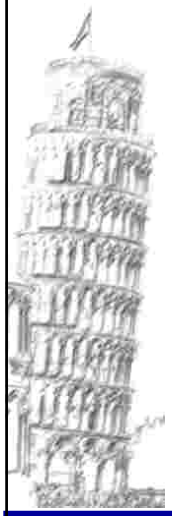
Progettazione a RadioFrequenza



D. Zito

Prof. B. Neri

Dipartimento di Ingegneria dell'Informazione:
Elettronica, Informatica, Telecomunicazioni

*"**Seminario d'Introduzione alla Progettazione a Radiofrequenza e Simulatori**"*

Sommario

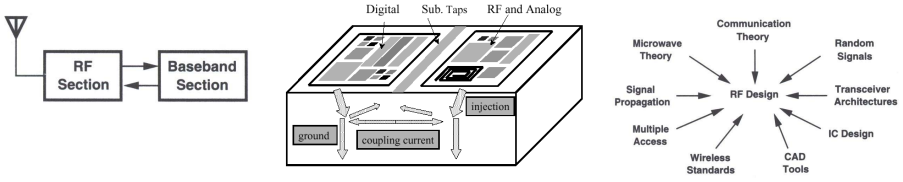
- Introduzione alla Progettazione RF
- Progettazione di Front-end RF
  - ❑ Simulazioni Elettromagnetiche
  - ❑ Tecnologie e CAD Tools
  - ❑ Low Noise Amplifier (LNA)
  - ❑ Mixer
- Front-End Multi-Standard per WLAN 5-6 GHz
- Riepilogo e Conclusioni

Introduzione alla Progettazione RF

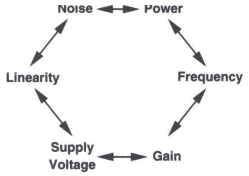
- Aspetti Generali
- Concetti di Base
  - ❑ Linearità
  - ❑ Noise Figure
- Architetture
  - ❑ Eterodina
  - ❑ Omodina

Aspetti Generali (1)

- Multidisciplinare



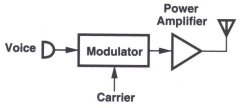
- Trade-Offs



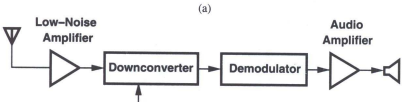
- Design Tools: General to Special Purpose

Aspetti Generali (2)

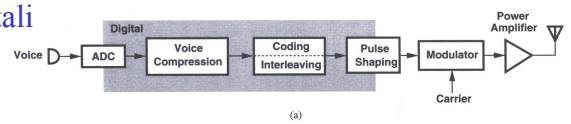
- Analogici



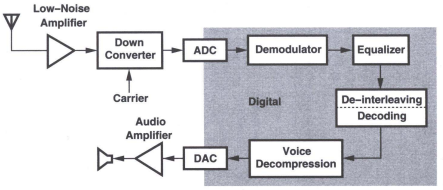
(a)



- Digitali



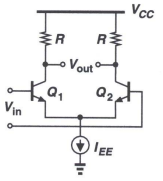
(a)



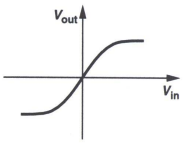
(b)

Concetti di Base: Linearità (1)

- Armoniche



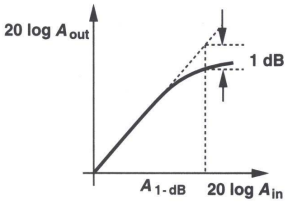
(a)



(b)

$$y(t) \approx \alpha_1 x(t) + \alpha_2 x^2(t) + \alpha_3 x^3(t) = \frac{\alpha_2 A^2}{2} + \left(\alpha_1 A + \frac{3\alpha_3 A^3}{4}\right)\cos\omega t + \frac{\alpha_2 A^2}{2}\cos 2\omega t + \frac{\alpha_3 A^3}{4}\cos 3\omega t$$

- Punto di Compressione a 1dB: CP_{1dB}



Concetti di Base: Linearità (2)

- Intermodulazione

$$x(t) = A_1 \cos \omega_1 t + A_2 \cos \omega_2 t$$

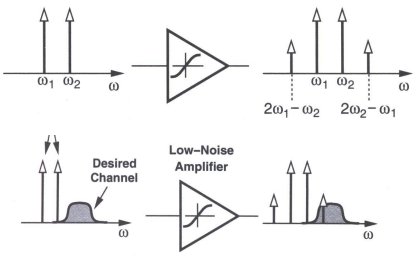
$$y(t) = \alpha_1(A_1 \cos \omega_1 t + A_2 \cos \omega_2 t) + \alpha_2(A_1 \cos \omega_1 t + A_2 \cos \omega_2 t)^2 + {}_3(A_1 \cos \omega_1 t + A_2 \cos \omega_2 t)^3$$

$$\omega_1 \pm \omega_2 : \alpha_2 A_1 A_2 \cos(\omega_1 + \omega_2)t + \alpha_2 A_1 A_2 \cos(\omega_1 - \omega_2)t$$

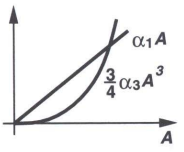
$$2\omega_1 \pm \omega_2 : \frac{3\alpha_3 A_1^2 A_2}{4} \cos(2\omega_1 + \omega_2)t + \frac{3\alpha_3 A_1^2 A_2}{4} \cos(2\omega_1 - \omega_2)t$$

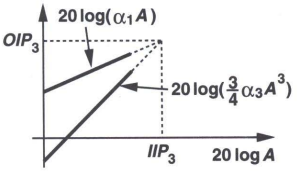
$$2\omega_2 \pm \omega_1 : \frac{3\alpha_3 A_2^2 A_1}{4} \cos(2\omega_2 + \omega_1)t + \frac{3\alpha_3 A_2^2 A_1}{4} \cos(2\omega_2 - \omega_1)t$$

$$\omega = \omega_1, \omega_2 : \left(\alpha_1 A_1 + \frac{3}{4}\alpha_3 A_1^3 + \frac{3}{2}\alpha_3 A_1 A_2^2\right) \cos \omega_1 t + \left(\alpha_1 A_2 + \frac{3}{4}\alpha_3 A_2^3 + \frac{3}{2}\alpha_3 A_2 A_1^2\right) \cos \omega_2 t.$$



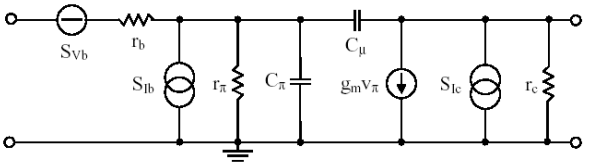
- Intercetta 3° Ordine: IP_3





Concetti di Base: Noise Figure (1)

- Sorgenti di Rumore



$$S_{Vb} = 4kTr_b \qquad [V^2/Hz]$$

$$S_{Ib} = 2qI_B + \frac{A}{f} + \frac{B}{f^2} \qquad [A^2/Hz]$$

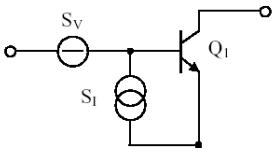
$$S_{Ic} = 2qI_C \qquad [A^2/Hz]$$

- Noise Figure (NF)

$$NF = 10 \log \frac{Si/Ni}{Su/Nu} \qquad Ga = \frac{Su}{Si} \qquad NF = 10 \log \frac{Nu}{Ga\, Ni}$$

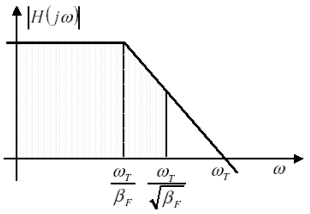
Concetti di Base: Noise Figure (2)

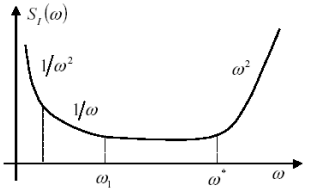
- Rumore riportato in ingresso



$$S_V = 4kT \cdot \left(r_b + \frac{1}{2g_m} \right)$$

$$S_I = 2q \cdot \left[I_B + I_C \cdot (\omega/\omega_T)^2 \right]$$

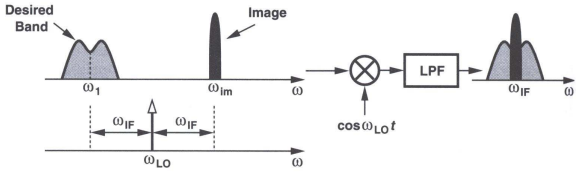




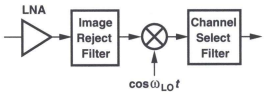
- NF per 2 stadi in cascata (formula di Friis)

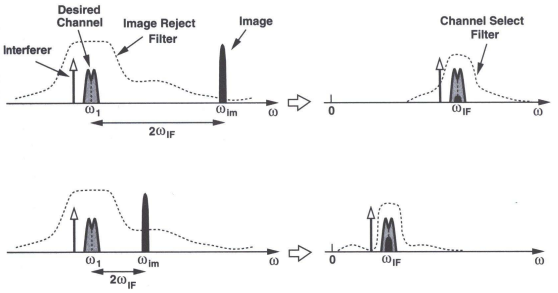
$$NF_T = NF_1 + \frac{NF_2 - 1}{Ga_1}$$

Architetture: Eterodina (1)



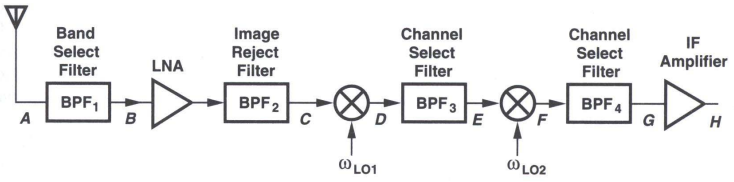
❑ Reiezione Immagine





Architetture: Eterodina (2)

• Eterodina a Doppia Conversione

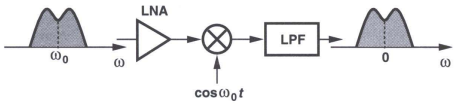


✓ Selectivity

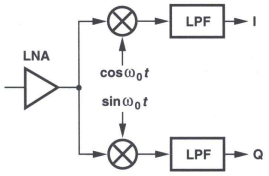
✓ Sensitivity

Architetture: Omodina

✓ Assenza Segnale Immagine



(a)



(b)

❑ Mutua Interferenza: RF – Oscillatore Locale

❑ LO Leakage e I/Q Mismatch

❑ Rumore Flicker

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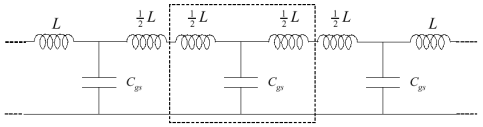
Simulazioni Elettromagnetiche

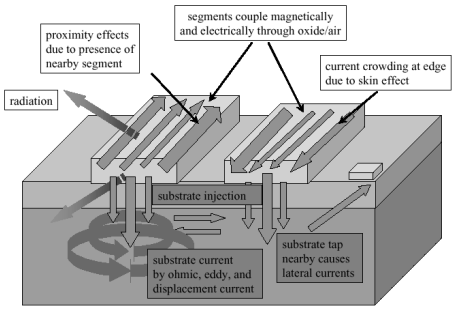
- Aspetti Generali
  - ❑ Approccio Elettromagnetico
  - ❑ Chip Packaging
- Simulatori
- ASITIC
  - ❑ Induttori
  - ❑ Trasformatori
- MicroWave Office
- HP HFSS (High Frequency Structures Simulator)

Approccio Elettromagnetico

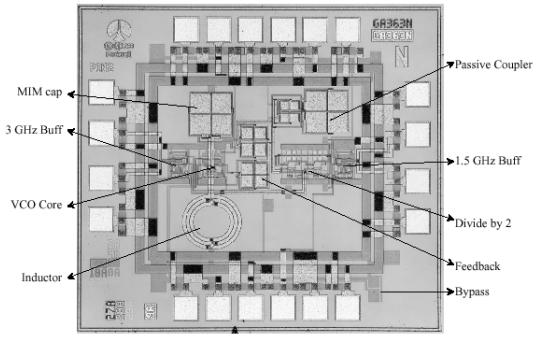
- Parametri Distribuiti

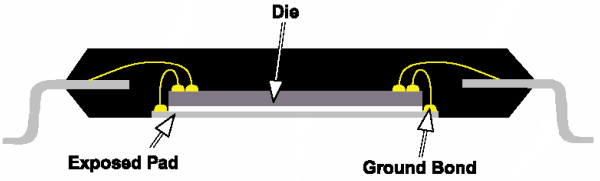


- Interazione Elettromagnetica



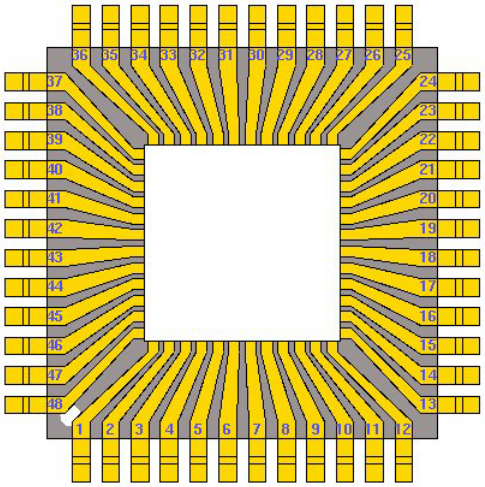
Chip Packaging (1)





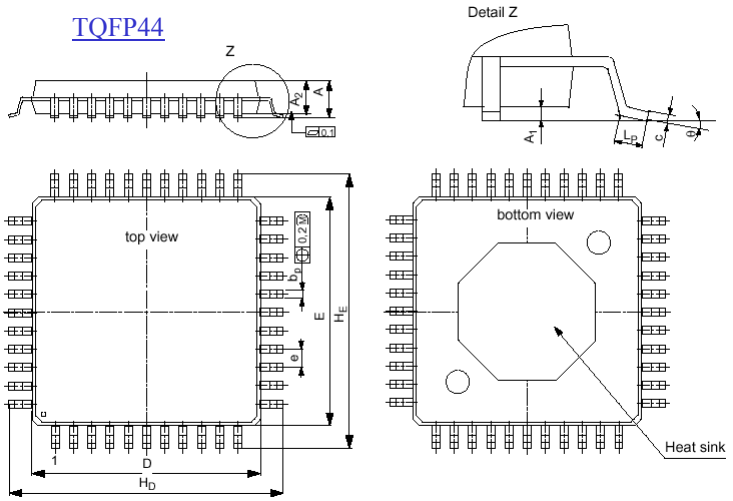
Chip Packaging (2)

TQFP48



Chip Packaging (3)

TQFP44

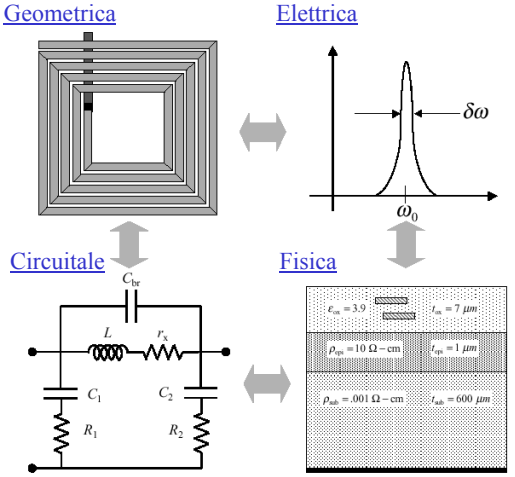


Simulatori Elettromagnetici

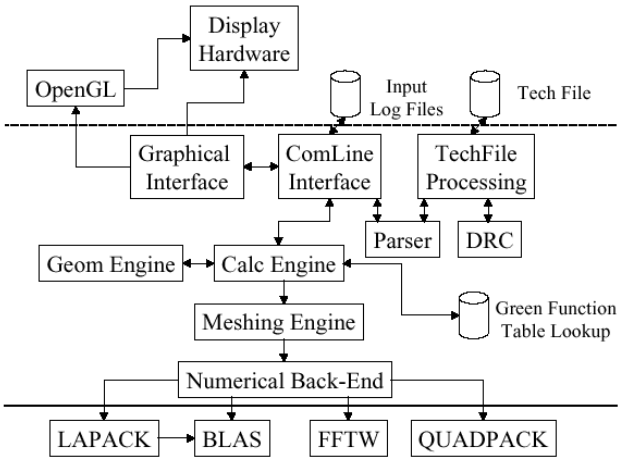
- Approccio Numerico
  - ❑ Time Domain (TD)
  - ❑ Frequency Domain (FD)
- Metodo Analitico
  - ❑ Momenti (FD)
  - ❑ Elementi Finiti (FD)
  - ❑ Differenze Finite (TD)
- Geometrie
  - ❑ 2D
  - ❑ 2D e ½ (ASITIC, MicroWave Office)
  - ❑ 3D (HP HFSS)

ASITIC: Flessibilità

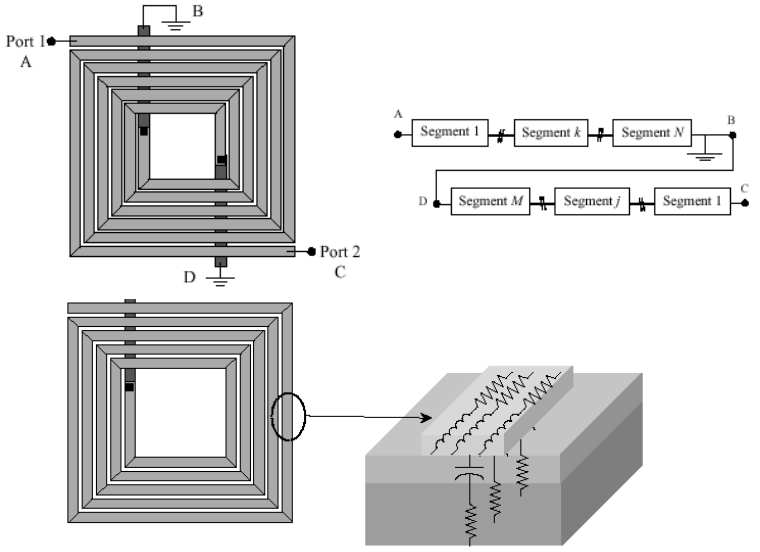
- 4 Descrizioni



ASITIC: Organizzazione

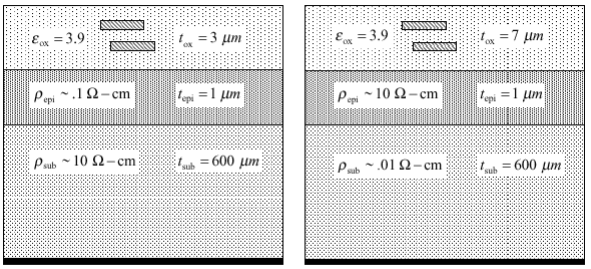


ASITIC: Segmentazione



ASITIC: Technology File

- File Testo e Descrizione Fisica



Bipolare CMOS

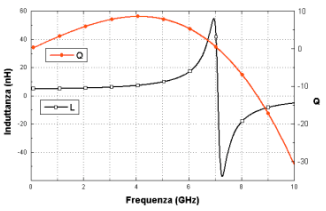
ASITIC: Spirals (Editing)

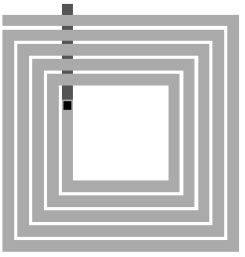
$$Q = \left\{ \frac{\mathrm{Im}(Z_L)}{\mathrm{Re}(Z_L)} \right\}$$

$$L = \mathrm{Im}\left\{ \frac{Z_L}{2\pi f} \right\}$$

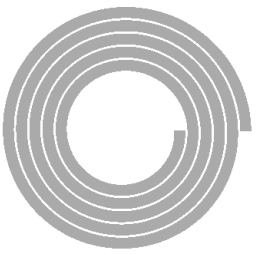
$$R_L = \rho \frac{D}{TW}$$

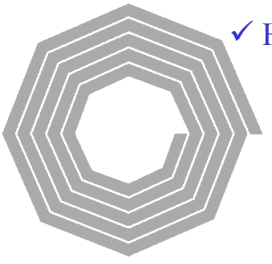
$$\delta = \sqrt{\frac{1}{\pi f \mu \sigma}}$$





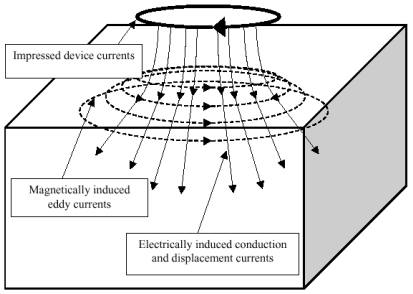
✓ Layout



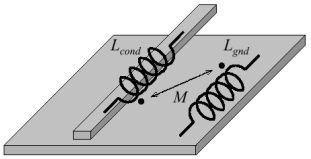


✓ High Q

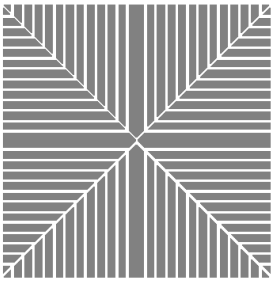
ASITIC: Eddy Current



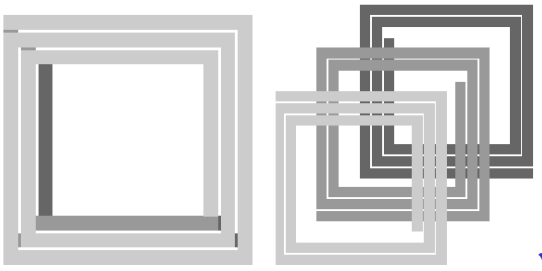
❑ Legge di Lenz



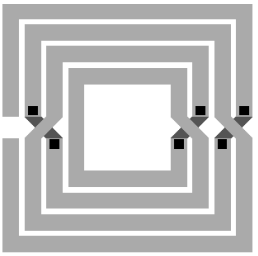
✓ Ground Pattern



ASITIC: Shunt and Symmetric Spirals

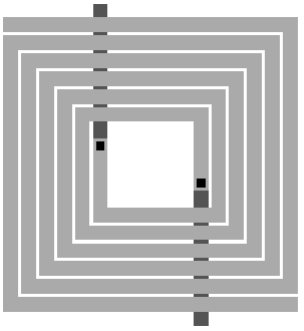


✓ High Q

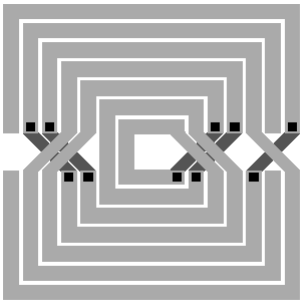


✓ Symmetry

ASITIC: Planar and Symmetric Transformers



✓ High Q



✓ Symmetry

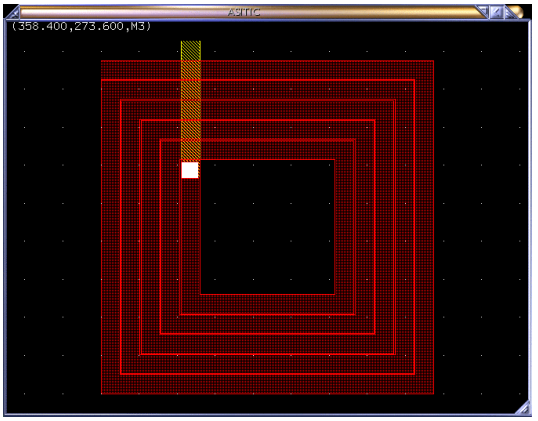
ASITIC: Semplice Sessione

```
<chip>
        chipx = 512     ; dimensions of the chip in x direction in microns
        chipy = 512     ; dimensions of the chip in y direction
        fftx = 256      ; x-fft size (must be a power of 2)
        ffty = 256      ; y-fft size
        TechFile = sample.tek   ; the name of this file
        TechPath = /home/niknejad/tekf ; the pathname of the data files
        freq = .1

<layer> 0       ; Bulk Substrate

        rho = .1                ; Resistivity:  ohm-cm
        t   = 400               ; Thickness:  microns
        eps = 11.9              ; Permitivity:  relative

<layer> 1       ; Epi Layer

        rho = 15                ; ohm-cm
        t = 1                   ; microns
        eps = 11.9              ; relative

<layer> 2       ; Oxide Layer

        rho = 1e10              ; ohm-cm
        t = 50                  ; microns
        eps = 4                 ; relative

<via> 0         ; metal 1 to substrate

        top = 1                 ; via connects up to this metal layer
        bottom = 0              ; via connects down to this metal layer
        r = 5                   ; resistance per via
        width = .4              ; width of via
        space = 1.3             ; minimum spacing between vias
        overplot1 = .3          ; minimum dist to substrate metal
        overplot2 = .3          ; minimum dist to metal 1
        name = via0             ; name in ASITIC
        color = purple          ; color in ASITIC
```

✓ Segmento di Techfile

Square Spiral (1)

```
tcsh> asitic -t sample1.tek

ASITIC>  sq name=a:len=175:w=10:s=.5:n=5:xorg=200:yorg=200:metal=m3:exit=m2
```



Square Spiral (2)

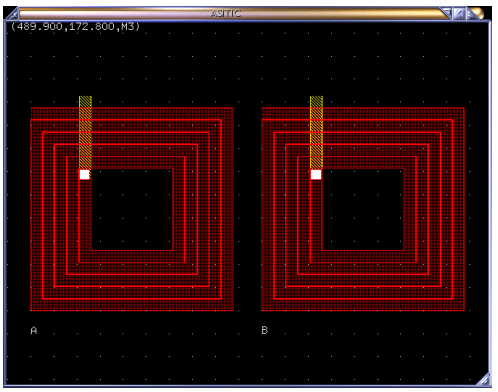
```
ASITIC>  ind a

Inductance of A = 4.13121 (nH)

ASITIC>  res a

Resistance of A = 4.246441 (Ohms)


ASITIC>  pix a 2

lambda = 37500.00, delta =  1.95

maxL = 1875.00, maxT =  1.56, maxW =  1.56
Performing Analysis at 2.00 GHz
Generating capacitance matrix (105x105)...
Generating inductance matrix (126x126)..
Inverting matrix......
Ind Timing:  tot =  1045, setup =    08, fill =   762
           invert =   266, reduce =    05, eddy =    00
Calc Times (ms):  total =  1378, cap =   309, ind =  1063, node =    05
Pi Model at f=2.00 GHz:  Q = 7.02, 7.16, 8.20
L  =  4.06 nH   R  =  5.29
Cs1=   104 fF   Rs1=   638
Cs2=    97 fF   Rs2=   710      f_res =  7.74GHz
```

Square Spiral (3)

```
ASITIC>  sq name=halo:len=200:wid=200:w=20:n=1:xorg=180:yorg=180:s=10:metal=msub
ASITIC>  mv halo 5 5
ASITIC>  pix a 2 halo

lambda = 37500.00, delta =  1.95

maxL = 1875.00, maxT =  1.56, maxW =  1.56
Performing Analysis at 2.00 GHz
Generating capacitance matrix (141x141)...
Generating inductance matrix (126x126)..
Inverting matrix......
Pi Model at f=2.00 GHz:  Q = 7.85, 7.81, 8.20
L   =  3.98 nH   R  =  5.83
Cs1=   117 fF   Rs1=  13.2
Cs2=   108 fF   Rs2=  29.5      f_res =  7.39GHz
```

Coupling (1)

```
ASITIC>  del halo
ASITIC>  cp a b
ASITIC>  mv a -100 0
ASITIC>  mv b 100 0
ASITIC>  friend a b
ASITIC>  mv a -25 0
```



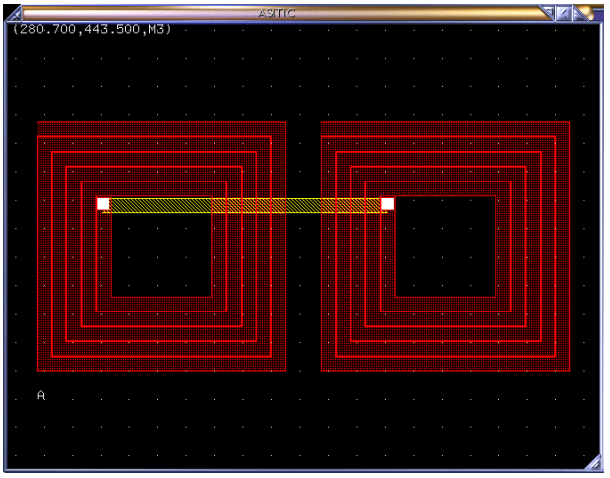
Coupling (2)

```
ASITIC>  k a b

Coupling coefficient of A and B: k =   -0.02748 and M =   -0.11355
(nH).

ASITIC>  k2 2 a b

lambda = 37500.00, delta =  1.95

maxL = 1875.00, maxT =  1.56, maxW =  1.56
Generating inductance matrix (252x252)..
Inverting matrix......
Ind Timing:  tot =  4673, setup =    20, fill =  2117
           invert =  2526, reduce =    33, eddy =    00
L(A,A) =    4.03648 nH  R(A,A) = 6.120
L(A,B) =   -0.11181 nH  R(A,B) = -0.074
L(B,B) =    4.03624 nH  R(B,B) = 6.127
```

Coupling (3)

$$Z = j\omega(L_1 + L_2 + 2M)$$

```
ASITIC>  showdir

ASITIC>  flip b

ASITIC>  phase b  -1

ASITIC>  join a c b

ASITIC>  ind a

Inductance of A = 8.80189 (nH)
```

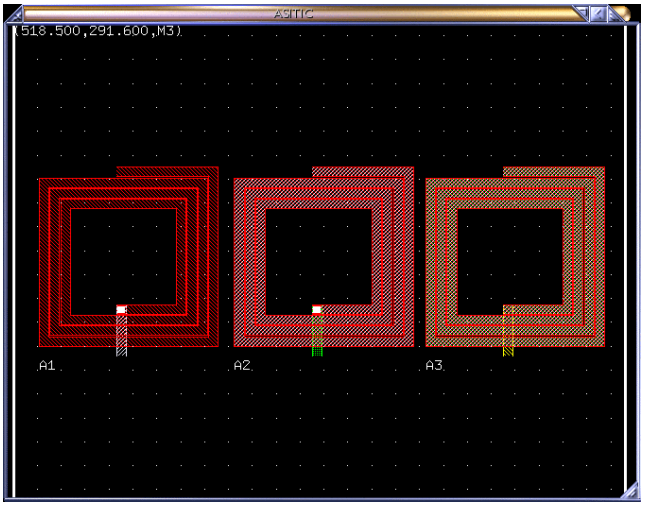


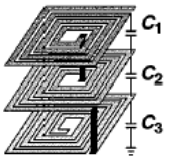
Coupling (4)

```
ASITIC>  pix a 2


lambda = 37500.00, delta =  1.95

maxL = 1875.00, maxT =  1.56, maxW =  1.56
Performing Analysis at 2.00 GHz
Generating capacitance matrix (205x205)...
Generating inductance matrix (246x246)..
Inverting matrix......
Ind Timing:  tot =  3964, setup =    02, fill =  1994
           invert =  1963, reduce =    04, eddy =    00
Calc Times (ms):  total =  6084, cap =  2099, ind =  3983, node =    02
Pi Model at f=2.00 GHz:  Q = 4.90, 4.77, 7.36
L  =  8.64 nH   R  =  7.67
Cs1=   187 fF   Rs1=   648
Cs2=   193 fF   Rs2=   624      f_res =  3.96GHz
```

Multi-Layers Spiral (1)

```
ASITIC>  sqsh name=a3:len=150:w=8:s=1:n=3.75:metal=m3:exit=m1:xorg=200:yorg=200:cbegin:cend:exit90
```



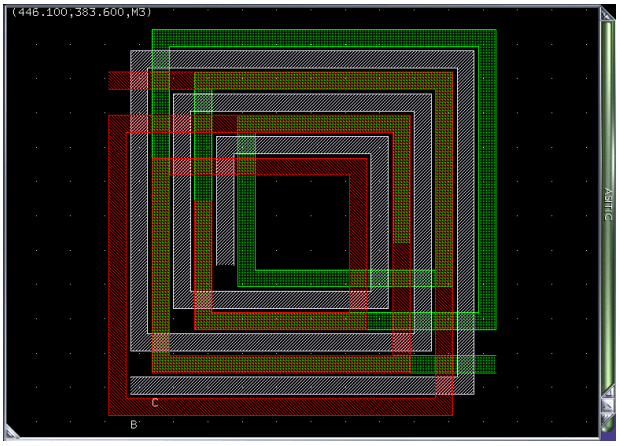


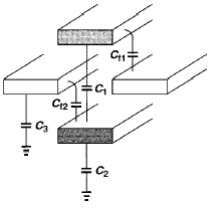
Multi-Layers Spiral (2)

```
ASITIC>  pix a3 3

lambda = 25000.00, delta =  1.84
maxL = 1250.00, maxT =  1.47, maxW =  1.47
Performing Analysis at 3.00 GHz
Generating capacitance matrix (184x184)...
Generating inductance matrix (230x230)..
Inverting matrix......
Ind Timing:  tot =  3006, setup =    32, fill =  2444
           invert =   495, reduce =    32, eddy =    00
Calc Times (ms):  total =  5508, cap =  2502, ind =  3000, node =    05

Pi Model at f=3.00 GHz:  Q = 7.33, 7.34, 8.59
L   =  2.21 nH   R  =  4.04
Cs1=  89.2 fF   Rs1=   665
Cs2=  89.7 fF   Rs2=   683      f res = 11.34GHz
```

Multi-Layers Spiral (3)

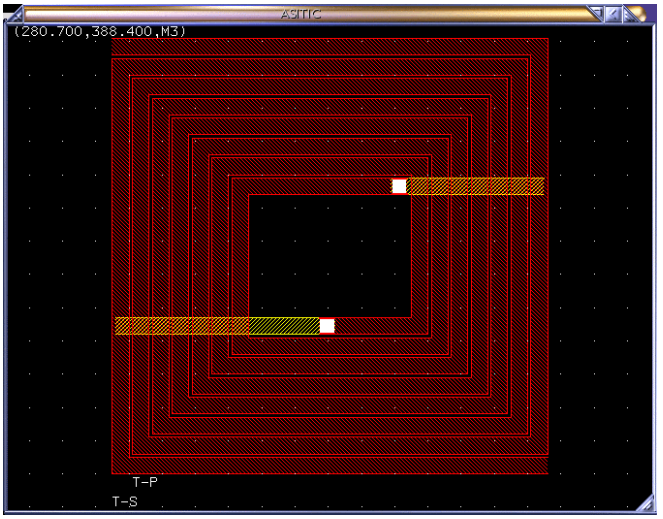
```
ASITIC>  del a1 a2 a3
ASITIC>  sq name=s1:len=200:w=10:s=1:n=4:metal=m3:exit=m2:xorg=200:yorg=200:exit90
ASITIC>  sqmm name=s2:len=200:w=10:s=1:n=4:metal=m3:exit=m2:xorg=200:yorg=200:exit90
```





Square Planar Transformer (1)

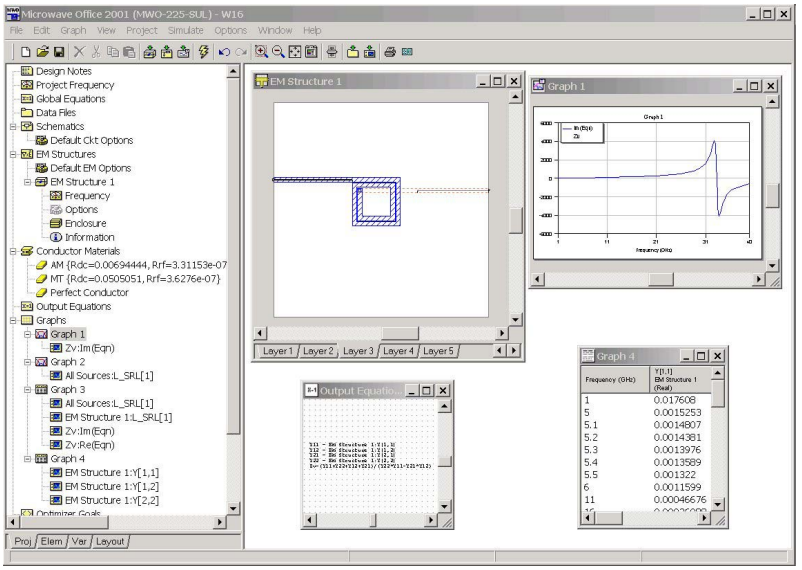
```
ASITIC>  trans name=t:len=250:w=10:s=2:n=3.75
ASITIC>  mv t-p 120 120
```



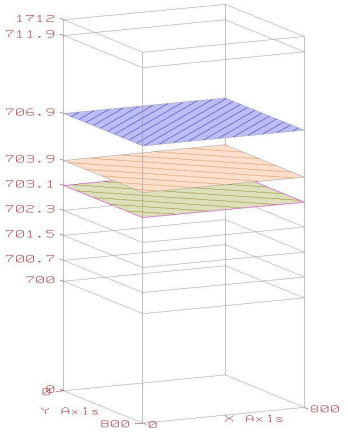
Square Transformer (2)

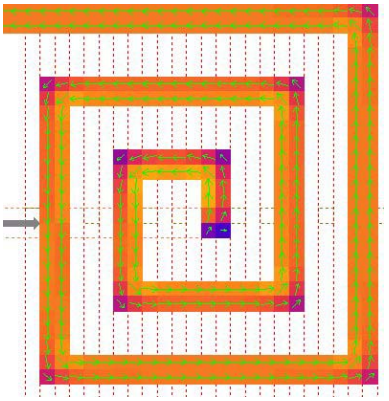
```
ASITIC>  k2 1.2 t-s t-p

lambda = 62500.00, delta =  2.52
maxL = 3125.00, maxT =  2.01, maxW =  2.01
Generating inductance matrix (160x160)..
Inverting matrix......
L(T-S,T-S) =    3.34111 nH      R(T-S,T-S) = 5.135
L(T-S,T-P) =    2.66867 nH      R(T-S,T-P) = 0.300
L(T-P,T-P) =    3.34187 nH      R(T-P,T-P) = 5.404

ASITIC>  calctrans t-s t-p 2

lambda = 37500.00, delta =  1.95
maxL = 1875.00, maxT =  1.56, maxW =  1.56
Performing Analysis at 2.00 GHz
Generating capacitance matrix (160x160)...
Generating inductance matrix (192x192)..
Inverting matrix......
Narrowband Model at f=2.00 GHz:
L1=   3.4  R1=  5.16  L2=   3.4 R2=  5.44 M=  2.73 (k= 0.805) Re(Z12) =  0.818
```

MicroWave Office: Finestra Principale

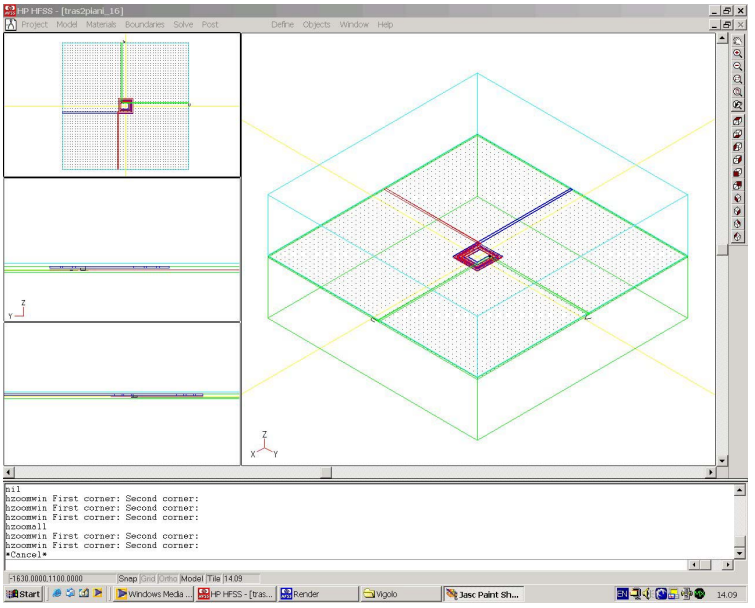


MicroWave Office: Grafica

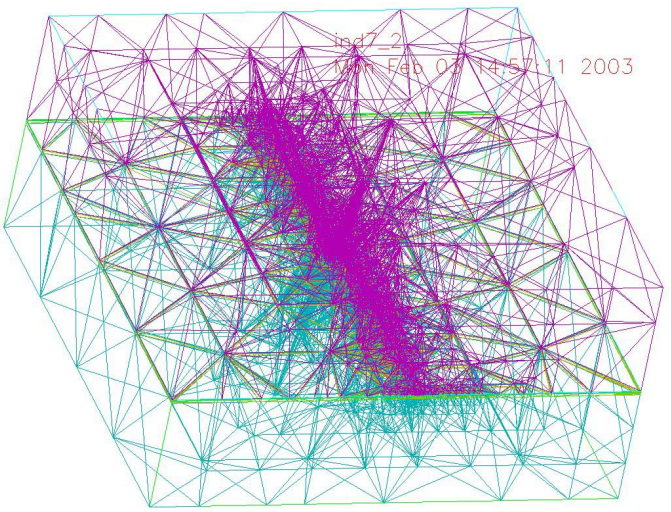




HP HFSS: Finestra Principale



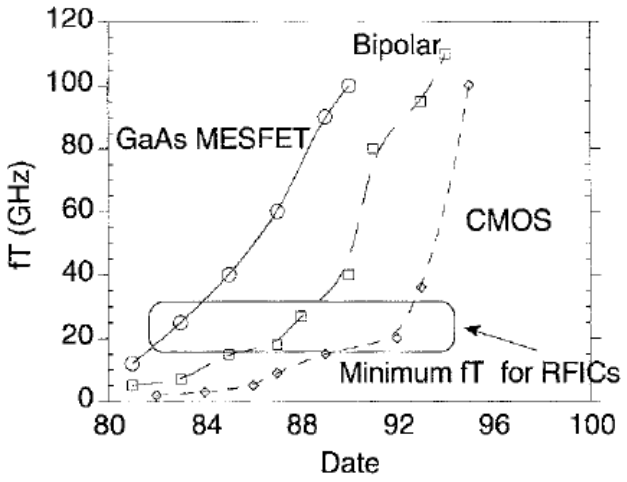
HP HFSS: Meshing



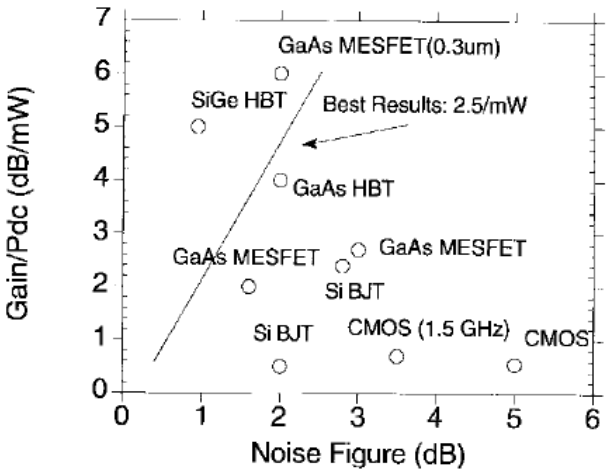
Sommario

- ✓ Introduzione alla Progettazione RF
- Progettazione di Front-end RF
  - ✓ Simulazioni Elettromagnetiche
  - ❑ Tecnologie e CAD Tools
  - ❑ Low Noise Amplifier (LNA)
  - ❑ Mixer
- Front-End Multi-Standard per WLAN 5-6 GHz
- Riepilogo e Conclusioni

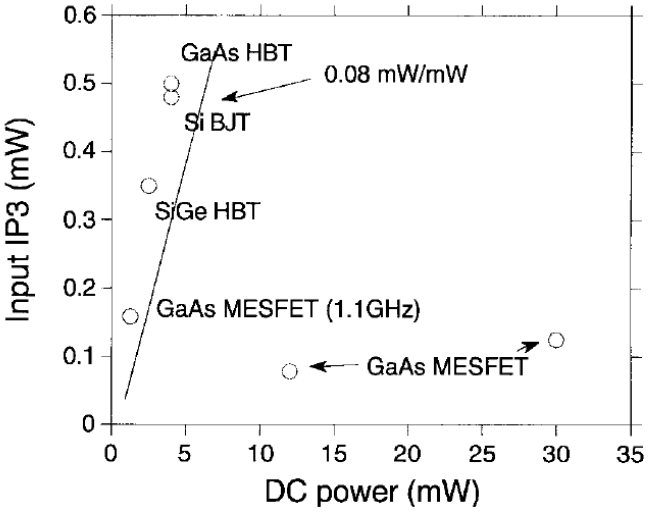
Tecnologie: Cut-Off Frequency (f_T)



Tecnologie: Gain-Noise



Tecnologie: IP3-Power



CAD Tools: Analisi Tradizionali

- DC
- AC (Lineare)
- Transitoria (Non Lineare)
- Sweep (Parametrica)
- Temperatura
- MonteCarlo
- Corner Analisys (Worst/Typical/Best Case)
- Sensitivity

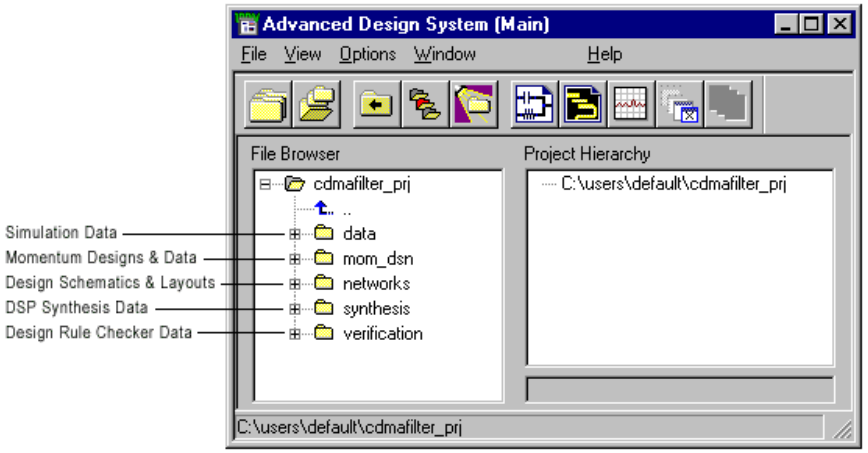
CAD Tools: Special Purpose

- Analisi Tradizionali
- S-Pameters (Lineare)
- Periodic Steady State (Non Lineare)
  - ❑ Harmonic Balance (ADS)
  - ❑ Shooting (SpectreRF)
- Ottimizzazione
- Piattaforme Software: Design Entry to Layout

Principali Tool

- ADS (Advanced Design Systems) - Agilent Technologies
  - Finestra principale
  - Analisi
  - Grafica
- Cadence Design Framework – Cadence
  - Finestra Principale
  - Grafica
  - Simulatore Analog Artist (SprectreRF)
  - Analisi

ADS: Finestra Principale



ADS: Analisi

NOMINAL OPTIMIZATION

Optim
Optim1
OptimType=Genetic
ErrorForm=L2
MaxIters=
P=2
DesiredError=0.0
StatusLevel=4
SetBestValues=yes
Seed=
SaveSolns=no
SaveOptimVars=no
SaveGoals=no
GoalName[1]="OptimGoal1"
GoalName[2]="OptimGoal2"
GoalName[3]=

GOAL

Goal
OptimGoal1
Expr="dB(S(1,1))"
SimInstanceName="SP1"
Min=-100
Max=-20
Weight=
RangeVar[1]=
RangeMin[1]=
RangeMax[1]=

GOAL

Goal
OptimGoal2
Expr="dB(S(2,1))"
SimInstanceName="SP1"
Min=25
Max=25.5
Weight=
RangeVar[1]=
RangeMin[1]=
RangeMax[1]=

HARMONIC BALANCE

HarmonicBalance
HB1
Freq[1]=50 MHz
Order[1]=3

TRANSIENT

Tran
Tran1
StopTime=5000 nsec
MaxTimeStep=100 nsec

S PARAMETERS

S_Param
SP1
Start=1.0 MHz
Stop=210 MHz
Step=1.0 MHz

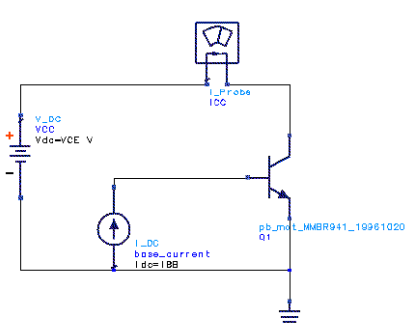
AC

AC
AC1
Start=1.0 MHz
Stop=210 MHz
Step=1 MHz

DC

DC
DC1

ADS: Grafica



SIMULATIONS

DC

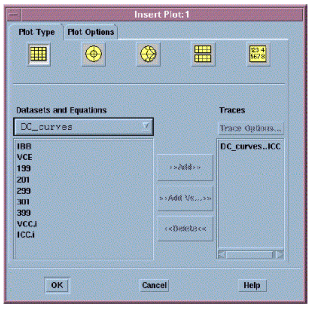
DC
DC1
SweepVar="VCE"
Start=0 V
Stop=8 V
Step=0.1V

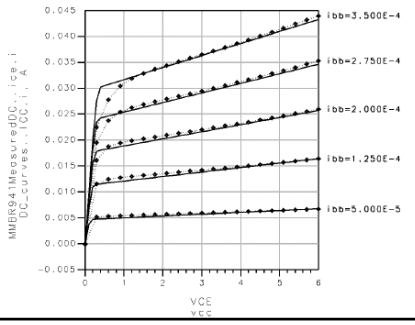
PARAMETER SWEEP

ParamSweep
Sweep1
SweepVar="IBB"
SimInstanceName[1]="DC1"
SimInstanceName[2]=
SimInstanceName[3]=
SimInstanceName[4]=
SimInstanceName[5]=
SimInstanceName[6]=
Start=50 uA
Stop=350 uA
Step=75 uA

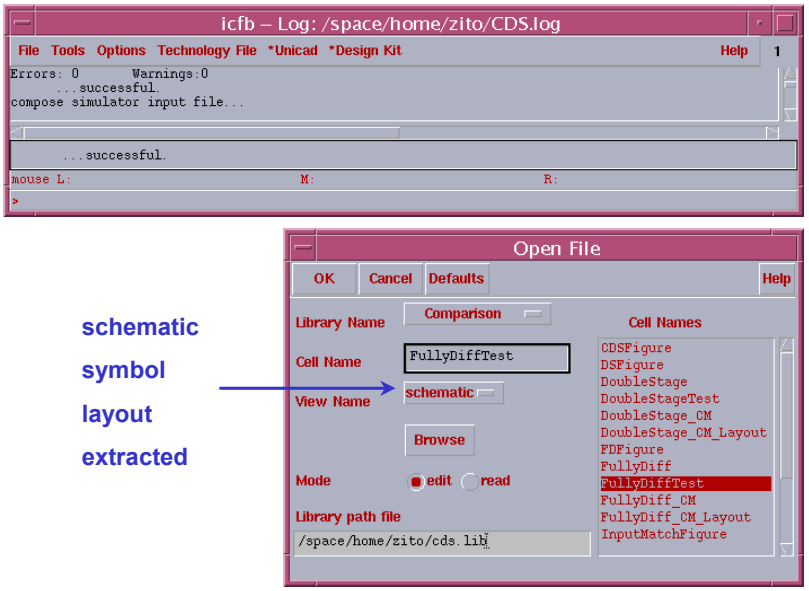
VARIABLES

Var Eqn
VAR
VAR1
VCE=0V
IBB=0A

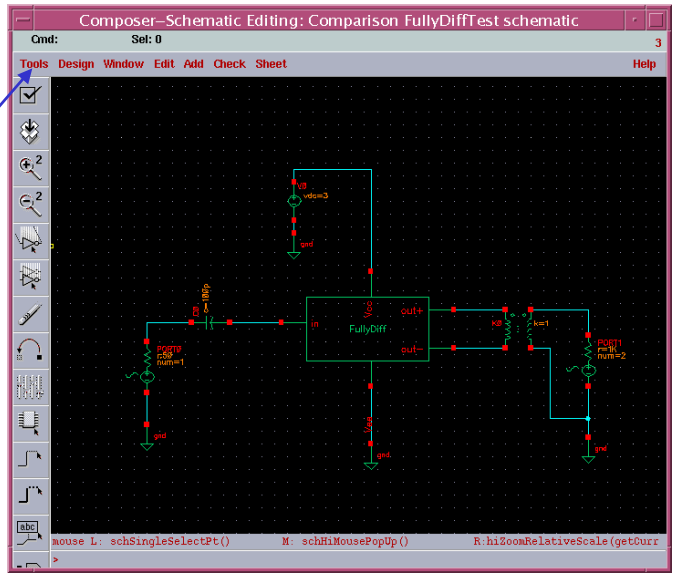




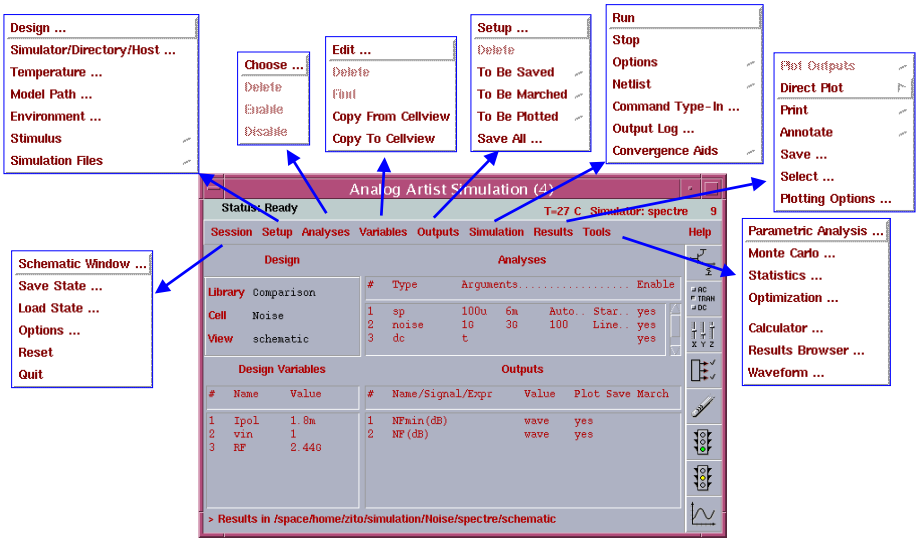
Cadence: Finestra Principale



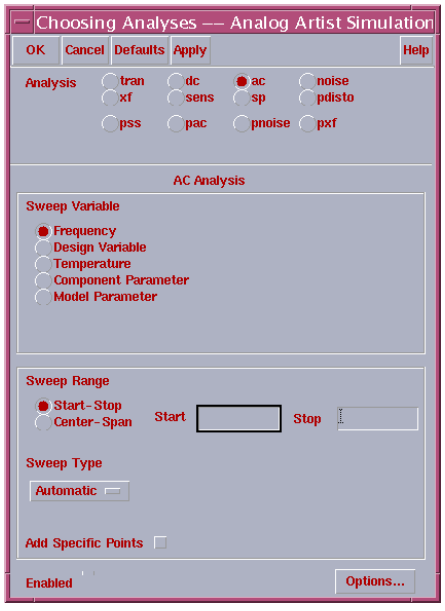
Cadence: Grafica



Simulatore: Analog Artist (Spectre RF)



Cadence: Analisi



Sommario

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  - ❑ Mixer
- Front-End Multi-Standard per WLAN 5-6 GHz
- Riepilogo e Conclusioni

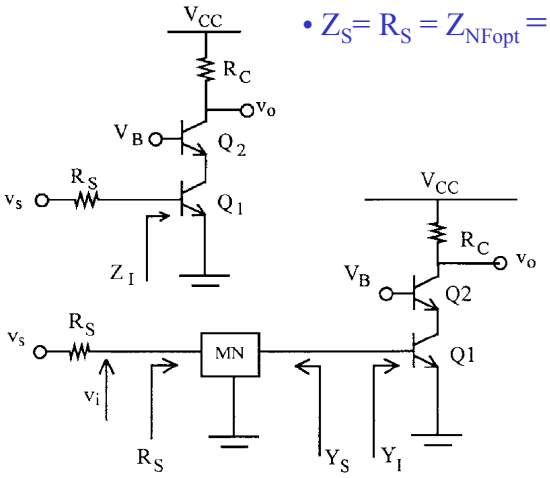
Low Noise Amplifier (LNA)

- Input Matching
- Noise Figure (NF)
- Scelta della Configurazione
- Guadagno
- Linearità
  - ❑ Punto di Compressione (CP1dB)
  - ❑ Intercetta del 3° Ordine (IP3)
- Stabilità
- Topologia Base Coupled Differential (BCD)
- LNA Selettivo Integrato: Boot-Strapped Inductor

- Parametri Tipici

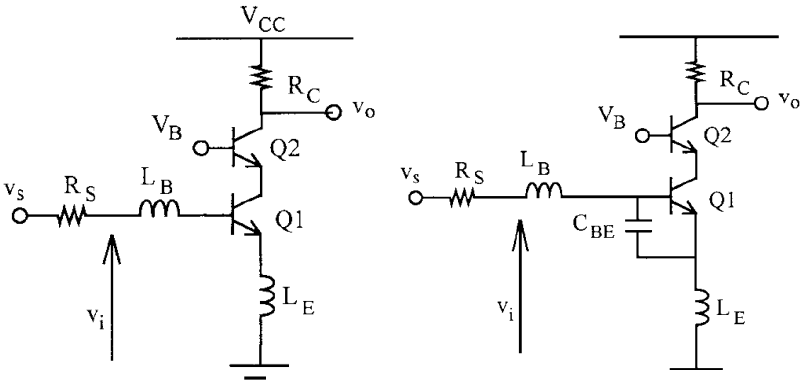
NF	2 dB
IIP_3	−10 dBm
Gain	15 dB
Input and Output Impedance	50 Ω
Input and Output Return Loss	−15 dB
Reverse Isolation	20 dB
Stability Factor	> 1

Input Matching



- $Z_S = R_S = Z_{NFopt} = Z_I$

Input Matching e Noise Figure



$$Z_{in} = r_b + \frac{g_m L_e}{C_\pi} + L_e s + \frac{1}{C_\pi s}$$

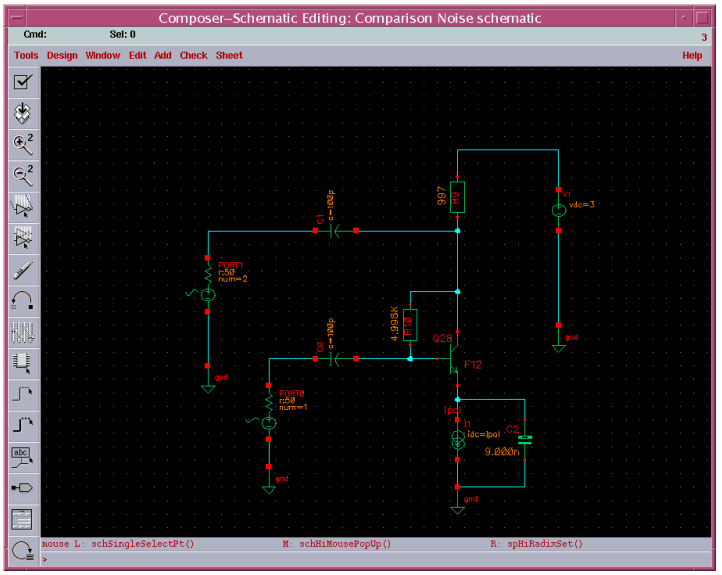
Input Matching e NF: Flusso di Progetto

- Test NF Minima

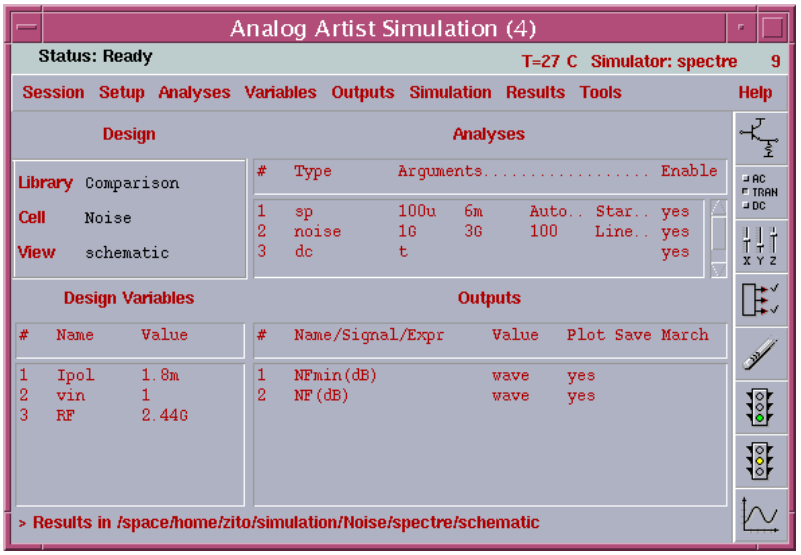
- Scelta del Numero di Transistori (R_{ON}, Area, PD_{MAX})

- Calcolo della Induttanza di Degenerazione

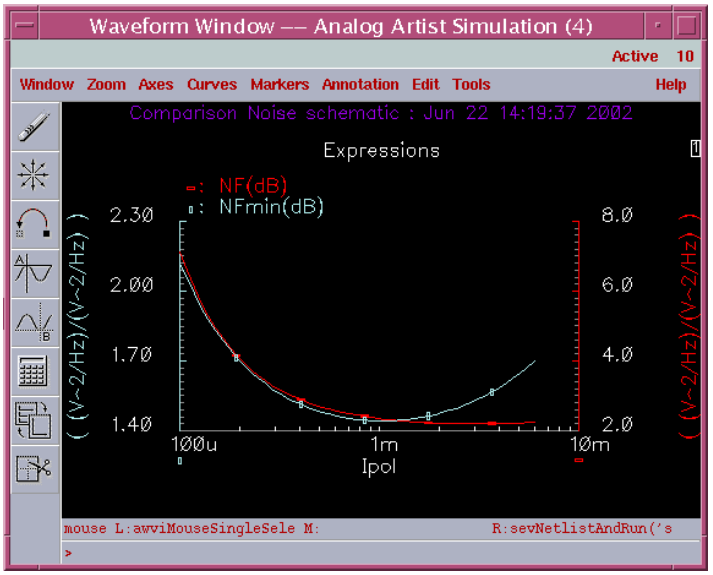
Input Matching e NF: NF_{Min} (1)



Input Matching e NF: NF_{Min} (2)



Input Matching e NF: NF_{Min} (3)

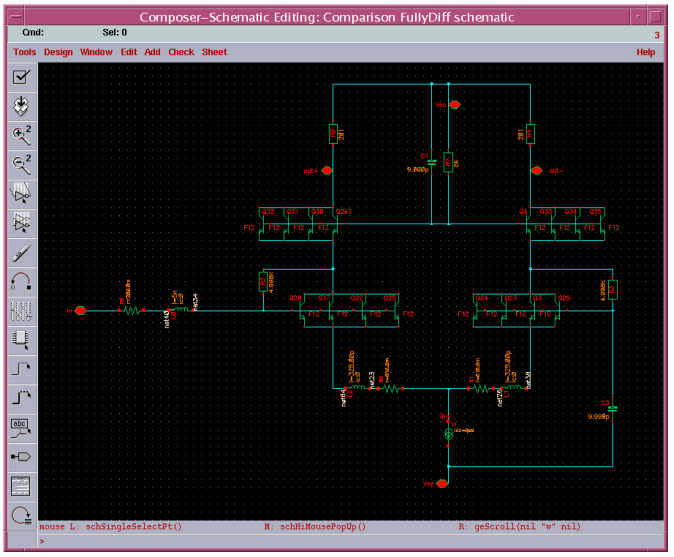


Scelta della Configurazione

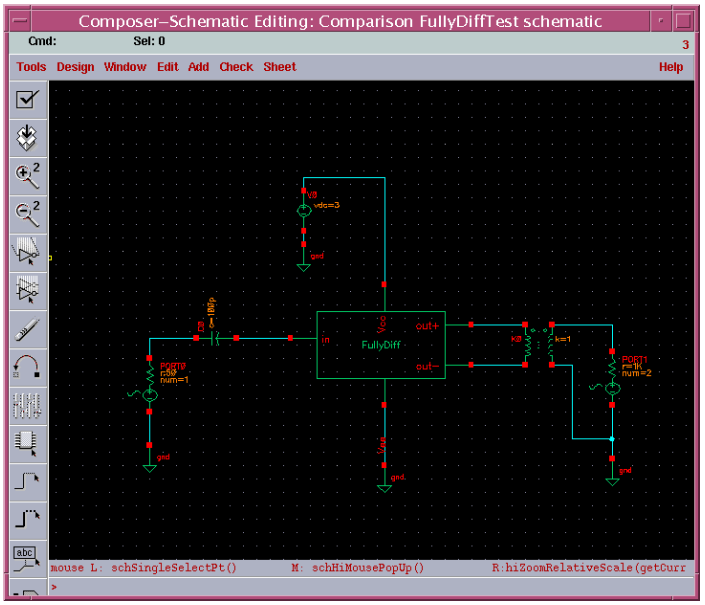
- Noise Figure
- Guadagno
- Limite Superiore di Banda
- Differenziale
  - ✓ Linearità, Immunità ai Disturbi
  - ❑ Consumo di Potenza
- Input Matching

✓ Cascode: Best Trade-Off

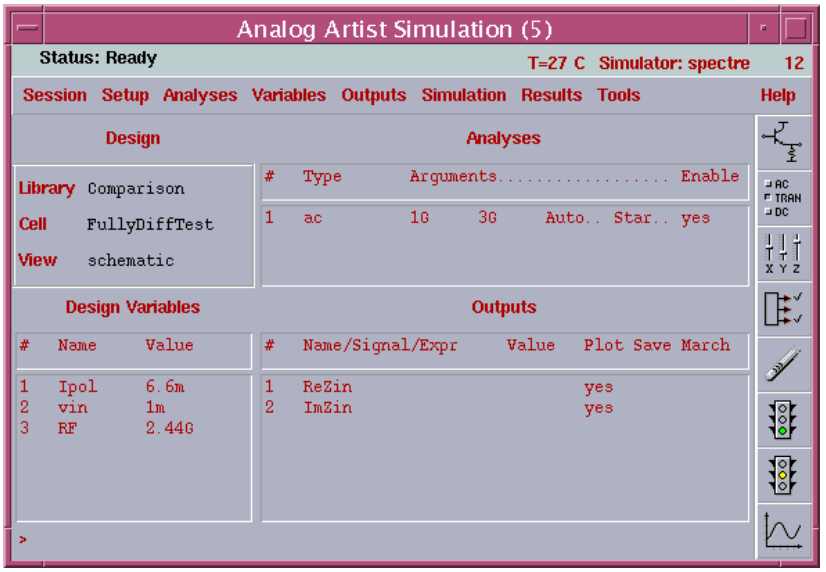
Scelta della Configurazione: Cascode Differenziale



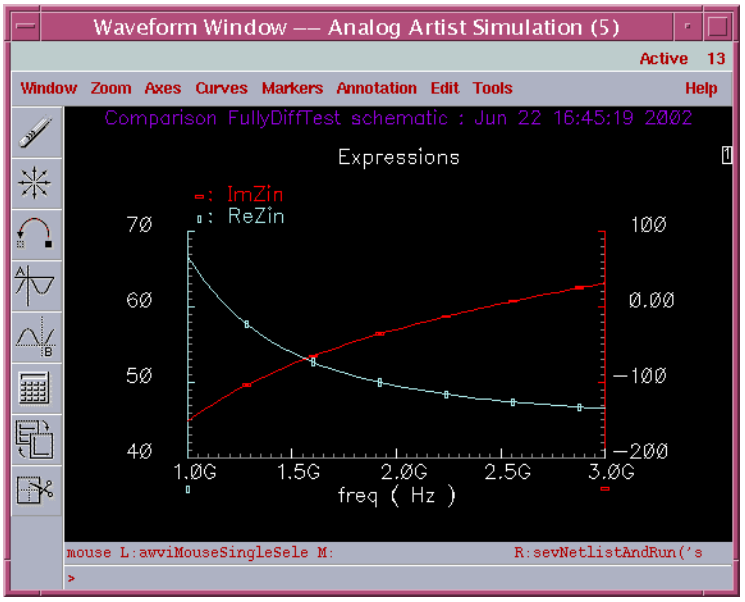
Schema di Simulazione



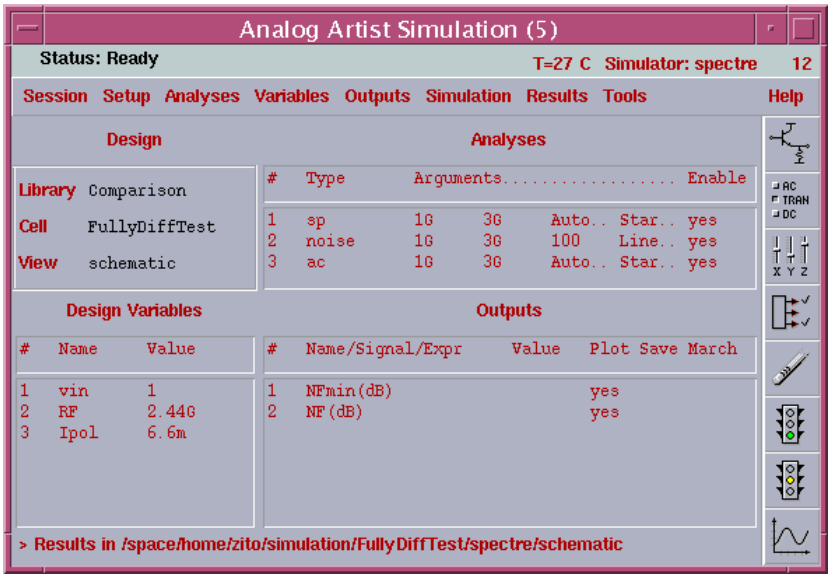
Input Matching: Z_{in} (1)



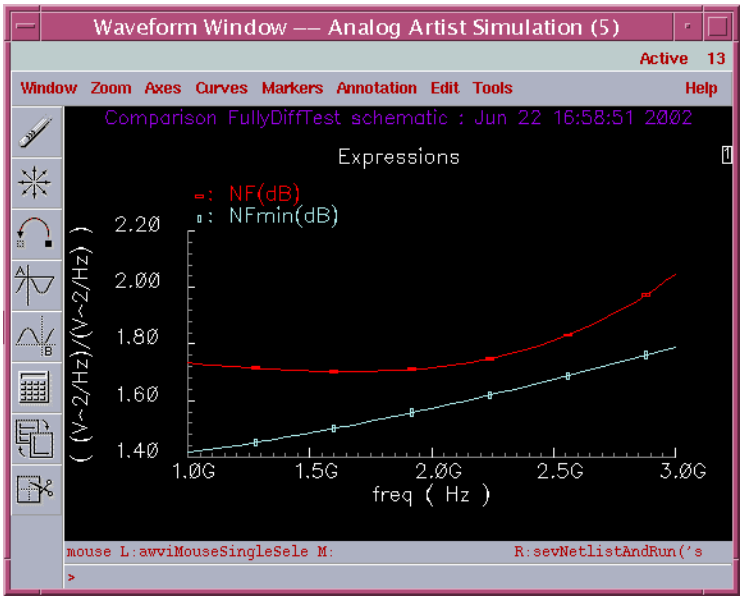
Input Matching: Z_{in} (2)



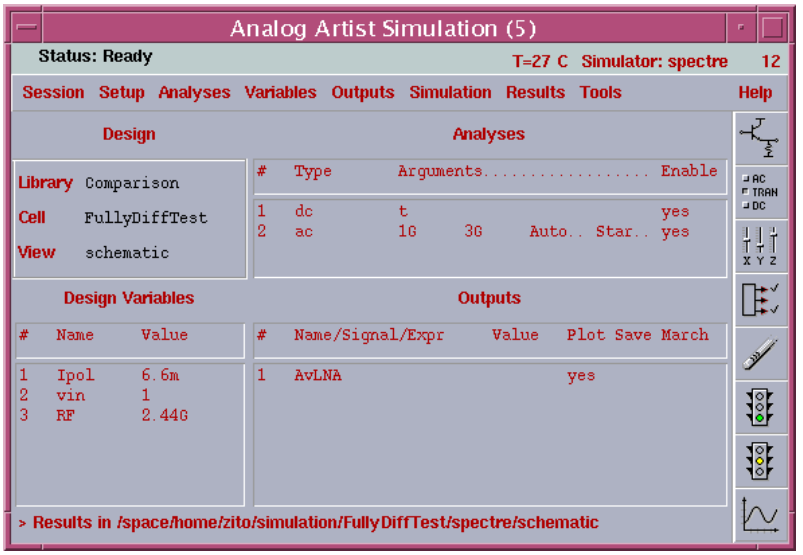
Input Matching: NF (1)



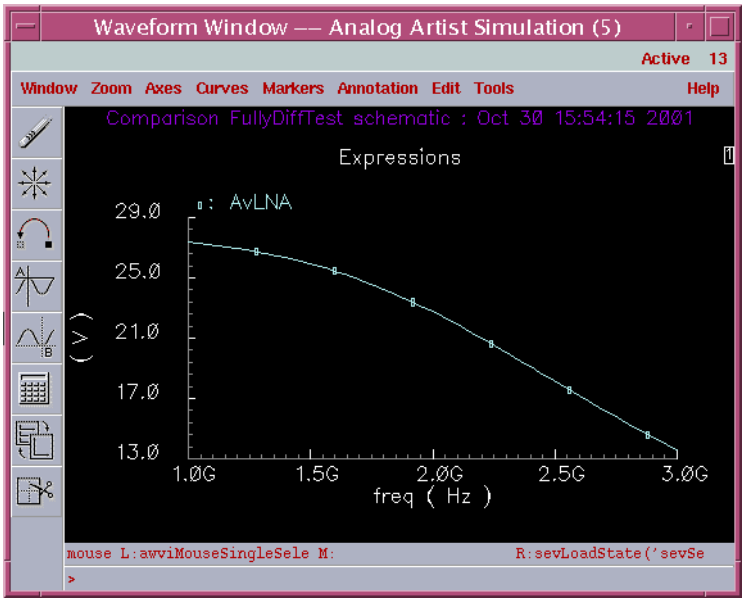
Input Matching: NF (2)



Guadagno: A_V (1)

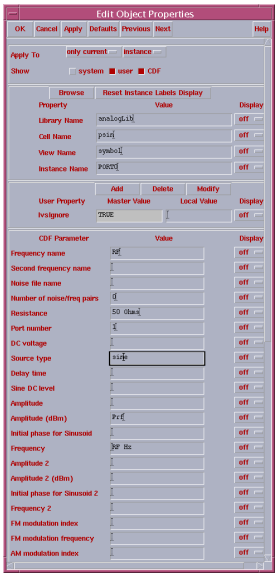


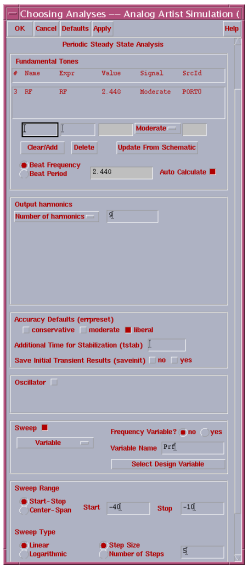
Guadagno: A_V (2)



Linearità: CP_{1dB} (1)

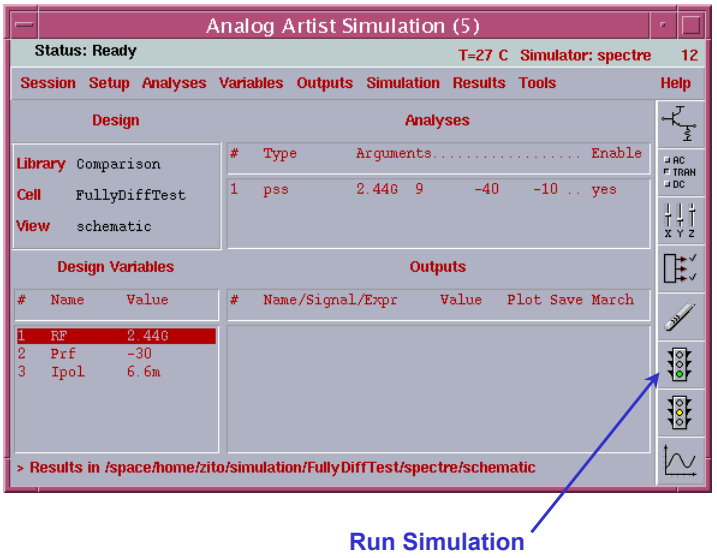
✓ Input Port



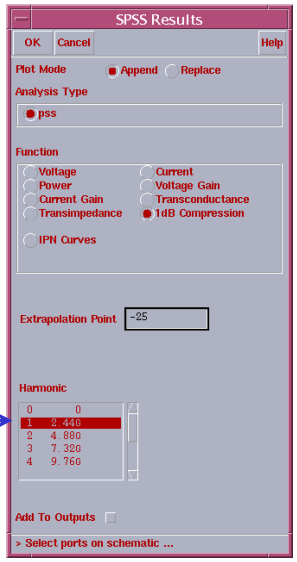


✓ PSS Analisys

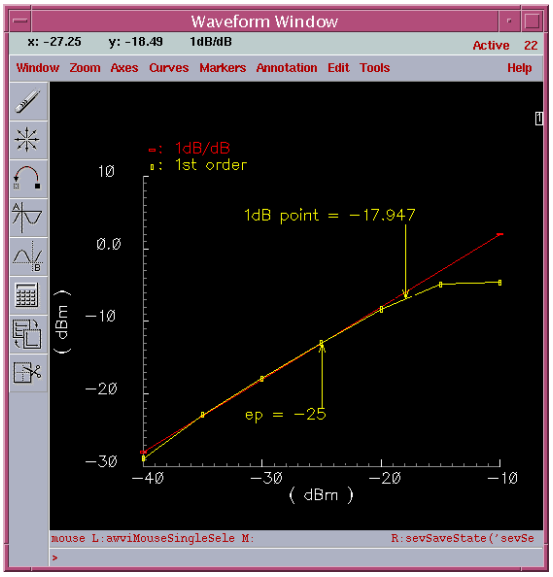
Linearità: CP_{1dB} (2)



Linearità: CP_{1dB} (3)

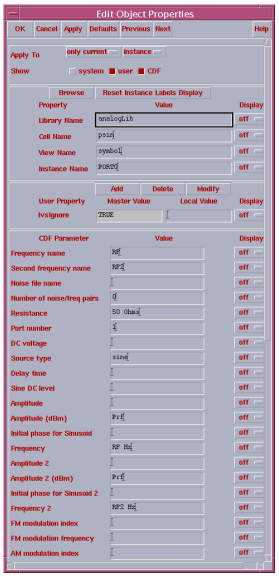


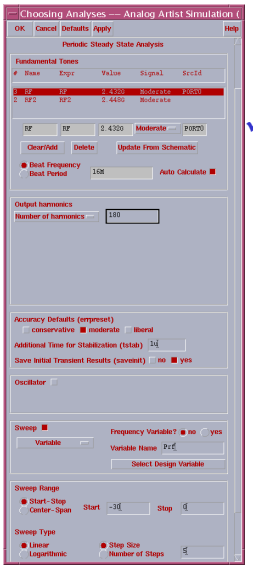
Linearità: CP_{1dB} (4)



Linearità: IP_3 (1)

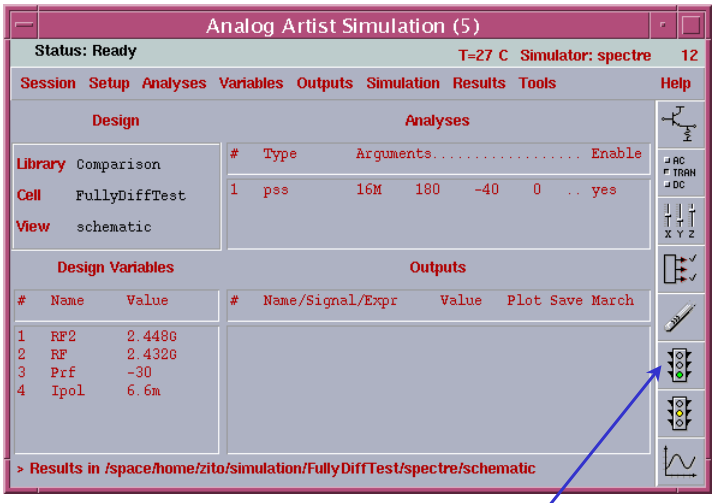
✓ Input Port



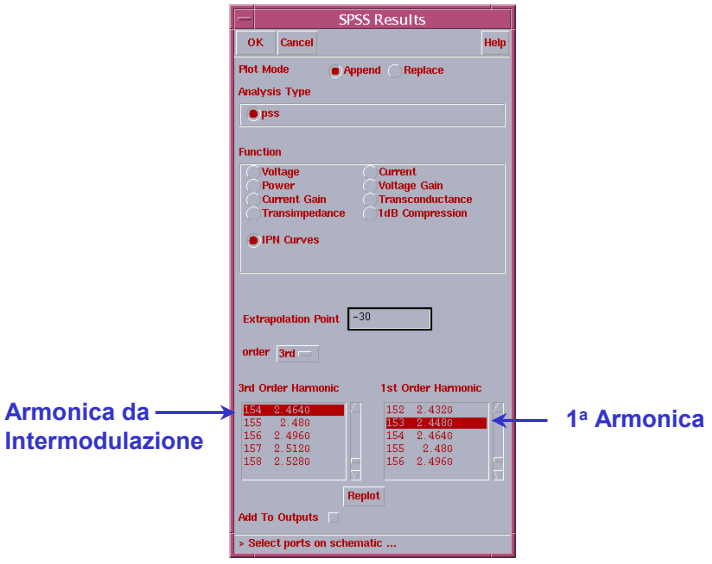


✓ PSS Analisys

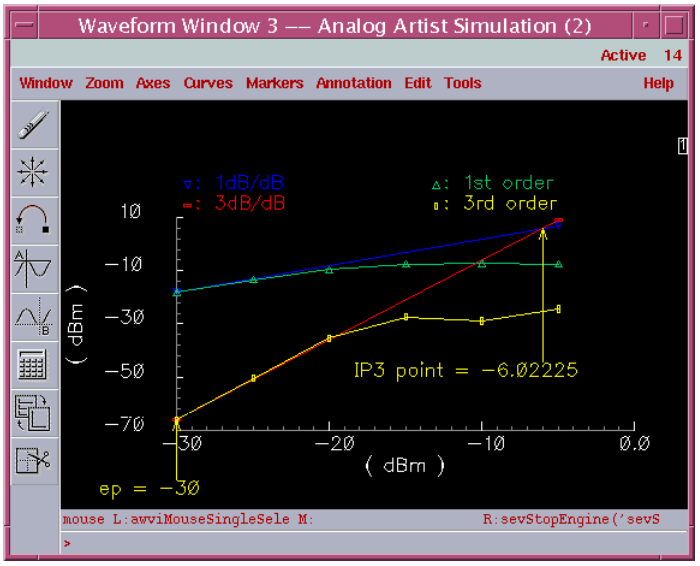
Linearità: IP_3 (2)



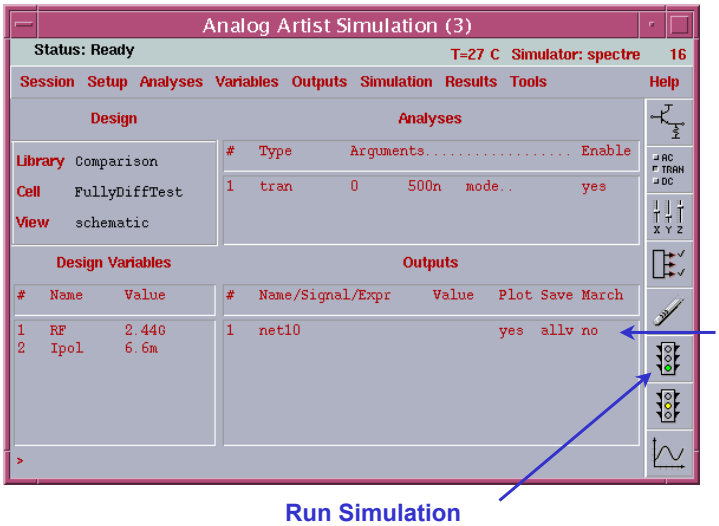
Linearità: IP_3 (3)



Linearità: IP_3 (4)



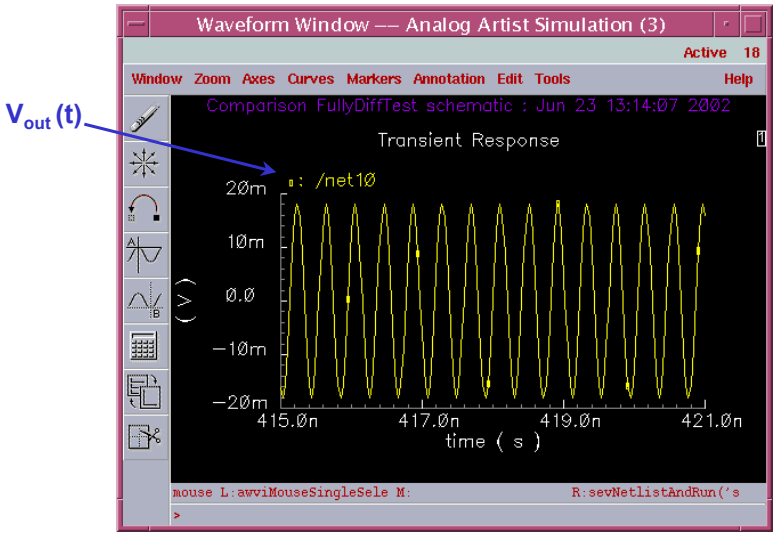
Stabilità: Analisi Transitoria (1)



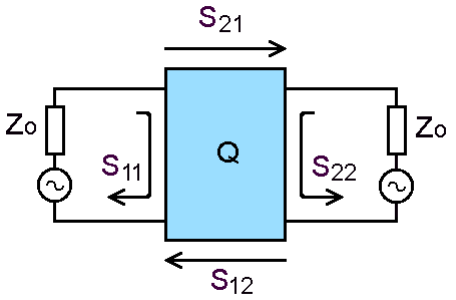
$V_{out}(t)$

Run Simulation

Stabilità: Analisi Transitoria (2)



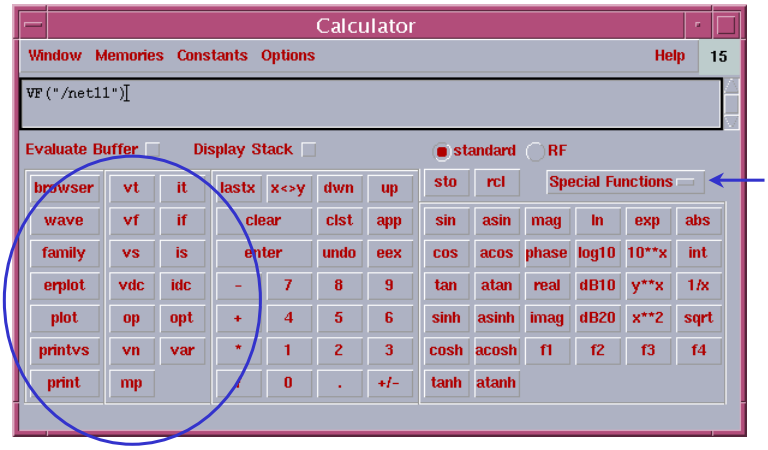
Stabilità: Incondizionata



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

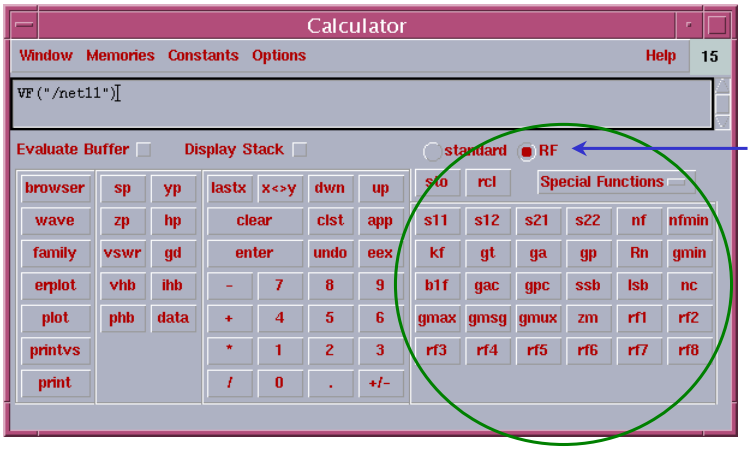
$$K \succ 1,\ |\Delta| \prec 1 \Rightarrow \text{Incondizionatamente Stabile}$$

Analog Artist: Calculator (1)



Bandwidth
DFT
Overshoot
Gain Margin
Xmax
Ymax
…
…

Analog Artist: Calculator (2)



RF

Riepilogo

- ✓ Introduzione alla Progettazione RF
- Progettazione di Front-end RF
  - ✓ Simulazioni Elettromagnetiche
  - ✓ Tecnologie e CAD Tools
  - ❑ Low Noise Amplifier (LNA)
    - ❑ Topologia BCD
    - ❑ LNA Selettivo Integrato
  - ❑ Mixer
- Front-End Multi-Standard per WLAN 5-6 GHz
- Riepilogo e Conclusioni