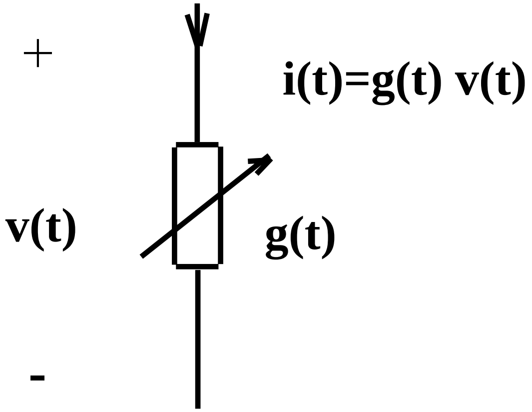
1. The principle of resistive mixers

Frequency translation by using resistive mixing



The current through the (timedependent) resistor is the product of the conductance and the applied voltage
We are interested in the frequencies generated by this multiplication in the time domain

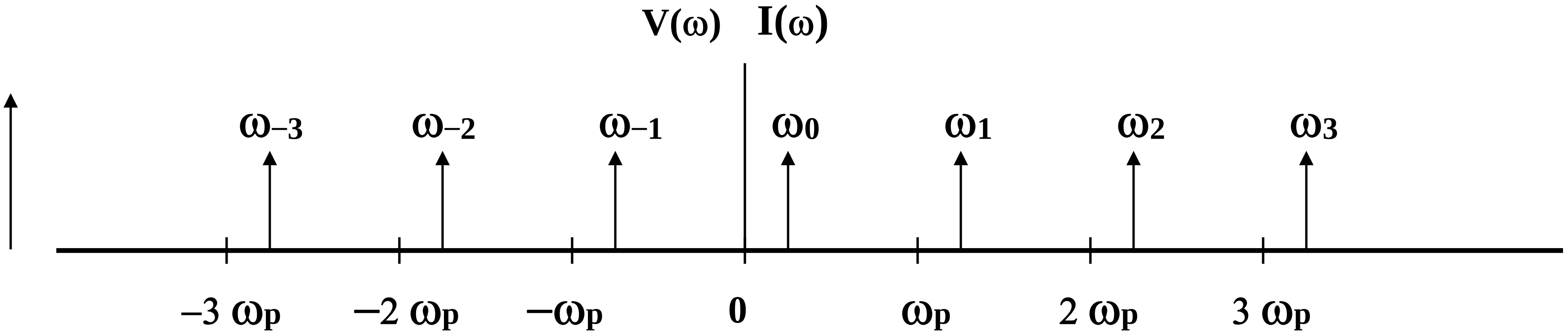
g(t) can be represented by a Fourier series with the fundamental frequency ω_p

$$g(t) = \sum_{n=-\infty}^{\infty} G_n \cdot \exp(j \cdot n \cdot \omega_p \cdot t)$$

See Steven Maas
Nonlinear Microwave Circuits
pp.114-137

small-signal analysis

Convenient representation of mixing frequencies $\omega_n=\omega_0+n\,\omega_p$



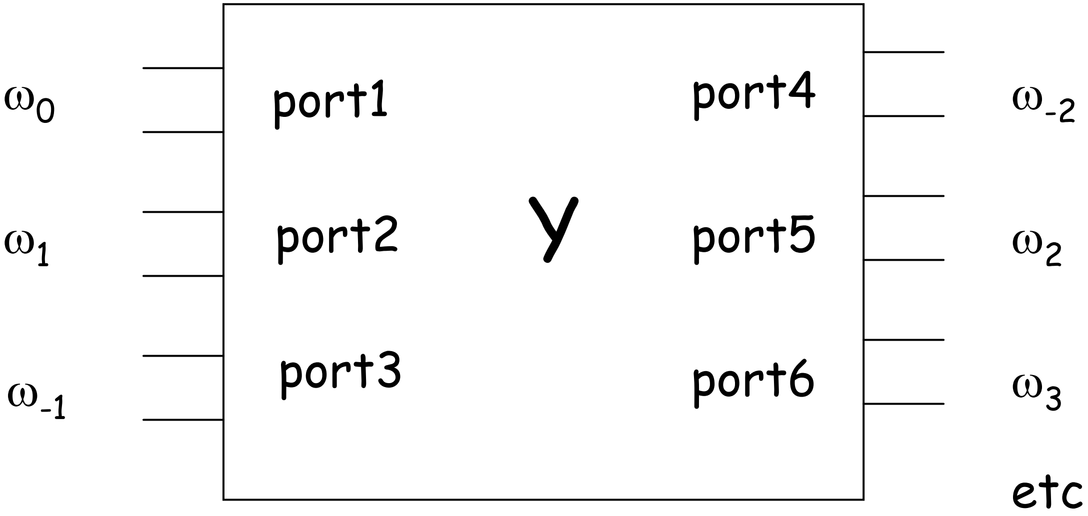
Assuming we know the variation of the resistance vs time, we can calculate the frequency conversion properties by using the conversion matrix approach:

$I = G \cdot V$ **G is the conversion matrix, I and V are vectors representing the current and voltage at each mixing frequency**

we get:

$$
\left[\begin{array}{c}
I_{-N}^{*} \\
I_{-N+1}^{*} \\
I_{-N+2}^{*} \\
\\
\\
\\
I_{-1}^{*} \\
I_{0} \\
I_{1} \\
\\
\\
\\
\\
I_{N-1} \\
I_{N}
\end{array}\right]
=
\left[\begin{array}{ccccccccccccccc}
G_{0} & G_{-1} & G_{-2} & & & & & & & & & & & & G_{-2N} \\
G_{1} & G_{0} & G_{-1} & & & & & & & & & & & & G_{-2N+1} \\
G_{2} & G_{-1} & G_{0} & & & & & & & & & & & & G_{-2N+2} \\
 & & & G_{0} & & & & & & & & & & & \\
 & & & & G_{0} & & & & & & & & & & \\
 & & & & & G_{0} & & & & & & & & & \\
G_{N-1} & G_{N-2} & G_{N-3} & & & G_{1} & G_{0} & G_{-1} & & & & & & & G_{-N-1} \\
G_{N} & G_{N-1} & G_{N-2} & & G_{3} & G_{2} & G_{1} & G_{0} & G_{-1} & G_{-2} & G_{-3} & & & & G_{-N} \\
G_{N+1} & G_{N} & G_{N-1} & & & & & G_{1} & G_{0} & G_{-1} & & & & & G_{-N+1} \\
 & & & & & & & & & G_{0} & & & & & \\
 & & & & & & & & & & G_{0} & & & & \\
 & & & & & & & & & & & G_{0} & & & \\
 & & & & & & & & & & & & G_{0} & & \\
 & & & & & & & & & & & & & G_{0} & \\
G_{2N} & G_{2N-1} & G_{2N-2} & & & & & & & & & & & & G_{0}
\end{array}\right]
\bullet
\left[\begin{array}{c}
V_{-N}^{*} \\
V_{-N+1}^{*} \\
\\
\\
\\
\\
V_{-1}^{*} \\
V_{0} \\
V_{1} \\
\\
\\
\\
\\
V_{N-1} \\
V_{N}
\end{array}\right]
$$

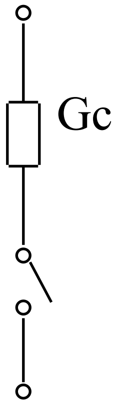
The conversion matrix can be extended by reactive components, forming a conversion matrix in admittance form. This is a valuable tool when analysing the properties of diode and transistor mixers. We have now transfered the nonlinear problem to the frequency domain and can use linear equations for solving the problem.

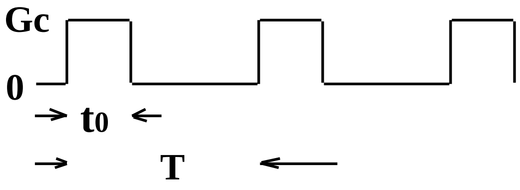


We want to know how the mixer properties depend on the characteristic of the conductance waveform and the embedding impedance

non-square waveform, harmonic response

To illustrate the harmonic response, lets look at G_n as a function of the duty-cycle for a simple case, an ideally switched conductance





$$g(t) = \sum_{n=-\infty}^{\infty} G_n \cdot \exp(j \cdot n \cdot \omega_p \cdot t)$$

$$G_n = \frac{1}{T} \int_{-\frac{T}{2}}^{\frac{T}{2}} g(t) \cdot \exp(-j \cdot n \cdot \omega \cdot t)$$

We obtain: $G_0 = \frac{t_0}{T} \cdot G_C$, $G_1 = \frac{G_C}{\pi} \cdot \sin(\pi \cdot \frac{t_0}{T})$

$G_2 = \frac{G_C}{2\pi} \cdot \sin(2\pi \cdot \frac{t_0}{T})$, $G_3 = \frac{G_C}{3\pi} \cdot \sin(3\pi \cdot \frac{t_0}{T})$

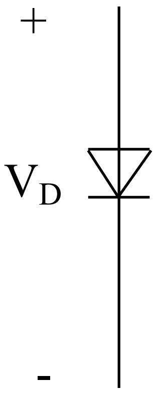
$G_4 = \frac{G_C}{4\pi} \cdot \sin(4\pi \cdot \frac{t_0}{T})$, $G_5 = \frac{G_C}{5\pi} \cdot \sin(5\pi \cdot \frac{t_0}{T})$

the diode and FET/HEMT as a variable resistance

The most used device for the resistive mixer is the Schottky diode, it can be used up to THz-frequencies.

The FET-based resistive mixer is an interesting alternative if

1. generation of intermodulation products is critical
2. FET/HEMT based MMIC designs are considered
3. LO and RF are close together and large bandwidth is required

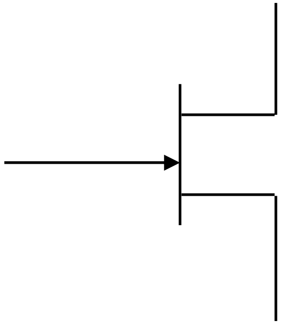


$$I_D = I_0 \cdot e^{q\cdot V_d/\eta kT}$$

$$r_B = \left(\frac{\partial I_D}{\partial V_D}\right)^{-1} \rightarrow \frac{\eta kT}{qI_D}$$

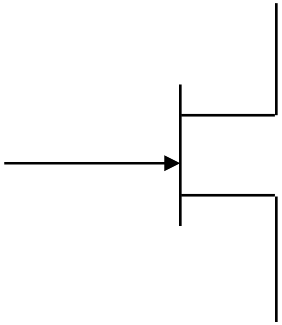
or $r_B = k \cdot e^{-q\cdot V_d/\eta kT}$

$$I_{DS} = K(V_{GS})\cdot\left(1+\lambda\cdot V_{DS}\right)\cdot\tanh(\alpha\cdot V_{DS})$$



2. FET-HEMT models for resistive mixers

The FET can be used as a variable resistance, controlled by the gate-voltage
The LO is applied to the gate, RF and IF to the drain, Vds≈0 V
The Id-Vd characteristic is approximately linear at low Vds which makes the FET-resistive mixer linear ! It's exponential for a diode !



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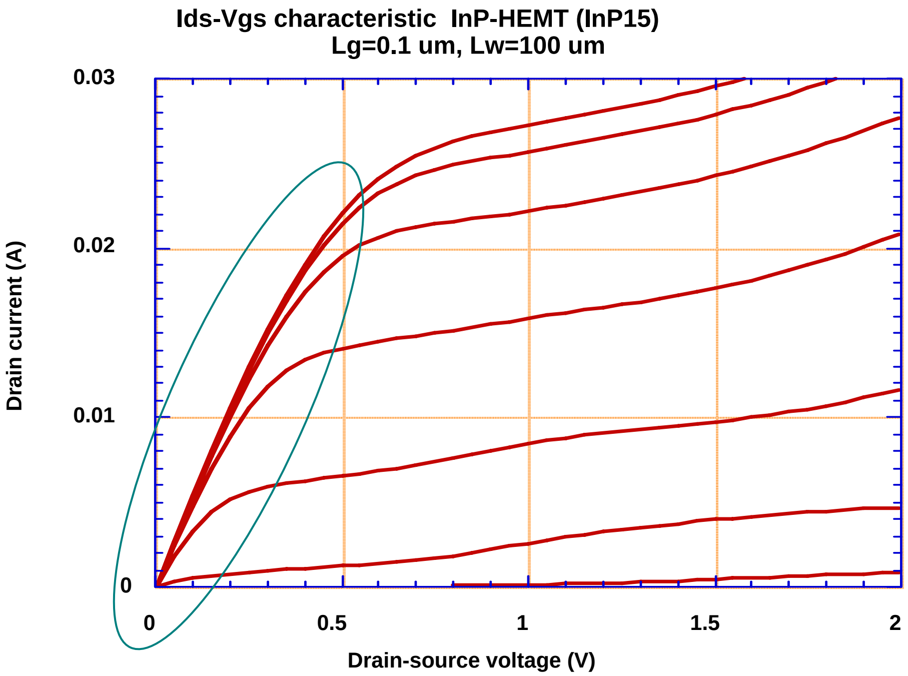
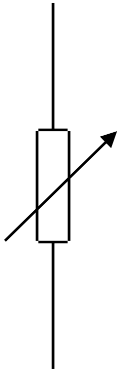
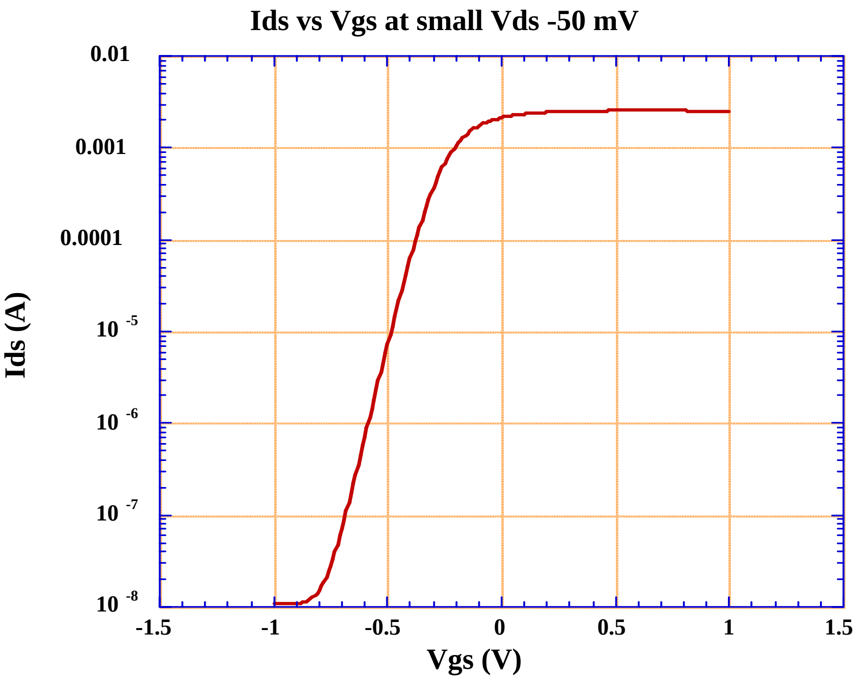


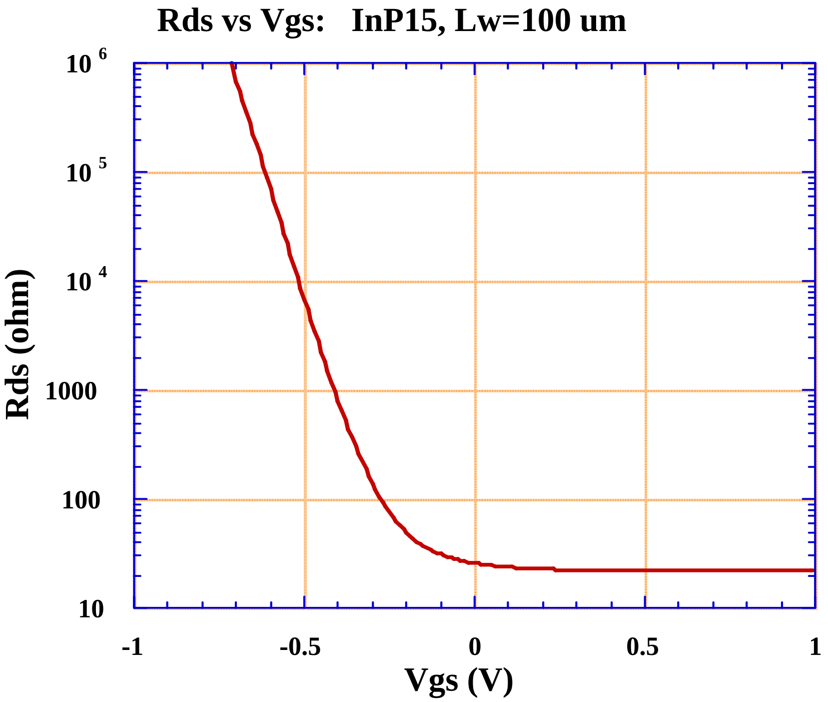
linear resistor
controlled by Vgs

=



The Rds-Vgs slope is important for the determination of the LO-power requirement of the mixer





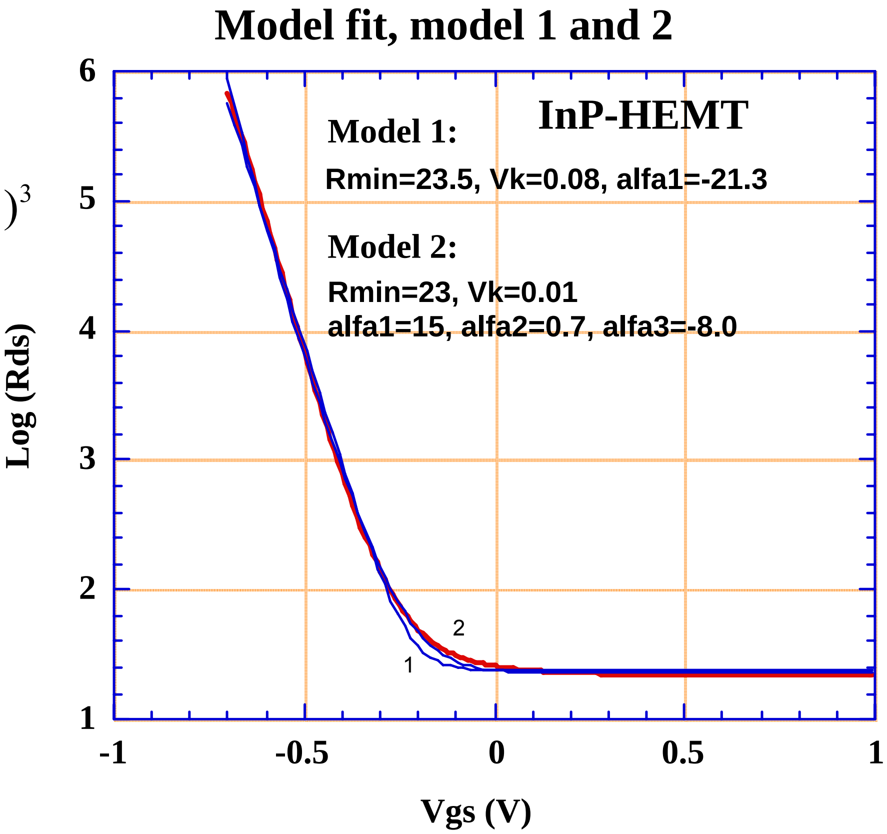
IEEE MMIC seminar Bergen 2006 10 06 H Zirath

In order to model the mixer performance, an empirical model describing the Rds-Vgs characteristic is useful. The example shows an InP-HEMT

Empirical model equations :

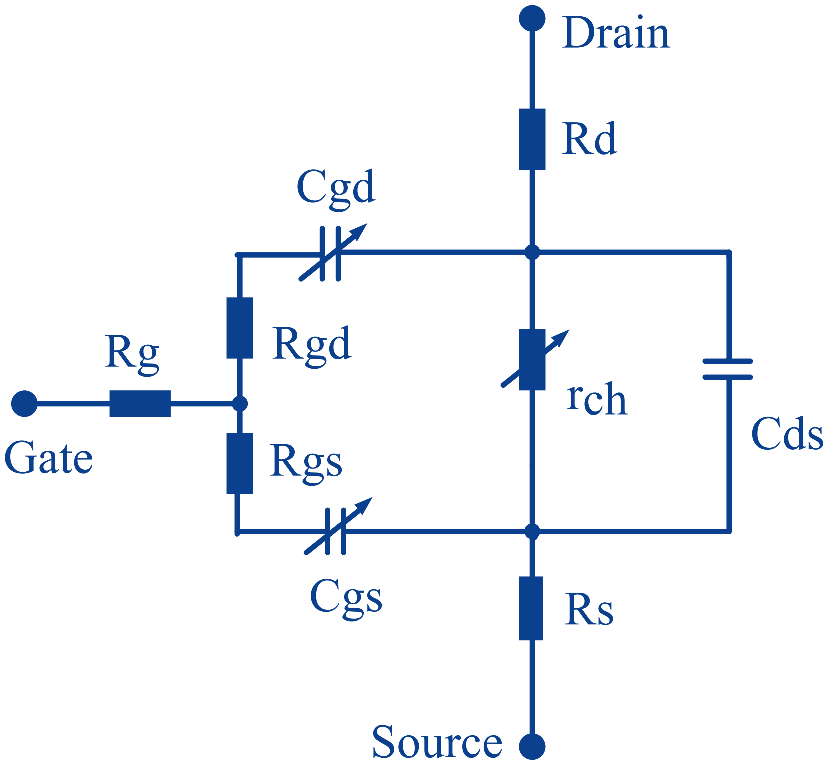
1. $R_{DS} = R_{MIN} \cdot (\exp(\alpha(V_{GS} - V_K)) + 1)$
2. $R_{DS} = R_{MIN} \cdot (\exp(\Psi) + 1)$

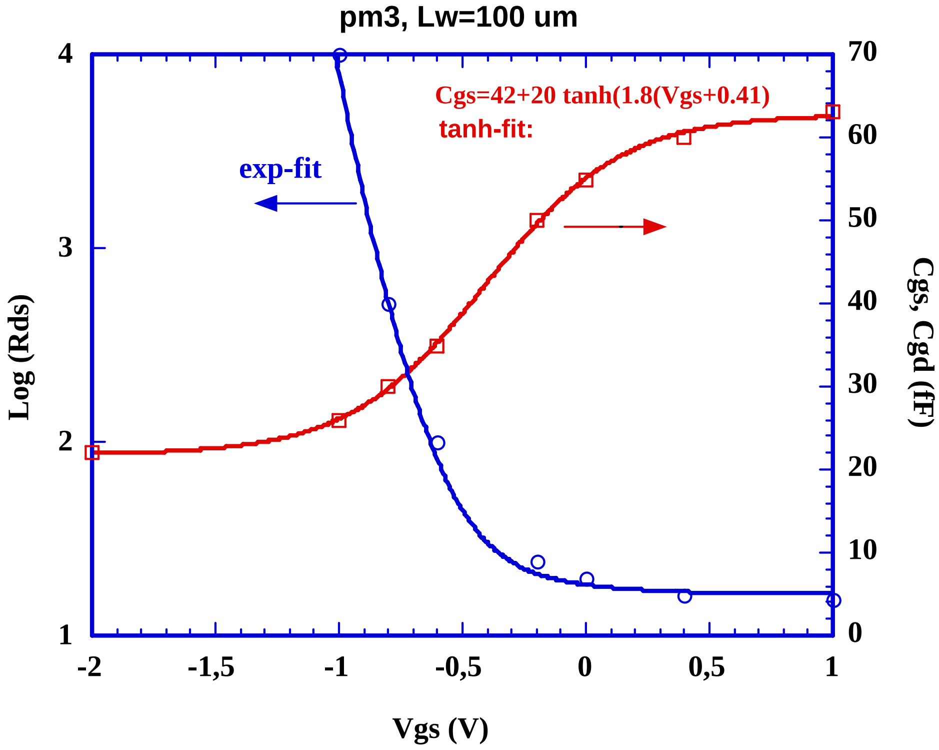
$$\Psi = \alpha_1 (V_{GS} - V_K) + \alpha_2 (V_{GS} - V_K)^2 + \alpha_3 (V_{GS} - V_K)^3$$



The equivalent circuit including capacitances

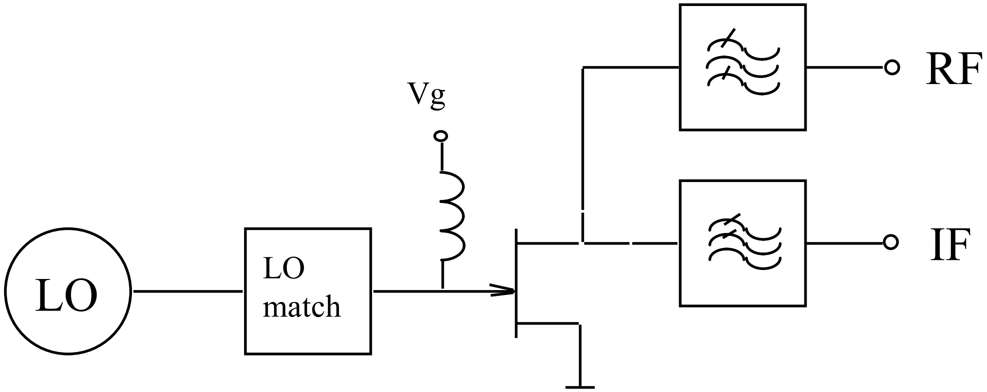
For 'small signal' simulations this equivalent circuit is used
rch and cgs,cgd are the most important bias-dependent parameters
(Rds is now split into Rd+rch+Rs)





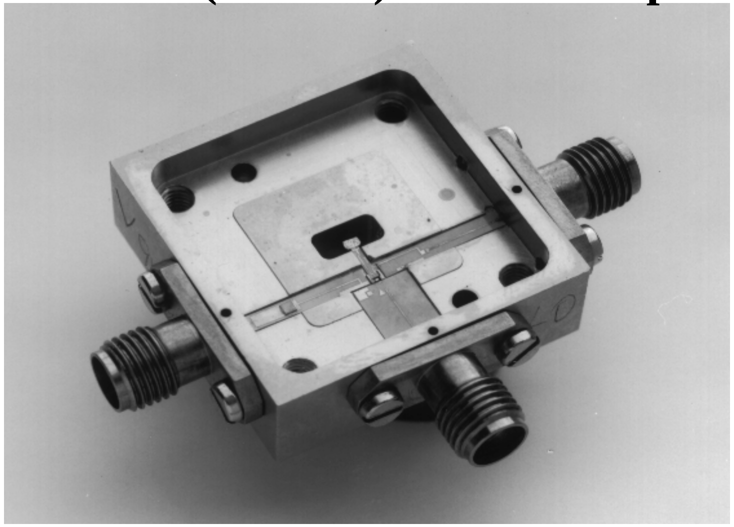
Performance of different FET-HEMT based resistive mixers

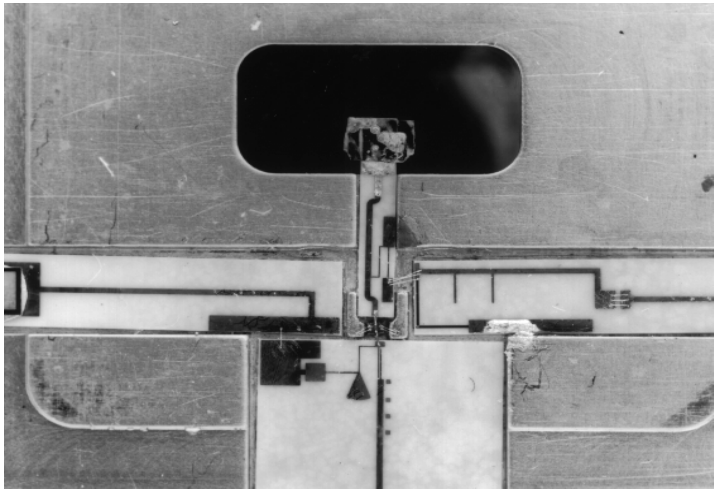
3. The single-ended mixer (1)



This mixer is simple since no hybrids/filters are needed for the LO-injection->high BW.
The LO-RF-isolation is of the order 10-20 dB depending mainly on the transistor design.
The total conversion loss is less than 6 dB
The required LO-power is typically 0-10 dBm depending mainly on the transistor type

Q-band-mixer (50 GHz) with WG-input:



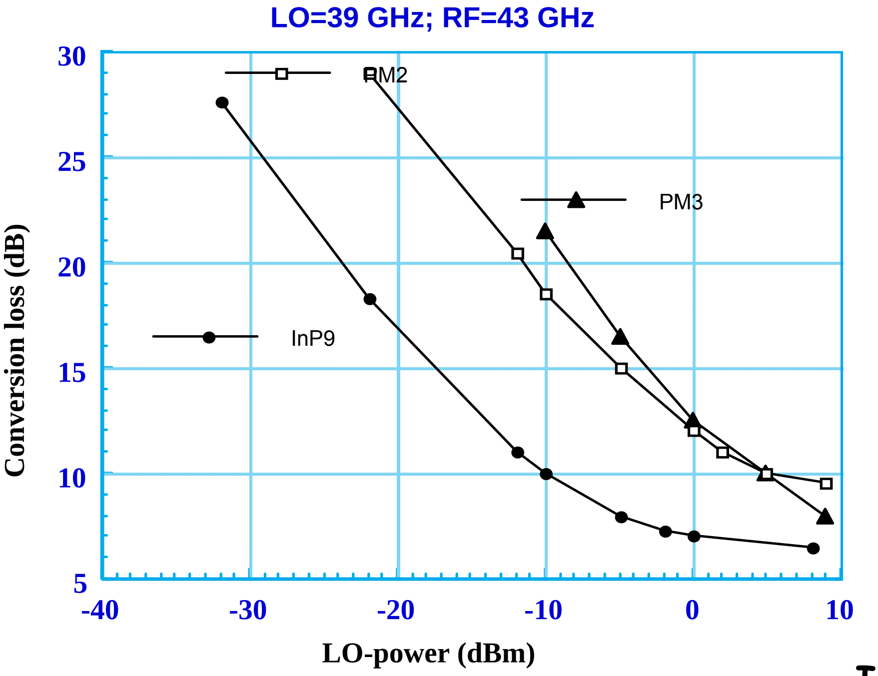


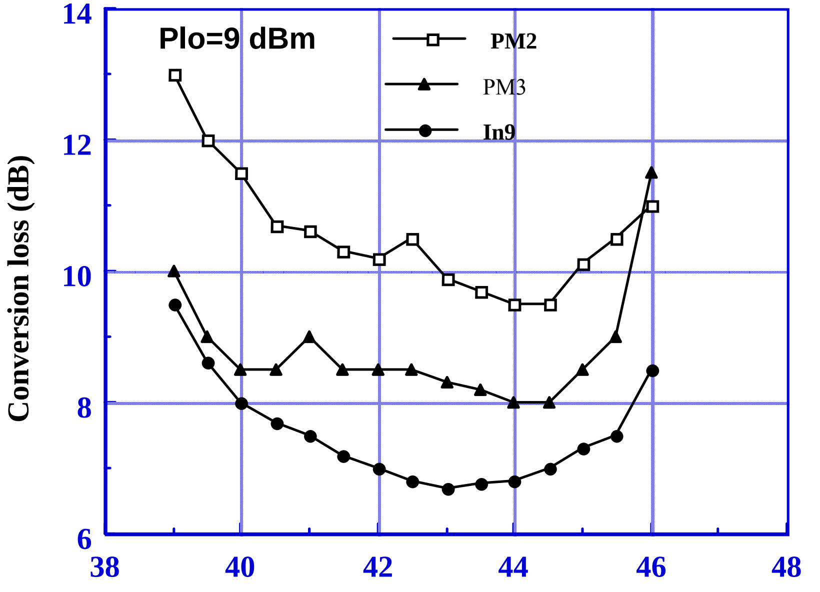
The single-ended mixer (2)

comparison between different HEMTs

Three different HEMTs where compared in a 40 GHz MIC-mixer:

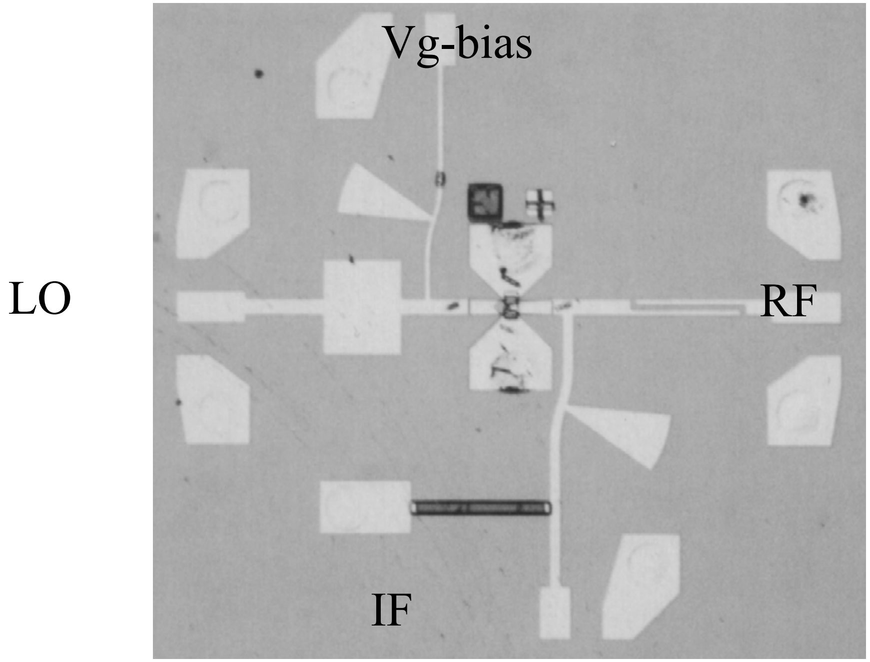
1. Single delta doped AlGaAs-InGaAs-GaAs HEMT. (PM2)
2. Double delta doped AlGaAs-InGaAs-GaAs HEMT. (PM3)
3. Single delta doped AlInAs-GaInAs-InP HEMT. (InP9)

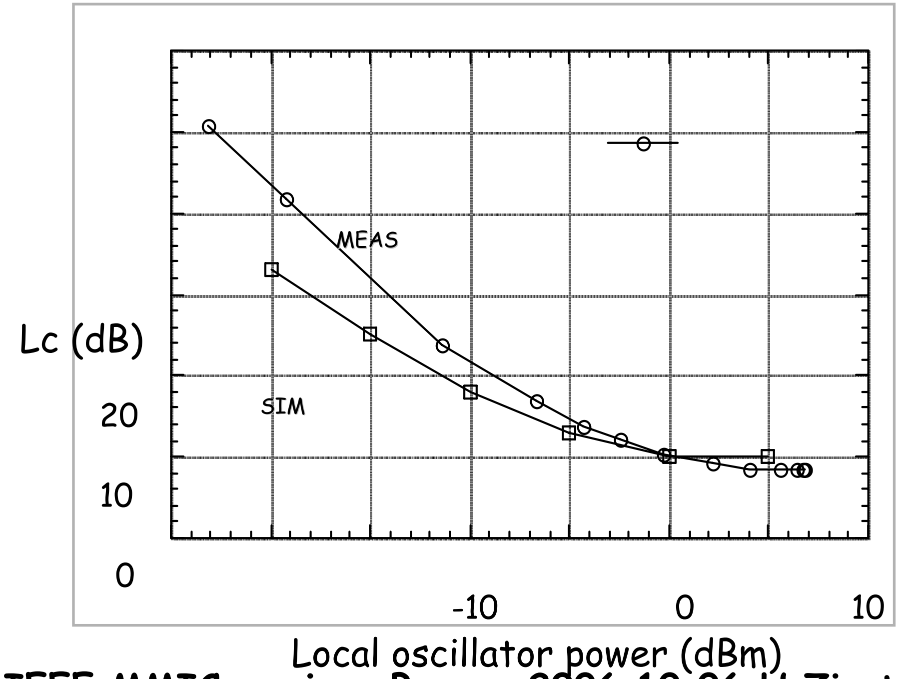

LO=39 GHz; RF=43 GHz



MMIC mixer

Resistive FET-mixers have been realized up to F-band, this monolithic mixer is based on an AlInAs-GaInAs-InP HEMT-technology (including vias) and made at CTH. The conversion loss is ≈ 9 dB at 4 dBm LO-power. Frequency is 115 GHz.



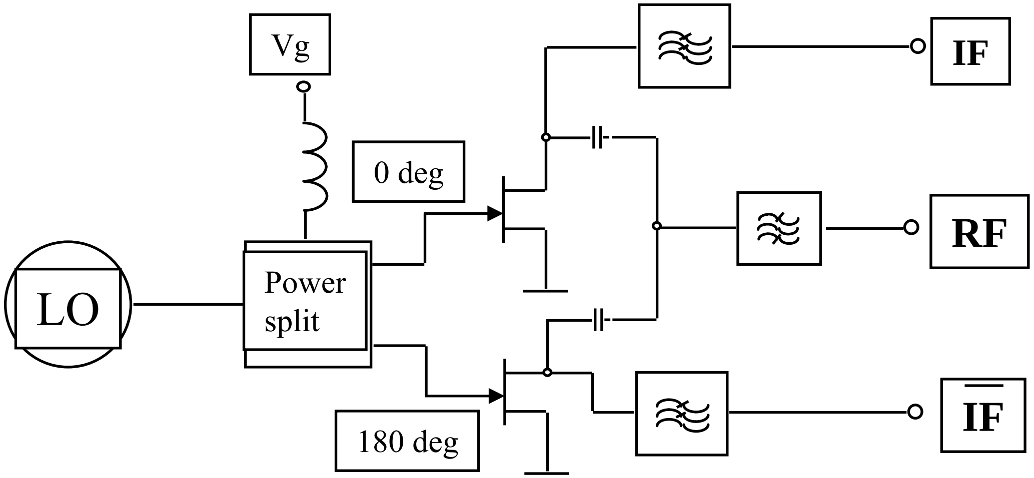


Balanced mixers

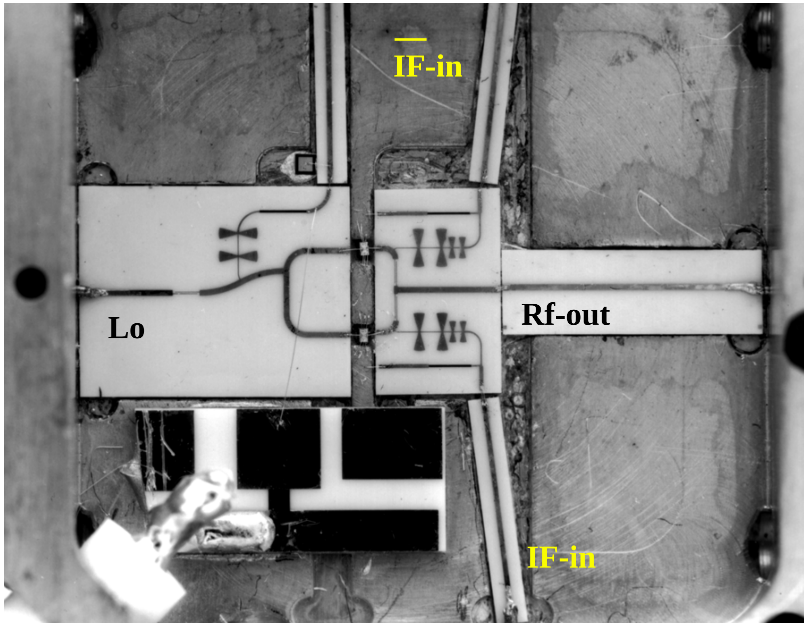
In applications where high LO-RF isolation is required, a balanced mixer can be used. The LO is splitted with 180 deg phase difference between the two ports. The residual LO at the drains will be minimized.

An LO-RF isolation of better than 35 dB and a total conversion loss of better than 10 dB was obtained for this balanced 50-60 GHz upconverting mixer with 5 dBm LO-power.

Block diagram:



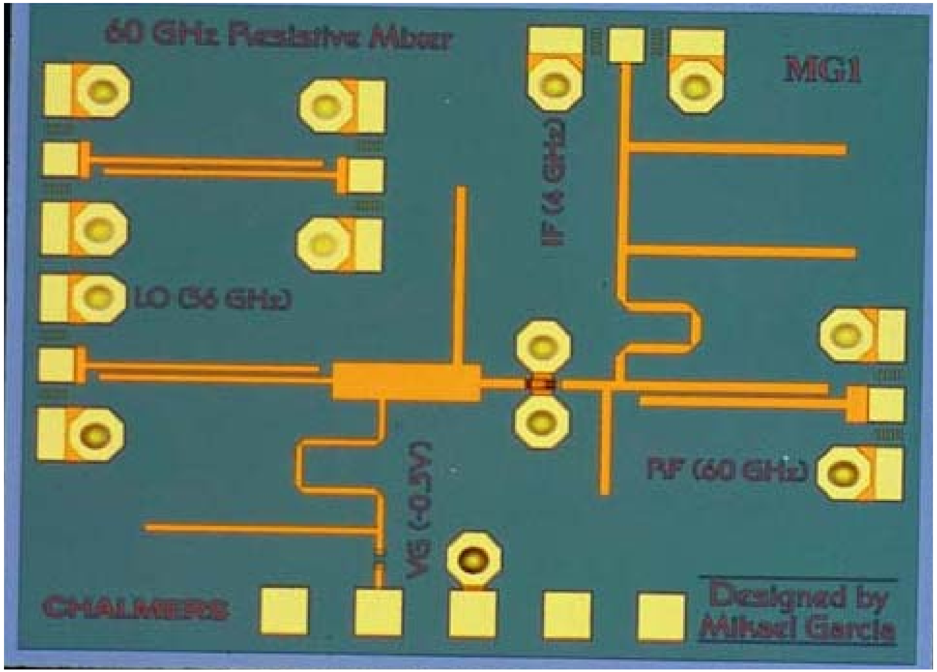
55 GHz Alumina MIC-mixer



60 GHz resistive mixer

MMIC implementation Process D01PH and D01MH

This mixer is based on the principle of resistive mixing i e the Local Oscillator power is applied to the gate causing the drain-source resistance to be time-dependent. The RF and IF signals are applied/ extracted to/from the drain through a diplexer. The mixer has usually good intermodulation properties.

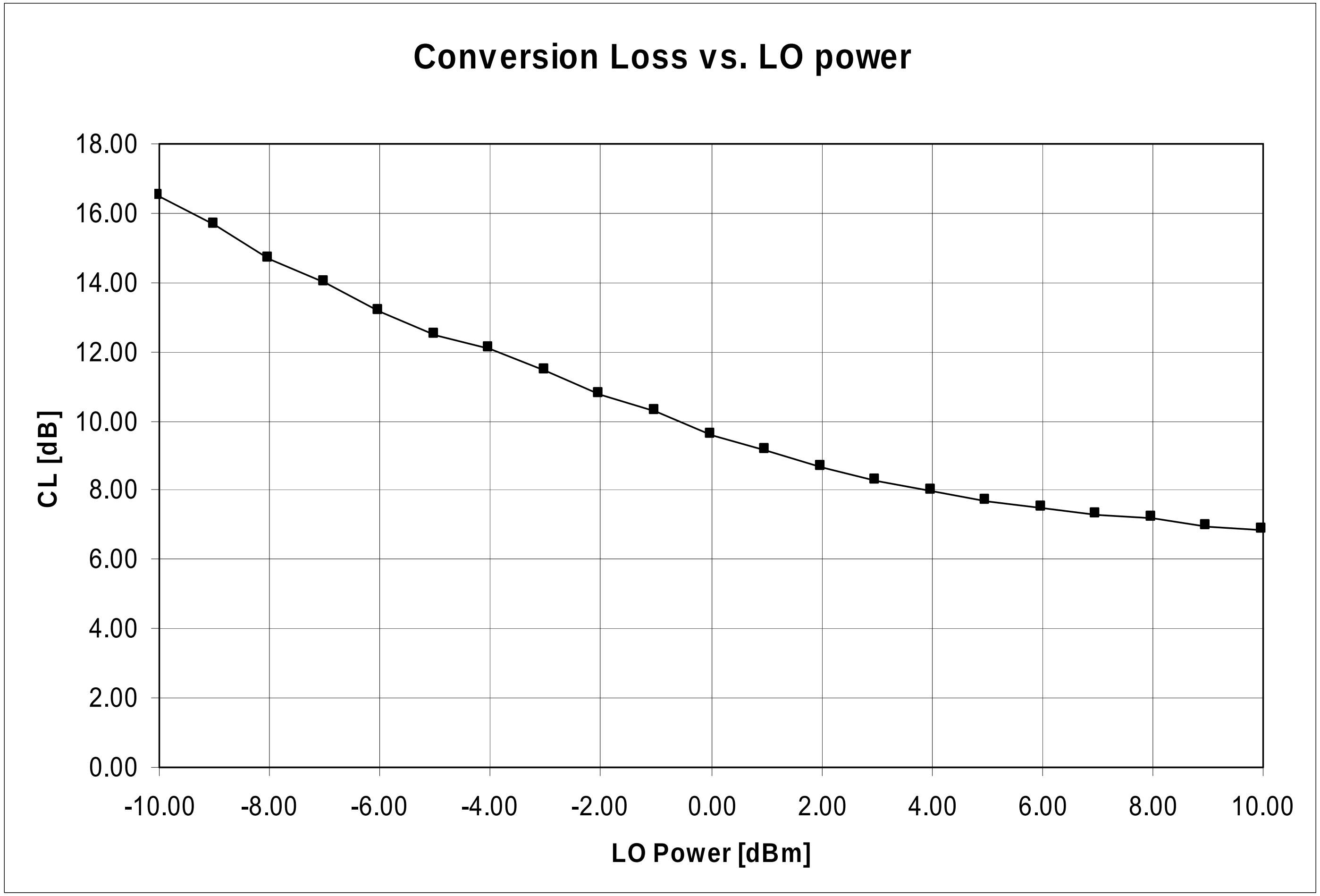


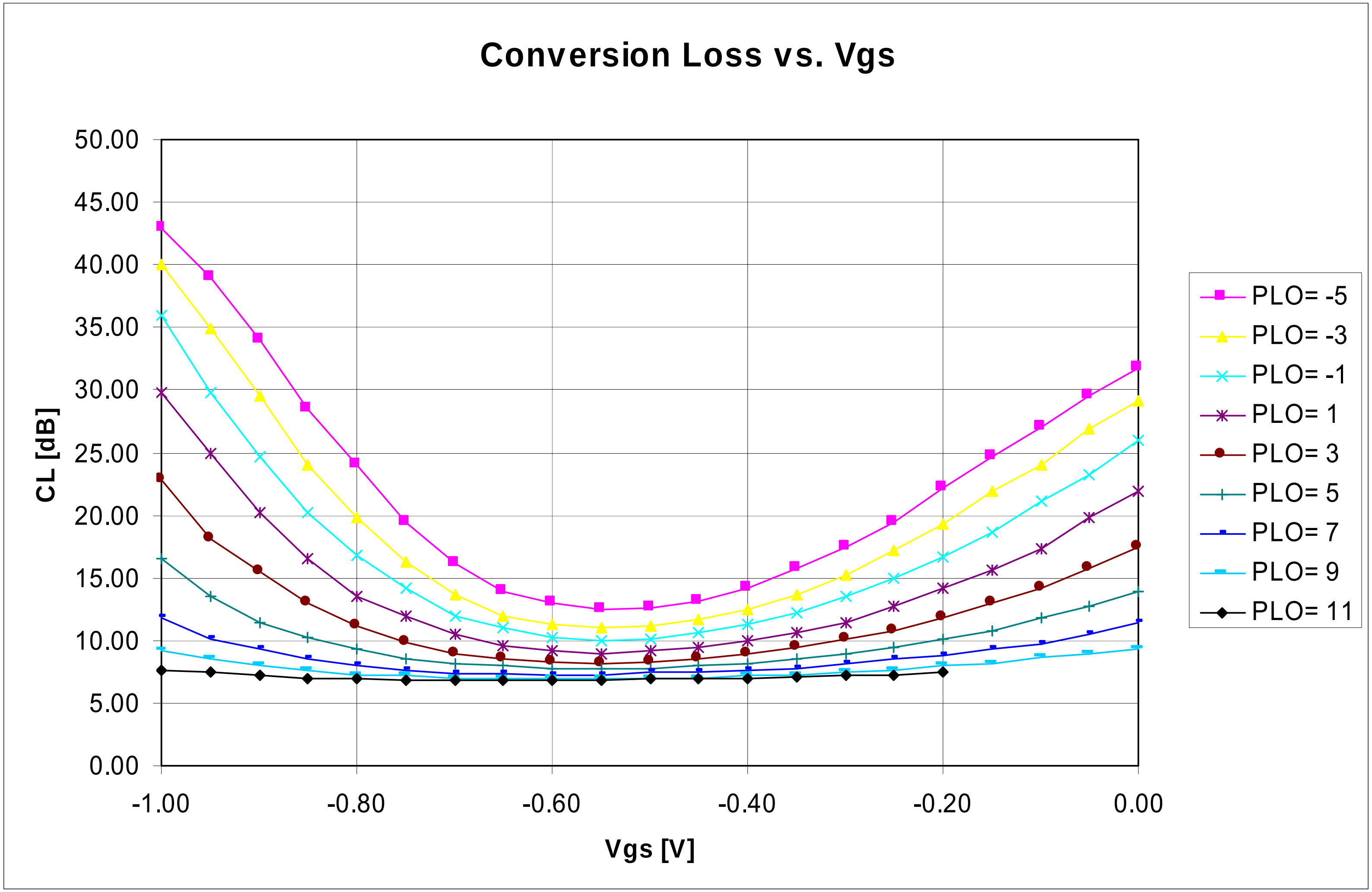
IF-out

LO-in

RF-in

Measured results 50-62 GHz:



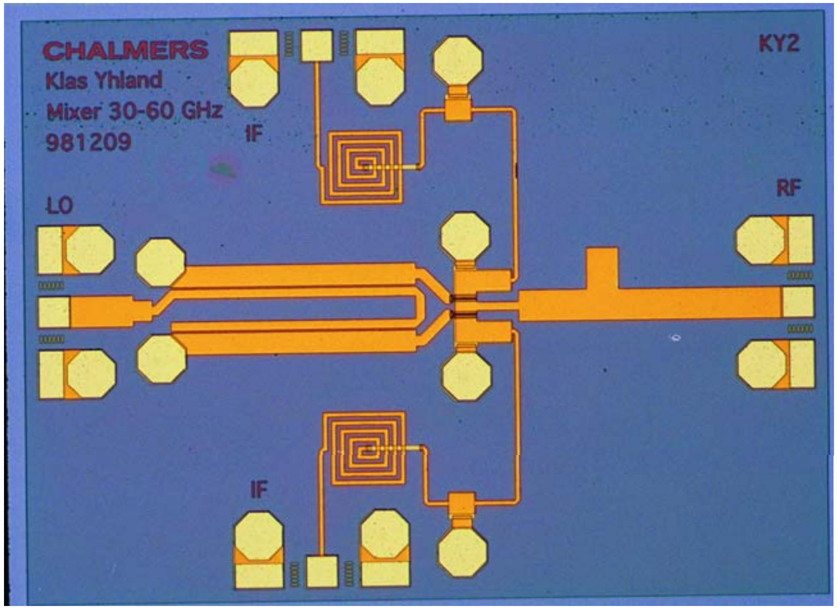

Conversion Loss vs. Vgs
CL [dB]
50.00
45.00
40.00
35.00
30.00
25.00
20.00
15.00
10.00
5.00
0.00
-1.00
-0.80
-0.60
-0.40
-0.20
0.00
Vgs [V]
PLO= -5
PLO= -3
PLO= -1
PLO= 1
PLO= 3
PLO= 5
PLO= 7
PLO= 9
PLO= 11

Balanced resistive mixer topology

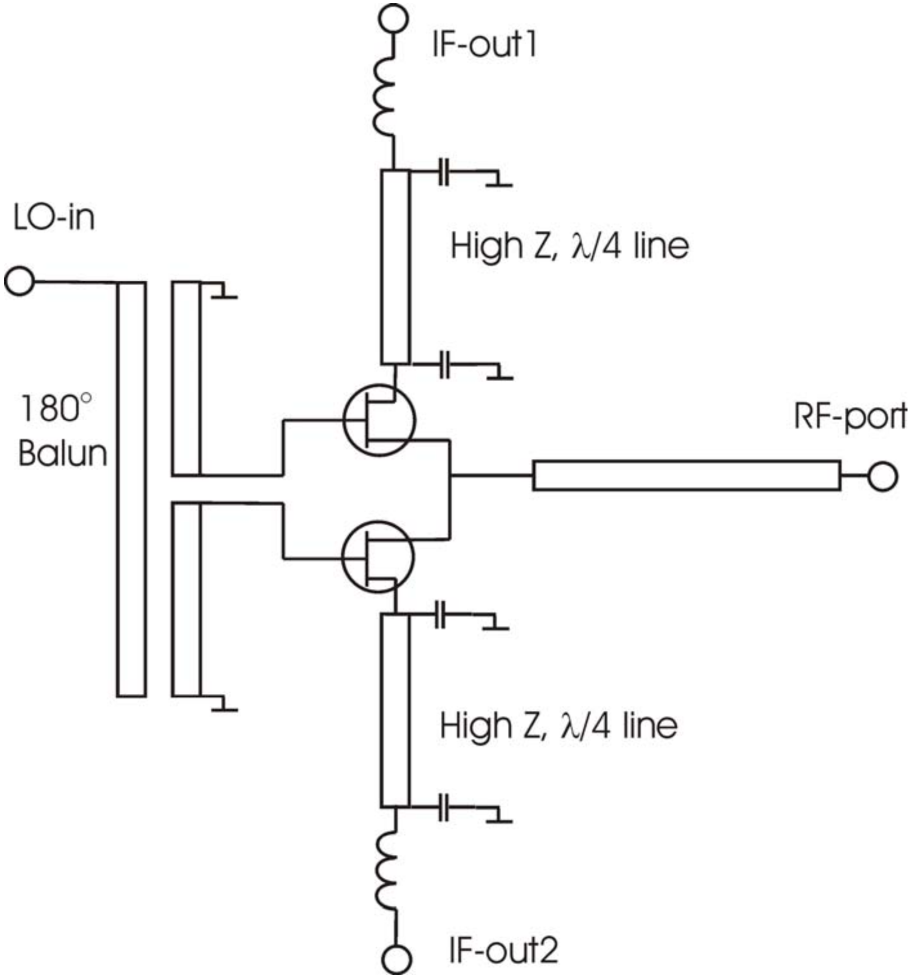
-LO is fed to mixers with a 180 deg phase difference->>>>

-The residual LO will cancel at the drain

-A Marchand balun for broadband operation...



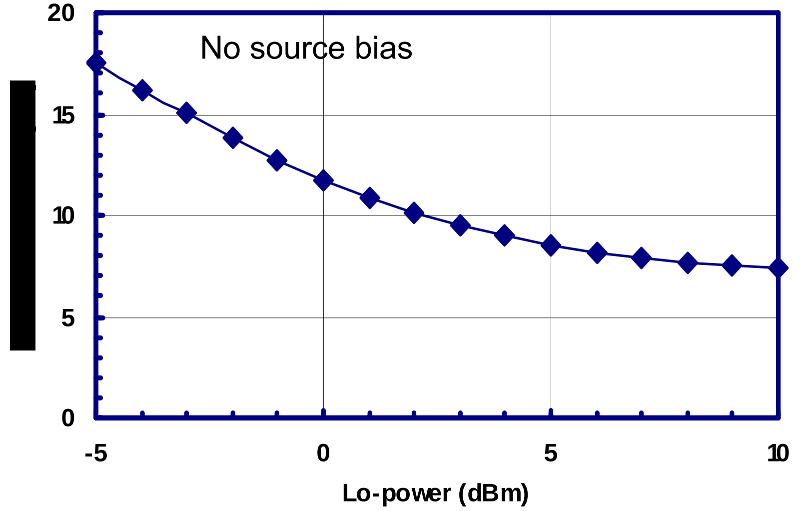
MMIC implementation Process D01PH and D01MH

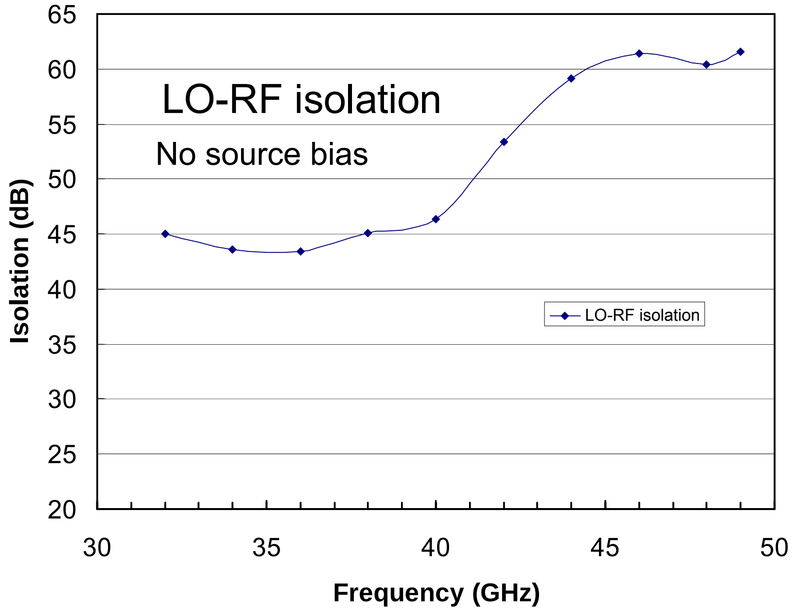


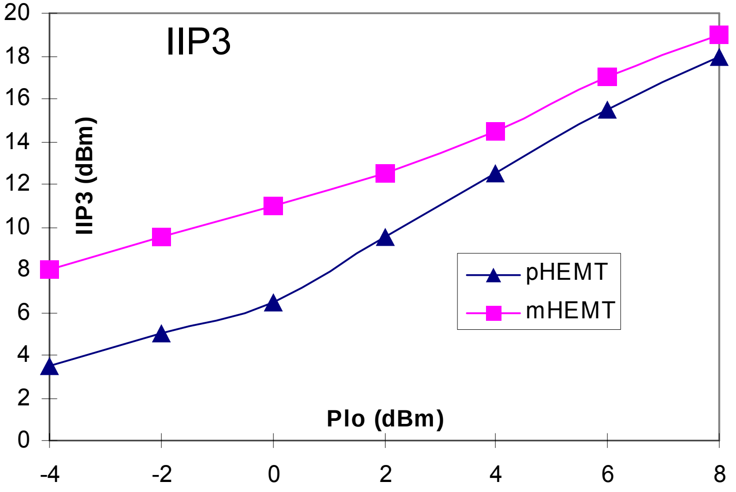
Short form data:

30-60 dB LO->RF isolation, IIP3 =19dBm at 8 dBm PLO

5-8 dB NF (DSB), $P_{-1} \approx P_{LO}+(2\text{-}4\text{dB})$


[redacted]





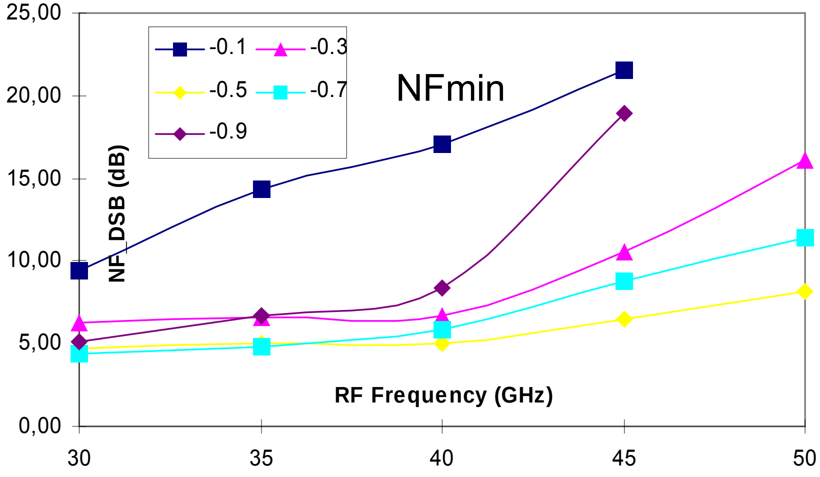
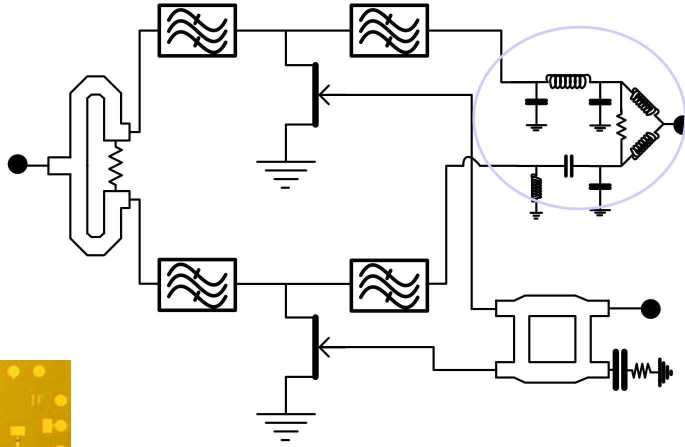


Image reject mixer (IRM)

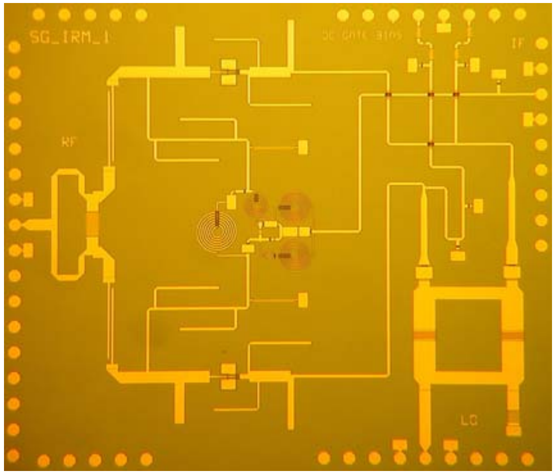
Three designs in WINs pHEMT/mHEMT technologies

Topology:

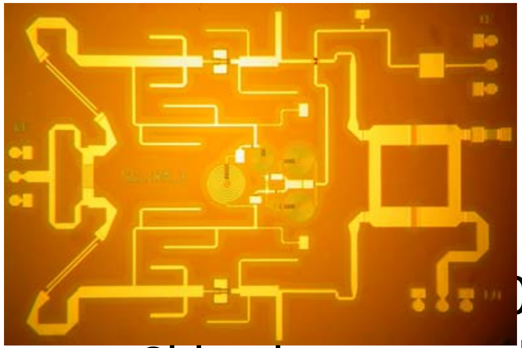


Design by
Tech. Lic. Dan
Kuylenstierna

Wil
sp

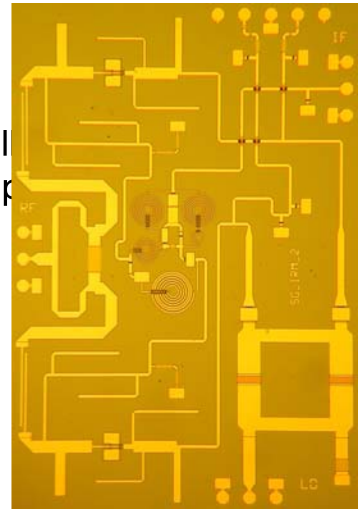


Chip photo,
pHEMT,
3.3 × 2.8 mm²



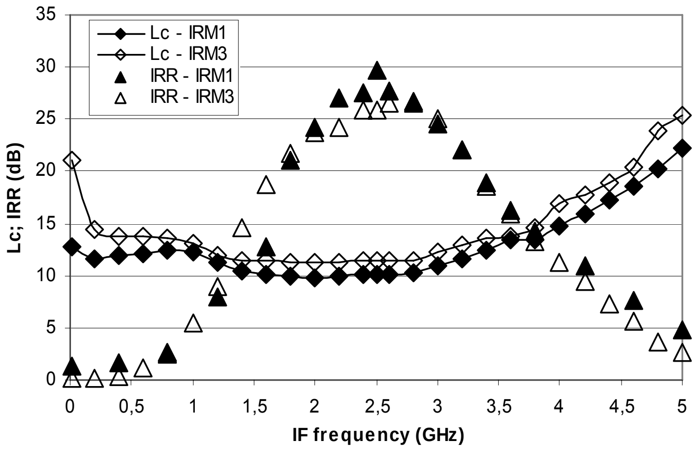
Chip photo,
mHEMT,
3.3 × 2.3 mm²

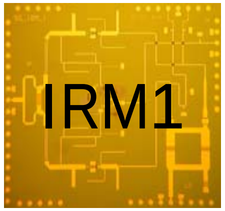
0GHz
RF

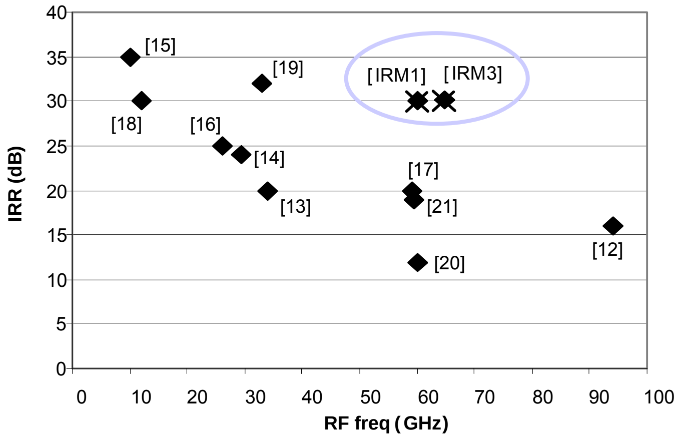


Chip photo,
RF filter
pHEMT,
2.0 × 2.9 mm²

Image reject mixer (IRM)







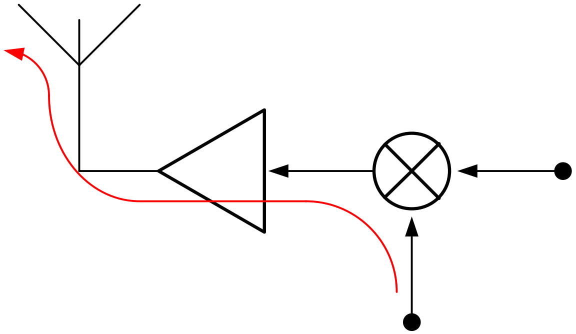
Conversion loss and image rejection ratio versus IF frequency

Comparison with IRMs published by others, (references according to paper E)

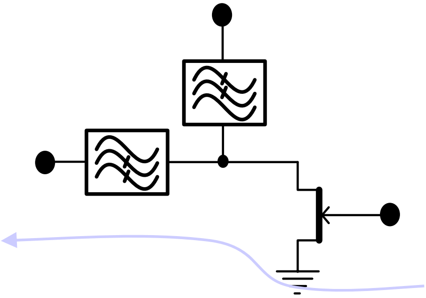
World record in image rejection ratio (IRR) versus RF frequency. Ultra wideband IF characteristics!

Balanced resistive mixer (BRM)

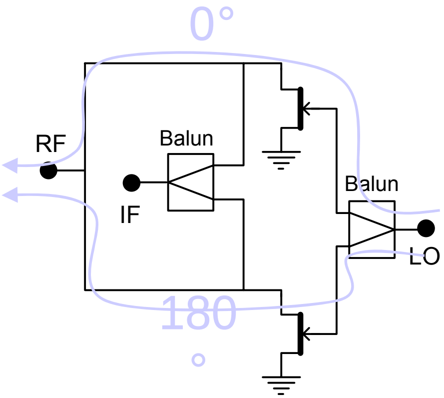
Motivation: Supresses the LO to RF leakage



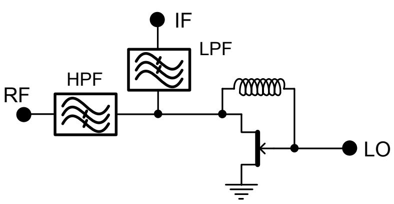
Simple transmitter

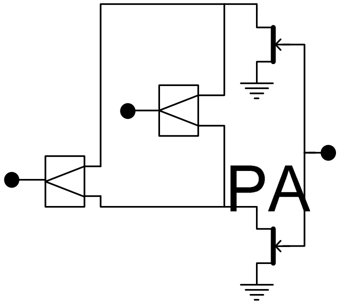


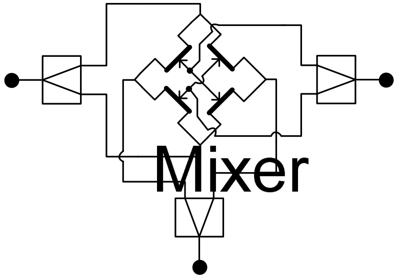
Single-ended resistive mixer

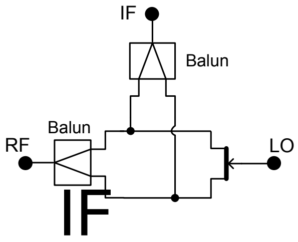


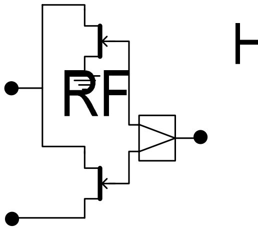
Balanced resistive mixer





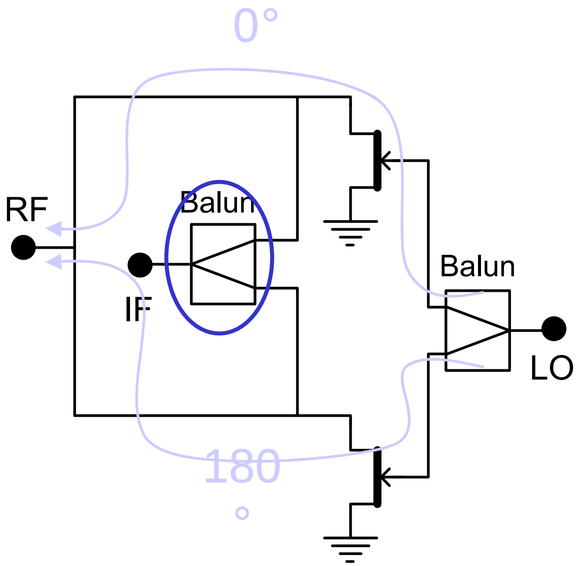




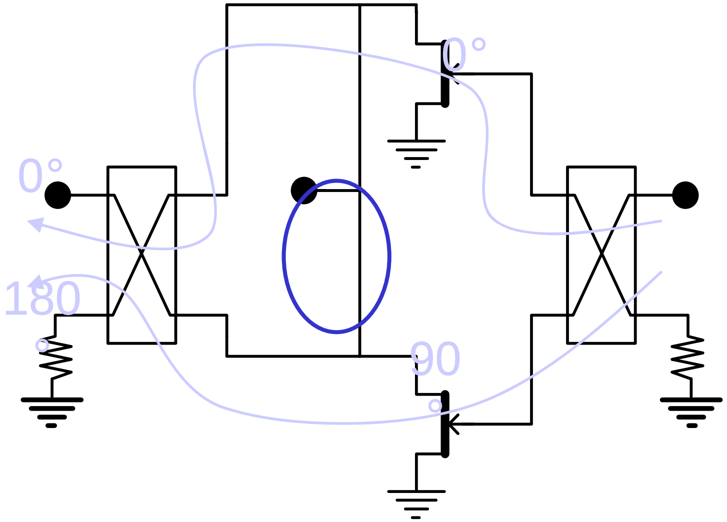


Dual-Quadrature mixer (DQM)

Motivation: Supresses the LO to RF leakage *while maintaining a broad IF bandwidth*



Balanced resistive mixer



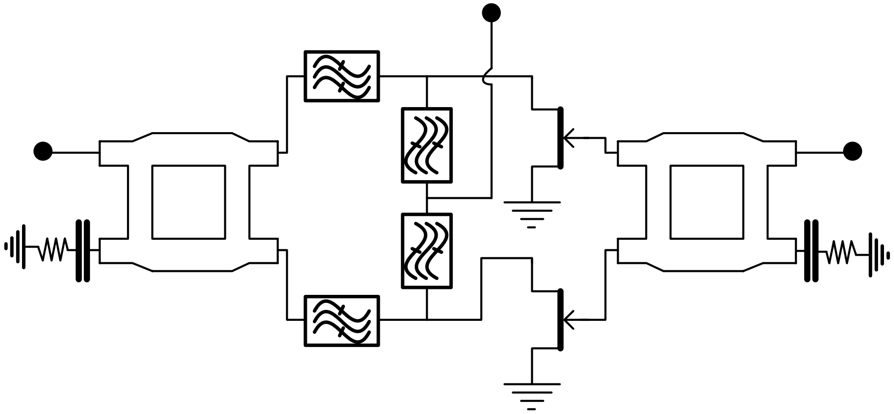
Dual-Quadrature mixer

The BRM requires an IF balun! A integrated IF balun has a typical bandwidth of a few 100 MHz.

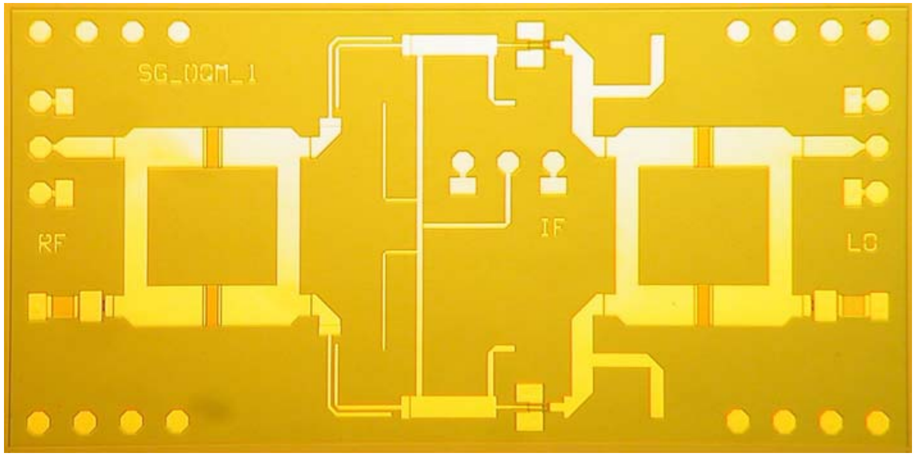
NO IF balun required in the DQM! An IF bandwidth of many GHz is possible!!

Dual-Quadrature mixer (DQM)

WIN pHEMT technology



Topology



Chip photo, 3 × 1.5 mm^2

RF filter

2.0 GHz
IF

60 GHz
RF

Branch Line
Coupler

Branch Line
Coupler

58 G
LO

IF filter

The DQM topology was for the first time recognized for its potential to achieve high LO to RF isolation (> 20 dB) while maintaining a very broad IF bandwidth (11.5 GHz!)

IF filter

Why 60 GHz?

- 59 – 63 GHz license free band
- 4 GHz (!) of bandwidth → High speed wireless communication
- High oxygen absorption → Less interference → Shorter cell re-use distance
- Today: Commercial GigaBit-Ethernet links (1.25 Gbps)
- Future: Multi-GigaBit links, FWA, WLAN, WPAN, Roadside communication...

TERABEAM
WIRELESS

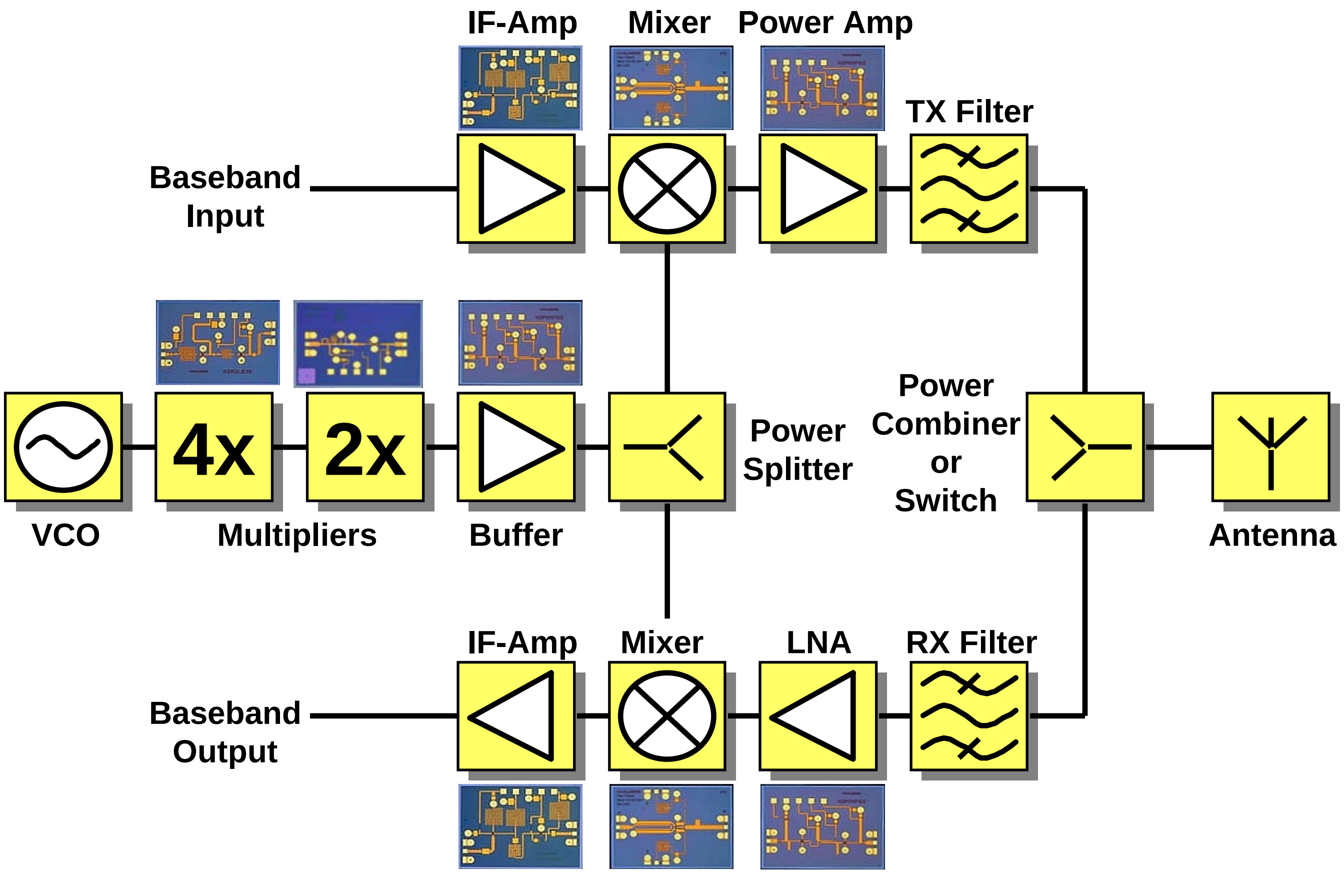
AirFiber

NRDtech® NRDtech Co., Ltd.
Non Radiative Dielectric

BridgeWave

60 GHz activities at Chalmers – the beginning

1997 – 2001 : The “60 GHz WLAN” project (CTH, Ericsson, KTH, and FOI within CHACH)



Paper B
and C

60 GHz activities at Chalmers – continuation

2003 – 2005 : The “60 GHz broadband wireless communication systems (BRAWO)” project (CTH and Ericsson within CHACH)

Integrate all sub-blocks in a 60 GHz front-end into single-chip transmitter (TX) and receiver (RX) MMICs

Three main design goals were formulated:

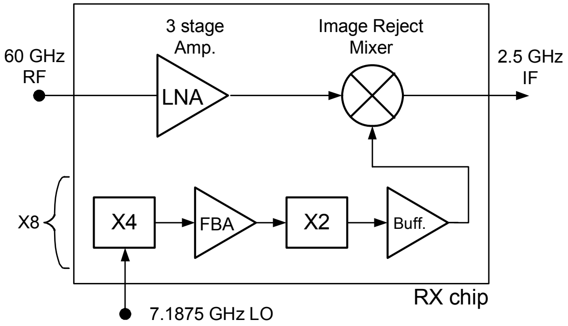
- As high level of integration as possible
- As general design in terms of modulation format as possible
- As high data rate as possible → Transmission of broadband signals, i.e. high data rate!!

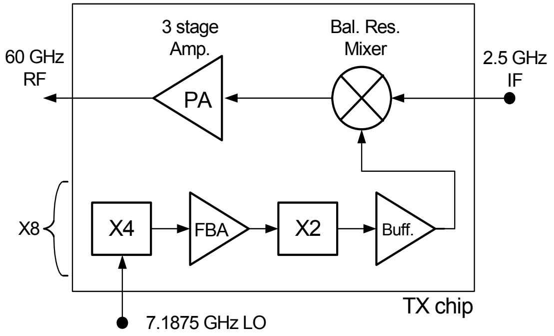
Design group at Chalmers: Sten E. Gunnarsson, Camilla Kärnfelt, Herbert Zirath, Rumen Kozhuharov, and Dan Kuylenstierna

Receiver (RX) and Transmitter (TX) chip designed at Chalmers – topology and chip photo

Two versions in WINs pHEMT/mHEMT technologies

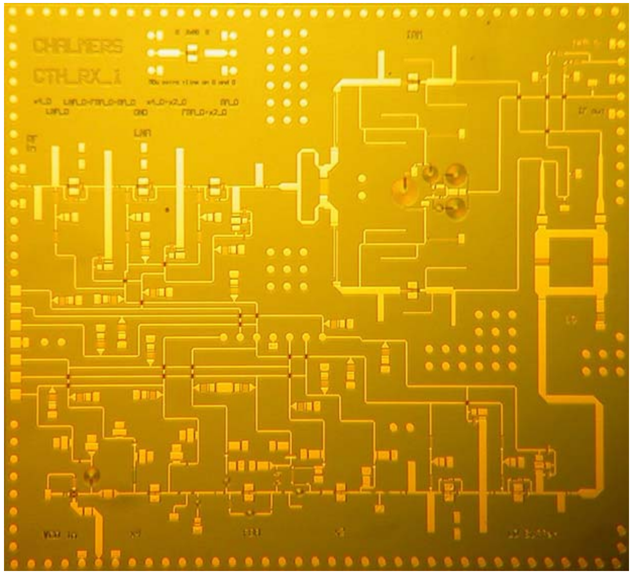
Topology
- RX

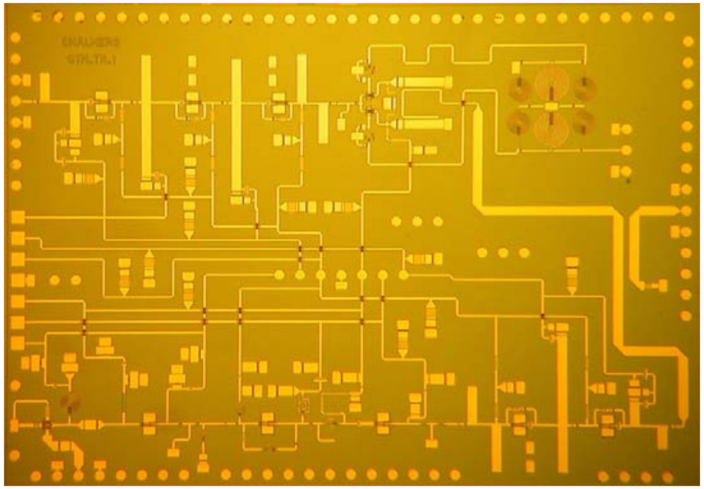




Topology
- TX

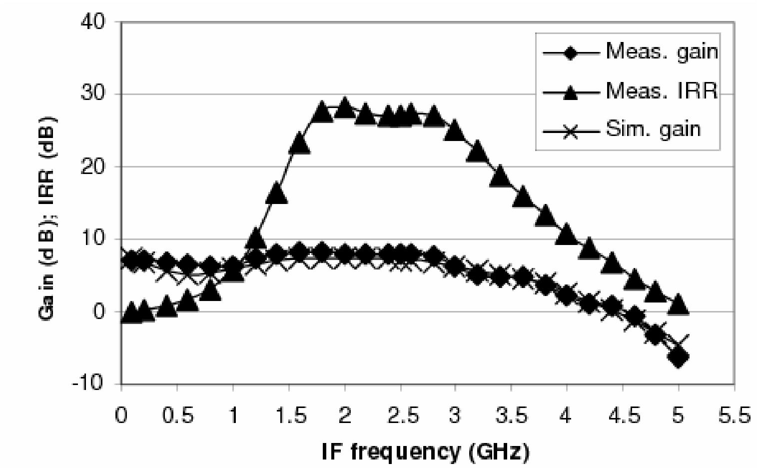
Chip photo,
pHEMT,
5.7 x 5 mm^2



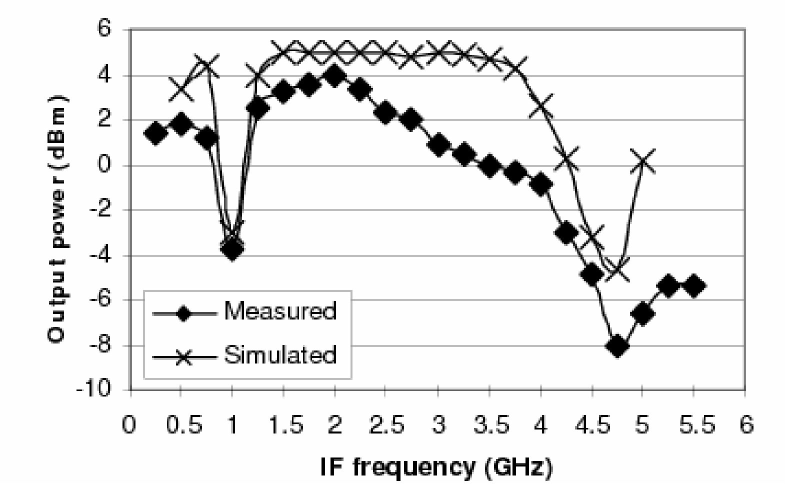


Chip photo,
pHEMT,
5 x 3.5 mm^2

Receiver (RX) and Transmitter (TX) chip designed at Chalmers – measured results



Conversion Gain and Image Rejection Ratio versus IF Frequency for the **RX chip**, f_{LO}=7.1875 × 8 =57.5 GHz.



Maximum output power versus IF frequency for the **TX chip**, f_{LO}=7.1875 GHz × 8 =57.5 GHz.

”First-shot” in pHEMT. *World record in terms of integration of a 60 GHz front-end*

Redesigned and more compact chips in mHEMT

- Smaller
- Higher gain
- Half of the DC power consumption