Mixer and Down-Conversion

by Manfred Thumm and Werner Wiesbeck
24GHz CW Doppler Radar

- Tx-Antenna
- Coupler (3dB)
- PIN-Modulator
- Dielectric Resonator
- Oscillator transistor
- Wilkinson-Devider
- Balanced Mixer 1 (6xλ/4)
- Rx-Antenna
- Coupler (3dB) for 2 balanced mixer
- Rx LNA
- Balanced Mixer 2 (6xλ/4)

Dimensions:
- 7.8cm
- 5.5cm

Courtesy Tyco
Mixing is in general the shifting of a signal or message along the frequency axis with the aid of a so-called local oscillator (LO) signal. Principally, a non-linear circuit element is required.

Mixing gives rise to three different frequency regions:

- the region on the frequency axis of the signal to be moved, \( f_{in} \)
- the LO signal, \( f_{LO} \)
- the resulting mixing product \( f_{IF} \) (IF = intermediate frequency)

LO signal is often called the pumping signal, since it modulates the non-linear mixing element.
Quadratic Mixer Characteristic

\[ f_{IF} = |f_{in} - f_{LO}| \]

\[ u_{IF}(t) = (u_{in}(t) + u_{LO}(t))^2 \]
\[ = (U_{in} \cos(\omega_{in}t) + U_{LO} \cos(\omega_{LO}t))^2 \]
\[ = U_{in}^2 \cos^2(\omega_{in}t) + 2 \cdot U_{in} \cos(\omega_{in}t) \cdot U_{LO} \cos(\omega_{LO}t) + U_{LO}^2 \cos^2(\omega_{LO}t) \]
\[ \propto \cos(2\omega_{in}t) + \cos(\omega_{in} + \omega_{LO})t + \cos(\omega_{in} - \omega_{LO})t + \cos(2\omega_{LO}t) \]
Circuit Symbols for Mixers

According to DIN EN 60617-10 predominantly in English literature
Mixer Classification by Relative Frequency Position

The multiplication factor $n$ is an integer, $n = 1, 2, 3, \ldots$.

$n = 1$ → fundamental wave mixing

$n > 1$ → harmonic mixing, mixer is called Harmonic Mixer
Further Distinction Criteria (I)

According to non linear element used:

- For mixing either non linear effective impedances or non linear reactances can be used.

Practically, a combination of both is used, but either the effective or reactive component is always dominant.

Mixing with effective impedances occurs when diodes or transistors are modulated in the non linear region of their characteristic curve.

Non linear modulation of varactors means mixing at a reactance.
Further Distinction Criteria (II)

According to modulation:

Self resonant mixer stage:
- A single element is simultaneously used for generating the LO signal and the mixing.

Externally modulated mixer stage:
- The LO signal is generated by an external circuit and fed into the mixer.
Further Distinction Criteria (III)

By combination of input signals:

Multiplicative mixing:
- The input signal and the LO signal are applied to different connector pairs of the same element. (e.g. dual gate MOSFET)

Additive mixing:
- Input and LO signal are applied at the same connector pair of the non linear element.
Active mixers:

- If elements that function as amplifier, e.g. Transistors are used as mixing elements, then this property can be exploited alongside the mixing.

- Mixers that simultaneously amplify the signal are described as active mixers. They need an additional power supply.

Passive mixers:

- Passive mixers do not amplify the output signal. Typical types are diode and varactor mixers. This type of mixer does not need supply voltage. A bias voltage can be used to operate the mixer in an ideal region of its characteristic curve.
In the general case more complex spectra than shown before arise during the modulation of a non linear element with different frequencies. The characteristic curve of an element used for mixing, e.g. a non linear effective conductance, can be written as a Taylor series.

\[ i(u) = \sum_{k=0}^{\infty} G_k u^k \]

At the output port one generally obtains signals of the frequencies:

\[ f_{IF} = \pm m f_e \pm n f_{LO} \quad m,n = 0,1,2,\ldots \]
The number of possible frequencies is only limited when the highest power of the above series is limited.

Distortion free shifting of a signal on the frequency axis is only possible for \( m=1 \) (linearity condition).

In practically implemented mixers, high, low and bandpass filters are combined to limit the spectrum of the combination frequencies.
Circuit Construction of Mixers

Depending on the application there are different options for the technical realization of mixers. This manifests itself in the connection of the mixing elements, but the external connection of these elements depends on the intended frequency range.

- low frequencies - up to a few GHz → coil transformers
- high frequencies → stripline circuits with couplers
- mm wave → waveguide and fin-line technology
Single ended mixers (single diode or unbalanced mixer) are easily constructed and can often be improvised with lab components. In addition to the often insufficient decoupling between LO and input signal, the amplitude and the side band noise of the LO signal lead to unwanted mixing products near the intermediate frequency. Moreover they do not fully exploit the power delivered from the inputs. This is however eliminated in mixers operated in Push pull mode.
The input and LO signals are fed to the mixing diodes through the band-pass filters. The generated IF is similarly extracted through the band-pass filter. The decoupling of the signals can not at all be guaranteed using this method, and only poorly guaranteed for narrow band signals. Since the LO signal is applied to the mixer at a relatively high level, crosstalk to the inputs and outputs and in other part of the circuits is to be expected.
Circuit Diagram of a Simple Single Ended Mixer (III)

- RF $f_{in}$
- Combiner
- Matching network
- Local oscillator $f_{LO}$
- DC BIAS
- DC Return
- LPF
- IF Signal $f_{IF}$
Circuit Diagram of a Simple Single Ended Mixer (III)
The circuit diagram for the microwave region is as follows. The input and LP signals are combined with the aid of a coupler. The bandwidth of the mixer is roughly that of the coupler used.
In addition to the often insufficient decoupling between LO and input signal, the amplitude and the side band noise of the LO signal lead to unwanted mixing products near the intermediate frequency. Moreover they do not fully exploit the power delivered from the inputs.

This is however eliminated in mixers operated in Push pull mode.
Two Diode Mixers - Push Pull Mixers (I)

The input signals $f_e$ and $f_{LO}$ are distributed by the transformer in such a way that the voltage $u_e + u_{LO}$ appears over diode D1 and the voltage $u_e - u_{LO}$ appears over diode D2. The following current then flows by the conductance $G_{IF}$.

$$i_{IF} = G_{IF}(u_{D2} - u_{D1}) = G_{IF}(u_{LO} - u_e) - G_{IF}(u_{LO} + u_e) = -2G_{IF}u_e$$

Each current supplied only by the local oscillator is suppressed and thus the amplitude variations of the local oscillator also do not affect the mixing process. The input for the LO signal is thus decoupled from the IF loop.
Push-Pull Mixer with a Differential Transformer (II)
Two Diode Mixers - Push-Pull Mixers (III)

In addition, no current can flow at all with an input signal $u_e$ in the IF loop. The degree of decoupling and thus the function of the push pull mixer is strongly dependant on the symmetry of the circuit. This means that the diodes used must be as identical as possible, and that the construction must be very precise. The differential transformer corresponds to the stripline 180 degrees -3 dB coupler (e.g. rat race coupler).
Push-Pull Mixer Circuit with Band-pass Filters (IV)
Two Diode Mixers - Push-Pull Mixers (V)

The feeding of the LO signal is done symmetrically in the centre of the inductors. If the circuit is constructed exactly symmetrically, the input and IF output are free of the LO voltage. The 2 diodes are driven in phase by the LO signal. But the input signal is applied out of phase to the 2 diodes. Due to the oscillation circuits used, this concept is suitable for narrowband applications. For wideband applications, these circuits would be replaced by transformers.
Active Push-Pull Mixer with FET (VI)
The input signal is added to the drain current using a transformer. The local oscillators modulates the FETs via the gate conductors. At all source connections the mixing product via the transformer can be assumed. This mixer has a DC connection to be able to supply the drain current via the centre tap of the input transformer. The gain factor is on the order of 6 - 10 dB.
For the higher frequency range one can use couplers instead of transformers. The single ended mixer can be easily transformed to a push pull mixer.
Balanced Mixer with 180°-Ring Hybrid

Received Signal
Rat-Race-Mixer

Push-pull mixers of this type are used for frequencies above 5 GHz. For lower frequencies double balanced mixers can be used that have better decoupling properties. The shown circuit was designed for an LO frequency of 26.5 GHz and an IF of 3.5 GHz. The input frequency is 30 GHz. The bandwidth is up to 20%.
Circuit of a Double Balanced Mixer

An even better decoupling of the ports from each other than the push pull mixer can be achieved using the double balanced configuration. The push pull mixer is extended to a double balanced mixer (hence called a four diode mixer), by the insertion of two further diodes. Thus all inputs and outputs can be decoupled from each other by careful selection of diodes and symmetrical construction.
The 4 diodes form a ring which is often described as a ring in circuit diagrams. Thus, and because this mixer is often used for modulation in communication engineering, they are called ring modulators. The transformer coils used for the above circuits can be used to about 5 GHz with the core materials available currently. Strip-line have to be used for higher frequencies.
Ring Modulator (II)

The 4 diodes form a ring which is often described as a ring in circuit diagrams. Thus, and because this mixer is often used for modulation in communication engineering, they are called ring modulators. The transformer coils used for the above circuits can be used to about 5 GHz with the core materials available currently. Stripline have to be used for higher frequencies.
A completely symmetrical driving of the diode ring can also be done using striplines. The configuration of stripbaluns (simultaneously coupler and symmetry link) shown, gives such a good decoupling of the ports from each other that the individual frequency bands of the HF-, LO-, and IF- signals can even overlap.
Broadband Double Balanced Mixer with a Marchand Tapered Balun

The sketch shows the layout principle of a double balanced mixer with symmetric stripline element stages. The frequencies of input and LO signals can be between 2 and 18GHz. The transformers of the input and LO signals are realized by the gradual transition from microstrip to coplanar lines (called Marchand balun). On both sides of the substrate an inductance (L1, L2) is used in the output coupling to prevent a short circuit of the LO signal. Thus the IF is band-limited and can take values of a few 100 MHz. The 4 mixer diodes are usually monolithically integrated on the same substrate.
Star Mixers (I)

Star mixer with crossed Marchand baluns. The bridge is the crossed structure in the centre, the microstrip ground plane is the square structure surrounding the mixer.

The decoupling of the signals is done by 2 crossed Marchand baluns. Due to their orthogonal configuration a very good decoupling between RF and LO input is achieved.
Star Mixers (II)

The IF is extracted at the centre of the diode cross. By completely symmetric construction of the coupling structure, the IF connection is decoupled from the RF and the LO input. These can be used over multiple octaves of bandwidth and have equally good matching in IF range.

A major disadvantage of star mixer is that the input signals must cover the same frequency range due to the coupler used. In contrast, baluns for different frequency ranges can be laid out for ring mixers.
External Connections

The performance of a mixer is strongly dependant on its external circuit connections. An error can limit the functioning of a mixer. The outer connections must guarantee the following within the considered frequency ranges:

- **Matching** of the mixing element impedances to the applied signals.
- Maintaining the push-pull operation and **symmetric** behavior of the push-pull operation.
- **Filtering** of the operating frequency range for the suppression of interfering mixing products. (eg: Mirrored frequency suppression)
- The **currents** in different frequency ranges must be able to flow unimpeded from source to load.
- The diodes need a **DC path**

Ignoring this can lead to total malfunction of the mixer.
Signal Flow in a Mixer, Diode Grounded

For a down converter, i.e. the frequencies $f_e$ and $f_{LO}$ lie above the $f_{IF}$. The separation of the frequency components can be achieved simply by high pass or low pass filters. The currents of $f_e$ and $f_{LO}$ are combined in a coupler, pass the high pass filter, flow through the mixing element to ground.

Signal flow of the single ended down converter, ground path through the mixing element

The low pass filter blocks these signals so that the ground path remains through the diode. The generated low frequency mixing signals $f_{IF}$ are blocked by the high pass filter and thus flow through the low pass filter to the IF part (resistor), where they can flow to ground. The mixing element requires no direct connection to ground.
Signal Flow through a Mixer, Diode in Series

The single ended mixer has been modified so that its mixing element is in series with signal flow and has no direct ground connection.

The signal flow remains the same as before in principle except that the currents can no longer flow through the mixing element to ground. In this case the ground connection of the circuits around the mixer is extremely necessary to that the current loops of the respective frequency ranges can be closed.

Signal flow of the single ended down mixer. ground path through the external circuitry.
FM Radio Receiver Mixer Frequencies

\[ f_{\text{IF}} = f_{\text{in}} - f_{\text{LO}} = 10,7 \text{ MHz} \]

\[ f_{\text{Sum}} = f_{\text{in}} + f_{\text{LO}} \]

\[ f_{\text{in}} \approx 89, 99,7 \text{ MHz} \]

\[ f_{\text{LO}} \]

Amplitude
DSB Down Conversion

\[ f_{\text{IF}} = | f_{\text{in}} - f_{\text{LO}} | \]

\[ f_{\text{LO}} \]

\[ f \text{ in MHz} \]