

# A x4 Subharmonic Mixer for 24 GHz

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## INTRODUCTION

It's often been said that the heart of any transverter is a good local oscillator (LO). If you've built a homebrew transverter to get on any one of the microwave bands, you know first hand that the LO is a big part of the trick to getting equipment to work reliably. This seems to be especially true at the higher microwave bands.

Most of the transverters we use on the lower microwave bands use fundamental mode mixers – that is, the LO signal is equal to the difference between the RF frequency and the IF. For example, a 24 GHz system using a 144 MHz IF and low-side injection requires that the LO operate at:

$$\text{LO} = 24192 \text{ MHz} - 144 \text{ MHz} = 24048 \text{ MHz.}$$

At lower frequencies, the generation of the LO typically requires starting out at a lower frequency using a stable crystal oscillator or synthesizer, and then multiplying up to the needed local oscillator frequency. Low cost transistor and MMIC based multipliers work well to about 10 GHz. At 24 GHz and above, many of the low cost MMIC components we enjoy at lower frequencies simply don't work well. Generating a fundamental mode LO for the 24 GHz band just seems to be 'many dB harder' than is required for lower frequencies.

Another approach (as described here) is to use a subharmonic mixer – a mixer that uses a lower frequency LO that is a sub-multiple of the normal LO input frequency. It effectively multiplies the LO frequency by  $n$  within the mixer hardware to get to the desired higher frequency. So for instance, for an  $n=2$  subharmonic mixer operating at 24 GHz with a 144 IF, the LO is equal to:

$$\text{LO} = (24192 - 144) / 2 = 12024 \text{ MHz}$$

Several Frequency Mixing Schemes for 24 GHz are shown below.

IF Freq	Fundamental LO	LO / 2 Scheme
144 MHz	24,048 MHz	12,024 MHz
432 MHz	23,760	11,880
1296 MHz	22,896	11,448

Figure 1 – Several Frequency Mixing Schemes for 24 GHz

A subharmonic mixer has the advantage of making for simpler LO hardware. This is especially helpful in getting on a higher frequency band like 24 GHz.

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Figure 2 – HP 11970A Subharmonic Mixer

## TRADEOFFS

Like anything else in life, the subharmonic mixer involves tradeoffs. Using this type of mixer means a simpler LO, but somewhat more involved mixer hardware. The biggest tradeoff to using this type of mixer is that they're less efficient; the mixer conversion loss is usually a lot higher. As an example, the HP 11970A mixer pictured above has ~20 dB conversion loss! This is partly because of its broadband operation, but even over narrower bands for amateur use, a subharmonic mixer will still have more conversion loss than a standard fundamental mixer. Fortunately for us, most of our work involves narrow band operation, and over narrow operating bands the circuit efficiency can be greatly improved. Published narrowband x2-type subharmonic mixers for 24 GHz have typical conversion loss figures of 8-10 dB. In addition to higher conversion loss, a subharmonic mixer may have more undesired output frequencies and spurious signals due to the internal multiplication process. For broadband commercial applications this can be a real challenge, but for amateur applications this is not usually a problem.

## SUBHARMONIC MIXER WORK BY OTHERS

It's important to note that a number of other amateurs have published work on subharmonic mixers. Jim Dietrich WA0RDX published a novel x2 subharmonic mixer design for 1296 MHz in the October 1978 issue of Ham Radio magazine<sup>1</sup>. His mixer uses two back-to-back diodes in series with a microstrip transmission line resonant circuit. This appears to be a real classic on this type of work among amateurs. The DB6NT subharmonic mixer for 24 GHz (and other bands) appears to use this type of mixer topology.<sup>2</sup>

Brian Justin WA1ZMS has made good use of a waveguide type subharmonic mixer for his 145 and 241 GHz work<sup>3</sup> and in fact has set several amateur microwave DX records with this hardware. Brian modified a x3 multiplier for use as a subharmonic mixer by adding an IF lowpass filter and biasing the diodes. Brian also published a nice synopsis of various diode multiplier and mixer types in the 2005 Microwave Update Proceedings.<sup>4</sup>

This author's work focused on a 24 GHz subharmonic mixer design constructed in microstrip. Other waveguide subharmonic mixer designs exist and numerous articles have been published in DUBUS over the years. I have not done an exhaustive search on this subject but one such article uses a waveguide based subharmonic mixer for 47 GHz by Peter Riml OE9PMJ.<sup>5</sup>

## A HIGHER ORDER MIXER

Over the last year or so I set out to design a microstrip based subharmonic mixer for 24 GHz, that instead of using a x2 scheme, uses a **x4** LO scheme ( $n=4$  in the above discussion). My thought was that, if successful, this would make a 24 GHz transverter somewhat easier to build by requiring only a 6012 MHz LO for the typical 144 MHz IF scheme. I feel it's easier to generate a 6 GHz signal than it is to generate 12 GHz. So this scheme has the advantage of requiring a lower frequency LO, but the disadvantages of being a more complex design, and the expectation is that a higher order (x4) mixer would have more conversion loss.

After doing a lot of reading on the subject, the mixer topology that I settled on for this design (shown below) is based on work described in the IEEE literature by A. Madjar<sup>6</sup>.

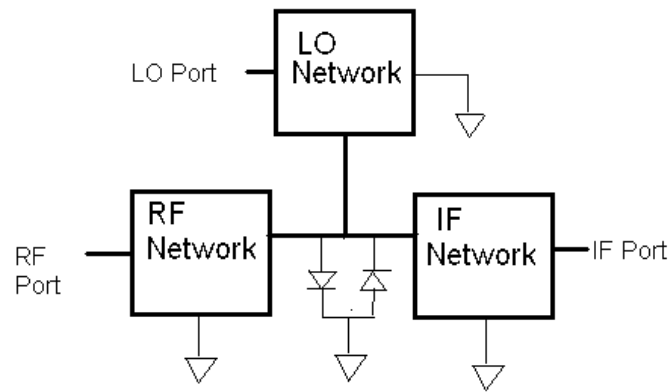


Figure 3 – Subharmonic Mixer Block Diagram

There are several keys to making the mixer circuit work as a subharmonic mixer. The first is that two diodes are used, placed back-to-back to ground: the so-called “anti-parallel” diode. This allows the mixer to have a frequency response that will work using a lower frequency LO input. The second key involves the filters that are used at the RF, IF, and LO ports of the mixer.

Like most high frequency circuits, the best performance is obtained by keeping all the parasitic inductance and capacitances as low as possible. This implies a *very* small component. It's also beneficial to use diodes that are well matched in their DC characteristics. Fortunately, some of the commercial semiconductor manufacturers have recognized the above and have made low cost, high frequency schottky diodes available to the industry. One such anti-parallel diode is the M/A Com MA4E1318, shown in Figure 4 below. Note that the parasitic capacitance is less than 0.06 pF for this diode pair!

The good news here is that diodes with good performance to high frequencies are at least offered in tiny surface-mount type packages, so that no specialized wire-bonding is required. A conductive epoxy can be used to attach the diodes to a small printed circuit board. The bad news is these devices are only 0.026 inches in length... really small! You need a microscope or high-powered magnifier, and a very steady hand to work with these components.

**MA4E1317, MA4E1318, MA4E1319-1,  
MA4E1319-2, MA4E2160**



GaAs Flip Chip Schottky Barrier Diodes

M/A-COM Products  
Rev. V3

**Electrical Specifications @ + 25 °C**

Parameters and Test Conditions	Symbol	Units	MA4E1317			MA4E1318		
			Min.	Typ.	Max.	Min.	Typ.	Max.
Junction Capacitance at 0V at 1 MHz	Cj	pF		.020			.020 <sup>3</sup>	
Total Capacitance at 0V at 1 MHz <sup>1</sup>	Ct	pF	.030	.045	.060	.030 <sup>2</sup>	.045 <sup>2</sup>	.060 <sup>2</sup>
Junction Capacitance Difference	DCj	pF					.005	.010
Series Resistance at +10mA <sup>2</sup>	Rs	Ohms		4	7		4	7
Forward Voltage at +1mA	Vf1	Volts	.60	.70	.80	.60	.70	.80
Forward Voltage Difference at 1mA	DVf	Volts					.005	.010
Reverse Breakdown Voltage at -10uA	Vbr	Volts	4.5	7				
SSB Noise Figure	NF	dB		6.5 <sup>4</sup>			6.5 <sup>4</sup>	

Figure 4-A – MA/COM Single and Anti-Parallel Mixer Diode Specifications.

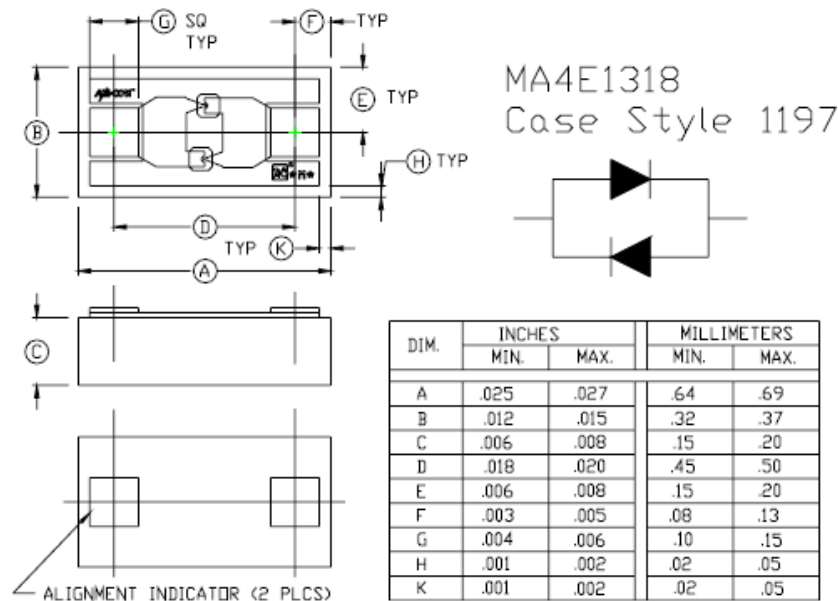


Figure 4-B – MA/COM Anti-Parallel Mixer Diode Package

## MIXER THEORY OF OPERATION

The mixer consists of the anti-parallel diodes, the RF Filter, LO Filter, and IF Filter networks (see block diagram in Figure 3). The mixer operation can be described as either a receiver mixer and a transmit mixer; we'll refer to it as a receiver mixer to keep things straight. Perhaps the best way to understand the mixer operation is to start at the LO input. An external 6 GHz local oscillator signal (approximately 10 dBm) is fed to the LO input connector.

The LO network is a narrowband edge coupled bandpass filter centered at 6 GHz. It filters the incoming LO energy, but perhaps more importantly, it looks very reflective to all other frequencies. When the incoming LO energy hits the diode pair, LO harmonics are internally generated. The harmonic that is four times the LO input frequency (6 GHz x4) becomes our desired high frequency LO within the mixer. In addition, LO harmonics are generated at the x2 and x3 multiples. All of these signals are essentially reflected back towards the mixer to improve the efficiency. The LO network also includes a small microstrip transmission line matching section to match from 50 ohms into the low impedance of the diodes.

The purpose of the RF network is several-fold. In general, it looks like a low loss, wideband bandpass filter centered at 24 GHz. As a BPF it provides some degree of out-of-band rejection, but more importantly it keeps the various LO signals from radiating out the RF input of the mixer. It also looks reflective to the LO energy which is reflected back towards the diodes.

Lastly, the IF section of the mixer passes the mixer's desired IF output energy, and just as in the other portions of the mixer, it also reflects the LO energy back toward the mixer diodes. This is done using high-Q *idler circuits* consisting of open circuited microstrip transmission lines. Each is resonant at the required frequency and reflects energy back towards the diodes for low mixer conversion loss. In fact, when you look at the final artwork for the mixer, you'll probably agree that the complexity of the IF section shows that there's a lot going on there.

Each of the main sections of the mixer is discussed in some detail as follows.

## RF FILTER SECTION

The RF bandpass filter is a simple arrangement of two short-circuited  $\lambda/4$  lines forming resonators at 24 GHz. The resonators are directly coupled through another transmission line, which is approximately  $\lambda/4$  in length. All lines are nominally 50 ohms. The resulting filter response is a broad bandwidth bandpass at 24 GHz.

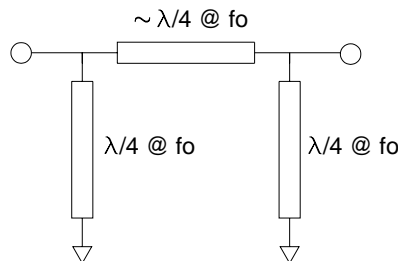


Figure 5 – Basic RF Filter

Next, resonant stubs were added to the filter at the input and output to provide a short circuit response at the LO and 2xLO frequencies. Each of the open circuited microstrip stubs are  $\sim \lambda/4$  in length at their respective frequencies. When an open circuit is rotated 90 degrees around the Smith chart, you see a

short circuit at the other end, so the filter may be viewed as having two resonant short circuits connected to it. These essentially look like trap filters at the LO and 2xLO frequencies.

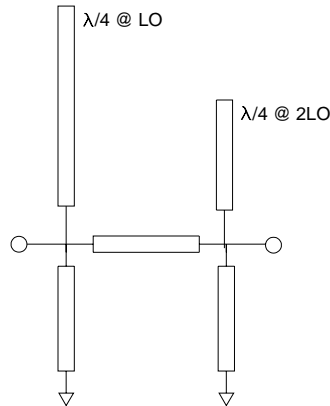


Figure 6 –RF Filter with Stubs Added

The filter section was designed using rough hand calculations and then the first iteration of the design was optimized using the student version of the Ansoft Designer circuit design software<sup>7</sup>. Line lengths were adjusted for best match and insertion loss at 24 GHz, and best resonance of each trap. The predicted RF filter response is shown in Figure 7. Low insertion loss is predicted at 24 GHz, with the LO and 2LO frequencies being highly attenuated (reflected). The second trace without markers shows the return loss at each frequency. The RF filter is designed to have a very good return loss at 24 GHz, and a reflective impedance at the LO and 2LO frequencies.

Note that three discrete attenuation nulls are seen on the plot below, with an unaccounted-for transmission zero at the 3LO frequency (roughly 18 GHz). There is no stub present for this frequency, so where did this come from? The answer is that the longer stub at the LO frequency is an odd multiple of a quarter at the 3LO frequency as well!

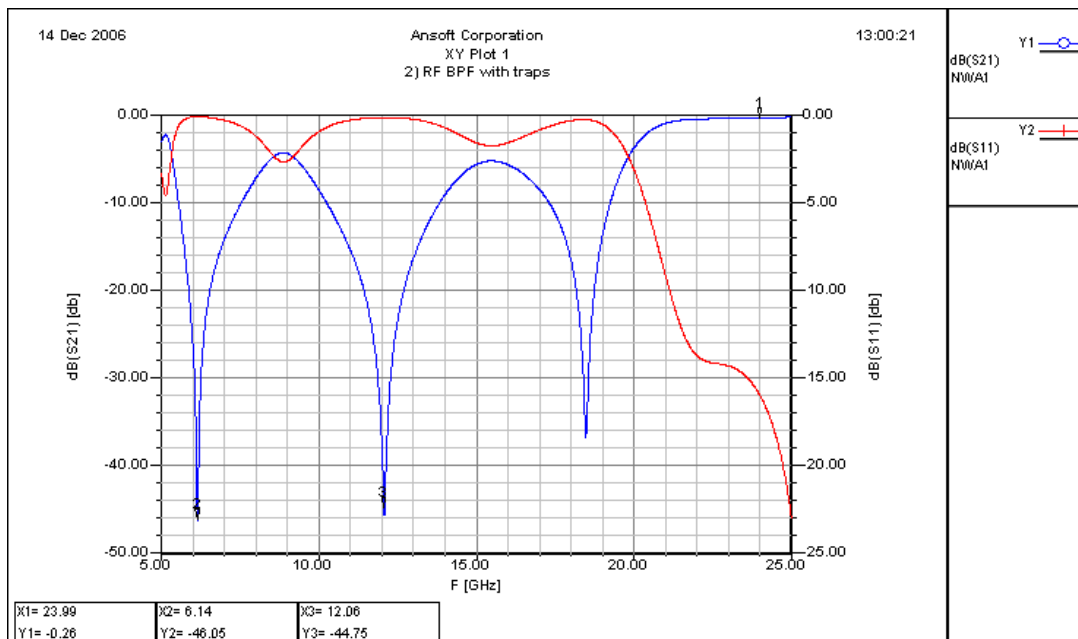


Figure 7 – Predicted Response of RF Filter with Stubs

## LO FILTER SECTION

The LO bandpass filter is a simple edge-coupled design made from two  $\lambda/4$  lines at the LO frequency. A more complex filter is unnecessary as the LO filter simply has to pass the LO and look reflective at the RF, 2LO, 3LO, and 4LO frequencies. The center frequency was designed for 6 GHz and the bandwidth was made wide enough to cover other possible desirable LO frequencies; in fact the bandwidth is considerably wider than necessary but this helps to ensure that reasonable etching process variations shouldn't spoil the performance. In order to present a 50-ohm impedance match at the filter input/output, the coupled transmission lines need to be a higher impedance and consequently end up being very narrow lines. The lines are ideally around 4 mils in width with 4 mil spacing, when made on 10 mil Rogers 5880 material. These line widths and spacing get to be a bit tricky to reliably etch by the board vendor. The author chose to compromise the design somewhat and make the coupled section lines wider and slightly farther apart in order to come up with a more manufacturable design. Of course, this degrades the impedance match, so in order to improve the match; the final filter has two low impedance stubs added at the input/output. As a point of reference, the coupled line section of the filter is approximately 0.4 inches in length.



Figure 8 – Layout of Edge Coupled LO Filter

The design of edge coupled filters can be especially troublesome unless the design includes all of the coupling effects, and the best way to do this is to make use of an electromagnetic (EM) simulator. The EM simulation showed that the basic design was shifted in frequency and would have given about a 3 dB insertion loss. With the aid of the EM simulation, the design was adjusted in length to give the desired center frequency.

The predicted LO filter response is shown in Figure 9 below. Insertion loss is under 0.5 dB and the return loss is better than 20 dB according to the simulation. The out of band response is not shown, but the filter is reflective at all the required frequencies.

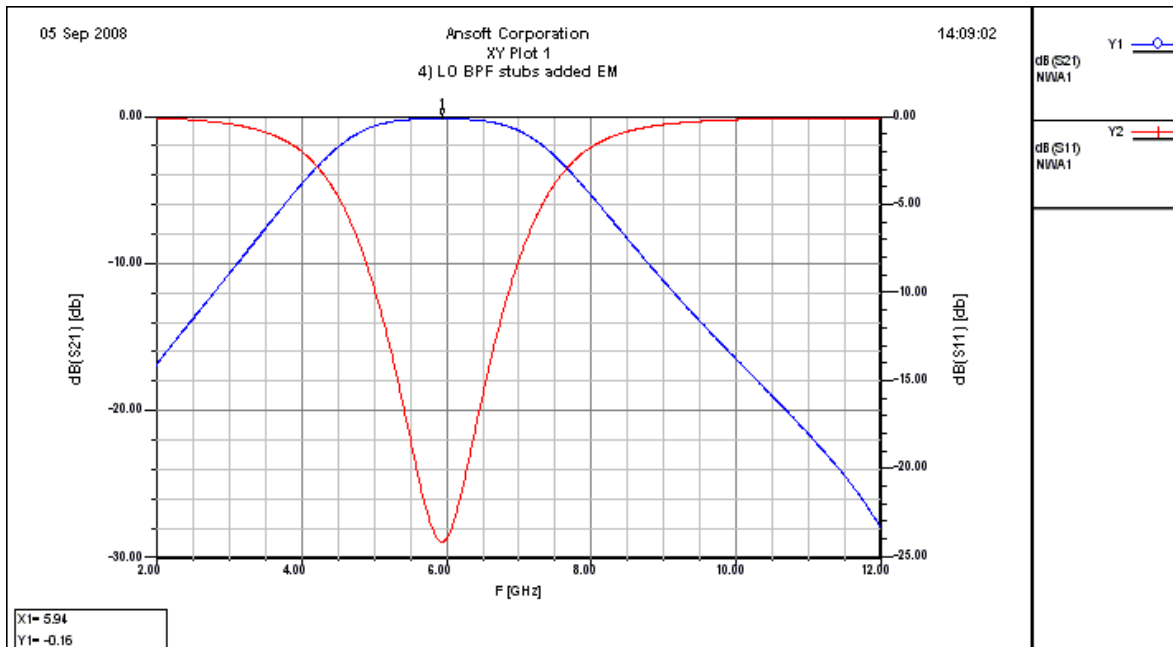


Figure 9 – Predicted Response of LO BPF

## IF NETWORK

As mentioned earlier, the IF portion of the mixer is just as complex as the other portions of the design. This network is responsible for injecting the LO energy into the mixer diodes, passing the mixer's desired IF energy, and reflecting the RF, LO, and 3LO energy back toward the diodes. The IF section reflects the RF energy and all LO products back toward the diodes for two reasons:

- To prevent undesired energy appearing at the IF output (i.e. to attenuate the RF, LO, and LO harmonics)
- To reflect all energy other than the desired IF back toward the diodes in order to achieve low conversion loss.

Each of the open circuited microstrip stubs are  $\sim 1/4$  wavelength at their respective frequencies and can also be thought of as high-Q *idler circuits*. This is not unlike the resonant stubs used in the 432 to 1296 tripler circuits of the past. All of the stub lengths are very sensitive in order to attain best mixer performance. Should a given stub be off by more than a couple of mils in length, the mixer performance will quickly degrade.

It should also be noted that it is no mistake that the high frequency stubs (i.e the RF and 3 LO stubs) are closest to the diodes. This keeps the reflected transmission path of the RF and 3 LO energy to be as short as possible for lowest loss. All of the interconnecting line lengths were optimized for best performance. Perhaps the most sensitive line length is the short line at the left side of the network - the line between the diodes and the RF stub. This line serves as an impedance match between the diodes and the rest of the 50 ohm circuit.

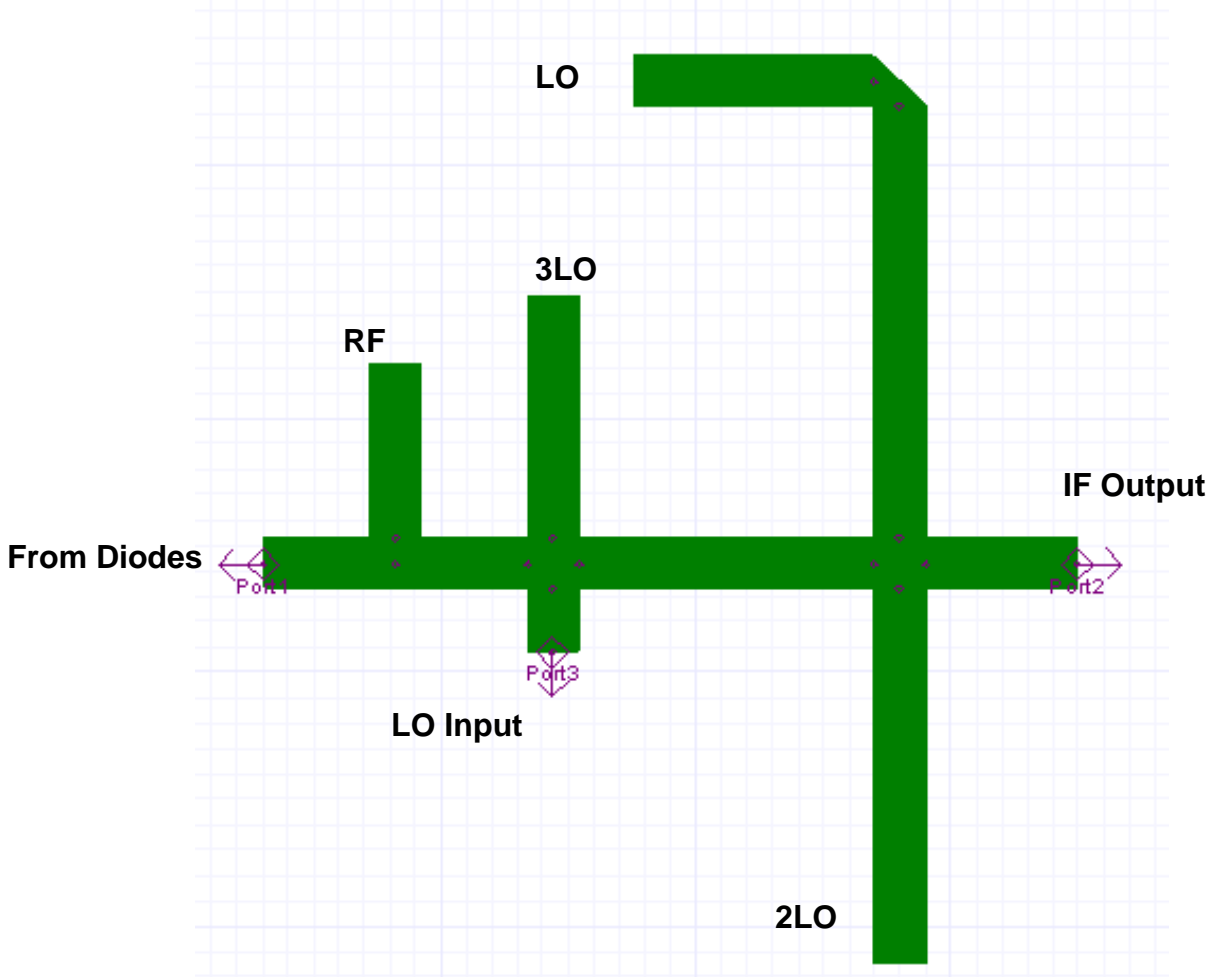


Figure 10 – IF / LO Injection Network

## CONNECTING IT ALL TOGETHER

The initial mixer was designed for 10 mil thick Rogers 5880 high frequency circuit board material. The Rogers material was chosen as it has very good high frequency circuit properties including low dielectric losses (loss tangent  $\sim 0.0009$  at 10 GHz). A 10 mil thick material was chosen in order to keep the transmission line widths a reasonable width considering the frequency of operation. At one point I considered using a 5 mil thick material, but I found that the thinner material would result in *extremely* narrow line widths in the LO bandpass filter, making it un-manufacturable on the thinner 5 mil material.

With the basic design of each of the mixer sections in hand, the next step was to connect it all together and analyze the circuit with the aid of Ansoft Designer, a nonlinear circuit simulator. An LO level of +10 dBm was assumed to start. The initial results were not all that encouraging... the first pass at the mixer design showed an insertion loss of over 20 dB! This isn't all that surprising for several reasons: 1) when connected together, there are interactions between the various networks 2) each of the filter networks were designed to work into a perfect 50 ohm load, and the diodes do not present an ideal 50-ohm

impedance and 3) since each of the reflective stubs are high-Q, it was assumed that some optimization would be required.

The next step in the design process was to go back and painstakingly optimize each stub and transmission line length in order to obtain the best performance. This included minimizing the mixer conversion loss and suppressing the output level of each of the undesired signals. Fortunately, the two are more or less related; as each of the undesired outputs is minimized, the mixer efficiency tends to improve. Several key changes gave a much improved mixer conversion loss, and suppression of the undesired signals, while further optimization yielded smaller improvements.

Once I was satisfied with the overall mixer performance as described above, a more accurate EM analysis approach could be implemented. As mentioned earlier, the use of electromagnetic analysis (EM analysis) gives much more accurate analysis results as it takes electromagnetic effects into account including mutual coupling between transmission lines. The downside is that this is a 'computationally demanding' exercise for the PC and it tends to be time consuming. Another issue is that during EM analysis, it is not possible to easily change the design to evaluate the effects of a change, so this makes it an iterative, somewhat labor intensive process. This author had decided that it would be worth the effort to go the extra step and to 'fine tune' the design using the more accurate EM analysis; this would give the best chance of a first-pass success. Additionally, two mixers were designed – one for a 144 IF, and another for a 432 IF.

Figure 11 illustrates the artwork layout of the mixer. The RF input is on the left, LO input at the bottom trace, and the IF is in the right. The mixer length is just over 0.75 inches. The LO filter appears as one solid line unless the view is greatly magnified.

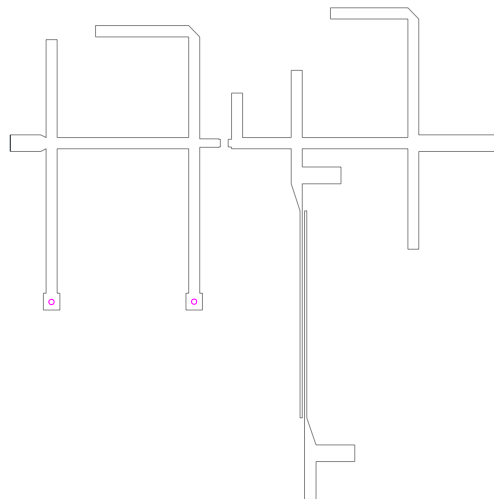


Figure 11 – Prototype Mixer Layout

The analysis plot in Figure 12 shows a predicted spectral plot of the mixer (432 IF version) when analyzed as a downconverter.

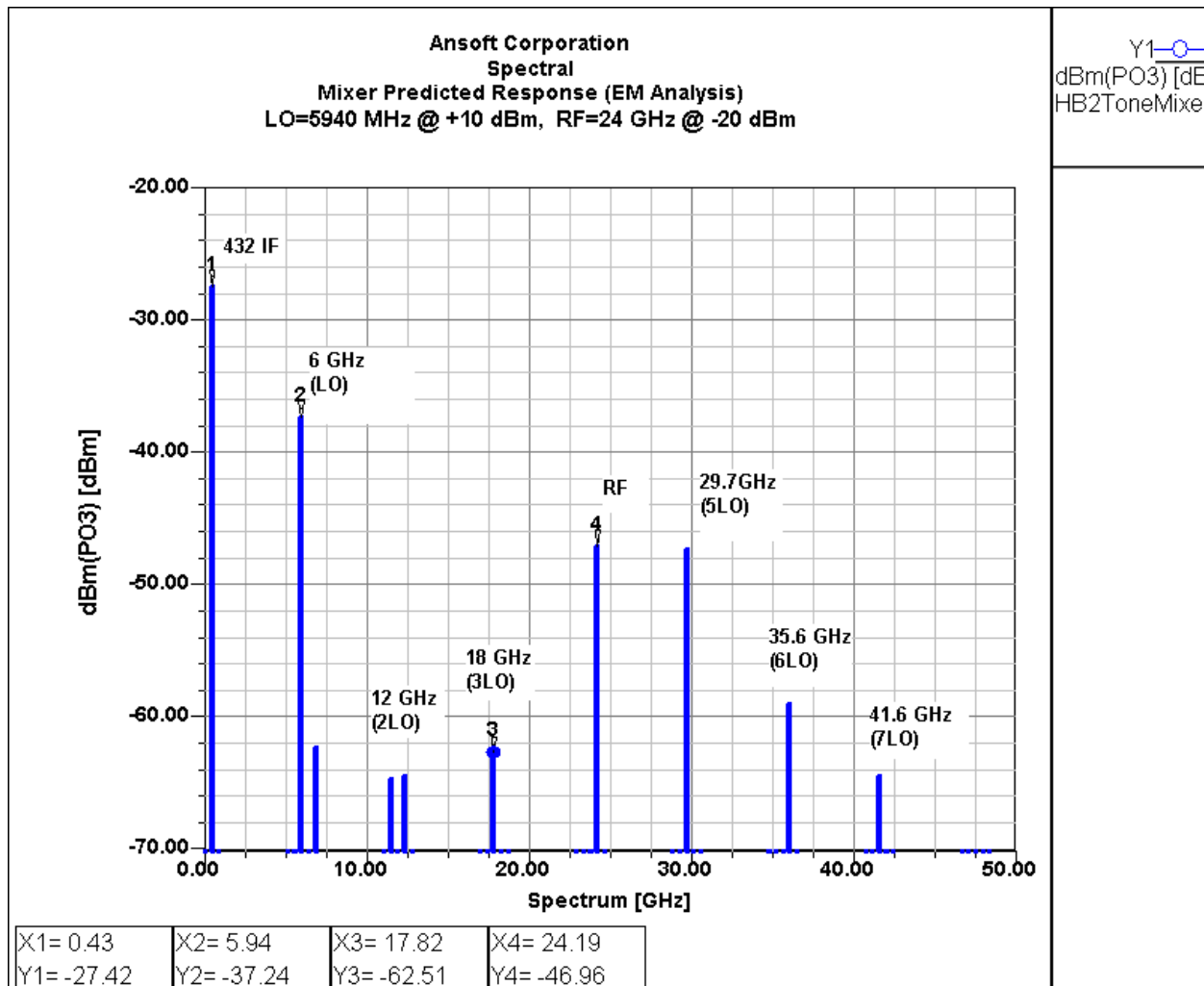


Figure 12 – Predicted Spectral Plot of 432 IF Mixer

For the mixer analysis the 24 GHz input level is at -20 dBm, and the 5940 MHz LO is at +10 dBm. The conversion loss is predicted at ~8 dB and the 6 GHz LO feed through is 10 dB below the desired IF signal level. Since the 6 GHz input is at +10 dBm and a level of -37 dBm is predicted at the mixer's IF connector, this represents some 47 dB of rejection of the LO as measured at the mixer IF. Note that the 2LO, 3LO, and RF signals are also very well attenuated. The 5LO, 6LO, and 7LO responses can also be seen but are not of much concern as they are well attenuated from the desired IF signal.

Although not shown here, the analysis results of the 144 MHz IF version of the mixer is practically identical to that shown above.

## A WAVEGUIDE TO MICROSTRIP TRANSITION

Since the mixer is designed in microstrip, the easiest way to couple RF energy into the mixer would use a high frequency SMA connector. Since most amateur systems however, utilize waveguide, some thought was given to providing a waveguide interface at the mixer RF input. This is normally accomplished using a waveguide to coax transition by soldering a small diameter pin to the microstrip, which in turn acts as a waveguide probe placed into guide with a waveguide backshort roughly  $1/4$  guide wavelength away from the probe. Paul Wade W1GHz recently presented the design of this type of coax to waveguide transition in a QEX article<sup>8</sup>.

The author has made his own WG to coax transitions and learned quite quickly that the length of the probe can be *very* tricky to get just right! The concern was that if a small wire is used as a probe, the preparation and placement of the wire probe might result in less than optimal performance if building more than one or two mixers. For this reason the author chose a different approach to this aspect of the problem. Instead, a direct microstrip to waveguide transition was designed where the microstrip itself becomes the probe for the transition. The design is illustrated in the figure below. The left side represents the 50ohm microstrip line while the rectangular block to the right represents a WR42 waveguide. The microstrip probe is widened in order to improve the impedance match over a relatively broad frequency range centered around 24 GHz. Note that the board itself is inserted into the guide. What's not shown directly is that the groundplane of the PC board is removed to allow the fields to pass through the board's dielectric.

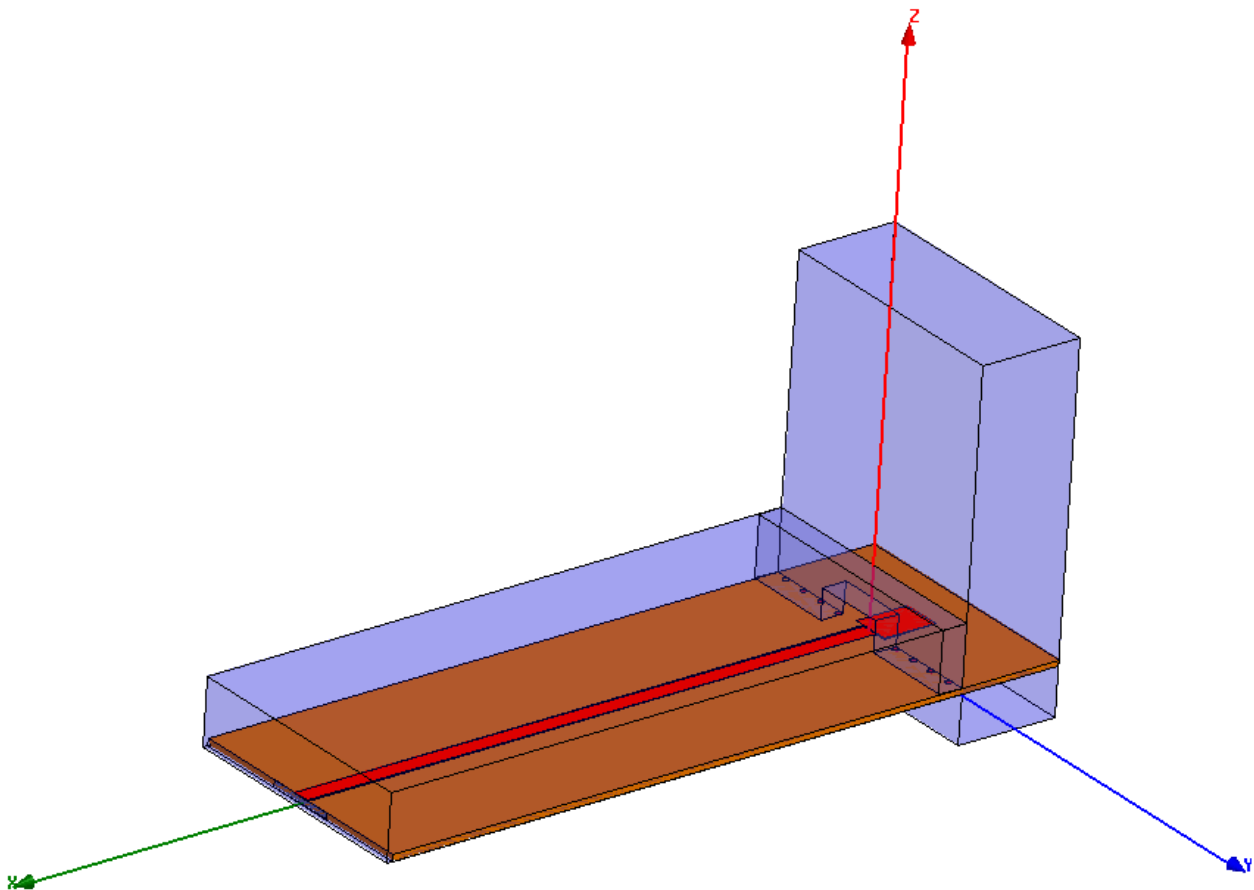


Figure 13 – A Microstrip to Waveguide Transition using Microstrip Probe

The above design was modeled using Ansoft HFSS, a full-wave EM simulator useful for analyzing 3D high frequency structures. The model predicts less than a 0.3 dB insertion loss and a very good return loss for this design.

## ASSEMBLING THE MIXER

A machined aluminum housing was designed to house the mixer assembly including the waveguide to microstrip transition; a WR-42 waveguide interface for the RF port is built directly into the mixer housing. The diodes are not shown in this conceptual drawing but are placed near the center portion of the microstrip transmission line. The LO input is the SMA connector at the lower edge and the connector at the right side is for the IF. The overall mixer measures approximately 1.5 x 2 inches. The board is attached to the housing using a conductive epoxy.

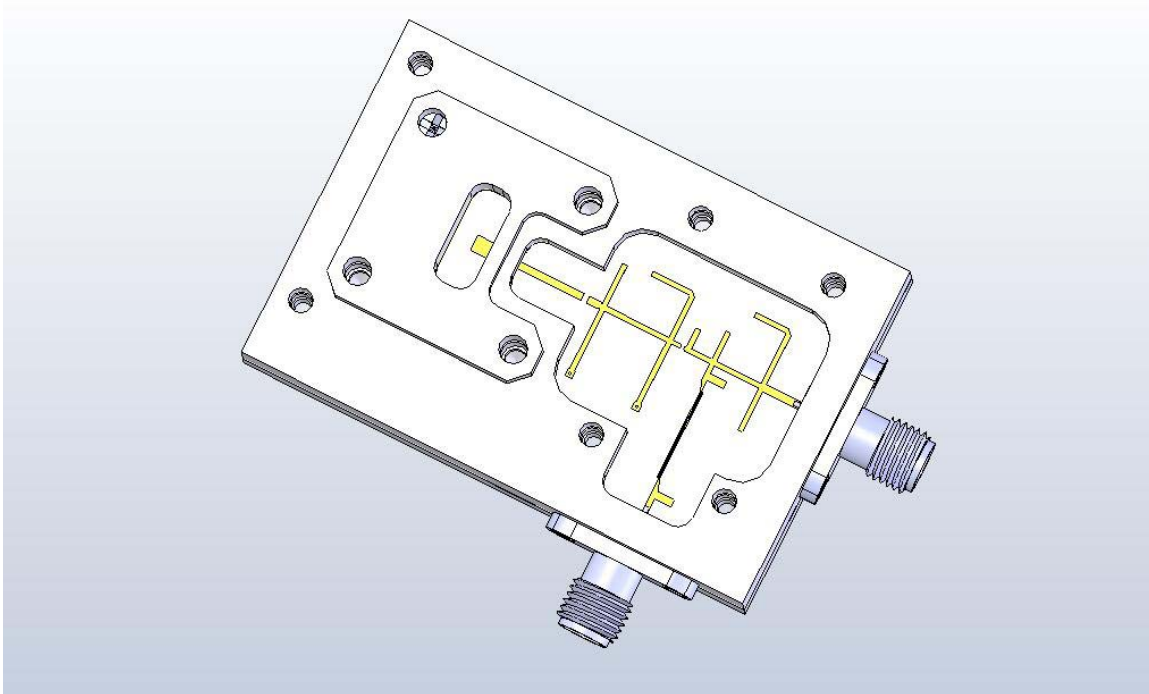


Figure 14 – Mixer Assembly

## MEASURED RESULTS of PROTOTYPE SUBHARMONIC MIXER

The mixer was first measured as a downconverter with a 24.192 GHz input of  $-20$  dBm and a  $+10$  dBm LO. The resulting 144 MHz IF signal is measured at  $-29.5$  dBm. This translates to a measured conversion loss of 9.5 dB. When varying the RF input signal, the mixer response is essentially flat to within 1 dB over an RF bandwidth of  $\sim 500$  MHz. The design works equally well at the 24.048 GHz amateur band used in Europe and elsewhere.

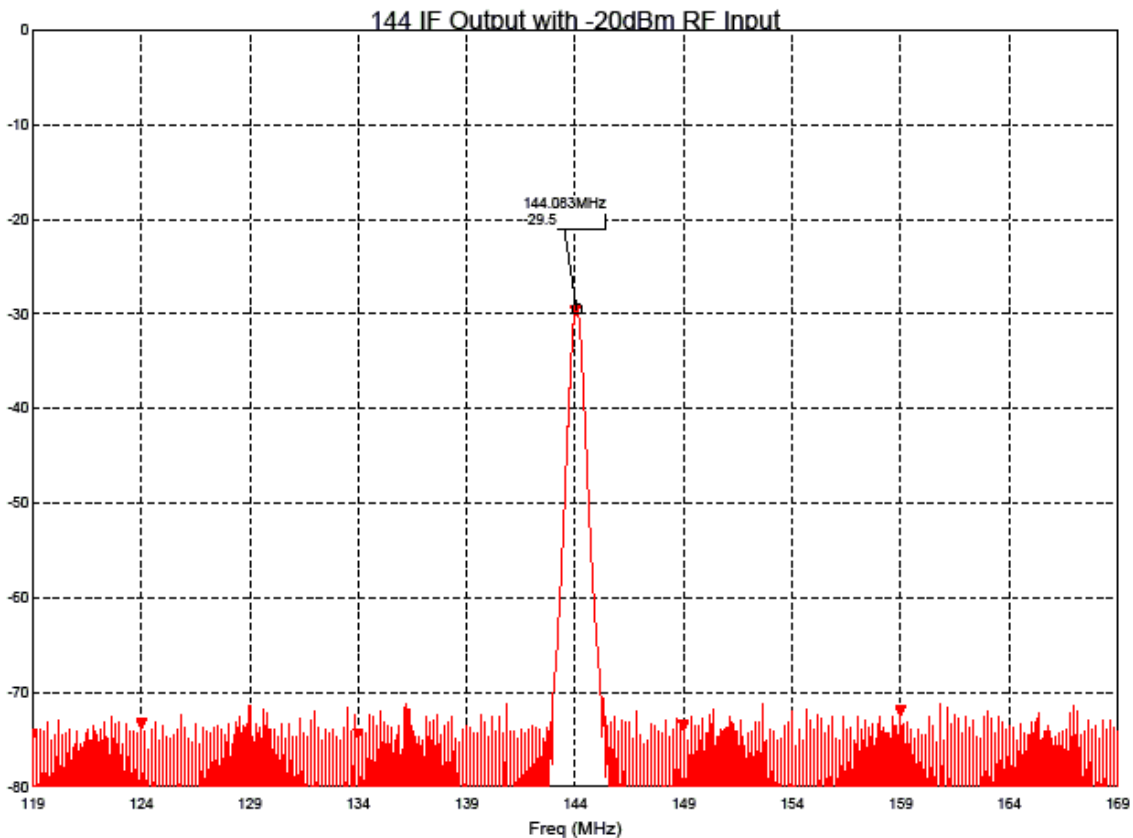


Figure 15 – Prototype Mixer Measured Results as a Receiver Mixer

Next, the prototype was measured as a transmit mixer with an output at 24.192 GHz. The LO level is  $+10$  dBm and the IF drive level was set at  $-10$  dBm. While slightly greater output could be attained by driving the mixer harder, an input of  $-10$  dBm represents the highest drive level without driving the mixer into compression. Note that as a transmit mixer, the conversion loss is again 9.5 dB. The measurement was made over a 100 MHz output bandwidth, and no close-in spurious signals were detected.

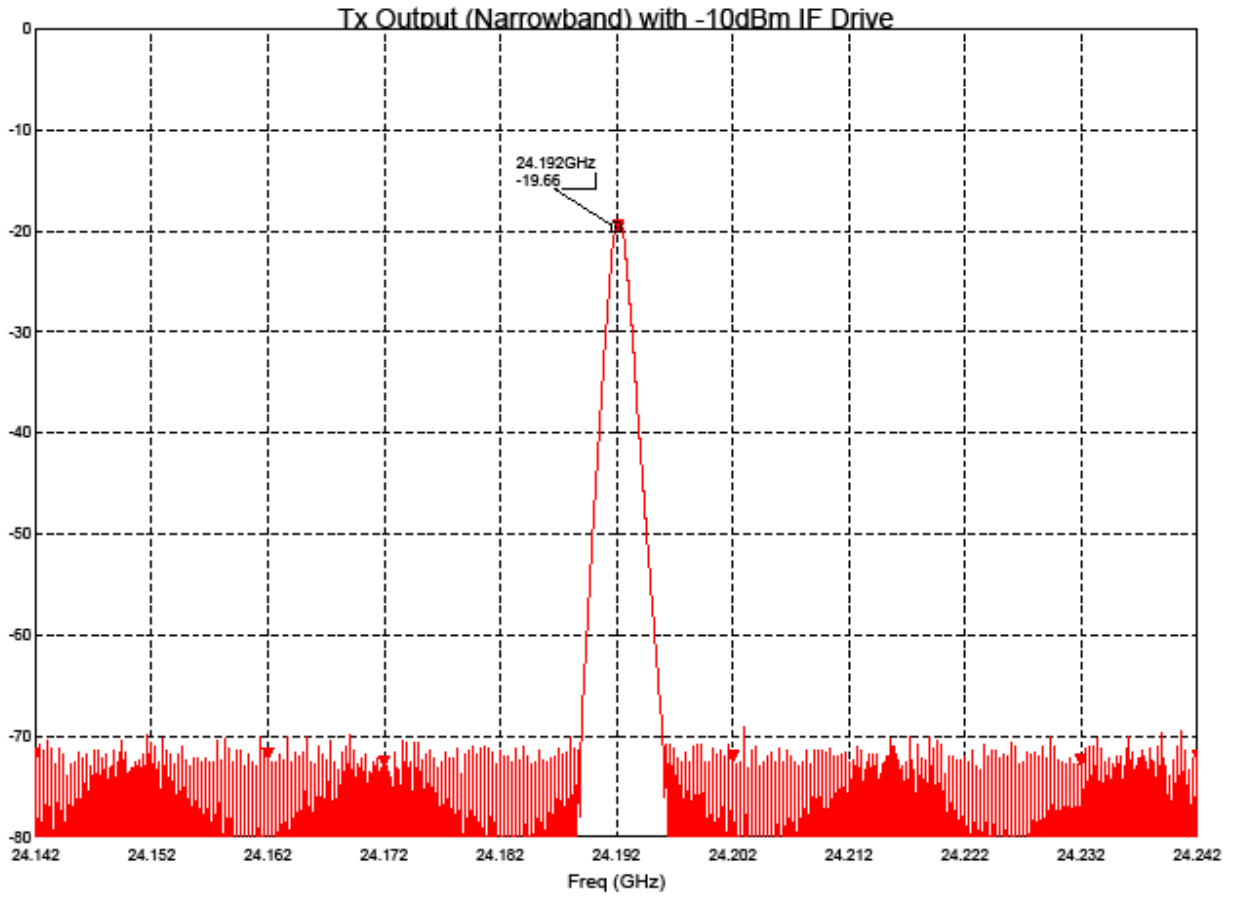


Figure 16 – Transmit Mode Results for Prototype Mixer (narrowband)

Finally, the transmit bandwidth was widened in order to measure the rejection of the close-in 4xLO signal. Results are shown in Figure 17 below.

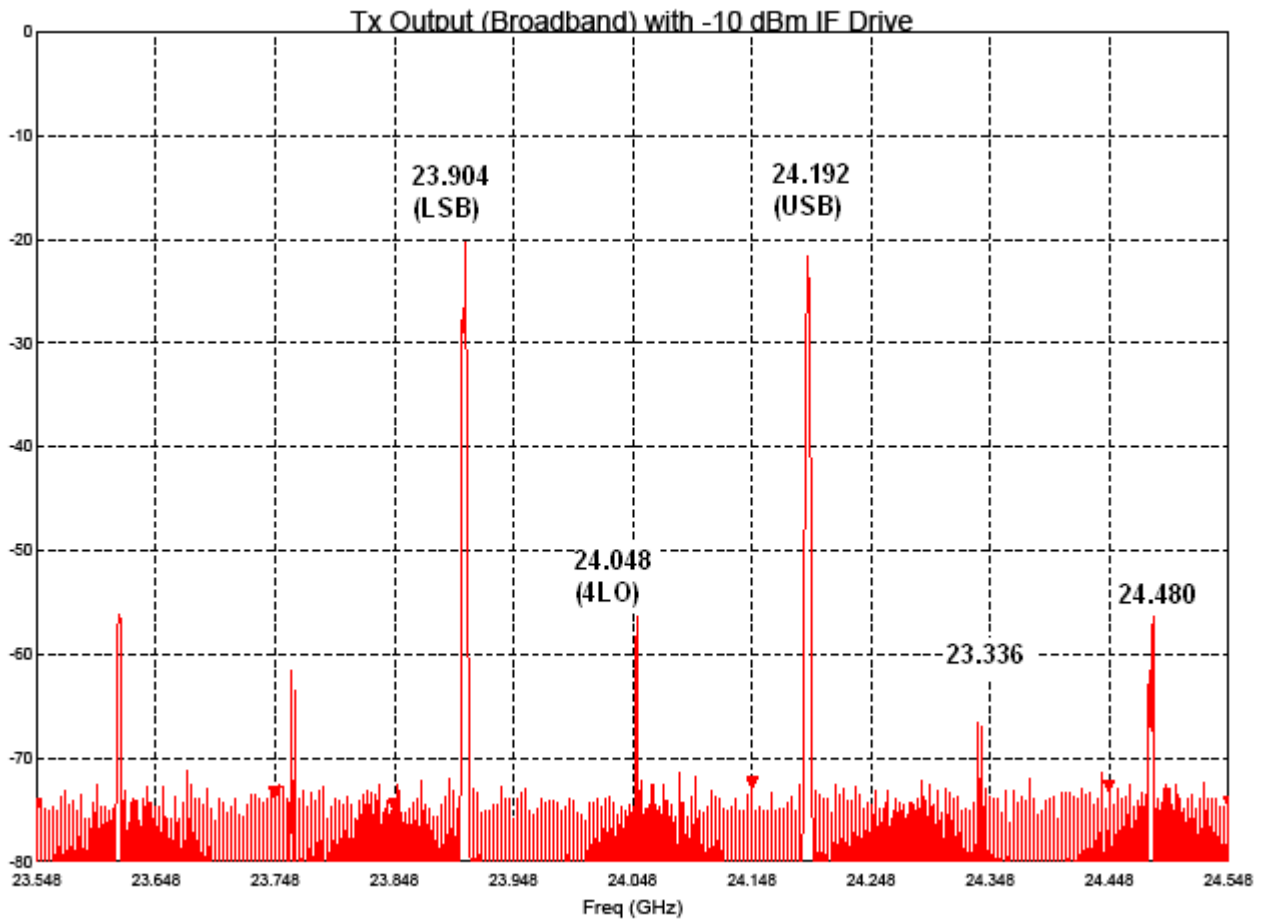


Figure 17 – Transmit Mode Results for Prototype Mixer (broadband)

The above broadband spectrum analyzer measurement was made over a 1 GHz bandwidth, and there are a number of undesired mixer signals, as expected. The desired RF signal at 24192 MHz is the USB mixing product and is seen at one and a half divisions to the right of center. The undesired LSB signal at 23.904 GHz is equal in amplitude to the desired RF signal. There are several additional mixing products every 144 MHz above our desired RF signal; however they are more than 35 dB below the desired. A surprising result can be viewed in this data. **Note that the 4LO signal (at the center) is more than 35 dB below the desired 24.192 GHz signal.** In most fundamental mode mixers that the author has measured, the LO signal is *at the same level* as the desired USB RF signal. While RF filtering is still obviously required, the x4 subharmonic mixer appears to require less filtering than a standard type mixer.

Lastly, one comment on the mixer's conversion loss is in order. Recall that the computer simulation of Figure 12 shows a predicted conversion loss of ~8 dB. The conversion loss figures on the prototype measure ~9.5 dB so there is a difference noted. Some of this can be attributed to etching tolerances, etc but there are two factors that were unaccounted for in the model prediction: the loss of the WG transition and the loss of the additional length of input microstrip between the WG transition and the actual mixer input. With these factors in mind, the predicted conversion loss is just shy of 9 dB. A measured conversion loss of 9.5 dB agrees very well with the predicted value.

## FUTURE EFFORTS

The prototype subharmonic mixer was designed using the 'primo' Teflon-based Rogers 5880 board material. The fabrication costs using this material are somewhat cost prohibitive for amateur radio applications. In an effort to get the costs down to more attractive levels, the author has redesigned the mixer to be fabricated on a lower cost Rogers 4350 type material. While the lower cost 4350 material has a disadvantage of higher dielectric losses, the performance tradeoff is felt to be minimal.

The author is also starting to take a look at this mixer topology for use on 47 GHz.

## CONCLUSION

A x4 subharmonic mixer has been designed and demonstrated with favorable results. It is my hope that this hardware will make it somewhat easier for amateurs to enjoy the 24 GHz band.

The author wishes to thank Al Ward W5LUA, Barry Malowanchuk VE4MA, and Brian Justin WA1ZMS for their thoughtful suggestions and inputs to this paper.

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<sup>1</sup> J. Dietrich, WA0RDX , "A Twin Diode Mixer – A New Microwave Mixer," Ham Radio Oct 1978

<sup>2</sup> M. Kuhne DB6NT, "A Transverter for 47 GHz," DUBUS 1992

<sup>3</sup> B. Justin, WA1ZMS, "An Example of Gear for the 241 GHz Amateur Band," Microwave Update Proceedings, 2002

<sup>4</sup> B. Justin, WA1ZMS, "A Primer on Millimeter –Wave Multipliers and Mixers," Microwave Update Proceedings 2002

<sup>5</sup> P. Riml, OE9PMJ, "A 47 GHz Station," DUBUS 3/1989

<sup>6</sup> A. Madjar, "A Novel General Approach for the Optimal Design of Microwave Subharmonic Mixers," IEEE MTT Transactions, Nov 1996.

<sup>7</sup> Ansoft Designer Student version may be downloaded from: [www.ansoft.com](http://www.ansoft.com)

<sup>8</sup> P. Wade W1GHZ, "Rectangular Waveguide to Coax Transition Design," QEX Nov/Dec 2006

<sup>9</sup> S. Mass, Microwave Mixers, Artech House Publishers 1993