1. The principle of resistive mixers

Frequency translation by using resistive mixing

\[ i(t) = g(t) \cdot v(t) \]

The current through the (time-dependent) 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.

\[ g(t) \text{ can be represented by a Fourier series with the fundamental frequency } \omega_p \]

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

See Steven Maas
Nonlinear Microwave Circuits
pp.114-137

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small-signal analysis

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

$\omega_0 \quad \omega_1 \quad \omega_2 \quad \omega_3$

$-3 \omega_p \quad -2 \omega_p \quad -\omega_p \quad 0 \quad \omega_p \quad 2 \omega_p \quad 3 \omega_p$

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:

\[
\begin{bmatrix}
    I_{-N}^* \\
    I_{-N+1}^* \\
    I_{-N+2}^* \\
    I_{-1}^* \\
    I_0 \\
    I_1 \\
    I_{N-1} \\
    I_N
\end{bmatrix}
\begin{bmatrix}
    G_0 & G_1 & G_2 \\
    G_1 & G_0 & G_1 \\
    G_2 & G_1 & G_0 \\
    G_{N-1} & G_{N-2} & G_{N-3} \\
    G_N & G_{N-1} & G_{N-2} \\
    G_{N+1} & G_N & G_{N-1} \\
    G_{2N} & G_{2N-1} & G_{2N-2}
\end{bmatrix}
\begin{bmatrix}
    G_{-N} \\
    G_{-N+1} \\
    G_{-N+2} \\
    G_{-1} \\
    G_N \\
    G_{N+1} \\
    G_{2N} \\
    G_0
\end{bmatrix}
= 
\begin{bmatrix}
    V_{-N}^* \\
    V_{-N+1}^* \\
    V_{-N+2}^* \\
    V_{-1}^* \\
    V_N \\
    V_{N+1} \\
    V_{2N} \\
    V_0
\end{bmatrix}
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 transferred 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.

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non-square waveform, harmonic response

To illustrate the harmonic response, let's look at \( G_n \) as a function of the duty-cycle for a simple case, an ideally switched conductance

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

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

We obtain

\[
G_0 = \frac{t_0}{T} \cdot G_c, \quad G = \frac{G_c}{\pi} \cdot \sin(\pi \cdot \frac{t_0}{T})
\]

\[
G_2 = \frac{G_c}{2\pi} \cdot \sin(2\pi \cdot \frac{t_0}{T}), \quad G_3 = \frac{G_c}{3\pi} \cdot \sin(3\pi \cdot \frac{t_0}{T})
\]

\[
G_4 = \frac{G_c}{4\pi} \cdot \sin(4\pi \cdot \frac{t_0}{T}), \quad G_5 = \frac{G_c}{5\pi} \cdot \sin(5\pi \cdot \frac{t_0}{T})
\]
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

\[
I_D = I_0 \cdot e^{qV_d / \eta kT}
\]

\[
V_D
\]

\[
r_B = \left( \frac{\partial I_D}{\partial V_D} \right)^{-1} \rightarrow \frac{\eta kT}{q I_D}
\]

or

\[
r_B = k \cdot e^{-q \cdot V_d / \eta kT}
\]

\[
I_{DS} = K(V_{GS}) \cdot (1 + \lambda \cdot V_{DS}) \cdot \tanh(\alpha \cdot V_{DS})
\]
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, $V_{ds} \approx 0 \, V$. The $I_d-V_d$ characteristic is approximately linear at low $V_{ds}$ which makes the FET-resistive mixer linear! It's exponential for a diode!

![Diagram](image)
The Rds-Vgs slope is important for the determination of the LO-power requirement of the mixer.
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. 

$\mathbf{r}_{\text{ch}}$ and $\mathbf{C}_{\text{gs}}, \mathbf{C}_{\text{gd}}$ are the most important bias-dependent parameters. 

($\mathbf{R}_{\text{ds}}$ is now split into $\mathbf{R}_{\text{d}} + \mathbf{r}_{\text{ch}} + \mathbf{R}_{\text{s}}$)
Performance of different FET-HEMT based resistive mixers

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

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.
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)
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 $\approx 9 \text{ dB}$ at $4 \text{ dBm}$ 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 split 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
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.
Conversion Loss vs. LO power

Measured results 50-62 GHz:
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 = 19 dBm at 8 dBm PLO
5-8 dB NF (DSB), \( P_{-1} \approx P_{LO} + (2-4) \text{dB} \)
Image reject mixer (IRM)
Three designs in WINs pHEMT/mHEMT technologies

Topology:

Chip photo, pHEMT, 3.3 × 2.8 mm²
Chip photo, mHEMT, 3.3 × 2.3 mm²
Chip photo, pHEMT, 2.0 × 2.9 mm²

Design by Tech. Lic. Dan Kuylenstierna
Image reject mixer (IRM)

Conversion loss and image rejection ratio versus IF frequency

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

Motivation: Suppresses the LO to RF leakage
Dual-Quadrature mixer (DQM)

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

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

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!)

2.0 GHz
IF

11.5 GHz!
IF filter

58 GHz
LO

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**Multifunctional MMICs**

**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…
60 GHz activities at Chalmers – the beginning

1997 – 2001: The “60 GHz WLAN” project (CTH, Ericsson, KTH, and FOI within CHACH)
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 Kärfelt, 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
Receiver (RX) and Transmitter (TX) chip designed at Chalmers - measured results

Conversion Gain and Image Rejection Ratio versus IF Frequency for the **RX chip**, $f_{\text{LO}} = 7.1875 \times 8 = 57.5$ 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

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