Applying double-balanced mixers

Darren Conway illustrates how to get the best from double-balanced diode mixers.

Double-balanced diode mixers are widely used in communications equipment. Their wide dynamic range and relatively low noise has made them a popular choice.

When properly applied, very good results can be obtained with diode mixers, but designing circuits that include them is not a trivial task. The main difficulty with applying the double balanced diode mixer is that mismatch at any of the three ports degrades performance.

These mixers are particularly sensitive to mismatch at the IF port, which results in greater conversion loss and the generation of unwanted mixer products. Ideally, the IF port should be terminated into a post mixer filter with a constant input impedance and a low pass frequency response.

This article uses simulation to compare various designs for post mixer IF filters with the purpose of identifying an optimum design.

Applying diode mixers

The following research was completed as part of the design of a satellite receiver capable of detecting low earth orbital satellites transmitting on about 137.6MHz. The design is an entirely conventional double superheterodyne. Its first intermediate frequency is 37.5MHz selected largely because of the ready availability of cheap and effective SAW filters commonly found in televisions.

Surface acoustic wave filters are physically small, require no tuning, and are easy to interface. The type used features a 3MHz band width. This means that it is also suitable for the front end of a receiver designed for high data rates available from many satellites.

For the first mixer, a double balanced diode type was selected because of the wide dynamic range and a relatively good noise figure. The wide dynamic range is necessary so that the weak satellite signals can be received in the presence of strong interference from any nearby transmitters. A low noise figure improves the ability to detect and demodulate very weak signals.

Matching problems

The effect of termination mismatch on a double balanced diode mixer is not the same for each port. Mismatch at the rf port is the least problematical, which is fortunate because in many applications it is not practical to match to this port. Mismatch between the local oscillator and the mixer degrades third-order performance but can be improved simply by adding a –3dB 50Ω pad. The output level of the local oscillator needs to be adjusted to overcome the loss. The effects of having each port reactively terminated are shown in **Table 1**. Performance is degraded even further if more than one port is mismatched.

To achieve minimum conversion loss through the diode mixer and prevent harmonics reflecting back into the mixer, it is particularly important that the IF output is correctly matched to a 50+j0Ω resistance.

If the term $F_{LO}+F_{RF}$ is reactively terminated, then it will reflect back into the mixer and combine in anti-phase with the local oscillator to produce the terms $F_{LO}+F_{RF}-F_{LO}$, and $2F_{LO}+F_{RF}$. This causes conversion loss and produces spurious responses.

It is not sufficient to properly match the IF port to the low order harmonics. In order to achieve the best performance from a mixer, it is necessary for the IF port to be terminated with a 50+j0Ω resistance over an extensive frequency range.

Table 1. Effects of terminating the double-balanced diode mixer's ports reactively.

Termination condition	Conversion loss	RF compression level	RF desensitisation level	Harmonic modulation products	Third-order IM products
IF=reactive	can vary ±3dB	can vary ±3dB	can vary ±3dB	can vary ±20dB	can vary ±20dB
LO=reactive	No effect if LO drive adequate	No effect if LO drive adequate	No effect if LO drive adequate	can vary ±10dB	can vary ±10dB
RF=reactive	Typically ±0.5dB for 2:1 vswr	±0.5dB	±0.5dB	No first-order effect	No third-order effect

*source, reference 3

In this application, it means that the post mixer IF filter should be matched to at least 200MHz. Proper matching at higher frequencies is highly desirable.

It is possible to achieve good matching by terminating the IF output with a 50Ω resistor followed by a post mixer IF amplifier. The problem with this method is that the amplifier applies equal gain to all harmonics in addition to the wanted IF. This increases the risk of over driving the post mixer amplifier and generating additional harmonics.

The diode mixer should therefore be followed by a low pass filter with a constant input impedance of 50+j0Ω. Output of the filter should then be matched to the IF amplifier

Specifying the IF filter

The intention in this application was to find an efficient IF filter circuit that gave the best performance from the least number of components. The desired specifications of the IF filter are as follows:

- A return loss of no less than –20dB across the frequency spectrum as specified by the diode mixer manufacturer.

  Insertion loss of no more than –0.25dB. The insertion loss adds directly to the noise figure of the mixer and should be as low as possible.
- No more than three inductors. Limiting the number of inductors in a filter automatically limits the filter order and complexity
- A low-pass filter function with a roll off of at least –18dB/octave. Good frequency roll off is required because the low-order, high-amplitude mixer products are relatively close to the IF.
- Easy to design, build and set up.

Analysing performance

Analysis of the circuits described below was completed using the MicroSim version 6.2 Spice simulator. The quality of the circuits was evaluated using four parameters.

Return loss was calculated using the network of resistors $R_{1\text{-}4}$ and a 2× voltage gain block[7] to provide a voltage across R_{rl} which is plotted as VdB(Rrl)

Ideally, the return loss should be very large across the frequency spectrum, indicating that energy has been efficiently transferred from the mixer output to the filter circuit. A small return loss approaching 0dB indicates that all energy is being reflected back to the source.

Resistor R_c which has a value of 1μΩ is used as a sense resistor to measure current and voltage applied to the test circuit. Input impedance is calculated using the voltage and current passing through R_c and is plotted as V(Rc:1)/I(Rc).

The variable $-I_p(R_c)$ measures the angular phase of the input current. Input current phase indicates the reactance of the test circuit. A purely resistive circuit will have zero phase shift. A capacitive or inductive component will cause the current phase to rotate. In this application, the IF filter should ideally be purely resistive at all frequencies.

The frequency response is measured across the load resistor R_l. All IF filters analysed here have been designed for an IF of 37.5MHz, but the values can easily be modified for other frequencies. Plots of these four parameters are combined on single graphs and fully define the important characteristics of the IF filters under test.

LC tuned tank

The *LC* tuned tank circuit, **Fig. 1** represents a simplistic solution to the IF filter problem that has been used in early receiver designs. It consists of an *LC* pair tuned to the IF at which point it appears to have a 50+j0Ω input impedance. This is shown in the Spice analysis in **Fig. 2**, where at

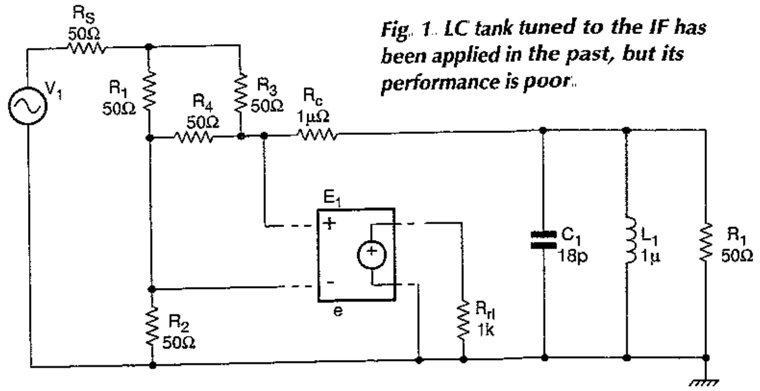


Fig. 1. LC tank tuned to the IF has been applied in the past, but its performance is poor.

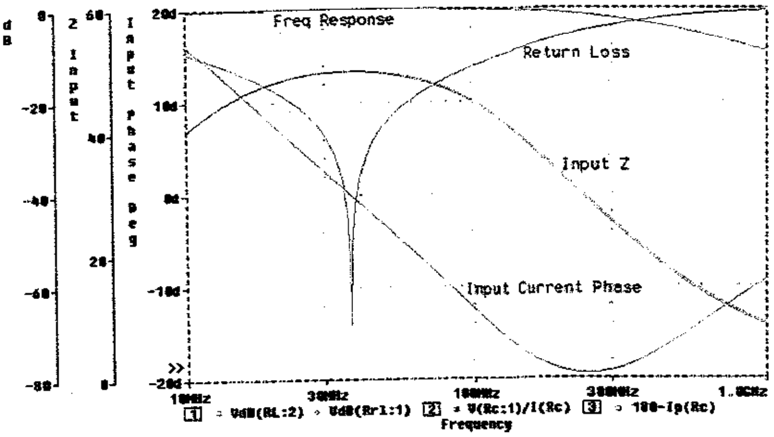


Fig. 2. Analysis of the LC tuned tank, Fig. 1

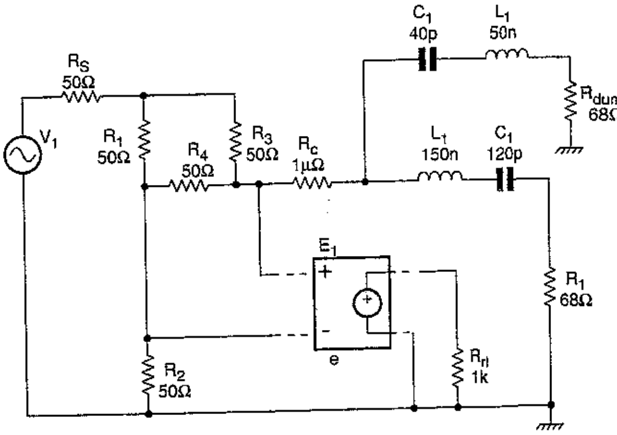


Fig. 3. Series tuned diplexer. Although this circuit is an improvement on the LC tank, its performance is far from ideal.

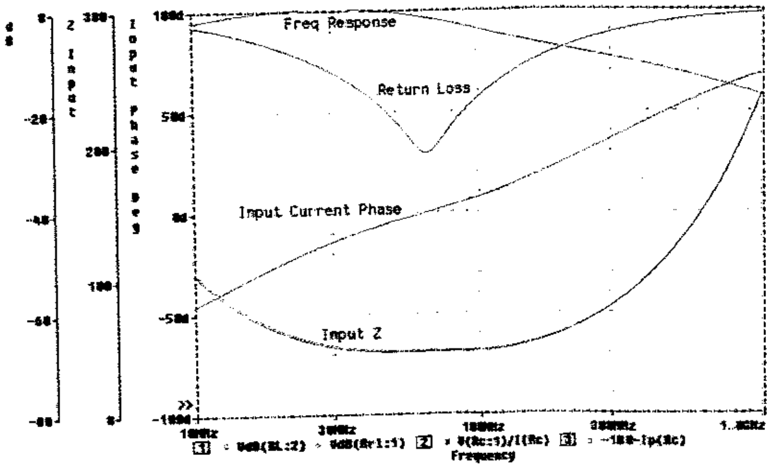


Fig. 4. Analysis of the series tuned diplexer, Fig. 3.

37.5MHz the input impedance is 50Ω. the input current phase is 0° and the return loss is very high.

At all other frequencies the circuit is reactive and reflects significant harmonics back into the mixer. The frequency response is particularly poor giving only –1dB attenuation at 200MHz.

The *LC* tuned tank circuit demonstrates all the undesirable features of a bad IF filter. Any receiver that uses this circuit would probably give better performance if the capacitor and inductor were removed, leaving only the 50Ω resistor.

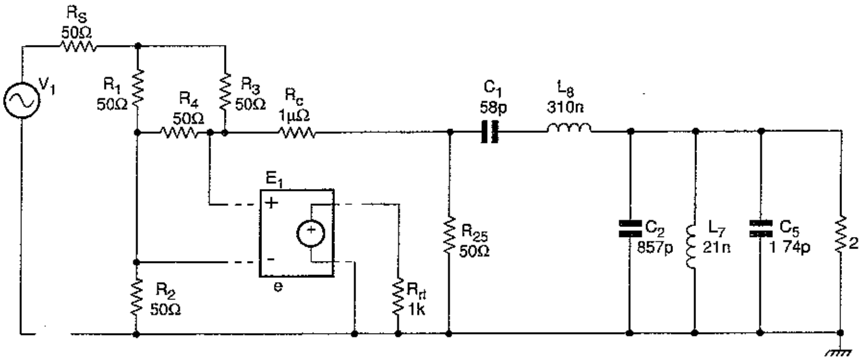


Fig. 5. IF filter comprising a Butterworth band-pass circuit. One of its useful features is that it displays constant impedance through the pass band.

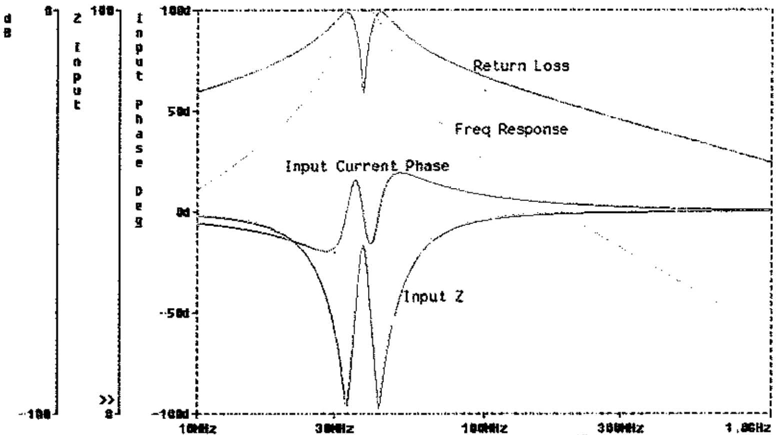


Fig. 6. Analysis of the Butterworth band-pass IF filter, Fig. 5, with 37.5MHz centre frequency and 10MHz band width.

Series-tuned diplexer

The series-tuned diplexer design is intended to terminate both the IF and the third-harmonic (3.IF) into 50+j0Ω loads. This circuit is designed to provide a resistive termination to the most troublesome low-order mixer products.

Values of the inductors and capacitors shown in **Fig. 3** were selected simply to resonate at the correct frequencies. You can see from **Fig. 4** that the input impedance is reasonably well matched between about 25MHz and 150MHz. Normally the signals are terminated into 50Ω resistors but analysis showed that 68Ω resistors are required to achieve a 50Ω input impedance.

The plot of input current phase shows that this filter is reactive at all frequencies except one. This characteristic combined with the increasing impedance at higher frequencies means that harmonics will be reflected back into the mixer.

Frequency response is also poor providing only –7dB attenuation at 200MHz. Although this circuit is an improvement on the *LC* tank circuit, the performance is far from ideal.

Butterworth band pass

An IF filter based on a band-pass Butterworth filter appeared to offer some hope. One of the useful properties of Butterworth filters is that they ideally display a constant impedance through the pass band.

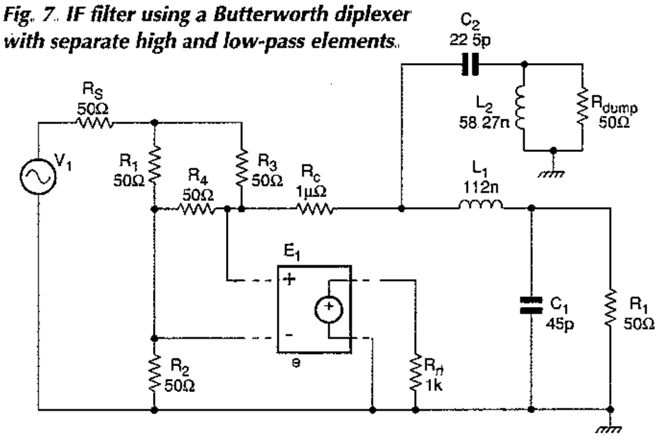
Outside the pass band, the impedance increases or decreases depending on the filter topography. In addition, they can be designed to have different input and output impedances.

The filter shown in **Fig. 5** is designed with a pass band centred at 37.5MHz and a 10MHz band width. The input is matched to a source impedance of 25Ω defined by the impedance of the mixer and the 50Ω resistor.

Output impedance of the filter is 250Ω, intended to provide some degree of matching to the IF amplifier. The analysis results in **Fig. 6** show an improvement in overall performance compared to the previous filters but there are still major flaws with this circuit. The insertion loss of –0.8dB in the pass band is higher than desired but attenuation at 200MHz is a healthy –52dB. The return loss and input impedance vary significantly over the pass band, which is likely to create unwanted reflections from received signals close to the rf input. From a practical constructive view, the 21nH inductor is a very small value and would be difficult to implement. The sharp dip in the return loss at 37.5MHz makes this filter sensitive to component drift and tuning errors.

Although this circuit offers reasonable performance in theory, it would be very difficult to construct and tune. It is therefore not recommended.

Fig. 7. IF filter using a Butterworth diplexer with separate high and low-pass elements.



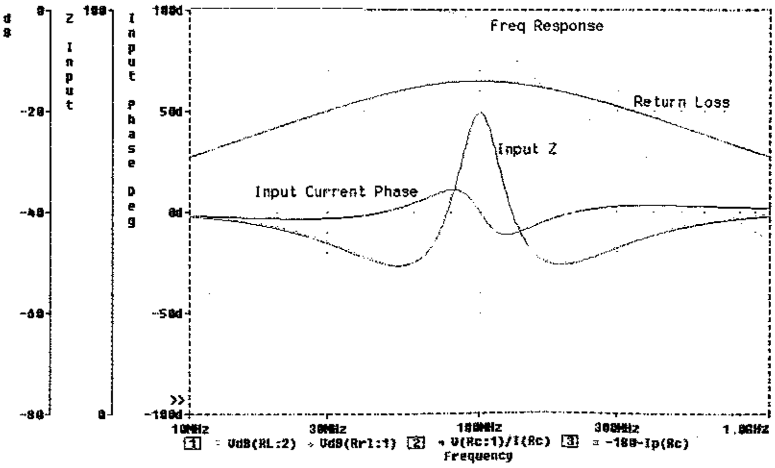


Fig. 8. Analysis of the 100MHz centre-frequency Butterworth diplexer, Fig. 7, shows that attenuation at 200MHz is a modest –18dB.

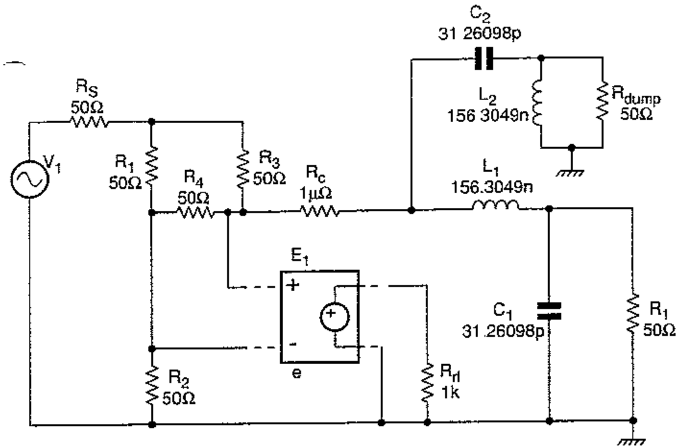


Fig. 9. Weinreich-Carroll diplexer with centre frequency of 72MHz exhibits insertion loss of –3dB at IF.

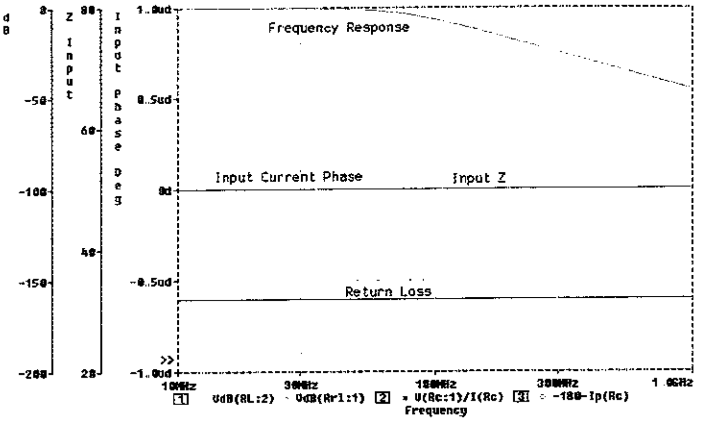


Fig. 10. Weinreich-Carroll diplexer analysis. Although simple, this circuit achieves perfect matching across the entire rf spectrum.

Butterworth diplexer

As a variation to the Butterworth filter theme, separate high-pass and low-pass filters were configured as a diplexer centred on 100MHz as shown in **Fig. 7**

The results show that this circuit has better characteristics in the Butterworth band-pass filter above At worst the return loss is –14dB which is 6dB less than the required value of –20dB. Both the input impedance and the input current phase remain reasonably close to ideal across the frequency spectrum.

Upward deflection of the frequency response plot at 150MHz is due to interaction between the high and low pass sections at their inputs Insertion loss at 37.5MHz is only –0.084dB while attenuation at 200MHz is a modest –18dB

None of the plots exhibits any excessively sharp peaks or dips which in this case means that the circuit is tolerant to component errors and drift. The values of the inductors are not too widely spread and are large enough to allow a practical filter to be constructed

This circuit has the same number of components as the diplexer shown in Fig 3 and yet displays superior performance. In spite of this, the Butterworth diplexer does not conform to the required specifications and a better solution was sought.

Weinreich-Carroll diplexer

The Weinreich-Carroll diplexer[1] is a second-order filter designed so that all capacitors and inductors have an impedance of $\sqrt{2\times50}=70.7$ at the centre frequency. A centre frequency of 72MHz was selected for this circuit, being the geometric centre between the IF and the image, $\sqrt{(F_{IF}.F_{LO+IF})}$. This results in an insertion loss at the IF of –0.3dB

Attenuation at 200MHz is a modest –17.9dB. The analysis plots in **Fig. 10** show that this very simple circuit achieves perfect impedance matching across the entire rf spectrum. These ideal results will not be achieved in practice because of the effects of component errors, drift and parasitics High quality components should however provide results close to those shown in Fig. 10. The only disadvantages with this circuit are the slow frequency roll off and the mediocre attenuation of harmonics.

Weinburg diplexer

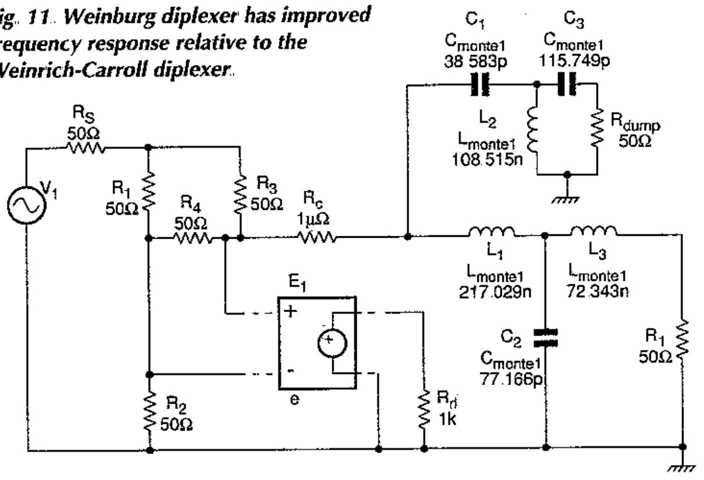
A better frequency response can be obtained using a third order diplexer shown in **Fig. 11**. Like the Weinreich-Carroll diplexer, the Weinburg diplexer has the ideal constant input impedance of 50+j0Ω at all frequencies, resulting in a very high return loss, **Fig. 12**. It also has a much better frequency response providing 33.8dB attenuation at 200MHz.

This circuit has been designed using the values[10] in **Table** , with a centre frequency of 55MHz The sharper roll off means that a lower centre frequency can be used without an excessive insertion loss. At 37.5MHz, the insertion loss is 0.418dB.

Additional simulations were run to further define the performance of this diplexer The graphs in **Fig. 13** show a Monte-Carlo analysis based on a 10% component variation to determine how sensitive the circuit is to component errors The upper graph plots variations in input impedance The lower graph plots variations in return loss and frequency response

These plots show that the return loss is very sensitive to

Fig. 11. Weinburg diplexer has improved frequency response relative to the Weinrich-Carroll diplexer.



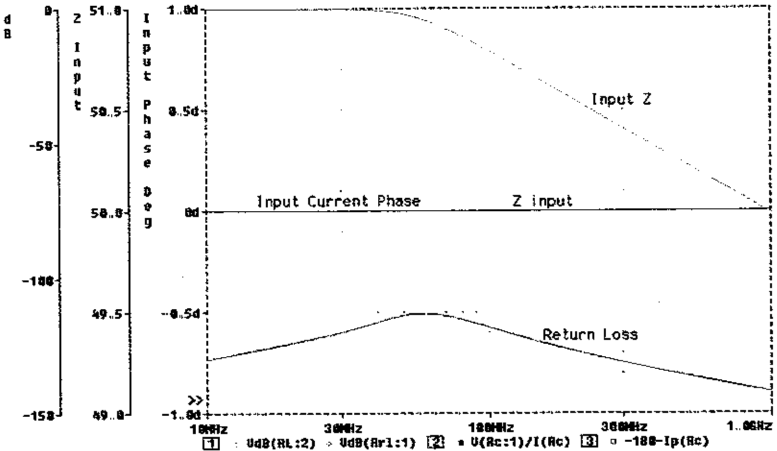


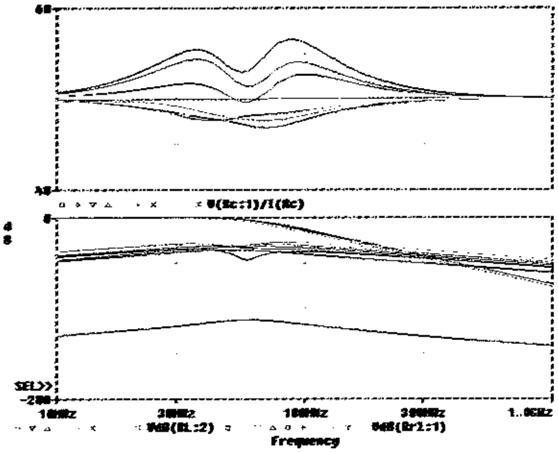
Fig. 12. Weinburg diplexer analysis. Sharper roll-off means that a lower centre frequency can be used without excessive insertion loss.

component errors varying over a range of about 90dB. At worst, the return loss is –24dB which remains within the required specification. Perfect results can only be achieved with perfect components

Table 2. Weinburg diplexer normalised values.

Low pass	L_1	C_2	L_3
Third	3/2	4/3	1/2
High pass	$1/C_1$	$1/L_2$	$1/C_3$

Fig. 13. Weinburg Monte-Carlo analysis based on 10% component variation demonstrates the circuit's sensitivity to component errors. Upper plots are input impedance while lower are return loss and frequency response.



Veltrop-Wilds diplexer

Diplexers based on modified Chebyshev filter tables offer good frequency response with near ideal input impedance. The diplexer shown in **Fig. 14** is based on formula by Veltrop-Wilds[2]. The circuit was calculated for a 3dB point of 55MHz which was selected to achieve an insertion loss of less than 0.25dB at the IF. This circuit yields the results shown in **Fig. 15**. Input impedance varies between 46Ω and 54.8Ω, which is not ideal, but entirely adequate. Return loss is at worst –25.3dB and improves at higher frequencies. The insertion loss at 37.5MHz is only –0.238dB while the attenuation at 200MHz is a respectable –39.7dB.

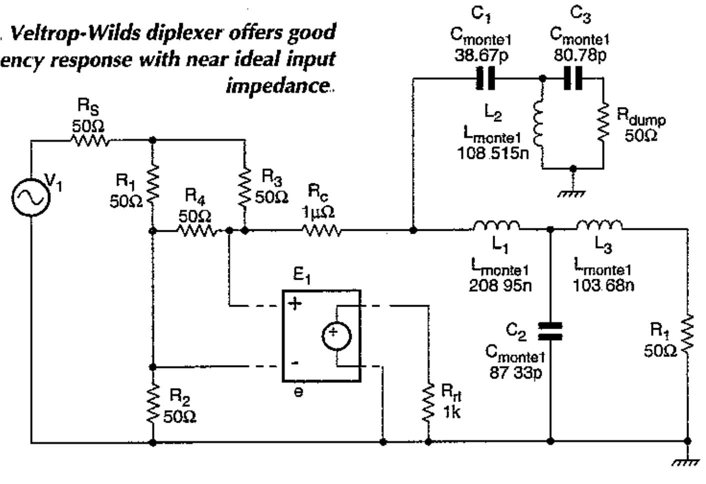
For applications requiring a steeper frequency roll off, the values for normalised 3rd, 5th and 7th order filters are shown in **Table 3**. Band-pass/stop diplexers may also be implemented with the values in Table 3 using the same techniques used to calculate component values with standard filter tables

As before, a Monte-Carlo simulation based on a 10% component variation was run for the Veltrop-Wilds diplexer. The results of this analysis in **Fig. 16** show the return loss is at worst –23.3dB which remains within the specifications and is only slightly lower than for the Monte-Carlo analysis of Weinburg diplexer

Likewise, the input impedances for the two filters look similar. In real circuits with parasitics and component errors, there is unlikely to be any significant difference in measured return loss between a Weinburg or a Veltrop-Wilds diplexer.

Having determined that the input characteristics of the Veltrop-Wilds and the Weinburg in a real circuit are likely to be almost identical, a closer analysis of the output charac-

Fig. 14. Veltrop-Wilds diplexer offers good frequency response with near ideal input impedance.



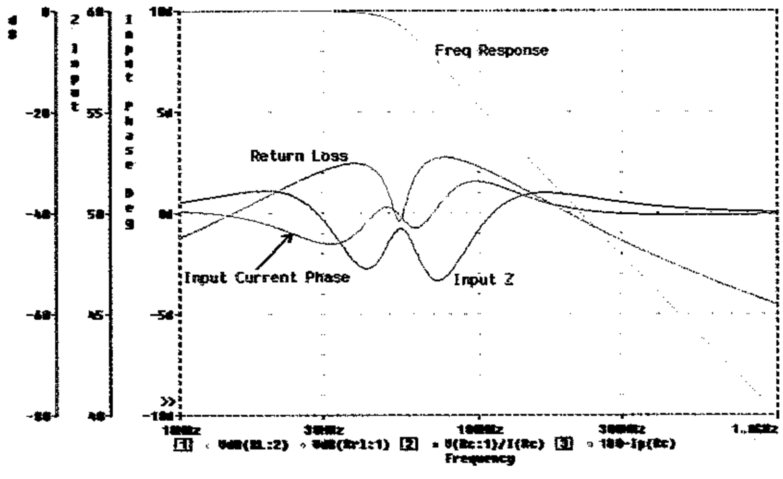


Fig. 15. Analysis of the Veltrop-Wilds diplexer reveals that input impedance varies between 46 and 54.8Ω.

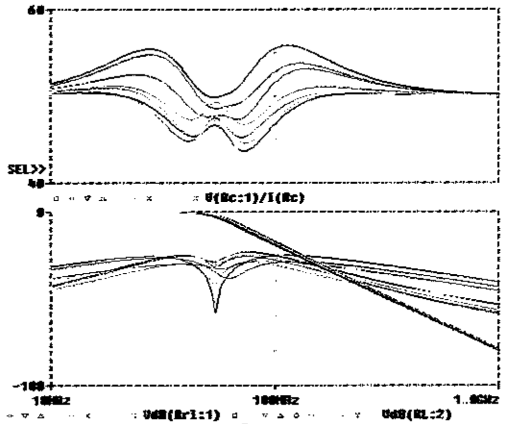


Fig. 16. Veltrop-Wilds Monte-Carlo analysis with 10% component variation show that return loss is at worst –23.3dB.

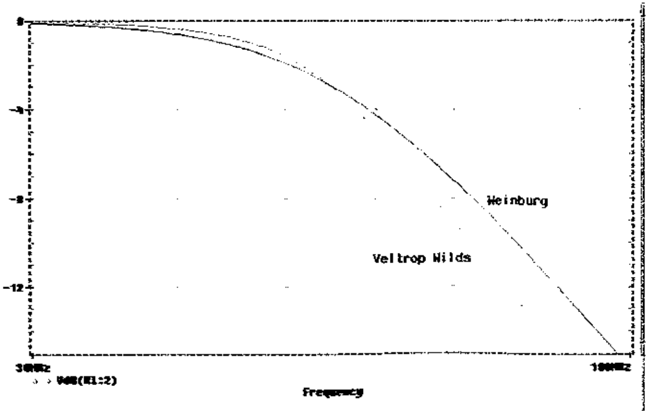


Fig. 17. Frequency-response comparison between the Veltrop-Wilds and Weinburg diplexers.

ristics was conducted The results are plotted in **Fig. 17** which shows a close in view of the frequency responses of both the Veltrop-Wilds and Weinburg diplexers.

You can see that the –3dB point for both diplexers occurs at 55MHz as expected. The Veltrop-Wilds diplexer has the advantage of a sharper roll off resulting in an additional –4.25dB attenuation at higher frequencies compared to the Weinburg diplexer In addition, at the IF of 37.5MHz, the insertion loss differs by 40% in favour of the Veltrop-Wilds diplexer

Analysis of the filter output characteristics shows that the Veltrop-Wilds diplexer has a small but significant advantage over the Weinburg diplexer.

Final selection

The Veltrop-Wilds diplexer circuit shown in Fig. 14 and selected for this application exceeds all specifications and comes close to the 'ideal' IF filter. It does not provide a perfect 50+j0Ω input impedance seen in the Weinreich-Carroll or the Weinburg diplexers, but it is close enough for practical purposes.

Compared with the Weinreich-Carroll or Weinburg diplexers, the Veltrop-Wilds diplexer has a better frequency sponse and there is the potential for further improvement by increasing the order of the filter. For this application, the Veltrop Wilds diplexer is considered to display the best overall characteristics.

Designing the Veltrop-Wilds diplexer

The design principle of the Veltrop-Wilds diplexer is to modify the values of standard Chebyshev low-pass filters in order to produce a diplexer with a constant input impedance This is accomplished using the following general equations:

$$\varepsilon=[(\text{antilog}(A_m/10))-1]$$

$$\omega'_{3dB}=\cosh(1/n.\cosh^{-1}\surd[(1+2\varepsilon)/\varepsilon])$$

when n is even and,

$$\omega'_{3dB}=\cosh(1/n.\cosh^{-1}\surd[(1/\varepsilon])$$

when n is odd, where A_m is the ripple value in dB and ω'_{3dB} is the modification factor Full mathematical derivation can be found in reference 2.

The result is a modification factor ω'_{3dB} that is multiplied with each capacitor and inductor to obtain the modified low-pass table values. To obtain the modified element values for the high pass filter, each modified inductor is replaced with a capacitor equal to $1/C$ farads, and each modified capacitor is replaced with an inductor equal to $1/L$ henries. The 0.5 normalised conductance values for the high pass and low pass filters are now placed at the crossover frequency of $\omega=1$

Tuning the filter

The results of the Monte-Carlo analysis indicate which variable should be used to 'tune' the filter. Frequency response does not vary greatly with component errors and is therefore unsuitable for tuning the filter.

Return loss is the most sensitive to component errors and varies by up to about 30dB in the analysis of both the Veltrop-Wilds and Weinburg diplexers. For optimum performance, a network analyser used to measure return loss will provide the most effective means of tuning the filter.

The next best alternative is use a grid-dip meter and capacitance meter First, accurately measure and set the values of each capacitor allowing about 3pF for in circuit parasitics, then selectively fit inductors to form LC pairs. Using the grid-dip meter, each inductor is adjusted until the LC pair resonates at the correct frequency.

By fitting and removing components to create LC tuned circuits, the correct values can be set in circuit and the final filter response should closely match the simulated results When constructing these filters, every effort should be made to minimise both parasitics and component errors in order to obtain results like those shown in the simulations

Table 3. Veltrop-Wilds diplexer normalised values for 0.1dB ripple.

Low pass	L_1	C_2	L_3	C_4	L_5	C_6	L_7
3rd	1.5133	1.509	0.7164				
5th	1.561	1.8069	1.7659	1.4173	0.6507		
7th	1.5748	1.8577	1.921	1.827	1.734	1.3786	0.6307
High pass	$1/C_1$	$1/L_2$	$1/C_3$	$1/L_4$	$1/C_5$	$1/L_6$	$1/C_7$
Input end							Output end

In summary

One of the important results of these simulations is that good performance does not necessarily require complex designs and high component counts.

The most complicated circuit analysed has six reactive components, while the simplest has just two. A wide range of results from the positively bad to nearly ideal were obtained from circuits that at a glance look remarkably similar.

The results graphically display the importance of selecting the right circuit for the right job. Design efficiency can be measured in terms of performance *versus* complexity. Complex designs are usually difficult to build and maintain There are significant downstream advantages in ensuring that the most efficient design is used.

The above simulations show that some commonly used post diode mixer IF filters perform very poorly compared to the ideal IF filter. Performance can be improved using constant-impedance filters based on the Butterworth function but they are not recommended.

At all frequencies, the Weinreich-Carroll diplexer has a perfectly matched 50+j0Ω impedance, but its frequency response is only mediocre. The Weinburg diplexer also has a perfectly matched input impedance combined with a good frequency response. The best results are obtained using the Veltrop-Wilds diplexer which combines near ideal input matching with a superior frequency response.

Unlike the Weinreich-Carroll diplexer, the frequency response of the Veltrop-Wilds diplexer can be improved by using higher order variants

The Veltrop-Wilds diplexer is recommended above all others for use with double balanced diode mixers ■

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