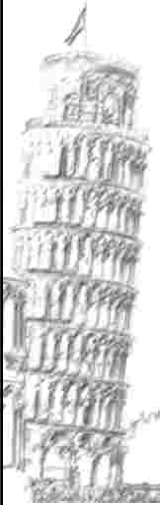


Progettazione a RadioFrequenza



D. Zito

Prof. B. Neri



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

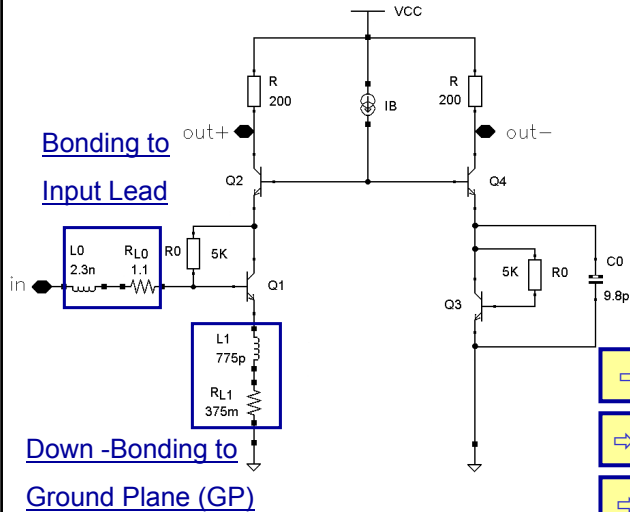
***“Seminario d'Introduzione alla
Progettazione a Radiofrequenza e Simulatori”***

D.Zito, 19-20 Maggio 2003, Pisa - Parte 2

Sommario

- ✓ 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

Base Coupled Differential (BCD) LNA Topology



Bonding to

Input Lead

Down -Bonding to

Ground Plane (GP)

$$1) i_{b2} = -i_{b4}$$

$$2) h_{fe2} = h_{fe4}$$

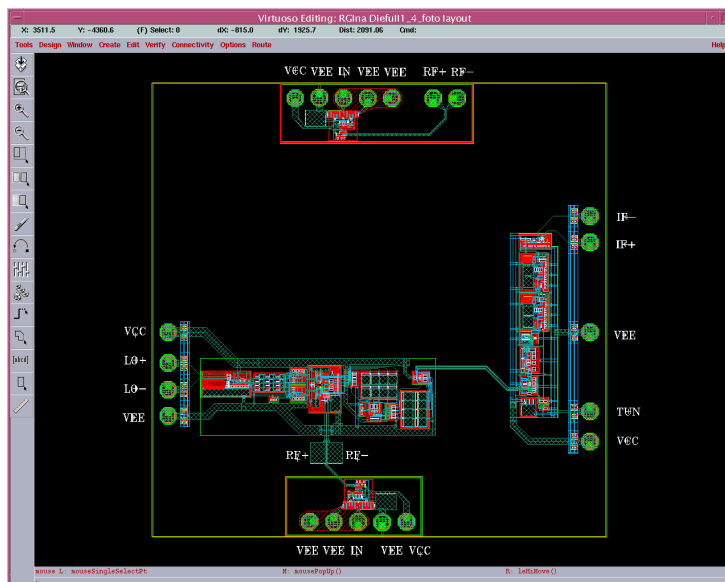
$$\Rightarrow i_{c2} = -i_{c4}$$

\Rightarrow *Uscite Simmetriche*

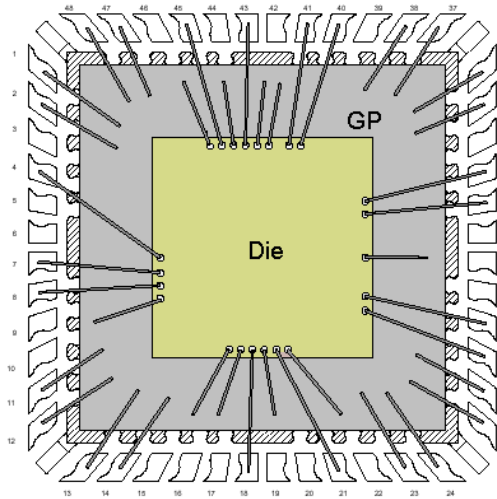
\Rightarrow *Single to Differential*

\Rightarrow *No Induttori Integrati*

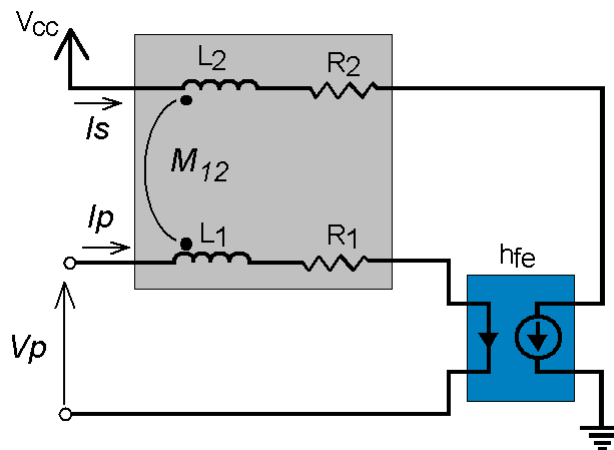
Front-End per Bluetooth (2.4 GHz): Layout



Front-End per Bluetooth: Bonding Diagram

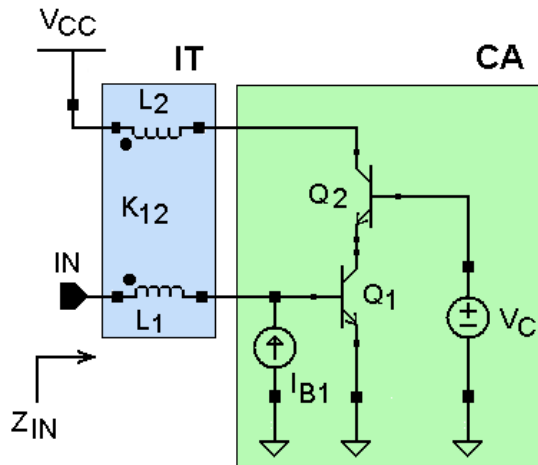


LNA Selettivo Integrato: Boot-Strapped Inductor (BSI)



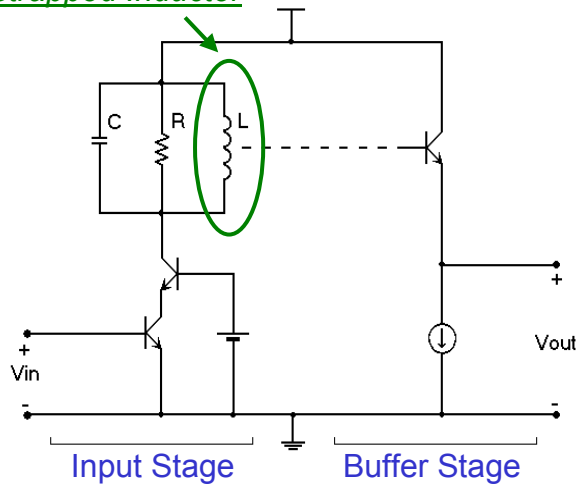
$$Z_p = R_1 + j\omega(L_1 + h_{fe}M_{12})$$

Boot-Strapped Inductor (BSI)

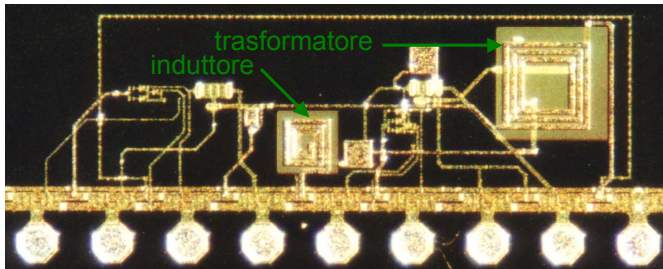


LNA Selettivo Integrato: Idea

Boot-Strapped Inductor

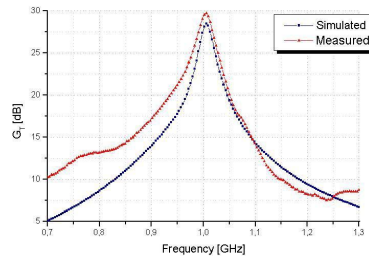
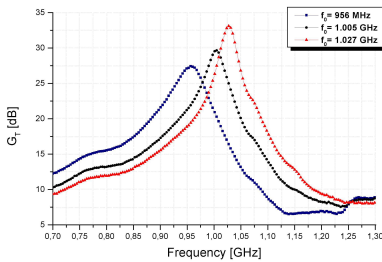


LNA Selettivo Integrato: Chip e Misure

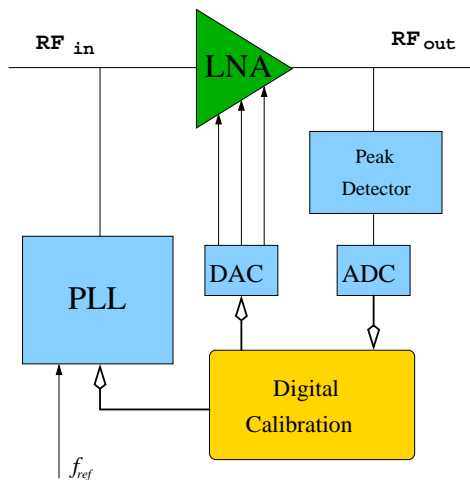


STM Si Bipolar
 $f_T = 25 \text{ GHz}$

Area = $1200 \times 700 \mu\text{m}^2$



Controllo Adattivo e LNA Selettivo per WLAN Multi-Standard (5-6 GHz)



In collaborazione con l'Univ. di Berkeley (California, USA)

- LNA Selettivo Tunable (5.15-5.825 GHz)
- Auto-Calibrazione Digitale

IBM SiGe-CMOS
 $0.25 \mu\text{m}$, $f_T = 47 \text{ GHz}$

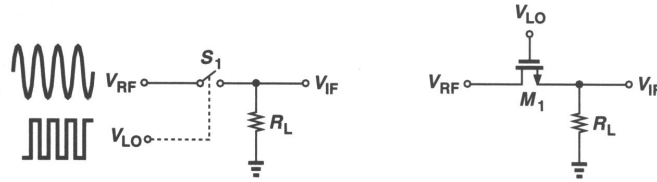
Sommario

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Mixer

- Principio di Funzionamento
- Cella di Gilbert
- Isolamenti
- Noise Figure
- Guadagno di Conversione
- Linearità
 - ☐ Punto di Compressione (CP1dB)
 - ☐ Intercetta del 3° Ordine (IP3)
- Mixer a Reiezione (del Segnale Immagine)

Principio di Funzionamento (1)

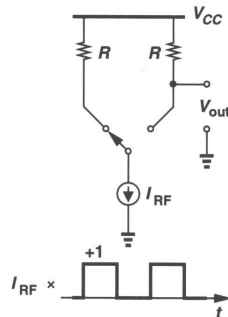


• Parametri Tipici

NF	12 dB
IIP_3	+5 dBm
Gain	10 dB
Input Impedance (Heterodyne)	50 Ω
Port-to-Port Isolation	10–20 dB

Principio di Funzionamento (2)

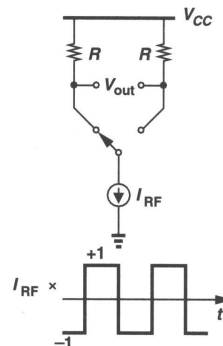
□ Single-Ended



$$V_{out}(t) = I_{RF}R[a + bS(t)]$$

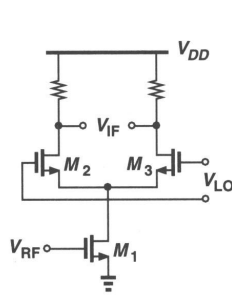
$$V_{out}(f) = aI_{RF}(f)R + bI_{RF}(f)R \sum_{n=-\infty}^{n=+\infty} \frac{\sin(n\pi/2)}{n\pi} \delta\left(f - \frac{n}{T}\right)$$

□ Differenziale

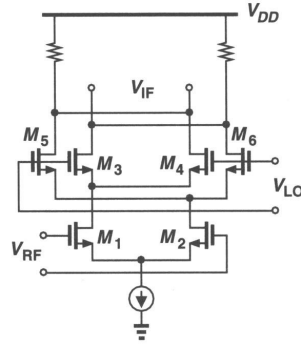


Cella di Gilbert (1)

- Struttura

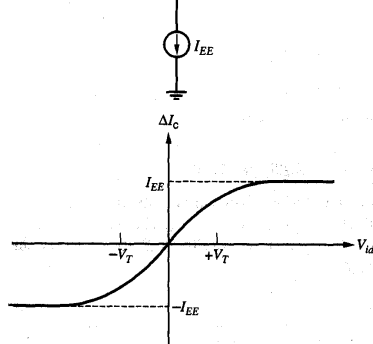
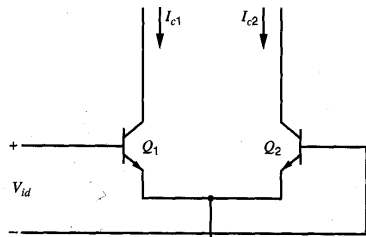


☐ Singolarmente Bilanciata



☐ Doppiaemente Bilanciata

Cella di Gilbert (2)



$$I_{c1} = \frac{I_{EE}}{1 + \exp\left(-\frac{V_{id}}{V_T}\right)}$$

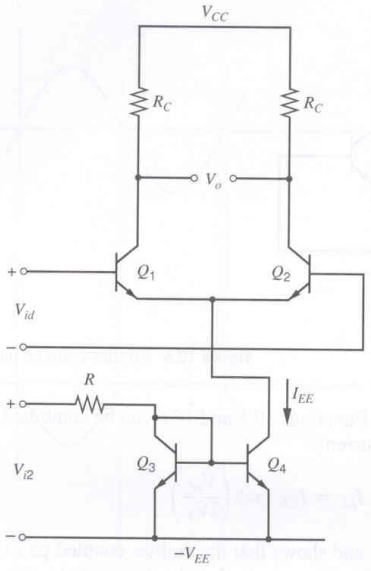
$$I_{c2} = \frac{I_{EE}}{1 + \exp\left(\frac{V_{id}}{V_T}\right)}$$

$$\Delta I_c = I_{c1} - I_{c2} = I_{EE} \tanh\left(\frac{V_{id}}{2V_T}\right)$$

$$\tanh\frac{V_{id}}{2V_T} \approx \frac{V_{id}}{2V_T} \quad \frac{V_{id}}{2V_T} \ll 1$$

$$\Delta I_c \approx I_{EE} \left(\frac{V_{id}}{2V_T}\right)$$

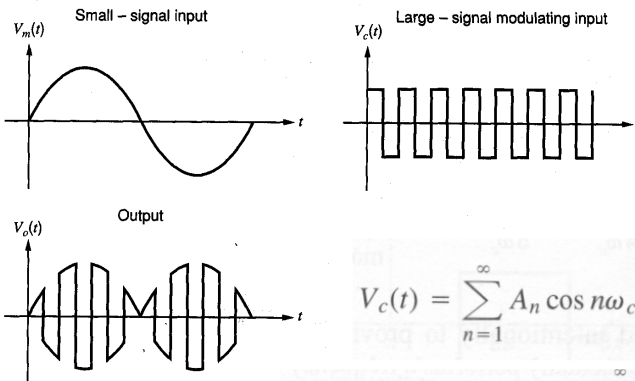
Cella di Gilbert (3)



$$I_{EE} \approx K_o(V_{i2} - V_{BE(\text{on})})$$

$$\Delta I_c = \frac{K_o V_{id}(V_{i2} - V_{BE(\text{on})})}{2V_T}$$

Cella di Gilbert (4)

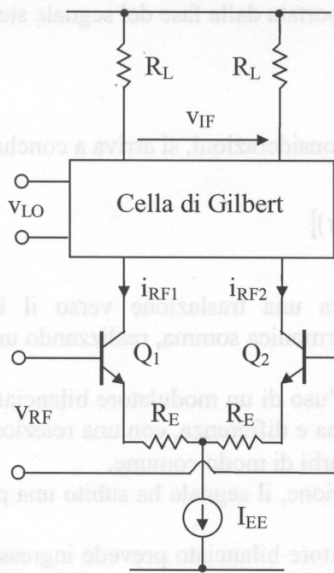


$$V_c(t) = \sum_{n=1}^{\infty} A_n \cos n\omega_c t, \quad A_n = \frac{\sin \frac{n\pi}{2}}{\frac{n\pi}{4}}$$

$$V_o(t) = K[V_c(t)V_m(t)] = K \sum_{n=1}^{\infty} A_n V_m \cos \omega_n t \cos n\omega_c t$$

$$= K \sum_{n=1}^{\infty} \frac{A_n V_m}{2} [\cos(n\omega_c + \omega_m)t + \cos(n\omega_c - \omega_m)t]$$

Cella di Gilbert (5)



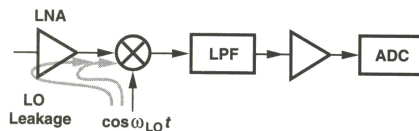
$$v_{IF} = \frac{2}{\pi} \cdot \frac{R_L}{R_E} \cdot A_{RF} \cdot \cos[\omega_{IF}t - \phi_M(t)]$$

$$v_{IF} = \frac{2}{\pi} \cdot \frac{g_{m1,2}}{1 + g_{m1,2}R_E} \cdot A_{RF} \cdot \cos[\omega_{IF}t - \phi_M(t)] \cdot R_L$$

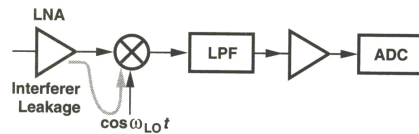
$$i_{RF} = i_{RF1} - i_{RF2} = \frac{g_{m1,2}}{1 + g_{m1,2}R_E} \cdot v_{RF}$$

$$V_{RF}(t) = A_{RF} \cos(\omega_{RF}t - \phi_M(t))$$

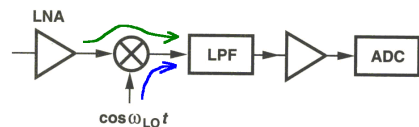
Isolamenti e Noise Figure



$$I_{OL-RF} = \frac{P_{OL-OL}}{P_{OL-RF}}$$



$$\bullet I_{RF-FI} = \frac{P_{RF-RF}}{P_{RF-FI}}$$



$$\bullet I_{OL-FI} = \frac{P_{OL-OL}}{P_{OL-FI}}$$

$$\text{Noise Figure} = \frac{[S/N]_{RF} \text{ dovuto al segnale a frequenza RF}}{[S/N]_{IF} \text{ totale a frequenza IF}}$$

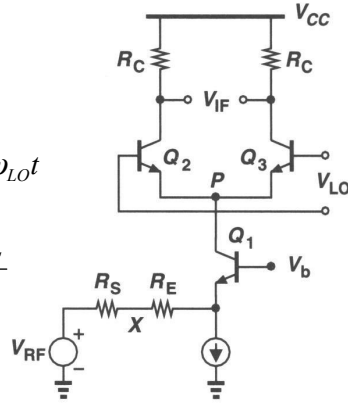
Guadagno di Conversione

$$G_C = \frac{[P_{IF}]_{IF}}{[P_{ARF}]_{RF}}$$

$$V_{out}(t) = \frac{V_{RF}(t) R_C}{R_S + R_E + 1/gm_1} \frac{4}{\pi} \cos \omega_{LO} t$$

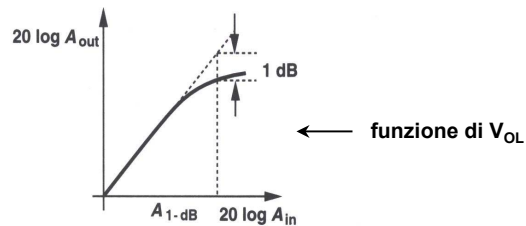
$$V_{IF}(\omega) = \frac{V_{RF}(\omega - \omega_{FI}) R_C}{R_S + R_E + 1/gm_1} \frac{2R_C}{\pi}$$

$$G_C = \frac{1}{\pi^2} \frac{2R_C}{R_S}$$

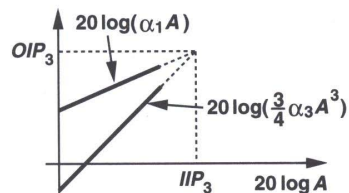
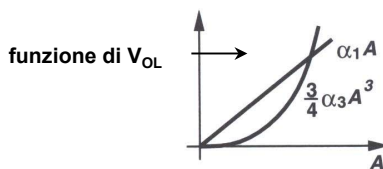


Linearità

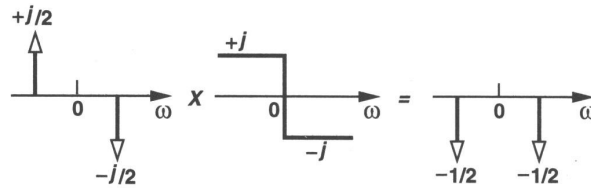
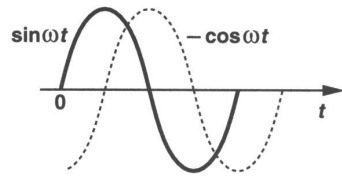
- Punto di Compressione a -1dB : $CP_{1\text{dB}}$



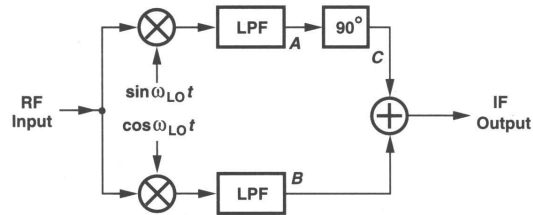
- Intercetta 3° Ordine: IP_3



Mixer a Reiezione (1)



Mixer a Reiezione (2)



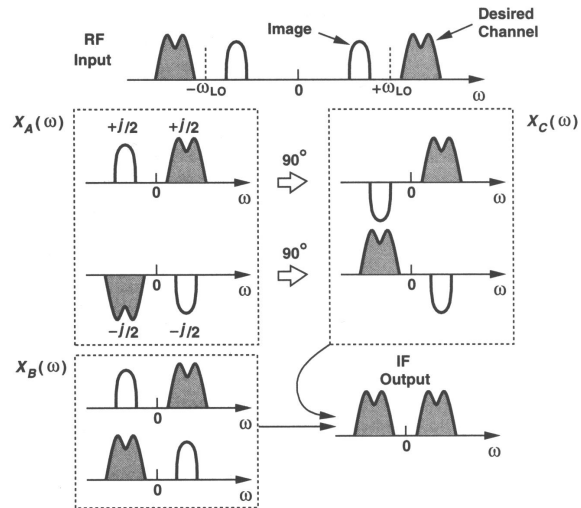
$$x_A(t) = \frac{A_{RF}}{2} \sin(\omega_{LO} - \omega_{RF})t + \frac{A_{im}}{2} \sin(\omega_{LO} - \omega_{im})t$$

$$x_B(t) = \frac{A_{RF}}{2} \cos(\omega_{LO} - \omega_{RF})t + \frac{A_{im}}{2} \cos(\omega_{LO} - \omega_{im})t$$

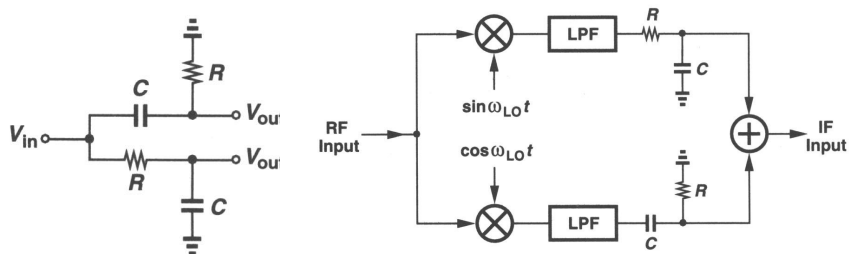
$$x_A(t) = -\frac{A_{RF}}{2} \sin(\omega_{RF} - \omega_{LO})t + \frac{A_{im}}{2} \sin(\omega_{LO} - \omega_{im})t$$

$$x_C(t) = +\frac{A_{RF}}{2} \cos(\omega_{RF} - \omega_{LO})t - \frac{A_{im}}{2} \cos(\omega_{LO} - \omega_{im})t$$

Mixer a Reiezione (3)



Mixer a Reiezione (4)



$$\frac{P_{im}}{P_{sig}} \Big|_{out} = \frac{A_{im}^2}{A_{RF}^2} \frac{(A_{LO} + \epsilon)^2 - 2A_{LO}(A_{LO} + \epsilon) \cos \theta + A_{LO}^2}{(A_{LO} + \epsilon)^2 + 2A_{LO}(A_{LO} + \epsilon) \cos \theta + A_{LO}^2}$$

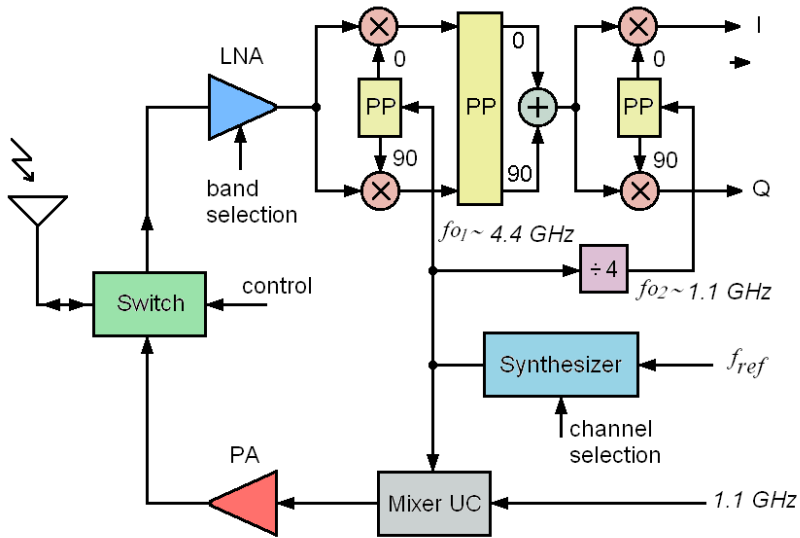
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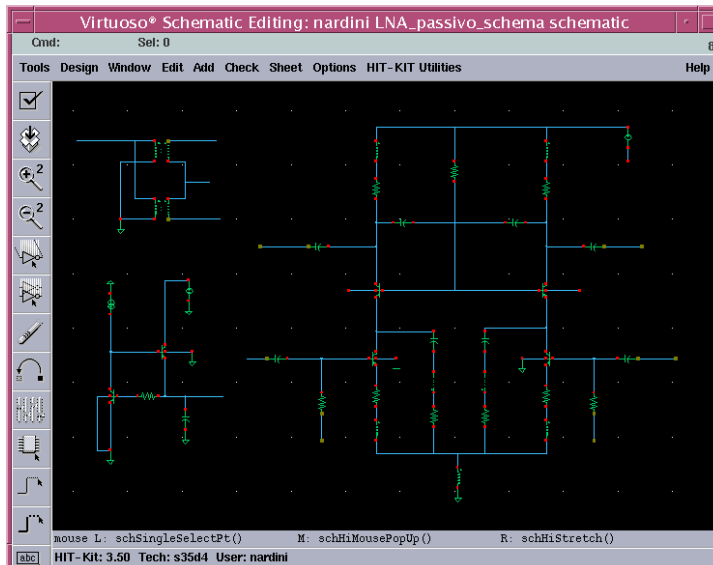
Front-End Multi-Standard (802.11a, HiPerLAN2) per WLAN 5-6 GHz

- Architettura a doppia conversione (IF- zero IF)
- Low Noise Amplifier (LNA)
- Mixer a Reiezione della Frequenza Immagine
- LNA + Mixer: Risultati delle Simulazioni
 - Noise Figure
 - Image Rejection
 - Analisi Transitoria

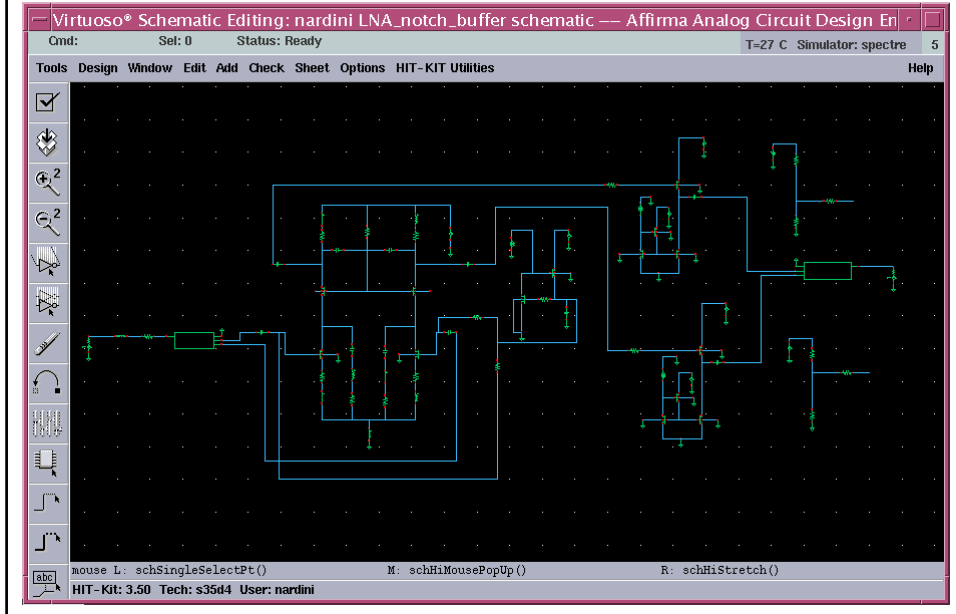
Front-End Multi-Standard (802.11a, HiPerLAN2) per WLAN 5-6 GHz



Low Noise Amplifier (Topology BCD)



LNA + Buffer: Topologia BCD



LNA: Analisi Lineari

Affirma Analog Circuit Design Environment (1)

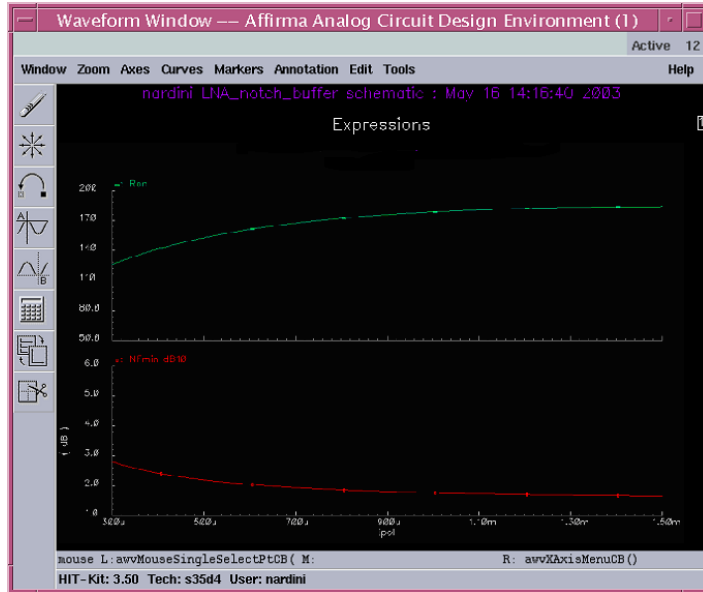
Status: Ready T=27 C Simulator: spectre 10

Session Setup Analyses Variables Outputs Simulation Results Tools Help

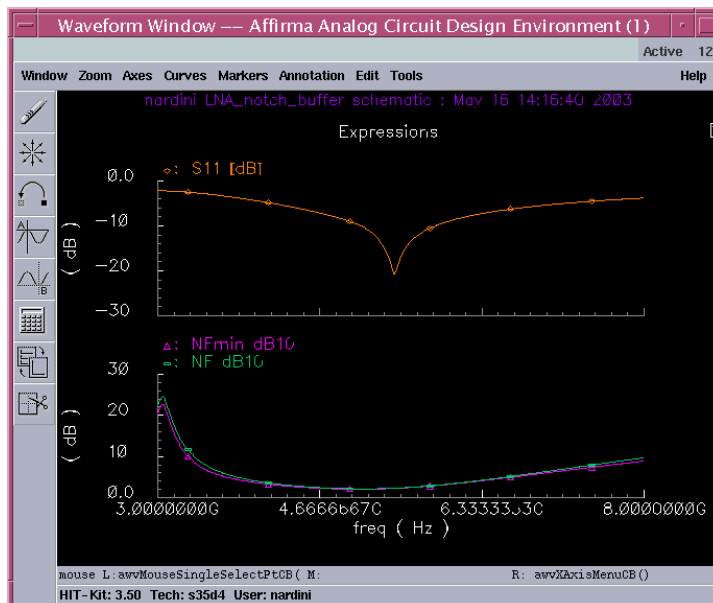
Design		Analyses			
Library	nardini	#	Type	Arguments.....	Enable
Cell	LNA_notch_buffer	1	sp	20 20G 2K	Line.. no
View	schematic	2	ac	20 20G 2K	Line.. no
		3	dc	t	yes

Design Variables			Outputs			
#	Name	Value	#	Name/Signal/Expr	Value	Plot Save March
1	RF	5.25G	1	GT dB10		yes
2	Rb	0	2	NF dB10		yes
3	C	2.72p	3	NFmin dB10		yes
4	Ipol	3.8m	4	Kf		yes
			5	GA dB10		yes
			6	S11 [dB]		yes

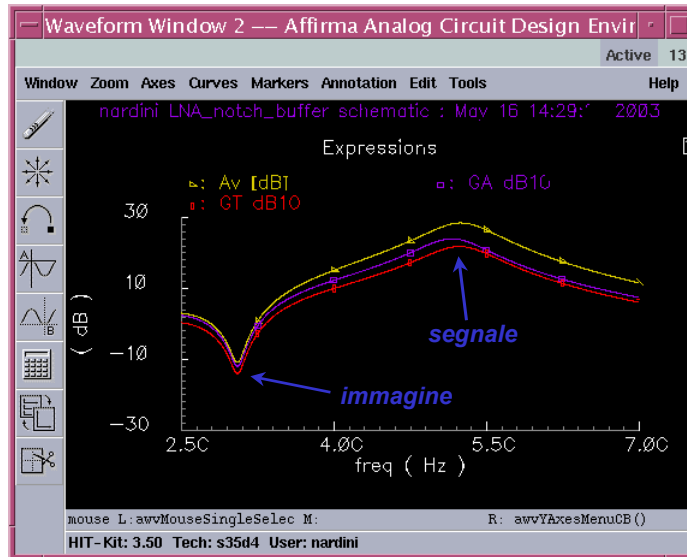
Low Noise Amplifier: NFmin e Ron



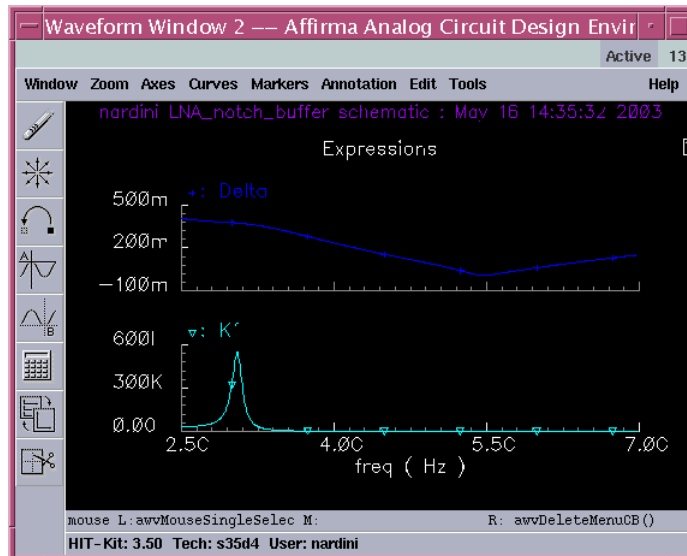
Low Noise Amplifier: Noise Figure



LNA: Risposta in Frequenza



LNA: Fattore di Stabilità



LNA: Analisi Transistoria

The screenshot shows the Affirma Analog Circuit Design Environment (1) interface. The status bar indicates "Status: Simulate..." and "T=27 C Simulator: spectre 10". The menu bar includes "Session Setup Analyses Variables Outputs Simulation Results Tools Help".

Design

Library: nardini
Cell: LNA_notch_buffer
View: schematic

Analyses

#	Type	Arguments	Enable
1	tran	0 60n libe..	yes

Design Variables

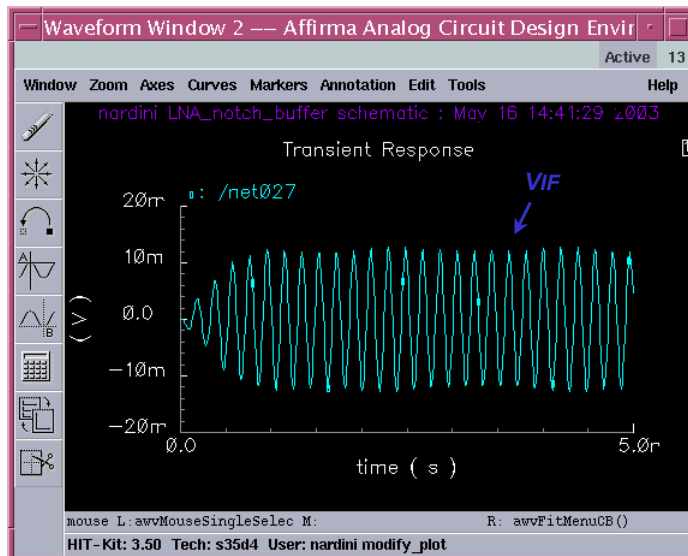
#	Name	Value
1	RF	5.25G
2	Rb	0
3	C	2.72p
4	Ipo1	3.8m

Outputs

#	Name/Signal/Expr	Value	Plot	Save	March
---	------------------	-------	------	------	-------

> Results in ..._exp/home/nardini/Sim/LNA_notch_buffer/spectre/schematic

LNA: Stabilità (transitorio)



LNA: Linearità (CP1dB)

Affirma Analog Circuit Design Environment (1)

Status: Simulate... T=27 C Simulator: spectre 10

Session Setup Analyses Variables Outputs Simulation Results Tools Help

Design

Library nardini
Cell LNA_notch_buffer
View schematic

Analyses

#	Type	Arguments	Enable
1	pss	50M 110 -30 -5	yes

Design Variables

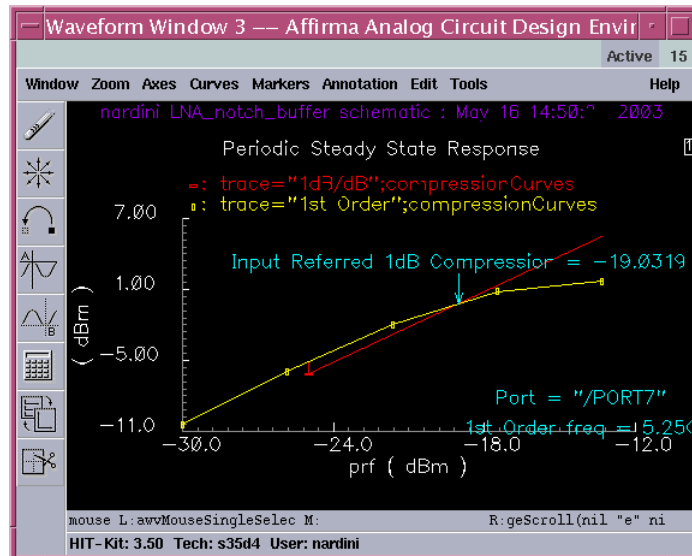
#	Name	Value
1	prf	-20
2	RF	5.25G
3	Rb	0
4	C	2.72p
5	Ipo1	3.8m

Outputs

#	Name/Signal/Expr	Value	Plot	Save	March
---	------------------	-------	------	------	-------

> Results in ..._exp/home/nardini/Sim/LNA_notch_buffer/spectre/schematic

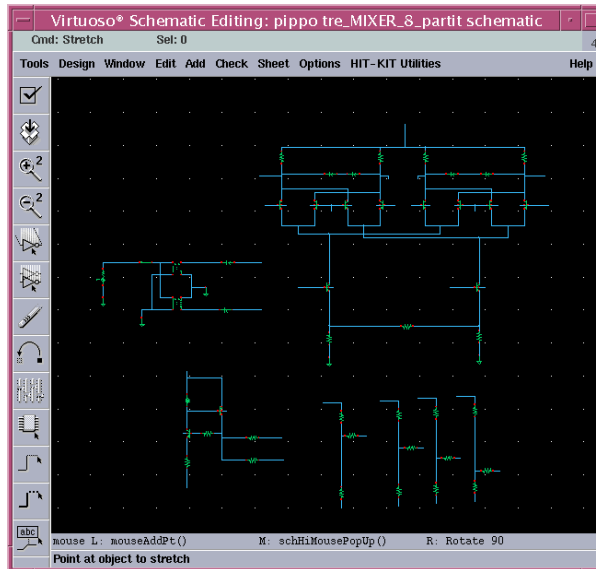
LNA: Linearità (CP1dB)



Mixer a Reiezione della Frequenza Immagine: Cella di Gilbert

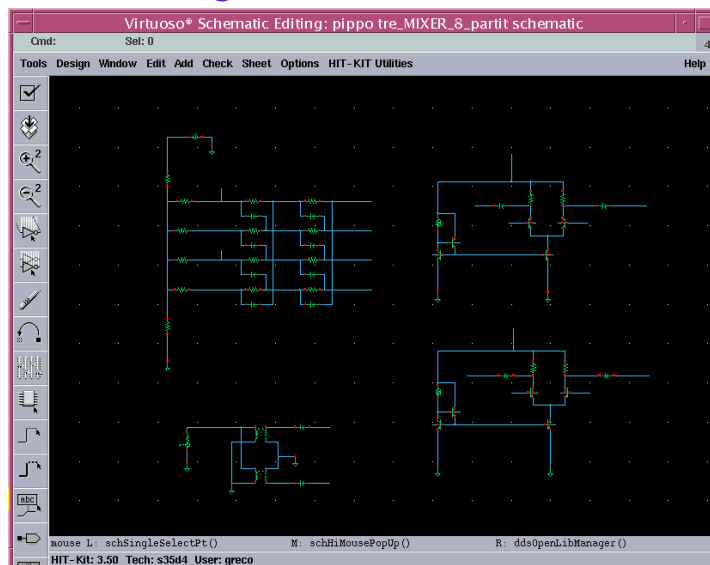
$$f_{RF} = 5.25 \text{ GHz}$$

$$f_{LO} = 4.15 \text{ GHz}$$



Mixer a Reiezione della Frequenza Immagine: Stadio OL

$$f_{LO} = 4.15 \text{ GHz}$$

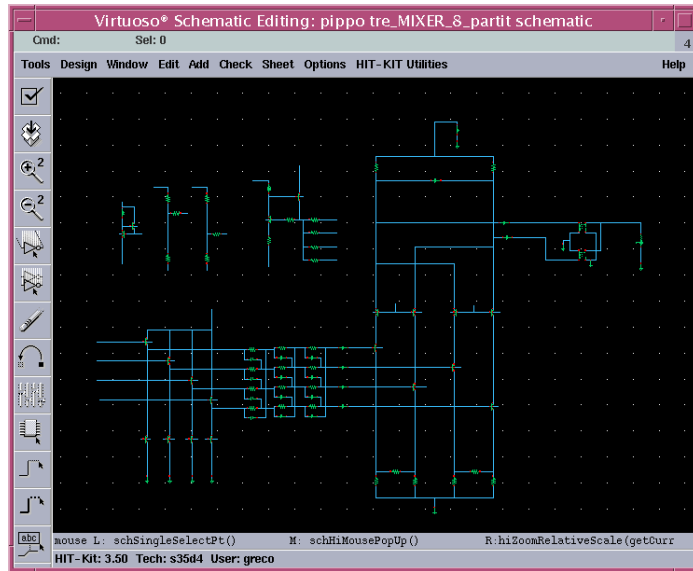


Mixer a Reiezione dell'Immagine: Stadio IF (Buffer + PP + Sommatore)

$$f_{RF} = 5.25 \text{ GHz}$$

$$f_{LO} = 4.15 \text{ GHz}$$

$$f_{IF} = 1.1 \text{ GHz}$$

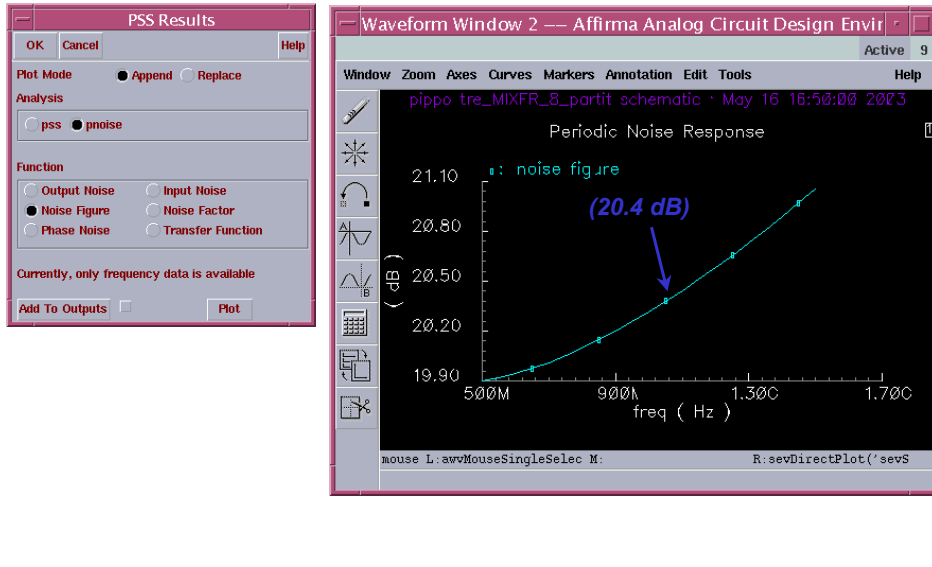


Mixer: Analisi Pnoise

#	Type	Arguments	Enable
1	pnoise	30 500M 1.5G 20 ..	yes
2	pss	4.15G 0	yes

#	Name	Value
1	vrf	-30
2	vol	-3
3	Iad	2.4m
4	frf	5.25G
5	fol	4.15G

Mixer: Noise Figure



Mixer: Analisi PXF

Affirma Analog Circuit Design Environment (1)

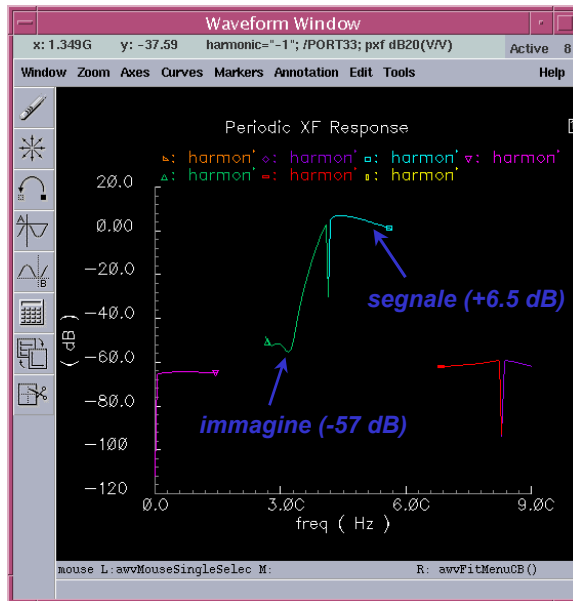
Status: Ready T=27 C Simulator: spectre 5

Session Setup Analyses Variables Outputs Simulation Results Tools Help

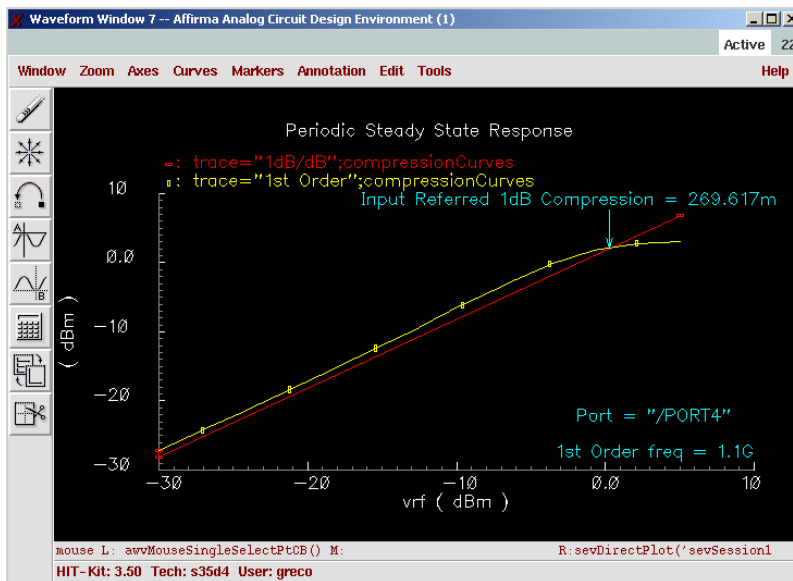
Design		Analyses			
Library	Cell	#	Type	Arguments	Enable
pippo	tre_MIXER_8_parti	1	pss	4.15G 0	yes
		2	pxf	3 1M 1.5G 30 ..	yes

Design Variables			Outputs			
#	Name	Value	#	Name/Signal/Expr	Value	Plot Save March
1	vrf	-30				
2	vol	-3				
3	Iad	2.4m				
4	frf	5.25G				
5	fol	4.15G				

Mixer: GC e Reiezione dell'Immagine



Mixer: Linearità (CP1dB)



LNA + Mixer: Analisi Pnoise

The screenshot shows the Affirma Analog Circuit Design Environment (2) interface. The status bar indicates "Status: Ready" and "T=27 C Simulator: spectre 10". The menu bar includes "Session Setup Analyses Variables Outputs Simulation Results Tools Help".

The **Design** section shows:

- Library: pippo
- Cell: lna_mixer_notchpass
- View: schematic

The **Analyses** table is as follows:

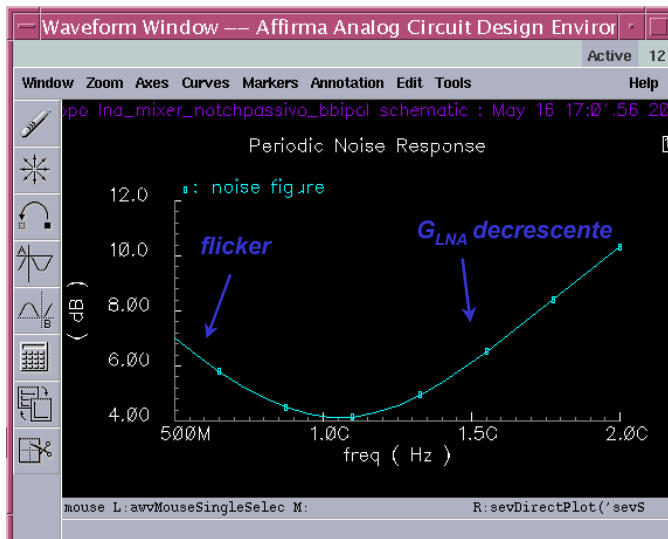
#	Type	Arguments	Enable
1	pss	4.15G 0	yes
2	pnoise	30 500M 2G 20	yes

The **Design Variables** table is as follows:

#	Name	Value
1	RF	5.25G
2	prf	1m
3	Ipol	3.8m
4	Iad	2.4m
5	vol	-3
6	fol	4.15G

The **Outputs** table is currently empty.

LNA + Mixer: Noise Figure



LNA + Mixer: Analisi Transitoria

Status: Ready T=27 C Simulator: spectre 10

Session Setup Analyses Variables Outputs Simulation Results Tools Help

Design

Library pippo
 Cell lna_mixer_notchpassivo_bbipol
 View schematic

Analyses

#	Type	Arguments	Enable
1	tran	0 60n libe..	yes

Design Variables

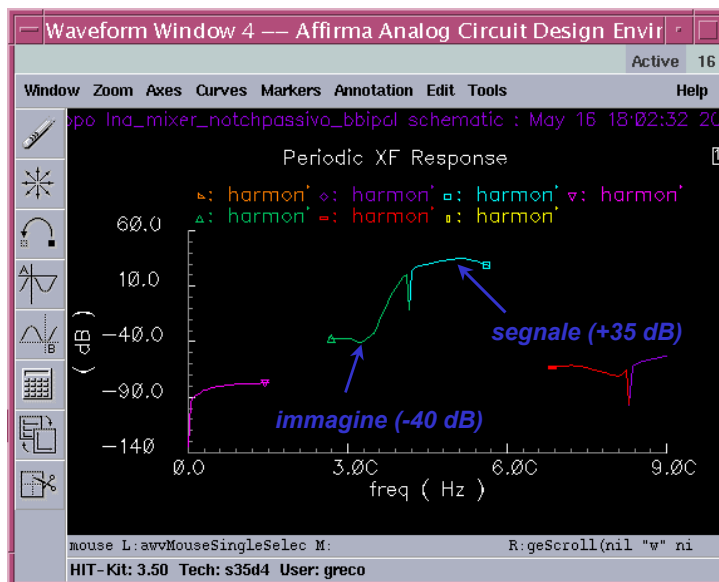
#	Name	Value
1	RF	5.25G
2	prf	1m
3	Ipol	3.8m
4	Iad	2.4m
5	vol	-3
6	fol	4.15G

Outputs

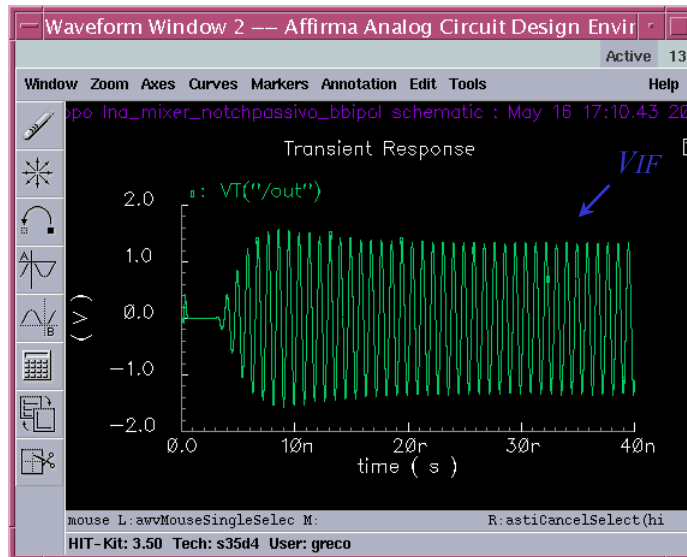
#	Name/Signal/Expr	Value	Plot	Save	March

> Results in ...greco/Sim/lna_mixer_notchpassivo_bbipol/spectre/schematic

LNA + Mixer: GC e Image Rejection



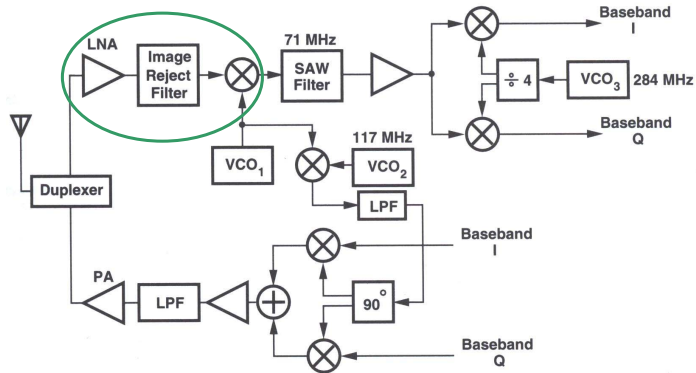
LNA + Mixer: Transistorio



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

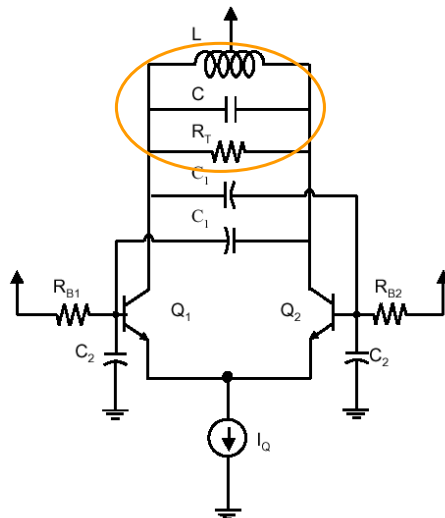
Conclusioni



❑ Power Amplifier (PA)

❑ Voltage Controlled Oscillator (VCO)

Voltage Controlled Oscillator (VCO)



Riferimenti

❑ RF and Microwave Circuit Design for Wireless Communications – L.E.Larson Editor – Artech House

❑ RF Microelectronics – B. Razavi – Prentice Hall

❑ Analysis and Design of Analog Integrated Circuits Fourth Edition – P.Gray, R.Meyer, et al. – Wiley

❑ ASITIC: <http://formosa.eecs.berkeley.edu/~niknejad/asitic.html>

❑ E-mail: d.zito@iet.unipi.it