Hoch- und Höchstfrequenzhalbleiterschaltungen (HHHS)
Millimetre-wave monolithic integrated circuit design

Winter term 2013/2014

Frequency Mixer

INSTITUT FÜR HOCHFREQUENZTECHNIK UND ELEKTRONIK

lecture outline

- fundamentals of frequency mixing
- applications and figures of merit
- circuit topologies to realize diode and FET based mixers
  - diode mixer
  - passive FET mixer
  - active FET mixer
  - balanced mixer
  - IQ mixer

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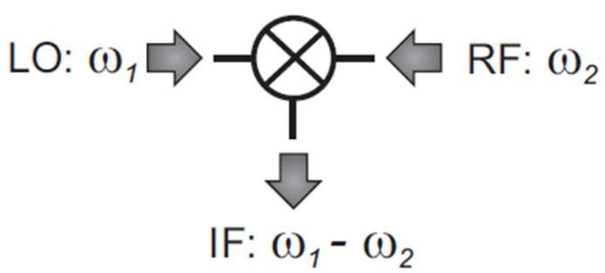
frequency translating circuits

- This part of the lecture is based on the lecture “Active integrated circuits for millimetre wave applications (AICMMA)”, which was given by Prof. Ingmar Kallfass, who is now with the University of Stuttgart.
- Additionally, it is based on the thesis “Broadband Transceiver Circuits for Millimeter-Wave Wireless Communication” by Daniel Lopez-Diaz

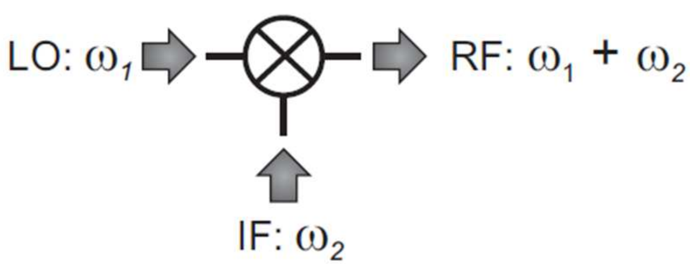
function	input frequency	output frequency
amplifier	f_0	f_0
harmonic generator	f_0	$i * f_0$, $i = 1, 2, \ldots$
frequency multiplier	f_0	$n * f_0$
(fundamental) mixer	f_0	f_{LO} +/- f_0
sub-harmonic mixer	f_0	$n * f_{LO}$ +/- f_0

mixer: a three-port device

- RF, radio frequency
  - input in a receiver or output in a transmitter
  - a modulated signal in the mmW frequency range
- LO, local oscillator
  - input in the same frequency range as the RF signal (fundamental mixer)
  - input at 1/n-th RF frequency range (sub-harmonic mixer)
- IF, intermediate frequency
  - output in a receiver or input in a transmitter
  - usually, a low frequency signal



- mixer as down-converter



- mixer as up-converter

frequency conversion

- down-conversion mixer
  - e.g. mixer acts as signal adder

$$v_{IF}(t) = V_{LO}\cos(\omega_{LO}t) + V_{RF}\cos(\omega_{RF}t)$$

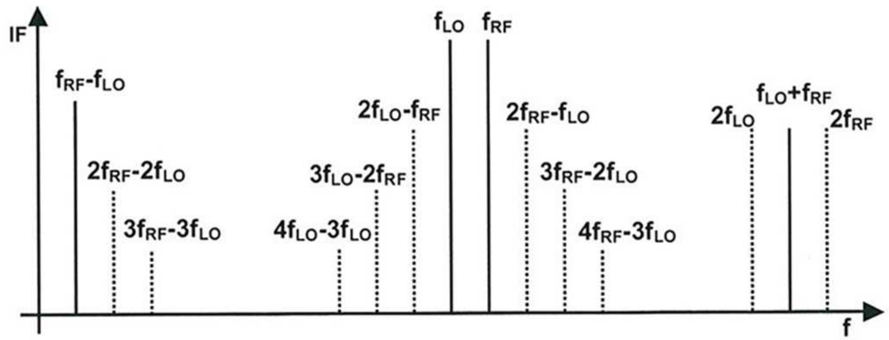
- current characteristics of nonlinear device
  - constants c_n determined by individual current vs. voltage characteristics of device
  - BJT: exponential function // FET: quadratic term

$$i_{IF}(t) = c_0 + c_1 v_{IF}(t) + c_2 v_{IF}^2(t) + c_3 v_{IF}^3(t) \ldots + c_n v_{IF}^n(t)$$

- IF current contains DC + 2nd harmonics + 2nd order intermodulation products

  → IF filter required

$$i_{IF}(t) = c_0 + c_1\left[V_{RF}\cos(\omega_{RF}t) + V_{LO}\cos(\omega_{LO}t)\right] + c_2\left[\frac{V_{RF}^2}{2}\left(1+\cos(\omega_{RF}t)\right) + \frac{V_{LO}^2}{2}\left(1+\cos(\omega_{LO}t)\right) + \frac{V_{RF}V_{LO}}{2}\left(\cos(\omega_{LO}t+\omega_{LO}t) + \cos(\omega_{LO}t-\omega_{LO}t)\right)\right] + \ldots$$



Ellinger: “RF IC and techn.”

mixer analysis

- general case
  - a nonlinear transfer characteristic produces an output spectrum with components at DC and $nf_1 \pm mf_2\,,\, n,m = 0,1,2,3..$
- RF signal has small amplitude
  - linear approximation (small-signal) sufficient
- LO signal has large amplitude
  - higher order harmonics included in analysis
- example: diode

$$I(V)/I_s = e^{\frac{1}{V_t}(s_1+s_2)} = e^{\frac{s_1}{V_t}} \cdot e^{\frac{s_2}{V_t}} = \underbrace{\left(1+\tfrac{s_1}{V_t}\right)}_{!}\left(1+\tfrac{s_2}{V_t}+\tfrac{1}{2}\left(\tfrac{s_2}{V_t}\right)^2+\ldots\right)$$

- output spectrum

$$f_1 \pm mf_2$$

classification of mixers

	passive	active
single-ended	diode $I(V)$ diode $C(V)$ resistive FET	gate mixer drain mixer dual-gate mixer
single-balanced	diodes	balanced FET Half Gilbert cell
double-balanced	diode rings	FET ring Gilbert cell
IQ	any of the above	
image-reject	any of the above	

- passive
  - (Schottky, PIN, …) diode
  - SIS: superconductor – insulator – superconductor
  - transistor BJT (HBT), FET (HEMT)
- active
  - transistor BJT (HBT), FET (HEMT)

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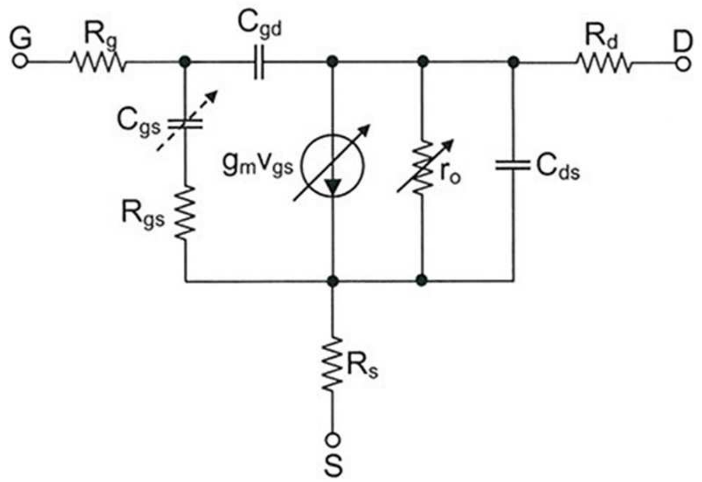
non-linear effects

- element variations of 90 nm n-channel SOI MOSFET with w_g = 64 µm

Element	Variation, $f(V_{gs})$	Variation, $f(V_{ds})$	Resulting nonlinear effect
R_g, R_d, R_s	Small values, negligible dependency		Very weak
R_{gs}	<20%		Weak, path dominated by series C_{gs}
C_{ds}	<10%		Weak since dominated by par. R_{ds}
C_{gd}	30%		Weak miller effect due to mixer bias, major input capacitance is C_{gs}
C_{gs}	30%	25%	Moderate
r_o	6 Ω–2 kΩ		Strong
g_m	0–80 mS		Very strong

- FET equivalent circuit with its non-linear elements

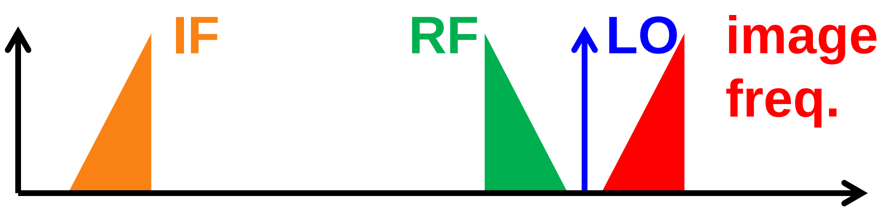


Ellinger: "RF IC and techn."

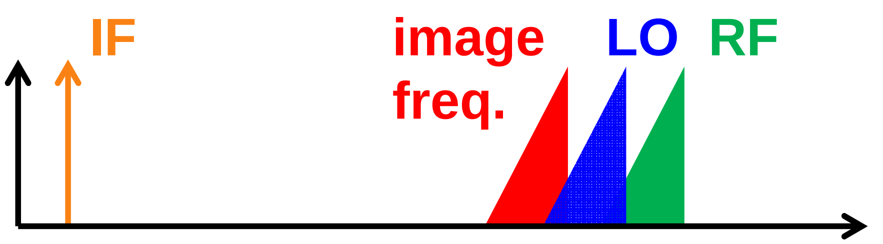
conversion modes

- frequent terms
  - up- or down-conversion
  - fixed-LO (IF sweep), fixed-IF (LO sweep)
  - high-side injection (LO > RF, HSI), low-side injection (LO < RF, LSI)

- fixed LO
- down- or up-conversion
- low-side injection



- fixed LO
- down- or up-conversion
- high-side injection



- fixed IF
- down- or up-conversion
- high- or low-side injection

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- applications and figures of merit
- circuit topologies to realize diode and FET based mixers
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  - active FET mixer
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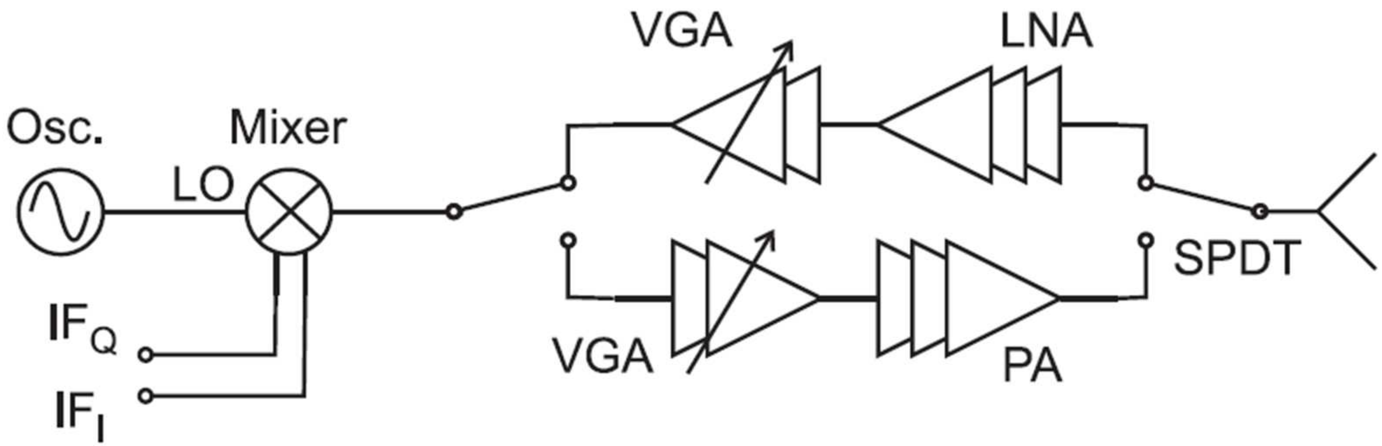
mixer applications

- mixers are used for...
  - shifting (translating) signals in the frequency domain (RF ←→ IF)
  - modulation and de-modulation of signals
  - phase detection, e.g. in PLL
  - frequency multiplication and division



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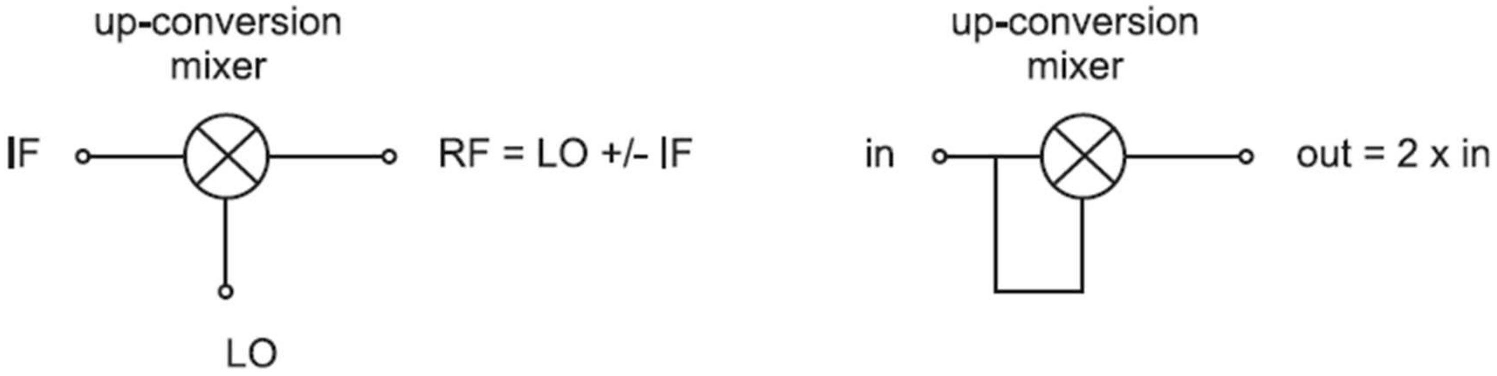
frequency multiplication using mixers

- operating a mixer as frequency multiplier

$$f_{RF} = f_{LO} \pm f_{IF}$$

route the input (IF) to LO port: $f_{LO} = f_{IF}$

upper sideband (+): $\rightarrow f_{RF} = 2 f_{IF}$



frequency division using mixers

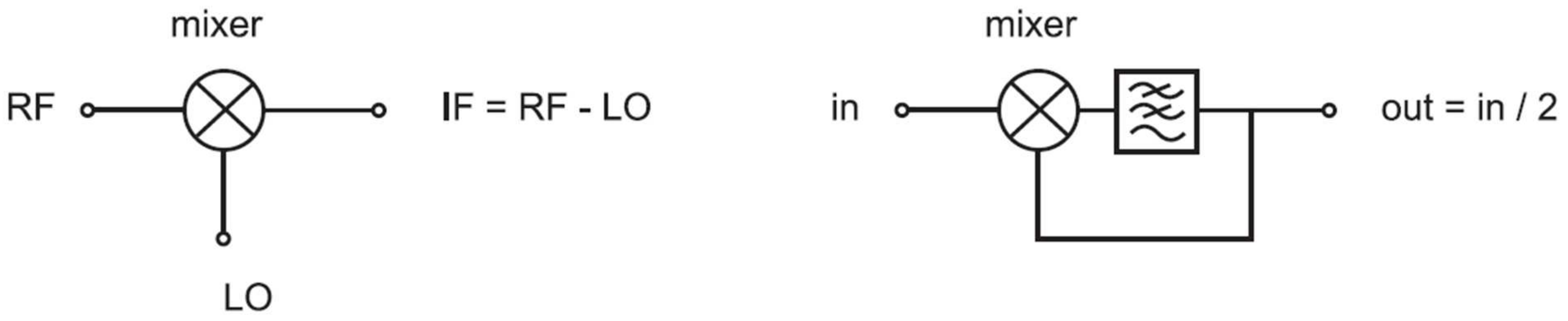
- operating a down-conversion mixer as frequency divider

$$f_{\mathrm{IF}} = f_{\mathrm{RF}} - f_{\mathrm{LO}}$$

route the output (IF) to the LO port: $f_{\mathrm{LO}} = f_{\mathrm{IF}}$

$$\rightarrow f_{\mathrm{IF}} = \tfrac{1}{2} f_{\mathrm{RF}}$$

- dynamic frequency divider
  - if using mixer topology: so-called “regenerative” divider



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phase detection using mixers

- operating a down-conversion mixer as phase detector

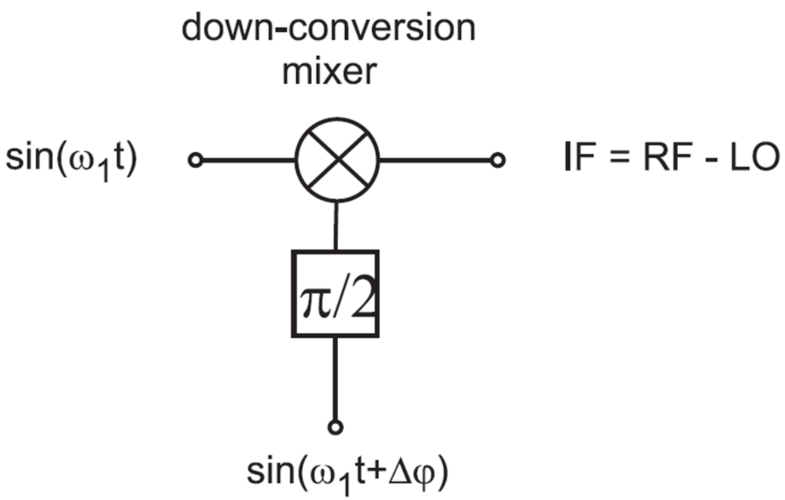
$f_{RF} = a_1 \sin \omega_1 t$

$f_{LO} = a_2 \sin(\omega_1 t + \pi/2 + \Delta\phi) = a_2 \cos(\omega_1 t + \Delta\phi)$

multiplication:

- $f_o = a_1 a_2 \sin \omega_1 t \cos(\omega_1 t + \Delta\phi) = a_1 a_2 \frac{1}{2} (\sin(\omega_1 t - \omega_1 t - \Delta\phi) - \sin(\omega_1 t + \omega_1 t + \Delta\phi))$
- DC term: $-\frac{1}{2} a_1 a_2 \sin \Delta\phi \rightarrow$ zero if $\Delta\phi = 0$

!



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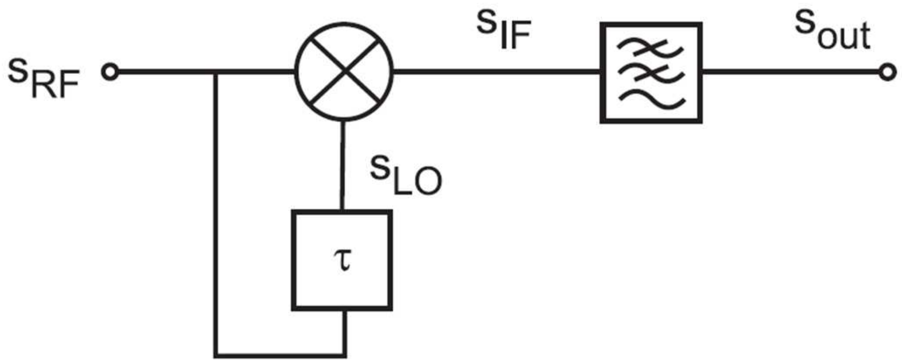
demodulation using mixers

- example: quadrature frequency modulation (FM) de-modulation

$$s_{\mathrm{RF}} = a_1 \sin((\omega_1 + \omega_m) t)$$

route via time delay to LO port: $\tau = \frac{\pi}{2\omega_1}$

$$s_{\mathrm{LO}} = a_1 \sin((\omega_1 + \omega_m)(t - \tau))$$

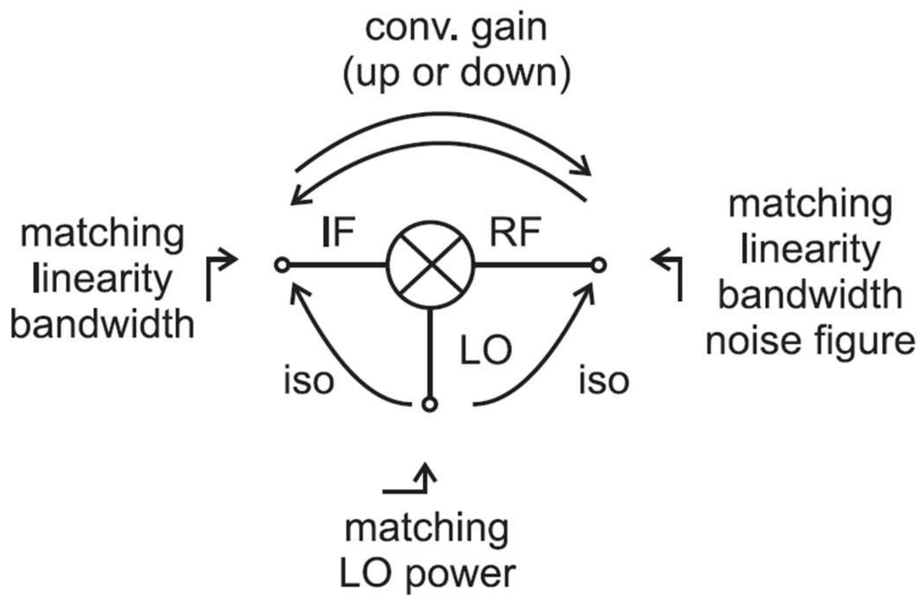


- multiplication of RF and "LO" leads to IF
  - $s_{\mathrm{IF}} = \frac{a_1^2}{2} \sin((\omega_1 + \omega_m) t) \sin((\omega_1 + \omega_m)(t - \tau))$
  - after LPF: $s_{\mathrm{out}} = \frac{a_1^2}{2} \cos((\omega_1 + \omega_m) \tau)$

- IF signal with tau $\tau = \frac{\pi}{2\omega_1}$
  - $s_{\mathrm{out}} = \frac{a_1^2}{2} \cos(\omega_1 \tau + \omega_m \tau) = \frac{a_1^2}{2} \cos\left(\frac{\pi}{2} + \omega_m \frac{\pi}{2\omega_1}\right) = -\sin\left(\frac{\pi}{2} \frac{\omega_m}{\omega_1}\right)$
  - for $\left|\frac{\pi}{2} \frac{\omega_m}{\omega_1}\right| \ll 1$: $s_{\mathrm{out}} = -\frac{\pi}{2} \frac{\omega_m}{\omega_1}$

mixer figures of merit

	entity	symbol	unit
conv.	conv. gain	G_C	dB
RF	RF bandwidth	B	GHz
	RF linearity		dBm
	Noise Figure	NF	dB
	LO/IF-RF isolation		dB
	RF power matching		dB
IF	IF bandwidth	B	GHz
	IF linearity		dBm
	RF/LO-IF isolation		dB
	IF power matching		
LO	required LO power	P_{LO}	dBm
	RF/IF-LO isolation		dB
	LO power matching		dB
others	power consumption		



- conversion efficiency

$$\eta_c = \frac{P_{IF}}{P_{RF} + P_{LO} + P_{dc}}$$

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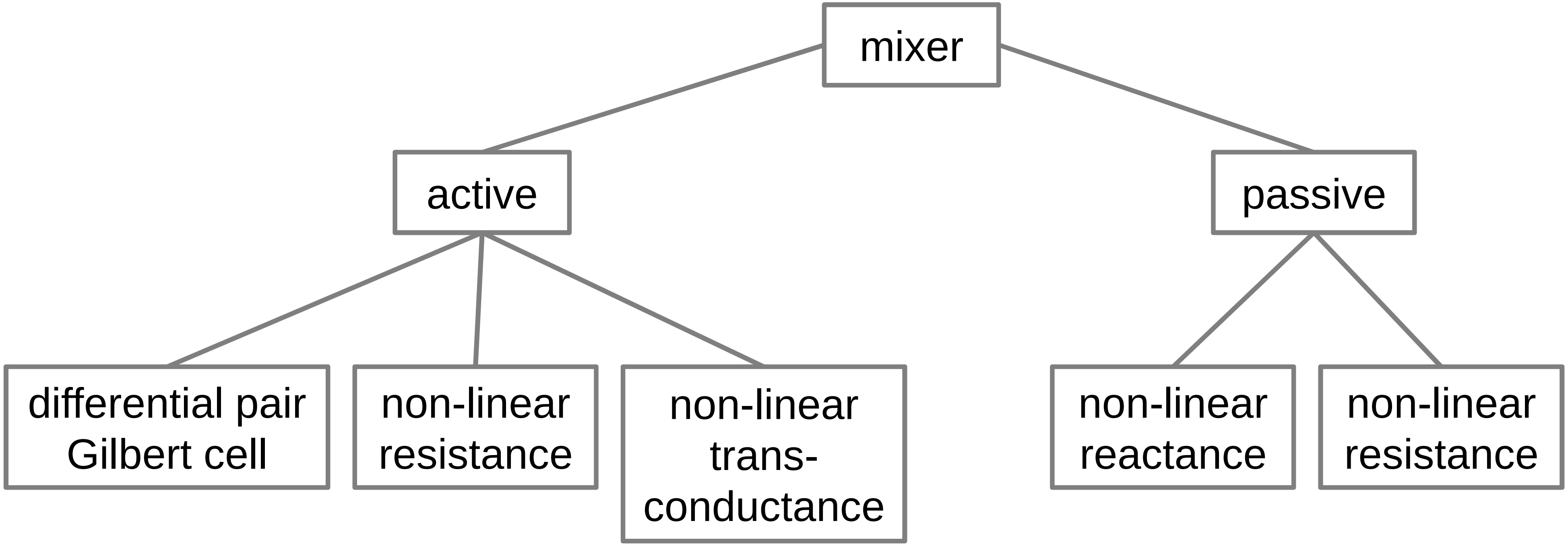
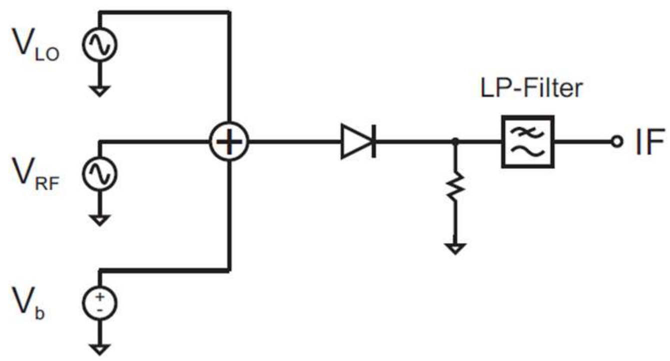
mixer topologies

- overview of mixer topologies and corresponding non-linearities



diode mixers

- single-ended down-conversion diode mixer
  - apply LO and RF signal to the diode
  - use a subsequent filter to separate the IF signal



- diode current

$$I_D(V_D) \approx I_S(e^{\frac{V_{LO}+V_{RF}+V_b}{nV_T}})$$

$$= I_S(e^{\frac{V_b}{nV_T}} \cdot e^{\frac{V_{LO}}{nV_T}} \cdot e^{\frac{V_{RF}}{nV_T}})$$

$$= I_b \cdot I_S \cdot [(1 + \frac{V_{LO}}{nV_T} + \frac{V_{LO}^2}{(nV_T)^2} + \cdots) \cdot (1 + \frac{V_{RF}}{nV_T} + \frac{V_{RF}^2}{(nV_T)^2} + \cdots)]$$

- mixing occurs in the second order intermodulation product

$$I_b \cdot I_S \cdot \frac{V_{LO} \cdot V_{RF}}{(nV_T)^2}$$

diode conversion gain

- IF voltage
  - theory: IF power increases linear with LO power
  - practical: LO voltage is clamped by diode

$$V_{IF} \propto \frac{I_b I_S A_{RF} A_{LO}}{2(nV_T)^2} \cdot cos((\omega_{RF} - \omega_{LO})t)$$

- conversion gain of a diode mixer

$$CG = 20log\left(\frac{V_{IF}}{V_{RF}}\right)$$

- conversion gain
  - ideal (n=1) diode mixer AND large A_{LO} → CG = - 6 dB
  - practical: -3 … -10 dB

FET as diode mixer

- high ideality factor of the mHEMT gate diode makes is less suitable for mixers
- diode current

$$I_D(V_D) = I_S(e^{\frac{V_D}{nV_T}} - 1)$$

- down-conversion IF voltage

$$V_{IF} \propto \frac{I_b I_S A_{RF} A_{LO}}{2(nV_T)^2} \cdot cos((\omega_{RF} - \omega_{LO})t)$$

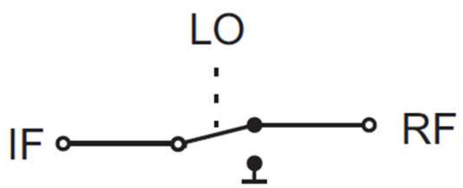
- conversion gain
  - decreases with the square of the ideality factor

$$CG = 20log\left(\frac{V_{IF}}{V_{RF}}\right)$$

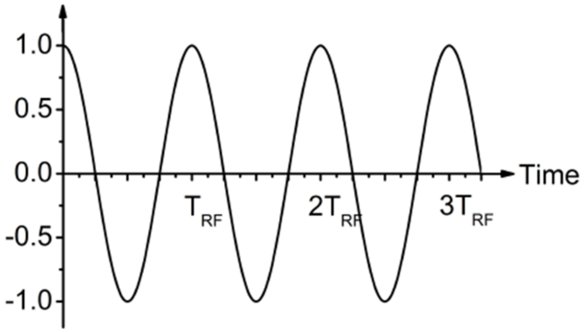
Technology	n	$R_S[Ohm]$
HEMT gate Schottky contact	2.25	23
Monolithic membrane diode	1.5	15-20
Air-bridged Schottky diode	1.172	10.68
Dot type Schottky diode	1.41	18.3

switch as mixer (1)

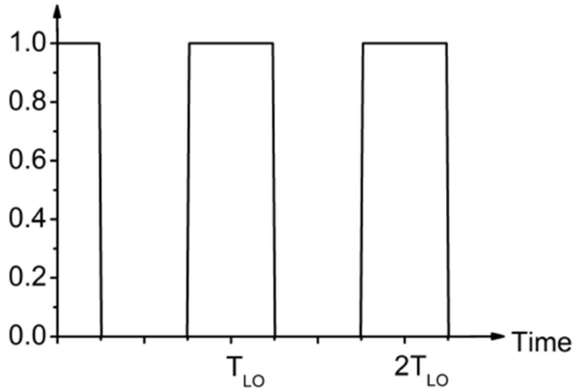
- e.g. resistive mixer with large LO drive



- RF input signal
  - $f_{RF} = 1/T_{RF}$



- pulse wave train of control signal
  - $f_{LO} = 1/T_{LO}$
  - duty cycle d = 50 %



switch as mixer (2)

- Fourier series of a pulse train with an amplitude of one and d = 1/2

$$f(t) = \frac{1}{2} + \sum_{n=1}^{\infty} \frac{2}{n\pi} sin\left(\frac{\pi n}{2}\right) cos\left(\omega_{LO} nt - \frac{\pi n}{2}\right)$$

- due to symmetry → no even signals

$$f(t) = \frac{1}{2} + \frac{2}{\pi} sin(\omega_{LO} t) + \frac{2}{3\pi} sin(3\omega_{LO}) + \frac{2}{5\pi} sin(5\omega_{LO}) + \ldots$$

- output signal
  - higher order spurious signals by the odd harmonics of the LO
  - direct RF feed through to the output

  → filter required

$$V_{out}(t) = \frac{1V_{RF}}{2} cos(\omega_{RF} t) + \frac{2V_{RF}}{\pi} sin(\omega_{LO} t) cos(\omega_{RF} t) + \ldots$$

- theoretical conversion gain (CG)

$$CG = 20 log\left(\frac{1}{\pi}\right) = -9.94 dB$$

- theoretical CG of balanced mixer
  - 0/1 → -1/+1 pulse train → factor 2

$$CG_{DSB} = 20 log\left(\tfrac{2}{\pi}\right) = -3.92 dB$$

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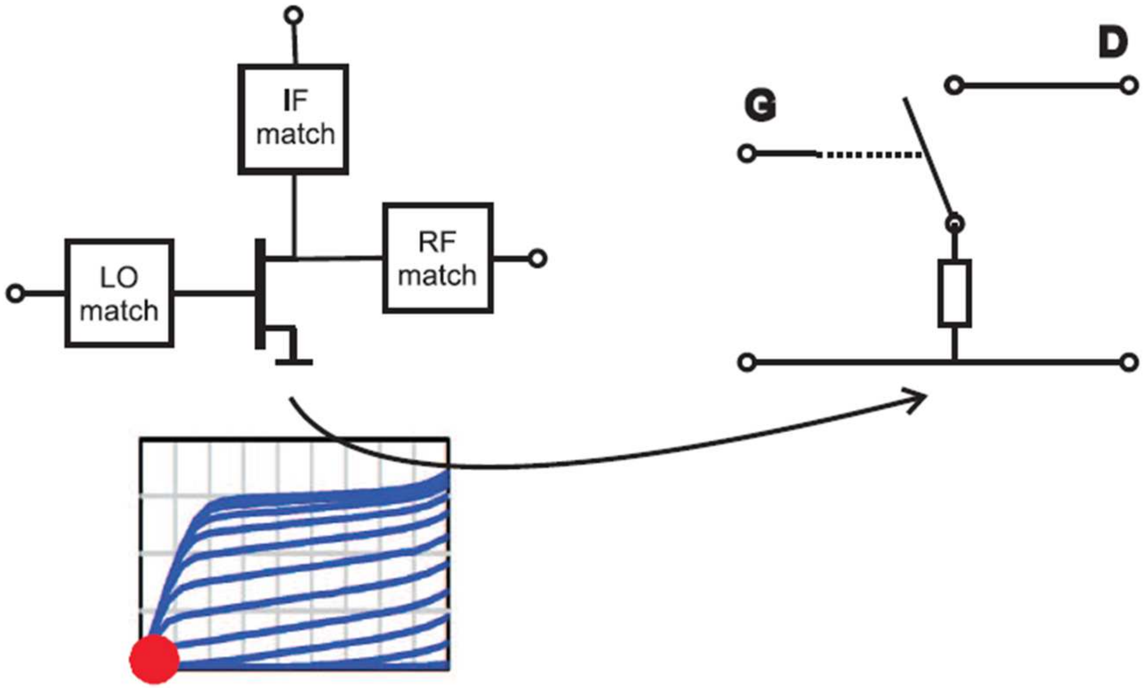
single-ended mixer: resistive FET mixer

- FET used as voltage-controlled resistor ($V_D = 0$ V)
  - LO modulates channel conductance
  - typical operating point: $V_G = V_{th}$ for minimum LO power requirement
- advantages
  - can be used for down- and up-conversion (reciprocal)
  - high linearity
  - simple topology
  - no DC consumption
- disadvantages
  - high conversion loss
  - requires high LO power
- theoretical CG
  - same as switch
    (when operating as such)

$$CG = 20log\left(\frac{1}{\pi}\right) = -9.94dB$$



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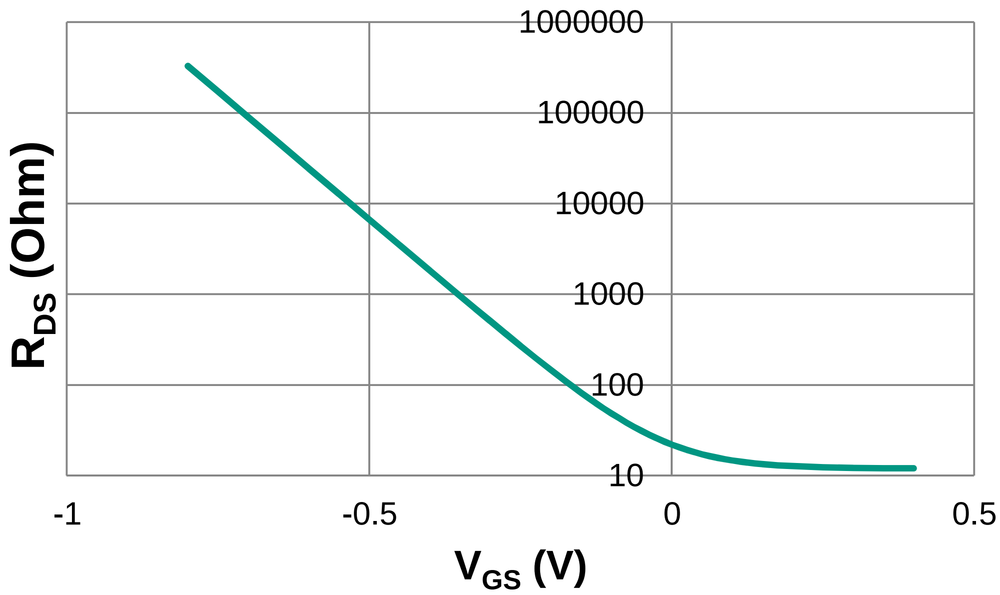
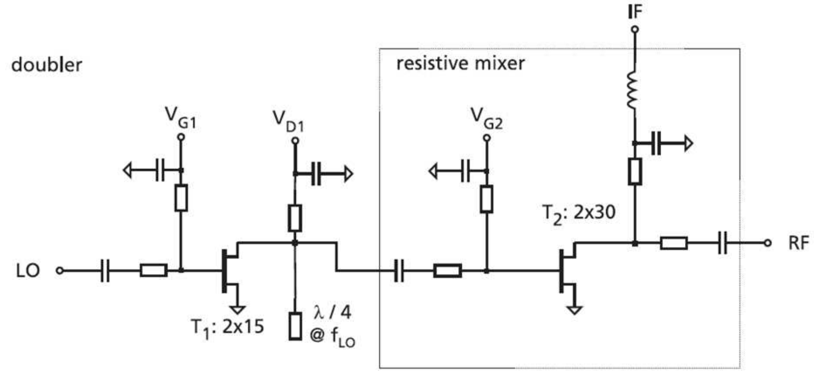
resistive FET mixer: resistance

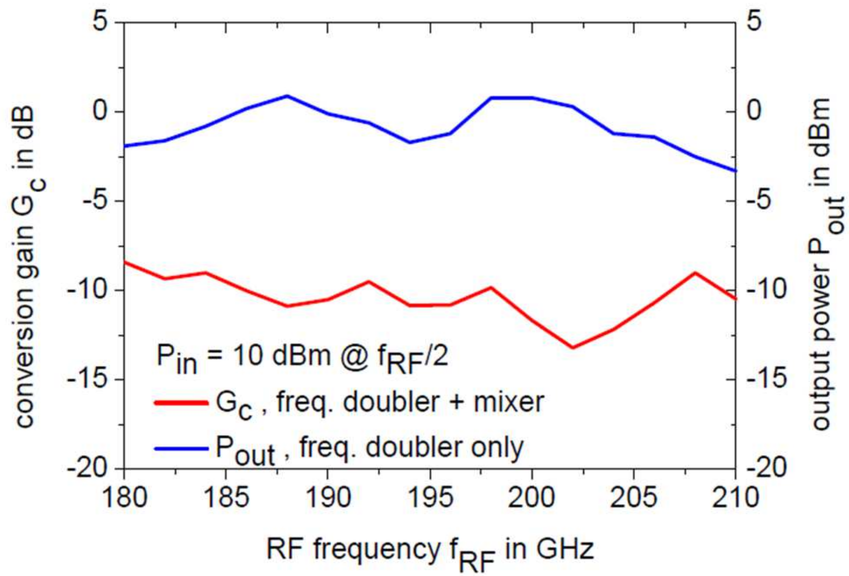
- ideal
  - $R_{on} = 0$; R_{off} = infinity
- practical
  - 50 nm mHEMT: R_{on} ~ 12 Ohm; R_{off} ~ 700 kOhm
    - higher insertion loss during the on-state
    - less isolation when turned off
    - associated pulse train of this lossy switch has a smaller amplitude

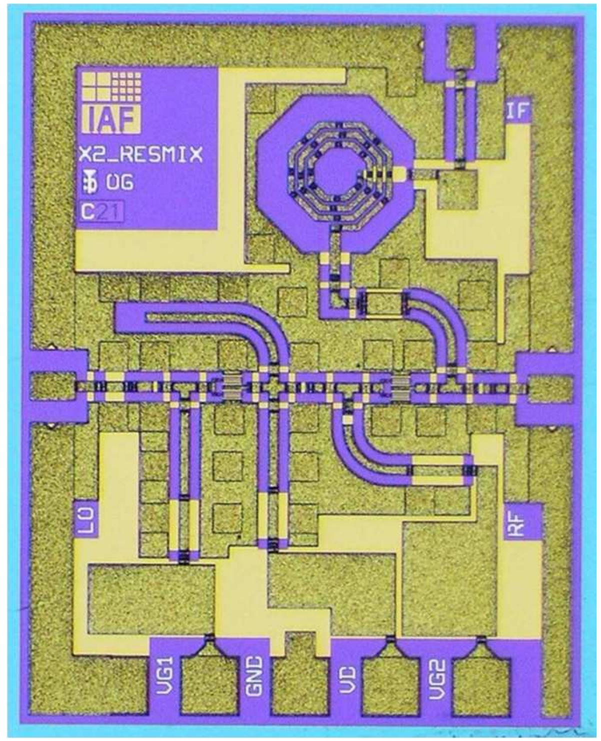


example: G-band doubler plus resistive mixer

- 100 nm gate-length mHEMT technology
- frequency doubler plus mixer
  - doubler 100 to 200 GHz
    - provides LO signal to fundamental resistive mixer at RF around 200 GHz
  - 10 dBm LO power at ~100 GHz
  - ~0 dBm doubler output power at 200 GHz
  - ~10 dB conversion loss of mixer







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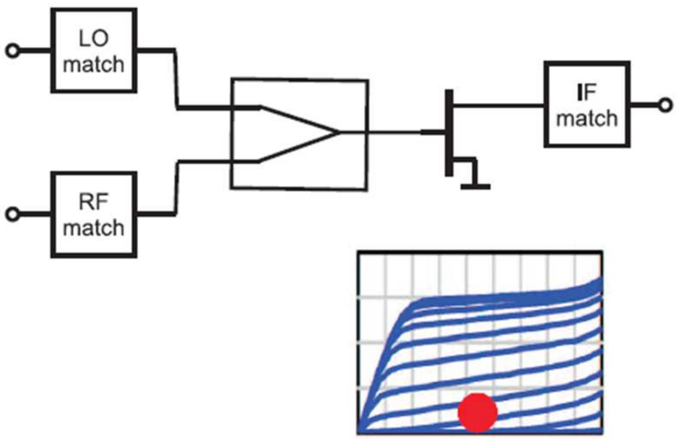
active FET mixer

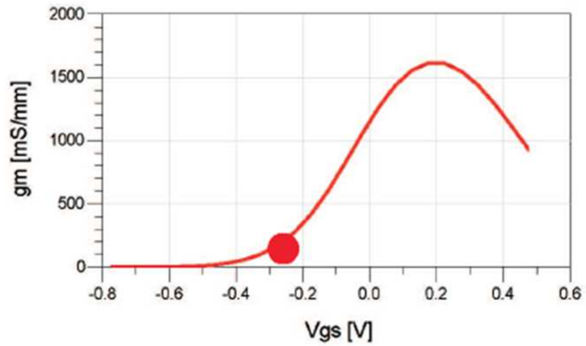
- the transistor is biased to provide trans-conductance
- additive mixers
  - similar to diode mixers: the mixing signals are applied to the gate
    - often called gate mixers (LO is fed to gate)
  - low isolation and many spectral components (LO/RF leakage, frequency difference and harmonics) at the IF output
  - frequency conversion occurs due to the incidental multiplication at the nonlinear transfer characteristic of the active device
  - poor port isolation and a lot of unwanted intermodulation components
  - to obtain good LO to RF isolation, diplexer networks are necessary
    - large chip area required

- multiplicative mixers
  - make use of a direct multiplication
    - fewer spurious signals
    - higher port isolation: the LO and RF signals are fed into separate terminals of the FET

gate mixer

- LO modulates FET trans-conductance
  - intrinsic voltage gain: $G_V = g_m(\mathrm{LO})\,\frac{1}{g_{ds}}$
- advantages
  - low LO power requirements
  - conversion gain possible (at mmW: low conversion loss)
- disadvantages
  - requires RF-LO-diplexer network





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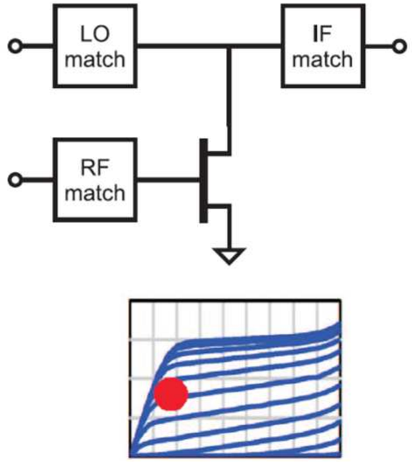
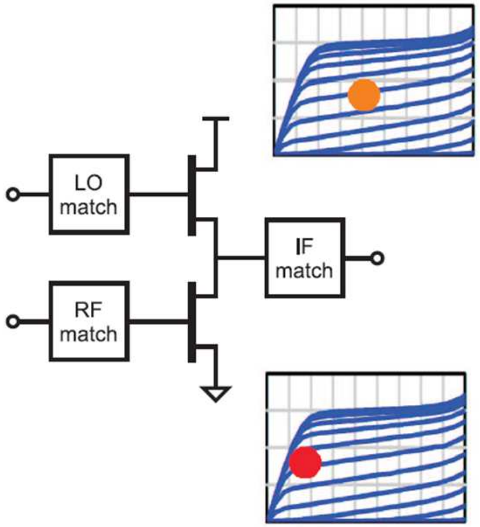
drain mixer

- conventional drain mixer
  - LO is fed to drain
  - modulation of g_m by variation of V_{ds} through large LO signal
  - RF signal is applied to the gate
  - IF signal is separated by a filter at the drain terminal
  - bias in knee region
    - transistor driven/switched between linear and saturated operation
    - LO modulates FET trans-conductance and output conductance
    - intrinsic voltage gain:

$$G_V = g_m(LO)\frac{1}{g_{ds}(LO)}$$



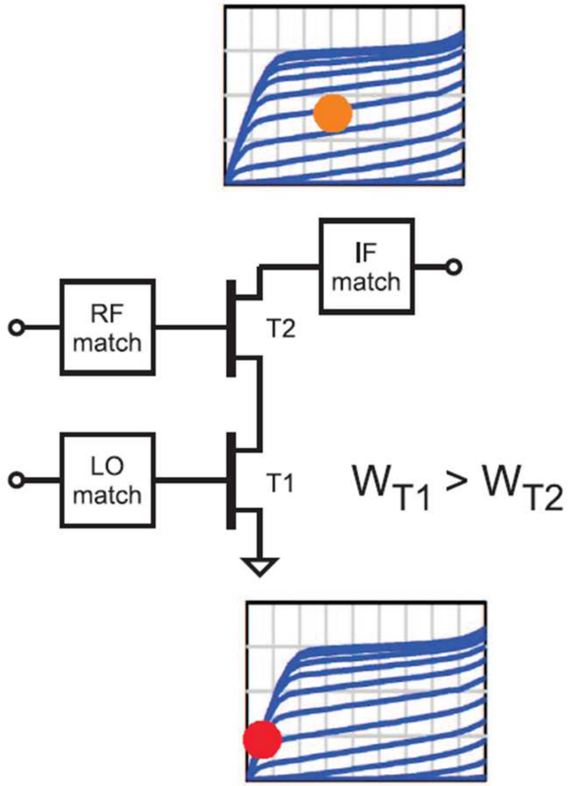
- drain mixer variant
  - LO supplied by common-drain (load) transistor
  - advantages
    - lower LO power requirements
    - inherent IF match due to low impedance of common-drain transistor



source feedback mixer

- T1 used as nonlinear resistor (requires $W_{T1} > W_{T2}$)
- LO varies source feedback for T2
- trans-conductance g_m

$$g_m = \frac{g_{m,T2}}{1 + g_{m,T2} \cdot g_{ds,T1}^{-1}(LO)}$$



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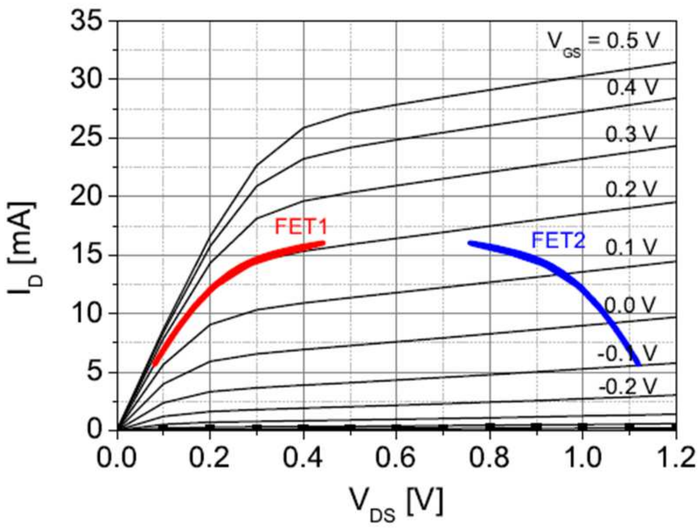
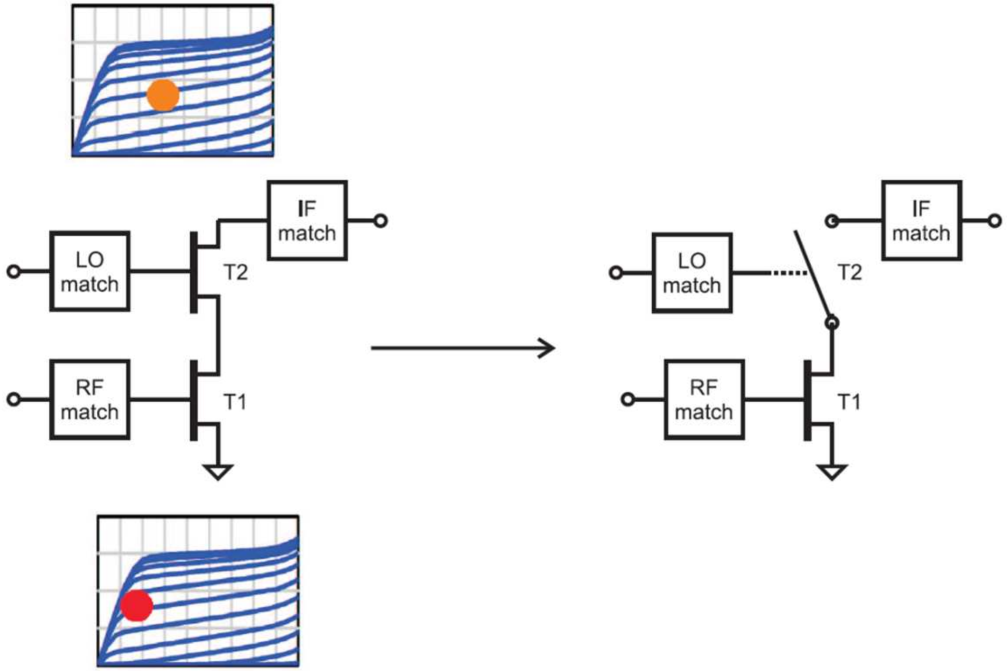
dual-gate mixer (1)

- quasi-cascode configuration
- mixing occurs through the variation of the drain voltage of T1
  - 0 V ... to FET saturation



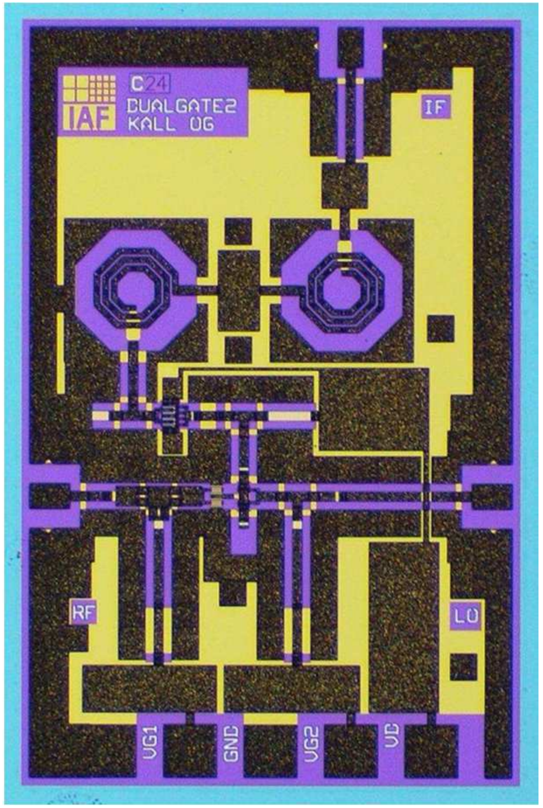


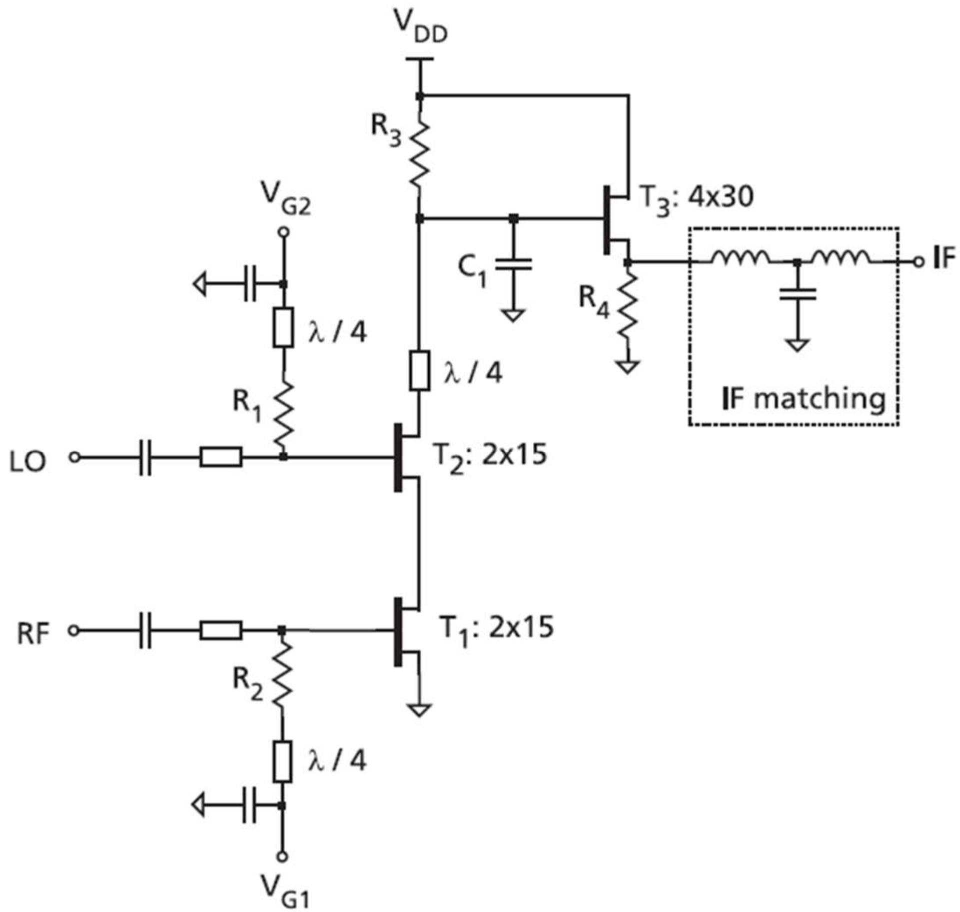
dual-gate mixer (2)

- advantages
  - low LO power requirements
  - conversion gain possible (at mmW: low conversion loss)
  - 3-port device
    - inherent port isolation
    - requires no diplexing/filtering, only port matching
- disadvantages
  - high IF impedance (cp. output impedance of cascode)
  - DC power consumption

example: 200 GHz dual-gate mixer

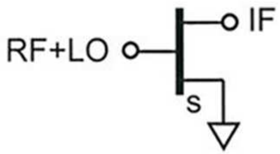
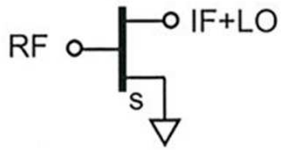
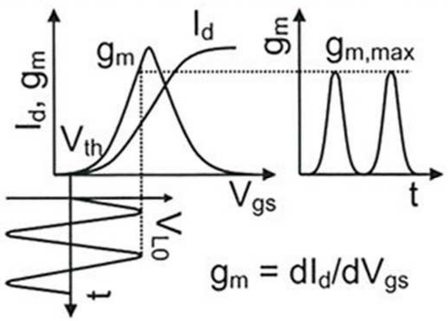
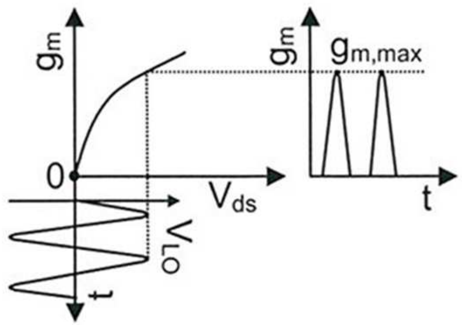
- 100 nm gate-length mHEMT technology
- output source follower for IF impedance transformation
- R_1, R_2 → stability
- R_3 → source follower bias
- C_1 → IF low-pass





trans-conductance mixer

- overview over trans-conductance mixer

	Gate pumped	Drain pumped	
Circuit schematics			
Functional principle			
V_{ds} bias	$> V_{ds,\ sat}$	$V_{ds,sat}$	0 V possible if $V_{ds,sat}$ small
V_{gs} bias	V_{th}	$V_{gs}>V_{th}$	
Non-linearity	$g_m=f(V_{gs})$	$g_m=f(V_{ds})$	

Ellinger: “RF IC and techn.”

mixer approaches

- qualitative comparison of mixer approaches

	Drain-pumped transconductance	Gate-pumped transconductance	Gate-pumped resistive	Differential gate-pumped resistive	Differential pair	Gilbert-cell
Conversion gain	Moderate	High	Low	Low	Very high	Very high
Linearity	Moderate	Low	High/very high	Very high	Moderate	Moderate/high
Noise	Low	Very low	Moderate	Moderate	High	High/very high
LO to IF suppression	Moderate (down-mixer) Low (up-mixer)	Low (down-mixer) Moderate (up-mixer)	Low	Low	Moderate	Very high
Power consumption	Low/zero	Moderate/low	Zero	Zero	High	Very high
Chip area	Moderate/large (inductors)	Moderate/large (inductors)	Moderate/large (inductors)	Moderate/large (inductors)	Small (RC load) Moderate/large (LC load)	Small/moderate (RC load) Large (LC load)
System integration	May be limited since single-ended	May be limited since single-ended	May be limited since single-ended	Good/very good	Good (LO, IF differential)	Very good

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lecture outline

- fundamentals of frequency mixing
- applications and figures of merit
- circuit topologies to realize diode and FET based mixers
  - diode mixer
  - passive FET mixer
  - active FET mixer
  - balanced mixer
  - IQ mixer

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sub-harmonic mixers

- $f_o = n\, f_{LO} \pm f_1$
- also called “harmonic mixers”, n-th harmonic of LO-frequency is used for mixing
- nonlinear device is biased and matched to maximise n-th LO harmonic (and reject other LO harmonics)

- advantages
  - higher LO power available
  - better LO-RF isolation
    - critical isolation is now: n × LO-RF
- disadvantages
  - lower conversion gain
  - typically also conversion from other LO harmonics → ambiguity

sub-harmonic resistive mixer

- x2: only half of the RF frequency as LO signal is required
  - LO source can provide required drive power more easily
- gate bias voltage modifies the duty cycle of the LO signal
  - affects the coefficients of the Fourier series
- Fourier series of a pulse train with an amplitude of one
  - second order component is of special interest
  - depending on the duty cycle d, it varies from 0 to 1/π

$$f(t) = d + \sum_{n=1}^{\infty} \frac{2}{n\pi} sin(\pi nd)\, cos(\omega_{LO} nt - \pi nd)$$

- maximum conversion gain

$$CG = 20 log\left(\frac{1}{2\pi}\right) = -15.96\ dB$$

- maximum conversion gain for balanced sub-harmonic resistive mixer

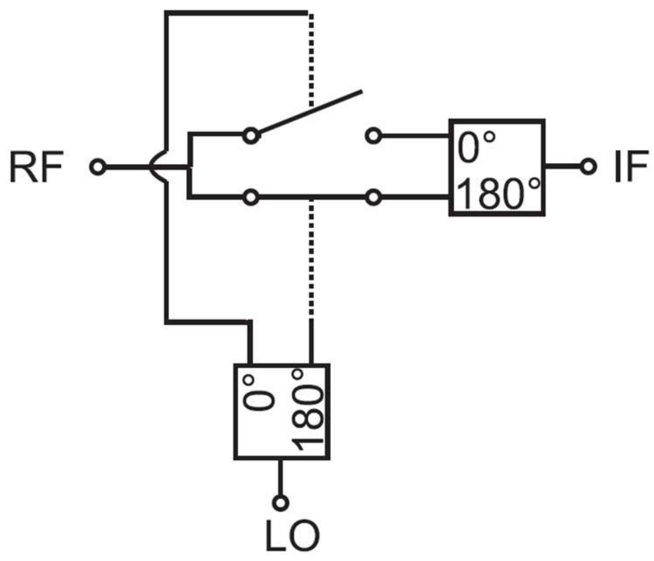
$$CG = 20 log\left(\frac{1}{\pi}\right) = -9.94\ dB$$

balanced mixers

- unbalanced or single-ended
  - all input signals are single-ended
  - unwanted frequencies have to be suppressed (matching networks or filters)
  - most important: e.g. f_{LO} at RF port for LO-to-RF isolation (LO leakage to antenna)
- balanced mixer
  - use destructive interference of balanced signals for signal cancellation
  - single balanced
    - one signal (RF or LO) is applied in balanced mode
  - double balanced
    - two signals (RF and LO) are applied in balanced mode
- advantage
  - improved port isolation as long as…
    - the balanced signals are 180° out of phase
    - the mixing devices match each other
- challenge
  - provide sufficient LO drive power: signal source + coupler losses + power division

single-balanced mixer (1)

- single-balanced topology (example: RF isolation)
  - RF cancelled at IF port due to IF BALUN
  - RF node is virtual ground for LO
    - LO cancelled at RF port
- single-balanced analysis



output signal: $s_o = s_1 \cdot \mathrm{sgn}(\sin \omega_{\mathrm{LO}} t)$

$s_o = a_1 \sin \omega_1 t \cdot \frac{\pi}{4} \left(\sin \omega_{\mathrm{LO}} t + \frac{1}{3} \sin 3\omega_{\mathrm{LO}} t \ldots \right)$

2^{nd} order intermodulation: $\frac{\pi}{4} a_1 \sin \omega_1 t \cdot \sin \omega_{\mathrm{LO}} t$

filtering of unwanted sum component: $s_o = \frac{\pi}{8} a_1 \cos \omega_{\mathrm{IF}} t$

- balanced switches
  - the effect of the (ideal) balanced switches is a phase-reversal of the RF
  - = multiplication with signum function
  - = mixing effect through 2nd order intermodulation

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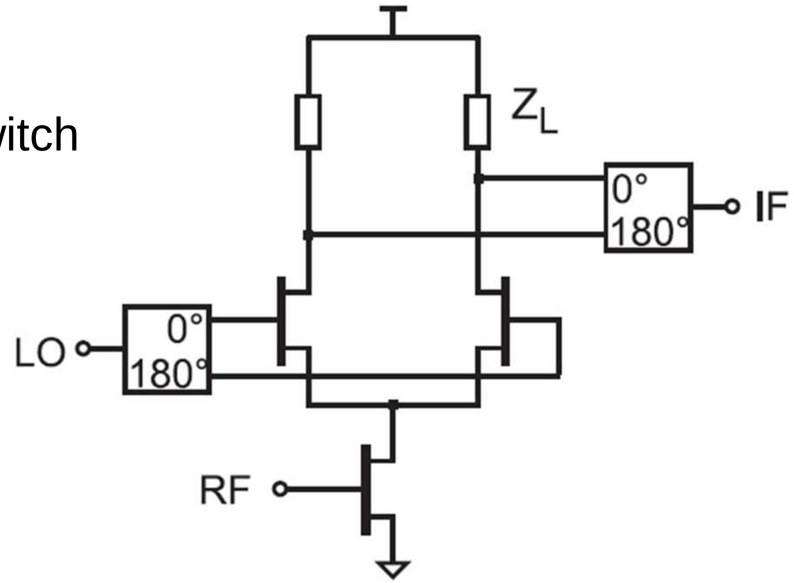
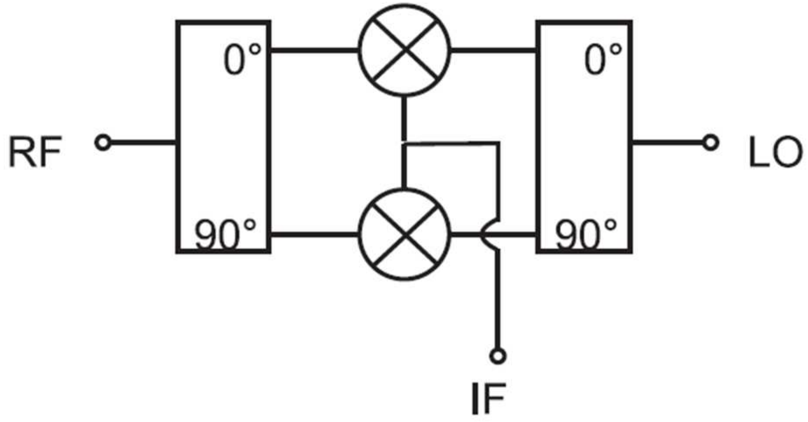
single-balanced mixer (2)

- half Gilbert cell
  - think of a half Gilbert cell as:
    common-source amplifier + phase-reversing switch



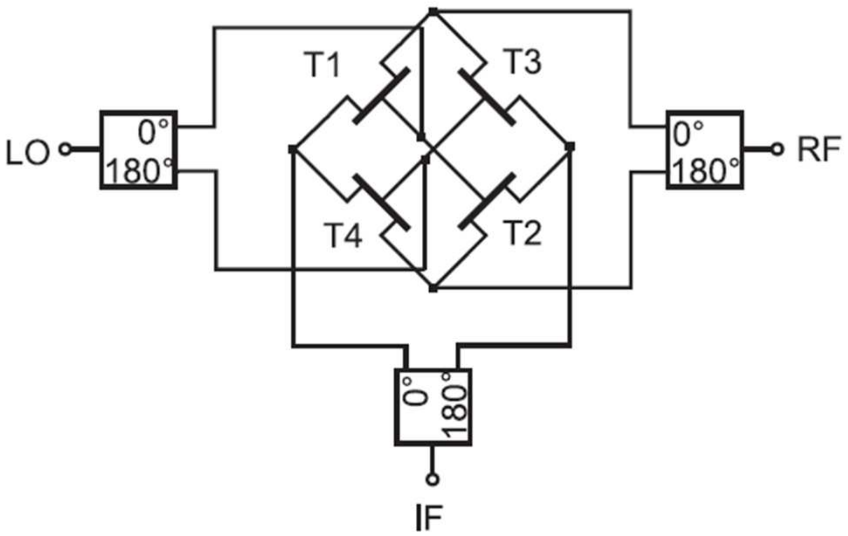
- single-balanced mixers using 90° couplers
  - RF / LO signal undergoes additional 2 × 90° phase shift
  - cancellation with in-phase component at LO / RF port



double-balanced mixer

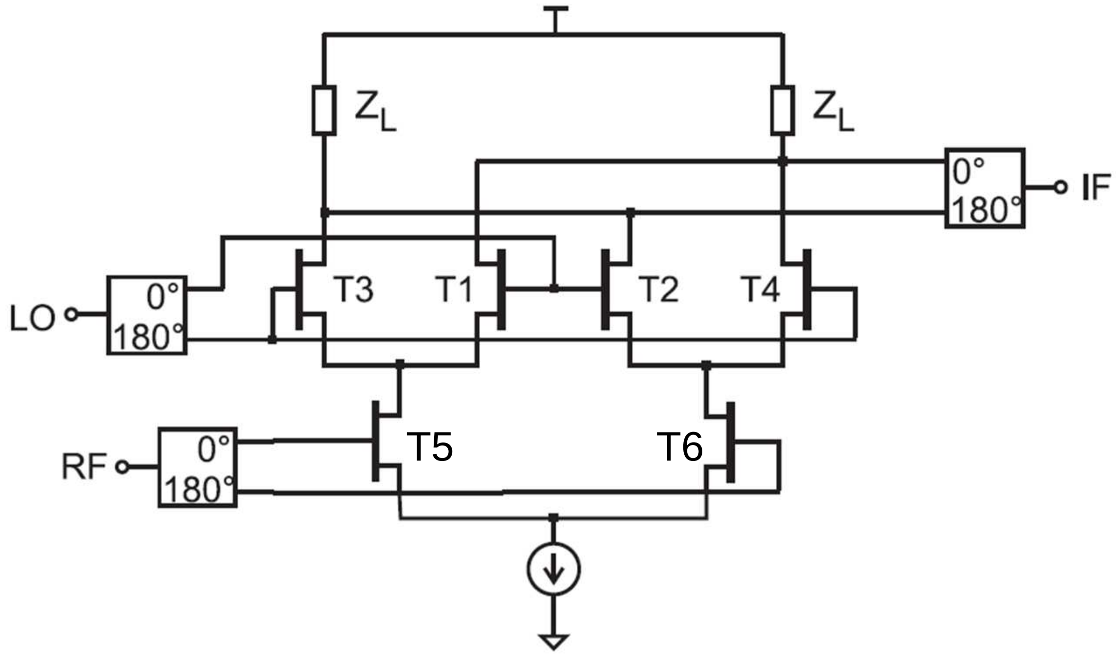
- double-balanced operation
  - RF and LO signal are balanced
  - all ports are inherently isolated from each other

- example: FET ring mixer
  - LO alternately turns on T1/T2 and T3/T4
  - signal at IF = RF signal multiplied by LO square wave



Gilbert cell mixer

- four-quadrant analogue multiplier
- usually realized to operational frequencies up to $f_t/3$
- think of a Gilbert cell mixer as: differential amplifier + phase-reversing switch
- T1-T4 are called the “switching quad”
- similar to a double balanced dual gate FET mixer
- large LO signal is applied to the transistor pairs T1/T3 and T2/T4
  - pairs operate as commutating switches
- RF signal is applied to the differential amplifier formed by pair T5 / T6
  - output is modulated by the switching transistors

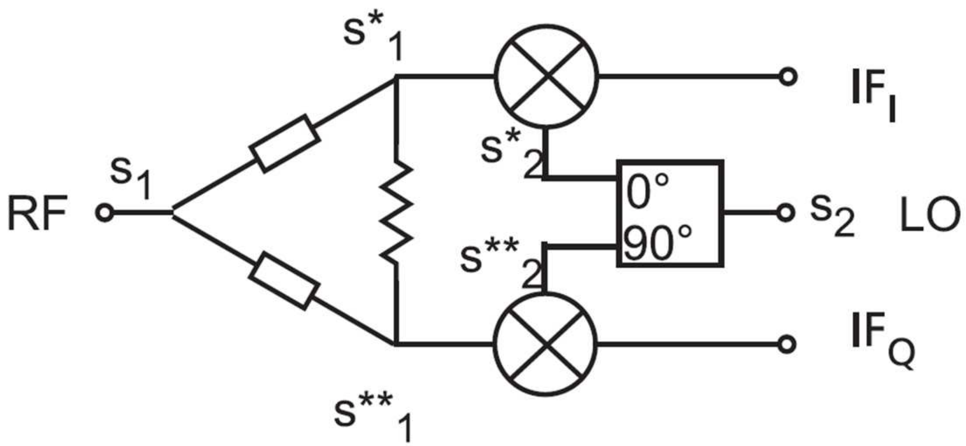


IQ mixer

- IQ mixer architecture
  - LO applied via 90° hybrid to two mixer cores
  - in-phase IF component (IFI) and quadrature component (IFQ)
- analysis
  - I and Q components are in quadrature = 90° out of phase

$$IF_I = \frac{\pi}{8} a_1 a_2 \left(\cos\left(\omega_2 - \omega_1\right) t - \cos\left(\omega_2 + \omega_1\right) t\right)$$

$$IF_Q = \frac{\pi}{8} a_1 a_2 \left(\cos\left(\left(\omega_2 - \omega_1\right) t + \frac{\pi}{2}\right) - \cos\left(\left(\omega_2 + \omega_1\right) t - \frac{\pi}{2}\right)\right)$$



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