

The Tuned Circuit LC Phase Modulator

Virgil Leenerts

WØINK

8 March 2005

The tuned circuit or LC phase modulator is one of several methods used to generate phase modulation for communications transmitters. Although the general aspects on the workings of the LC phase modulator have been described in many articles and textbooks, the operation of the modulator, with respect to the distortion and the effects of the voltage variable capacitor, is not well documented in current literature.

In Summary:

This paper shows that the main distortion product from an LC phase modulator is from the nonlinear phase shift curve of a resonant circuit and not from the varicap used to modulate the circuit.

The operation of an LC phase modulator:

There are various designs of phase modulators that are referred to as reactance modulators and the LC phase modulator is one form of a reactance modulator. The LC modulator is a circuit that is resonant at the frequency that is to be phase modulated. The circuit can be a parallel or series resonant circuit, however the series circuit is the most common. Whether the circuit is parallel or series, the operation principle is the same.

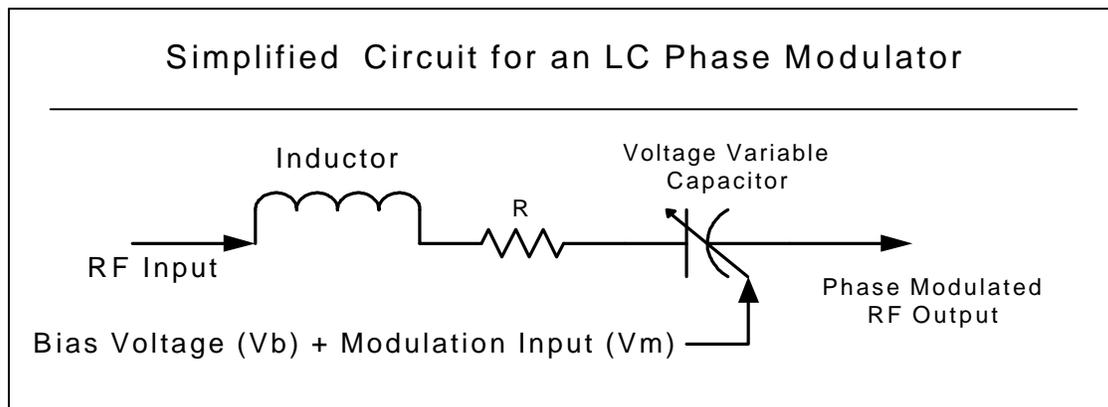


Figure 1.

In the simplified circuit for an LC phase modulator, the value of the inductor and the capacitor are selected to be resonant at the frequency of the RF input. The resistor value sets the Q or bandwidth of the circuit. Since inductors have finite Q , the resistor also includes the resistance of the inductor.

The voltage variable capacitor is commonly known as a varactor or varicap diode. The bias voltage (V_b) sets the desired capacitance to be resonant at the RF input frequency with the inductor. When the modulation voltage (which is summed with the bias voltage) is applied, the resonant frequency of the circuit varies above and below the center frequency at the modulation voltage magnitude.

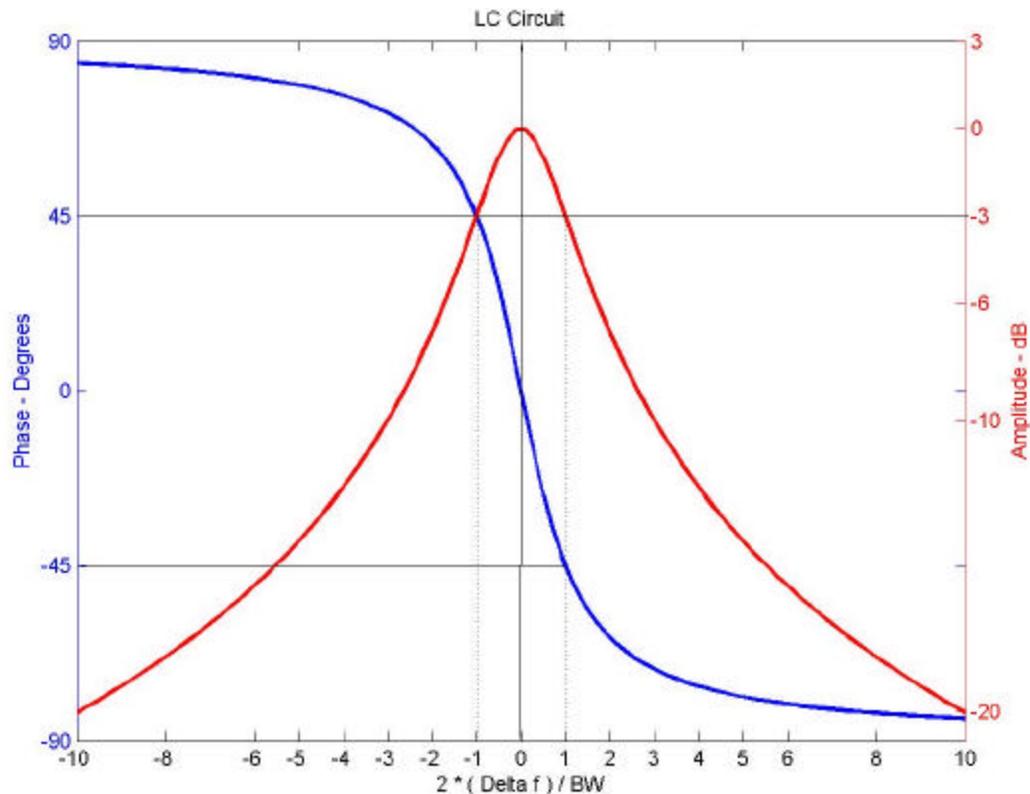


Figure 2.

Figure 2 shows the amplitude and phase of a single tuned resonant circuit. The plot is normalized so units are independent of Q . The plot shows the phase shift of 45 degrees (0.785 radians) at the -3 dB points on the amplitude curve. The curve for phase is a tangent curve and goes from $+90$ to -90 degrees with zero degrees at resonance. The modulation of the voltage to the varicap shifting the resonant frequency results in phase shifting the output following the phase response curve.

Simulation and Measurement of the LC phase modulator:

The simulation to determine the theoretical distortion for a LC phase modulator was to apply a sine wave to a tangent function block and then measure the distortion after it passes through the tangent function block with an FFT for the %THD. This is essentially a mathematical model of the phase modulator.

The measurement of a real LC phase modulator proved to be more difficult as the amount of delta frequency (100 Hz) at a typical channel element frequency was very small. This required building an FM discriminator with high sensitivity and low noise for the measurements. Even with a very good PLL PM discriminator, the distortion measurements were made with a spectrum analyzer (HP3580A) to measure the distortion components relative to the fundamental because of the broadband noise floor.

The circuit was essentially the simplified circuit of figure 1 with an RF signal generator driving the input and the output connected to the 50 ohm input of the FM discriminator. The frequency used was 11 MHz.

Measurements were made with two different Q's (10 and 30) and two different diodes: (MV209 and the GE varicap).

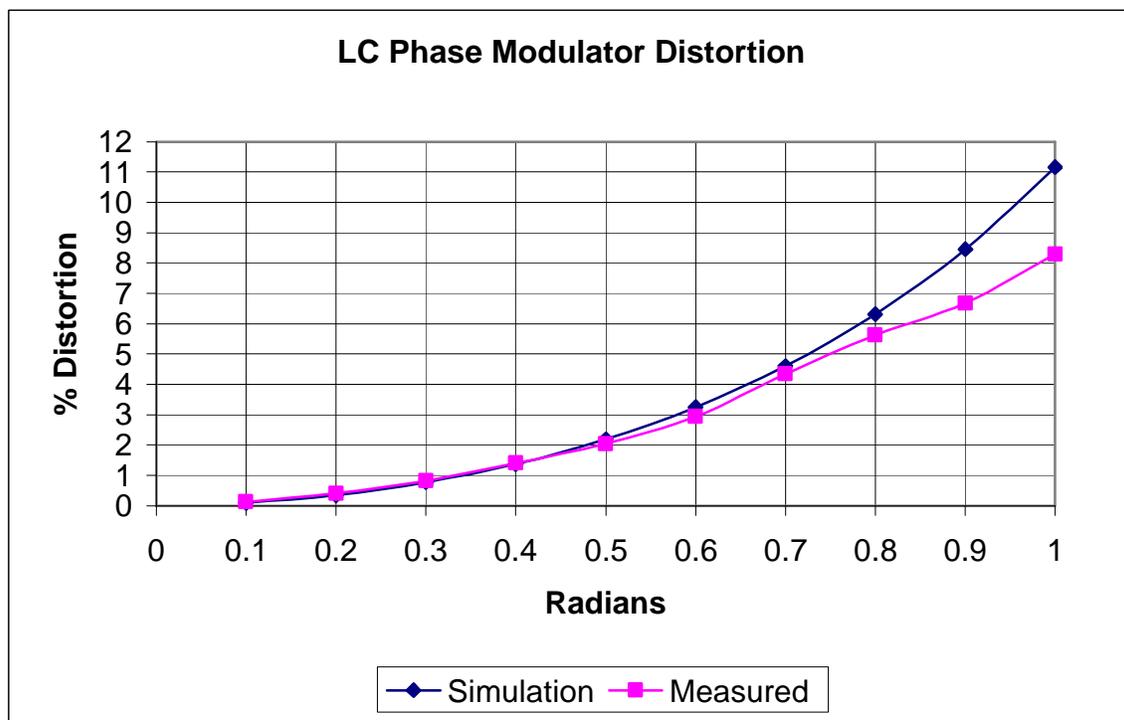


Figure 3.

There was not a significant difference between the four measurement results, so only one curve is shown for the measured distortion. It was expected that Q would not be a factor in the distortion, but it was unexpected that the varicap was not a contributor to the distortion. In fact the varicap actually makes the distortion lower past about 0.7 radians. Contrary to popular belief, the varicap is not the element causing the distortion. Instead, the distortion is predictable and is due to the nonlinear phase shift of the $\tan x$ function. Figure 3 is a comparison of calculated or simulated results with measured results (de-emphasis output).

FM Discriminator output results:

The distortion results in figure 3 were measured at the de-emphasis output of the FM discriminator because the output at the FM discriminator has a 6 dB per octave rising response and as a result, the distortion would be higher than the phase modulated input.

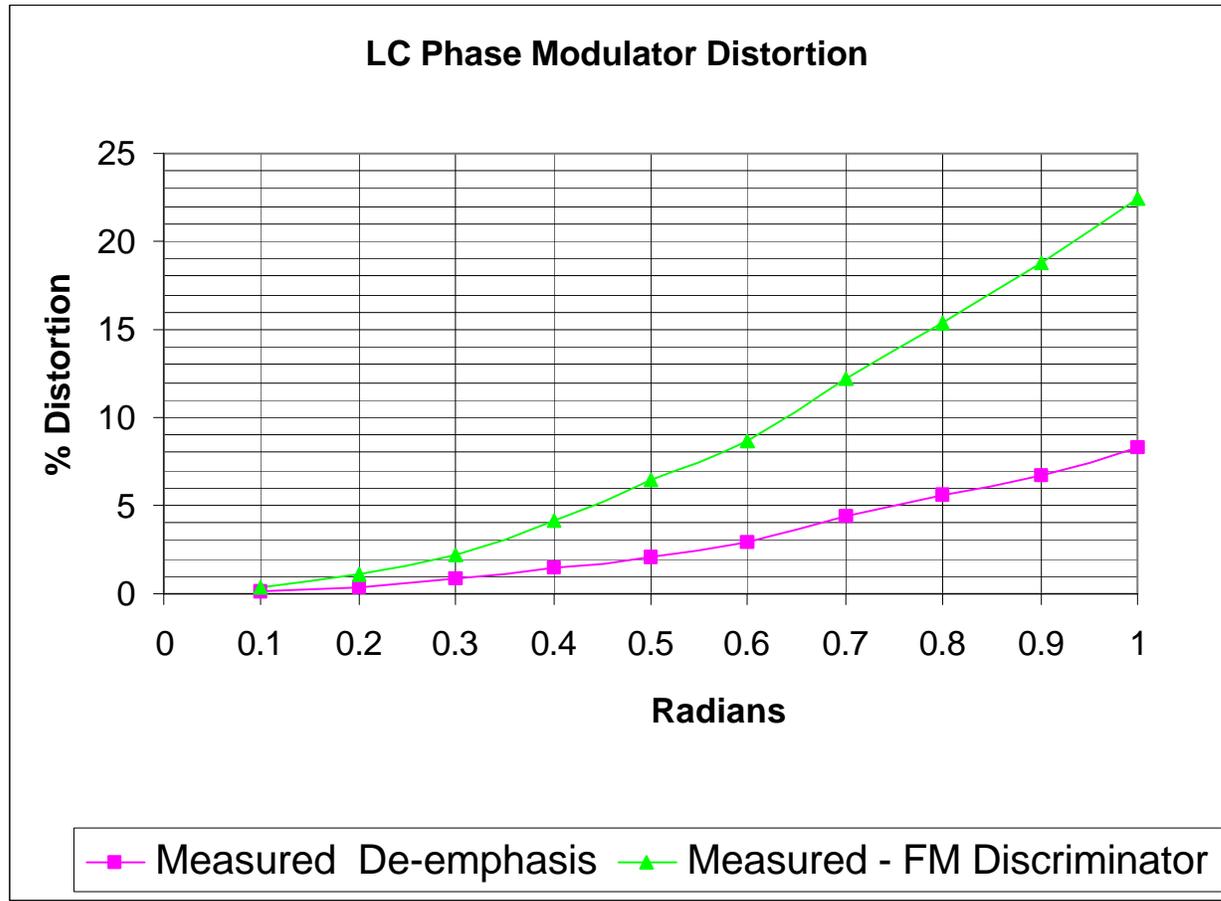


Figure 4.

The dominant distortion product from the LC phase modulator is the third harmonic. The rising response of the FM discriminator then causes the third harmonic to be a factor of 3 or 10 dB higher relative to the fundamental than it would be after de-emphasis to restore the modulation of the phase modulated signal. Figure 4 shows the factor of 3 higher distortion at the FM discriminator output relative to the integrated or de-emphasis output.

Distortion relative to the transmitter output:

So far, the distortion has been presented in the phase modulator terms, that is, delta phase shift in radians. Normally transmitters are specified in terms of delta frequency shift (deviation) in Hertz. In angle modulation transmitters (FM or PM modulators) the unit that connects them is the modulation index (Note: Frequency and phase modulation occur simultaneously together and each represent a different aspect of the same thing, angle modulation). It follows that the modulation index = delta-phase (radians) = delta-frequency (Hertz) (deviation) / modulating frequency. Thus the relationship between the two is the modulating frequency. For example, if the deviation is known, then divide the deviation by the modulating frequency for phase shift in radians. If this is for the transmitter output, then divide the result by the transmitter multiplier number for the phase shift in radians at the modulator.

For example, the GE 450 MHz exciter has a X36 multiplier, so for the distortion of this exciter at 5 KHz deviation and a 1KHz modulating frequency (modulation index = 5) (5 radians / 36 = 0.14 radians) would be about 0.2% assuming no other contributions to the distortion other than the phase modulator itself.

GE 450 MHz Exciter measurement results:

Before distortion measurements were made on the exciter, careful adjustment of the LC modulator and the first two multiplier stages were made for minimum distortion. It was found that these adjustments greatly affected the distortion. A spectrum analyzer connected to the FM discriminator was used to make the adjustments. During the adjustments, it was found that a second harmonic component was also present which set the lowest level of distortion for the exciter.

The measurements were made by connecting an audio generator to the microphone input and adjusting the output level for 4 KHz of deviation at all the test frequencies. This simulates a typical voice spectrum input to the modulator. The deviation level was set to max to insure that the audio limiter was not creating any distortion also the measurements were done at the CG input with the same results.

Modulation Frequency	Delta Radians at RF Output	Delta Radians at LC Modulator	Simulated % Distortion 3 rd Harmonic	Measured % Distortion THD HP333A
200 Hz	20.0	0.56	2.8	2.24
300 Hz	12.6	0.35	1.0	1.0
500 Hz	8.0	0.22	0.4	0.4
1000 Hz	4.0	0.11	0.1	0.4
2000 Hz	2.0	0.056	0.05	0.4
3000 Hz	1.3	0.036	0.04	0.4

As noted in the adjustment phase, the second harmonic kept the distortion from going lower as would be expected at 1000 Hz and above.

Since the distortion after adjustment is a reasonable number, the most significant step in lowering distortion of a GE exciter is to adjust the modulator and the first and second multipliers for lowest distortion. I accomplished the adjustment using my FM discriminator and a HP3580A audio spectrum analyzer.

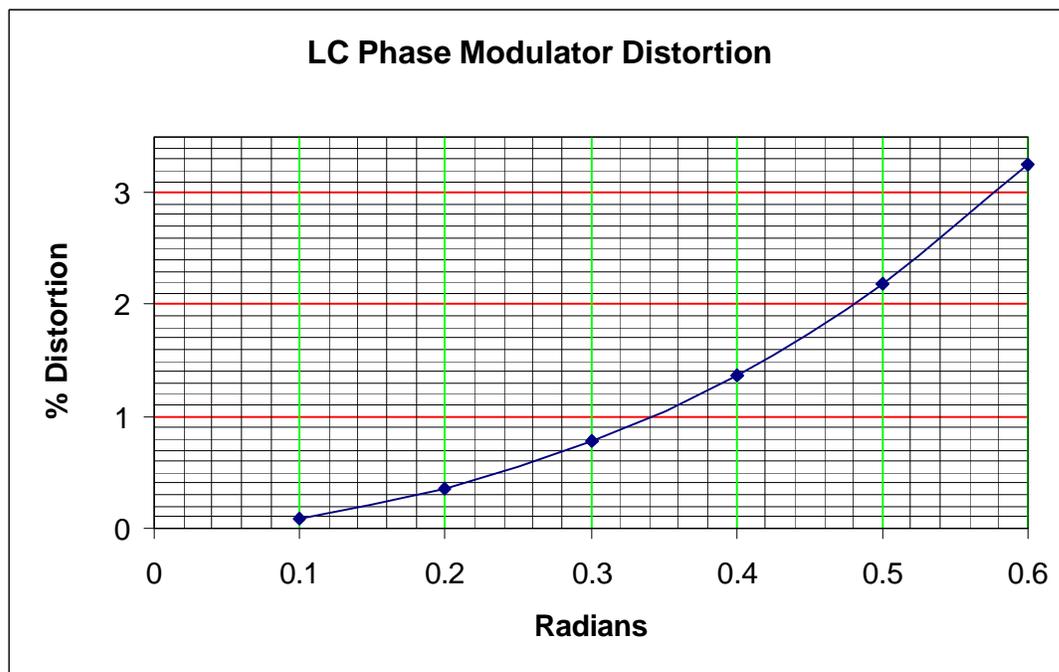
Conclusion:

The distortion data presented can now be used to determine what the distortion level will be in an LC Phase Modulator exciter on a theoretical basis and allow evaluation if the distortion is at an acceptable level. Also with the known minimum level of distortion known, measurement of a distortion level that is higher means the exciter is not properly designed or adjusted. Another interesting aspect is that there may be the possibility of pre-distorting the modulation to the phase modulator to cancel the distortion at higher levels of phase shift.

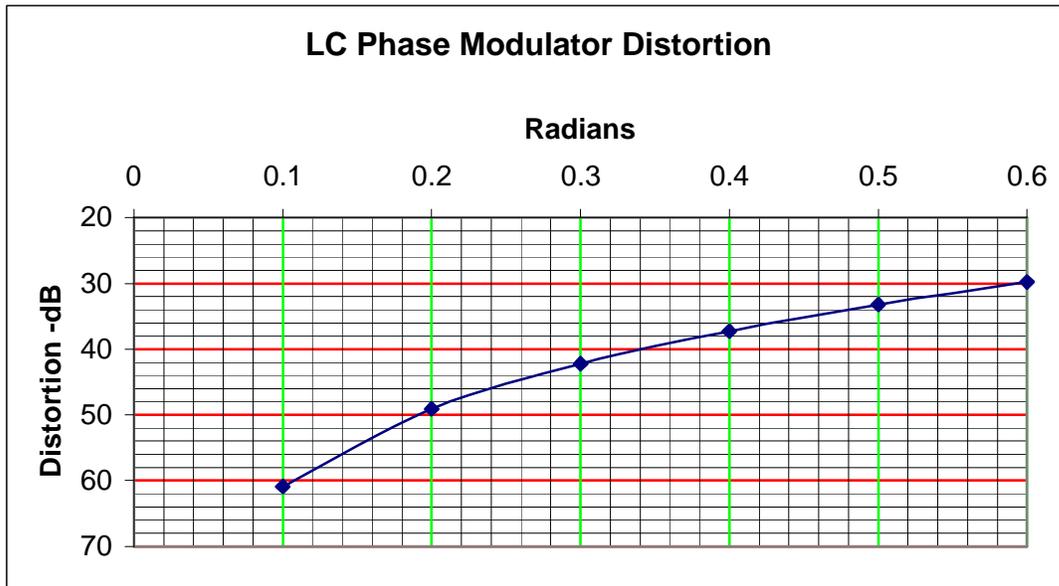
Appendix A: Plot Data and Plots

Delta Radians Radians / Degrees	Tan X Degrees	“Simulated” Tan X % / dB Distortion	Measured: % Distortion De-emphasis Output	Measured: % Distortion FM Discriminator Output
0.1 / 05.7	0.100	00.09 / -60.9	00.13	00.38
0.2 / 11.5	0.203	00.35 / -49.1	00.41	01.15
0.3 / 17.2	0.309	00.78 / -42.2	00.82	02.24
0.4 / 22.9	0.423	01.37 / -37.3	01.41	04.10
0.5 / 28.6	0.546	02.19 / -33.2	02.05	06.50
0.6 / 34.4	0.684	03.25 / -29.8	02.94	08.66
0.7 / 40.1	0.843	04.60 / -26.7	04.34	12.23
0.8 / 45.8	1.029	06.31 / -24.0	05.62	15.40
0.9 / 51.6	1.260	08.45 / -21.5	06.68	18.84
1.0 / 57.3	1.557	11.16 / -19.0	08.30	22.39

The above is the calculated and measured data for distortion plots.



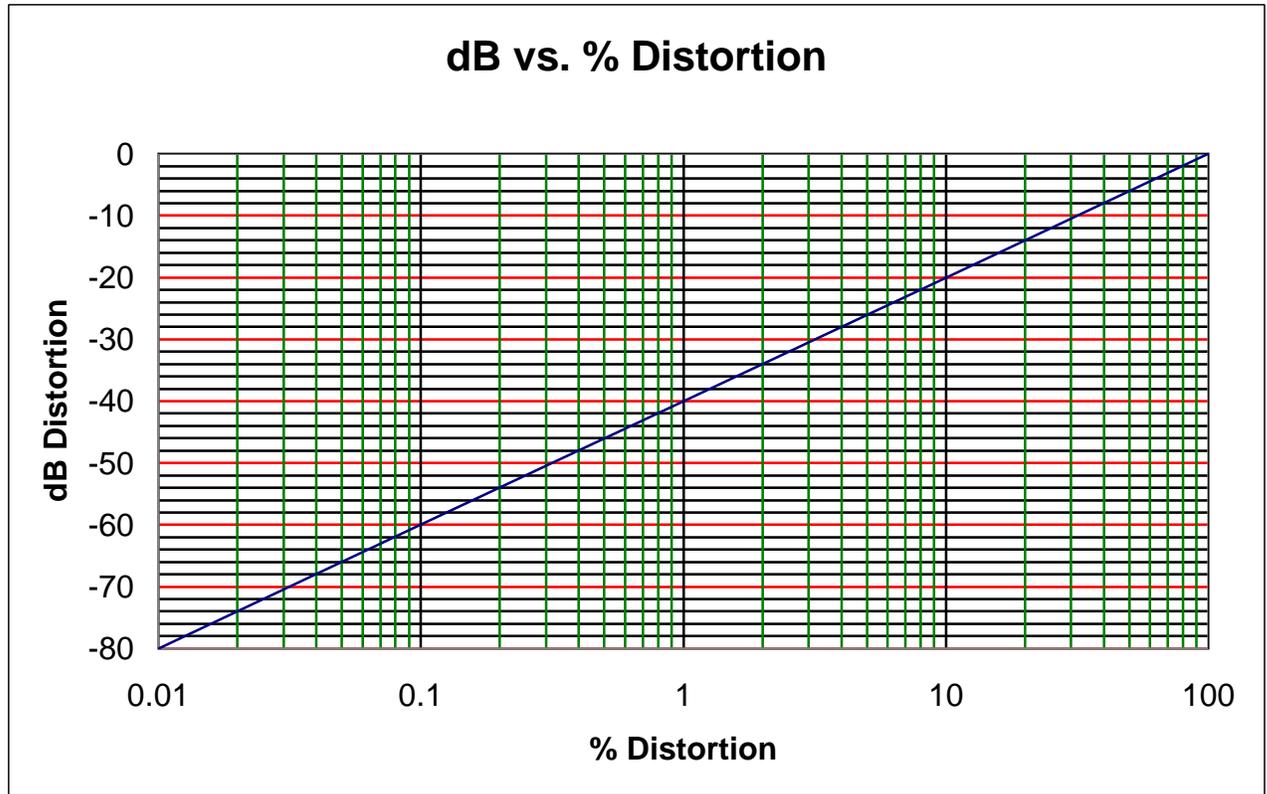
The above is an expanded plot of %Distortion vs Radians out to 0.6 Radians.



The above is an expanded plot of dB Distortion vs Radians out to 0.6 Radians.

$$(\text{dB Distortion} = 20 \text{ Log} (\% \text{ Distortion} / 100))$$

$$(\% \text{ Distortion} = (10^{-\text{dB}/20}) * (100))$$



Appendix B: Radians:

Radians are used extensively in the mathematical and engineering domain; for example $\omega = 2\pi f$ is radians per second. Radians are commonly used to express phase shift along with degrees. There are 2π radians or 360 degrees in a circle, or one cycle of a sine wave. One radian is equal to 57.296 degrees, and conversely, one degree is equal to 0.01745 radians.

The modulation index for FM and PM is expressed in radians.

Modulation Index (PM) = Delta-Phase (Radians)

Modulation Index (FM) = Delta-Frequency/Modulating Frequency

Modulation Index (PM) = Modulation Index (FM)

45 degrees (delta-f @ bw) = 0.785 radians

Appendix C: The LC Modulator Test Circuit.

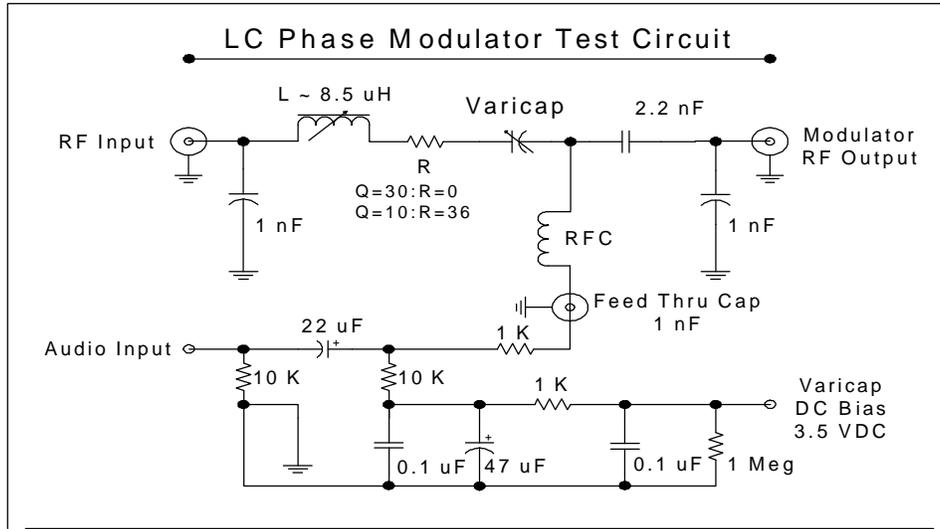


Photo of LC Modulator Test Circuit

Appendix D: LC Modulator “Q” and delta-f:

The third order distortion of an LC modulator is independent of Q, however the second order distortion and sensitivity are not independent of Q.

Second order distortion (or any even order distortion) is caused by errors in the waveform that are not symmetrical. That is, errors that cause a waveform to not have equal areas on both positive and negative portions of the waveform will generate second order distortion. Two contributors for this to occur in the LC modulator are the nonlinearity of the varicap (not likely) and the fact that the resonant frequency of an LC circuit is the geometric mean of F1 and F2 (F1 & F2 are the lower and upper -3 dB points) and not the arithmetic mean as assumed when calculating Q. These factors contribute less to the distortion as Q increases. When an LC modulator is adjusted for lowest distortion, it will be found that the second order distortion is the most sensitive to adjustment and can be made very low such that it is not a significant contributor to the overall distortion. The third order distortion caused by the tan x function cannot be adjusted out.

The sensitivity of the modulator to the modulating voltage varies inversely with the Q of the LC circuit. As the Q goes up, the modulating voltage level goes down for a given peak phase shift.

It should be noted that the delta-f of the resonant circuit shifted by the modulating voltage is not the same as the delta-f deviation of the resulting modulation. The delta-f bw of the resonant circuit is equal to $F_0 / 2Q$. The delta-f resonant circuit is equal to delta-f bw * (Radians modulation / Radians bw). Note - 0.785 radians at bw.

Example: Modulator radians = (4000 Hz deviation/1000 Hz tone) / 36 = 0.11 radians and 110 Hz deviation.

$F_0 = 12.6 \text{ MHz}$ and $Q = 15$ and Radians modulation = 0.11.

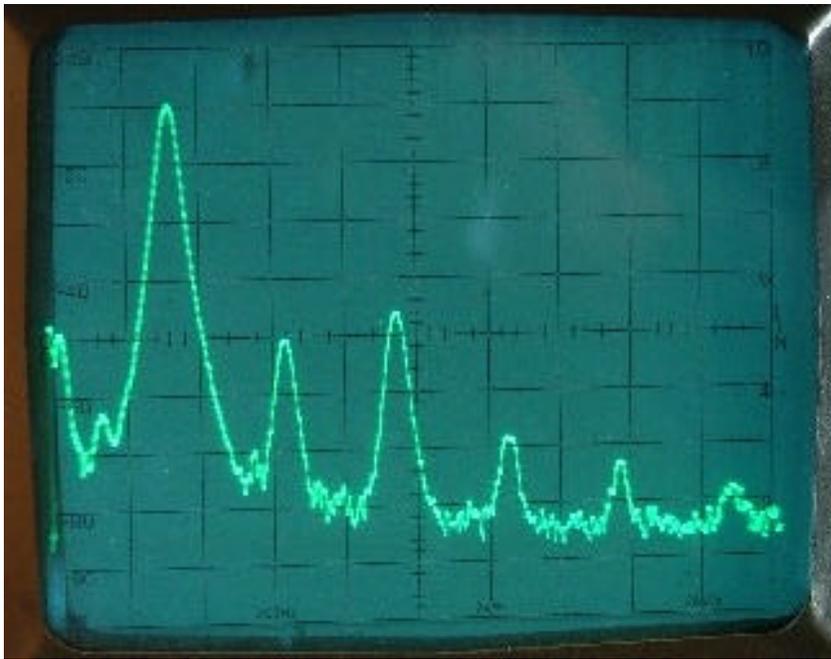
? f bw = $12.6 \text{ MHz} / (2 * 15) = 420 \text{ KHz}$.

? f resonant circuit = $(420 \text{ KHz}) * (0.11 / 0.785) = 58.85 \text{ KHz}$.

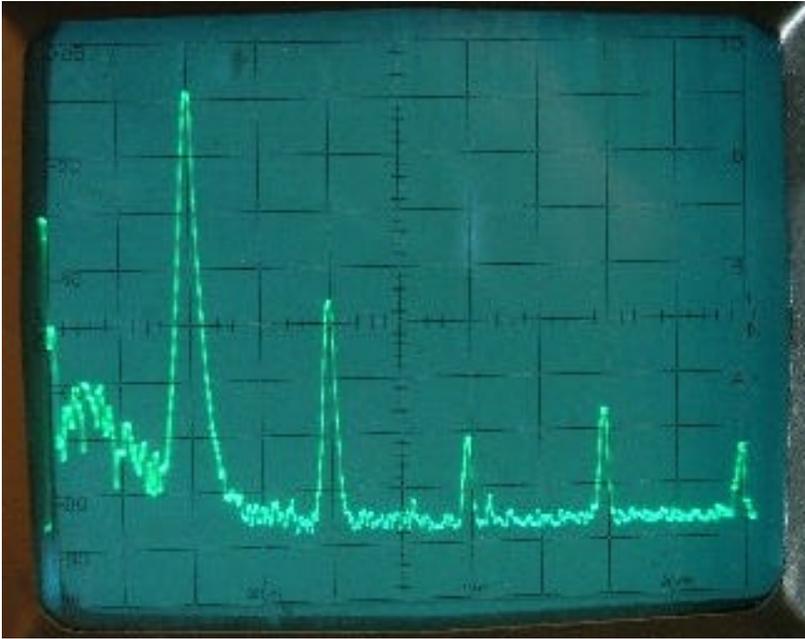
Thus for a deviation of 110 Hz at the modulator, the delta-f of the resonant circuit shifts by 58.85 KHz. This is the amount the varicap shifts the resonant frequency of the circuit to cause a phase shift of 0.11 radians.

Appendix E: Comments on the GE 450 MHz exciter.

A lot of time was spent to see if any improvements could be made to the LC modulator so that the distortion level would be less susceptible to the tuning of the first multiplier stage. Also from a practical point of view, a distortion level of 1% to 3% is very acceptable in the voice communication systems for which these radios were designed. In summary, I found no improvement that could lower the modulators distortion levels or its sensitivity to adjustments. The LC modulator's high RF drive levels and lack of isolation from other circuits makes further improvement impractical. One concern with the current design is that any distortion products generated in the modulator can cause a widening of the signal bandwidth if the products are outside the normal expected audio bandwidth. Following are examples of spectrum analyzer plots from the GE 450 exciter that I have been working with. Note that these are representative distortion product levels of the exciter only, as adjustment can greatly vary the levels of the distortion products.



The above plot is with a 300 Hz modulating frequency at a 4 KHz deviation level. The spectrum analyzer span is 200 Hz/div or a total span of 2 KHz.



The above plot is with a 1KHz modulating frequency at a 4 KHz deviation level. The spectrum analyzer span is 500 Hz/div or a total span of 5 KHz.

Appendix F: An experimental LC phase modulator.

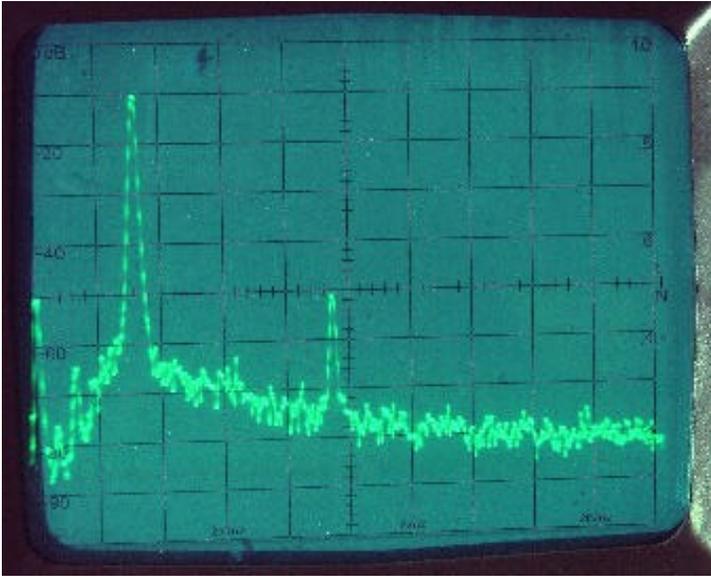
After working with and understanding the parameters for the best LC phase modulator performance, I designed and built a breadboard of a well-designed LC phase modulator. Of the things I learned is that a well-designed LC PM needs to be well isolated from the input and output circuits and have low-level RF and audio to the varicap with a modest Q for the resonant circuit. Also the output of an LC phase modulator has an AM component due to amplitude changes of the resonant circuit as it is being modulated and thus a limiter to take out the AM component is desirable.



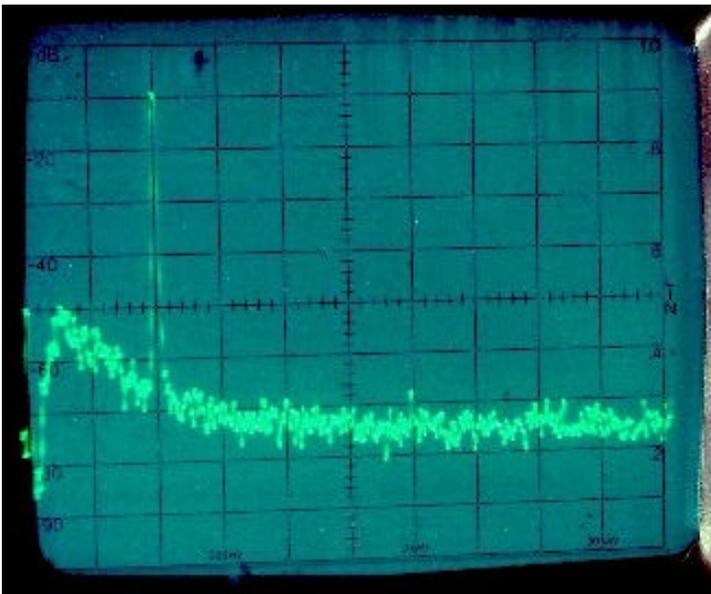
The above photo shows the phase modulator breadboard. It consists of the GE channel element as the oscillator driving the resonant circuit through a 10:1 step down RF transformer. This provides isolation to the RF oscillator from the modulating voltage as well as a low level and low-impedance drive source for the resonant circuit. The output of the phase modulator is taken across the resistor that sets the Q (~ 20) of the circuit. This output is amplified by an isolation amp, which is connected through a resonant circuit that drives the limiting amplifier. The output of the limiting amplifier then drives the first tripler transistors in the GE exciter. Instead of a variable inductor, I choose to tune the circuit by slightly varying the bias voltage for the varicap. Note the two pots, one for coarse adjustment and the other for fine adjustment of the circuit for lowest distortion.

A complete description with schematic diagram will be presented in another paper.

The audio level to the modulator was set for a deviation of 0.35 radians at 300 Hz and 0.11 radians at 1000 Hz. This results in a deviation of 4 KHz at the exciter RF output at both 300 Hz and 1000 Hz.

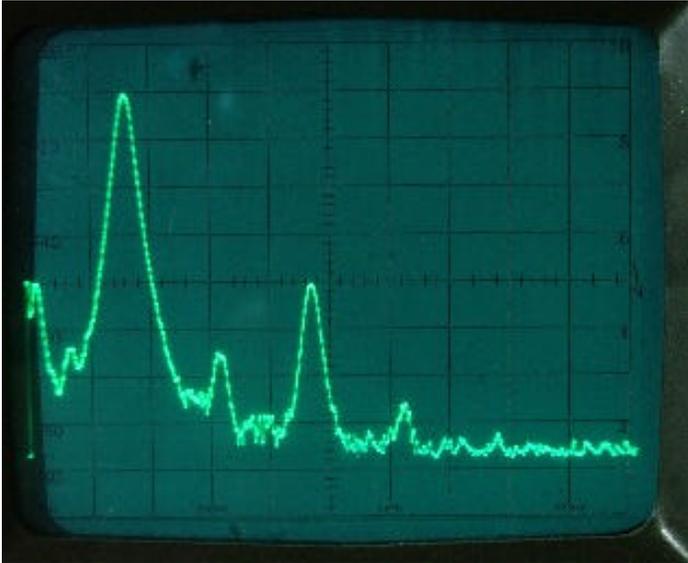


Plot of phase modulator distortion at the channel element frequency (12.619 MHz) modulated at 300 Hz. Note that the 3rd harmonic is at the predicted level of -40 dB below the fundamental frequency and that the 2nd harmonic could be adjusted to a minimum level of about -54 dB below the carrier.

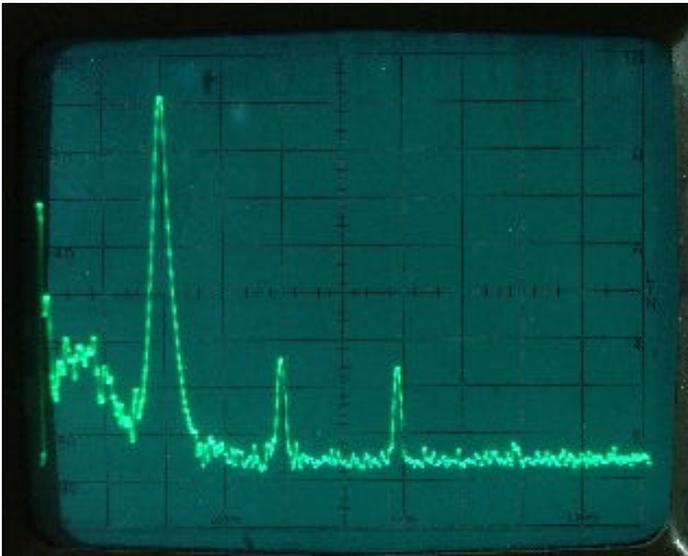


Plot of phase modulator distortion at the channel element frequency (12.619 MHz) modulated at 1000 Hz. Note that the 3rd harmonic is at the predicted level of -58 dB below the fundamental frequency and the 2nd harmonic could be adjusted to a minimum level of about -58 dB below the carrier.

The output was then connected to the GE exciter with the results shown below. It was also noted that tuning the first tripler stage had no effect on the distortion products.



Plot of GE exciter distortion at a frequency of 454.30 MHz modulated at 300 Hz. Note that the 3rd harmonic distortion remained at the level of -40 db below the fundamental modulating frequency and that the 2nd harmonic remained about -54 dB below the fundamental modulating frequency.



Plot of GE exciter distortion at a frequency 454.30 MHz modulated at 1000Hz. Note that the 3rd harmonic distortion remained at the level of -58 dB below the fundamental modulating frequency and that the 2nd harmonic remained close to modulator at about -56 dB below the fundamental modulating frequency.

END