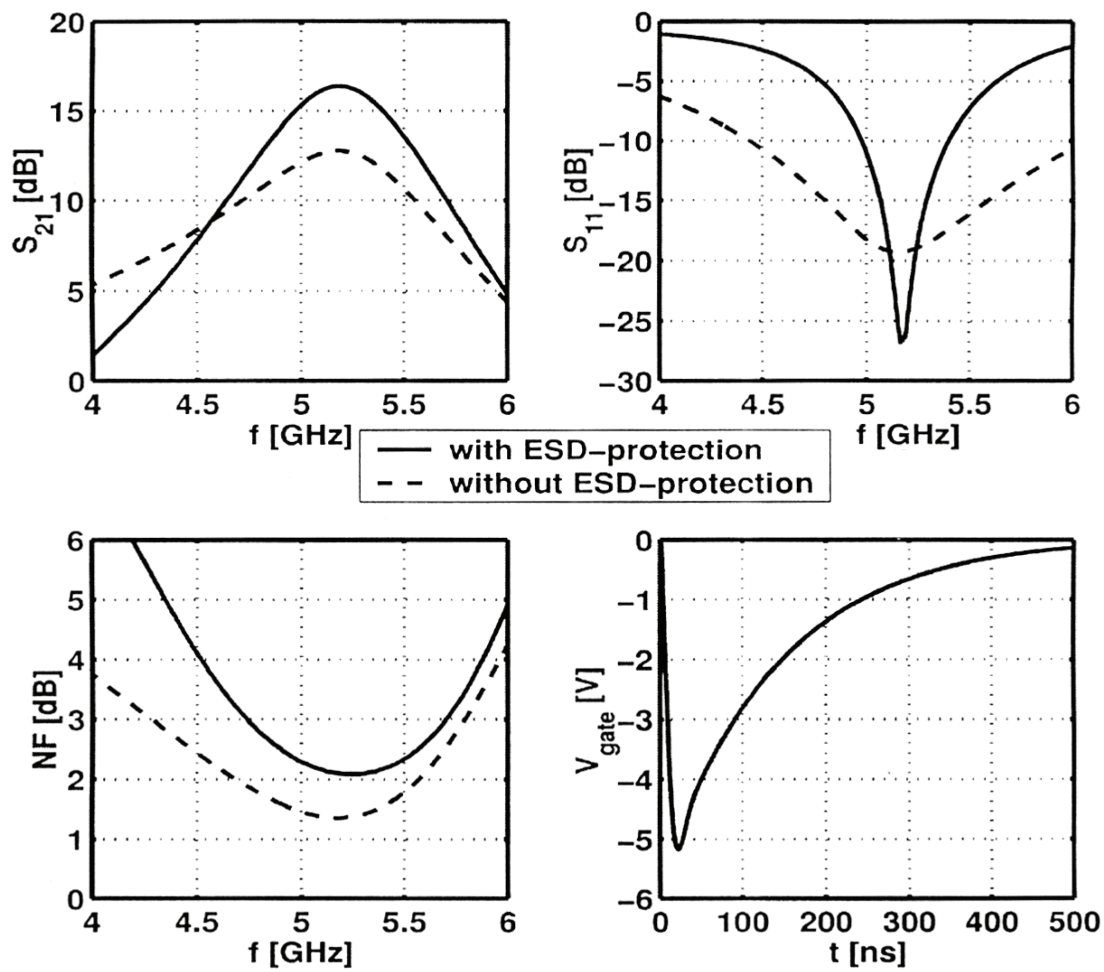


5 GHz
24 MHz
NF < 10 dB
IIP3 > -10dBm

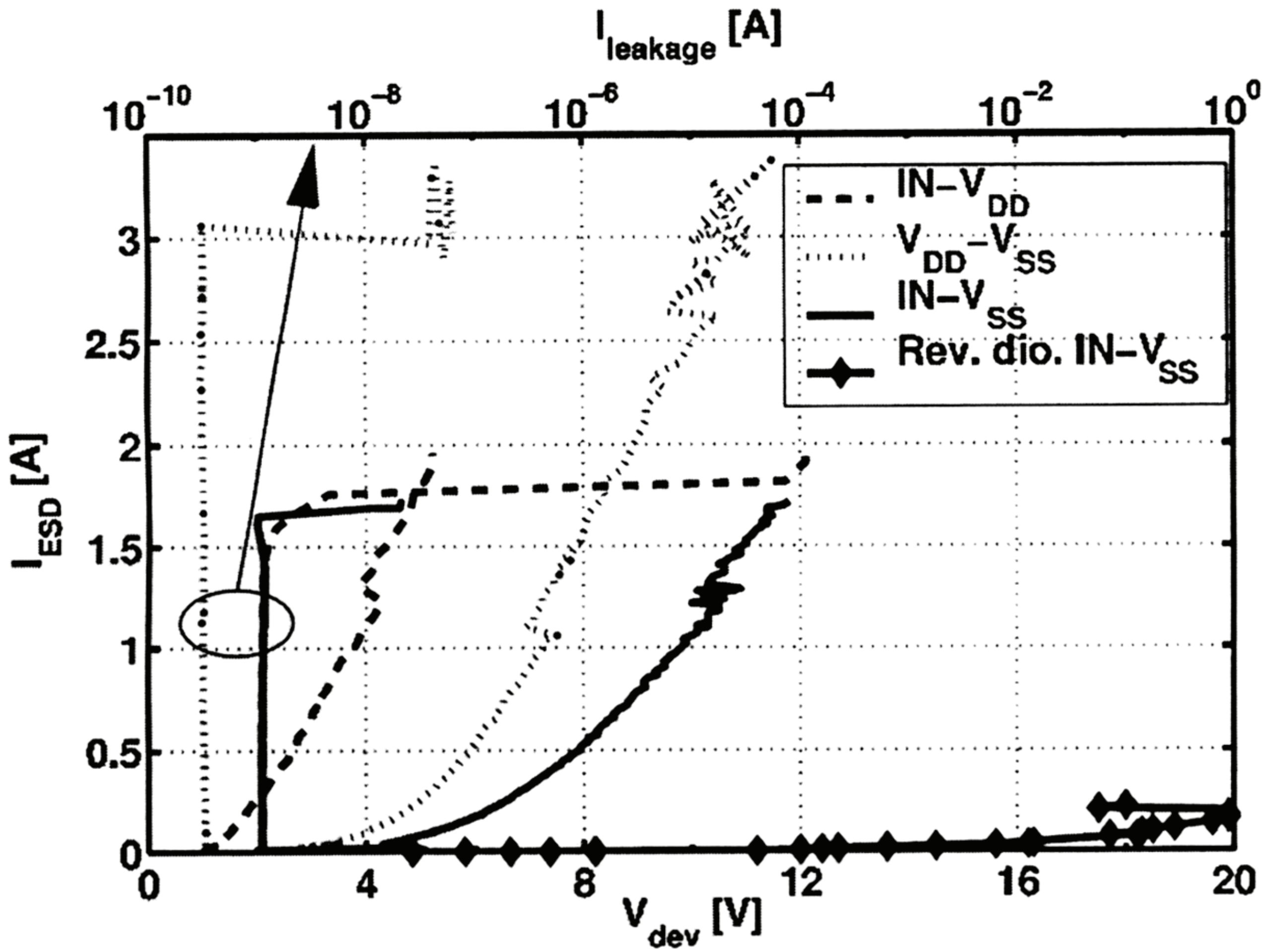
0.18 μm CMOS
8 mA/1.5 V
3 kV ESD-prot.

Leroux,.., AACD 2003, 207-225

Effect of ESD on performance



TLP Characteristics



Transmission Line Pulse

Table of contents

- Noise Figure and Impedance Matching
- LNA specifications and linearity
- Input amplifier or cascode
- Non-quasi-static MOST model
- More realizations
- Inductive ESD protection