

# Locked VCXOs for Stable Microwave Local Oscillators with Low Phase Noise

*Paul Wade W1GHZ* ©2013  
**w1ghz@arri.net**

A good local oscillator has been a perennial problem for microwave operators. An ideal LO would be stable, provide frequency accuracy, have low phase noise, and be free from birdies and other unwanted artifacts.

Early microwave work relied on inefficient diode multipliers – it was a real challenge just generating enough power to drive a diode mixer. They also required critical tuning. The advent of MMICs, providing cheap gain, solved the power problem and made “no-tune” transverters possible.

The next problem was frequency stability and accuracy. Crystals drift and age and large multiplication factors increase the effect. Microwave operation always involved lots of tuning to find signals. Some operators would bury the main oscillator underground, to keep the temperature constant, and run it continuously. Recent developments in frequency synthesizer chips have made synthesized local oscillators popular. The synthesizers are readily locked to an accurate frequency reference, like a Rubidium standard or a GPS-disciplined oscillator, so that we are able to operate on microwaves without a need for tuning.

However, the phase noise generated by almost all synthesizers is significantly worse than a good crystal oscillator. For very weak signals, my experiments<sup>1</sup> suggest that the difference in Minimum Detectable Signal is about 2 dB. On the other hand, 10 GHz MDS tests at the NEWS picnic over several years suggest that knowing the frequency of a very weak signal can improve the MDS by up to 5 dB, when listening by ear. The addition of an SDR waterfall display eliminates the unknown frequency problem – all signals appear on the screen – so minimizing phase noise can help to hear very weak signals.

## **VCXO**

Is it possible to have a crystal oscillator, for low phase noise, and frequency accuracy? A VCXO, Voltage Controlled Crystal Oscillator, can be adjusted in frequency by varying a control voltage, so we can compensate for drift and aging. One way to do this would be to simply adjust the frequency at the beginning of each operating session to match some reference. Or we can add circuitry to do this automatically and continuously, so that our frequency is locked to some reference.

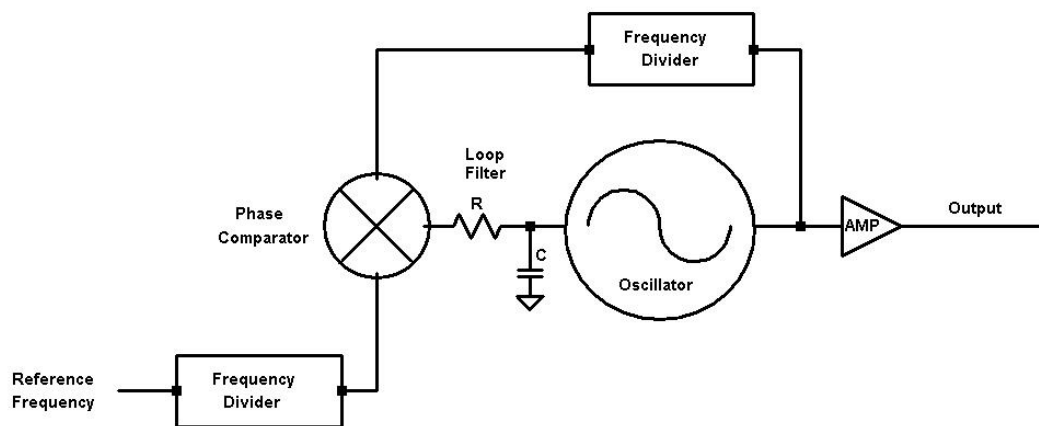
Why is a VCXO better than a typical synthesizer? Most synthesizers use a VCO, Voltage Controlled Oscillator, a free-running oscillator with wide tuning range. The VCO has poor

inherent stability without the synthesizer controlling it, and the wide tuning range makes it very sensitive to noise.

As an example, a typical local oscillator frequency for 1296 MHz operation is 1152 MHz. A synthesizer for this frequency might use a VCO like the Minicircuits ROS-1285-119+, which tunes from 1115 to 1285 MHz for a tuning voltage of 0 to 5 volts. Tuning sensitivity is specified as about 56 MHz per volt – one microvolt of noise will move the frequency by 56 Hz, and a millivolt of noise will move the frequency by 56 KHz. A VCXO has much lower tuning sensitivity; I measured a 96 MHz VCXO to vary 16.5 KHz for a tuning voltage of 0 to 3.3 volts, so the tuning sensitivity is about 5 KHz per volt, roughly 10,000 times less sensitive. When multiplied by 12 to 1152 MHz, the tuning sensitivity is about 60 KHz per volt, still 1000 times better than the VCO. One millivolt of noise will move the VCXO frequency by 60 Hz, or the VCO frequency by 56 KHz. Even one microvolt of noise will move the VCO frequency by 56 Hz. Any noise voltage is constantly moving the oscillator frequency around – we call it phase noise. In real equipment, it is easy to keep noise well below a millivolt, but getting below a microvolt is a lot harder. It is really hard to keep the noise on the tuning voltage low enough to eliminate it as a source of phase noise (of course, there are other sources).

## Frequency Synthesizers

A frequency synthesizer generates a desired frequency by comparing the frequency of the oscillator in the synthesizer with a reference frequency and correcting the oscillator frequency until it is on the desired frequency. Since the desired frequency is not the same as the reference (otherwise the synthesizer is not required), the frequencies must be converted to a common frequency for comparison. One technique is to generate harmonics of the reference and do the comparison at the oscillator frequency. A more common and versatile technique, shown in Figure 1, is to digitally divide one or both frequencies to a lower common frequency and then compare.



**Figure 1 – Simplified Frequency Synthesizer**

Some of the division schemes can get pretty fancy, in order to generate a wide range of frequencies with very small step increments, and to change frequencies quickly. Most of them also use some form of processor chip. All of this tends to generate digital noise.

For the VCXO, we are making a very simple synthesizer, hard-wired for one specific frequency. The goal is to generate a clean, stable signal. For simplicity, only integer dividers are used, using ordinary CMOS logic devices. This limits the choice of frequencies, but only a limited number of VCXO devices are readily available; however, several of them are quite useful for microwave Local Oscillators.

The perceived wisdom for minimizing phase noise in synthesizers includes:

- A stable oscillator with small tuning range
- High comparison frequency
- Integer dividers
- Slow loop filter time constant
- Clean, stable power supply

I have tried to incorporate all of these in the VCXO circuit.

## **VCXO Board**

The schematic of the VCXO board is shown in Figure 2. The board assumes a packaged VCXO, but it could also control a homebrew one to operate at some other frequency. The VCXO frequency range is roughly 50 to 200 MHz, and the CMOS logic is only guaranteed to operate up to about 30 MHz, so the first divider is a prescaler chip. Several prescalers fit in this location, allowing divide ratios of 2 to 80, selected by three selection pins. The prescalers will operate up to at least 1100 MHz, so higher frequency oscillators are also possible. After the prescaler, two CMOS logic chips are available – U5 can be wired for any divisor between 2 and 16, while U6 has two sections each with fixed divisors of 2 and 5. To divide by 28, for example, one chip would divide by 14 and the other by 2. All the dividers are programmed by jumper wires – simple, effective, and fine for fixed frequency operation.

The programmable divider sections may be used for either the oscillator frequency or the reference frequency, in order to arrive at a common frequency. Examples will be shown for all the useful VCXO frequencies that I have found. At the common frequency, both signals go to the comparator – this is a logical Exclusive-OR (XOR) gate. The XOR gate output is high when both signals are the same and low when they are different. When the frequencies are the same, the output will be high for part of each cycle and low for part of each cycle. The output is averaged to create a DC tuning voltage which just happens to be the voltage for the desired frequency. If the frequencies were different, the voltage would be higher or lower, forcing the oscillator toward the desired frequency.

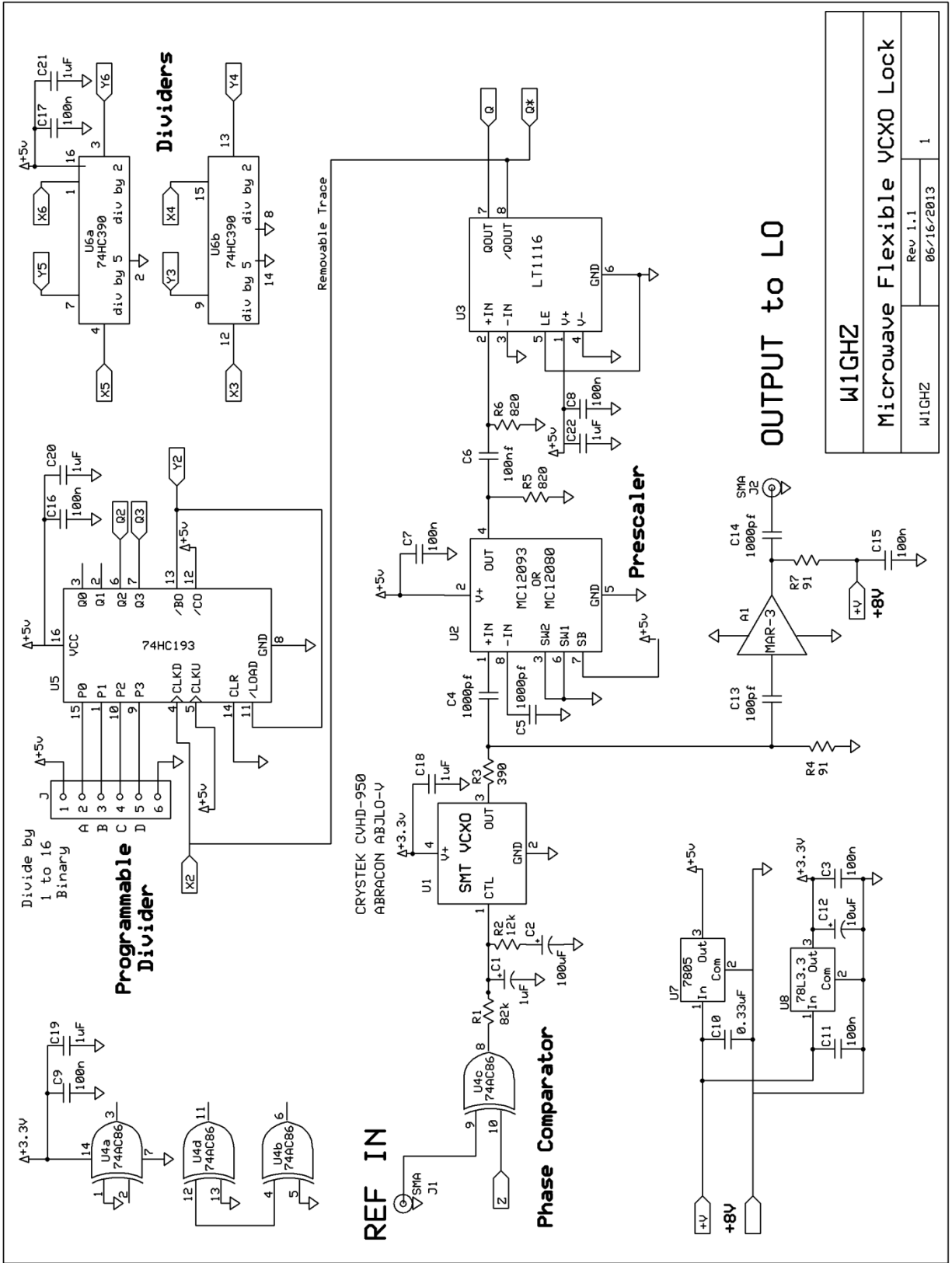


Figure 2 – Microwave VCXO Board Schematic

The output averaging is done in the loop filter, an RC filter with a long time constant, so that the oscillator is gently guided onto frequency. During testing, I can see the oscillator waveform on an oscilloscope shift frequency over several seconds to line up with the reference waveform.

Finally, there is a MMIC buffer amplifier for the oscillator output.

While all my examples use a 10 MHz reference frequency, other references can also work. If you have a good reference oscillator at another frequency, use it. Only integer dividers are available, so an integer VCXO requires an integer reference. On the other hand, to lock an odd frequency, perhaps for a beacon, an odd reference is required that can achieve a common reference frequency. A couple of possibilities are a programmable Rubidium source or a reverse DDS source.

## VCXO Examples

**80 MHz** – The simplest example is an 80 MHz VXCO, useful as the LO source to multiply to 2160 MHz (2304), 3600 MHz (3456), and 10800 MHz (10368). The board is shown in Figure 3 – 80 MHz is divided by 8 in the MC12093 prescaler chip (select  $\div 8$  by grounding pins 3 and 6) to 10 MHz, then compared directly with the 10 MHz reference. This board locks right up with a clean output.

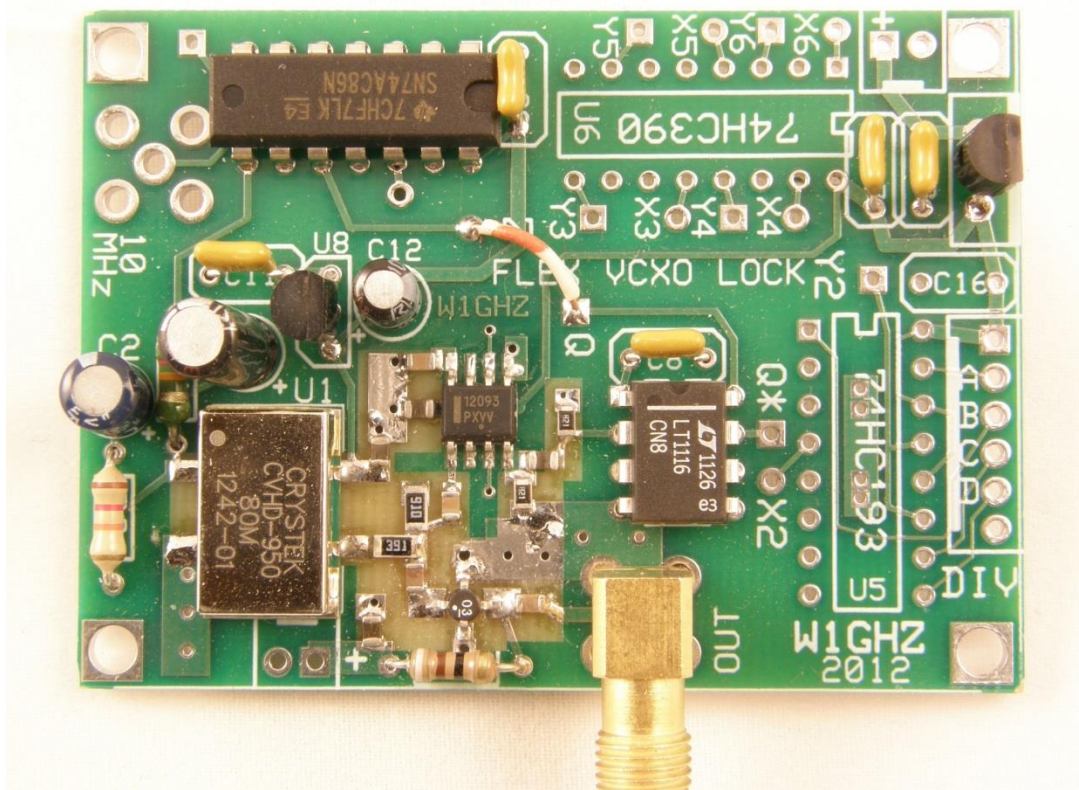
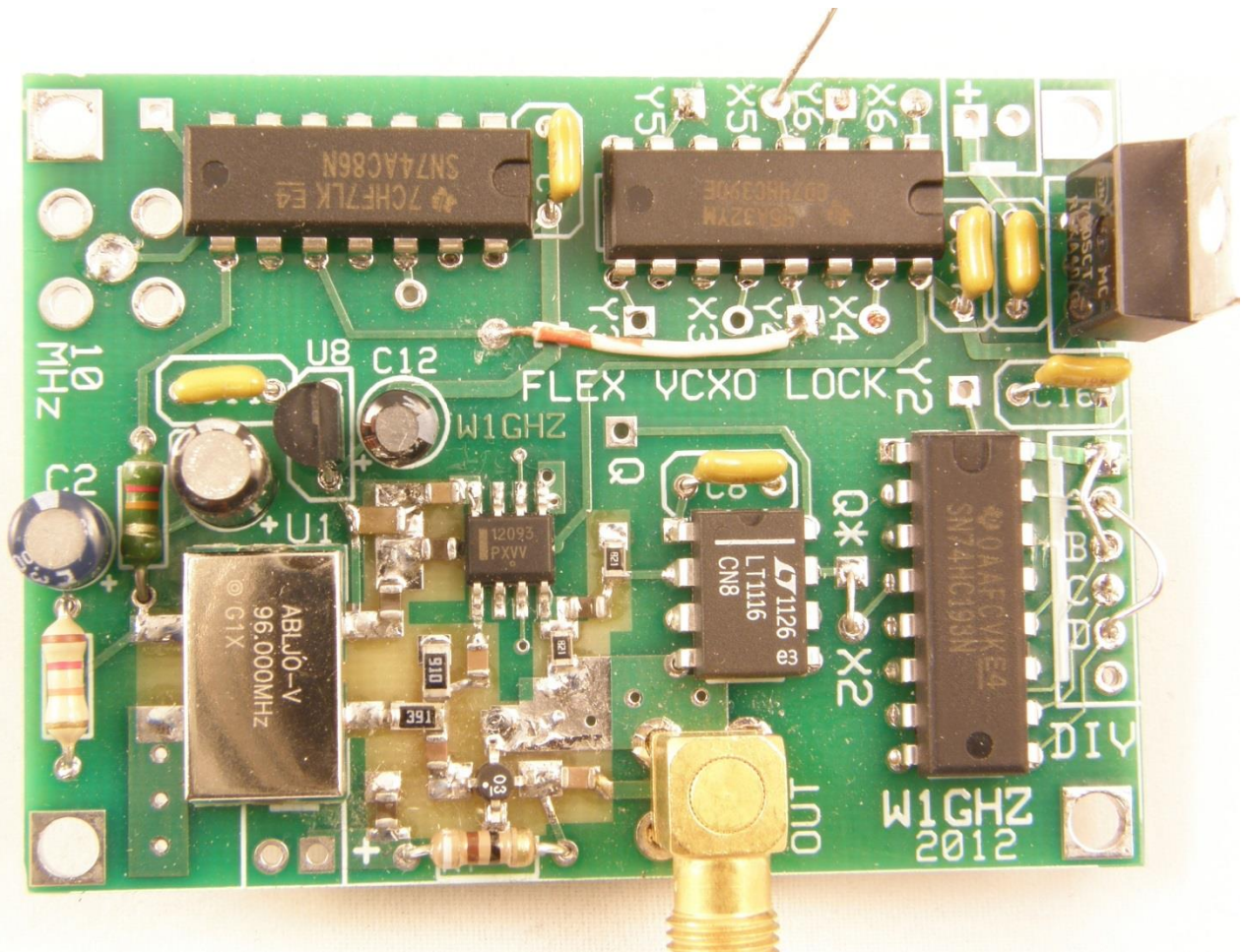


Figure 3 – 80 MHz VCXO Board



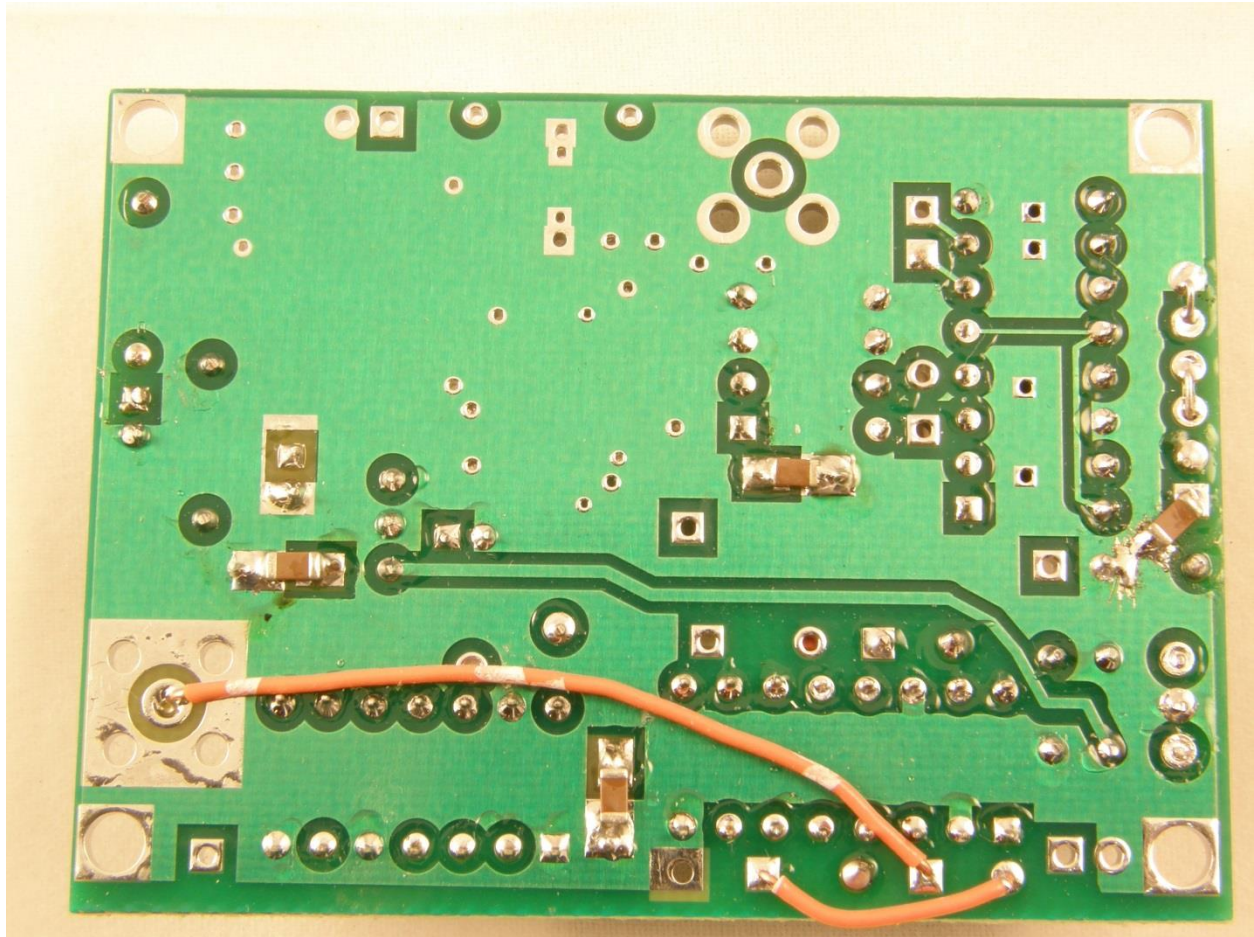
**96 MHz** – Another very useful frequency is 96 MHz, which is multiplied to 1152 MHz for the popular LO for 1296, with harmonics providing markers on many microwave bands. On the board shown in Figure 4, 96 MHz is divided by 8 in the MC12093 prescaler chip to 12 MHz. Then we must divide by 12 to 1 MHz, and divide the 10 MHz reference by 10 to compare at 1 MHz. I tried dividing by 12 directly in the 74HC193 chip, but the output was very asymmetric, with only a narrow pulse – this would not work well with the XOR comparator. Instead, the 74HC193 is wired to divide by six, followed by a divide by two in the 74HC390 chip – a divide-by-two always generates a square wave output. Other sections of the 74CH390 divide the 10 MHz reference by five, then two, to provide a square wave as well. This board also locks right up; the output has small spurs 1 MHz on each side of the main output.

The divisor of the 74HC193 chip, U5, is programmed by the ABCD jumpers on the right side of the board with the binary version of the divisor. For instance, a divisor of 12 = 1100 binary, so jumpers A and B are wired HIGH, to +5volts, and jumpers C and D are wired LOW, to ground. The board in Figure 4 is wired for a divisor of 6 = 0110 binary.



**Figure 4 – 96 MHz VCXO board**

The bottom of the board, shown in Figure 5, has the wiring connections to divide the 10 MHz reference by 10 to 1 MHz. The input for the 10 MHz reference is at location X5.



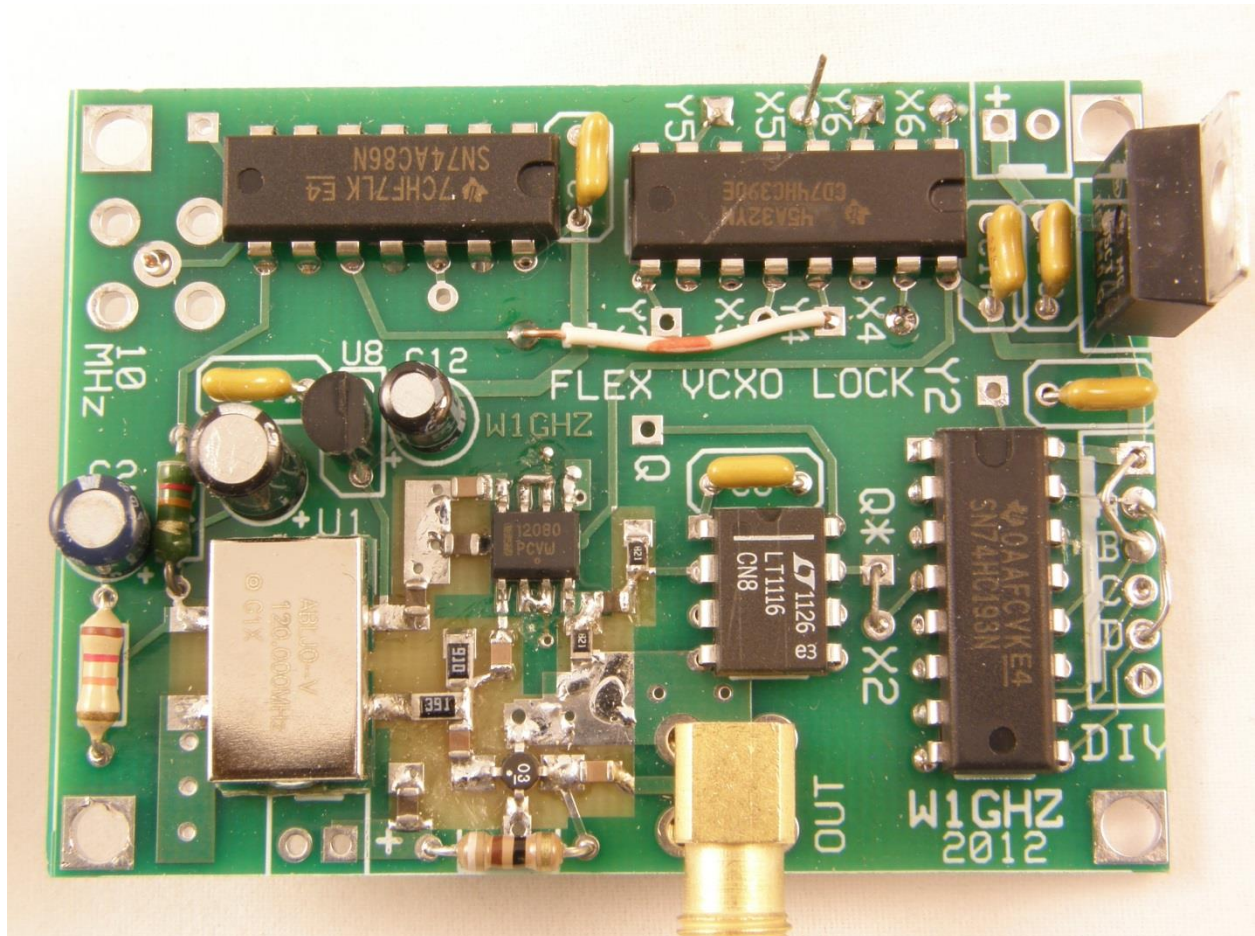
**Figure 5 – Bottom side of 96 MHz VCXO board**







**120 MHz** – provides a stable LO for 144 MHz. As shown in Figure 7, the prescaler is a MC12080 programmed to divide by 10, to 12 MHz. Selection of divide-by-10 requires changing both pins 3 and 6 from ground to high, by cutting the PCB traces and adding jumper wires from pin 3 to pin 2 and from pin 6 to pin 7. The rest of the wiring is the same as the 96 MHz board. This board also locks right up; the output has small spurs 1 MHz on each side of the main output.

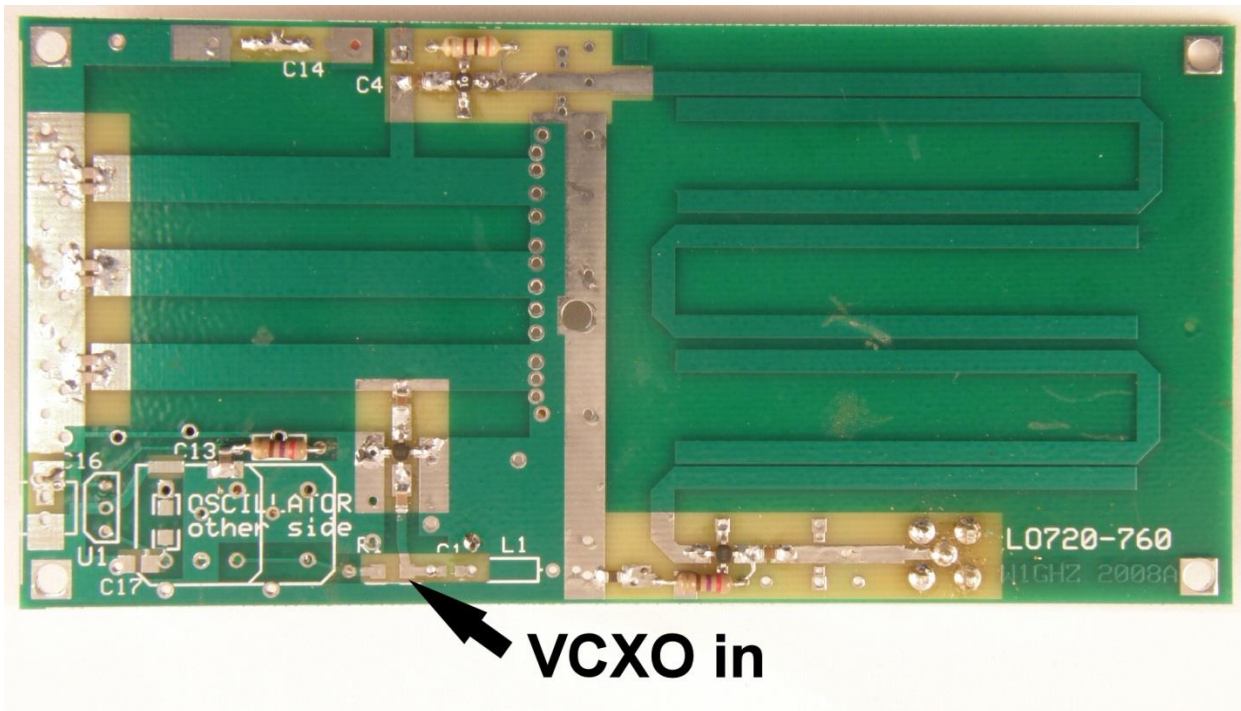


**Figure 7 – 120 MHz VCXO board**

**108 MHz** – I haven't yet found a VCXO for this frequency, but WA1MBA says it would be a useful frequency, and it provides another example. The prescaler must divide by 9 to 12 MHz; the MC12026 can be programmed for this. The rest of the wiring is the same as the 96 MHz board.

## Multiplier Board

To multiply from the VCXO board to the microwave LO frequency, I use the LO boards for my simple rover transverters<sup>2</sup>, replacing the oscillator with the signal from the VCXO board. The 80 MHz VCXO drives the 720 MHz LO board – the frequency is further multiplied in the 2304 or 3456 MHz transverter. The multiplier board in photo in Figure 8 shows the input from the VCXO bypassing the oscillator section.



**Figure 8 – 720 MHz LO Multiplier board configured for external VCXO**

The 1152 MHz LO board originally used a 64 MHz crystal oscillator. To operate with 96 MHz input from the VCXO, the filter after the first tripler must be tuned to 288 MHz. With the 64 MHz oscillator, the combline filter was tuned to 192 MHz by capacitive loading of 36 pf (two 18 pf capacitors in parallel for lower loss). From the chart, Figure 7, in my transverter article<sup>2</sup>, I estimated the required capacitance for 288 MHz as 22 pf. The filter response in Figure 9 shows that the filter is tuned slightly high, with 288 MHz at the edge of the response. Increasing the capacitance to 23 pf, an 18 pf in parallel with 5 pf, centered the filter near 288 MHz. The parallel capacitors slightly reduced the loss. The input connection to this multiplier board, shown in Figure 10, is similar to the one in Figure 8.

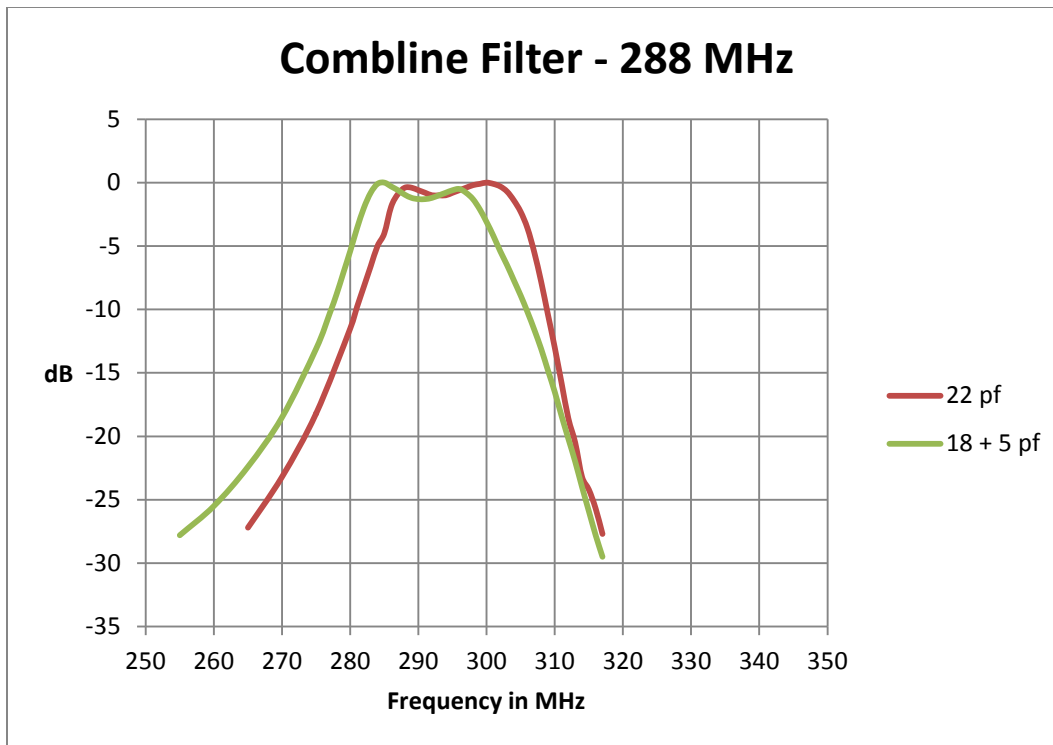


Figure 9 – Response of Comblin Filter for 288 MHz

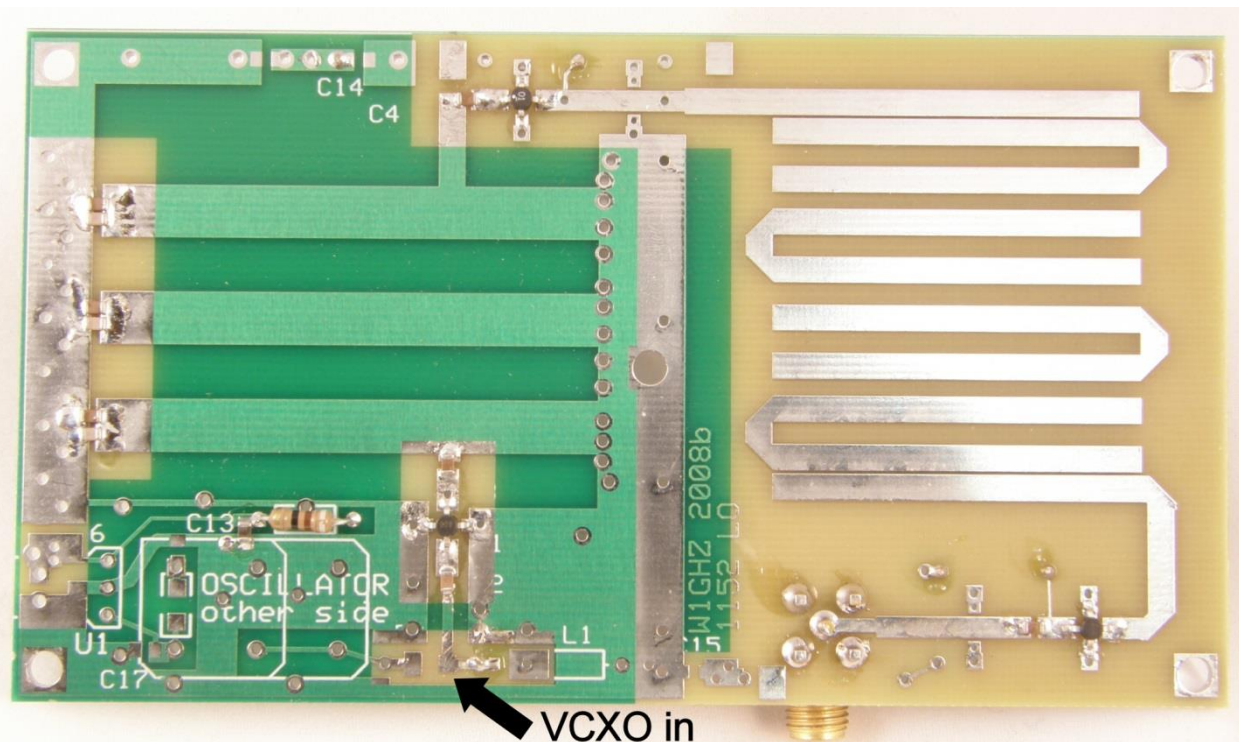


Figure 10 – 1152 MHz multiplier board configured for external 96 MHz VCXO input



## Phase Noise

While there is no reason to expect the VCXO to be more stable than a synthesizer, our goal is to reduce phase noise. I only have data on the 80 MHz version. Figure 11 shows the phase noise starting with a pretty good TCXO, the 80 MHz VCXO, and the VCXO multiplied to 720 MHz. We expect an 8 times multiplication to add about 18 dB of phase noise – the 80 MHz VCXO has about 18 dB more phase noise in the mid-range, but is somewhat worse at very low offset frequencies. A further 9 times multiplication to 720 MHz should add another 19 dB, which we can see in the mid-range as well. The 720 MHz curve generally has the same shape as the 10 MHz source, so most of the difference is due to frequency multiplication. Figure 12 compares the VCXO-based 720 MHz LO with one using an ordinary crystal oscillator. The VCXO is a few dB worse, but still really good.

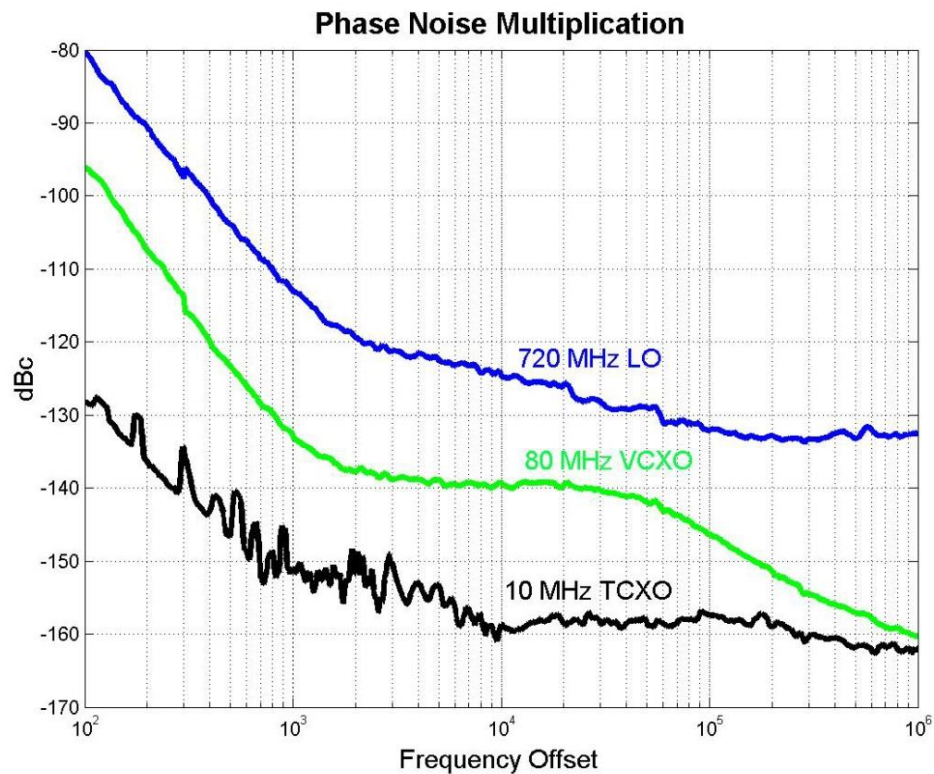
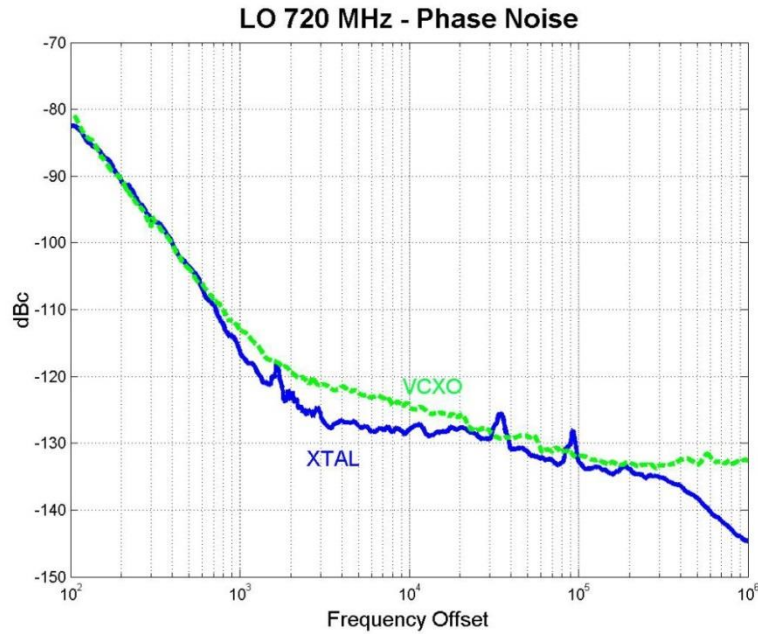


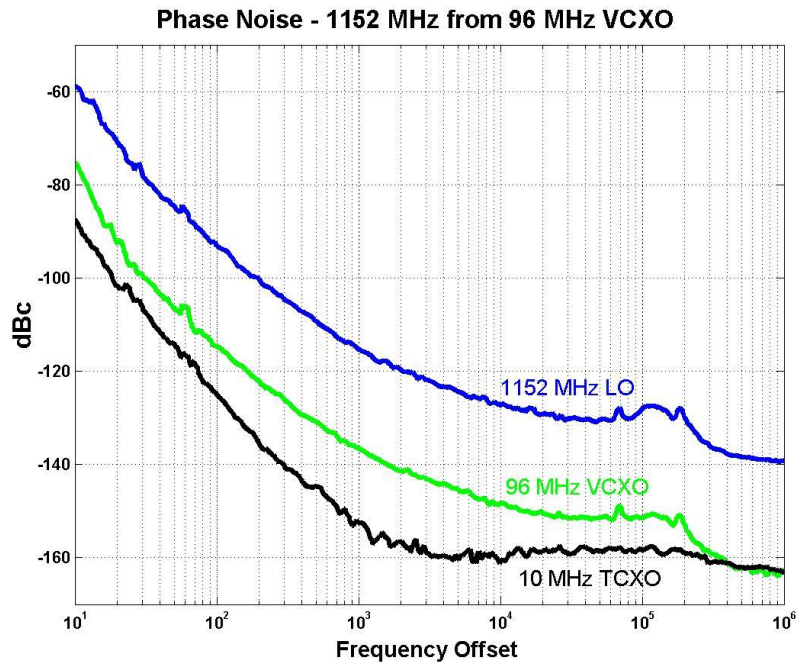
Figure 11 – Phase Noise of VCXO LO, showing increase with Frequency Multiplication





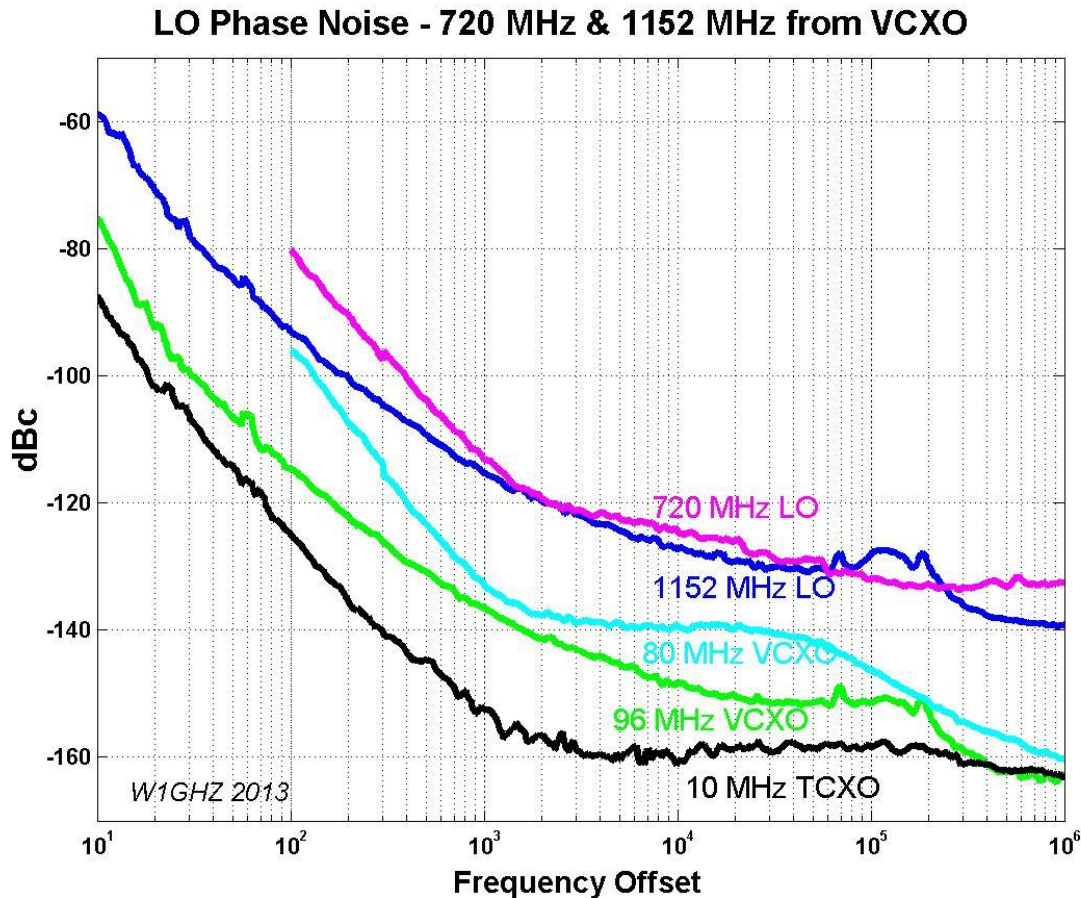
**Figure 12 – Comparison of 720 MHz LO with Crystal and VCXO as source**

An LO for 1152 MHz, starting with a 96 MHz VCXO, also looks very good. In Figure 13, we can see the phase noise for the same 10 MHz TCXO, the locked 96 MHz VCXO, and the 1152 MHz output from the multiplier board. The same phase noise multiplication with frequency multiplication is evident.



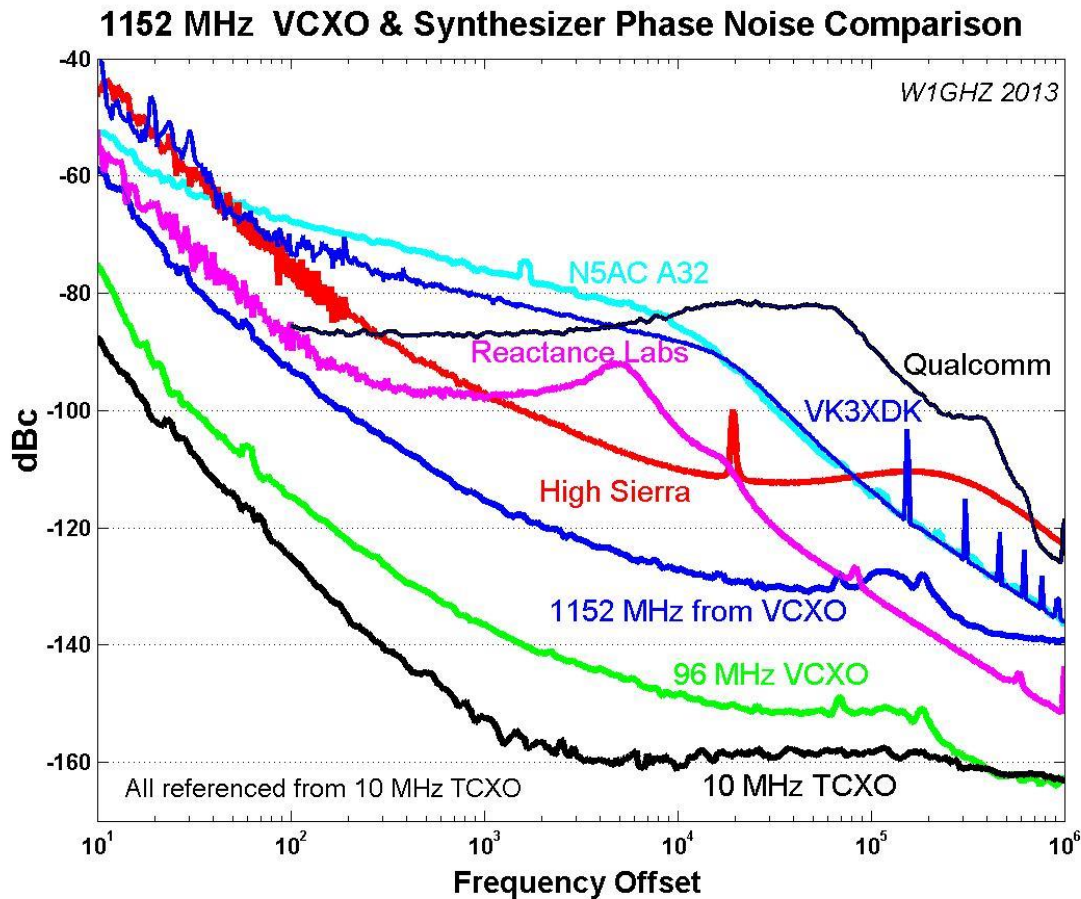
**Figure 13 – Phase Noise of 1152 MHz VCXO from locked 96 MHz VCXO**

The two VCXO-base LO chains are compared in Figure 14. We would expect the 1152 MHz phase noise to be about 4 dB worse due to the greater frequency multiplication. However, the 1152 MHz phase noise is lower than the 720 MHz version. A possible explanation is different crystals – the 80 MHz VCXO is made by Crystek, while the 96 MHz VCXO is made by Abracon.



**Figure 14 – Phase noise of both VCXO-based LO chains**

How do the VCXO-based LO chains compare with a synthesized LO? Figure 15 shows a comparison with several popular synthesizers, all operating at 1152 MHz. With this correction, the VCXO is at least 10 dB better than the best synthesizers in the important frequency offset range, the SSB passband. The most common synthesizers, the ApolLO (curve marked N5AC A32) and the Qualcomm, have phase noise nearly 40 dB worse than the VCXO.



**Figure 15 - Comparison of VCXO LO with several Synthesizers**

The Apollo synthesizer was used for the MDS tests<sup>1</sup> that showed a 2 dB difference from a crystal oscillator LO – and the difference in phase noise is ~40 dB. Would some of the better synthesizers, only 10 or 20 dB worse than a crystal source, be any different in MDS? Clearly, more work is needed.

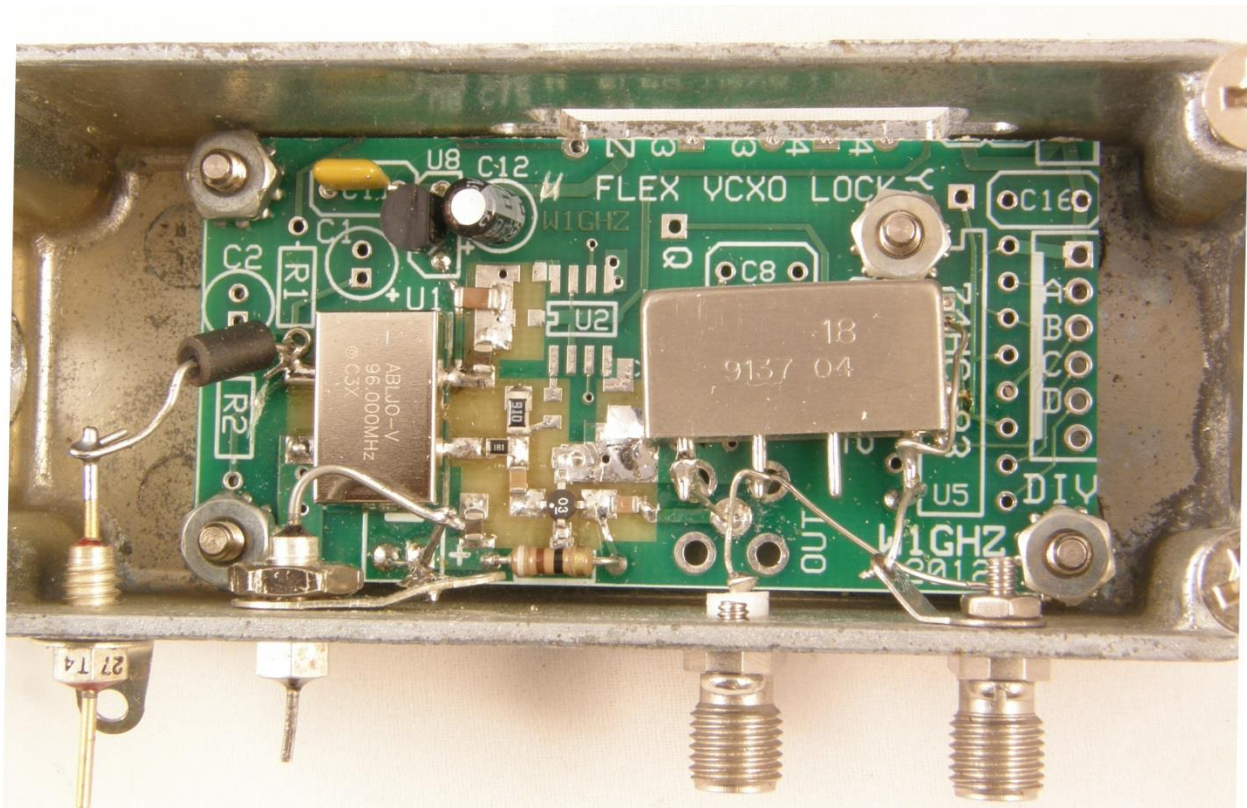
One problem is that I do not have equipment for phase noise measurement – measurement of the very low phase noise of a good oscillator is difficult. I rely on test equipment at various conferences. The results here were measured at the Eastern VHF/UHF Conference in 2012 and 2013, and at Microwave Update 2012. A few oscillators are measured at all three sessions to insure that the results are comparable. Special thanks are due to the folks who provide and operate this specialized test equipment, particularly Greg Bonaguide, WA1VUG, of Rohde & Schwarz.



## Spurious

On the versions that divide down to 1 MHz comparison frequency, like the 96 MHz version, I found small spurs 1 MHz on each side of the VCXO frequency. The spurs were about 65 dB down, but grew significantly larger after multiplication to 1152 MHz. I suspected inadequate bypassing – the 0.1  $\mu$ F capacitors at each chip are not enough to be effective at low frequencies. A quick experiment showed that the problem was at the VCXO power pin rather than the tuning voltage.

I added a 1  $\mu$ F chip capacitor at the VCXO and at each IC with a 1 MHz signal. The spurs were reduced to about 72 dB down, and reduced a similar amount after multiplication. This still isn't good enough, so I put the VCXO on a separate board with separate voltage regulator in a separate enclosure, shown in Figure 16. I added a Minicircuits directional coupler (door prize at some conference) to pick off some signal for the prescaler on the other board

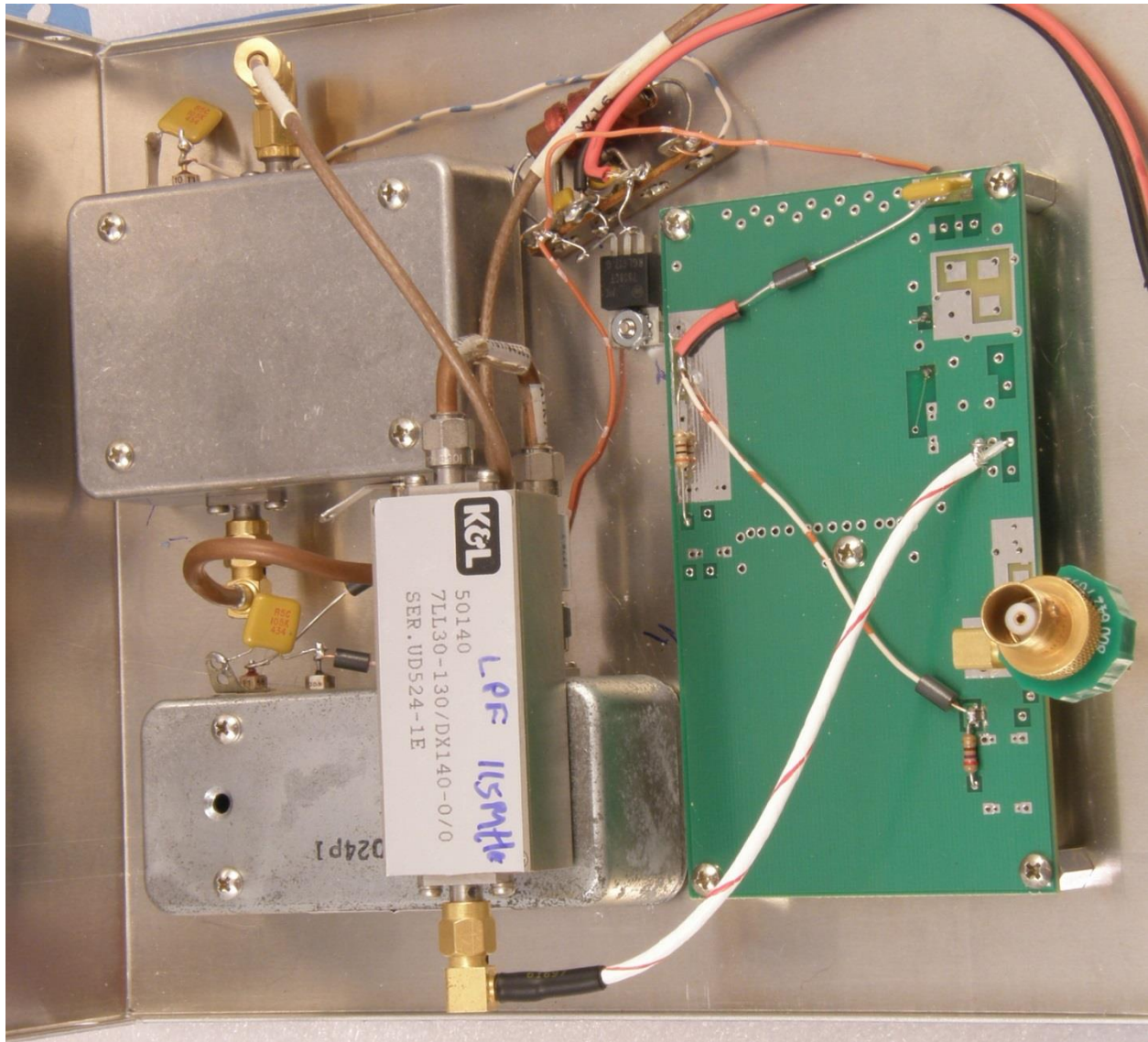


**Figure 16 – VCXO on separate board with buffer amp and directional coupler**

Another choice might be to use a 12 MHz reference, eliminating the 1 MHz component entirely. This could be provided by locking a 12 MHz VCXO to GPS<sup>3</sup>.

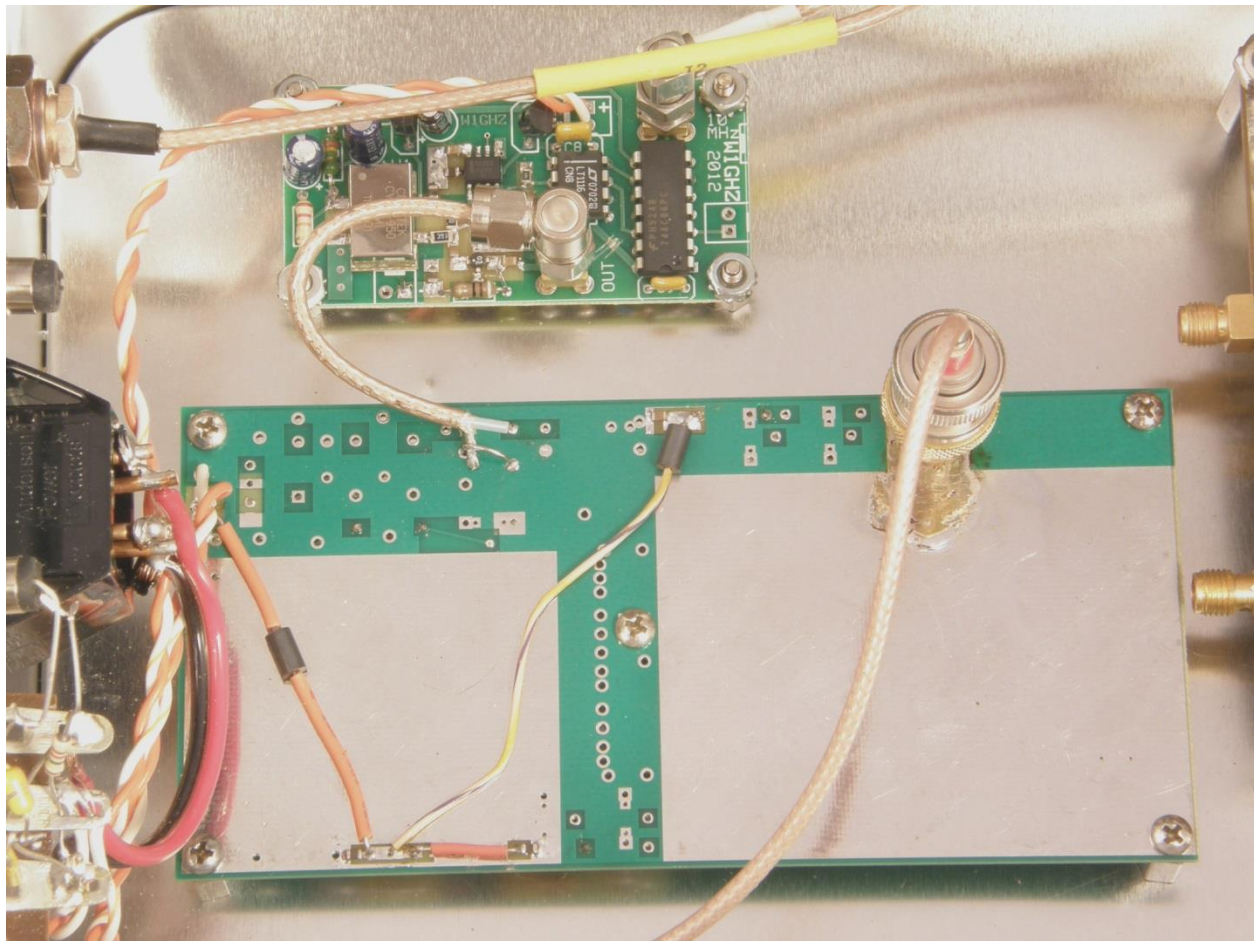


The complete 1152 MHz LO is shown in Figure 17, packaged up as the start of a new 1296 MHz transverter. When I did the initial assembly, the power output at 1152 MHz was quite low. After some experimentation, I found that the harmonics of 96 MHz in the VCXO output were causing low output from the multiplier board. A low-pass filter eliminates the harmonics – I found one in the junkbox for 115 MHz which works just fine, but it wouldn't be hard to make an adequate filter with a few coils and capacitors.



**Figure 17 – Complete packaged 1152 MHz LO based on locked 96 MHz VCXO**

I did not notice any problem with VCXO harmonics in the 720 MHz LO chain, shown in Figure 18, but it used an early prototype board. I'll have to check this out further.



**Figure 18 – Complete packaged 720 MHz LO based on locked 80 MHz VCXO**



## Update

I thought more about the 1 MHz spurs around the 96 MHz VCXO output. Since the problem seems to be with the power pin to the VCXO, I tried adding a separate 3.3 Volt regulator like U8 for the 74AC86 phase comparator U4, cutting the trace from U8, so that U8 only powers the VCXO. This moved the 1 MHz spurs below the noise on my spectrum analyzer.

I then packaged this unit up in a die-cast box, shown in Figure 19 and connected the output to the input of the low-pass filter in Figure 17. The output at 1152 MHz is fairly clean, with spurs at 12 MHz away that are 43 dB down. Smaller spurs are found 4, 6 and 8 MHz away, but more than 50 dB down. The only other visible signal is at 288 MHz, 40 dB down. While this LO version isn't as clean as the separate oscillator version in Figures 16 and 17, I'll bet that many transverters in use today are not any better.

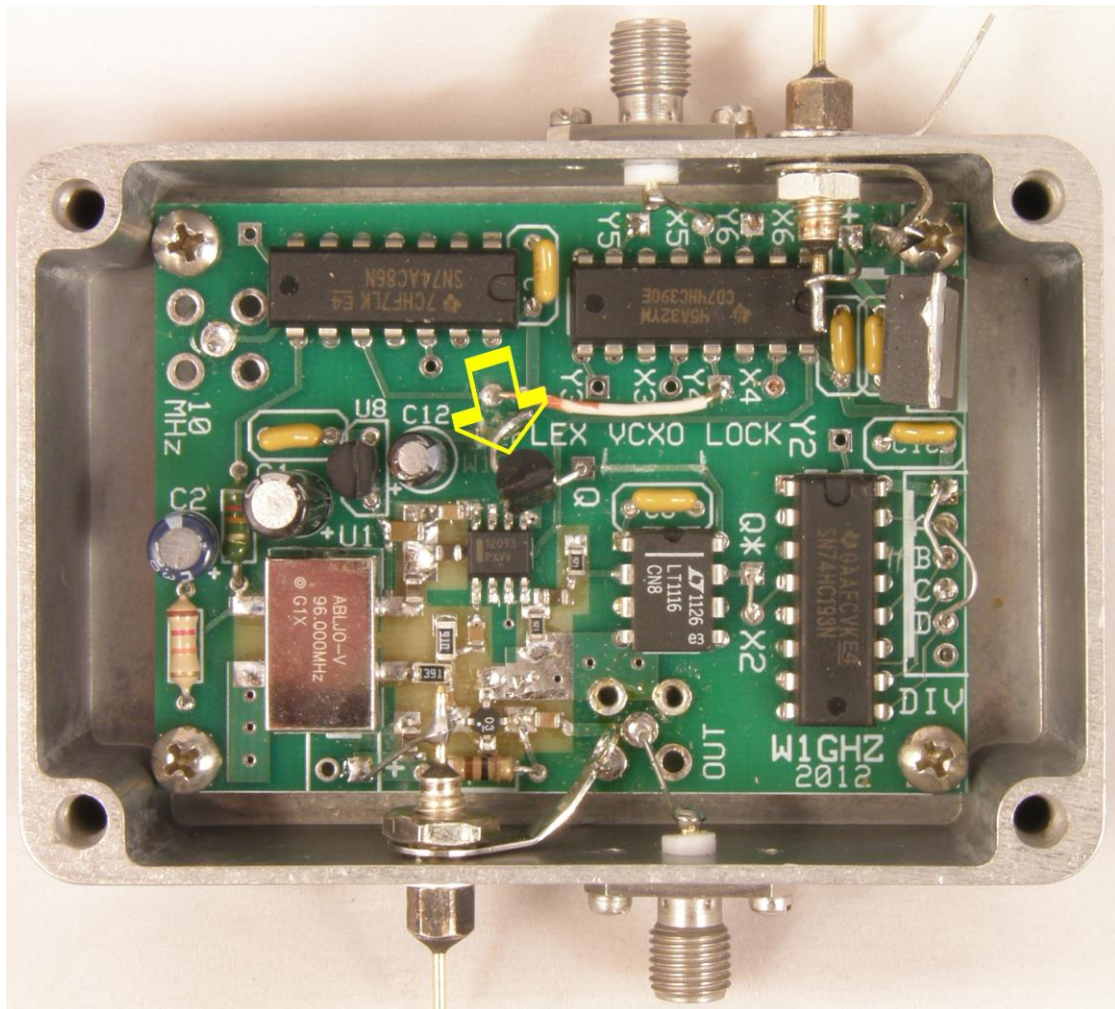


Figure 19 – 96 MHz locked VCXO in box.

Arrow points to added voltage regulator.

## Construction

Construction is fairly straightforward, with almost all of the components on the top side of the board, except for a few 1  $\mu$ F chip capacitors on the bottom side to for better bypassing of the 1 MHz signal in some of the dividers. The VCXO and prescaler are only available in surface-mount versions, and a few of the higher frequency components around them are also surface mount. The rest of the components are traditional thru-hole.

The Crystek VCXO shown in Figure 3 has four solder pads, matching the PC board, while the Abracon ABLJO-V VCXO used at the other frequencies have six pads. However, the middle ones are unused, so both types fit the PC board. I put a tiny dab of rosin paste flux on the VCXO pads before soldering. A VCXO is moderately expensive, but so are quality crystals.

Not all the ICs are needed for all options, and different prescalers are needed, as mentioned above. The final step is programming by soldering iron, adding the wires to select the appropriate divisors to bring the VCXO and reference frequencies to a common comparison frequency, with details in Appendix A. Appendix B is a parts list.

The 1  $\mu$ F chip capacitors, C18 thru C22, reduce the switching noise and resultant spurious signals in the versions with a 1 MHz comparison frequency, like 96 MHz. C18 can be seen in Figure 4, attached to the PC trace between U8 and the VCXO; the green soldermask must be scraped off the trace before it can be soldered. C19-22 are on the back side of the board, shown in Figure 5.

Other frequencies are certainly possible, but may require homebrewing your own VCXO. For instance, Down East Microwave has instructions for the crystal oscillator in some of their older transverters; this may be useful since crystals do tend drift slightly with aging. For odd frequencies that are not easily divided to 10 MHz, an odd reference frequency may be provided by a programmable Rubidium standard or by a reverse-DDS scheme<sup>4</sup>.

Output power at J2 is typically +3 to +5 dBm. It may be increased a bit by reducing the value of R3 – in my two piece version, R3 is 180 ohms and the output is about +10 dBm. This also increases the drive voltage to the prescaler, which should be 1000 millivolts max peak-to-peak (and at least 400 mV p-p); I used a directional coupler in the two-piece version to reduce the prescaler drive voltage.

PC boards are available.



## Summary

A local oscillator chain sourced from a locked VCXO can provide the frequency accuracy and stability of a good reference oscillator while maintaining the low phase noise of a crystal oscillator. Measured phase noise is 20 to 40 dB better than available synthesized local oscillators. Good packaged VCXOs are available for a few desirable frequencies at a cost comparable to a quality quartz crystal. Further experimentation is needed to determine whether the final system performance is significantly better than a good synthesizer.

## Notes

1. Paul Wade, W1GHZ, "Phase Noise and MDS," *Proceedings of Microwave Update 2009*, ARRL, 2009, pp. 193-196.
2. Paul Wade, W1GHZ, "Multiband Microwave Transverters for the Rover – Simple and Cheap," *Proceedings of Microwave Update 2008*, ARRL, 2008, pp. 40-67.
3. Paul Wade, W1GHZ, "A Flexible VCXO Locking Board," *Proceedings of Microwave Update 2012*, ARRL, 2012, pp. 101-113.
4. <http://myweb.tiscali.co.uk/g4nns/RevDDS.html> and <http://www.microwaves.dsl.pipex.com/RDDS/RDDSINDX.htm>

## Appendix A

### Microwave VCXO Board Programming

<u>Freq</u>	<u>VCXO</u>	<u>DigiKey</u>	<u>Prescaler</u>	<u>Prescale</u>	<u>Divide</u>	<u>ABCD*</u>	<u>÷2</u>	<u>Signal</u>	<u>Comparison</u>	<u>Ref ÷5</u>	<u>Ref ÷2</u>	<u>Reference</u>
					74HC193		74HC390		Frequency	74HC390	74HC390	
80 MHz	Crystek	744-1214-ND	MC12093	÷8	na	na	na	Q->Z	10 MHz	na	na	10MHz->REF
80 MHz	Abracon	535-11429-ND	MC12093	÷8	na	na	na	Q->Z	10 MHz	na	na	10MHz->REF
96 MHz	Abracon	535-11431-ND	MC12093	÷8	÷6	LHHL	Q2->X4	Y2->Z	1 MHz	10MHz->X5	Y5->X6	Y6->REF
100 MHz	Abracon	535-11433-ND	MC12080	÷10	na	na	na	Q->Z	10 MHz	na	na	10MHz->REF
120 MHz	Abracon	535-11437-ND	MC12080	÷10	÷6	LHHL	Q2->X4	Y2->Z	1 MHz	10MHz->X5	Y5->X6	Y6->REF
200 MHz	Abracon	535-11451-ND	MC12080	÷20	na	na	na	Q->Z	10 MHz	na	na	10MHz->REF
108 MHz	homebrew?		MC12026	÷9	÷6	LHHL	Q2->X4	Y2->Z	1 MHz	10MHz->X5	Y5->X6	Y6->REF

#### NOTES:

Y5->X6 means add a wire from point y5 to point X6, etc.

\* ABCD = LHHL: L is ground, H is +5 Volts

na means not applicable - chip may be left out

MC12093 ÷8: pins 3 and 6 grounded (unmodified board)

MC12080 ÷10: pins 3 and 6 high (jumpers to pins 2 and 7)

MC12080 ÷20: pins 3 grounded (unmodified) and pin 6 high (jumper to pin 7)

Crystek VCXO are CVHD-950 series

Abracon VCXO are ABLJO-V series

Comparator 74AC86 compares Z and REF inputs

PC Boards marked 2013a are good for all frequencies

PC Boards marked 2012 are good for 80, 100, and 200 MHz. A wire is needed from Pin 1 of U4 (LT116) to +5 Volts.

## Appendix B – Parts List

<u>Refdes</u>	<u>Value</u>	<u>Description</u>	<u>Digikey</u>	<u>Mouser</u>
A1	MAR-3SM	MMIC	Minicircuits	
C1	1 uF	electrolytic	P14054-ND	
C2	100 uF	electrolytic	P5123-ND	
C3,7,8,9,11,16,17	0.1 uF			581-SR215C104K
C4,5,14	1000pf	chip		
C6,15	0.1 uF	chip		
C10	0.33 uF		478-3194-ND	581-SR215E334M
C12	10 uF		P813-ND	
C13	100 pf	chip		
C18-22	1 uF	chip	478-5906-1-ND	
R1	82K	1/4 watt	CF14JT82K0CT-ND	
R2	12K	1/4 watt		
R3	390	chip		
R4	91	chip		
R5,6	820	chip		
R7	91	1/4 watt		
U1	VCXO		see Appendix A	
U2	Prescaler		see Appendix A	
U3	LT1116		LT1116CN8*PBF-ND	
U4	74AC86		296-4345-5-ND	512-74AC86PC
U5	74HC193		296-8262-5-ND	
U6	74HC390		296-9199-5-ND	
U7	7805	78L05 adequate for 80 MHz version		
U8	78L3.3		497-7287-1-ND	