AC 2009-1048: FREQUENCY RESPONSE OF RF TRANSCEIVER FILTERS USING LOW-COST VECTOR NETWORK ANALYZER

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Frequency Response of RF Transceiver Filters Using Low-Cost Vector Network Analyzers

Abstract

This paper focuses on the construction and testing of a 7 MHz Radio Frequency (RF) transceiver to provide a "Project Based Learning" RF capstone experience for students in Electrical and Computer Engineering Technology. The Transceiver Project is structured to support course goals and objectives of "Topics of RF Communications" offered as a technical elective at the beginning of the senior year. The paper presents the "project concept" together with the authors experience in introducing three low-cost (less than $650) Vector Network Analyzers (VNAs) to accelerate the testing of RF critical sections of the transceiver. Each student is required to build and test a complete transceiver system. Students may "team-up" in groups of no more than two students for the purpose of cost sharing, but each student must contribute equally to the building and testing phases of the project. An additional goal of the project is to introduce students to radio frequency transceiver concepts, and to prepare students for the upcoming Senior Design Capstone Experience required for a baccalaureate degree in engineering technology. Students are required to maintain a detailed project journal to record test results, and experiences throughout the project. To date, student feedback on this project has been very positive and a representative selection of student comments is included in the paper.

Introduction

For the last ten years the author has been teaching a senior level course in Radio Frequency Communications. The course content has changed over the last five years based on revisions and improvements in accreditation standards. The course has changed from being mostly mathematical, to a course based on Project Based Learning which incorporates "problem based learning" via seventeen laboratory exercises. The author's life-long interest in amateur radio coupled with the discovery of a textbook entitled the "Electronics of Radio" by Rutledge [1], based on a transceiver designed by Burdick [2], made the course extremely practical with emphasis on construction techniques and subsystem testing. In addition, only a modest amount on non-calculus mathematics is required for the student to gain an adequate understanding of transceiver design concepts.

Professor Rutledge's textbook uses an off-the-shelf 7 MHz RF transceiver kit known as the NorCal 40A as a vehicle for teaching RF circuit analysis and design. The term NorCal is an abbreviation for Northern California amateur radio club which initially participated in the

prototype development. The transceiver is designed for continuous wave (CW) operation on 7 MHz which is more commonly known as the 40 meter amateur radio band. The "A" or improved version of the transceiver kit contains all necessary parts, building and operating instructions, together with an attractive enclosure. The transceiver is currently marketed by Wilderness Radio [3] and costs about $140.

Figure 1 shows a completed NorCal 40A transceiver. The top view of the transceiver shows the 2.1 MHz variable frequency oscillator (VFO), output power transistor and its associated heat sink. An additional 12 volt power supply and antenna is required to make the transceiver operational. The transceiver includes a superhetrodyne receiver and a transmitter subsection.

2-3 Watts

Buffer: 300µW, Driver: 20 mW, Amp: 2W

2N3553

View of Front

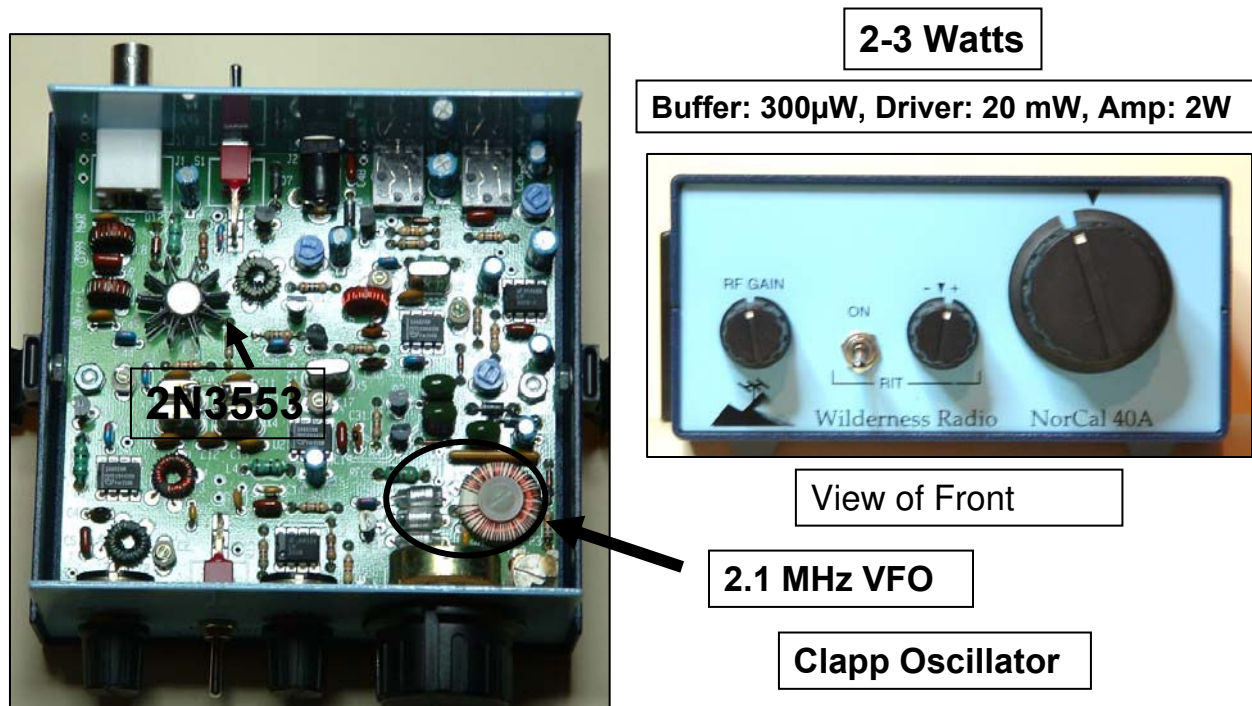**2.1 MHz VFO**

Clapp Oscillator

Figure 1 – Completed NorCal 40A 7 MHz CW Transceiver

Figure 2 shows a block diagram of the transceiver with the transmitter on the left side and the receiver on the right. The top of the block diagram shows the external dipole antenna and the bidirectional nature of the transceiver. The harmonic filter is common to both the transmitter and the receiver with the direction of flow controlled by an electronic transmit/receive switch (not shown in this diagram). Doubly-balanced mixer summation frequencies are noted by + signs, and difference frequencies by - signs. The transmit signal is processes through three amplification stages resulting in an output power just over 2 watts.
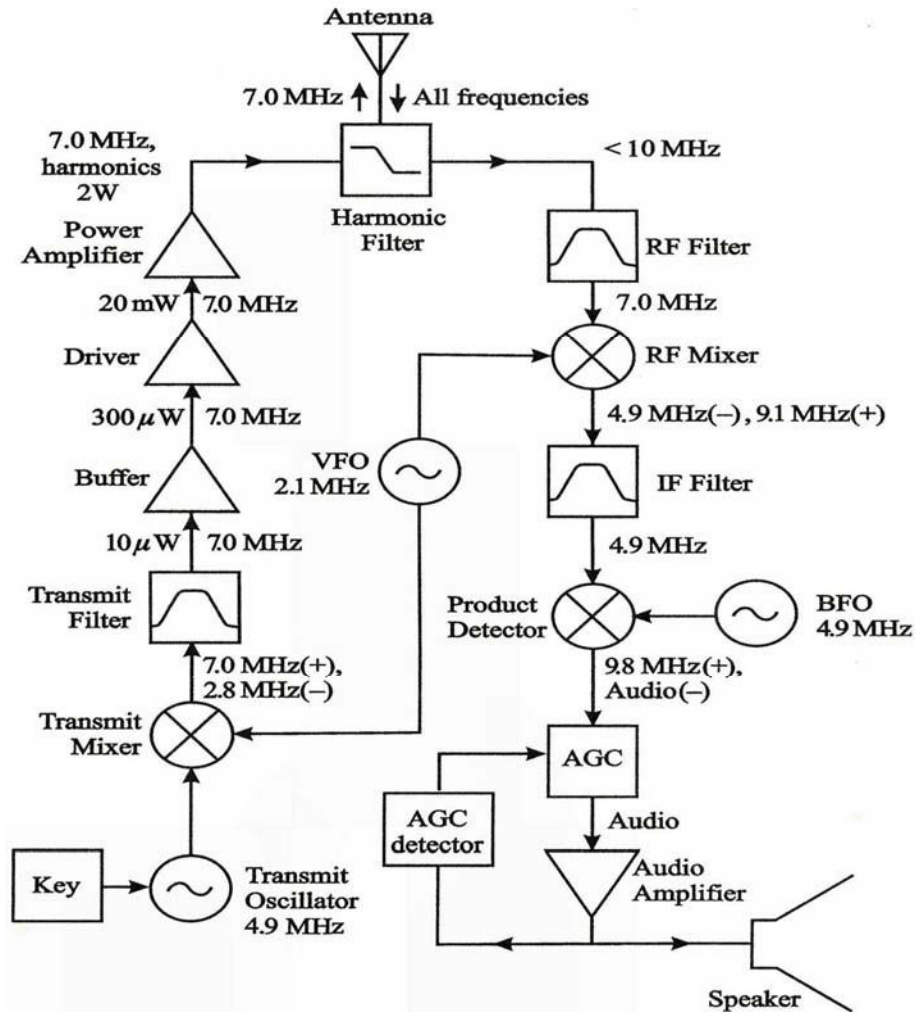
Figure 2 – Block Diagram of the NorCal 40A Transceiver

Students enrolled in RF Communications have previously taken a three course sequence in Electronics, a course in Electronic Communications, and a junior level course in Digital Communications. The concepts selected from Professor Rutledge's text that I included in RF Communications are outlined in Table 1. The table lists specific Problems and Technical Topics that are designated in the partial schematics shown in Figures 3 and 4 using a "#" symbol to highlight specific Problem Based Learning tasks associated with construction and testing phases of the Transceiver Project.

Note from Table 1 that seventeen exercises distributed over a ten week quarter results in an almost impossible teaching schedule. Fortunately, technology in the form of Vector Network Analyzers was used to streamline some of the laboratory exercises in order to maintain the breadth and the depth of the material in the textbook. The "low cost" VNAs enriched the testing phase and nicely complemented the use of oscilloscopes and function generators.

Table 1- Topics Covered in RF Communications Course

Problems	Technical Topics
7	Parallel-to Serial Conversion
8	Series Resonance
9	Parallel Resonance
13	Harmonic Filter
14	IF Crystal Filter
15	Driver Transformer
16	Tuned Transformer
19	Receiver Switch
20	Transmitter Switch
21	Drive Amplifier
22	Emitter Degeneration
24	Power Amplifier
26	VFO Butler Oscillator
33	Alignment
34	Receiver Response
35	Intermodulation
36	Project Demonstration

Figure 5 shows a picture of the three VNAs used in this study. They are the Ten-Tec/TAPR model 6000 [4], the miniVNA from MRS [5], and a homebrew version of the N2PK [6]. These units were chosen because they are relatively inexpensive (less than $650/unit), cover the 3-30 MHz high frequency (HF) spectrum, plus they have reasonably decent technical specifications.

The remaining sections of the paper introduce Scattering or "S" parameters which turn out to be the language of network analyzers. Also, each of the three VNAs tested in this paper has its own "unique to the device" software front-end and, for comparison purposes, a common data display format was implemented. For each filter examined, a picture is presented showing the location of the filter on the NorCal 40A printed circuit board, followed by a schematic diagram of the selected filter configured for the network analyzer test set-up. Also, when appropriate, three plots of the circuit's performance using each of the analyzers will be presented. Comments will be made concerning any major differences between the three VNAs. Finally, a selection of student comments is included in the paper.
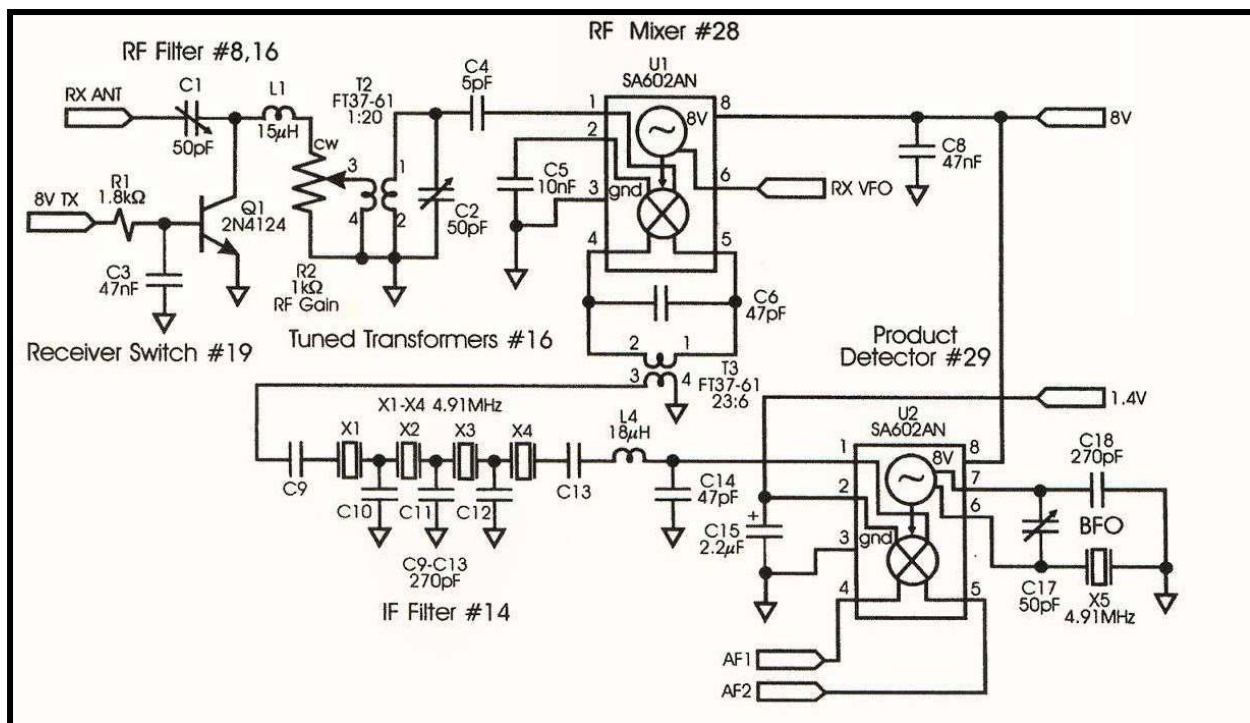
Figure 3 – Portion of the NorCal 40A showing Problems #8, #14, #16, #19, and #29
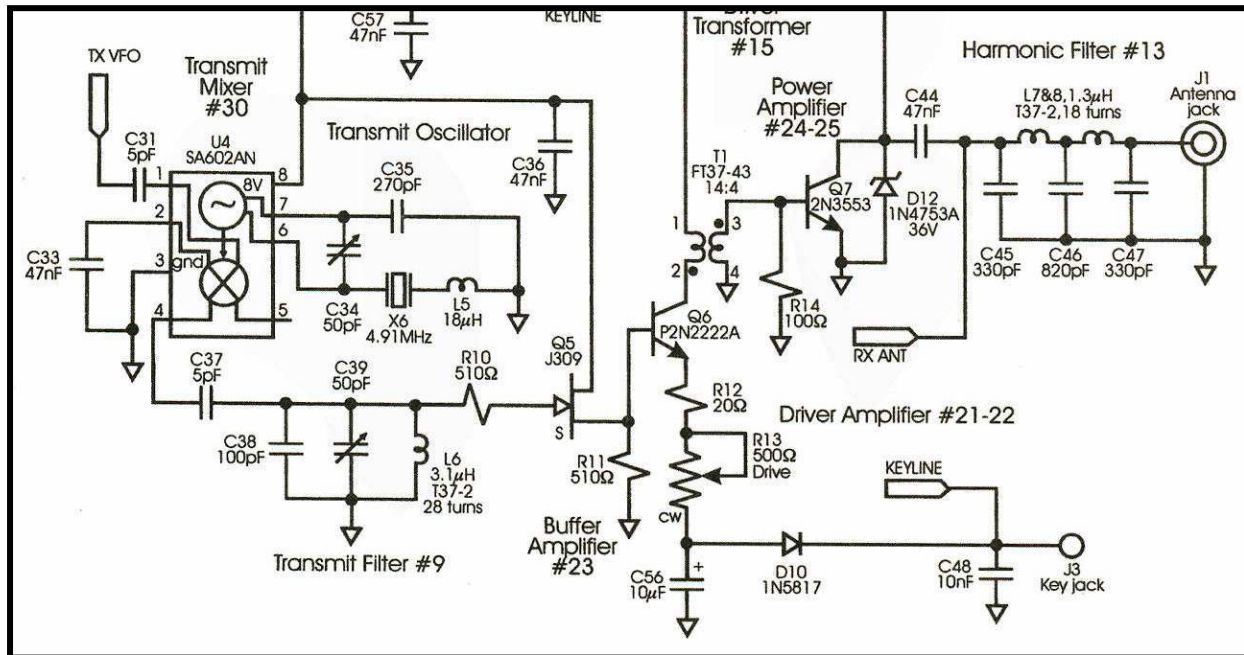

Figure 4 – NorCal 40A Schematic showing Problems #9, #13, #15, #21-22, #24-25, and #30
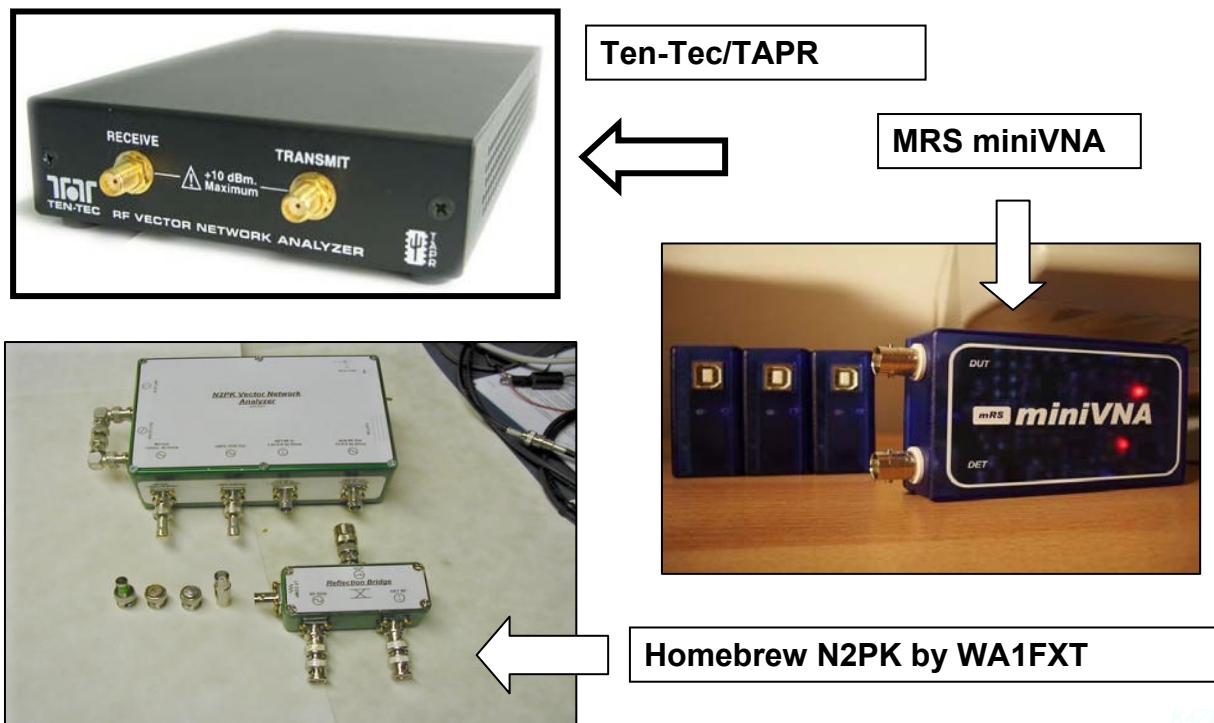
Figure 5 – Selection of Vector Network Analyzers used for testing

What are S-Parameters (S_{11}, S_{21})

Scattering or "S" parameters are the language of network analyzers. The numbers after the letter "S" conform to the following standard. The first number is the output port and the second number is the input port. Let's consider in common terms how each parameter is known.

> S_{11} - Input return loss
> S_{21} - Forward gain (may be negative gain - loss)
> S_{22} - Output return loss
> S_{12} - Reverse gain (again, it may be a negative gain – loss)

A graphical representation of S-parameters is shown in Figure 6. This figure depicts a two-port device.
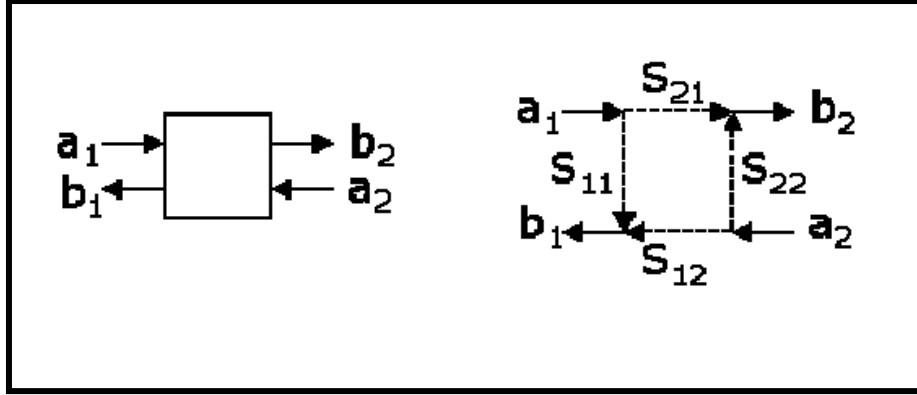
Figure 6 - Block Diagram Defining Scattering Parameters

The left side of each "box" is Port 1, and the right side is Port 2. S-parameters are defined as the ratio of voltages. A voltage injected into Port 1 is represented as a_1 and a voltage injected into Port 2 is represented as a_2. Similarly, the voltage out of Port 1 is represented as b_1 and the voltage out of Port 2 as b_2. The arrows associated with each variable indicate the appropriate direction.

Using the above "word definitions" one can state that the voltage out of Port 1 (b_1) is the sum of the input voltage to that port (a_1) times the return loss (S_{11}) of that port plus the voltage injected into Port 2 (a_2) times the reverse gain of Port 2 (S_{12}). Similarly, the voltage out of Port 2 (b_2) is the sum of the voltage injected into Port 1 (a_1) times the forward gain (S_{21}) plus the voltage injected into Port 2 (a_2) times the output return loss (S_{22}). Stated mathematically:

$$b_1 = a_1 * S_{11} + a_2 * S_{12} \tag{1}$$
$$b_2 = a_1 * S_{21} + a_2 * S_{22}$$

Now consider that in using a "low cost" VNA, one does not impress a voltage back into port 2. The term a_2 is therefore zero and drops the right most components of the above equations. S_{11} now equals b_1 / a_1 and S_{21} equals b_2 / a_1. For low cost VNAs, as described in this paper, one must physically reverse connections to Ports 1 and 2 to determine S_{21} and S_{12}.

Each S-parameter is a complex number and is expressed in both rectangular and polar forms depending on the use. Unless the device under test is perfectly matched at a given frequency, there will be a reflected voltage that is not in phase with the incident or applied voltage. Similarly, the voltage b_2 has been altered either because of gain/loss and group delay through the network such that it is also out of phase with voltage a_1. The difference between a vector network analyzer and a scalar network analyzer is that the VNA can measure both the magnitude and phase components and displays the S_{12} (input reflection loss) and S_{21} (forward transmission gain/loss) in those terms. As a matter of fact the Smith Chart [7], used in transmission line

analysis, is a representation of a normalized polar plot of the reflection coefficient magnitude (Rho) and the reflection phase angle. Other graphical depictions of S_{11} are:

- The absolute value of the reflection coefficient magnitude (Rho)
- The reflection phase angle itself
- Return Loss (RL), which is the reflection magnitude plotted in dB units
- VSWR, which is VSWR = $(1+|S_{11}|)/(1-|S_{11}|)$ where $|S_{11}|$ is the magnitude of the complex reflection coefficient
- Percent reflected power, which is (b1 / a1) * 100

These values are usually plotted against frequency.

Also, S_{21} is usually plotted in terms of:

- Transmission Loss (TL) which is the forward gain/loss magnitude plotted in db units.
- Phase angle

Another derived parameter that is useful to know is the group delay through the device. This happens because the input waveform can not transition the device at the speed of light, thus inducing a delay from input to output. This is useful for calculating the velocity factor of transmission lines.

Each of the three VNAs tested in this paper has its own "unique to the device" software front end. Each device approaches the set-up, calibration, and display functions in different ways and uses slightly different language to describe or display the same set of data. For comparison purposes one needs some way to, at the very least, display data in a common format. The next section describes a solution to this problem.

Output Data Translation to Microsoft® Excel

A search of the Internet revealed a program written by Maguire [8] that provides a convenient "Microsoft® Excel back-end" for the N2PK VNA and MRS miniVNA. Actually, the program can control the operation of the miniVNA. This software imports comma separated variable (.csv) files from these VNAs (and others) into Excel and makes plots of data in common display format. Each graph of VNA data in this paper was produced with "Z-plots +" which allows, if desired, the following derived parameters to be plotted:

- SWR - Standing Wave Ratio
- Rs - Resistance, series form
- Xs - Reactance, series form
- Zmag - Impedance magnitude
- Theta (deg) - Impedance angle

- Rho - Reflection coefficient magnitude
- RL (dB) - Return Loss, plotted as a negative number to simulate "reverse scale"
- % Reflected Power
- Phase (deg) - Reflection coefficient angle
- Q - Quality factor, |Xs| / Rs
- Rp - Resistance, parallel form
- Xp - Reactance, parallel form
- Ls (μH) - Equivalent inductance for series Xs, both positive and negative
- Cs (pF) - Equivalent capacitance for series Xs, both positive and negative
- Lp (μH) - Equivalent inductance for parallel Xp, both positive and negative
- Cp (pF) - Equivalent capacitance for parallel Xp, both positive and negative

It is noteworthy to observe that Plotting Phase (deg) - Reflection coefficient angle and Rho – Reflection coefficient magnitude on a polar plot is essentially nothing more than a Smith Chart plot.

Technical Approach

The author used the NorCal 40A transceiver kit for this VNA comparison study. The NorCal 40 was chosen because the transceiver design is "technically sound", and contains representative circuitry that the author felt could be adequately examined with the chosen VNAs. The following four filters were selected for analysis with the VNAs:

- Transmit Harmonic Filter – A five-pole low pass filter,
- Transmit Mixer Filter – Parallel resonance filter,
- Intermediate Frequency (IF) Crystal Filter – Four-pole Cohn-type crystal ladder filter,
- Receiver Front End Filter – Second-order Butterworth band-pass filter.

For each filter examined, a picture is presented showing the location of the filter on the NorCal 40A printed circuit board, followed by a schematic diagram of the selected filter configured for the network analyzer test set-up. Also, when appropriate, three plots of the circuit's performance using each of the analyzers will be presented. Comments will be made concerning any major differences between the three VNAs.

Harmonic Filter

The harmonic filter, otherwise known as the output low-pass filter, is used to insure that the spectral content of the output signal is compliant with Federal Communications Commission (FCC) requirements. The NorCal-40A harmonic filter is five-pole filter and does not technically comply with either Butterworth or Chebychev designs. In addition, it will be shown that the five-pole response does not meet current FCC requirements for second harmonic suppression for new transmitters. In the example that follows a standard five-pole Butterworth low-pass design is used. For most transceiver designs the harmonic filter is a doubly terminated 50Ω filter and the

Butterworth design is a typical "middle-of-the-road" low-pass filter that is suitable as a design example. Later, the frequency domain sweeps using the vector network analyzers will be of the actual filter used in the NorCal-40A.

The familiar normalized C and L values for doubly terminated Butterworth filter response are tabulated in Table 2.

Table 2. Normalized C and L values for Butterworth Response

N	C1	L1	C2	L2	C3	L3	C4
2	1.4140	1.4140					
3	1.0000	2.0000	1.0000				
4	0.7654	1.8500	1.8500	0.7654			
5	**0.6180**	**1.6180**	**2.0000**	**1.6180**	**0.6180**		
6	0.5176	1.4140	1.9320	1.9320	0.1414	0.5176	
7	0.4450	1.2470	1.8020	2.0000	1.8020	1.2470	0.4450

As an example of the design process, assume for a moment that the NorCal-40A harmonic filter is a five pole Butterworth design. These capacitors are designated on the NorCal-40A schematic as C_{45}, C_{46}, and C_{47} and would be determined by the following formulas using the normalized values of C_1 and C_2 from the table:

$$C_{45} = C_{47} = \frac{C_1}{2\pi\, f_C\, R_L}, \quad \text{and} \quad C_{46} = \frac{C_2}{2\pi\, f_C\, R_L} \tag{2}$$

In the formulas f_c is the filter -3dB cutoff frequency and is chosen to be a factor of 1.2 higher than the normal operating frequency. The resistor R_L is the termination resistance and is assumed to be 50Ω. Please note that the values for C_1 and C_3 for N=5 are the same in the normalized table. Since L_1 and L_2 in the table are also the same value the inductors L_6 and L_7 on the NorCal-40A schematic will be determined for a Butterworth implementation by the following equation:

$$L_6 = L_7 = \frac{L_1 R_L}{2\pi\, f_C} \tag{3}$$

These equations given for the inductance and capacitance are examples of frequency and impedance scaling of the normalized values in the Butterworth table. The location of the harmonic filter on the printed circuit board is shown in Figure 7. A close-up view of the filter is also shown in the figure.
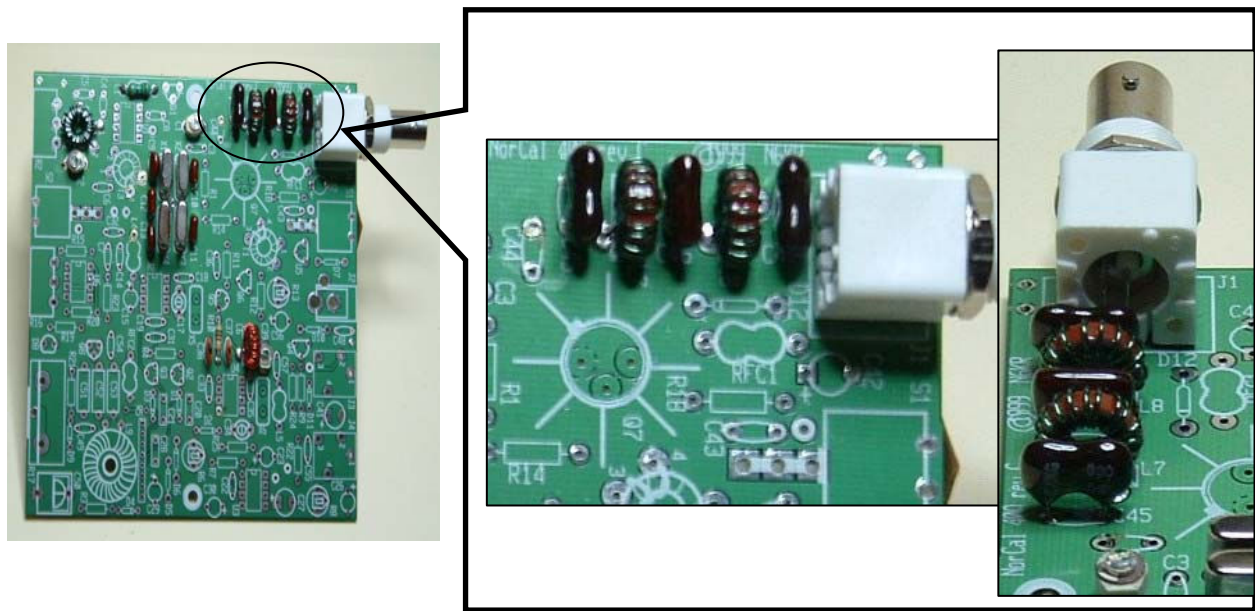
Figure 7 - Five Pole Butterworth Low-pass Filter

The capacitors shown are silver mica and are a substitute for the stock disk ceramic supplied in the kit. Silver mica capacitors are preferred because of their temperature stability and the fact that they come in 5% values. A schematic of the test set-up of the harmonic filter used for VNA sweeps is shown in Figure 8.
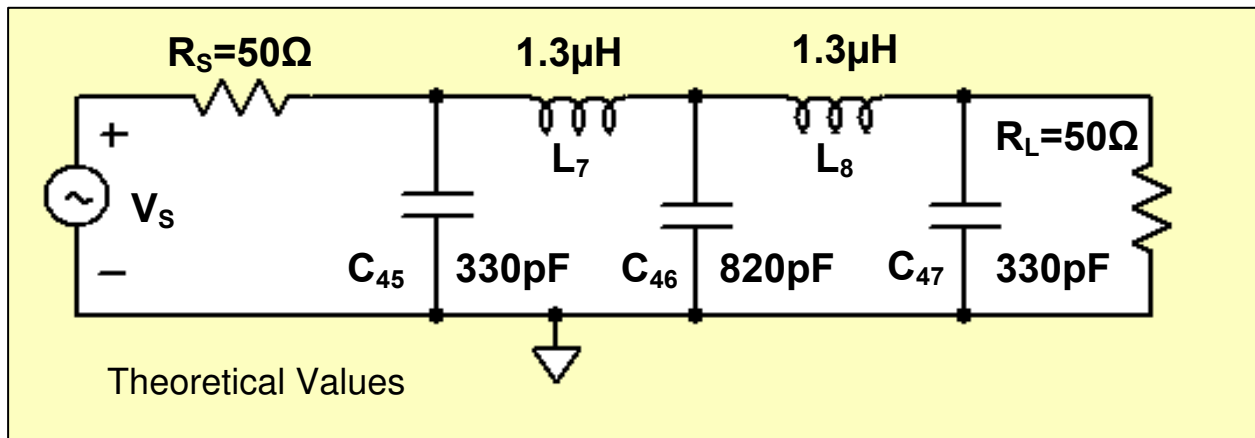

Figure 8 - Harmonic Filter Test Set-up for Network Analyzer

The filter is terminated in 50Ω and the VNA source resistance is also assumed to be 50Ω. Figure 9 is a sweep from a calibrated N2PK VNA. Notice that the insertion loss at 7.04 MHz is only

0.38dB. Also notice a disappointing 24.87dB rejection for the second harmonic. This does not meet the current FCC specification of -43 dB for new transmitter designs.
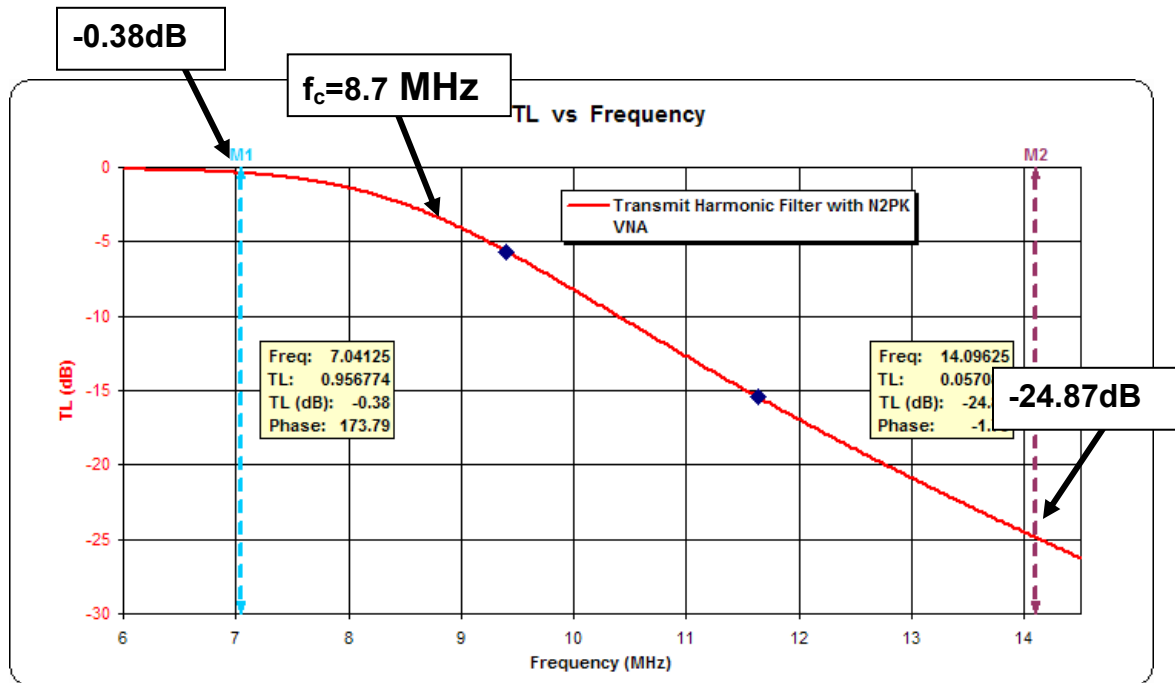
Figure 9 - Harmonic Filter Frequency Response for N2PK Vector Network Analyzer

Similar results are shown in Figures 10 and 11 for the mini and Ten-Tec VNA's. The calibration procedure for the mini VNA is the least sophisticated of the three VNAs examined.
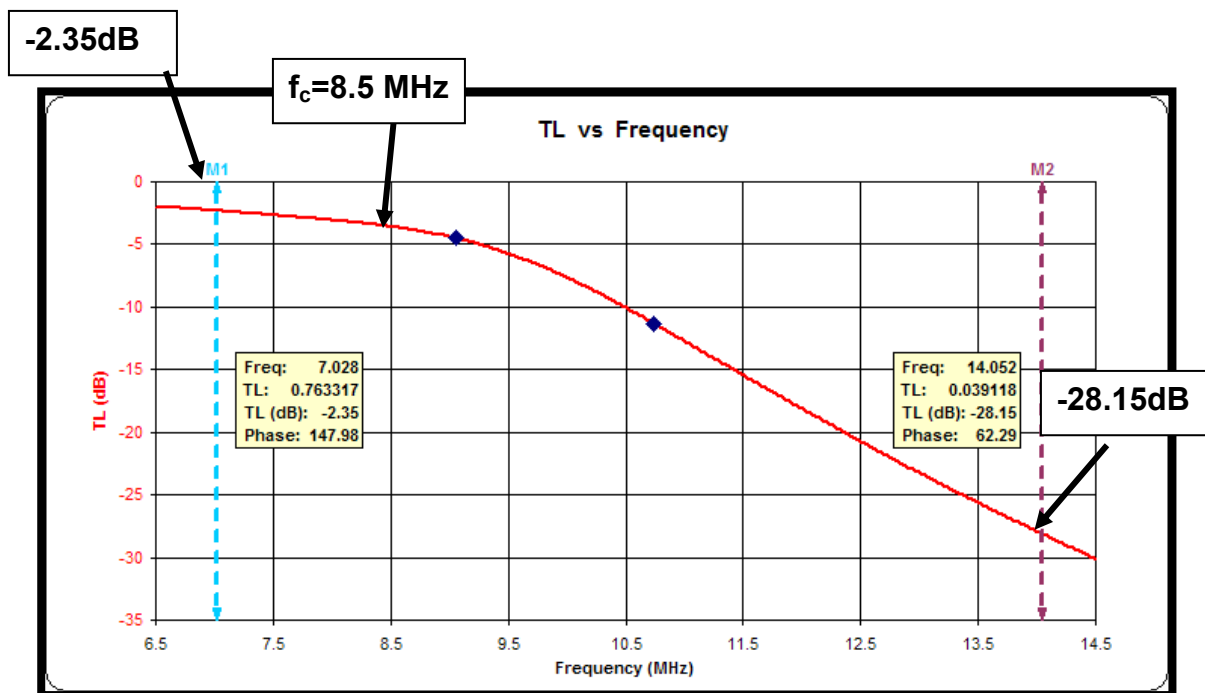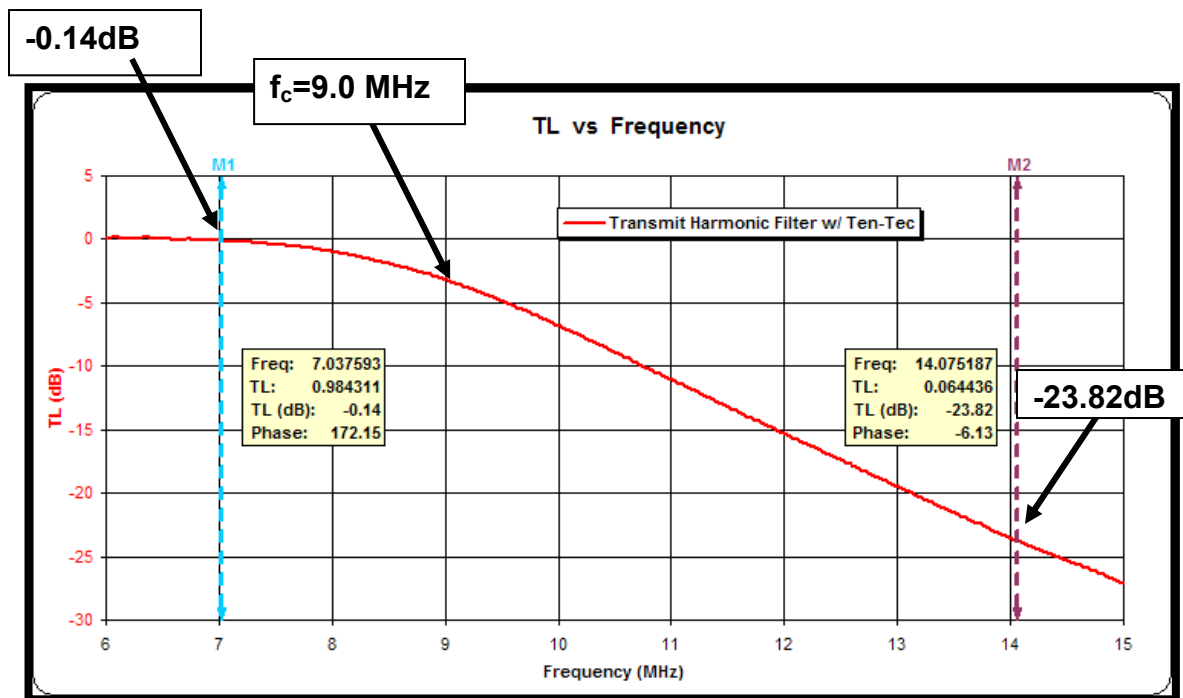
Figure 10 - Harmonic Filter Frequency Response for mini Vector Network Analyzer

Figure 11 - Harmonic Filter Frequency Response for Ten-Tec Vector Network Analyzer

The additional loss in the pass-band has since been corrected by the manufacturer with newer releases of the software. At this point it would appear that a seven-pole filter or other more robust design such as an elliptic filter should be considered for new five watt transmitter designs.

Transmit Filter

The NorCal40A transmit filter, shown in Figure 12, is a perfect example of using a simple parallel resonant circuit as a filter. A useful feature of this circuit is the high impedance exhibited on both the input and output sides of the filter. The input to the filter is from the transmit mixer formed by a SA602 balanced modulator. In the NorCal 40A transceiver, the transmit signal is produced by mixing the 2.1 MHz variable frequency oscillator (VFO) signal with the transmit oscillator operating at 4.9 MHz. Thus the transmitter frequency is the sum of these two frequencies and results in a 7 MHz signal.
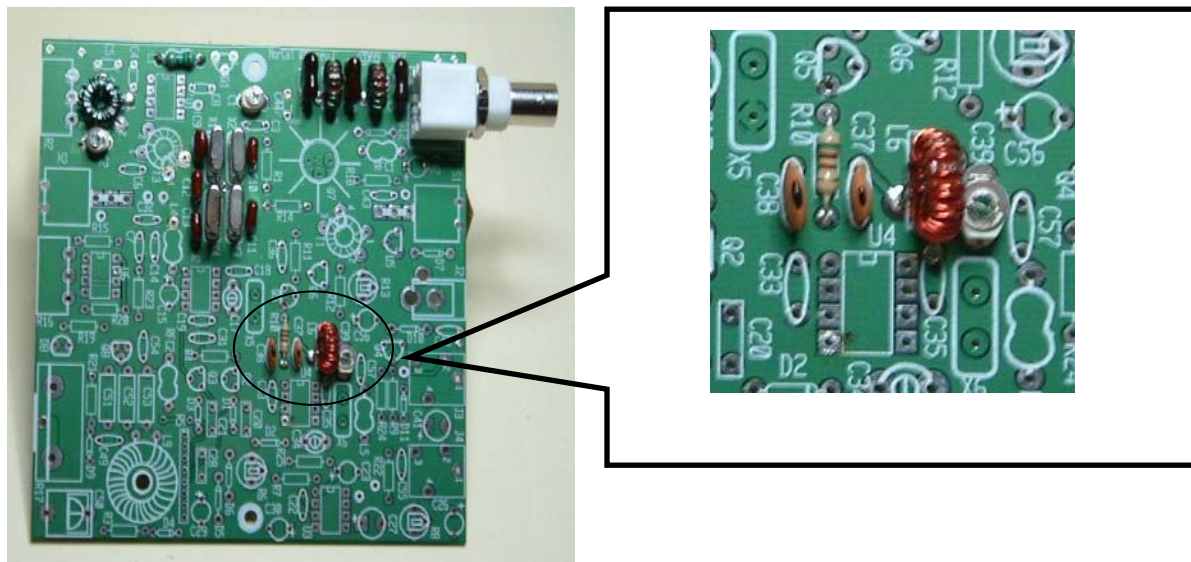

Figure 12 - Parallel Resonant Circuit used for Transmit Filter

The doubly balanced mixer also produces a difference signal at 2.8 MHz and must be removed by the transmit filter. At 7.040 MHz the -3dB bandwidth of the filter is calculated to be 84.8 kHz which results in a filter Q of 82.6. The important feature of the filter is its ability to reject the mixer difference frequency at 2.8 MHz. A schematic diagram showing the test set-up for the network analyzers is shown in Figure 13.
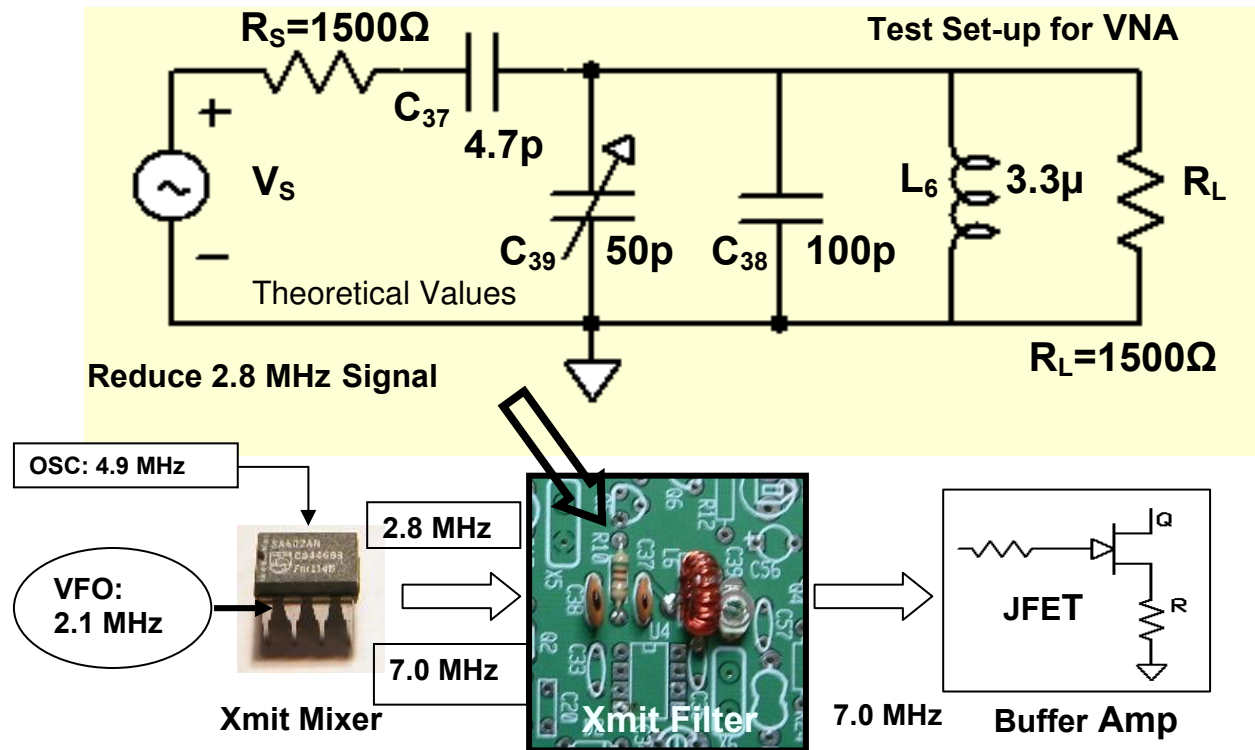
Figure 13 - Schematic Representing Test Set-up for Parallel Resonant Transmit Filter

The Thevenin equivalent source resistance of 1500Ω represents the output of the SA602 doubly balanced mixer. In the test set-up the output of the filter is terminated in 1500Ω to represent the input resistance of the junction field effect transistor (JFET). As with the previous filter three VNA measurements were taken and the results are almost identical. The lower dynamic range of the mini VNA somewhat limited it's response near 2.8 MHz. The scan from the Ten-Tec VNA, shown in Figure 14, is typical of the other two devices and indicates approximately 53 dB of suppression of the 2.8 MHz difference signal. It is interesting to note that removal of the C_{37} coupling capacitor reduces the filter Q but the response asymptotically approaches the original filter response yielding over 50 dB of suppression of the signal at 2.8 MHz. The VNA is quite useful in gaining a visual understanding the operation of the transmit filter and the influence of the coupling capacitor on the Q of the transmit filter circuit. The next section introduces an architecture employing quartz crystals to achieve a narrow-band filter response.

Quartz Crystal Filter Overview

An objective of this paper is to introduce the use of a vector network analyzer to verify "filter performance" of practical quartz crystal filters. A four-crystal Cohn [9] filter centered at 4.9152 MHz and having a 400 Hz bandwidth is presented and is representative of the type of filters currently employed in transceivers like the NorCal-40A. A 200Ω doubly terminated end

resistance is anticipated with this filter. Transformer coupling as well as L-network coupling is used to match the output and input resistances of the filter to SA612 double-balanced mixers. It worth noting that minimum-loss Cohn crystal filters are very popular in transceiver design and have the unique feature that all capacitors in the filter have the same value.
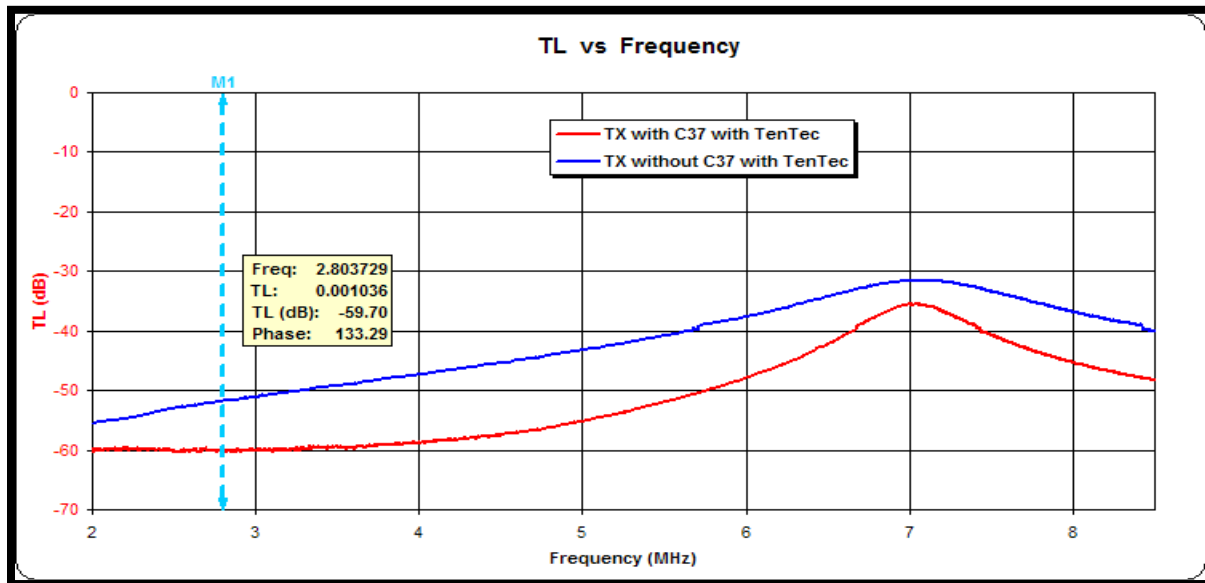

Figure 14 - Transmit Filter Parallel Resonance Response using the Ten-Tec Analyzer

Prior to shipment of the NorCal40A kit from Wilderness Radio the six quartz crystals used in the transceiver are matched to ensure that the series resonance frequency of each crystal is within 20 Hz of each other. Appropriate impedance matching techniques are then used to interface the filter to other circuit components like a SA612 doubly-balanced mixer.

A photograph of the crystal filter, as placed on the NorCal 40A printed circuit board, is shown in Figure 15, and the lower sideband crystal filter architecture is shown in Figure 16. A schematic of the crystal filter used in the test set-up is shown in Figure 17. Note that although the schematic shows a 200Ω termination resistance on each side, the VNA supplies 50Ω via its internal
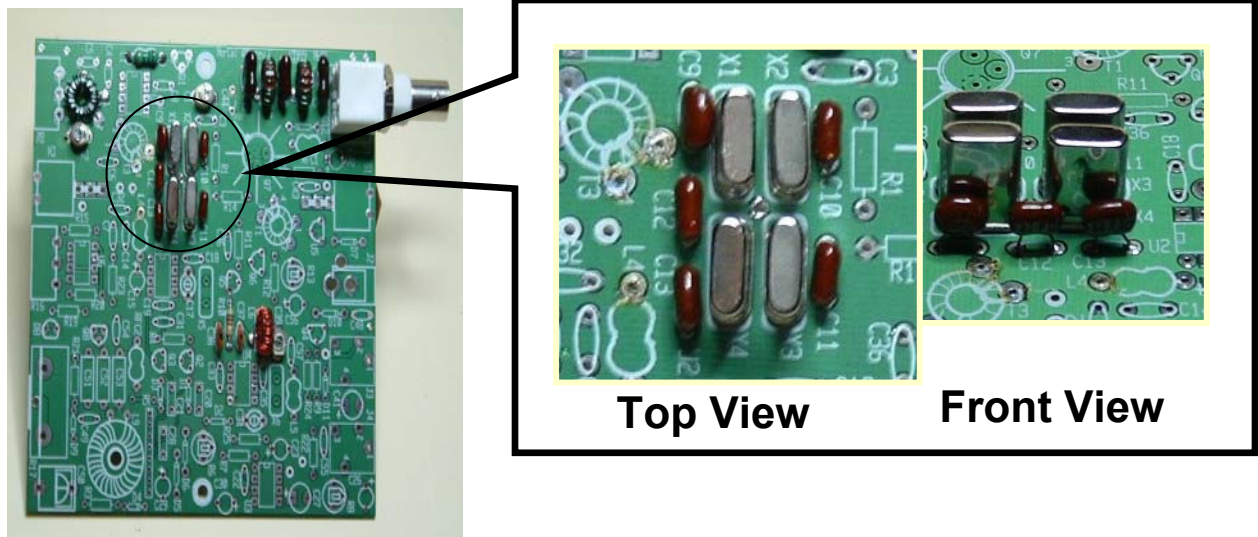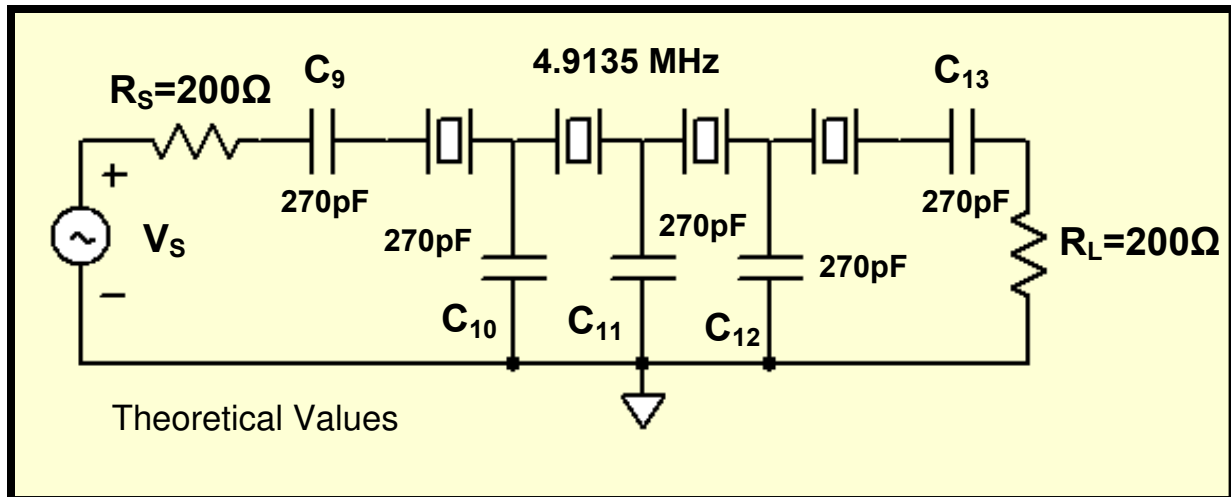
Figures 15 - Location of the Crystal Filter on the NorCal 40A Printed Circuit Board

resistance and thus only an additional 150Ω resistor is placed in series with the VNA transmit and receive ports for VNA testing.
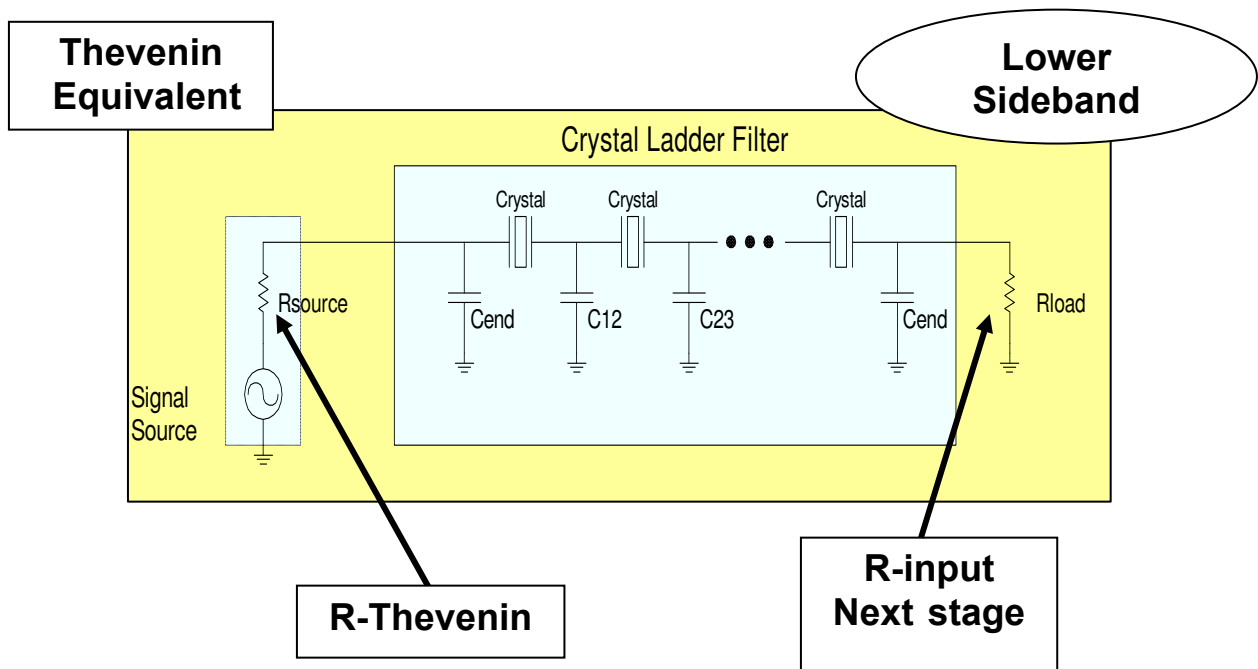
Figures 16 - Crystal Filter Lower Sideband Architecture

Figures 17 - Crystal Filter Test Set-up for VNA Analysis

The six 4.9152 MHz crystals supplied with the NorCal 40A kit were evaluated using a simplified test set-up, shown in Figure 18, designed by Hardcastle [10] for determining the equivalent electric circuit parameters of quartz crystals. The equivalent circuit of a quartz crystal is represented by a simple RLC series circuit shunted by a capacitance representing the influence of the crystal's metal case. The electrical parameters for the four crystals used for the filter were averaged to form a smoothed estimate. Representative data for the crystal parameters are:

fs = 4.913605 MHz - Crystal series resonant frequency
Cm = 1.5100E-14 Farad- Crystal series circuit motional capacitance
Lm = 0.069312 Henry- Series motional inductance
Rs = 21.1 Ohms- Crystal Series circuit resistance
C_0 = 3.0 pF-Parallel metal capacitance
Q = 101,100- Crystal Q normally over 50,000
Δf = 90.0 Hz - Crystal 3 dB bandwidth

Students are required to measure the electrical parameters of the crystals provided with their NorCal 40A kit and to simulate the crystal filters performance using software provided with the text. The result of the computer simulation corresponds well with the actual VNA test results.
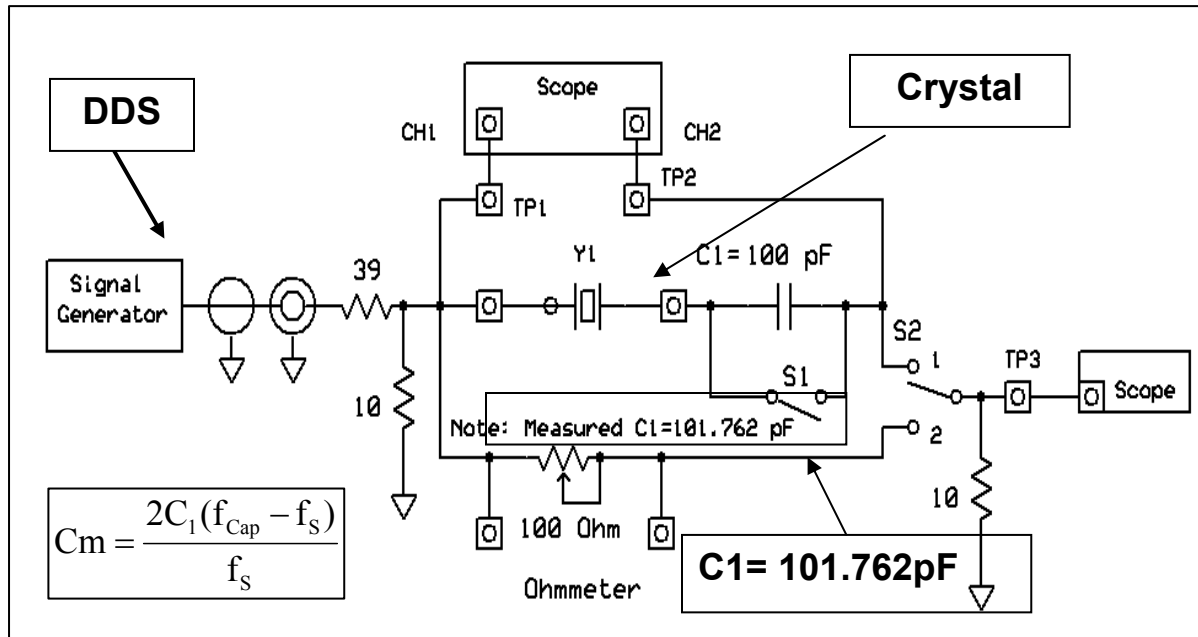
Figures 18 - Crystal Test Fixture designed by Hardcastle, QEX, January 2002

Figure 19 illustrates that the four-pole Cohn filter bandwidth (431 Hz) is very close to the design value of 400 Hz. The filter insertion loss of 14.97 dB is recovered by the gain of the active doubly-balanced modulator in the next stage. The other VNAs provided similar responses and insertion losses. These plots also closely matched the computer analysis of the filter using the measured electrical parameters of the quartz crystals. The remaining filter to be examined is "front-end filter" having the design characteristics of a Butterworth band-pass filter

Input Band-pass Filter

The input band-pass filter employs combined simple series and parallel resonant circuits. Figure 20 shows the filter location on the NorCal 40A printed circuit board
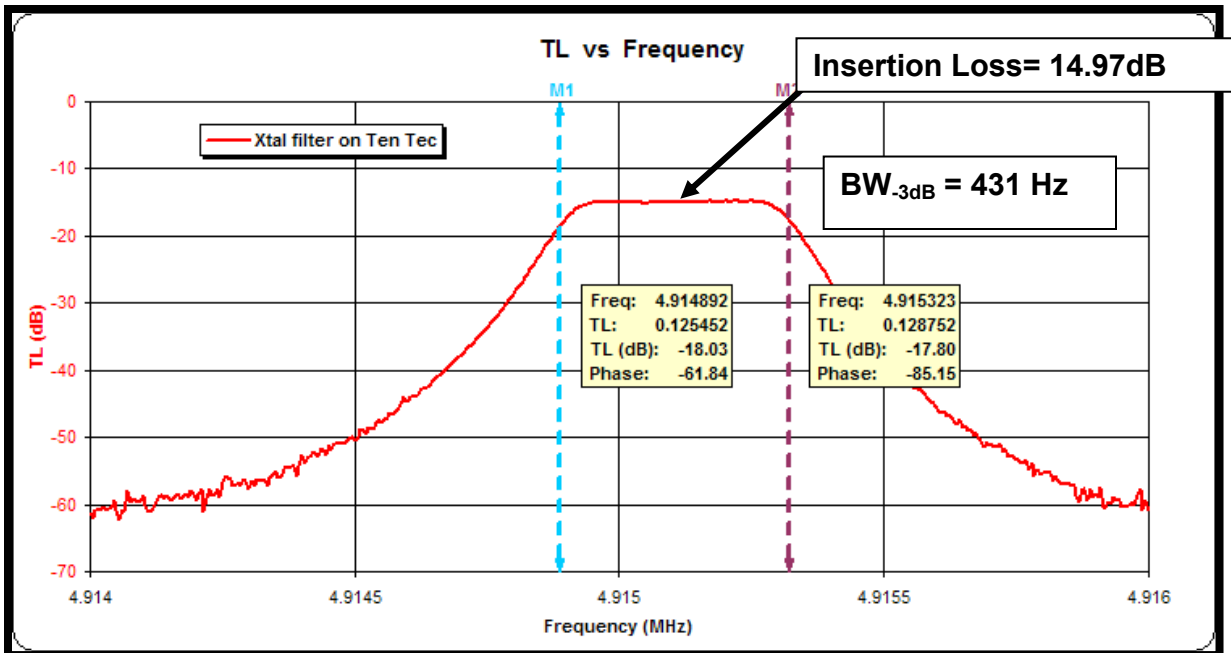
Figures 19 - Four-Pole Cohn Crystal Filter Frequency Response using Ten-Tec Analyzer
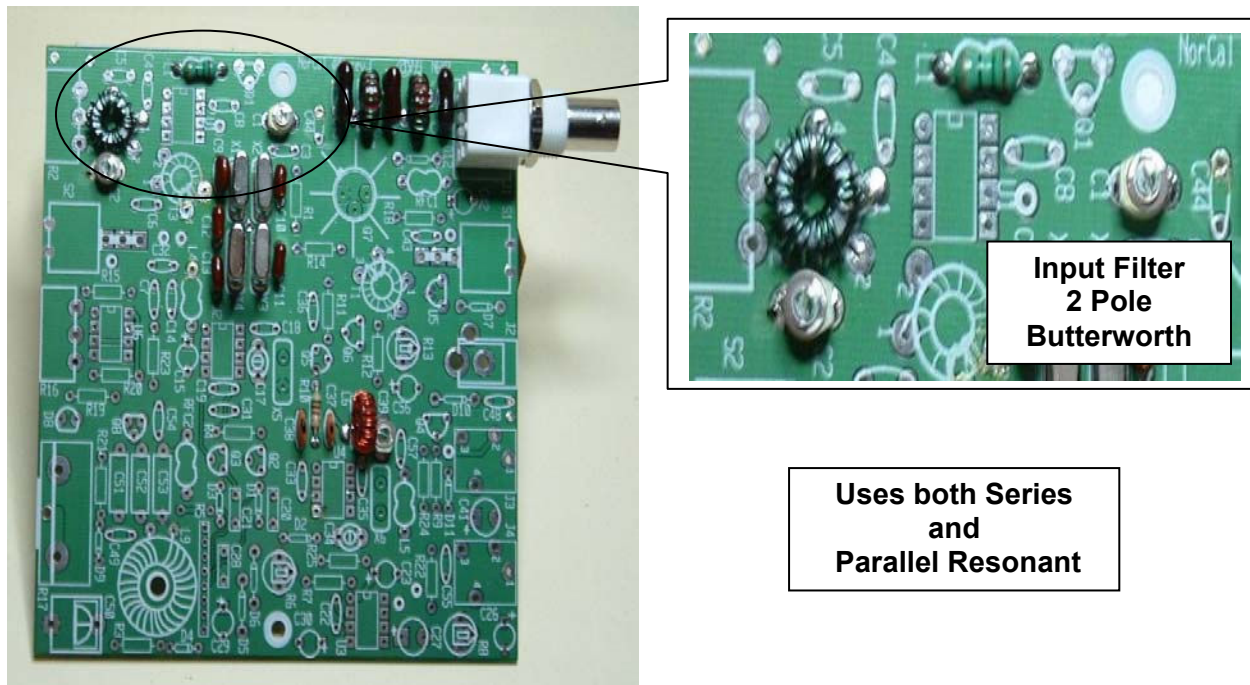
Figures 20 - Input Band-Pass Filter Placement on the Printer Circuit Board

Notice in Figure 21 that the filter input (from right to left) is series tuned and then transformer coupled via a 1:20 turns ratio by as simple toroidal transformer. The parallel resonant circuit

transforms the 1500Ω input resistance of the SA602A doubly-balanced mixer to 50Ω. Upon close examination of the filter structure it can be easily shown the input band-pass filter is a two-pole Butterworth filter centered at 7.040 MHz with a -3dB bandwidth of approximately 600 kHz.
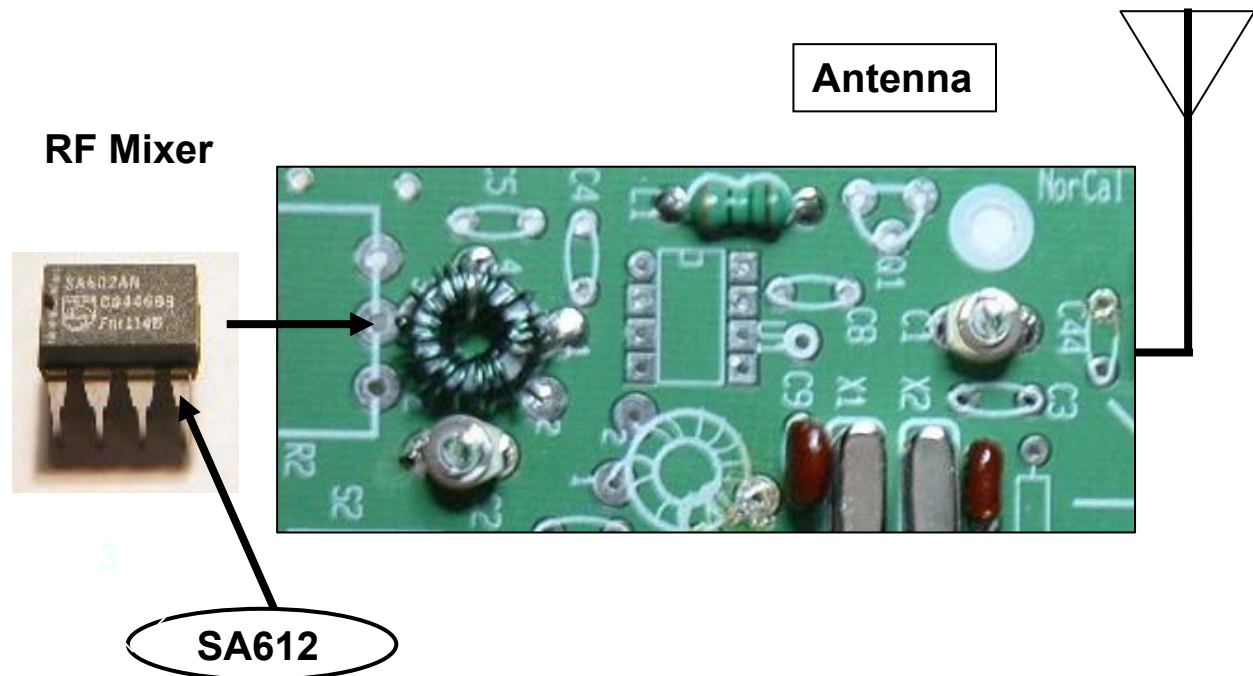
Figures 21 - Two-Pole Butterworth Band-pass Filter Connected between Antenna and Mixer

The filter is easy to construct and adjusting the variable capacitors to form a band-pass filter is illuminating. It is easy to illustrate that two separate "humps" appear in the filter response with a slight detuning of the filter. A schematic illustrating the electrical characteristics of the filter is shown in Figure 22. The filter is terminated with resistors R_{in} and R_{ant} in order to make the sweep
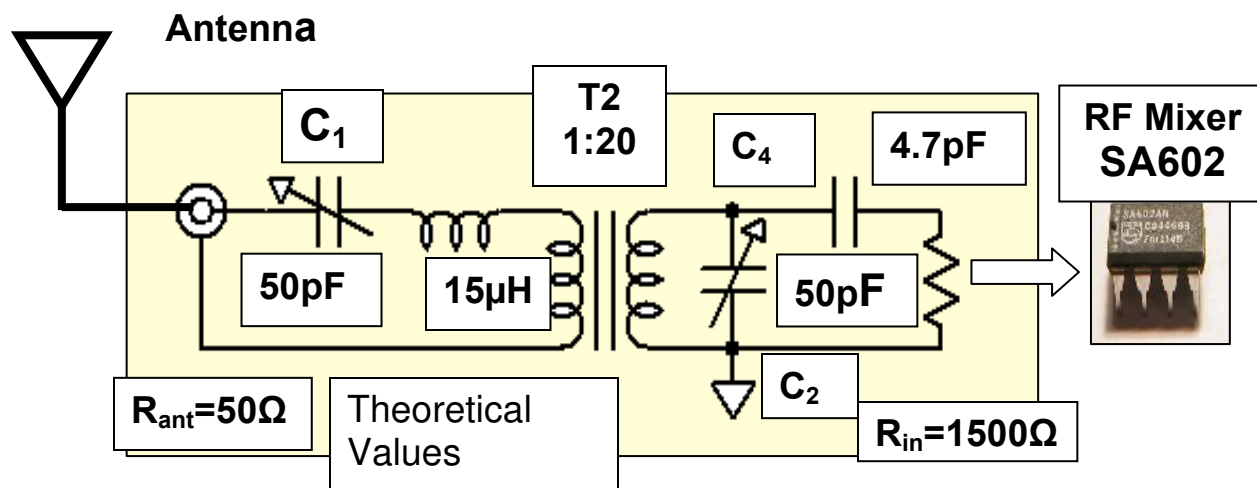
Figures 22 - Schematic of Two-Pole Butterworth Band-pass Filter used with Analyzer

with the VNA. Notice in Figure 23 that an insertion loss of approximately 18dB results from using this filter structure and this loss must be made-up by the employing the approximately 20dB of gain derived from the active SA602 doubly-balanced mixer.
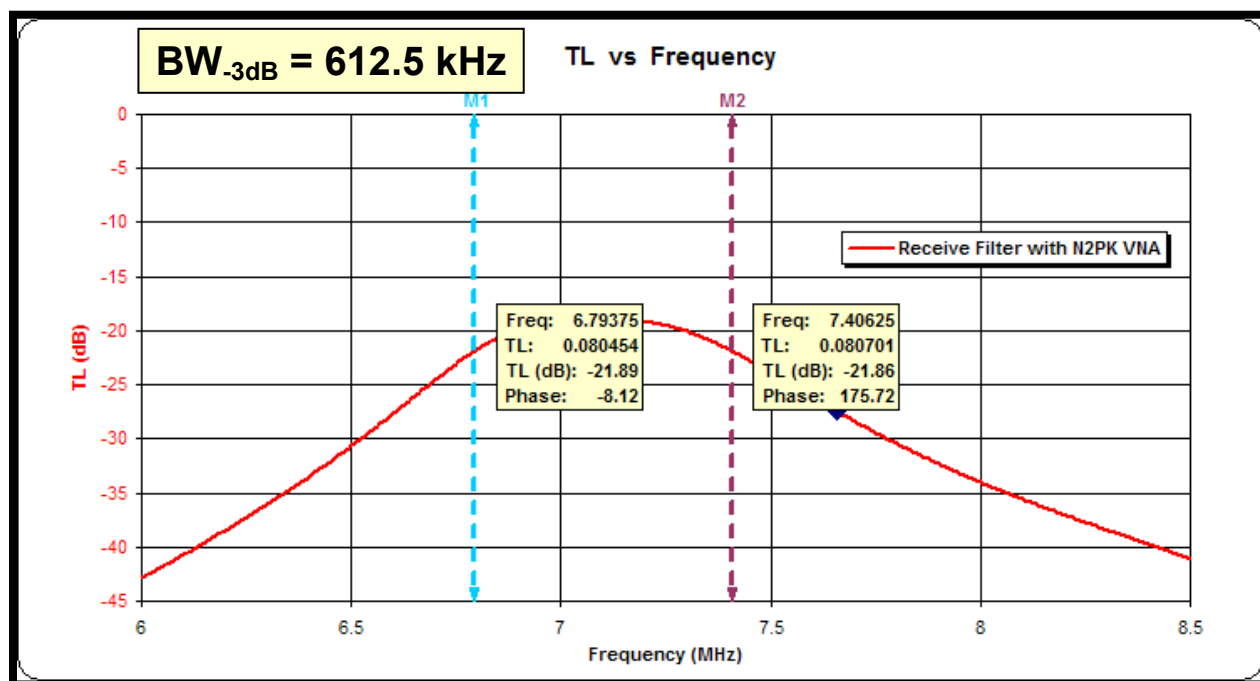
Figures 23 - Two-Pole Butterworth Band-pass Filter used with Analyzer

The Butterworth band-pass filter offers a 3 dB bandwidth of 612.5 kHz centered around 7040 kHz. This simple filter structure is remarkably selective for the Morse Code portion of the 40 meter amateur radio portion of the RF spectrum.

Engineering Project Notebook

Each student is required to maintain an Engineering Project Notebook [11] in the laboratory to record the student's journey through the course with emphasis being placed on recording test data, transceiver construction notes, and final calibration and testing of the transceiver. Many students also use the notebook as a journal and often record their frustrations as well as their successes. Laboratory time is also used for informal discussion groups which deal with problems encountered during the building and testing phase of the project. The concept of "test as you build" is emphasized in the discussions and students share ideas and problems during group discussions. Also, each student is required to develop a simple "Gantt Chart" to show project progress during the building and testing phases of the project. A handout is given in lecture that describes the "Gantt Chart" technique for implementing the project schedule, but the actual development and updating of the chart occurs during the laboratory period. The chart is used as a project management tool and must be included in the student notebook.

Student Assessment

To date, qualitative and quantitative student feedback on the course structure and project has been very positive and representative selections of student comments are presented in the following student assessments.

The following comments are extracted from course assessment forms developed by the authors. Four questions were presented to the students during the last class of RF Communications during Spring Quarter of 2008. Overall, the comments are very encouraging:

1.0 Did the class project illustrate the concepts presented in the course?

> "The transceiver project covered just about all of the concepts presented in the course. I was intimidated by all the testing presented in the text. The problems all looked difficult and I was glad we worked the problems in class and then built the circuits in the laboratory. We explored filter design and tested each filter. I liked using the VNA rather than taking data by hand. I really enjoyed making and testing the crystal filter. We developed testing procedures for step-by-step project construction. I was tempted to just put all the parts on the PCB but soon learned to test the circuits after I built them."

2.0 Was the class project effective in enhancing your technical skills?

"The project introduced the soldering of many different components onto a printed circuit board, which I had no prior experience with in the past. In addition, this project allowed me to learn about inductors and coils. I always wondered about resonant circuits and was able to gain an understanding as to how they work in a circuit. Also, it was necessary to use a wide range of test equipment to accomplish the tasks outlined in the problems presented in the text. For this course troubleshooting skills were a must. I feel that the project provided an excellent review that spread across concepts which had been presented in several different courses. It was interesting to see a practical application of all of the concepts that were covered in the course. This was also my first experience in working with RF concepts and I was pleased that my transceiver worked the first time."

3.0 Was the class project rewarding?

"I feel that this class project was very rewarding and I enjoyed seeing the subsystem components coming together to form a complete system. The project walked us through a complete RF system which emulated concepts that I will need in the senior design process, and in addition to the material I learned about RF systems the course provided a review of earlier coursework. I feel that I am well prepared to start senior design next year. I also would have liked to learn about Microsoft Project beyond the simple Gantt chart because I plan to use project management software for senior design."

4.0 Rate this course overall, based on its effectiveness and helpfulness in utilizing your past coursework experiences and preparing you for senior design.

"This course proved to be quite enjoyable. Introducing vector network analyzers for testing was a high point of the class. Also this was the first large scale project system project that I have encountered, outside a previous Honors project that I completed. One of the nice things about the course is that once it is all said and done you are able to walk away with a completed project that has a certain level of professionalism that cannot be achieved in labs where simple breadboards and jumpers are used. Also, I feel that this course provided a solid foundation troubleshooting that can be taken into Senior Design."

Conclusion

This senior level laboratory course capstone design project relies heavily on knowledge and skills previously learned in both the analog and digital electronic sequences at the University of _____. Only a modest amount of mechanical construction is required for the project. On the other hand a reasonable amount of soldering thru-hole components, coil winding, electronic

testing, and troubleshooting are required by each student. Also, calibration skills are required for successful completion of the project. Over the past five years the author has found that student attitude towards the course and subsequent feedback to be most rewarding, and I was very encouraged by the level of student involvement in the project. In addition, the effort expended in hardware construction and testing offered students an opportunity to gain a "broader technical view" of the radio frequency communication process.

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