MICROWAVE MIXER DESIGN

1. Introduction

Mixers are frequency translation devices. They allow the conversion of signals between a high frequency (the RF frequency) and a lower Intermediate Frequency (IF) or baseband. In communications systems the RF is the transmission frequency, which is converted to an IF to allow improved selectivity (filtering) and an easier implementation of low noise and high gain amplification. This paper details the design of mixer circuits, concentrating on low cost Printed Circuit Board (PCB) based designs using discrete Surface Mount Technology (SMT) components.

2. The Fundamentals

The non-linear behaviour of a mixing device is used to realise the mixing function. Diodes, Field Effect Transistors (FETs) and bipolar transistors can all be used as mixers and are all covered in this paper. Figure 1 shows the typical I-V characteristics of a Schottky diode, which can be described by equation (1).

$$I = a_1V + a_2V^2 + a_3V^3 + a_4V^4 + \dots\dots\dots \qquad (1)$$

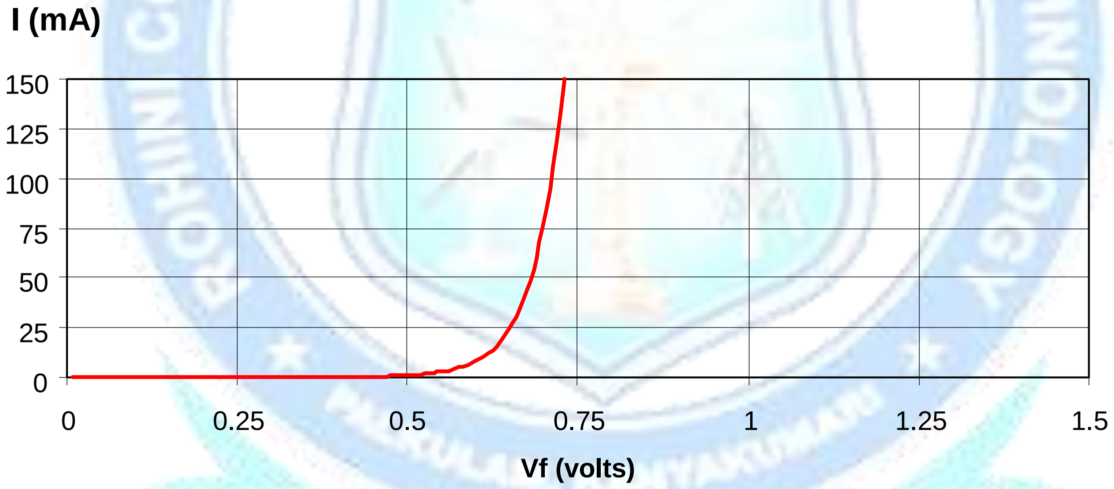

Figure 1: Typical forward I-V Characteristics of a diode

If the diode is excited by two sinusoids, Cos(ω_1t) and Cos(ω_2t) the current through the diode is given by equation (2).

$$I = a_1(Cos(\omega_1 t) + Cos(\omega_2 t)) + a_2(Cos(\omega_1 t) + Cos(\omega_2 t))^2 + \dots \qquad (2)$$

When expanded this contains the term $2a_2$Cos(ω_1t)Cos(ω_2t) which has the trigonometrical relationship shown in (3). It is either the sum or difference term that is the desired output of a mixer.

$$2Cos(\omega_1 t)Cos(\omega_2 t) = Cos((\omega_1 - \omega_2)t) + Cos((\omega_1 + \omega_2)t) \qquad (3)$$

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Diodes are “square-law” devices, which means the function describing their non-linear behaviour has a strong a_2 component. This means that if excited correctly they should be able to produce a strong mixing product. Thus the basic mixer design entails injecting the signals to be mixed and extracting the desired mixing product whilst maximising the efficiency of the conversion. One significant problem with mixers is that in addition to the wanted product, there are also numerous unwanted spurious products, often referred to as “spurs”. Figure 2 depicts the spectral output of a downconverting mixer. The Local Oscillator (LO) is mixed with the wanted RF signal to produce a copy of the RF signal at the difference frequency (the IF). In general the mixer will generate outputs at a range of frequencies given by mRF ± nLO. The spectrum shown in Figure 2 has an LO frequency below the IF, this is known as low-side injection.

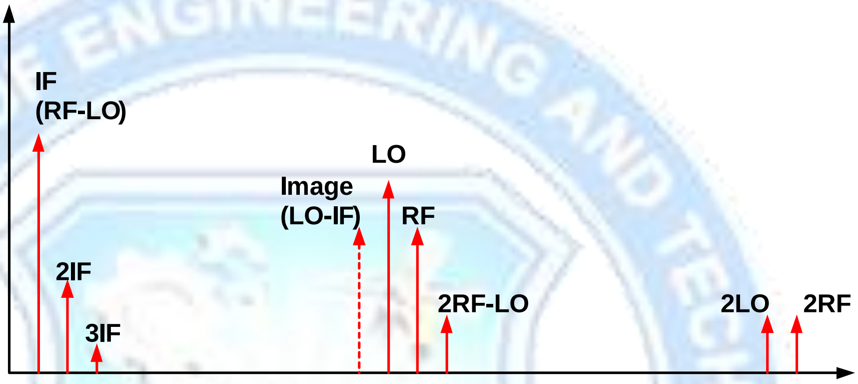


Figure 2: Mixer spectral output

One frequency of particular importance is the image frequency. This is 2IF away from the RF and will be converted directly to the same IF frequency as the RF. Noise and unwanted signals present at this frequency can severely degrade the system performance. Filtering and/or image reject mixers (covered later in this paper) are normally incorporated to address this problem. More detailed information on the system design can be found in [1].

In the case of upconverting mixers the input signal is the IF and the desired output signal is either the product or difference of the LO and IF frequencies, depending whether high-side or low-side injection is being used. If the wanted output is LO+IF, the difference product (LO-IF) is termed the unwanted side-band, or image and must be rejected by filtering or the use of an image-reject mixer.

Most mixers incorporate some form of filtering which helps to reduce the levels of the unwanted spurious outputs. Another commonly used technique, which helps reduce spurious outputs, is the use of balanced mixer designs. More detail on balanced mixer design is included in Section 4.

3. Mixer Terminologies

Listed below are some of the terms used in referring to mixers or mixing performance:

Conversion loss: The ratio of the wanted output signal level to the input, normally expressed in dB.

Noise Figure: The ratio of the Signal to Noise Ratio (SNR) at the input compared to the SNR at the output, measured at 290K. To avoid ambiguity this paper will use the term noise figure to refer to the value of this ratio in dB and the term noise factor to refer to the value as an absolute ratio.

Double Sideband (DSB) Noise Figure: Includes noise and signal contributions at both the RF and the image frequencies.

Single Sideband (SSB) Noise Figure: No image signal is included although image noise is included. Provided the mixer performance is the same at the image and the wanted frequencies, the SSB noise factor = twice the DSB noise factor.

Compression: For small input signal levels, each dB increase in signal level results in a dB increase in the output signal level. As the input signal level continues to increase, the conversion loss of the mixer will eventually start to increase. The 1dB compression point is the input signal level at which the conversion loss has increased by 1dB. Mixers should be used "backed-off" from the 1dB compression point as in addition to distortion of the wanted signal, operation at or close to it would give rise to significant increases in the levels of the spurious outputs.

Third Order Intercept Point. This is a figure of merit to give an indication of the mixer's signal handling capability. In particular it provides an indication of the levels of third order products a mixer is likely to produce under multi-tone excitation. It is measured by applying two closely spaced input tones at frequencies F_1 and F_2. Third order products from the mixing of these tones with the LO (at frequency F_{LO}) occur at frequencies given by: $(2F_1 \pm F_2) \pm F_{LO}$ and $(2F_2 \pm F_1) \pm F_{LO}$. In the case of downconvert mixer, the third order products of most interest are $(2F_1 - F_2)F_{LO}$ and $(2F_2 - F_1) - F_{LO}$ as they fall in, or close to the IF band. Figure 3 depicts the IF output spectrum of a downconvert mixer under two-tone excitation.

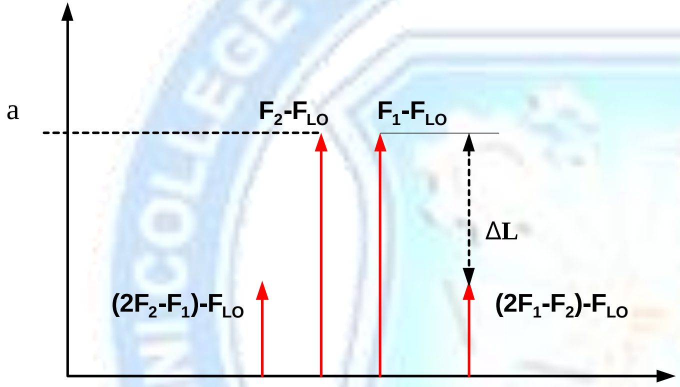


Figure 3: IF spectrum for mixer third order intercept point measurement

The third order intercept point itself is an entirely imaginary point, at which the third order product becomes as large as the direct downconverted product. The level of the third order products rises at three times the rate of increase of the input signal level and fundamental output level. The mixer's output referred third order intercept point (TOI_{out}) is given by equation (4), all values are in dB and it is the dB value of ΔL which is divided by 2.

$$TOI_{out} = P_{IF} + \frac{\Delta L}{2} \qquad (4)$$

With mixers, the third order intercept point is often referred to the input, which just requires adding the conversion loss to TOI_{out}.

Linearity. The linearity of a mixer refers to its signal level handling ability. Thus a mixer with high linearity will have a high TOI.

Spur's. An abbreviation of spurious product. The term is used to describe any unwanted mixing product.

Sub-harmonic mixer. This is a mixer circuit designed to accept an LO input at a fraction (often a half) of the desired LO mixing frequency.

Harmonic mixer. This is just another term for sub-harmonic mixer but is more commonly used for circuits employing higher multiples of the input LO to produce the mixing LO.

Pump. A term sometimes used to describe the LO drive. The LO input is said to be "pumping" the mixer.

Image frequency. For high side injection ($F_{LO} > F_{RF}$) this is $F_{LO} + F_{IF}$, for low side injection ($F_{LO} < F_{RF}$) it is $F_{LO} - F_{IF}$. In downconvert mixers, it is a frequency that is converted directly to IF along with the IF itself. In upconvert mixers it is an unwanted sideband which, without additional filtering, is usually at a similar level to the wanted signal.

Image-reject mixers. A more complex mixer configuration, which has the advantage of providing inherent cancellation of the image signal.

Image enhancement. A method for reducing the conversion loss of a mixer by terminating the image frequency in an appropriate reactive impedance. Should be used with caution as the resultant mixer can have severely degraded intermodulation performance [5]. Also, the exact image impedance is normally found empirically.

4. Diode Mixers

Most modern diode mixer designs use Schottky diodes. The main reason for this is that the Schottky diode is a majority carrier device which means it has a higher switching speed than p-n junction diodes [2]. In-expensive plastic packaged diodes are now available, which are suitable for designing mixers up to around 13GHz. Manufactures normally specify the intended application of a particular diode and the selection of a suitable diode is a vital step in diode mixer design. It is also common for manufacturers to refer to diodes as low, medium or high barrier. The higher the barrier height, the higher the forward voltage required to turn the diode on. The exact definition of what constitutes a low, medium or high barrier is open to the manufacturer's interpretation. However, broadly speaking, for a forward current of 1mA, low barrier diodes require a forward voltage of around 0.2 - 0.3V, medium 0.4 - 0.5V and high 0.6 - 0.7V. The higher the barrier, the higher the LO drive which will be required to obtain low loss mixing but the resultant mixer should have greater linearity.

The electrical equivalent circuit for a packaged Schottky diode is shown in Figure 4. Also shown in Figure 4 is a typical RF Schottky diode in a SOT23 package; with a pencil tip for size comparison, Lp and Cp are the packaging parasitics. Rs is the parasitic series resistance of the diode and Cj and Rj are the non-linear components of the Schottky diode junction. The non-linearity of Rj is responsible for the square law behaviour of the diodes DC characteristics (Figure 1).

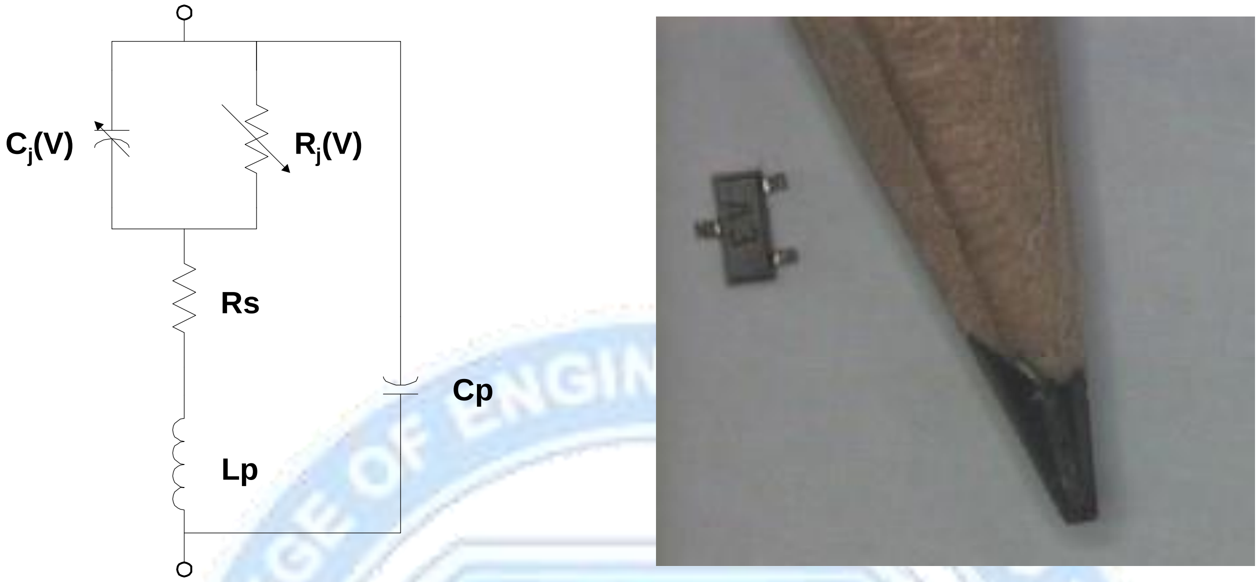


Figure 4: Equivalent circuit of a packaged Schottky diode and a photograph of a SOT23 packaged diode, with pencil tip for size reference

Most diode mixer designs utilise unbiased diodes, however forward biasing of the diodes, so a small DC current flows, can offer reduced conversion losses. This is particularly the case when limited LO drive is available. The diode is biased to have a quiescent operating point close to the region of maximum non-linearity in its operating characteristics which allows the diodes square law characteristic to be traversed with lower levels of LO drive.

4.1. Single-ended Diode Mixers

Mixers, which utilise a single diode as the mixing element, have no inherent isolation between the mixer ports and are known as single-ended designs. Figure 5 shows a basic block diagram of a single-ended mixer.

One of the main difficulties with single-ended designs is that the LO and RF inputs must be separated with a diplexer filter. They are normally relatively closely spaced and separating the two frequency bands can be problematic. Coupled with this, the fact that no inherent spurious suppression is afforded by this topology, it is not surprising that few modern diode mixer designs are single-ended. The exception to this is high mm-wave frequency designs, which are still often realised with a single diode.

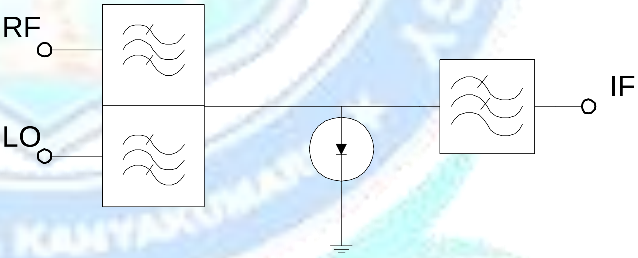


Figure 5: Basic block diagram of a single-ended mixer

A step-by-step procedure for designing a single ended mixer is given below:

1. Choose a suitable diode for the application. Factors effecting this choice include operating frequency, available LO drive, cost versus performance trade-offs and package style.
2. Design the IF filter, the techniques described in [3] can be used. In addition to having low insertion loss it is important that it presents a high input impedance at the LO and RF frequency's. See also the comments on matching, below.
3. Design the RF and LO filters [3], in addition to having low loss and providing a diplexing action which gives isolation between the two inputs, the common output of these filters must provide a high impedance across the IF frequency band. See also the comments on matching, below.

4. Large signal simulators are now commonly available and most manufacturers supply large signal models for their diodes. It is strongly recommended that, when possible, a large signal analysis of the mixer be carried out prior to fabrication.

Matching: If a diode is considered as a switch, being either open or short-circuit, then impedance matching between the mixer ports and the diode is not possible and indeed not necessary. However, it is more appropriate to think of a mixer diode as a square-law device. The impedance that the diode presents is a time varying impedance, dependent on the LO level and frequency. It is the time-averaged value of the diode’s impedance, which must be used if matching is attempted. If an accurate large signal model and the packaging parasitics are available, simulation of the LO-dependant diode impedance is possible. For those without access to a largesignal simulator an estimate of the time-averaged value of Rj(V) and Cj(V) can be made. Matching to the diode can improve the performance of a mixer but it must be addressed with care. It is important to note that the filter requirements detailed in steps 2 and 3, above must still be satisfied with any matching networks present.

Linearity: The best way to improve the linearity of a diode mixer is to increase the LO drive level. Higher barrier-height diodes should be used for best performance, provided that adequate LO drive is available. Techniques such as image-enhancement should be avoided as this can degrade linearity [5].

4.2. Single-balanced Diode Mixers

A single-balanced diode mixer uses two diodes. Either the LO drive or the RF signal is balanced (applied in anti-phase), adding destructively at the IF port of the mixer and providing inherent rejection. The level of rejection is dependent on the amplitude and phase balance of the balun, providing the balanced drive, and the matching between the two diodes. A rejection of 20 to 30dB is normally possible for good discrete designs. Other advantages of a singly-balanced design are rejection certain mixer spurious products, depending on the exact configuration, and suppression of Amplitude Modulated (AM) LO noise. AM noise could be a significant problem in early microwave and mm-wave receivers where the available LO sources were very noisy. Modern wireless transceivers tend to make use of synthesised LO drives and the LO phase noise gives more of a problem than the AM noise.

One disadvantage of balanced designs is that they require a higher LO drive level. Figure 6 shows a block diagram of a singlebalanced mixer. It utilises an anti-podal diode pair. Matched diode pairs, in various configurations, are readily available in low-cost plastic packages. Other configurations of single-balanced mixers are possible, more details can be found in [2].

For the topology shown in Figure 6, the LO drive to the two diodes is in anti-phase (balanced) and the RF signal is in-phase. If the mixing products are at mRF ± nLO, this mixer will reject all products where m is even. If the RF drive were in anti-phase and the LO in-phase, all spurious products with n even would be rejected. The antiphase signal is also cancelled at the IF port. Because the LO drive should be at a significantly higher level than the RF signal, it is often chosen as the anti-phase signal to increase the LO to IF isolation. However, it is also important to consider the spurious rejection properties.

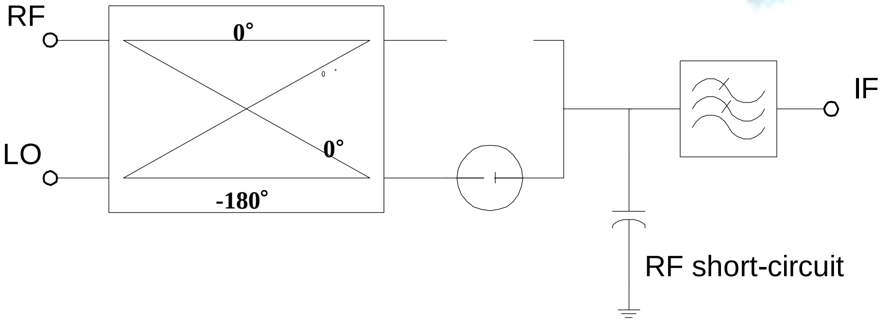


Figure 6: Block diagram of a single-balanced mixer

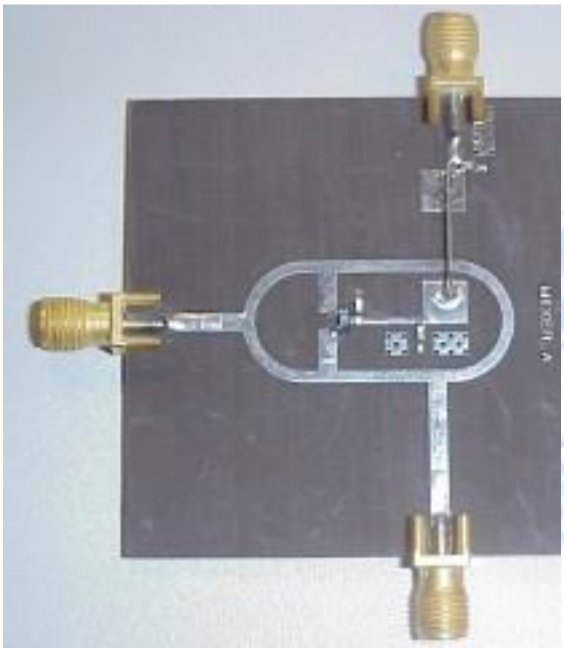


Figure 7: Photograph of a singlebalanced diode mixer using a Rat-Race balun

The RF short-circuit, shown at the IF port in Figure 6, is required for the mixer to function. Although shown explicitly here, it is normally incorporated in the IF low pass filter design. If the RF impedance at the IF port were high, the RF signal voltage across the diodes would be small and the mixer's conversion loss very high. The LO signal, however, does not require a low impedance at the IF port. Because the LO is a balanced signal across the diode pair, the common port of the diodes is a virtual earth to the LO. The LO drive across the two diodes adds destructively to a null at the common port, as if it were grounded. In most cases, however the LO and the RF are comparatively close in frequency and the RF short circuit will also be a good short circuit at the LO frequency.

The design procedure for a balanced diode mixer is similar to that for a single-ended. The only difference being that the balun structure providing the RF and LO isolation and its design must be considered as part of the RF/LO filter design. One option for the balun realisation is a Rat-Race coupler, as described in [4]. This is a very popular option at microwave frequencies where it is a comparatively small structure that can be produced inexpensively on a printed substrate. Figure 7 shows a photograph of a prototype realisation of such a mixer. It covers the HIPERLAN RF band of 5.15 to 5.35GHz with a 700MHz IF, measured conversion loss is 7dB and the input referred 1dB compression point is +5dBm for an LO drive level of +8dBm. A SOT23 packaged anti-podal diode pair has been used and a 1pF 0603 capacitor is used to realise the RF short at the IF port, whilst forming the first element of the IF low-pass filter.

Figure 8 shows a 1.5GHz single-balanced mixer realised on an FR4 substrate with a lumped element balun. This had a conversion loss of 9dB for an LO drive of +8dBm.

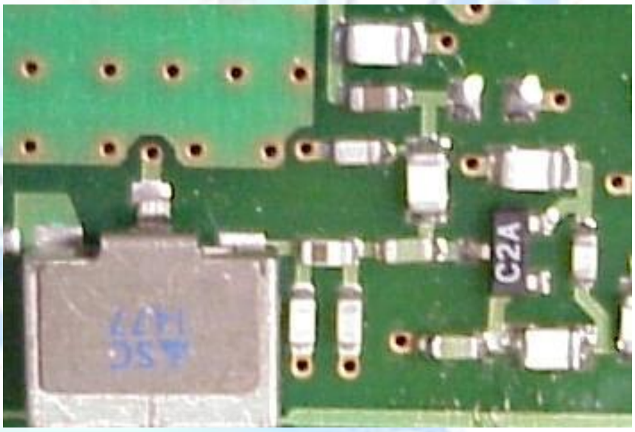


Figure 8: Photograph of a single-balanced mixer with lumped element balun

The ceramic resonator filter to the bottom left of Figure 8 is the RF image filter. At the output of this filter is the lumped element RF filter of the mixer. It connects to the common port of the antipodal diode pair (in the SOT23 package). The IF port of the mixer (at the top centre of Figure 8) is also connected to the common port of the diode pair via a filter. The output of the RF filter needs to present an open circuit to the output of the IF filter and vice-versa. The LO input is to the bottom right and a simple lumped element balun providing a differential drive across the diode pair.

4.3. Double-balanced Diode Mixers

A double-balanced diode mixer normally make use of four diodes in a ring or star configuration with both the LO and RF being balanced. All ports of the mixer are inherently isolated from each other. Matched diode rings (fabricated in close proximity on the same substrate material) are readily available in SOT143 plastic packages.

The advantages of a double-balanced design over a single balanced design are increased linearity, improved suppression of spurious products (all even order products of the LO and/or the RF are suppressed) ant the inherent isolation between all ports. The disadvantages are that they require a higher level LO drive and require two baluns. Figure 9 shows a block diagram of a doublebalanced quad-ring diode mixer. Details of the star topology can be found in [2].

The operation of a double balanced mixer is best understood by considering the diodes as switches. The LO alternately turns the right hand pair and left hand pair of diodes on and off in anti-phase.

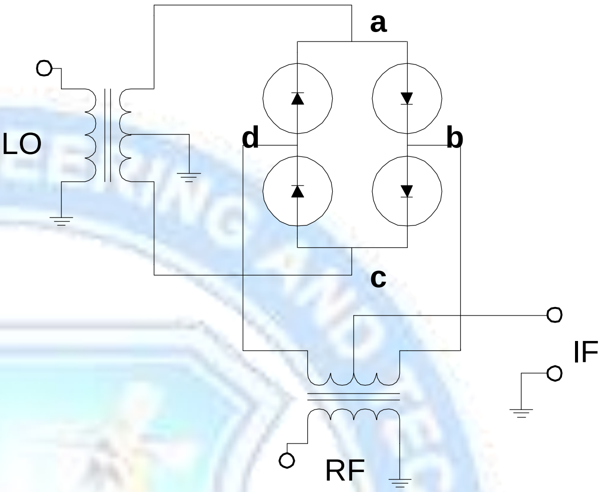


Figure 9: Block diagram of a double-balanced diode mixer

Points 'a' and 'c' are virtual earths to the RF signal and can be considered as connected to ground. Thus points 'b' and 'd' (the balanced RF signal) are alternately connected to ground (at points 'a' and 'c'). This means an in-phase RF signal and an anti-phase RF signal are alternately routed to the IF port under control of the LO. Thus the signal at the IF port is effectively the RF signal multiplied by an LO square wave of peak magnitude ±1.

This action is easily demonstrated using simple mathematical processing software. Figure 10 shows a sinusoidal voltage waveform at a frequency of 1GHz, this is the RF waveform. Figure 11 shows a square wave at a frequency of 870MHz, this is the LO switching waveform. Multiplication of the two will produce a waveform wit a strong component at the difference frequency (IF) of 130MHz.

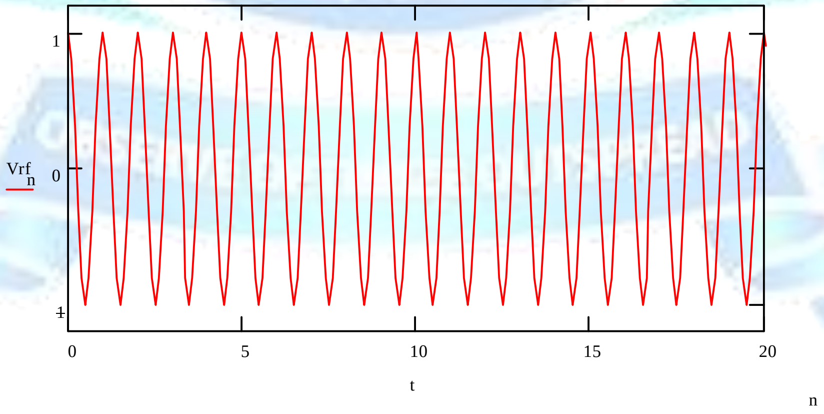


Figure 10: RF voltage waveform versus time in ns

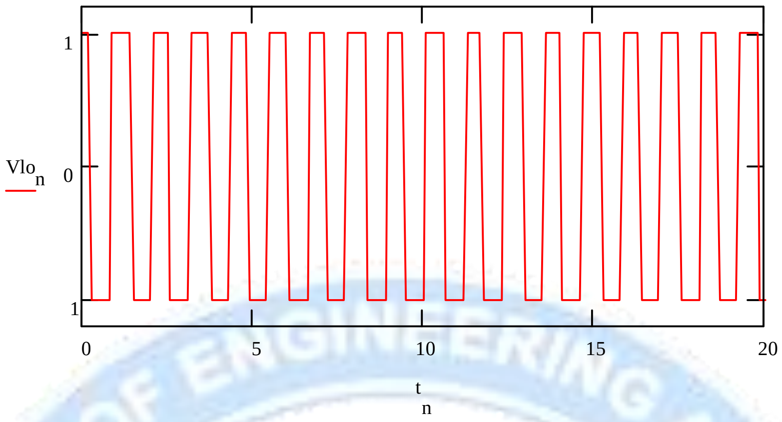


Figure 11: LO voltage waveform versus time in ns

Figure 12 shows the result of multiplying the RF and LO waveforms. A low frequency sinusoid is clearly visible. This is a replica of the RF signal (i.e. a sinusoid) translated to the IF frequency of 130MHz. Although this method of mixer analysis provides a qualitative understanding of how the mixer functions, it is not adequate to predict the RF functionality. Ideal square wave multiplication, such as this, results in a conversion loss of 3.9dB. In practice diode-ring mixers have additional losses (in the baluns and diodes) and imperfections which increase the conversion loss actually achieved. A loss of between 6 and 8dB is typical for a well designed diode ring mixer. In order to predict accurately the mixer's performance, large signal circuit simulation must be performed.

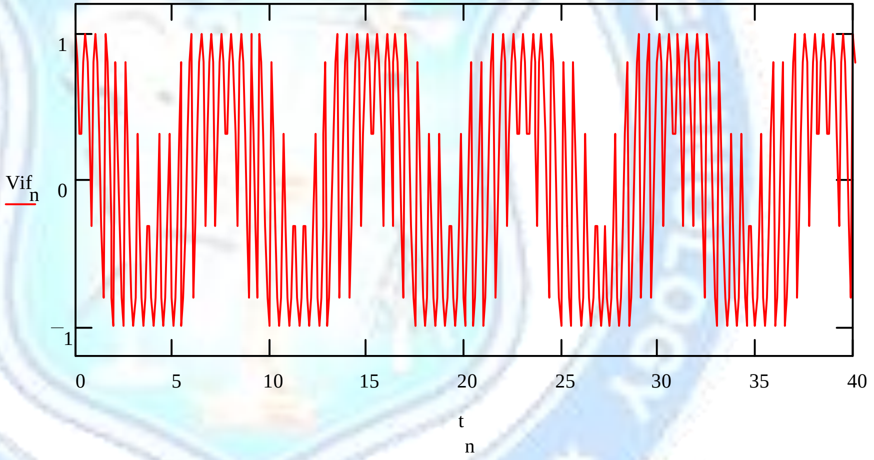


Figure 12: IF voltage waveform (Vrf*Vlo) versus time in ns

The block diagram in Figure 9 shows the differential RF and LO signals provided using wire-wound ferrite transformers. Wire-wound transformers can be used at frequencies up to over 2GHz but lower cost printed or lumped element baluns are often implemented in practical mixers. At higher frequencies wire wound transformers become impractical and printed and/or lumped baluns become the norm. Care should be taken to consider how the performance of these baluns differs from wound transformers; additional filtering may be necessary. An overview of practical balun configurations is given in Section 5.

4.4. Double doubly balanced diode mixers

As the name implies, a double doubly balanced mixer is an interconnection of two double balanced mixers. Figure 13 shows a block diagram. Increased linearity is the main advantage of the double doubly balanced topology (or treble balanced as it is also referred to). The reason for this is easily understood; the incident power is simply shared amongst a twice as many diodes, thus increasing the signal handling capability by 3dB. The main disadvantage is also obvious, increased complexity: A total of 3 baluns and 8 diodes are required. In addition to this, a higher level of LO drive (3dB more) must be provided. An alternative approach to realising high linearity mixers is the FET resistive mixer, detailed in Section 6. This can yield even higher linearity than the double doubly balanced topology whilst having a simpler circuit configuration.

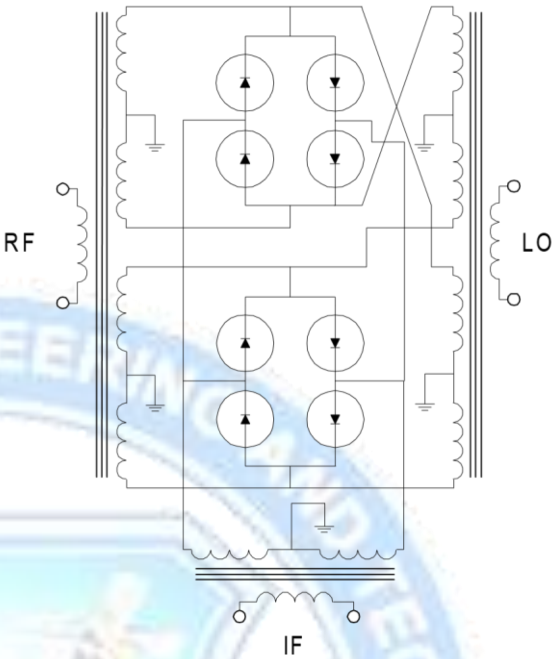


Figure 13: Block diagram of a double doubly balanced mixer

The transformer configuration shown in Figure 13 is from [5]. In practice such a complex arrangement of wire wound transformers is unlikely to be used and a more practical approach is to combine a pair of double balanced mixers using hybrid power combiners/splitters.

4.5. Sub-harmonic mixers Diode Mixers

A sub-harmonic, or sub-harmonically pumped, mixer has an LO input at F_{LO}/n but is designed to maximise the conversion efficiency of an F_{LO} product. They are useful at higher frequencies when it can be difficult to produce a suitable LO signal (low phase noise, tuning range and output power all become more difficult to achieve with increasing frequency, whilst cost increases). It is also possible to design frequency multipliers using transistors and/or diodes and to multiply an LO input before using it to drive a fundamental mixer. Such architectures are in common use but are not true sub-harmonic mixers. Figure 14 is a circuit configuration, which can be used to realise a sub-harmonic diode mixer. For an LO input at $F_{LO}/2$, the output is maximised at

$F_{LO} \pm F_{RF}$ (or $F_{LO} \pm IF$ when used as an upconverter).

The circuit makes use of an anti-parallel diode pair and provided the diodes are identical it has no fundamental mixing response. It also benefits from the fact that the F_{RF} and F_{LO} are normally relatively close in frequency (for a comparatively low IF). Thus the short circuit $\lambda_{LO}/2$ stub at the LO port is a quarter of a wavelength long at the input frequency of $F_{LO}/2$ and so is open circuit. However, at F_{RF} this stub is approximately a half wavelength long, so providing a short circuit to the RF signal. Conversely, at the RF input the open circuit $\lambda_{LO}/2$ stub presents a good open circuit to the RF but is a quarter wavelength long at the frequency $F_{LO}/2$ and so is short circuit. The IF is normally far enough away from the RF frequency to allow easy realisation of an IF filter presenting an open circuit output to the RF port.

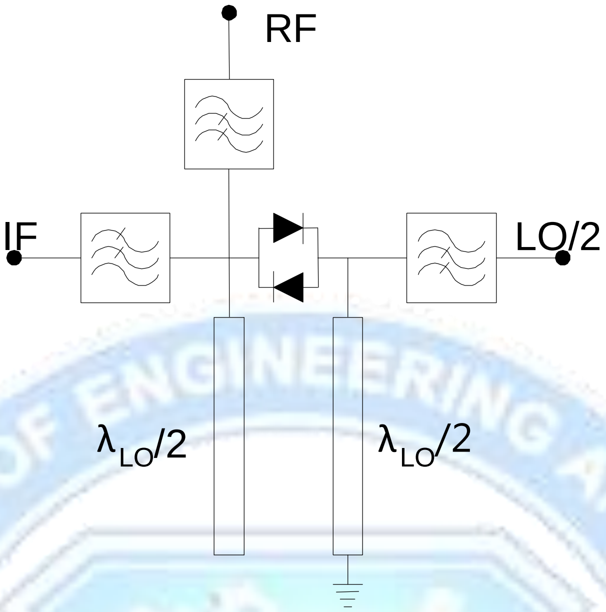


Figure 14: Block diagram of a sub-harmonic diode mixer

A photograph showing a practical implementation of this type of sub-harmonic mixer is shown in Figure 15. It uses an antiparallel diode pair in a low cost SOT 23 package. The IF port is to the left, going into a low pass filter ending in an 0402 chip inductor which is open circuit resonant at the RF frequency of 11.7 to 12.7GHz. The IF frequency is 1 to 2GHz and the F_{LO}/2 input is fixed at 5.35GHz (F_{LO}=10.7GHz).

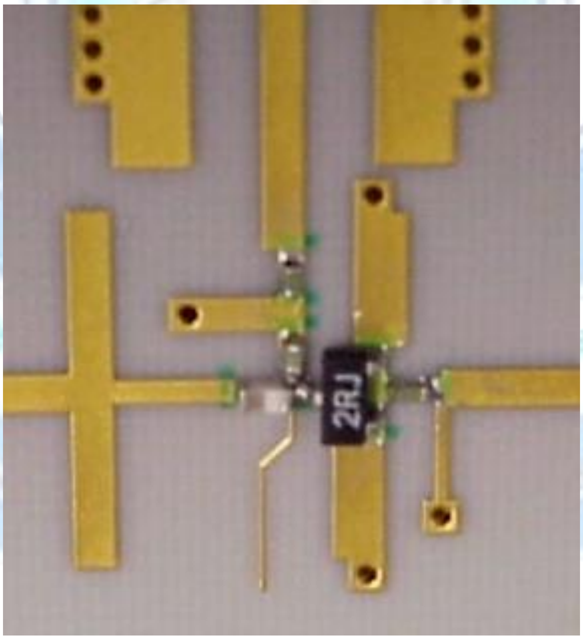


Figure 15: Photograph of a 12GHz sub-harmonically pumped mixer

The conversion loss versus RF frequency has been measured for this mixer at three LO input power levels (+5dBm, +8dBm and +10dBm), a graph of the results is shown in Figure 16. For LO drive levels of 8 or 10dBm the conversion loss is between 9.5 and 11dB, which is only slightly more than would have been achieved with a fundamental diode mixer design, with the advantage of only having to generate an LO signal at half the actual LO frequency. One disadvantage to the mixer compared to a fundamental design is increased spurious products. This is not only due to the fact that the mixer is not balanced but also that there are additional spurious products due to spurs with $F_{LO}/2$ products.

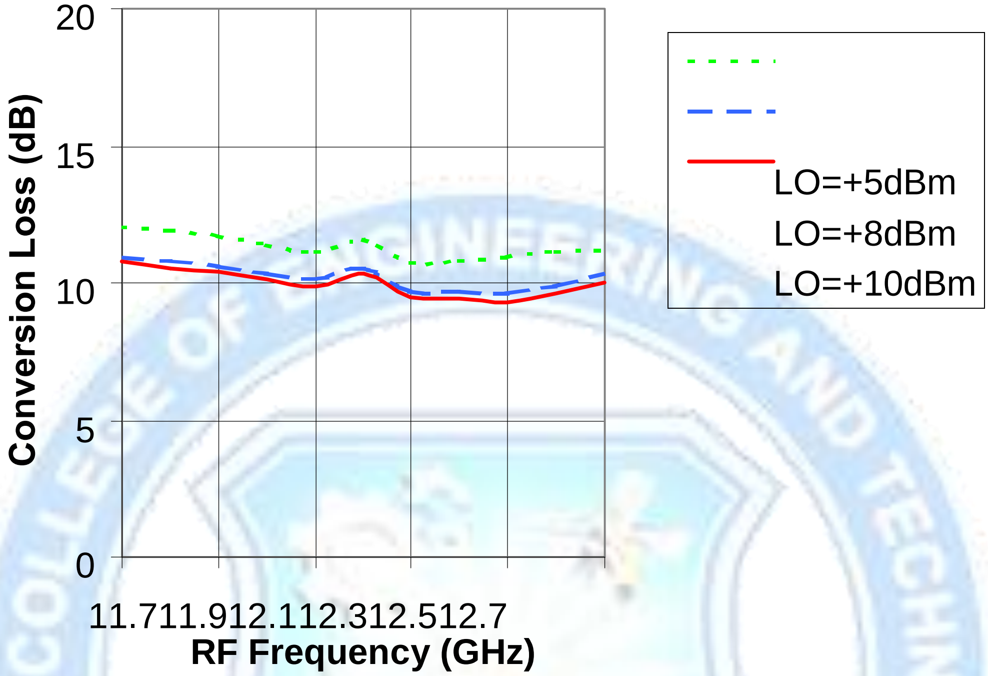


Figure 16: Measured conversion loss versus frequency for sub-harmonic mixer

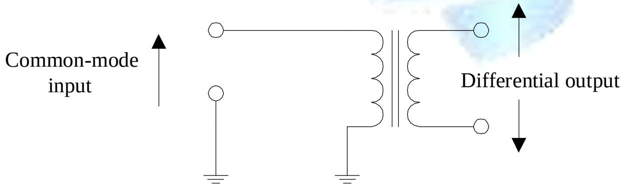
5. Baluns

A balun is used to transform a signal between BALanced and UNbalanced modes. An unbalanced signal is referenced to a ground plane, as in a coaxial cable or microstrip. A balanced signal is carried on two lines and is not referenced to a ground plane. Each line can be considered as carrying identical signal but with 180° of phase difference. A comprehensive presentation of balun design is beyond the scope of this paper but an overview of a number of practical implementations is given below and references are provided.

5.1. Wire-wound transformers

A wire-wound transformer provides an excellent balun and it has been used to represent the balun in all of the mixer topologies presented here. Miniature wire-wound transformers are commercially available covering frequencies from low kHz to beyond 2GHz [6]. They are often realised with a centre-tapped secondary winding, if grounded this provides a short circuit to even-mode (common-mode) signals whilst having no effect on the differential (odd-mode) signal.

Figure 17: Centre-tapped transformer as a balun



Wire-wound transformers are more expensive than the printed or lumped element baluns described below, which find greater adoption in practical mixer designs. It should be noted that most of these lumped element and printed baluns do not provide the centre-tapped ground to even mode signals and this fact must be accounted for in the mixer design.

5.2. Printed baluns

There are a wide range of printed balun topologies [7] they have the advantage of being inexpensive, realised as they are on the Printed Circuit Board (PCB) or Microwave Integrated Circuit (MIC) substrate. On the downside they can be quite large, particularly at lower RF frequencies. The rat-race coupler shown in Section 4.1 is commonly used at microwave frequencies for bandwidths of up to around 10-20%.

Figure 18: Simple coupled line balun

Possibly the simplest printed balun is the coupled line balun [8], also called a parallel-line balun shown in Figure 18. The structure is a quarter of a wavelength long at the centre frequency. It is capable of bandwidths of over an octave, provided the coupling between the lines is high enough. In practice this is not normally the case for the simple edge coupled balun shown in Figure 18. A more practical approach is to use multiple coupled lines as shown in Figure 19 or, where multi-layer substrate processing is available, to adopt a broad-side coupler topology as in Figure 20. This broadside-coupled implementation is often referred to as a parallel plate balun.

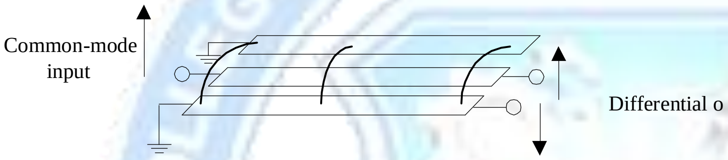


Figure 19: Coupled line balun using multiple coupled lines

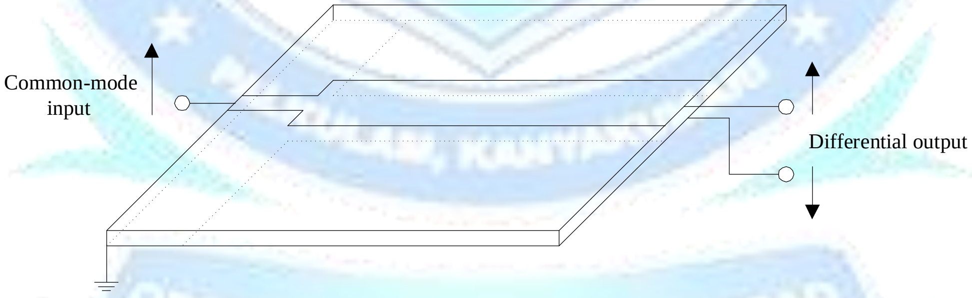


Figure 20: Coupled line balun, using broadside coupler structure

An improvement on the parallel-line balun is a printed version of the "Marchand Balun". This is derived from the co-axial balun, described by Nathan Marchand in 1944 [9]. The printed version of the Marchand balun is shown in its simplest form in Figure 21. This is more tolerant to low even mode impedance (low coupling ratio) than the parallel line balun and has a wider bandwidth.

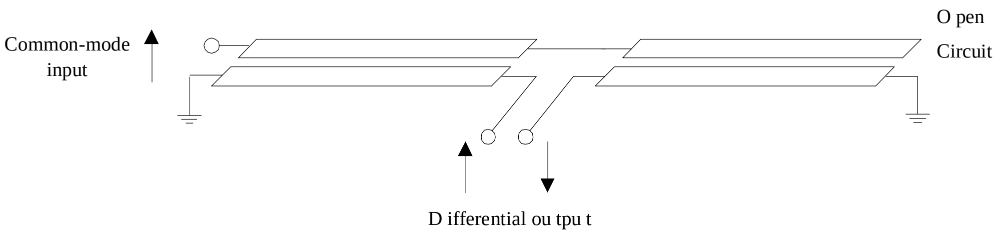


Figure 21: Printed Marchand Balun

As with the parallel line balun, improved performance is obtained if multiple planar section are used [10] or if a broadside coupling topology is adopted [11]. One draw back to using these printed baluns at lower RF frequencies is their size. One technique to reducing the size is to include lumped elements and printed structures, as shown in Figure 22. This allows acceptable balun performance to be achieved with significant area reduction [12]. As with the parallel line and Marchand baluns, the use of broadside, rather than edge, coupling will yield tighter coupling and improved performance.

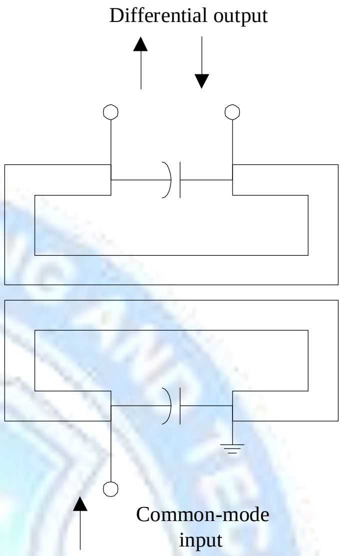
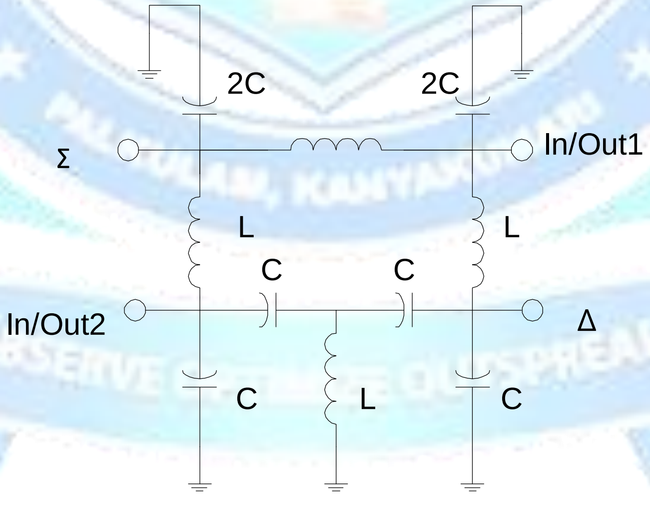


Figure 22: Reduced size printed balun

5.3. Lumped Element Baluns

Lumped element baluns are based around the fact that the insertion phase through a low pass filter lags the insertion phase through a high pass filter [13]. It therefore possible to design low pass and high pass filters that have a relatively constant 180° difference in insertion phase. A wide range of topologies is possible and for narrow band designs, very simple structures can be adequate [14]. Figure 23 shows a lumped element implementation of a rat-race splitter/combiner [7]. Signals incident on the Σ port split equally in amplitude and phase, whilst signals incident on the Δ port split equally in phase but have a 180° phase difference. Design equations are shown in the figure, Zo is the system impedance.



$$\omega_o L = \frac{1}{\omega_o C} = \sqrt{2} Z_o$$

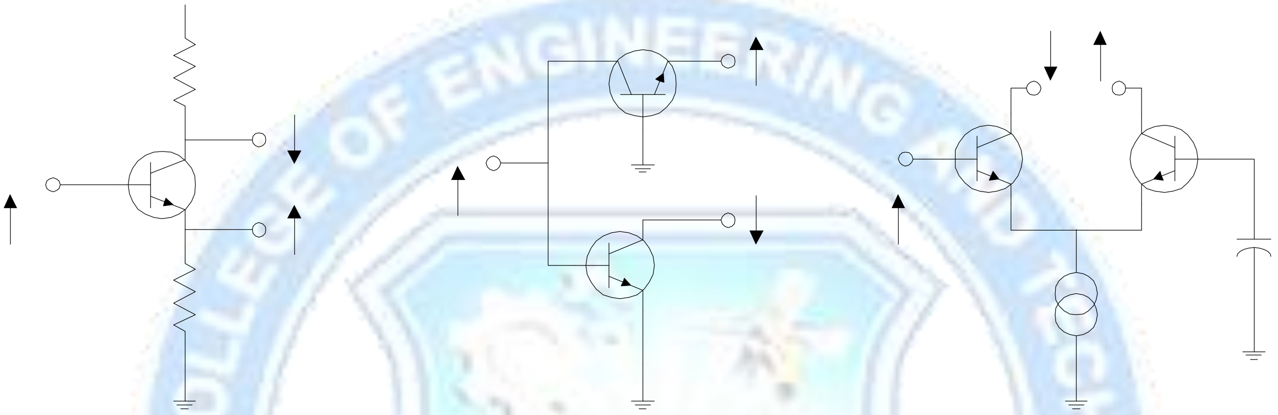
Figure 23: Lumped element realisation of a rat-race splitter

5.4. Active Baluns

Active baluns have a number of disadvantages:

- Degraded intermodulation performance for the resultant mixer
- Amplitude and phase balance is normally poorer than for passive designs
- Discrete realisations sensitive to package parasitics
- DC bias is required
- The output impedances of each port can be significantly different

Figure 24 shows three possible active balun realisations.



3-port phase splitter | C-B/C-E amplifier | Long-tail pair

Figure 24: Active balun topologies

The 3-port phase splitter only really works well at lower frequencies but can be quite compact. The C-B/C-E balun can work well over quite wide bandwidths provided parasitics are well modelled. The long-tail pair is commonly used in integrated realisations, closer inspection will reveal it is extremely similar in architecture to the C-B/C-E topology.

6. FET Mixers

FETs can be used in mixers in both active and passive modes. Active FET mixers are transconductance mixers using the LO signal to vary the transconductance of the transistor. They have the advantage of providing the possibility of conversion gain rather than loss and can also have lower noise figures than passive designs. Figure 25 shows the simplest realisation of a transconductance mixer, biasing circuitry has been omitted for clarity. The RF (and LO) short circuit at the drain is important to ensure that the value of Vds is not moved significantly from its DC bias point by the applied LO. This ensures the magnitude of the time varying transconductance is maximised so optimising the conversion gain. Unfortunately it also means that this mixer topology is not well suited to realising upconverters.

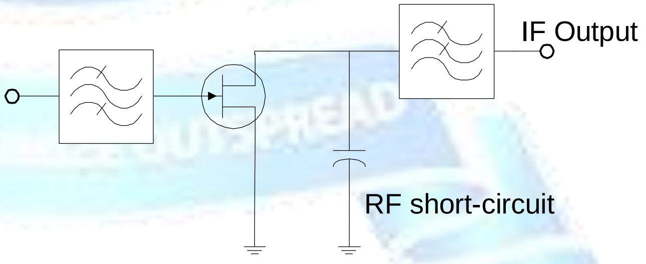


Figure 25: Simple transconductance mixer

The topology of Figure 25 has the disadvantage that some form of diplexing is required to separate the RF and LO inputs which are incident on the same port. For this reason dual gate FET mixers are often used. This toplogy is essentially a cascode arrangement of two transistors as shown in Figure 26, although in practice four terminal dual gate FET devices are sometimes used.

The RF input is applied to the bottom device which is matched using the well-known techniques developed for amplifier design, the LO signal is applied to the top device, which is often resistively matched. One advantage this structure has is that the LO and RF signals are inherently isolated. It can be used to develop compact mixers with conversion gain, as described in [15]. Although the potential of conversion gain rather than loss, which the transconductance mixer offers, is attractive the downside is that they tend to have lower linearity than passive designs.

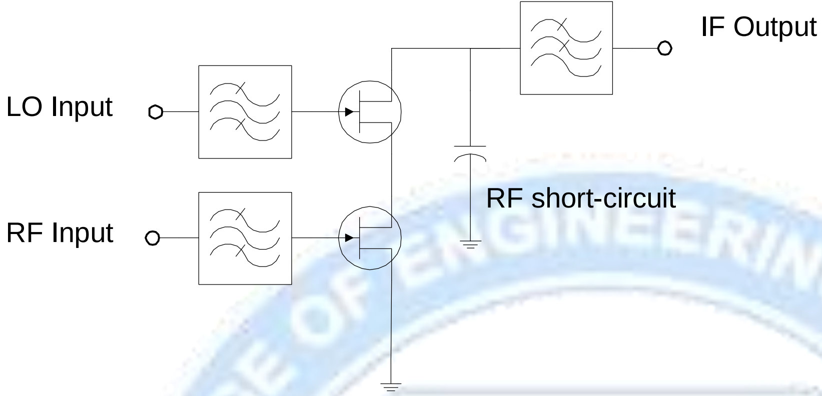


Figure 26: Dual gate FET mixer topology

When used in passive mode, the FET is used as a switch. Its suitability for switch realisation stems from the fact that its drain-source resistance behaves as a voltage variable resistor, the resistance being set by the gate-source voltage [16]. When used as a switch, a FET is operated with the drain and source at zero volts DC. The RF signal path is drain to source and the gate is the control terminal. It can be represented by the simplified equivalent circuit shown in Figure 27.

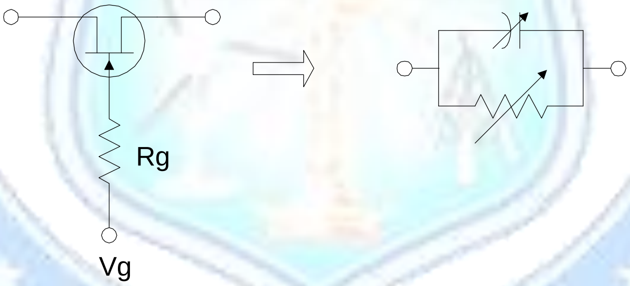


Figure 27: Simplified equivalent circuit of a passive switching FET

A simple FET switching mixer, which can provide high linearity for moderate LO drive levels, is shown in Figure 28. The gates of the FETs are biased part way between 0V and pinch off, this allows the LO signal to move the FETs between their “on” and “off” states. At lower RF frequencies FET gates have a high input impedance and the load for the differential LO signal is thus approximately 2Rg (Figure 28). By setting Rg to a moderately high value say (200 or 300Ω), increased gate voltage swing can be obtained for the same LO level as compared to driving a 100Ω differential load. At higher frequencies, the input capacitance of the FET gate presents a lower reactance and the LO voltage swing will be reduced for the same LO power level.

FET switching mixers will not function well if the gates are left unbiased. If the LO signal is large enough to turn the FETs “off” on the negative cycle, it will drive the gate-source junction in to forward bias on the positive cycle. It is vital that the gate bias voltage is set appropriately if optimum mixer performance is to be obtained. For discrete implementations this gives a problem as the specified range of pinch-off voltages for the FETs can be very wide (-0.5V to –2.5V is a typical range). Whilst integrated designs can overcome this problem with on-chip bias circuitry, for discrete designs there are two solutions: Select on test resistors can be used to set the bias or a supply of FETs with a reduced range of pinch-off voltages can be agreed with the manufacturer. Both solutions have cost penalties.

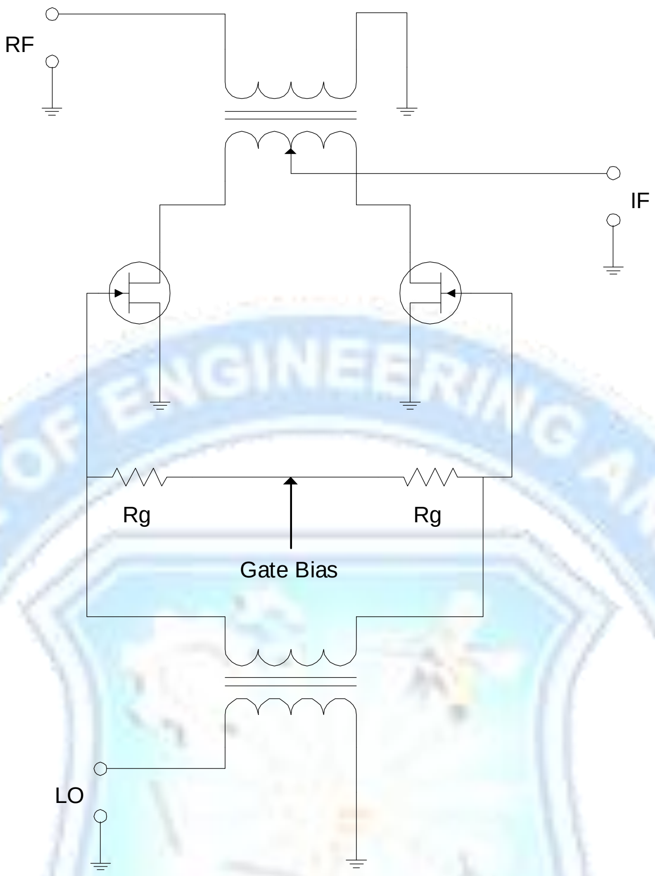


Figure 28: Circuit diagram of a FET based switching mixer

A practical implementation of this switching mixer is shown in Figure 29. Composite printed/lumped baluns, with broadside coupling, are used for the RF and LO. The IF is extracted from the centre point of the RF balun through an inductor (bottom left of the photograph) which is open-circuit resonant at the RF frequency. This mixer was part of an early GSM handset design. It had a conversion loss of 8dB and an input 1dB compression point of +8dBm for an LO signal level of +5dBm.

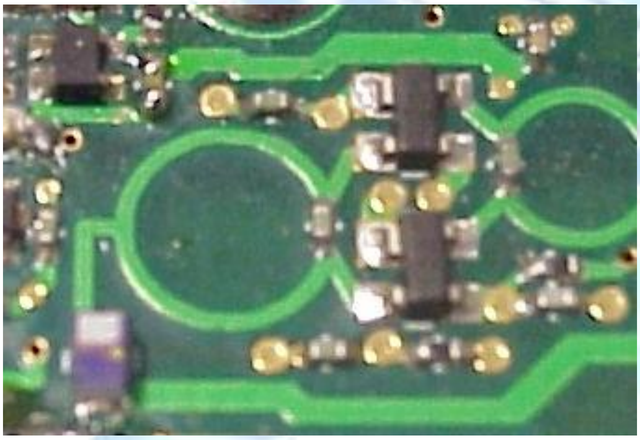


Figure 29: Photograph of a FET based switching mixer

Double-balanced FET quad ring mixers, analogous to the diode-ring mixer (Section 7) can also be used. An additional IF balun is required, as shown in Figure 30. The LO signal switches Q1 and Q3 on and off in anti-phase with Q2 and Q4. The effect of this is that the RF signal and a 180° phase shifted version of the RF signal are alternately routed through to the IF port. As with the diode ring, this means the IF output is effectively the RF signal multiplied by an LO square wave of peak magnitude ±1. The additional cost and complexity of this topology means it is not a popular choice for discrete realisations, although it has been used successfully on integrated designs [17].

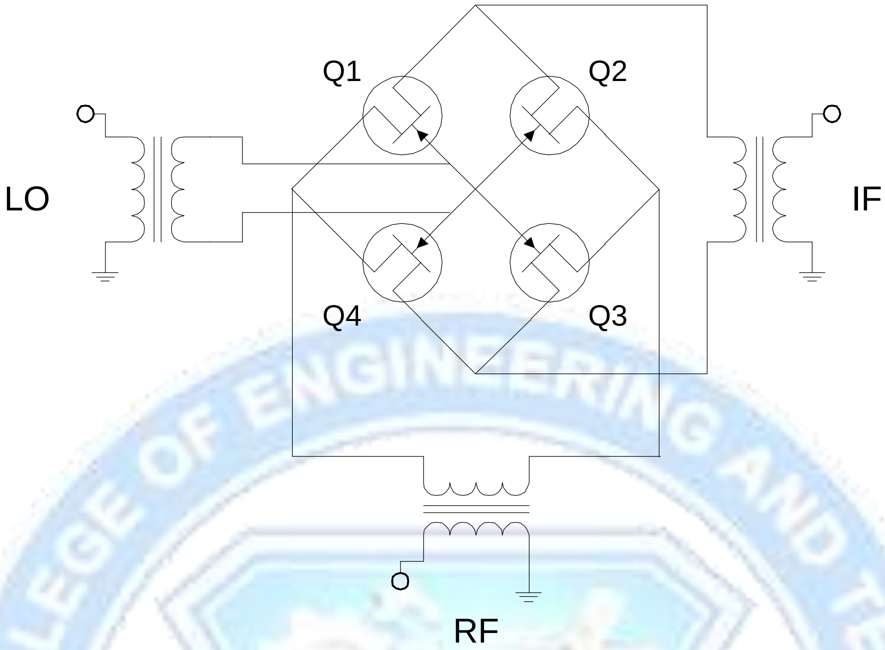


Figure 30: FET quad ring mixer

7. BJT Mixers

Discrete bipolar mixers tend to find applications in low cost, low power receivers such as discrete implementations of pager front ends. Designs can be compact, inexpensive and have conversion gain, however they tend to have poor linearity. Figure 31 shows two typical implementations of low cost, discrete bipolar mixers.

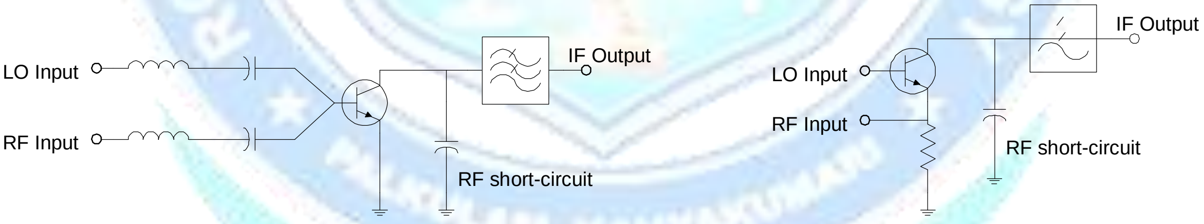


Figure 31: Low cost discrete bipolar mixer topologies

There is a wide range of commercially available Si bipolar integrated RF receivers and transceivers. The mixers they contain differ significantly from the discrete implementations described above. The transistors fabricated close to each other on an IC behave very similarly (they are well matched) and the die area they occupy is smaller than that occupied by passive components [18]. This leads to different circuit topologies being exploited with the almost universal choice for mixer realisation being the double-balanced “Gilbert Cell” [19] shown in Figure 32. A long-tail differential pair amplifies the RF input to the mixer. This determines the gain of the mixer and limits its linearity. The differential outputs of this amplifier are switched, by the LO signal, alternately to each of the differential IF outputs. Once again it is essentially a multiplication of the RF by ±1 at the LO frequency. This circuit relies on the different transistors being well matched and a discrete realisation is not practical.

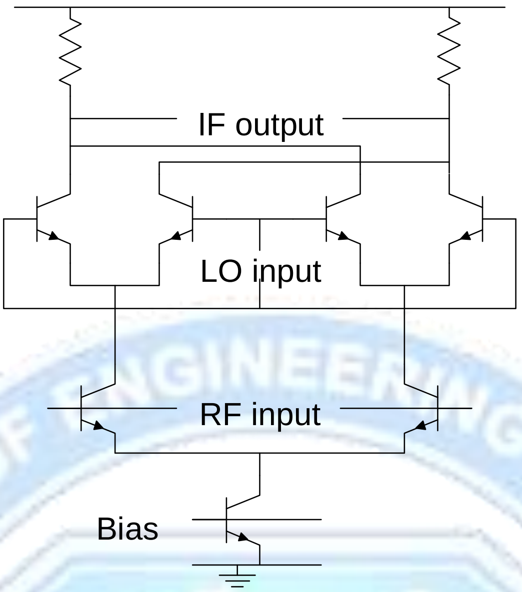


Figure 32: Double-balanced ("Gilbert Cell") mixer

8. Image Reject Mixers

Image reject mixers comprise two balanced mixers, of any topology, driven in quadrature by the RF signal. The LO drive to each mixer is in-phase and the IF output is combined in quadrature. Figure 33 shows a block diagram of an image reject mixer, the arrows representing the relative phases of the respective signals. M1 and M2 are the conversion gain/loss of the two mixers as a factor.

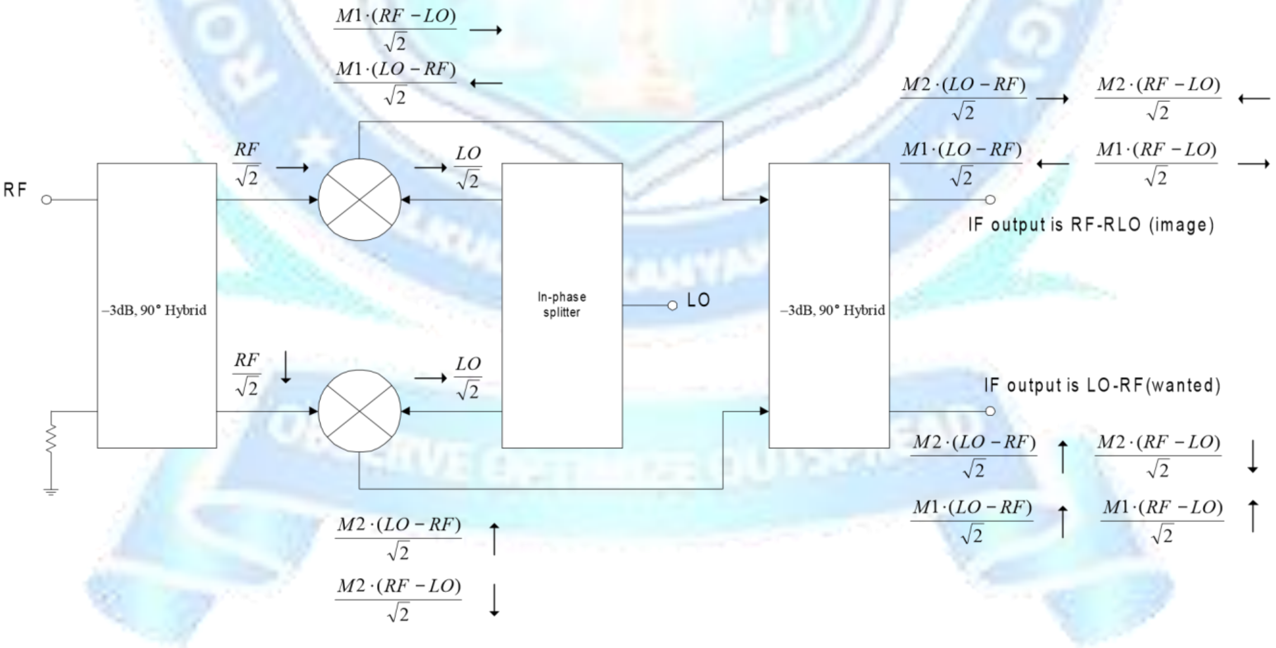


Figure 33: Block diagram of an image reject mixer

To achieve perfect image cancellation, the mixers must be identical and the amplitude balance and phase shift of all quadrature and in-phase splitters perfect. An integrated solution will yield higher image rejection than a discrete and image reject mixer ICs are commercially available. With care, a discrete implementation should be able to achieve over 20dB of image rejection. The rejection of a discrete implementation can be improved if tuning of the circuit is carried out but this is not normally a viable option for high volume commercial products.