LNA and Mixer Design in Millimeter wave

Presented By

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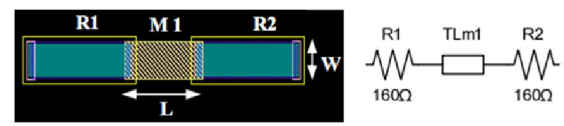
Outline

- Challenges in mm-wave design and passive components
- LNA design
  - General LNA topology
  - Design example of W-band LNA
- Challenges of mm-wave Mixer design
  - Homodyne and Heterodyne Mixer
  - Subharmonic Mixer
  - Mm-wave Passive Mixer
- Layout Methodology

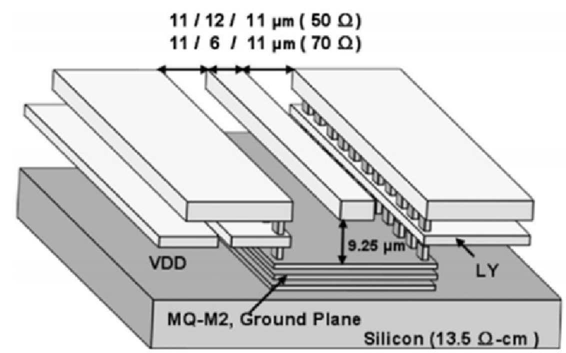
Challenges in mm-wave Design

- Wavelength is few millimeters. $\lambda = \frac{c}{f\sqrt{\varepsilon_{eff}}}$ so when signal traverse components with appreciable size of wavelength, their true nature is like wave .so distributed effect must be considered as a part of design process.



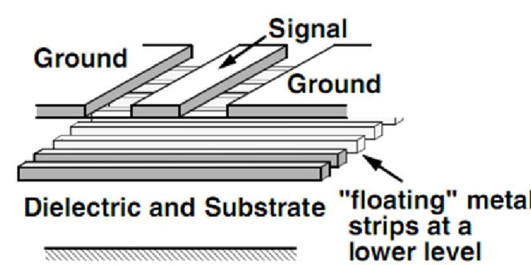
- Transmission lines provide better model accuracy than inductors due to well define ground planes.

- Ground shielded Coplanar waveguide (G-CPW) is widely used for matching of interconnection.



CPW (IBM SIGe BiCMOS process)

- Use of T-lines results noticeable increase in chip-area, alternatively SW-CPW are used.



SW-CPW

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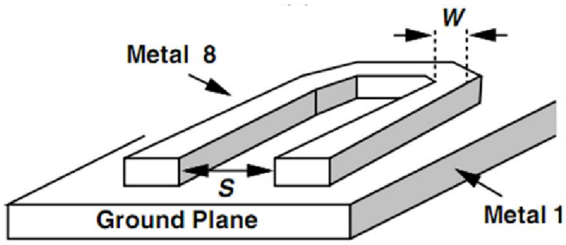
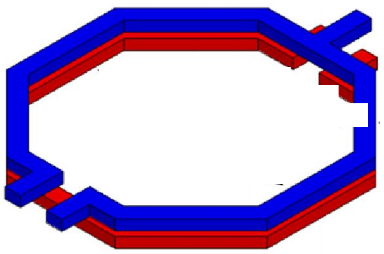
Passive components

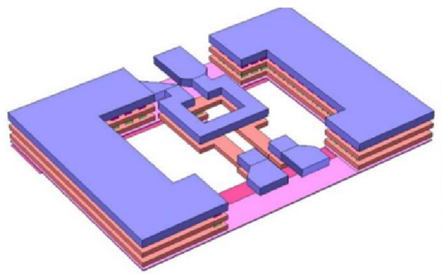
- Folded Microstrip lines can also be used for inductor.
- Transformer based balun is widely used to make single ended to differential. Usually Baluns are routed with top two thick metal layers.



Folded Microstrip line (90nm CMOS Tech.)

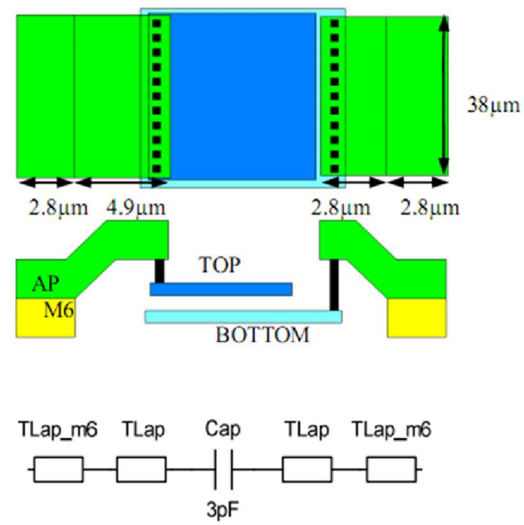


Octagonal Transformer (center tapped)



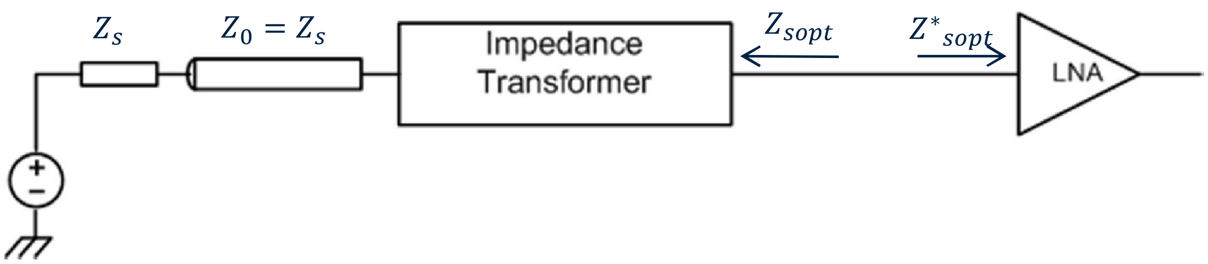
Square Transformer (SONNET Layout)

- Metal-insulator-metal (MIM) capacitor terminations must be considered as T-lines and modeled consequently.



3pF MIM Capacitor and its equivalent model (0.13um SiGe BiCMOS process)

LNA Design in mm-wave



- Simultaneous conjugate matching and noise matching at LNA input.
- Multistage LNA: Inter-stage matching and stability.
- Transistors operate close to their f_T ⇨ Lower gain
  ⇨ higher NF
- Device requirement : High -current gain, cutoff frequency and breakdown voltage.

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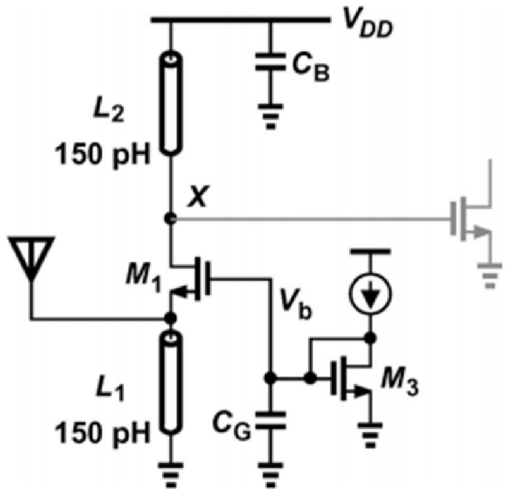
LNA topology

Common gate topology:



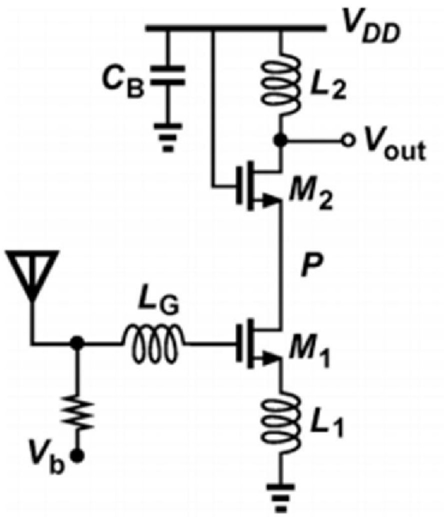
Two Serious Issues:

- Matching and Gain degrades because of a parasitic inductance between C_G and its connections to gate and to ground.
- Gain of CG stage is much lower at mm-wave frequency.

Reference: Bezad Razavi,Fellow,IEEE ,"Design of millimeter-wave CMOS Radios:A tutorial" ,IEEE transactions on circuits and systems,regular papers,VOL 56, No.1 Jan 2009

LNA topology (cont.)

Inductively degenerated cascode topology:



Input matching depends on package parasitic.

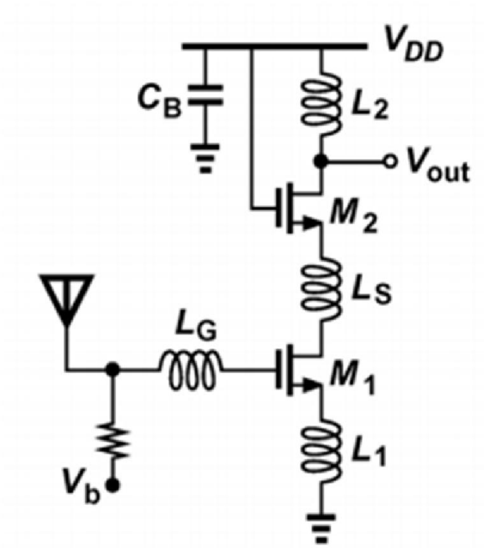
All inductors must be integrated on chip.

GND return path for L_1 and L_2 should display very low inductance. So careful layout consideration is needed.

A pole (in the order of $f_T/2$) adversely impact the gain and noise figure.

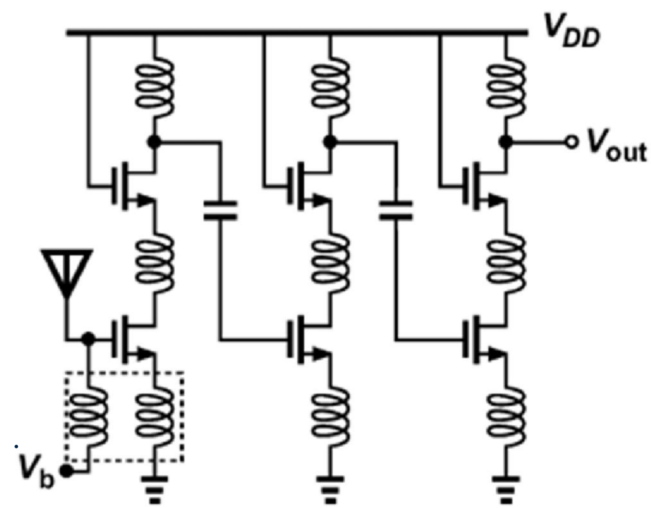
LNA topology (cont.)

L_s can be used as Series resonance, acts as inter-stage matching.



Cascading three stage

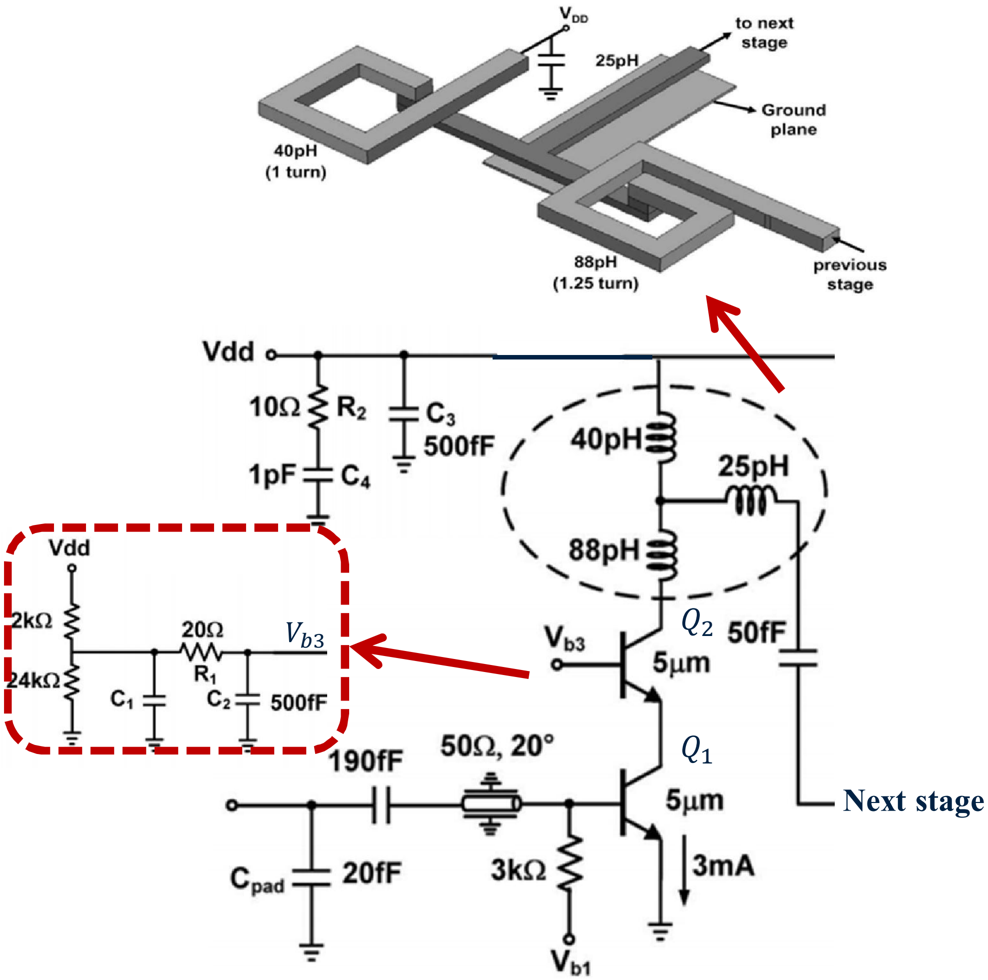
Transformer feedback LNA



Wide Band impedance & noise matching

Reference: Bezad Razavi,Fellow,IEEE ,"Design of millimeter-wave CMOS Radios:A tutorial" ,IEEE transactions on circuits and systems,regular papers,VOL 56, No.1 Jan 2009

W-band LNA

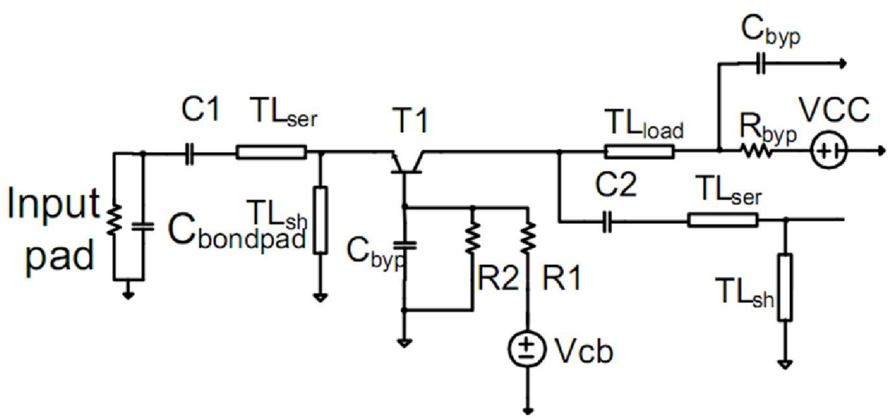


Four stage LNA, Gain=25 dB, NF=8.3 dB, 0.18um SiGe BiCMOS technology.

- Capacitance of GSG pad should be absorbed by input matching network.
- C_2 is put as close as possible to the base of Q_2 to minimize parasitic inductance and ensure stability.
- Local decoupling network for power supply is C_3 C_4, R_2 .
- To reduce footprint ,lumped inductors are used instead of T-lines, as well as inter-stage matching.

Reference: Zhiming cheng,chun-cheng wang,Hsin-cheng yao,Payam heydari,"A BiCMOS W-band 2× 2 focal-plane Array with On-chip Antenna", IEEE journal of Solid State Circuits,Vot.47,No.10,Octobar 2012.

Common base topology for BJT



245 GHz LNA, Gain=12 dB, NF= 9.4 dB, BW=26 GHz, Power consumption=28mW

- Common base can achieve higher gain, wider bandwidth and higher isolation than CE stage.
- Parasitic inductance at base introduces negative resistance at emitter by equation (1).
- Stability is ensured by reducing collector current which reduces ω_T.
- Parasitic inductance L_p can increase gain and lower NF.
- C_{byp} , R_{byp} improve isolation between CB stages.

Reference: Yanfei Mao,K. schmalz,J. Borngraber,J.C scheytt,“A 245GHz CB LNA in SiGe” ,Proceedings of 6th European Microwave Integrated circuits Conference

Challenges in Mixer Design in mm-wave

- **Homodyne Mixer :** High performance silicon base oscillator is very challenging in mm-wave frequency. so for direct conversion, LO is generated at a fraction of RF frequency and then use a multiplier prior to the frequency translation.

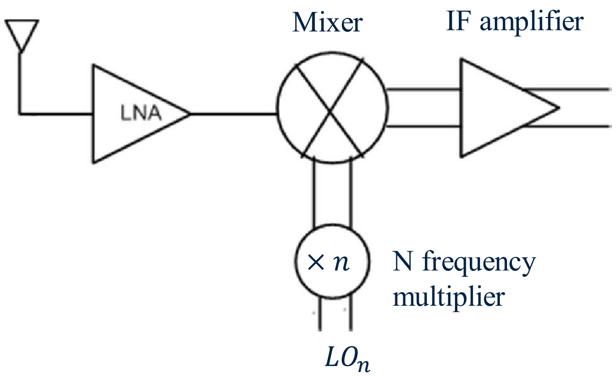
- **Heterodyne Mixer:** Double conversion mixer is used to relax oscillator and frequency divider requirement in mm-wave application.

- **IQ Mixer:** Generation of I Q phases of LO at mm-wave frequency and its balanced distribution is problematic. Quadrature operation typically degrades phase noise in mm-wave frequency.

- LO distribution is difficult because of significant loss and mismatch in interconnects at high frequency.

- AT mm-wave frequencies, it is difficult to get large LO signal, so conversion gain is low with weak LO signal.

- Parasitic and layout consideration is an important issue for port to port isolation and stability.



Homodyne mixer

Conversion Gain or Loss

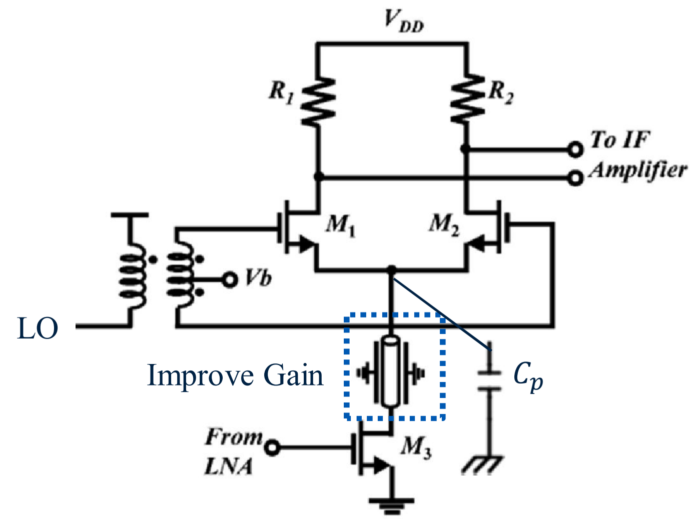
- Conversion gain or loss is the ratio of the desired IF output (voltage or power) to the RF input signal value (voltage or power).

$$\text{Voltage Conversion Gain} = \frac{\text{r.m.s. voltage of the IF signal}}{\text{r.m.s. voltage of the RF signal}}$$

$$CG = \frac{2}{\pi} g_{m3} R_1 \frac{g_{m1}}{\sqrt{C_p{}^2 \omega^2 + g_{m1}{}^2}}$$

To increase Gain:

- Transmission line is used to reduce the parasitic at the common node of switches.
- Optimize Transconductor bias current for high gain.



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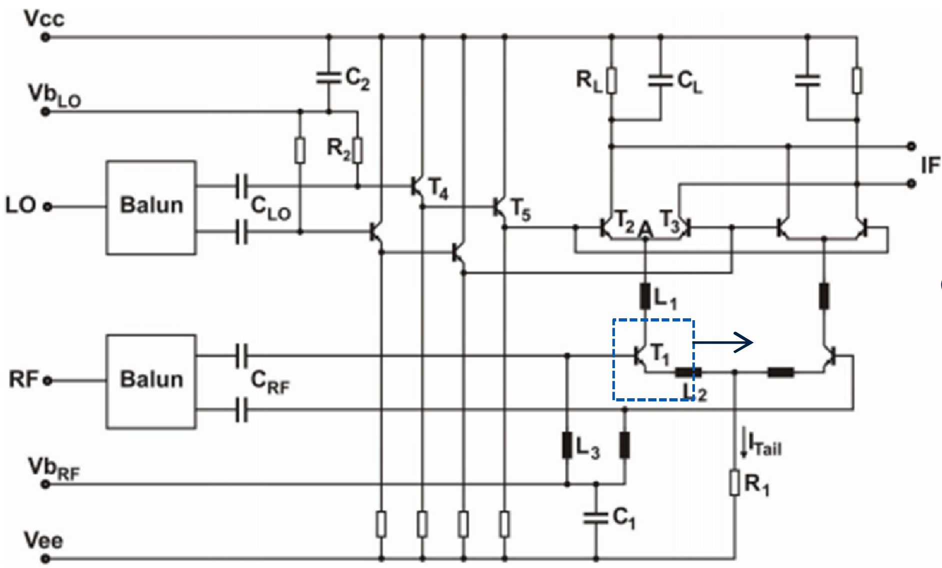
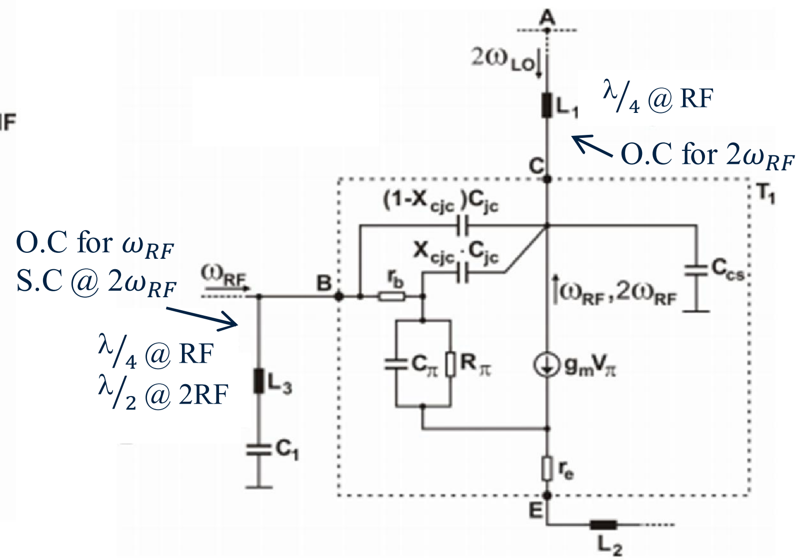
Homodyne Mixer in Millimeter wave



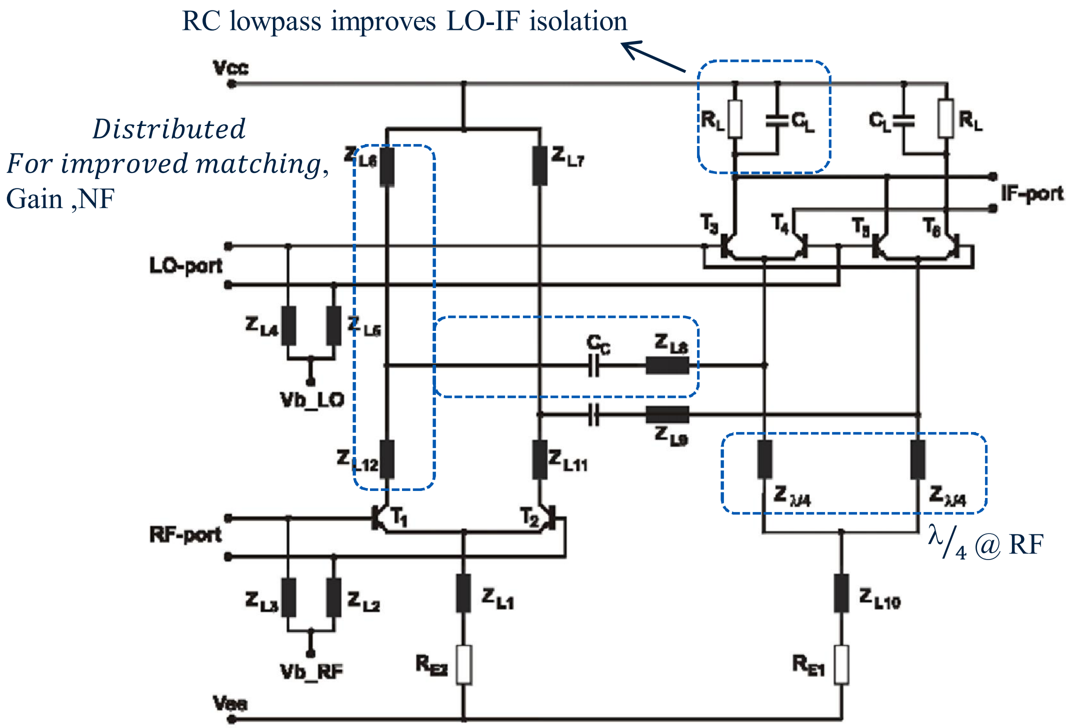


- RF=76GHZ, CG=15dB, SSB NF=11.2dB, IIP3=8.5dBm, Supply=5.5V, SiGe:C technology.
- Nonlinearity of B-E junction creates harmonics. High C_{bc}, L3-C1 represents very low impedance path for $2\omega_{RF}$ components generated by T1.
- The feedthrough $2\omega_{LO}$ $to\ T1$ can increase IM3,both $2\omega_{RF}$, $2\omega_{LO}$ is highly attenuated by Low pass filter consisting of Ccs-L1,as RF and LO frequency are quite close.
- The effect of parasitic capacitance at node A is lowered by L1 which also improves NF.
- L2 and R1 improves stability.

Reference: Saverio trotta ,bernhard Dehlink ,herbert Knapp ,Klaus Aufinger, Thomas F. Meister ,Josef Bock, Werne Simburger and Arpad L. Scholtz ,"Design considerations for low noise, Highly Linear Millimeter-wave Mixer in SiGe Bipolar Technology"

Folded structure

RF=76.5GHz, LO=38.25GHz, CG with IF amplifier=18dB, Supply 3.3V, 200 GHz f_T SiGe BiCMOS technology.



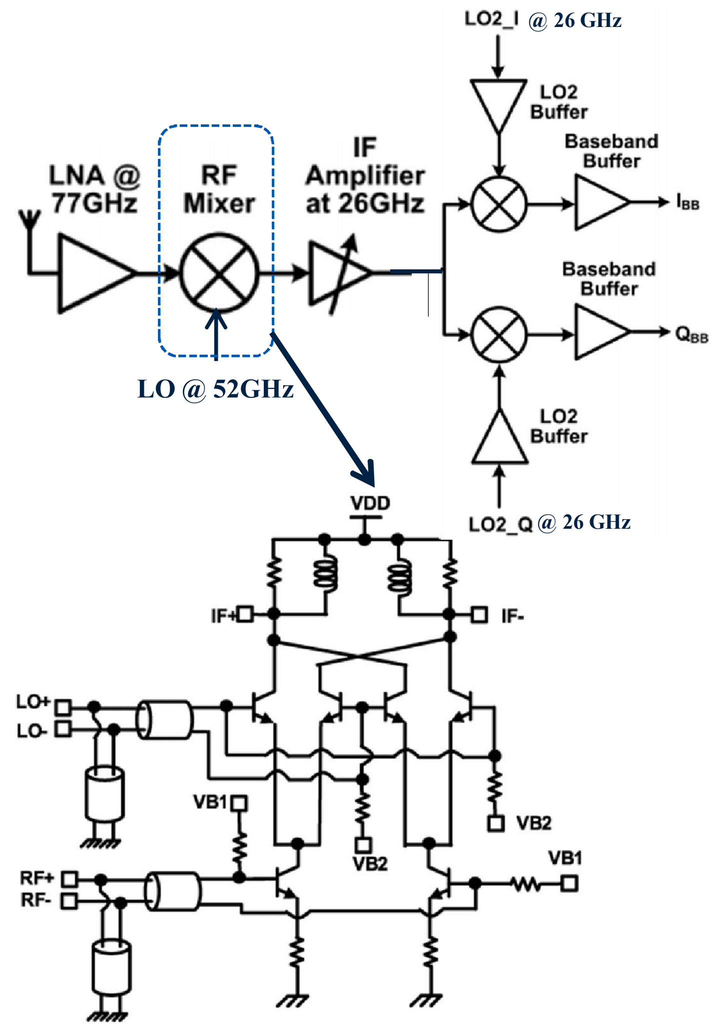
- Transistors are biased to get highest stable gain.
- Current in the input RF-pair can be optimized to improve NF and linearity.
- LO switch quad are biased in low current to reduce noise injected by these transistors.
- Voltage headroom available at the IF output help to avoid the clipping of mixer core.

Reference: S.trotta,B.Dehlink,R. Reuter,Y.Yin,J.John,J.Kirchgessner,D.Morgan,P.welch,J.J.Lin,B.Knappenberger,I.To and M.Huang,"A multi-channel Rx for 76.5GHz Automotive Radar Applications with 55dB IF Channel-to-Channel Isolation", 4th European Micorwave Integrated Circuits Conference,2009.

Heterodyne Mixer

Two step down conversion scheme with RF =76-81 GHz, IF= 25-27 GHz. CG=5dB,BW=10GHz,NF=11dB

- Second quadrature LO is generated by dividing first LO by 2. Single frequency synthesizer can be used as first and second LO generation.
- Shielded T-lines are used for matching circuits because required reactance is small, also These lines has high isolation, reduced coupling to adjacent circuits.
- Second Mixer achieves 6dB conversion gain and BW=8GHz in base band.



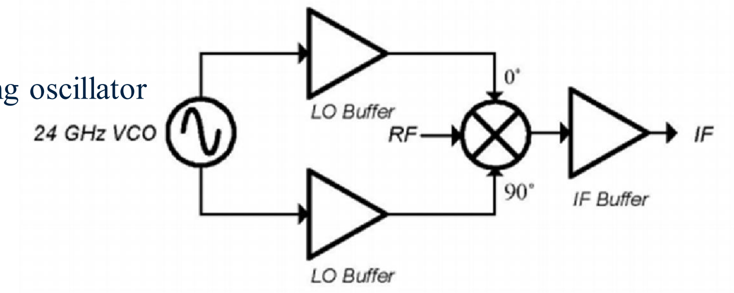
Reference: Aydin babakhani,Xiang Guan,Abbas komijani,Arun Natarajan,Ali hajimiri,"A &&GHz phased array transceiver with on chip antennas in Silicon:receiver and Antennas",IEEE journal of Solid State Circuit,vol.41,no.12,December 2006

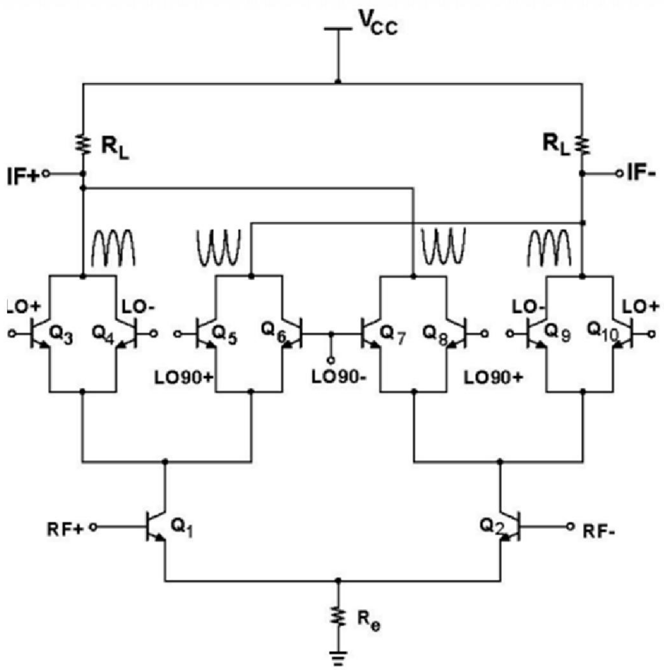
Subharmonic Mixer

- Subharmonic mixer offers an alternative solution to fundamental mixers in mm-wave range since they allow for an LO at lower frequency.so this technique avoids separate multiplier and associated circuitry, resulting in lower power consumption and low active area.
- Second harmonic or fourth harmonic of LO frequency are commonly used to downconvert RF signal to IF frequency.
- To increase the gain of subharmonic mixer, the desired harmonic mixing product should be maximized. Harmonic component of LO signal is a function of conduction duty cycle.

Subharmonic Mixer :Topology 1

Ring oscillator



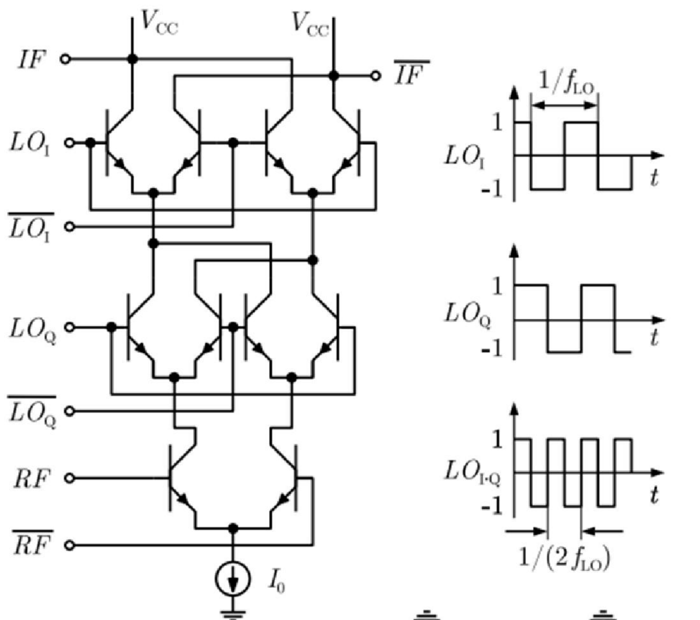


RF= 50GHz,LO=24 GHz,peak CG=9dB,NF=11.8 dB from 3.3V supply, 0.12um SiGe BiCMOS process.

- Second Harmonic of LO is used. Completely Doubled Balanced Gilbert cell.
- This topology uses just two level of transistors hence lower supply voltage.
- Differential Two stage ring oscillator is used to generate quadrature phase.
- The some of the collector current of all switching pair has $2\omega_{LO}$ component indicating frequency doubling.

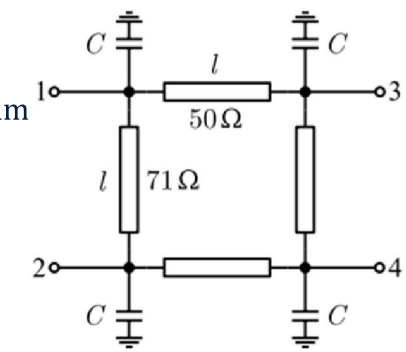
Reference: R.M. kodkani and L.E. larson,"An integrated 50GHz SiGe Subharmonic Mixer/downconverter with a quadrature ring VCO" ,IEEE 2007

Subharmonic mixer: Topology 2



$l = \frac{\lambda}{8}(60\text{ GHZ}) = 315\text{um}$

C=90fF



90 degree Hybrid

RF =122GHz,LO=60GHz,CG=23dB with +3dBm LO power ,SSB NF=12 dB, SiGe:C HBT technology.

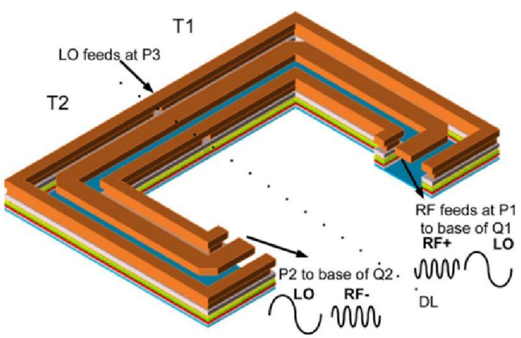
- Second Harmonic of LO is used.
- Quadrature signal is applied to the stacked LO stages yields the product of twice the LO switching cycle.
- Reduced size 90 degree Hybrid coupler is used to generate quadrature LO signal.
- This topology Requires High supply voltage, Supply 6.6V,power consumption 150mW.

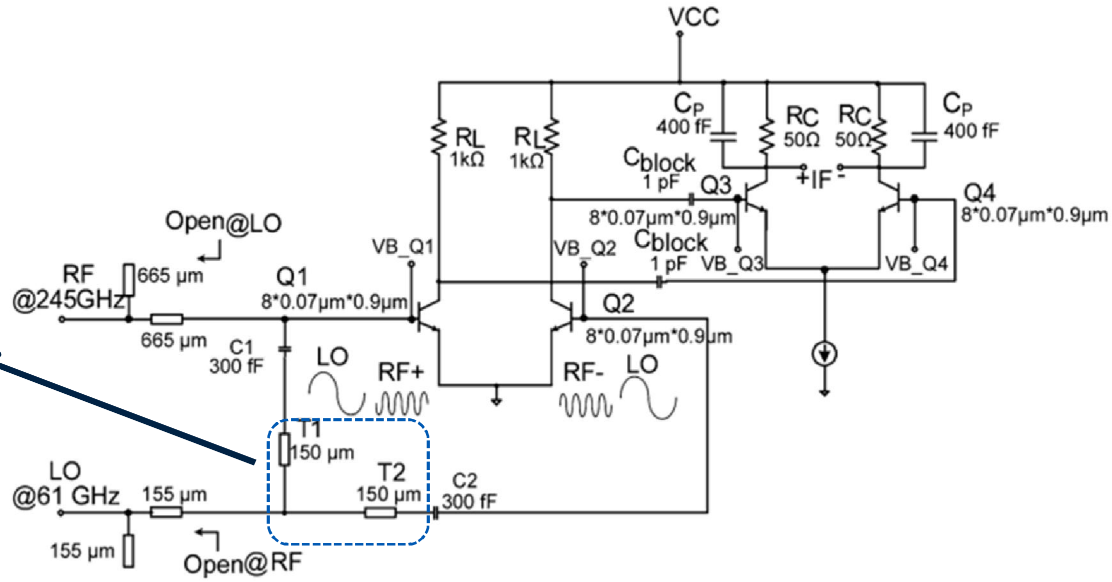
Reference: A.M¨ uller,M.Thiel,H.Irion,and H.-O.Ruoß,” A 122 GHz SiGe Active Subharmonic Mixer”.

Subharmonic Mixer: Topology 3

RF=245GHz,LO=60GHz,conversion gain 0.7dB, NF=23dB, P_{-1}=-9.1dBm.SiGe:C BiCMOS Technology, f_T=300GHz.

- Fourth Harmonic of LO is used.
- Transconductance mixing topology : Switching core may not work as a switch at frequency near f_T.

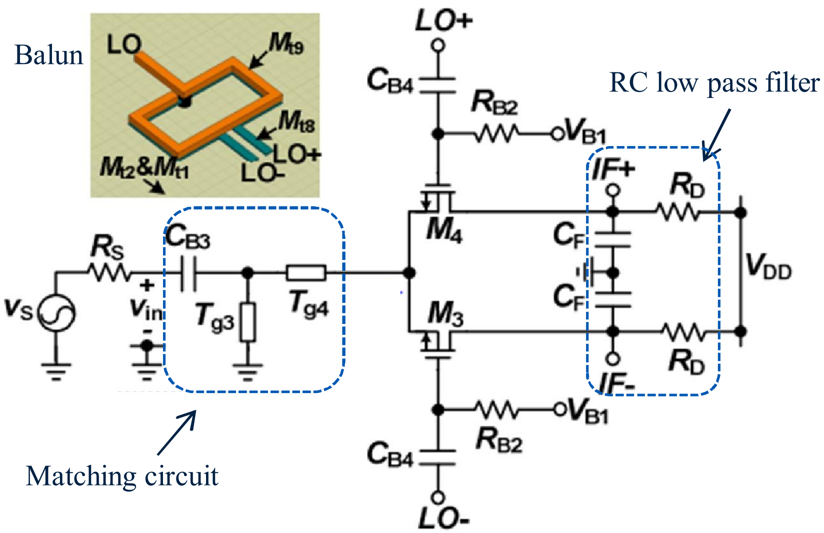


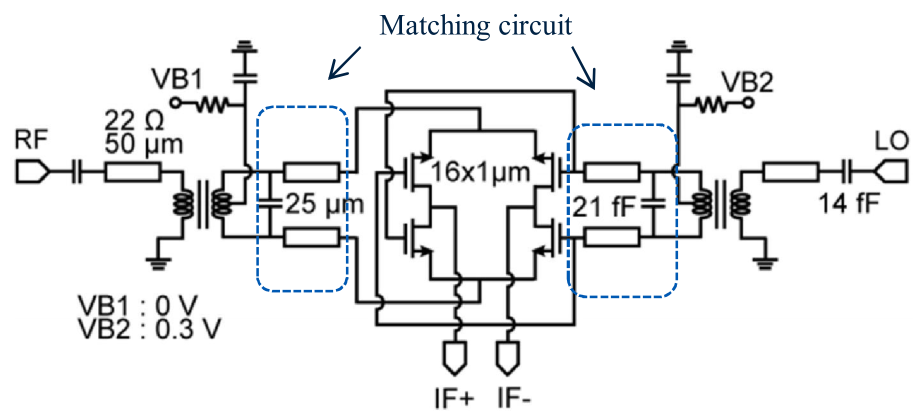


Reference: Yanfei Mao,Klaus schmalz,johannes Borgraber and john christoph scheytt ,"245GHz LNA, Mixer and Subharmonic receiver in SiGe technology", IEEE transactions On Microwave theory and Technique ,vol 60,no.12,december 2012.

Passive Mixer

- At very high frequency active mixers becomes complicated. In that case passive mixer can be used. As there is no conversion gain, passive mixer can reduce sensitivity of the receiver.





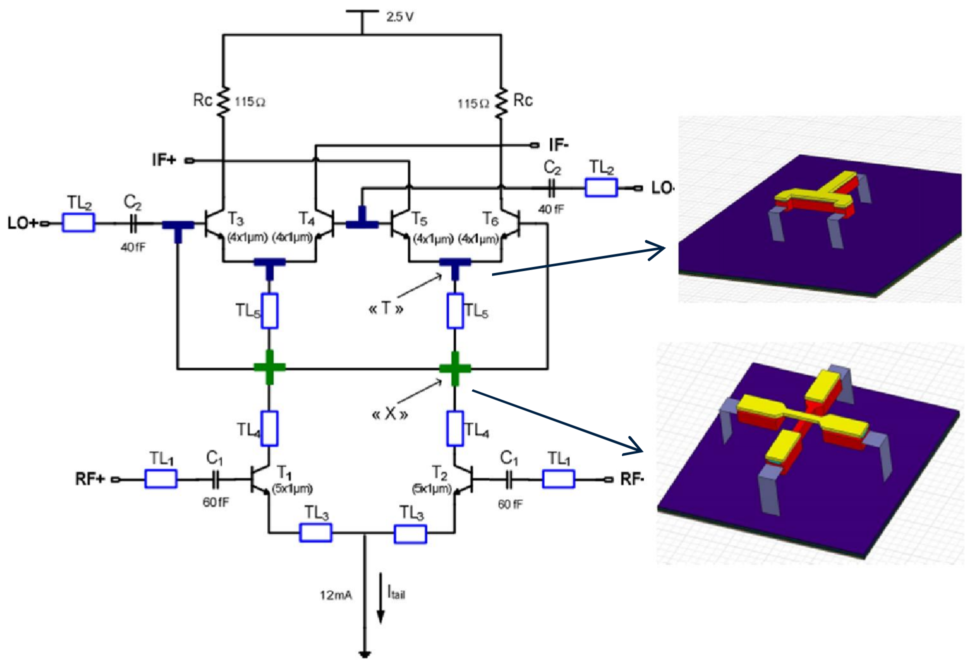
- Single balanced Mixer
- 65nm CMOS process
- 67~75GHz RF

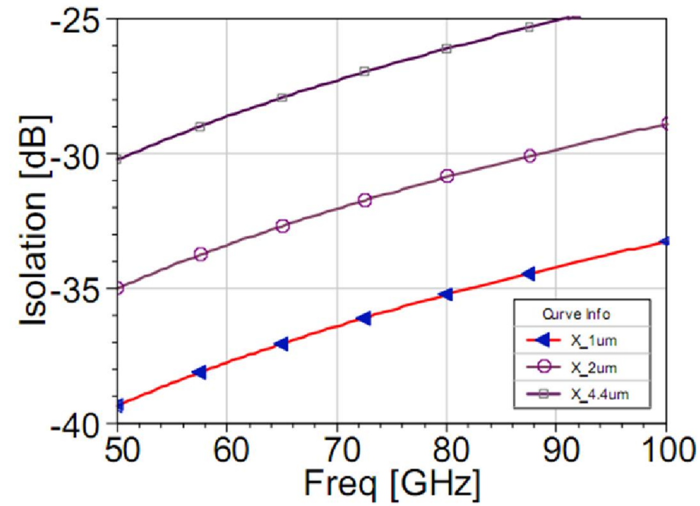
- Doubled balanced Mixer
- 45nm CMOS IBM12SOI process
- Wide band RF 130GHz-180GHz
- Conversion loss 12-13dB with 3dBm LO power

Reference: (1)16.9-mW 33.7-dB Gain mmWave Receiver Front-End in 65 nm CMOS, hun-Hsing Li and Chien-Nan Kuo, 2012 IEEE
(2)Double-Balanced 130-180 GHz Passive and Balanced 145-165 GHz Active Mixers in 45 nm CMOS , Ozgur Inac, Andy Fung2 and Gabriel M. Rebeiz, 2011 IEEE

Layout Methodology : Isolation

- LO-RF Isolation



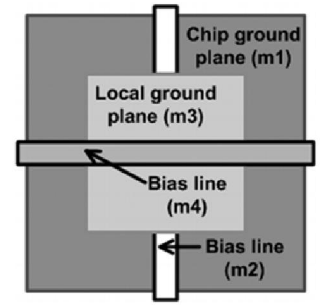


- RF frequency=77GHz,LO Frequency=80GHz,130nm BiCMOS Technology
- For X junction, reducing the width of path at crossing point allows minimizing the coupling effect.

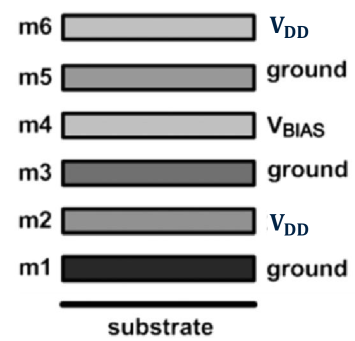
Reference:Low Power and High Gain Double-Balanced Mixer dedicated to 77 GHz Automotive Radar Applications, A. Mariano, T. Taris, B. Leite, C. Majek, Y. Deval, D. Belot, 2010 IEEE

Layout Methodology (cont.)

- Bias signals from large signal circuits (like the VCO and PA) must not be shared with sensitive circuit LNA.
- When bias lines of different blocks must be crossed, local ground plane should be placed between them to minimize their capacitive coupling.
- LNA should be placed as far as possible from frequency divider, PA .
- Capacitance of the metal planes contribute on-chip decoupling which prevents the propagation of high frequency noise between adjacent blocks.so power bias and ground planes are interlaced to increase their capacitance.
- Circuit blocks should be surrounded by n-well and p-well isolation ring to prevent noise from emerging or leaving.



Local GND plane used for isolation



Metal planes for bias and Power distribution (SiGe Tech.)

Summary

- Different passive components are described in mm-wave range. All passive components and transistor interconnections should be verified by EM simulation at this high frequency.
- A number of techniques have been described to design LNA and mixer that ameliorate the challenges in mm-wave design.
- Systematic methodologies in layout, coupling among building blocks through the power lines and substrate are critical tasks that must be addressed.

Thank you