

Oscillators

Theory and Practice

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***There is no magic in RF: There is a reason for everything
(the reason may not be obvious)***

OSCILLATORS BY TYPE

- **Feedback Oscillators**

- Most prevalent, many implementations, understand by recognizing component parts; RC, LC, other

- **Negative Resistance Oscillators**

- Less popular, mostly microwave implementations, often a single active device
-

- **Fixed Oscillators: single frequency operation**

- **Oscillators by resonator:** L-C, (R-C), Crystal oscillators (XO, TCXO, ovenized), SAW, CROs, DROs, Cavity

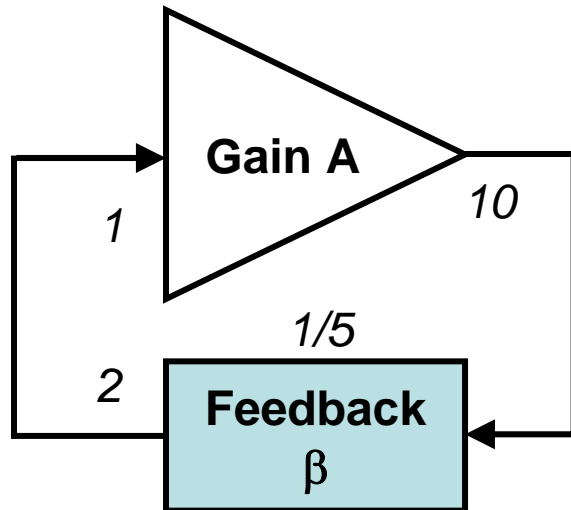
- **Tunable Oscillators**

- VCOs, VCXOs, mechanically tunable VFOs

Specifications and Considerations

- Operating Frequency
- Frequency Drift (ppm,..)
- Tuning Range
- Pulling (verses VSWR &/or transient)
- Pushing (kHz/volt)
- Noise (Phase noise & residual FM, AM noise)
- Temperature effects
- Reliable start-up and spurious modes
- Harmonic performance
- Frequency effects due to shock and vibration
- Injection locking
- Repeatability
- Power requirements including noise
- Mechanical considerations (size, weight, connectors)
- Environmental considerations (temperature, moisture, drop)

Feedback Oscillators



$$\text{Loop Gain} = A\beta$$

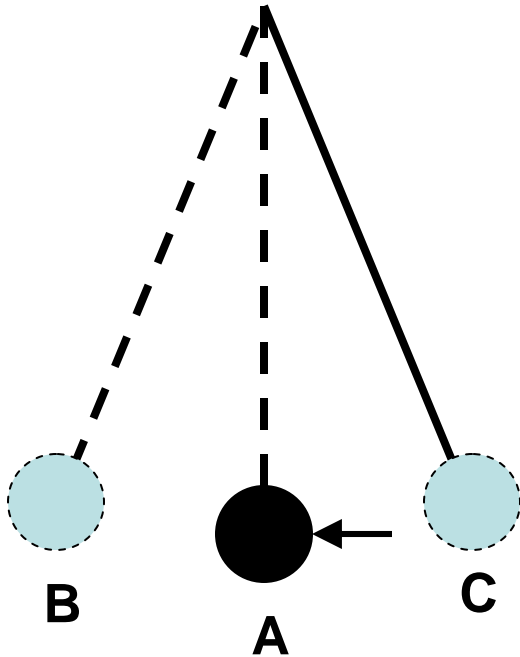
- Active amplification provides output and gain expressed as a ratio or in dB
 - Feedback is generally passive
 - Both blocks have individual transfer gain vs. frequency characteristics
 - Both blocks have individual transfer phase vs. freq. characteristics
 - Usually need one or more frequency selective elements
-
- Conditions for oscillation are (Barkhausen criteria):
 - Loop gain greater than one, so $A\beta > 1$ (sum > 0 dB)
 - Often want 3-4 dB margin, or controlled for waveform
 - Net phase shift around loop = zero degrees (really $N \times 360$)
 - Oscillations build up from noise/transient into saturation at the frequency that satisfies the Barkhausen conditions

Active Devices for Oscillators

- Op-amps and discrete for audio oscillators
- Bipolar transistors for low phase noise RF
 - Like low parasitics, good switching, low $1/F$ & NF
- FETs for high Q VCOs and general purpose
- Special purpose ICs including crystal oscillators
- RF amps for general purpose and higher power
- Microwave diodes above UHF (Gunn, Tunnel (Back), Impatts...)
- Tubes for higher power, legacy and sometimes low cost
 - Magnetrons, conventional, special applications

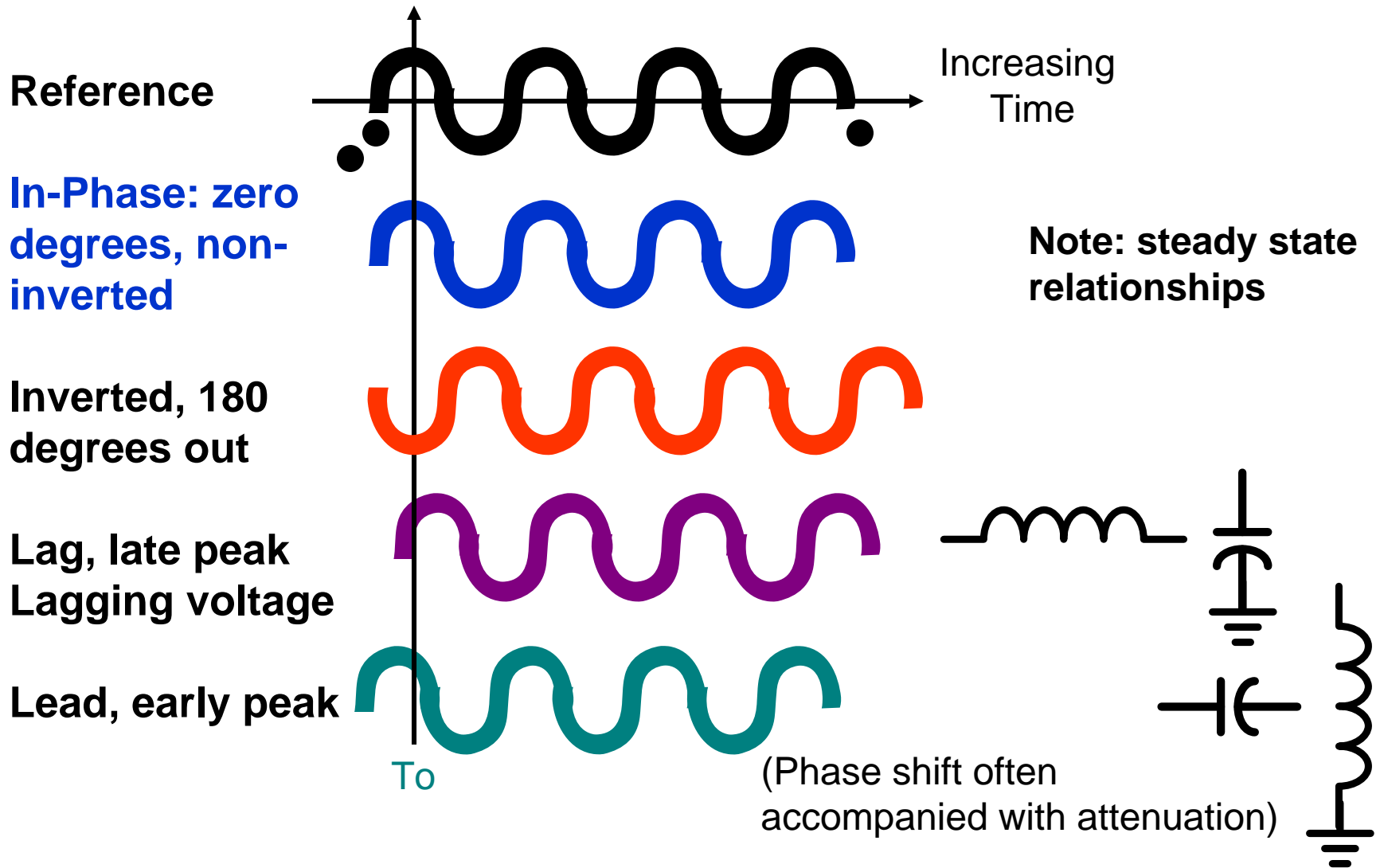
Explanation of Phase: Pendulum Example

Mechanical Oscillator Analogy



- Pendulum has a “natural freq.
- Consider in-phase verses out of phase or random excitation (tapping): only in-phase excitation sustains oscillation (motion)
- Consider rocking chair example with arm movement: arm must be in sync, i.e. correct frequency and in-phase with the rocking
- Phase is always relative to some reference

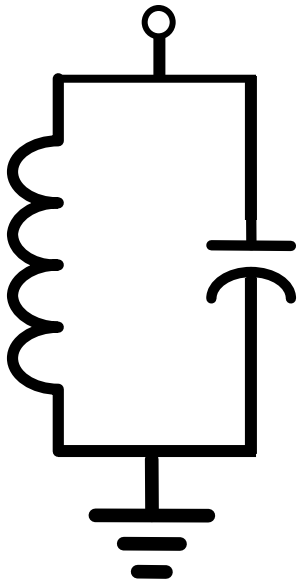
Sine Wave Phase Shift and Effects of Components



Capacitive Divider Resonator/Matching Circuits (Colpitts)

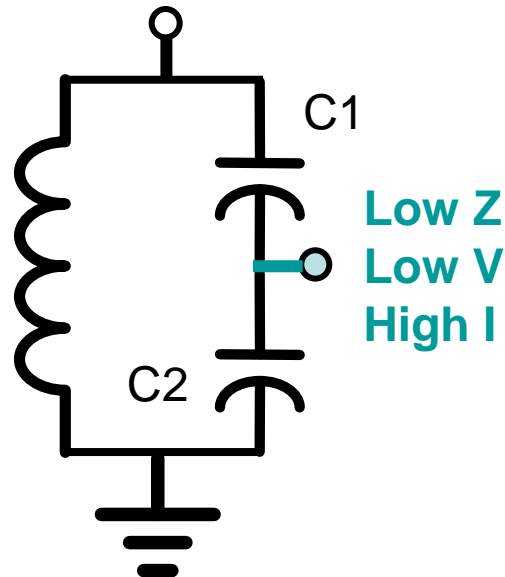
Basic Tank

High Z
@ Resonance



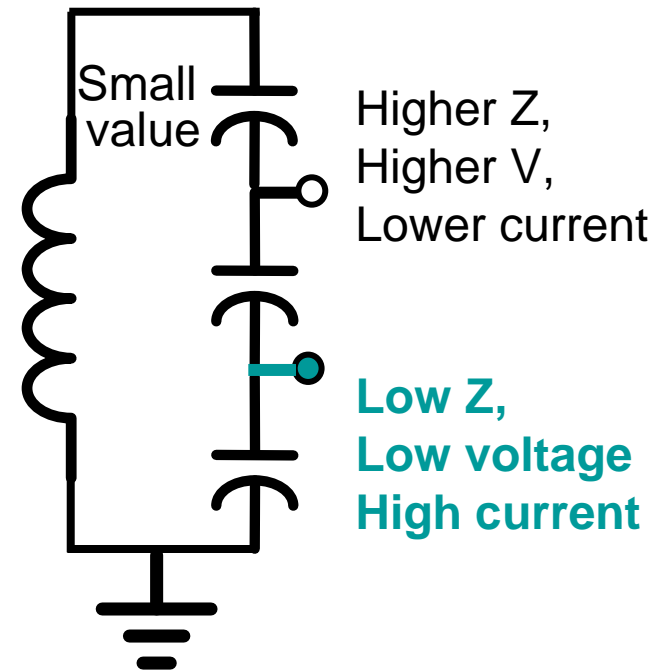
Split C

Hi Z, Hi V,
Low Current



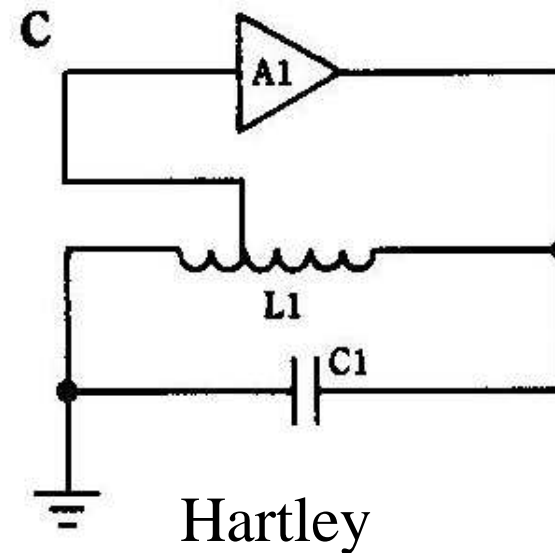
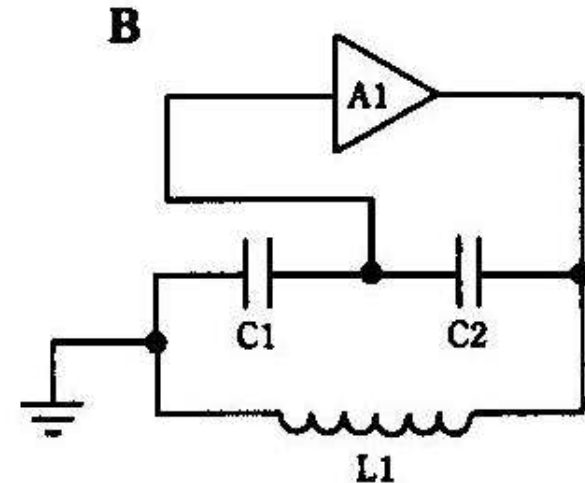
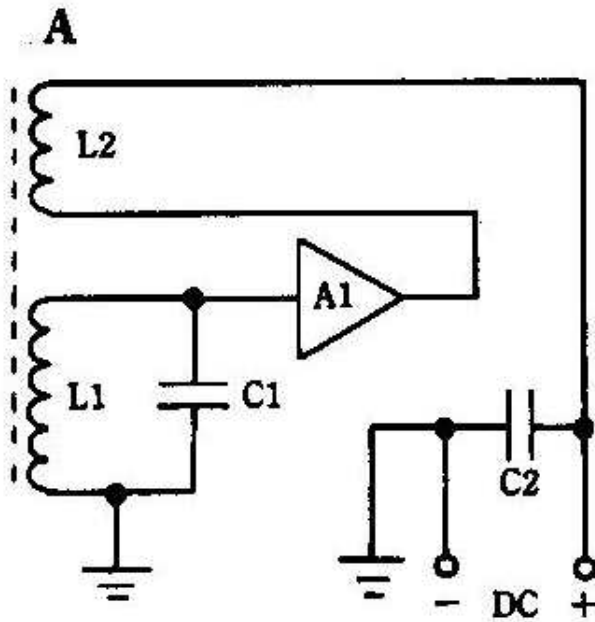
Seiler Modification

Higher Q in Tank



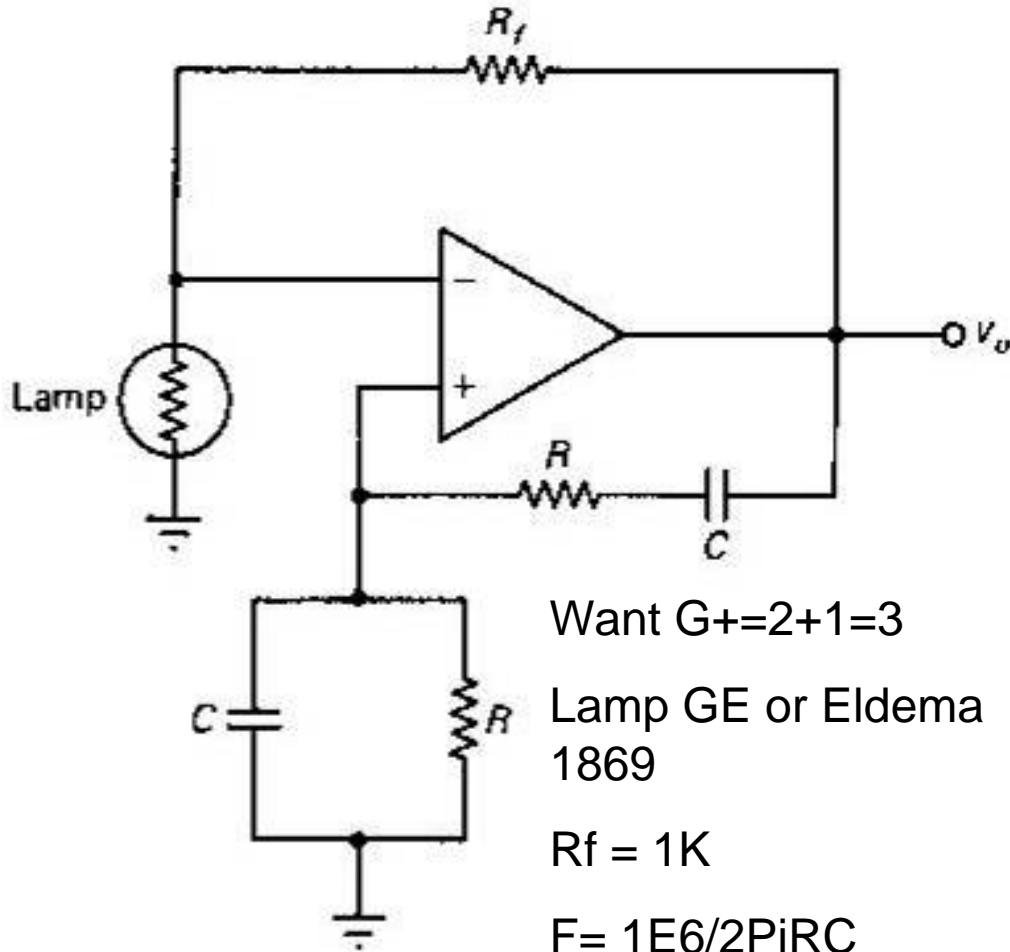
- All ports in-phase and resistive at resonance ($F=1/2\pi \text{ Root LC}$)
- Capacitors are small, inexpensive, precise
- Clapp added C in series with the inductor

Classic LC Feedback Oscillator Architectures



- Many different configurations of each depending on amplifier, bias, ...
- Other architectures as well such as Clapp, Seiler, Miller, Butler, Franklin ...

Wein (Bridge) Oscillator with Non-linear Device



Want $G_{+}=2+1=3$

Lamp GE or Eldema
1869

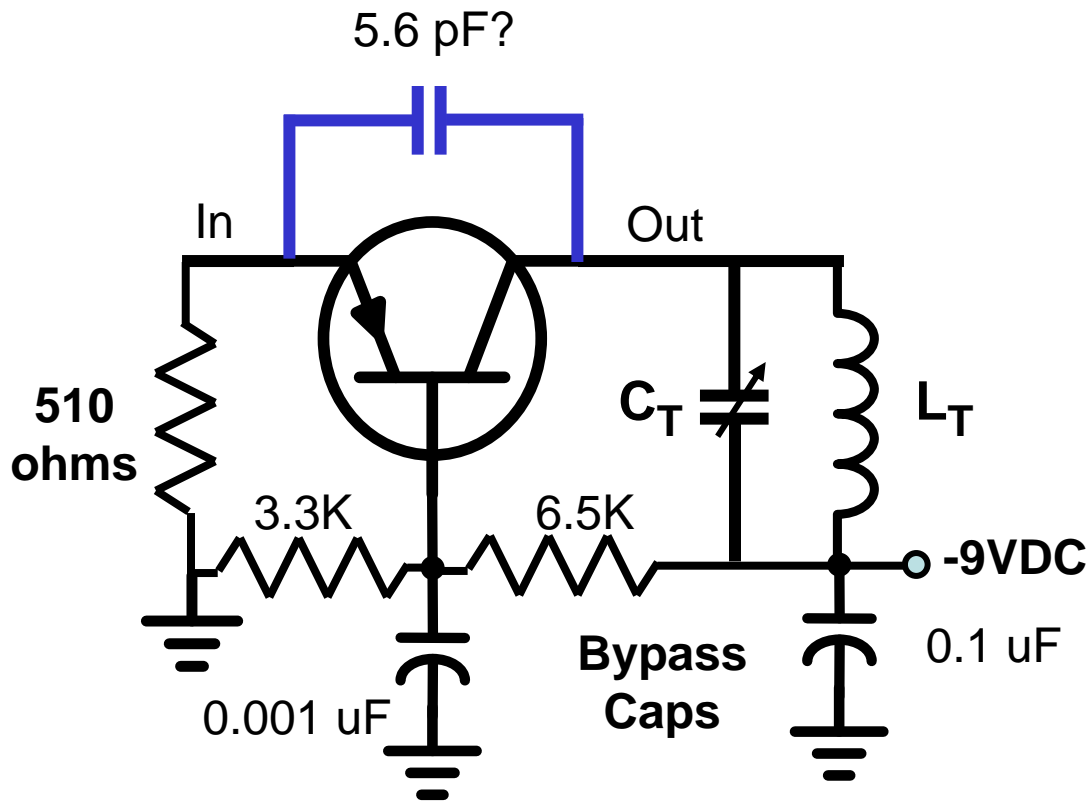
$R_f = 1K$

$F = 1E6/2\pi RC$

- Audio sine-wave RC Oscillator
- Upper circuit + amp constitutes a 0 degree amplifier
- Lower RCs implement the feedback path, get 0 degrees at F_{osc} (lag cancels lead)
- Lamp resistance increases with signal amplitude & reduces gain preventing amplifier saturation

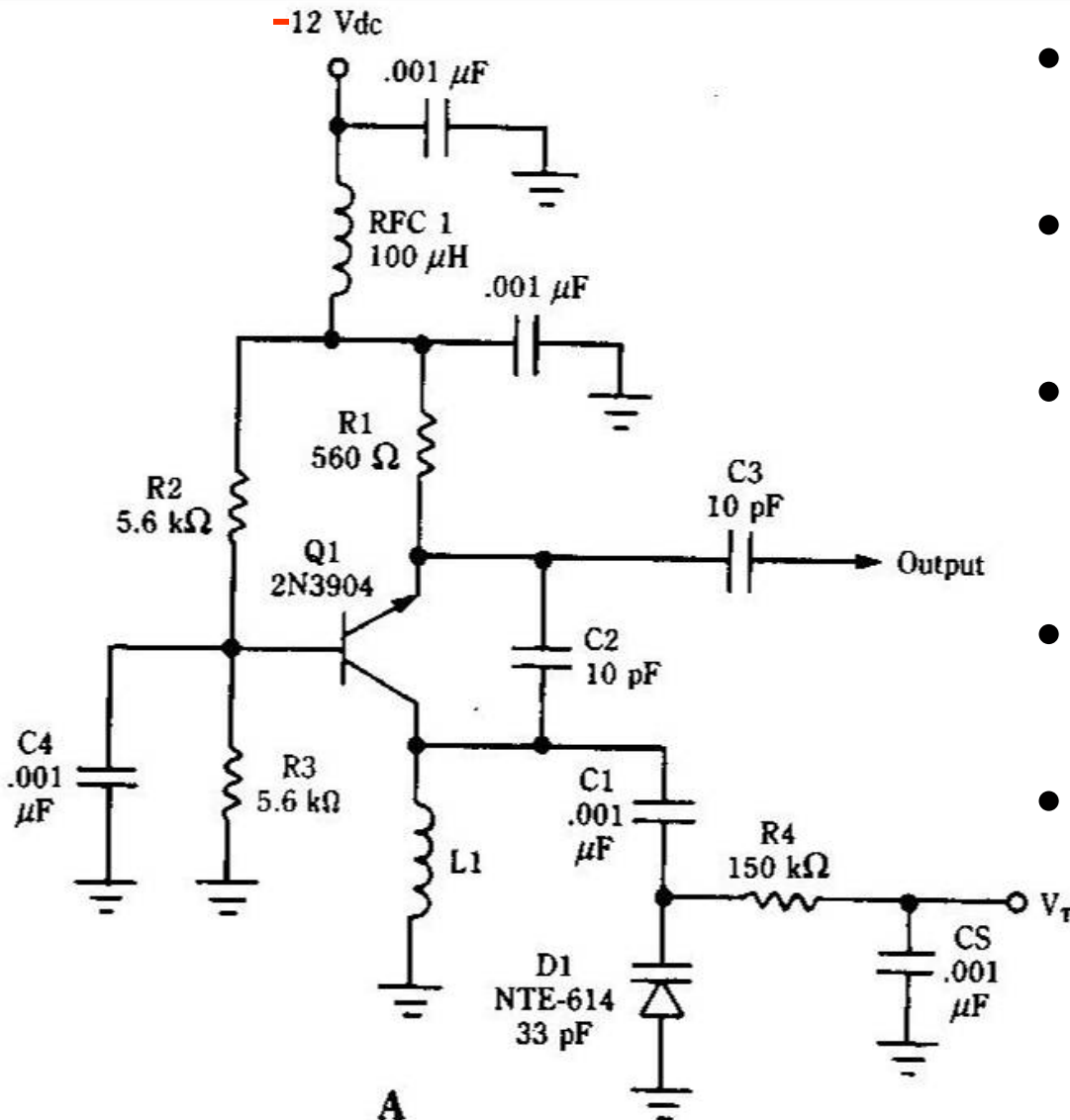
LM741+ Op Amp with balanced positive and negative supplies, high Z inputs

Common Base Oscillator: Basic circuit



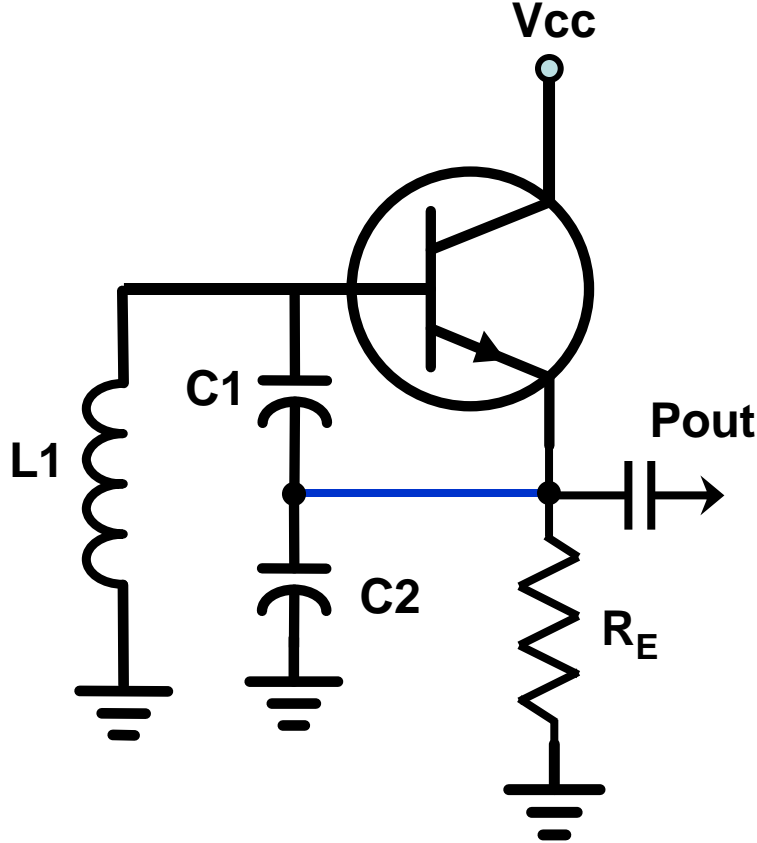
- Easy VHF feedback oscillator
 - Emitter & collector in-phase at lower freq.
 - Base at AC ground as well as lower portion of tank circuit
 - $C_T - L_T$ tank determine frequency
 - Feedback cap in blue, sometimes unnecessary
-
- Emitter capacitance and device lag correct feedback phase
 - Can add varactor or just modulate base to get some FM

Varactor Provides FM/VCO operation



- VHF voltage controlled oscillator
- Common base oscillator drawn “upside down”
- D1 varactor substituted for normal tank capacitor
- Can replace C1 with a second varactor
- *Negative supply*

Common Collector Oscillator



Colpitts version shown,
Clapp (and Seiler?) versions
are popular.

- Popular “emitter follower” oscillator, basic circuit, bias and DC block circuitry not shown.
- High base input impedance allows good Q
- Split C tank steps up voltage and *matches* low emitter output impedance to high base input impedance
- Can take harmonic output from a collector circuit
- FETs *with diode* work for higher noise applications
- Replace inductor with ()...

Crystal Oscillators

Ed Messer

2nd Half of Presentation

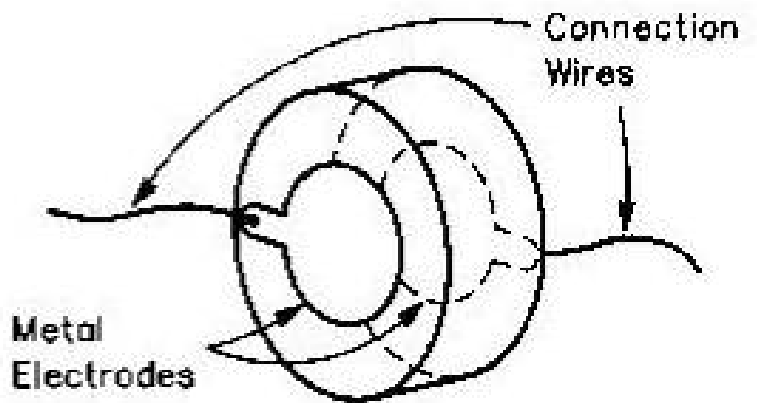
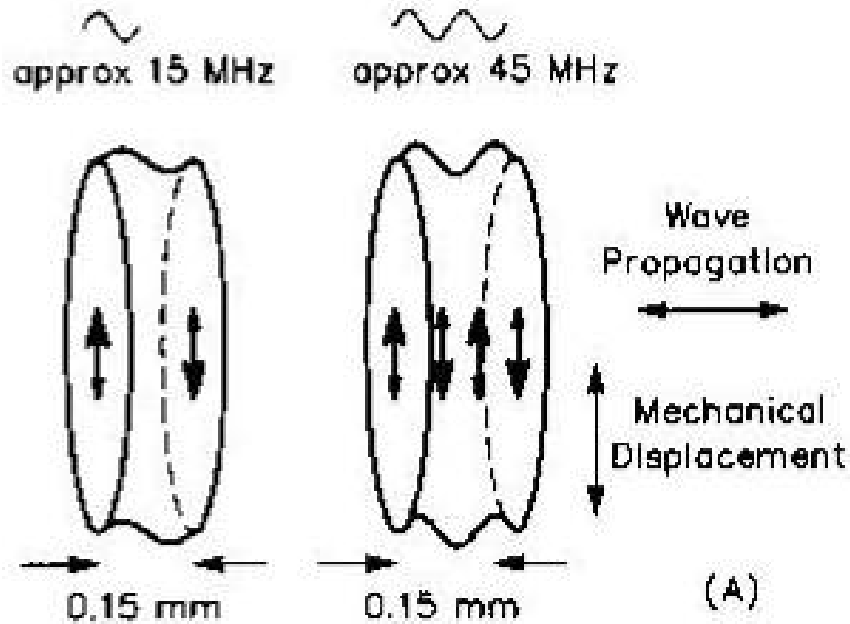
Crystal Oscillator Specifications

- Center Frequency: 30 kHz to 200 MHz
- Frequency accuracy: (initial & PTD) ± 10 PPM or other, 5 PPM first year
- Frequency accuracy vs. temperature: ± 10 PPM or other (2.5 PPM)
- Output power and tolerance
- Phase noise
- Set-ability: Range, to within...
- Electronic tuning: maybe 50- 200 PPM, maybe 500+ fundamental
 - Linearity consideration
- Start-up time: can be seconds
 - Can improve somewhat with introduced transient
- Warm up time: 15 seconds to many minutes
- Power Requirements: initially more if ovenized, more cold, regulator...
- Mechanical: size, weight, form factor
- Environmental
 - Shock: crystals don't like drop onto hard surfaces, also retrace consideration
 - Vibration

Partial List of Crystal Suppliers

- Mtronpti.com: Formerly PTI, High shock, high-rel, lesser
- Statek.com: miniature resonators, USA
- Greenrayindustries.com: T53 0.28 PPM Oscillator
- Crystekcrystal.com: Florida
- ICMFG.com (Kansas maybe or...)
- Bomarcystal.com (New Jersey & offshore)
- ESCXTAL.com
- OSCILENT.com (China, Korea)
- CTS (lower performance?, USA)
- FILTRO.com (USA, website unimpressive, but...)
- Quartztek: richard24@mindspring.com
- Suppliers: Mauser, Digikey, other
- Audience participation

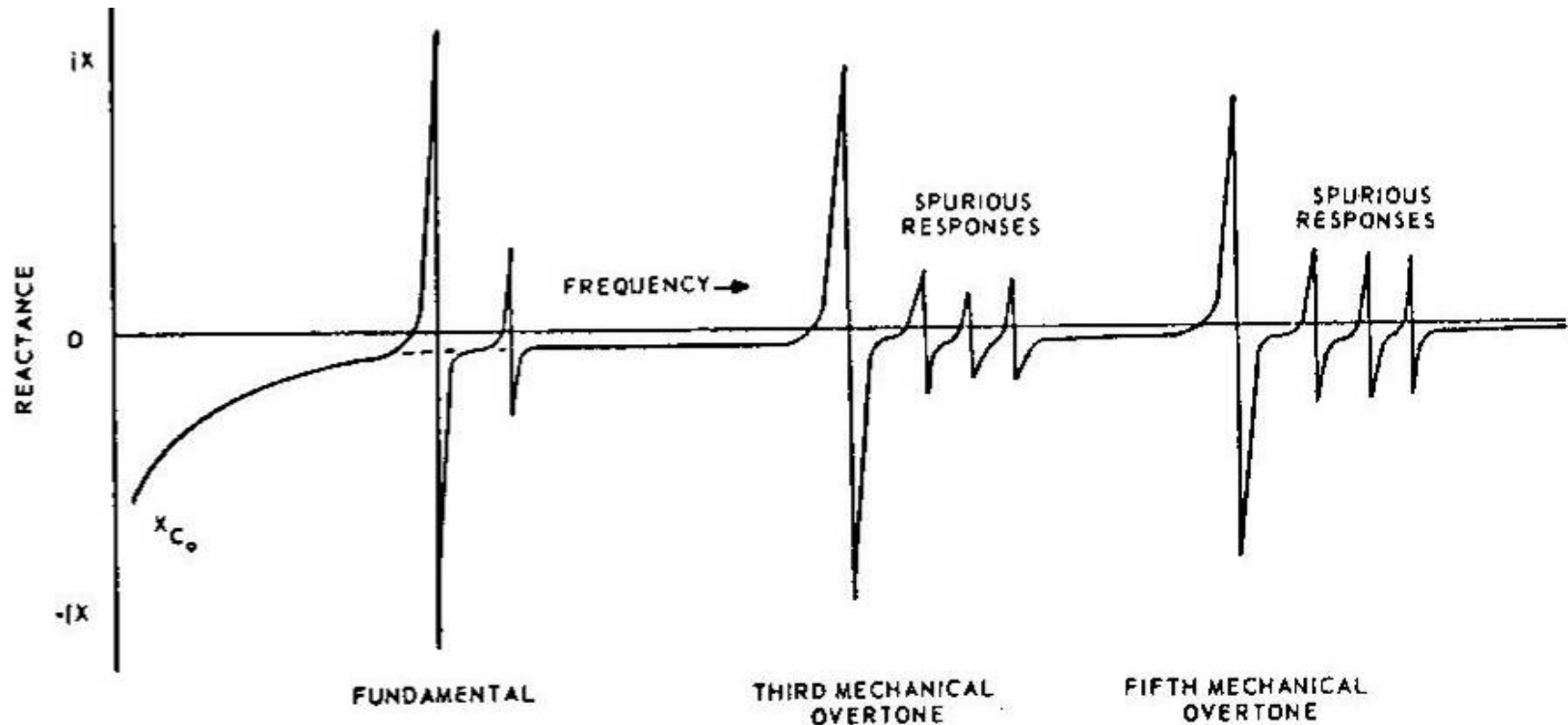
Crystal Operation and Construction



(thickness exaggerated
and not to scale)

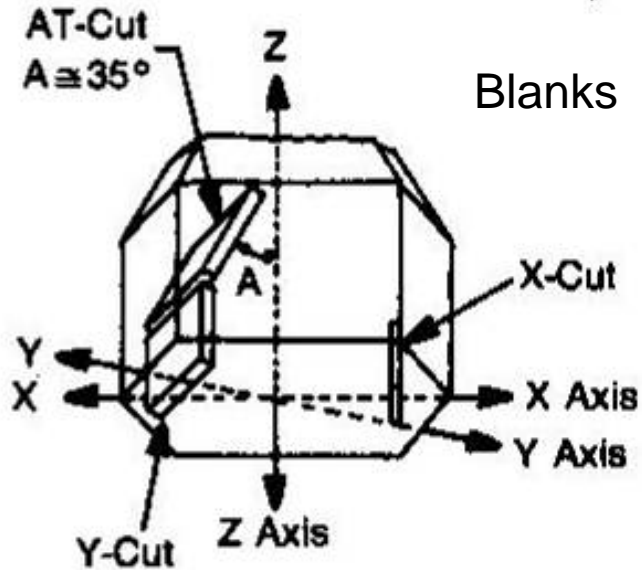
- Thickness-shear vibration at crystals fundamental and third overtone
 - See next slide for modes
- Bottom figure shows crystal internal construction
 - Metalized surfaces for connections
 - Disk is typically supported by the leads

Artists Rendition of Overtones and Spurious

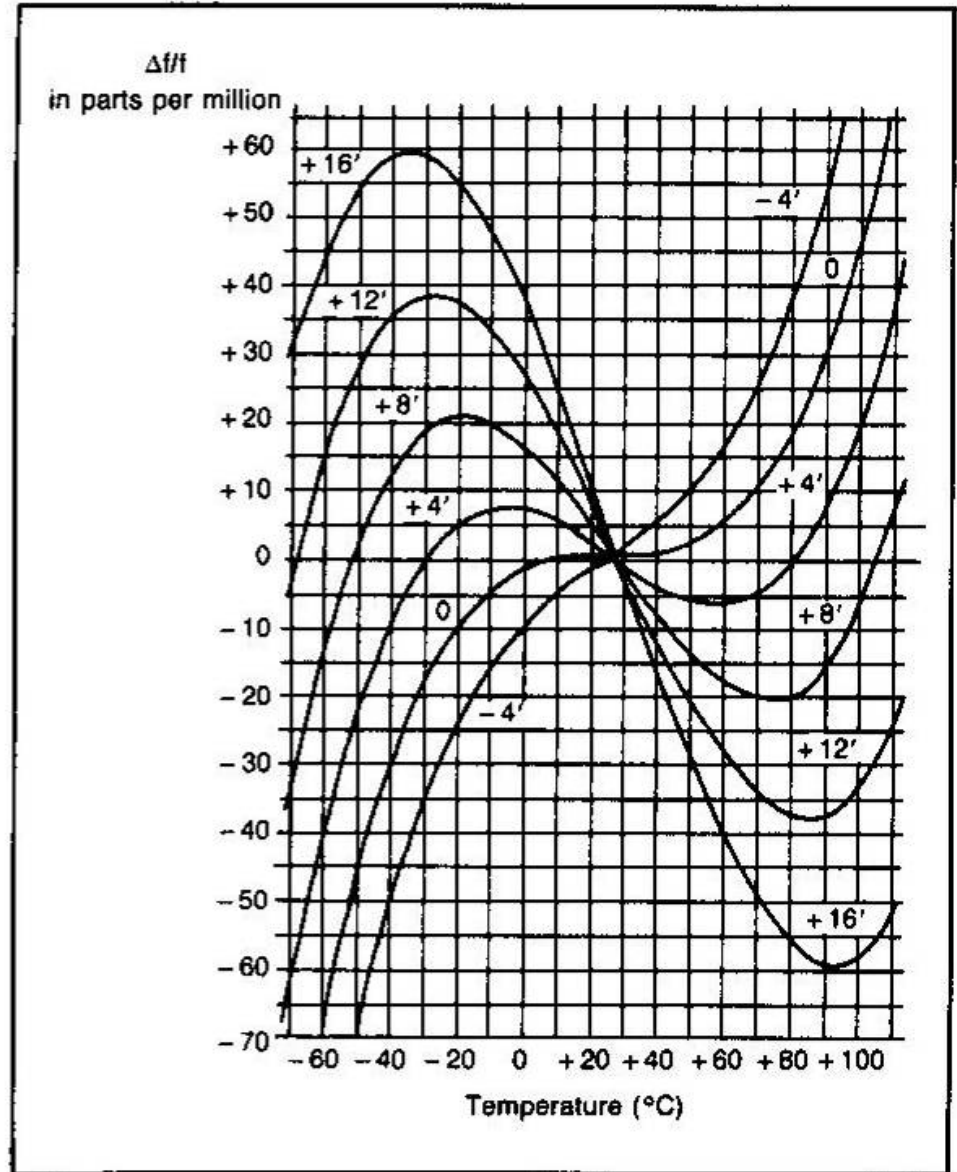


- Rendition of reactance verses frequency
- Shows fundamental, third and fifth overtones
- Spurious show up on high side (crystal filters also)
- An actual S21 sweep would probably show nothing because responses are so narrow (i.e. high Q)

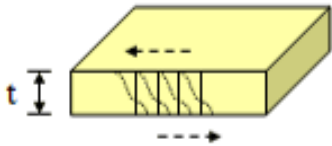
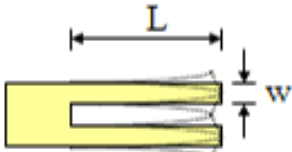
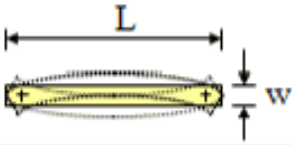
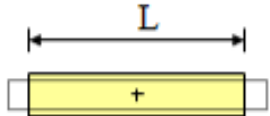
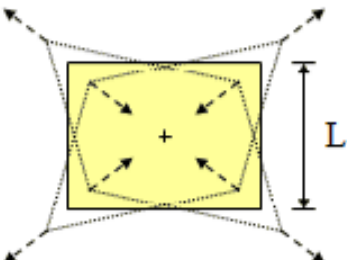
Crystal Temperature Drift Dependent on Cut



- Maybe choose cut based on temp range
- Compensation can be done with TC caps, or varactors coupled to thermistors or D/A & uP
- Limit drive levels to 1 mW or less as specified



Flexure Modes In Crystals

Mode of Vibration	Cut	Frequency Range (kHz)	Frequency Formula (kHz)	Capacitance Ratio (typical)
Thickness-Shear 	AT Fundamental	800 ~ 5,000 2,000 ~ 80,000	1,670/t 1,670/t	300 ~ 450 220
	AT 3rd Overtone	20,000 ~ 90,000	1,670 * n/t	n ² * 250 n = overtone mode
	AT 5th Overtone	40,000 ~ 130,000		
	AT 7th Overtone	100,000 ~ 200,000		
	AT 9th Overtone	150,000 ~ 230,000		
	BT Fundamental	2,000 ~ 35,000	2,560/t	650
Length-Width-Flexure 	+2°X	16 ~ 100	700 * w/L ²	450
Length-Width-Flexure 	XY NT	1 ~ 35 4 ~ 100	5,700 * t/L ² 5,000 * w/L ²	600 900
Length-Extensional 	+5°X	40 ~ 200	2,730/L	140
Face-Shear 	CT	250 ~ 1,000	3,080/L	400
	DT	80 ~ 500	2,070/L	450
	SL	300 ~ 1,100	460/L	450

Co/Cm(?)

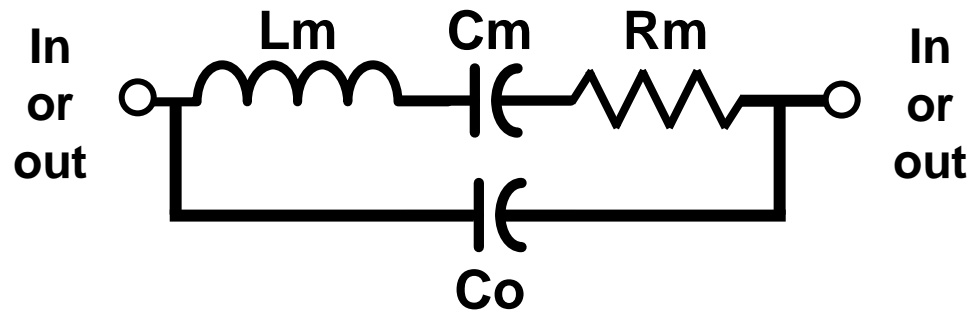
Lower
Better for
Pulling

N² ??

Thousands
For third OT?

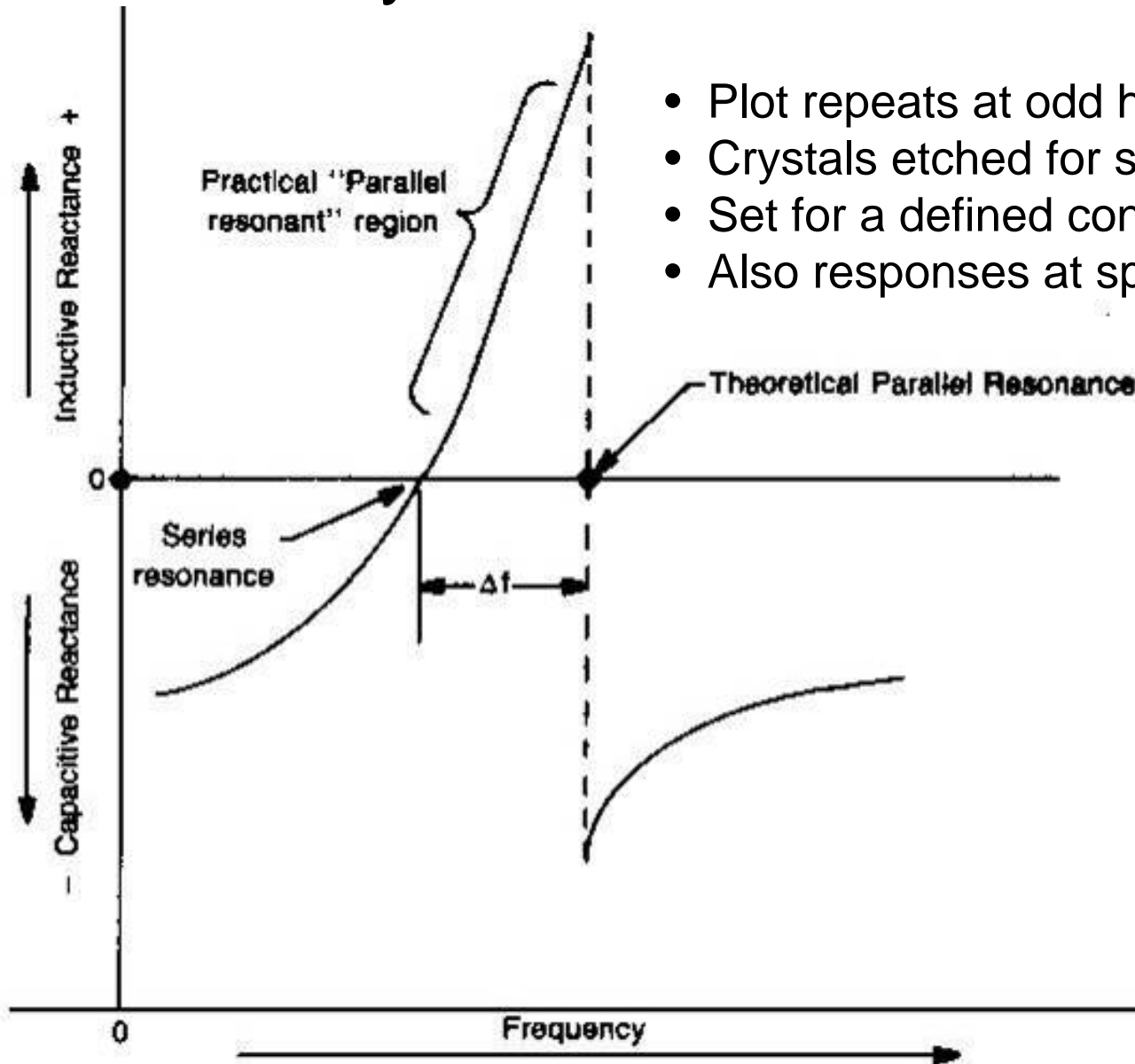
BT cut
apparently
thicker for
fundamental

Crystal Equivalent Circuit & Some Values



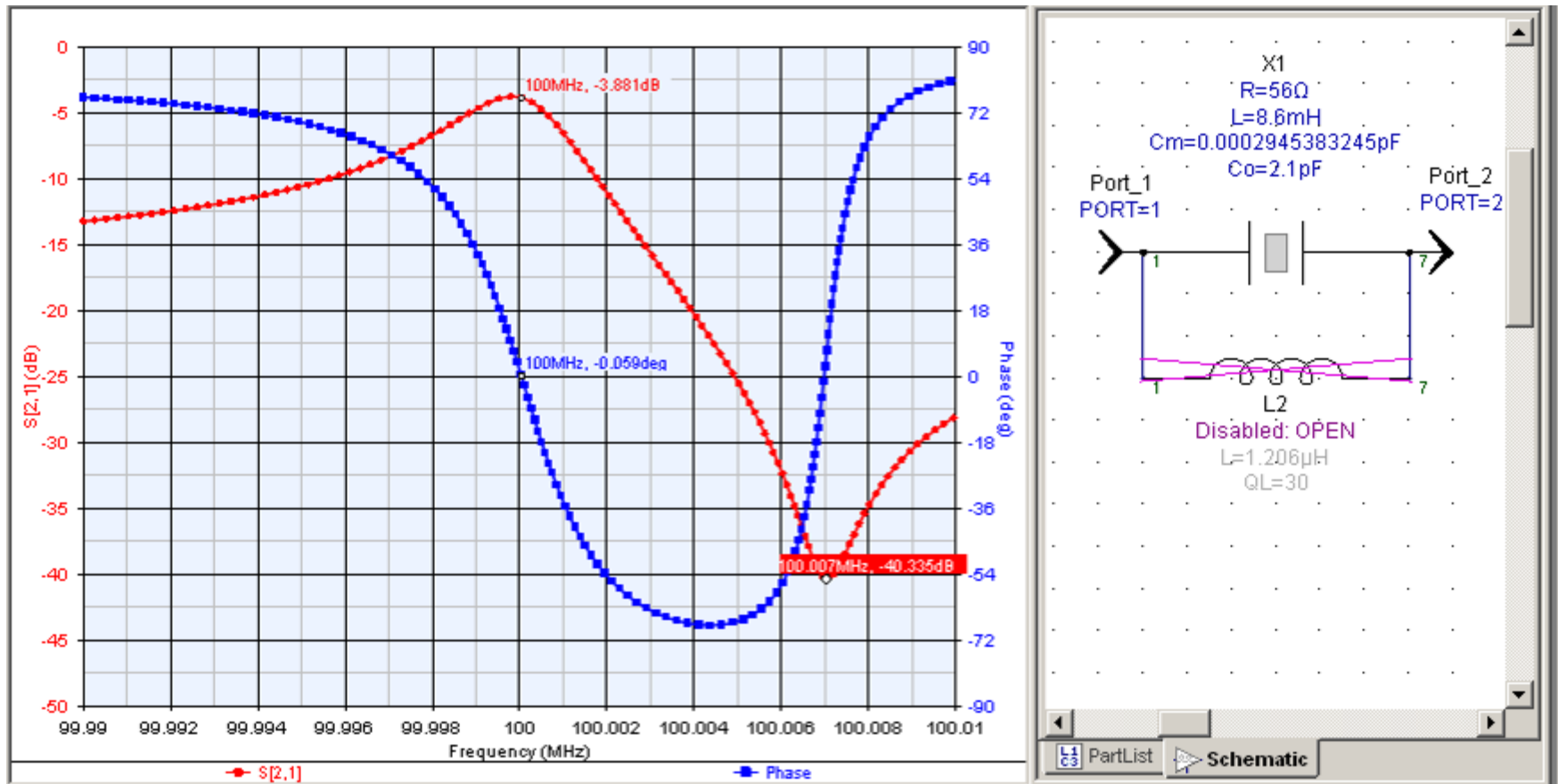
FREQ.	L	Cm	Co	R	Q	Delta F
(MHz)	(mH)	(pF)	(pF)	(Ohms)		(Hz)
1.0	3500	0.00724	3	340	64,647	2415
10.0	12.7	0.01997	5.7	8	99,695	35027
100.0	8.6	0.00029	2.1	56	96,443	14,040

Plot of Crystal Reactance vs. Frequency



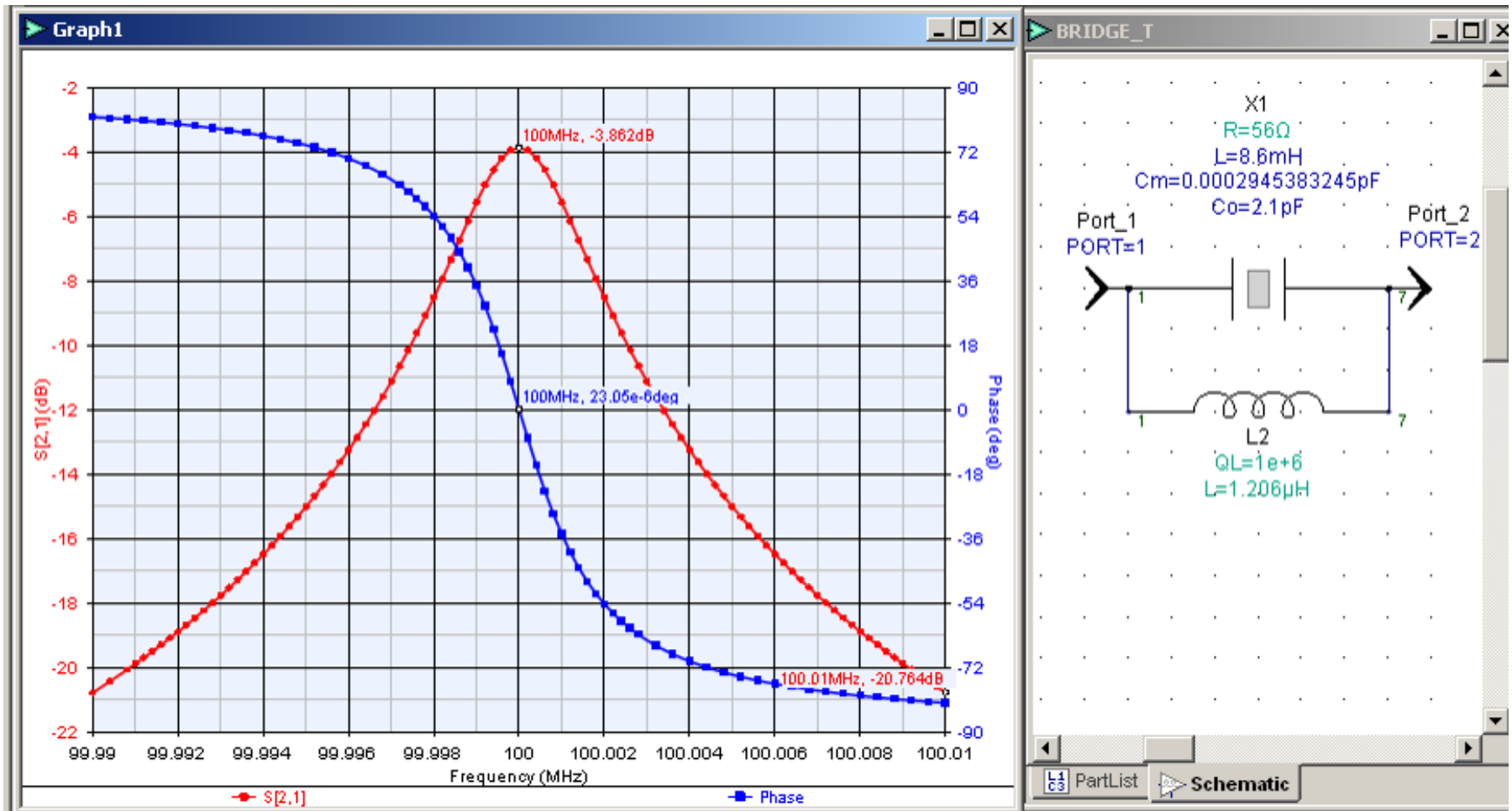
- Plot repeats at odd harmonic frequencies
- Crystals etched for series resonance
- Set for a defined condition
- Also responds at spurious frequencies

100 MHz Crystal Simulation: S21 Gain & Phase



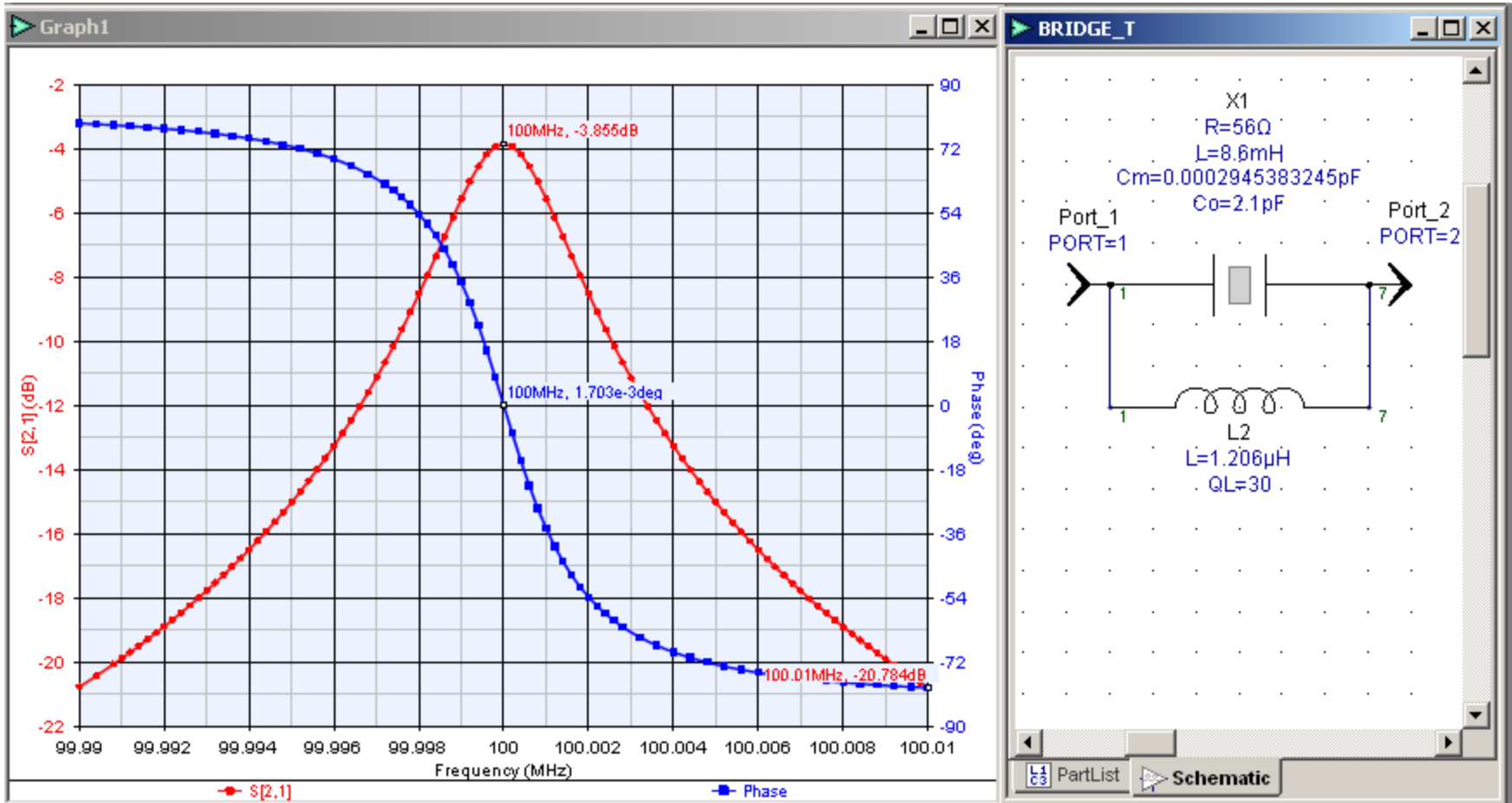
- Just the crystal, plot shows series and parallel resonances
- Zero phase is actually 30 Hz high of 100 MHz for values shown
- Parallel resonance (“anti-resonance”) is 7 kHz higher

CRYSTAL WITH HIGH Q PARALLEL RESONATING INDUCTOR



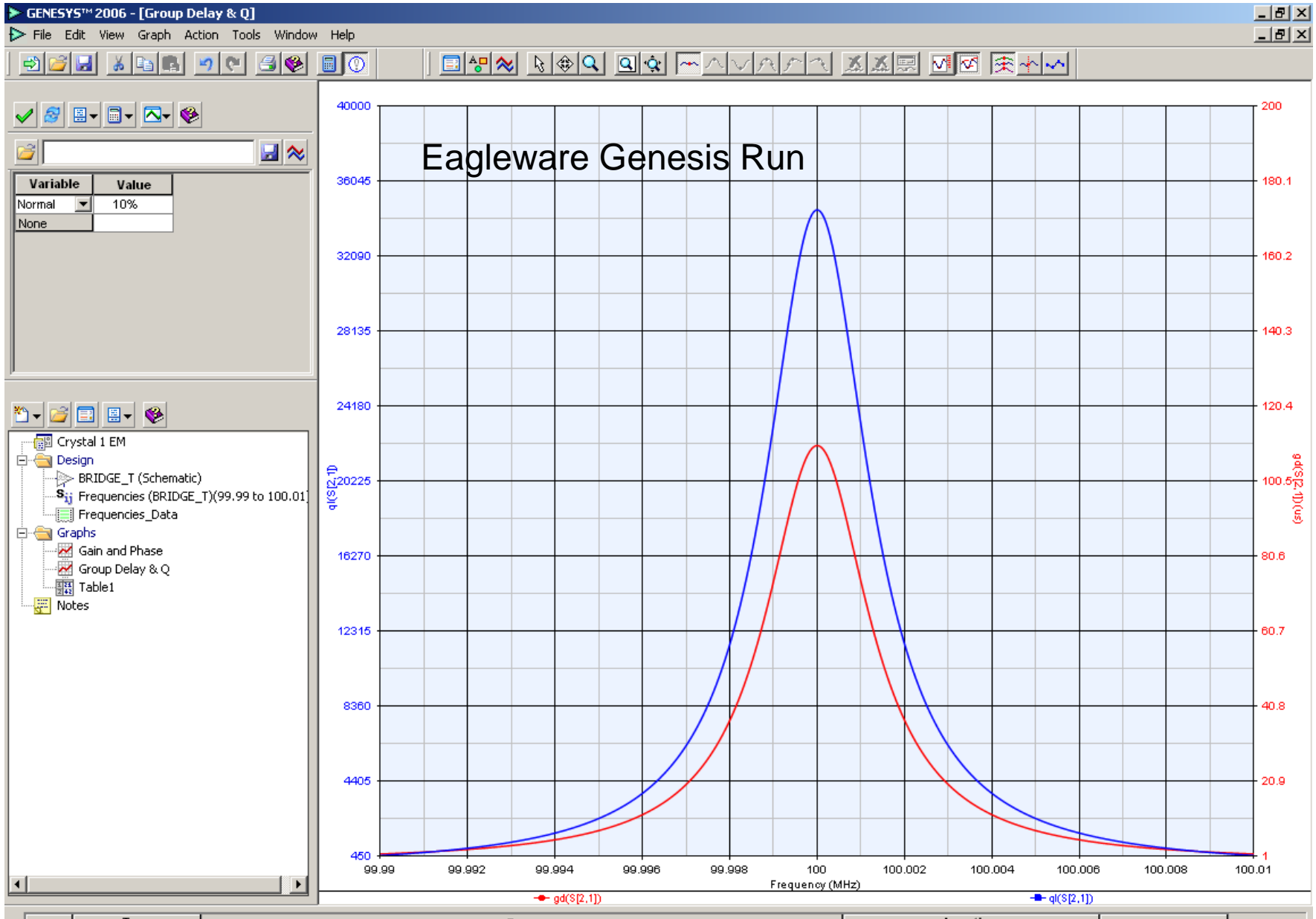
- In close the circuit acts like a pure series tank resonator
- Zero phase pretty much right at 100 MHz

CRYSTAL WITH LOW Q PARALLEL RESONATING INDUCTOR

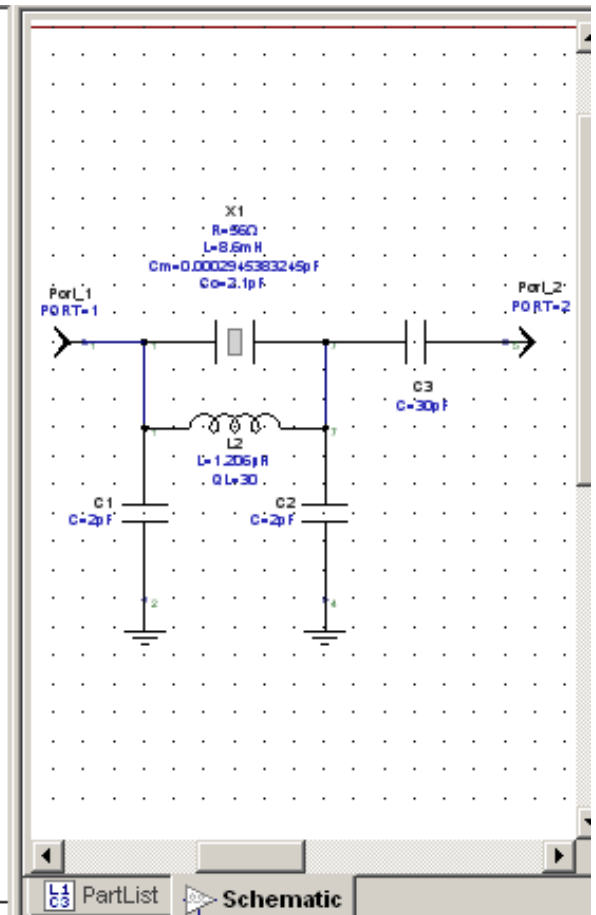
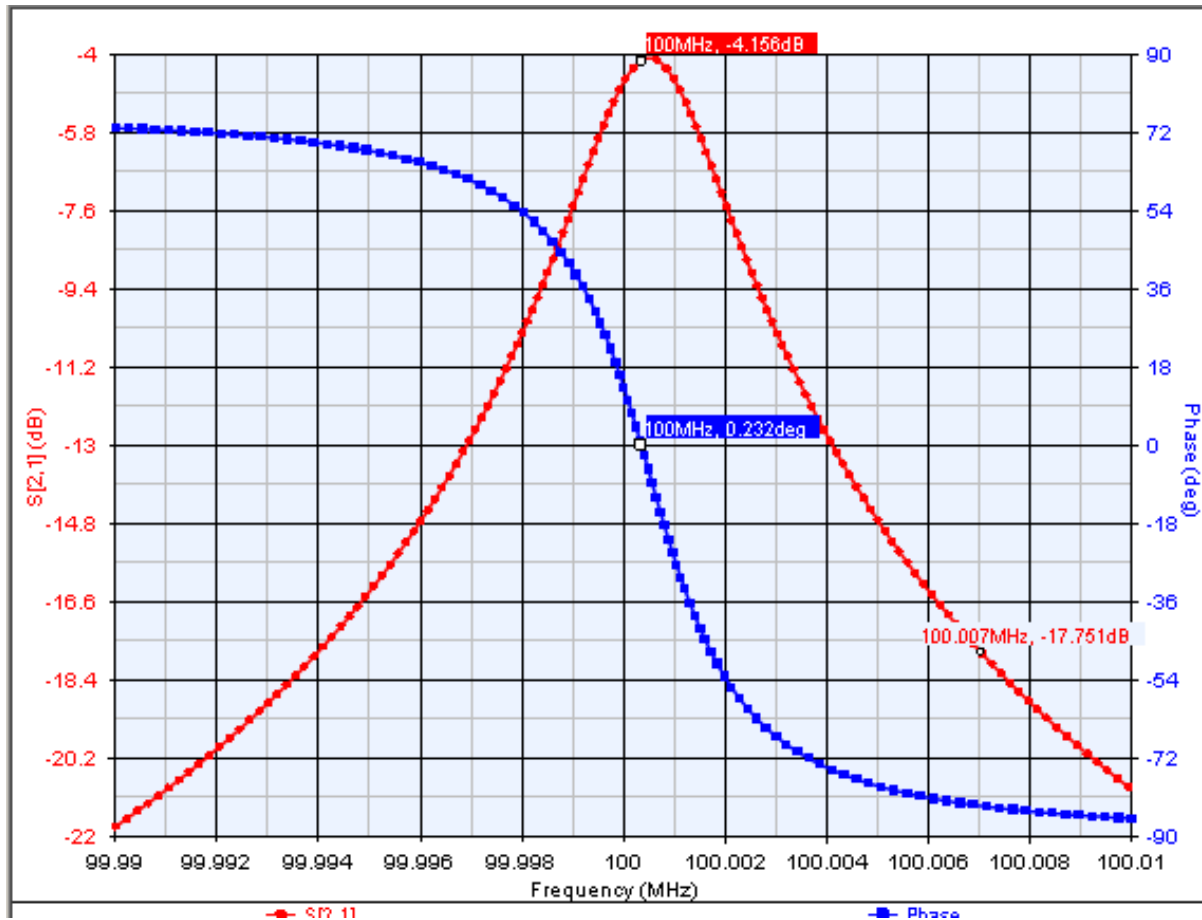


- Q=30 inductor does not hurt “phase rate”, i.e. loaded Q

Q Peaking at ~34000, and Delay Peaking at 110 uS

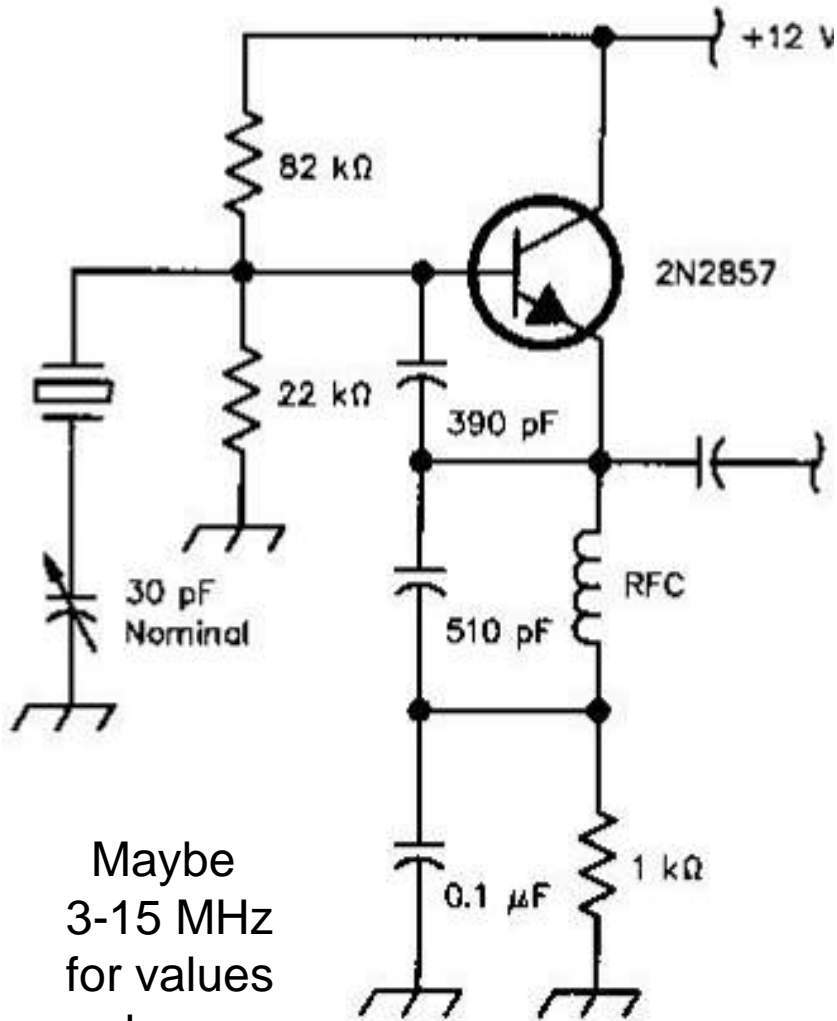


Crystal with Series C, L and Parasitics



- 30 pF series C with parasitics shift frequency up 340 Hz
- Dominate factor is series C, note: crystals are specified/etched with a specific series C in the circuit

Colpitts Crystal Oscillator

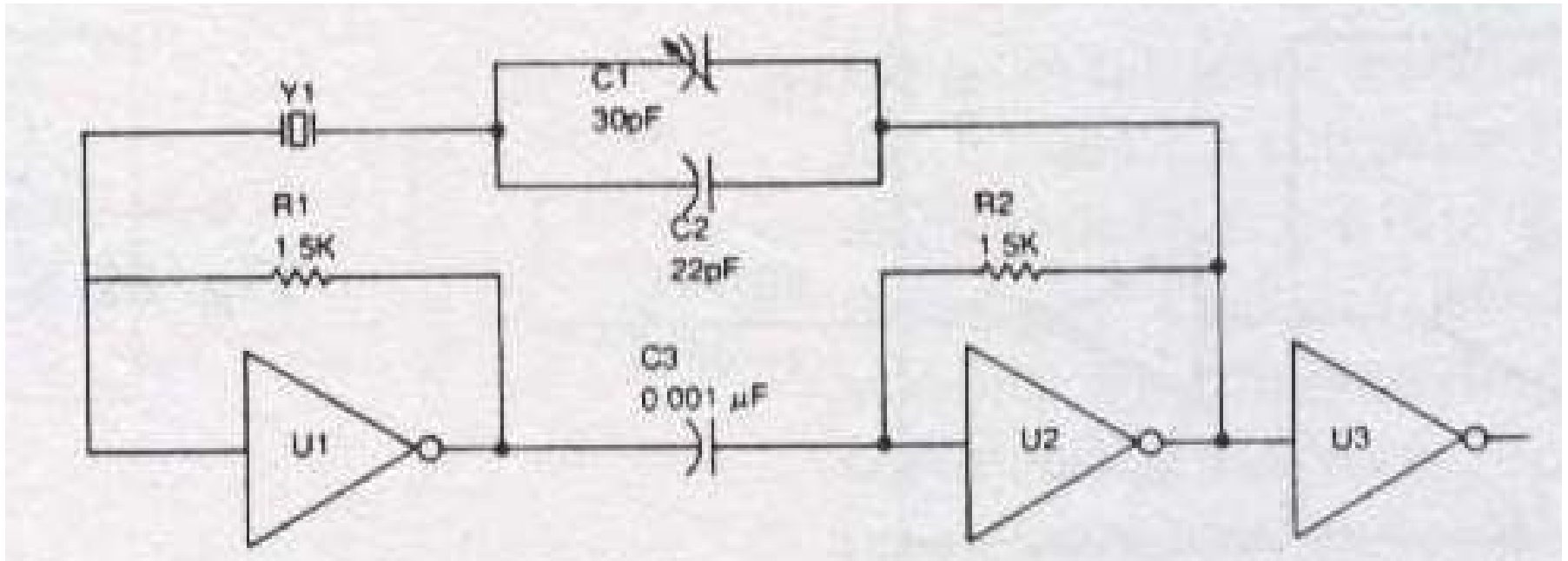


Maybe
3-15 MHz
for values
shown

- Schematic shows some practical values and one way to accomplish bias.
- Crystal operates above series resonance and acts like a very high Q inductor.
- Can replace tuning capacitor with a varactor circuit to implement electronic tuning.
- Room for improvement...

3K load , 10 mW?

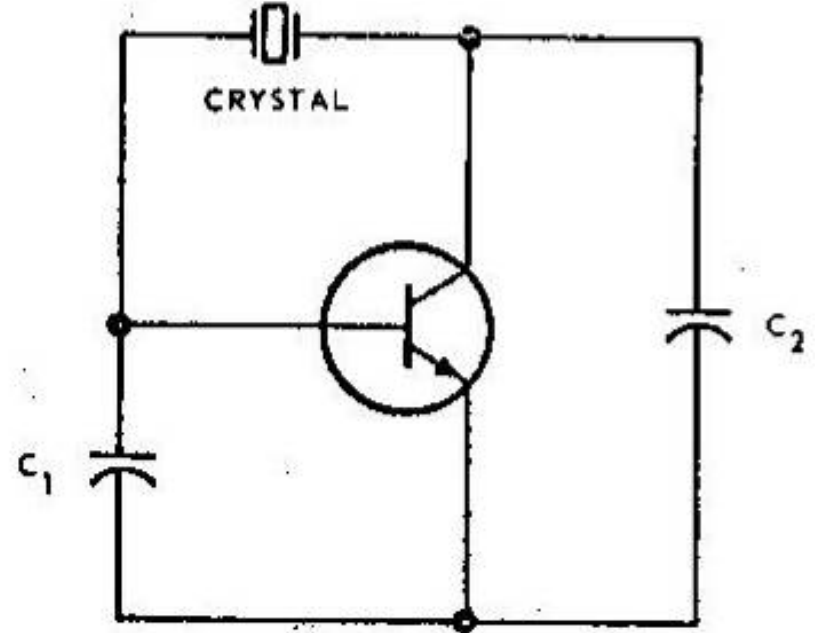
TTL Gate Crystal Oscillator



- One of many single and dual gate implementations
- Crystal runs fundamental series mode
- Crystal “sees” ~30 pF for correct frequency and trim
- Negative feedback resistors bias gates for startup
- Rectangular output, harmonic rich past 900 MHz
- Fine for digital / less critical applications, watch EMI

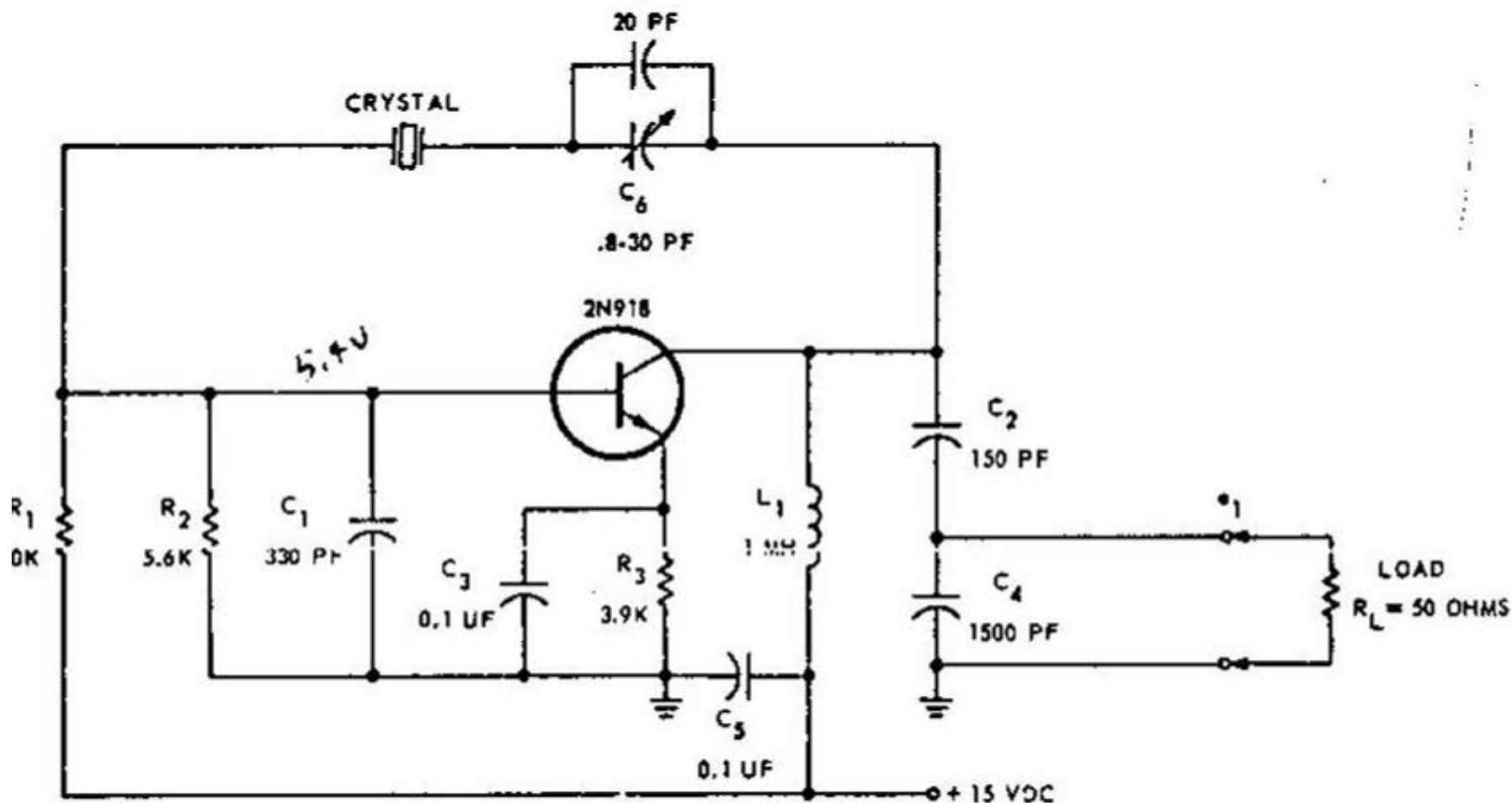
Pierce + Oscillator Simplified Schematic

Figure 9-8. Pierce, Colpitts, and Clapp Oscillators, Basic A-C Schematic Diagram



- Ostensibly an AC model of a Pierce Oscillator (grounded emitter)
 - Get extra 180° of phase shift from capacitors and crystal
- If you ground the collector and redraw you get a Colpitts (emitter follower) oscillator
- If you ground the base, you get you get yet a third (*Clapp? Messer says grounded base Colpitts*) design.
- If they are really all the same circuit then performance is ... similar?

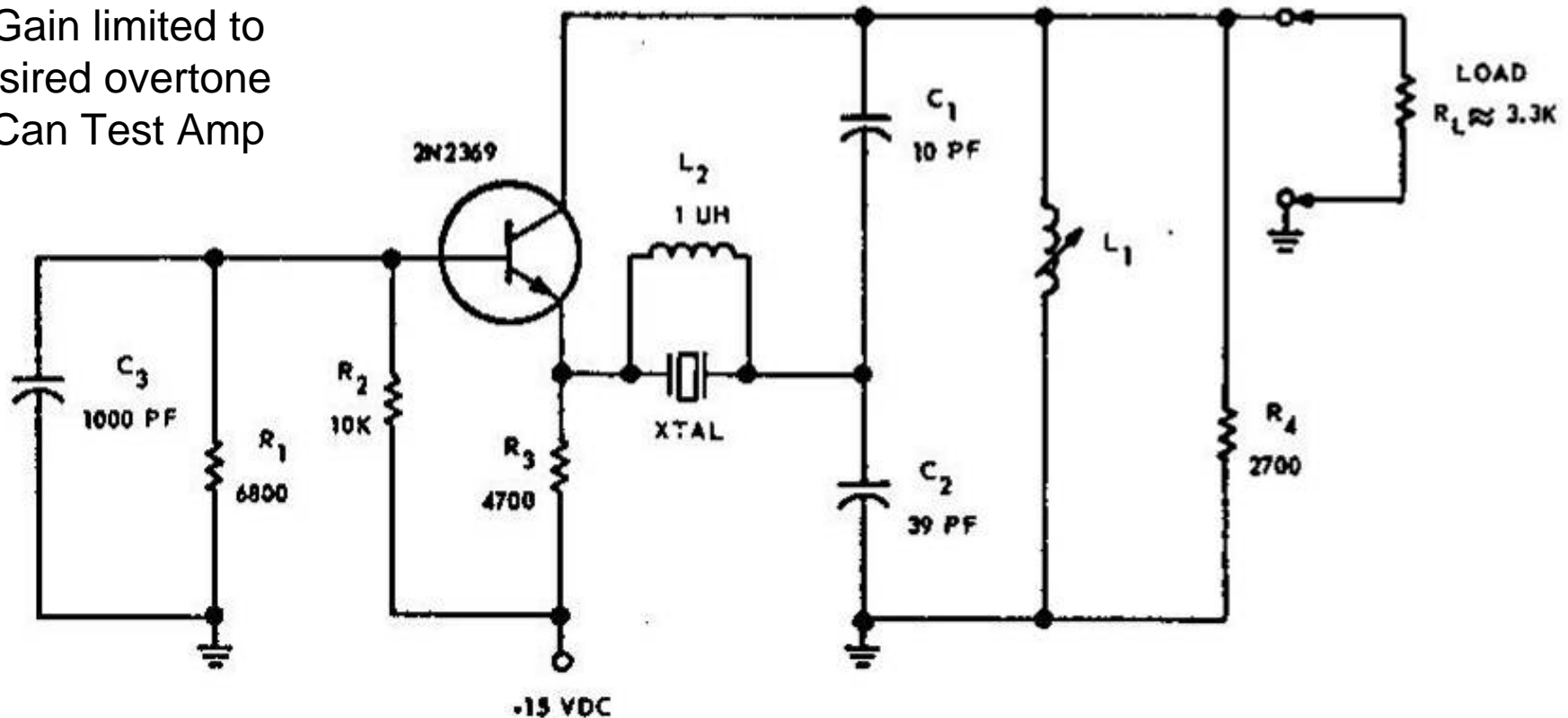
Pierce Oscillator Schematic



- Not a Messer favorite but recommended by Collins, worked well for Oscillatek
- Crystal operates as an inductor.
- Output tank tuned off (? , low) and helps suppress harmonics

75 MHz Oscillator, Some Redeeming Features

- Gain limited to desired overtone
- Can Test Amp

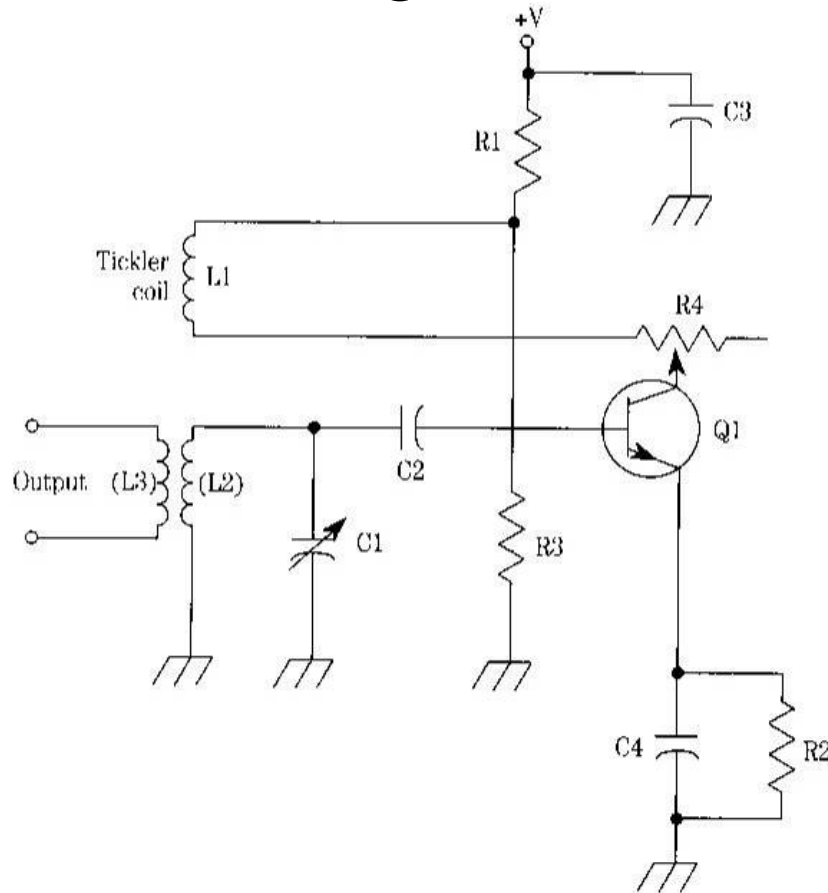


- Bypassing, regulator and buffer not shown
- Positive supply implementation probably preferred
- Can trim with resistor in place of crystal, crystal operated in series mode, can add series C with crystal

End of Crystal Oscillators

October 09

Regenerative Oscillator



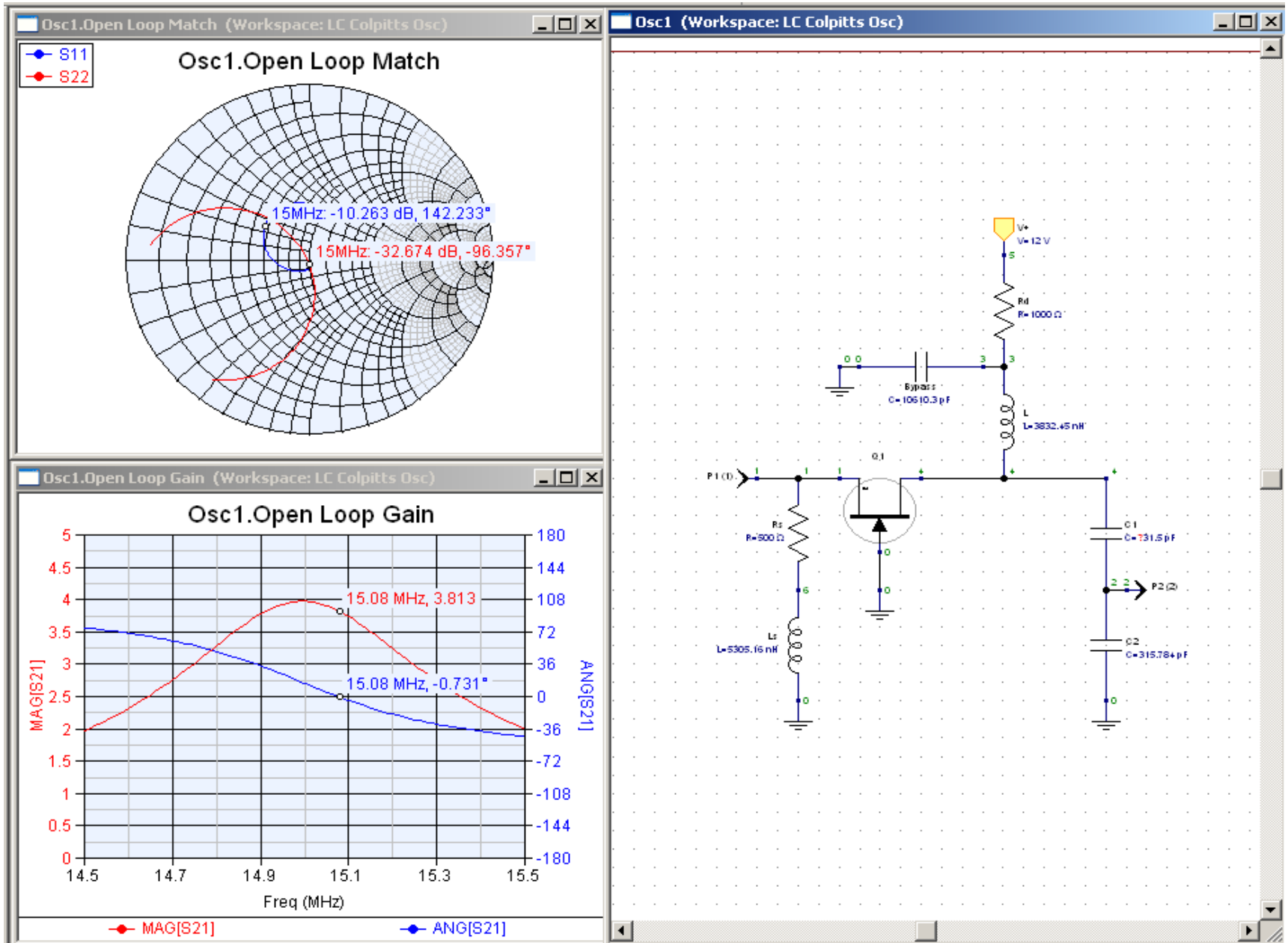
- Circuit captured for historical interest
- Not considered necessary for new designs

2-11 The Armstrong oscillator circuit is often used in regenerative radio receivers.

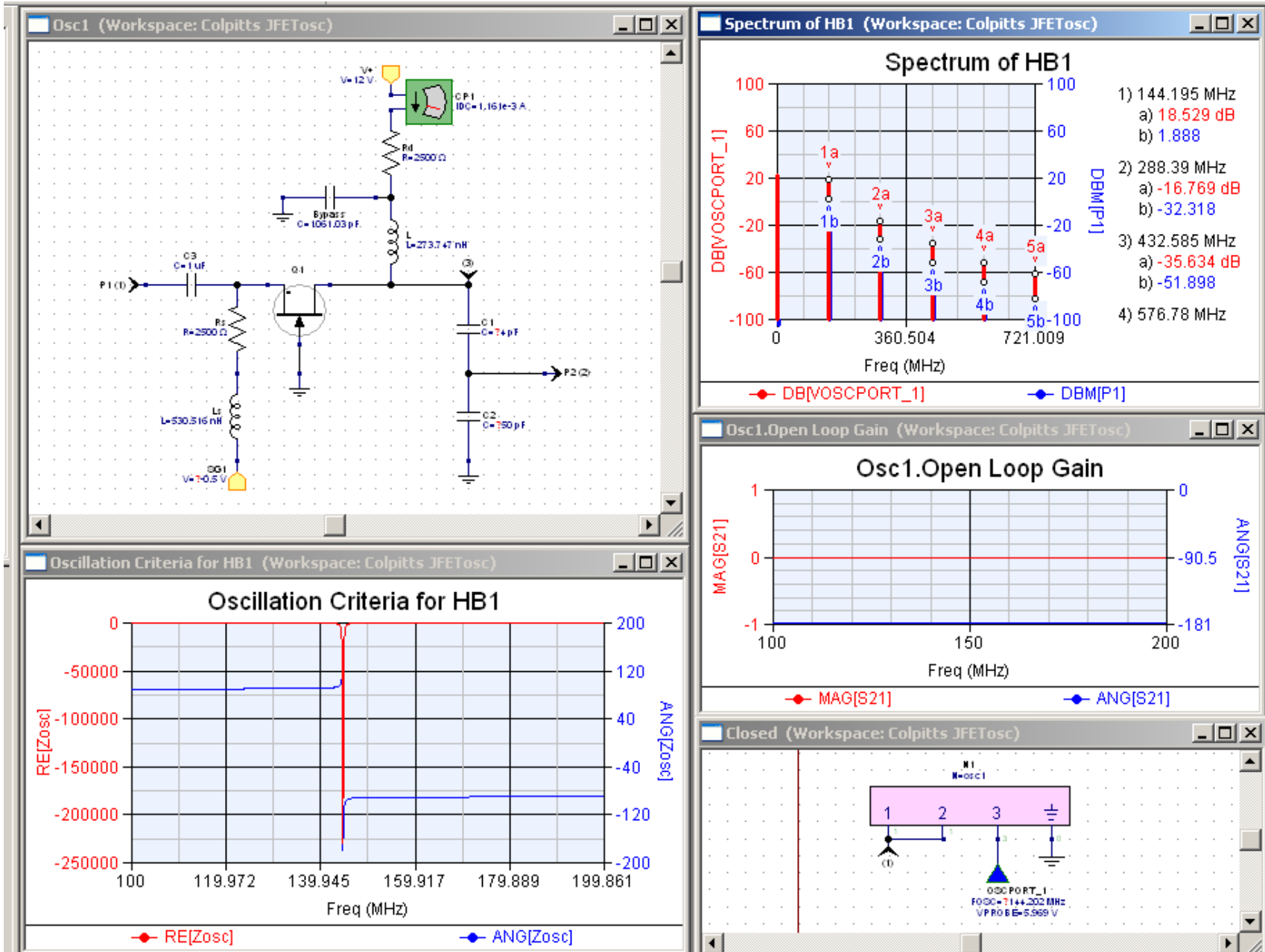
These coils must be very carefully positioned so that their mutual inductance is of the proper polarity, or the circuit might not oscillate reliably, if at all.

Potentiometer R4 controls the level of the current flowing in the tickler coil, and thus, the amount of feedback or regeneration. This potentiometer is omitted in some practical Armstrong oscillator circuits.

SMALL SIGNAL ANALYSIS OF OPEN LOOP CHARACTERISTICS

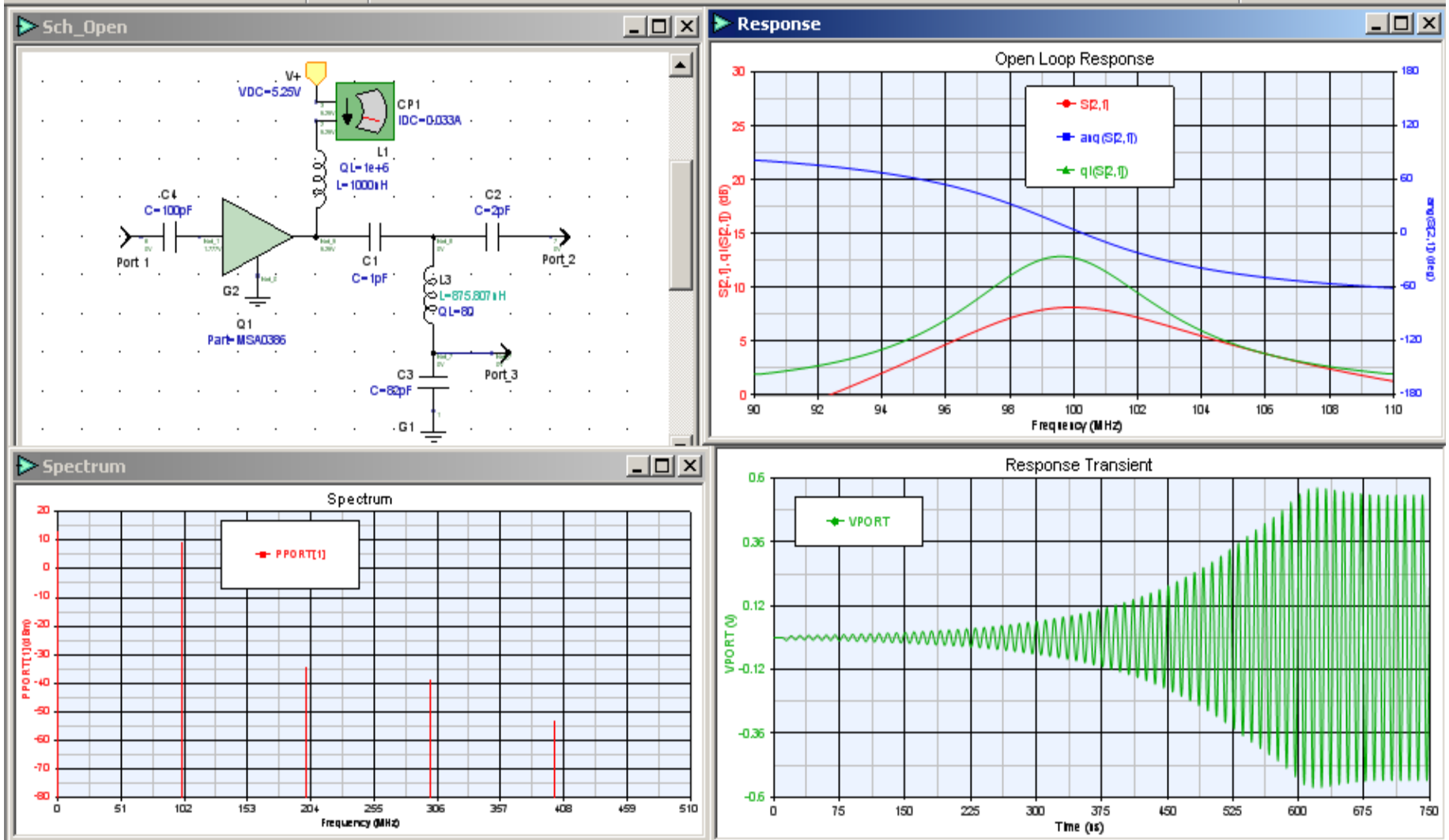


LARGE SIGNAL OSCILLATOR ANALYSIS USING GENESYS/HARBEC



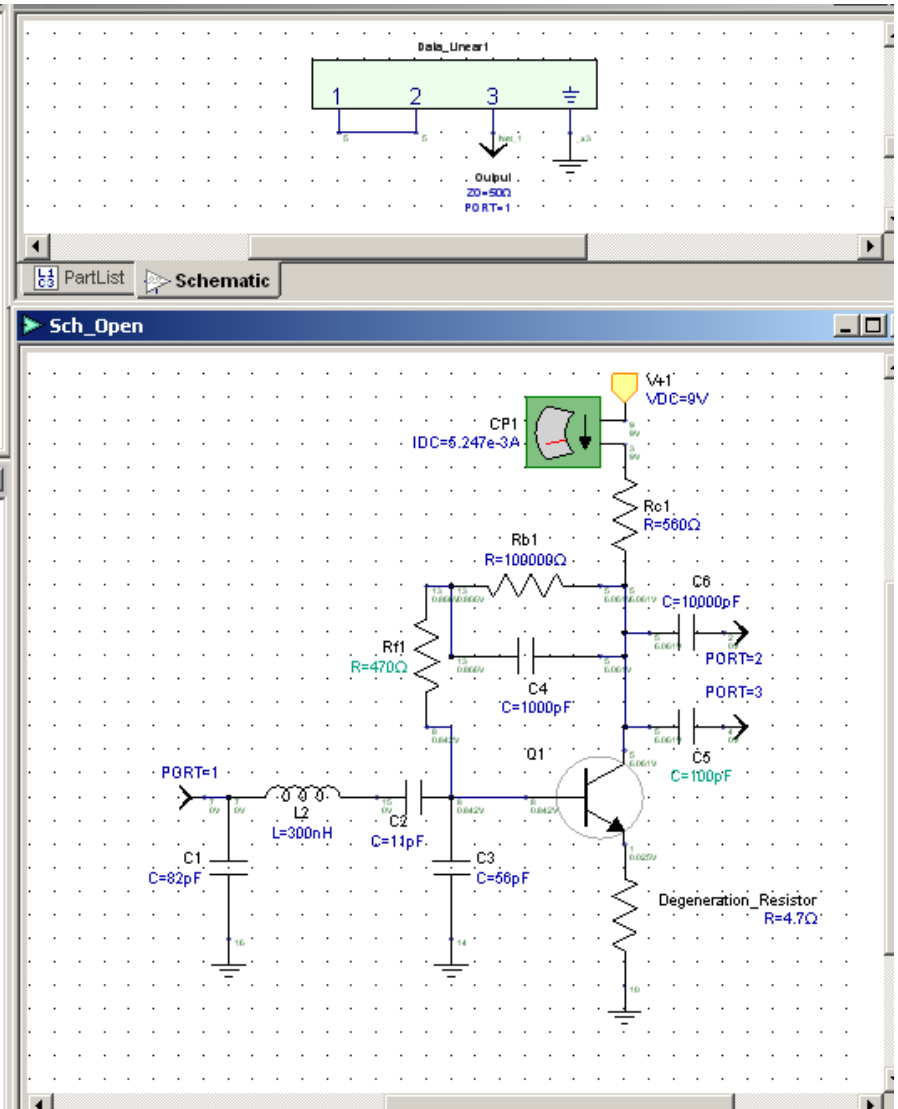
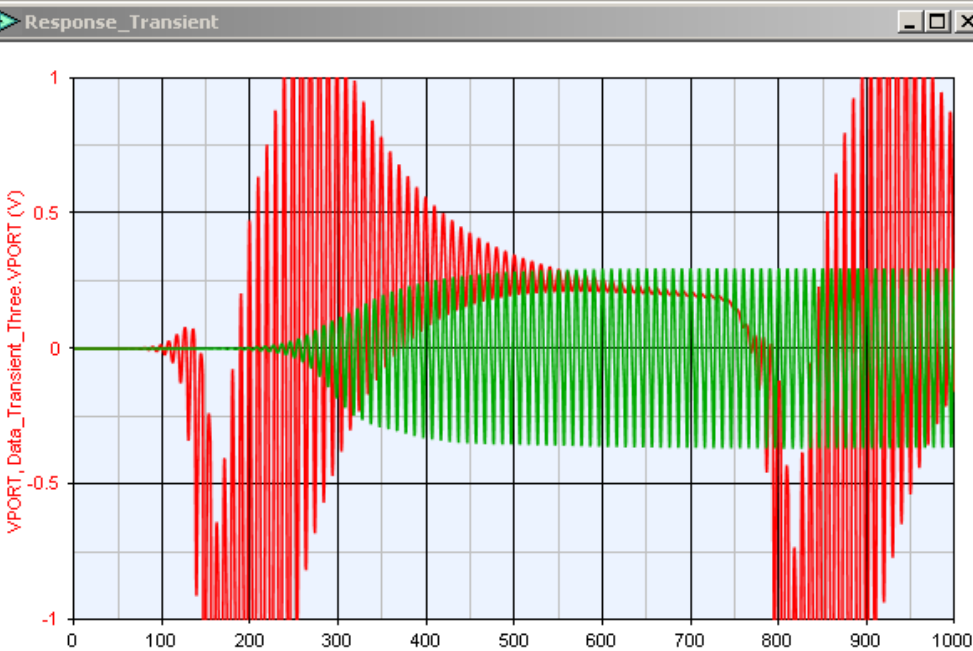
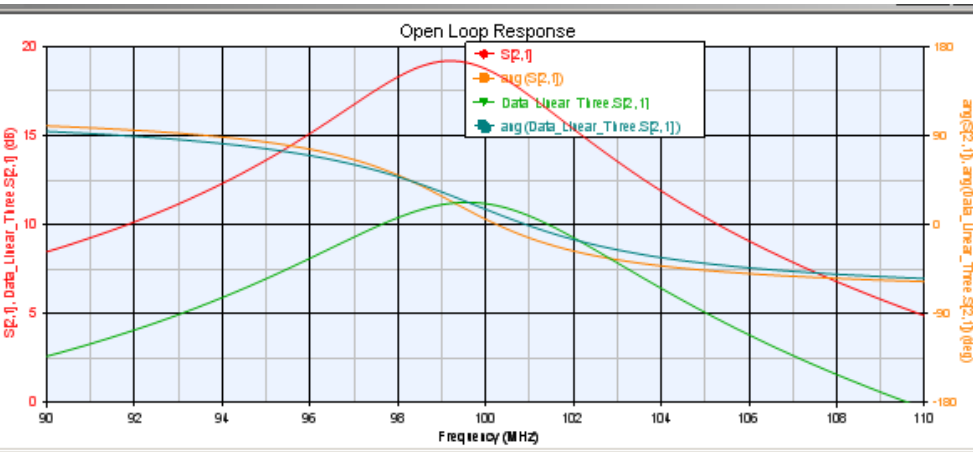
Large Signal Oscillator Analysis Using Genesis 2006 with Harbec

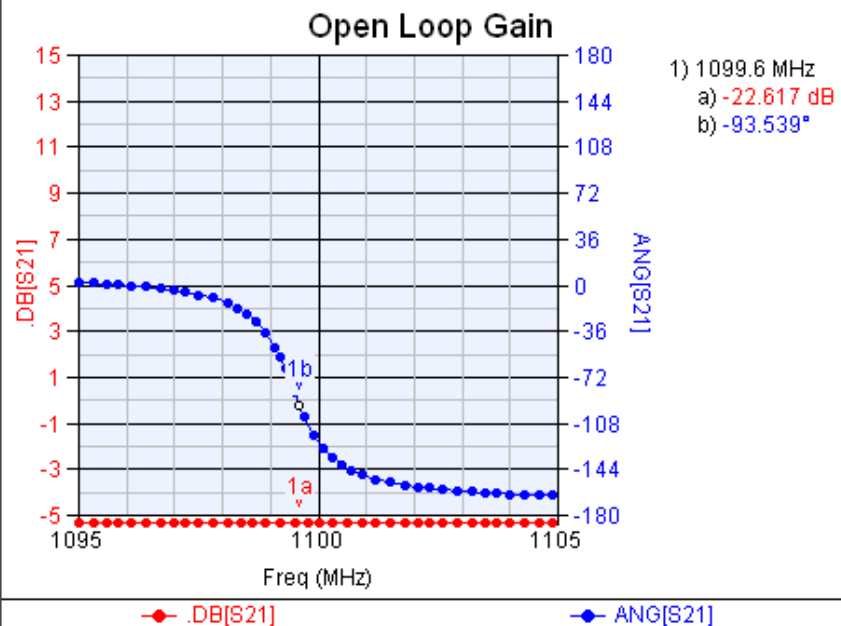
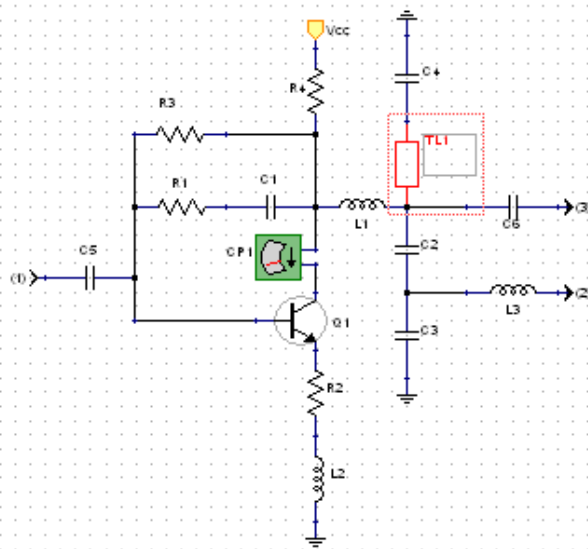
- Shows schematic, output spectrum, start-up, Q, phase, & loop gain
- Voltage plots can be used to see swings across VCO varactors



GENESYS NON-LINEAR OSCILLATOR SIMULATION

- Shows poor start-up & blocking (?) of a sub-optimum design (Cayenne)





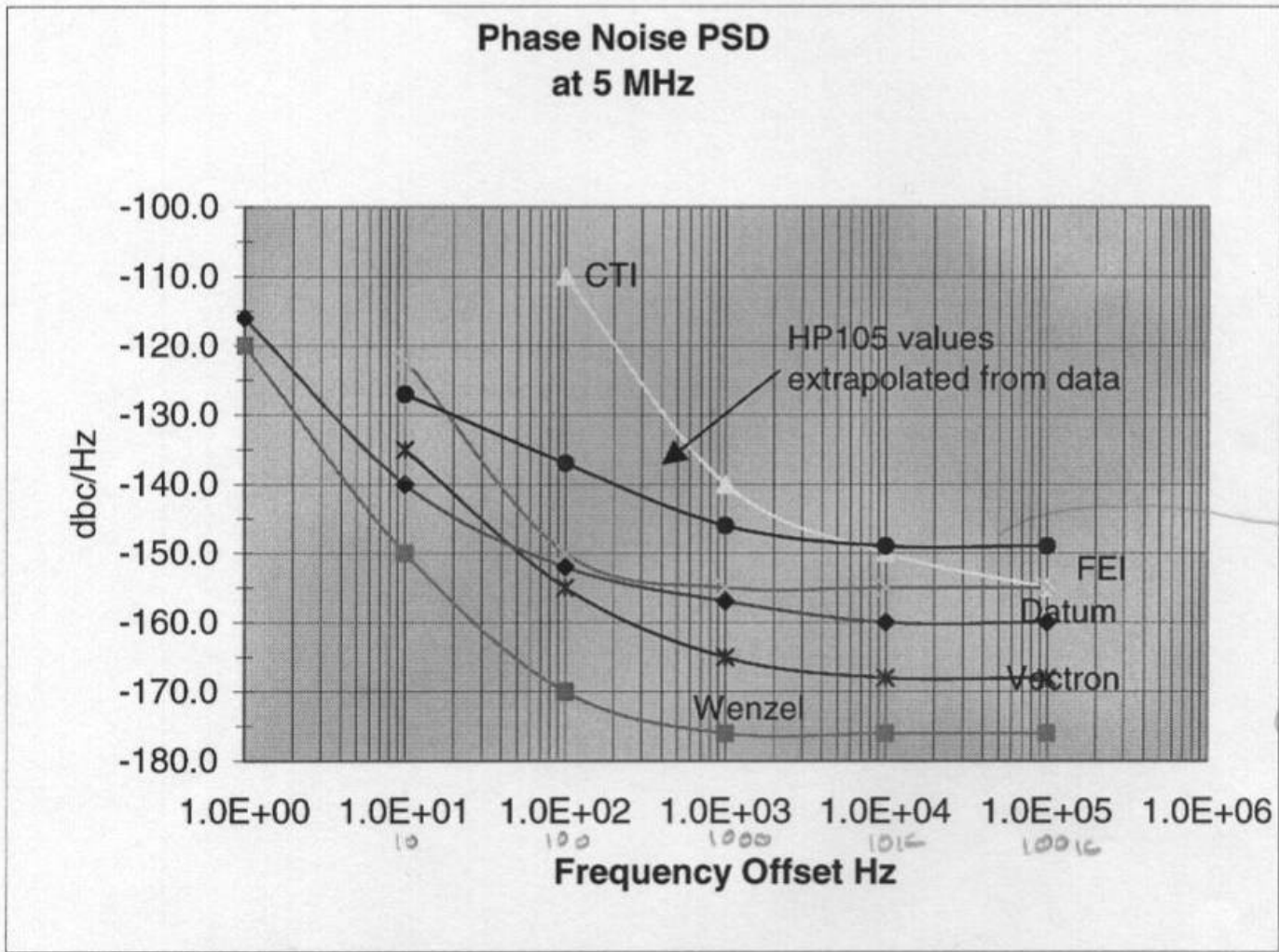
Notes (Workspace: Bipolar Cavity Oscillator)

This example shows how to complete nonlinear oscillator analysis in GENESYS using HARBEC. The oscillator simulated is a cavity oscillator taken from "Oscillator Design and Computer Simulation" by Randy Rhea, Noble Publishing, pages 225-231. A different device is used which results in slightly different component values. The first step in the analysis is to examine the open loop Bode response. The schematic "NL Open Loop" is constructed. Port 1 is the input port and port 2 the output port. In final configuration, port 1 will connect with port 2. The device was built with a nonlinear device model, allowing the DC bias points to be verified and displayed on the schematic. The frequency is swept over a narrow range as this is a particularly high Q oscillator. L1 was adjusted so that the gain peaked at the same frequency that the phase crosses zero degrees. This frequency, approximately 1100 MHz, should be near the frequency of oscillation. Next, the loop was closed, as shown in the schematic "NL Closed Loop." In addition, a source was attached to the loop, passing through a high-Q LC tank. The purpose of this source is to stimulate the circuit to incite oscillation; the purpose of the tank is to allow the signal to be fed at the fundamental but to otherwise isolate the source from loading the circuit. Then the frequency and amplitude of the source are adjusted until no current is being supplied through the LC tank. At that frequency and amplitude. In that state, the source will not be affecting the circuit, indicating that the state of oscillation has been found. To get the best starting point, a guess is made for the amplitude and the frequency of the source. The frequency is taken from the open loop analysis; the amplitude is set to 1 Volt as the voltage tap is base of the transistor. Then the a harmonic balance sweep is completed for both frequency and amplitude. The current supplied by the source is plotted for both sweeps ("Freq Sweep" and "Level Sweep"), showing a minimum current at about 1102 MHz and 1.02 Volts. With this starting point, the optimizer can be used to find the exact amplitude and frequency. Right click on "Opt1" and select "Optimize" to start the process. Open "Error Current" to watch the error current reduce as the frequency and voltage are adjusted. This same process can be used with any oscillator. It provides a very good estimate of the output amplitude frequency that can be combined with the phase noise calculated by using Lesson's Rule with loaded Q calculated from open loop analysis.

Phase Noise and Residual FM

- Voltage and current noise from devices, power supplies, and VCO control voltages modulate junction capacitances and cause PN/residual FM
- PN is characterized versus frequency f and/or overall in degrees or radians in a bandwidth of interest
 - Higher at lower frequency, $1/f$, other
- PN can be detrimental for three reasons:
 - Degrades phase demodulated Bit Error Rate
 - Reciprocal mixing raises Rx noise floor in the presence of large signals
 - Introduces noise in FM systems

Plot of Phase Noise vs. Offset Frequency in 1 Hz BW



Messer Integration
verses BW, start ?
N=1600 (8 GHz)
100K 1M 10M

HP105 (not visible)
1.6° 4.3° 12.2°

Datum 9600 10 MHz
N=800 8 GHz
0.21° 0.64° 2.0°

- The good stuff: Datum PTS9600, Vectron & Wenzel 501-07127 Oscillators,
- PN increases at 10 log BW and 20 Log N multiplication ratio

Equation (Workspace: Coaxial OSC)

```
Cv=77.343
Fo=850E6
PdBm=?7
kT=4E-21
NFdB=?6
F=10^(NFdB/10)
Flicker=?10000
Ps=1E-3*10^(PdBm/10)
```

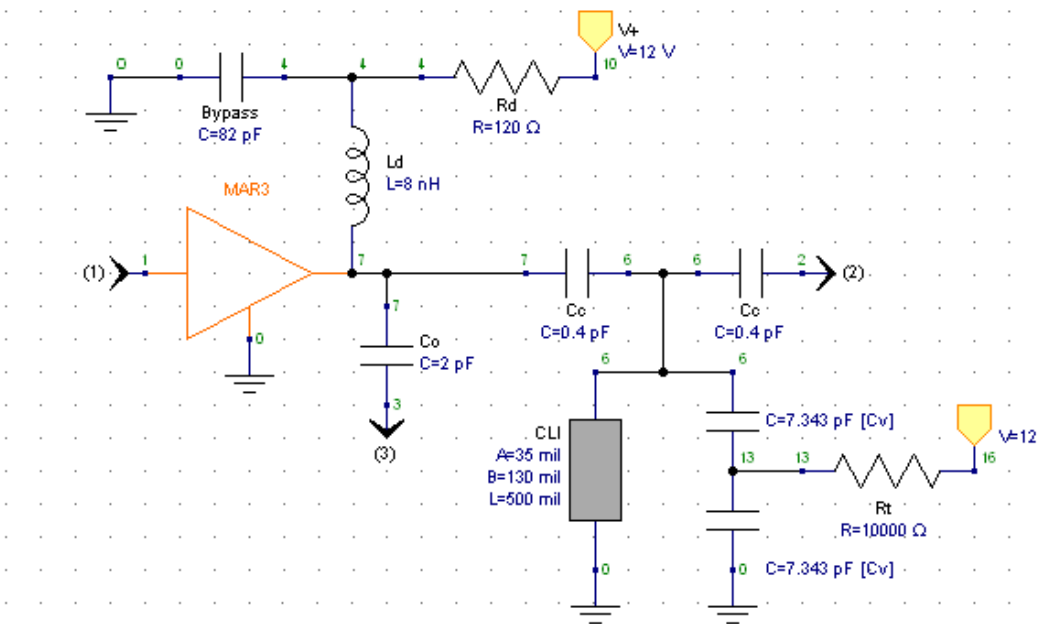
Reserved

'The function of the next line is not obvious: It gets the frequencies of the baseband simulation.
ssbfreq=1e6*freq+0*baseband.loop.db[s11]

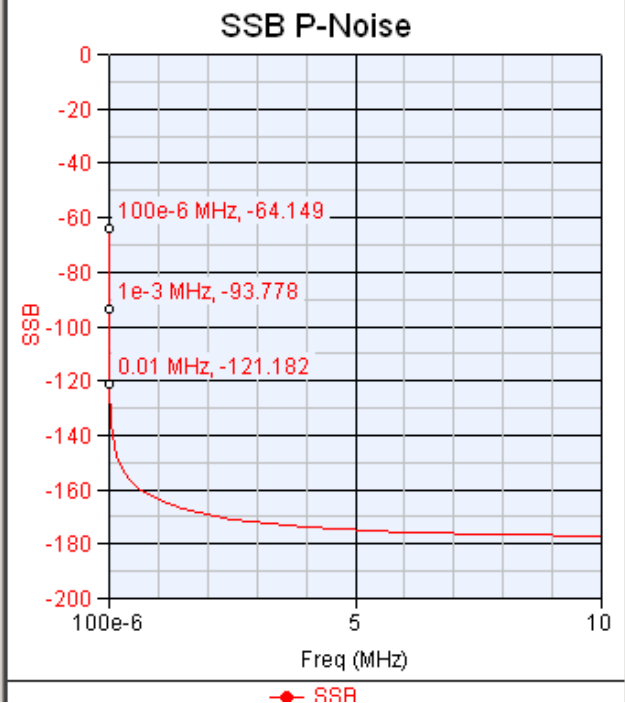
'Get the loaded q of the loop at the oscillation frequency.
Q=GETVALUEAT(linear1.loop.QL[S2 1],Fo)

'Calculate Leeson's equation to determine the noise.
ssb=10*log(0.5*(Flicker/ssbfreq+1)*((Fo/ssbfreq/2/Q)^2+1)*(kT*F/Ps))

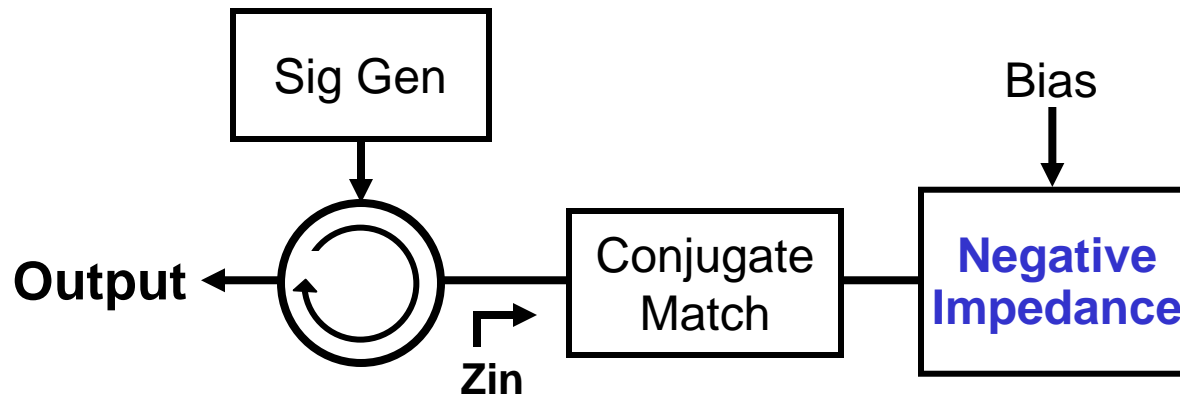
Loop (Workspace: Coaxial OSC)



SSB P-Noise (Workspace: Coaxial OSC)



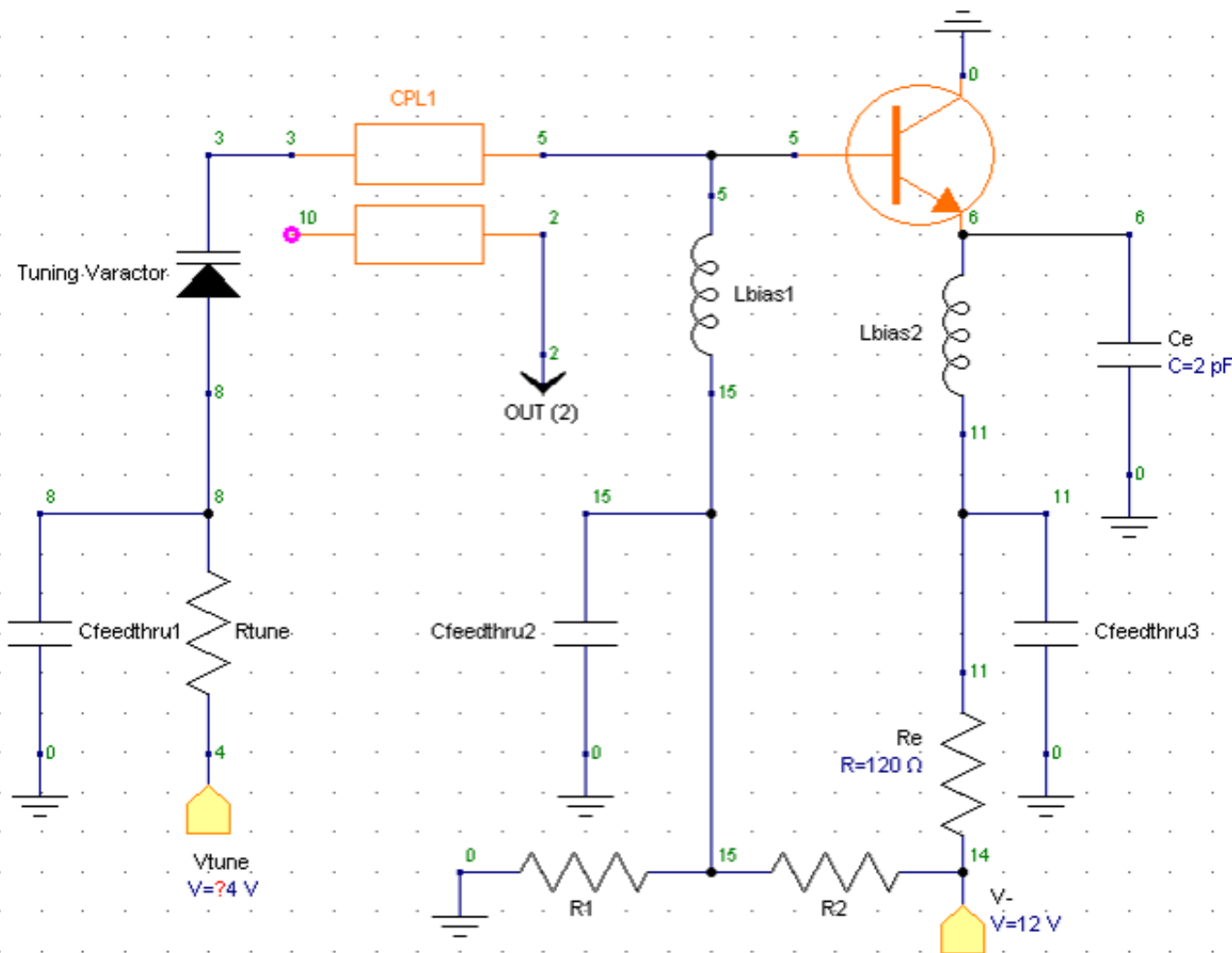
Negative Impedance Oscillator/Reflection Amplifier Configuration



- Signal circulates into negative impedance from signal generator and is reflected back out larger than the input.
 - Assumes the conjugate match is not perfect, for example if Z_{in} looks like -45 ohms
- IF the conjugate match is perfect the system will oscillate (-50 ohms)
 - If a signal is present and close on frequency the oscillator will get in phase step with the input
 - Injection gains in excess of 50 dB are possible at one temperature
- A frequency determining element like a resonator or cavity is useful
- Degrees of freedom are frequency and impedance shift on power up and saturation

4 GHz NEGATIVE RESISTANCE OSCILLATOR SCHEMATIC

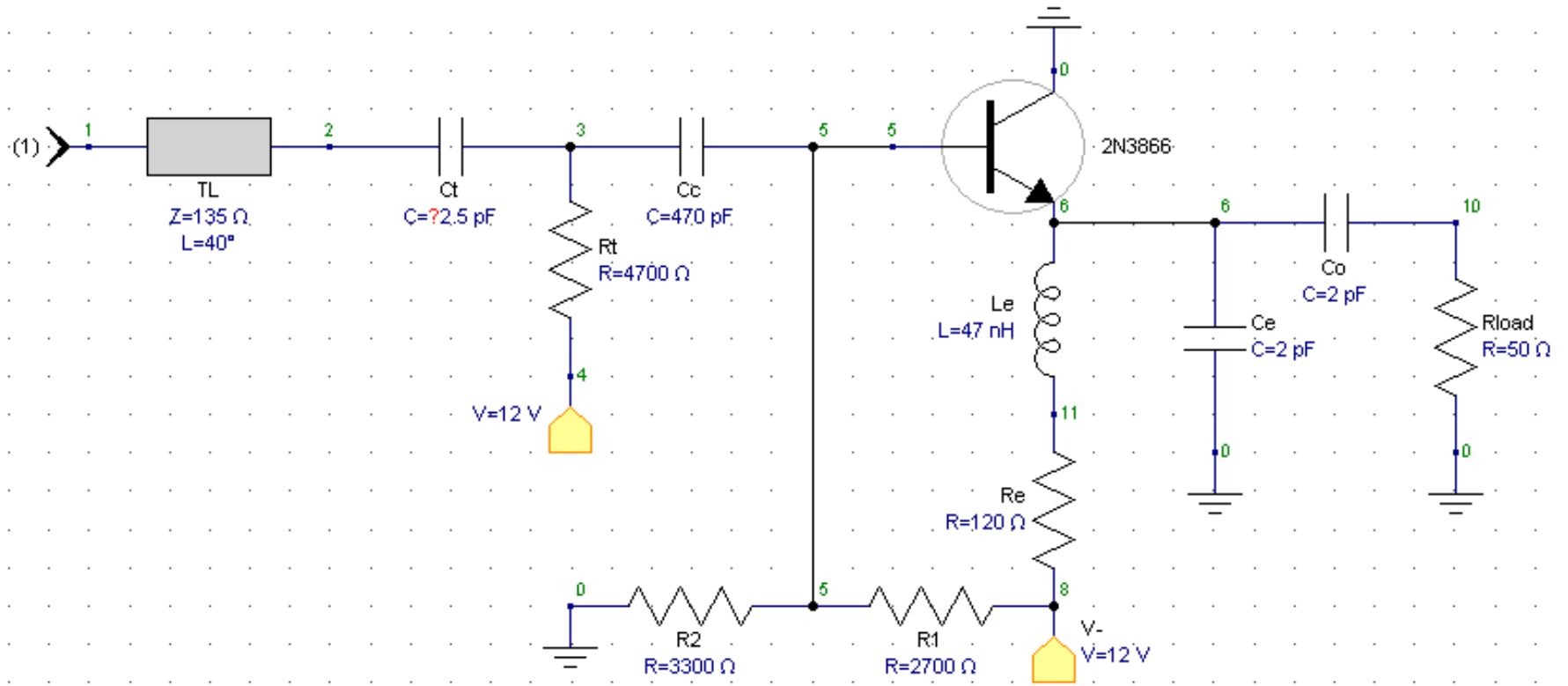
~Ala Bendix Avionics circa 1980, designer Andre Polichek



- ~400 mW output
- 200 MHz tuning
- Transistor $f_t \sim 6\text{ GHz}$, so beta is low, base and emitter RF current nearly equal
- Bias chokes present open circuit impedance
- Emitter capacitance creates negative impedance at base

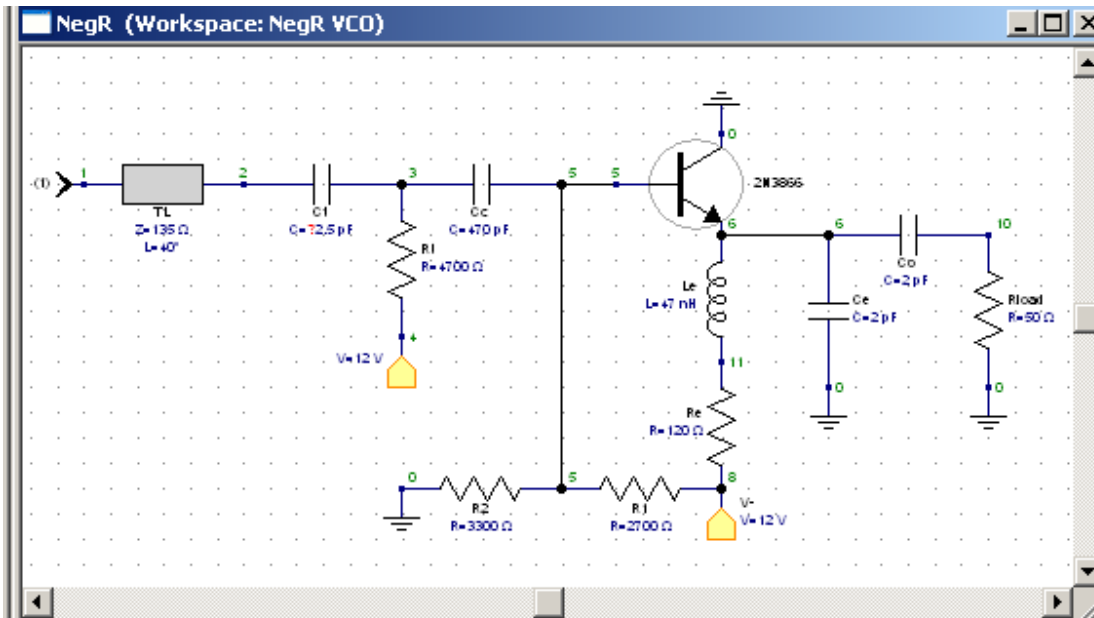
NEGATIVE RESISTANCE OSCILLATOR SCHEMATIC

850 MHz

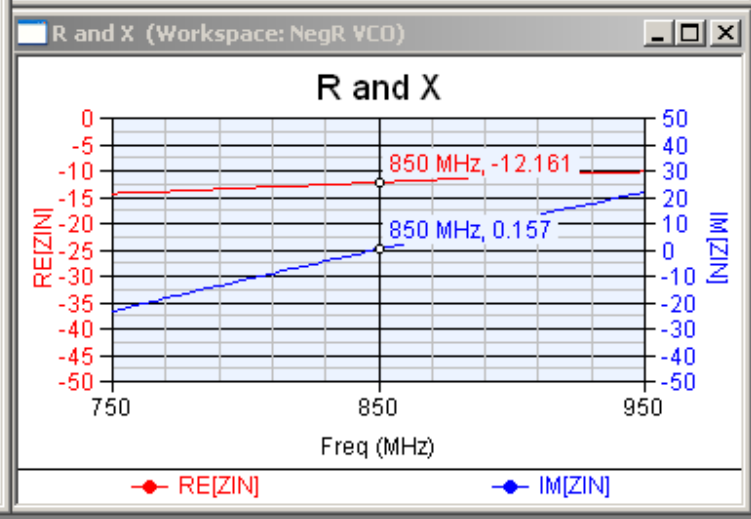
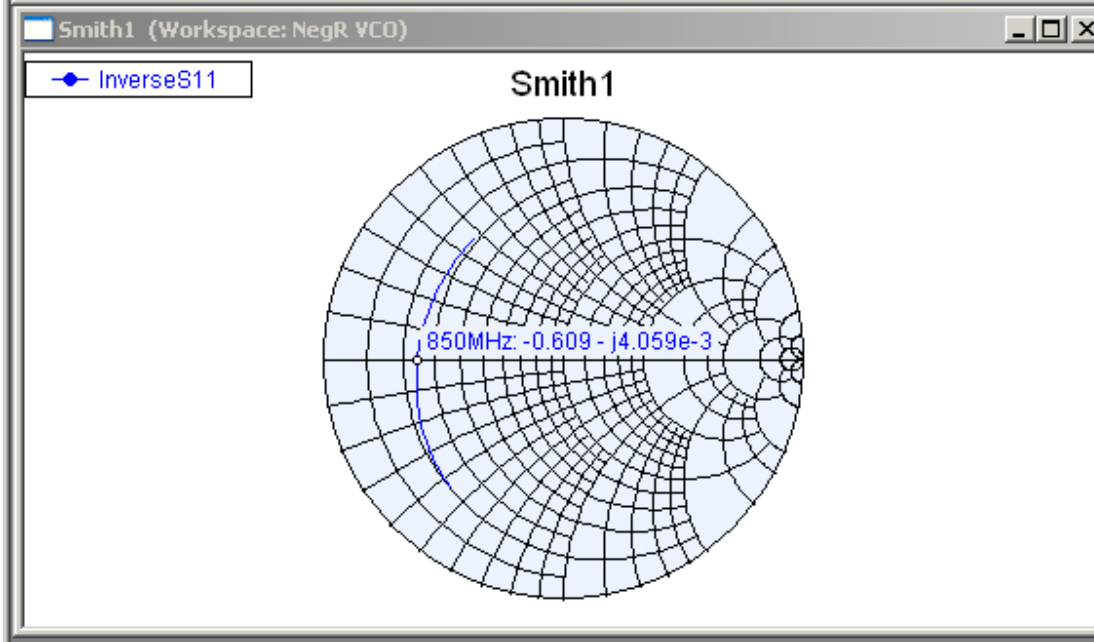
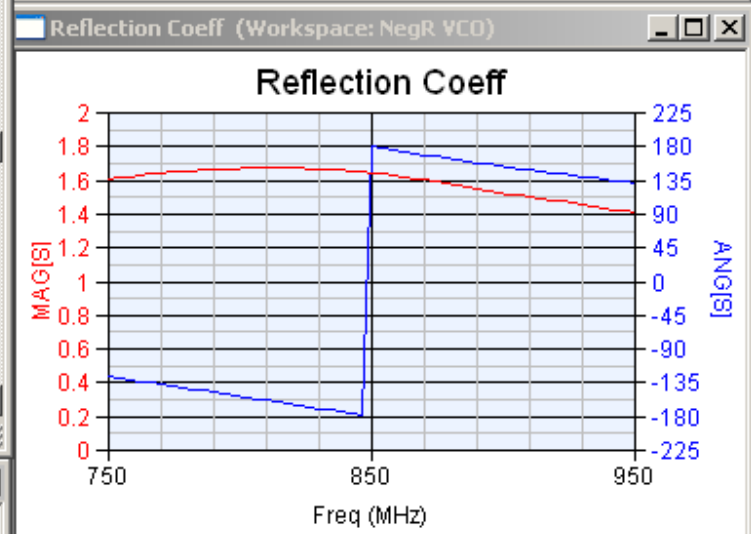


Eagleware Genesys Example

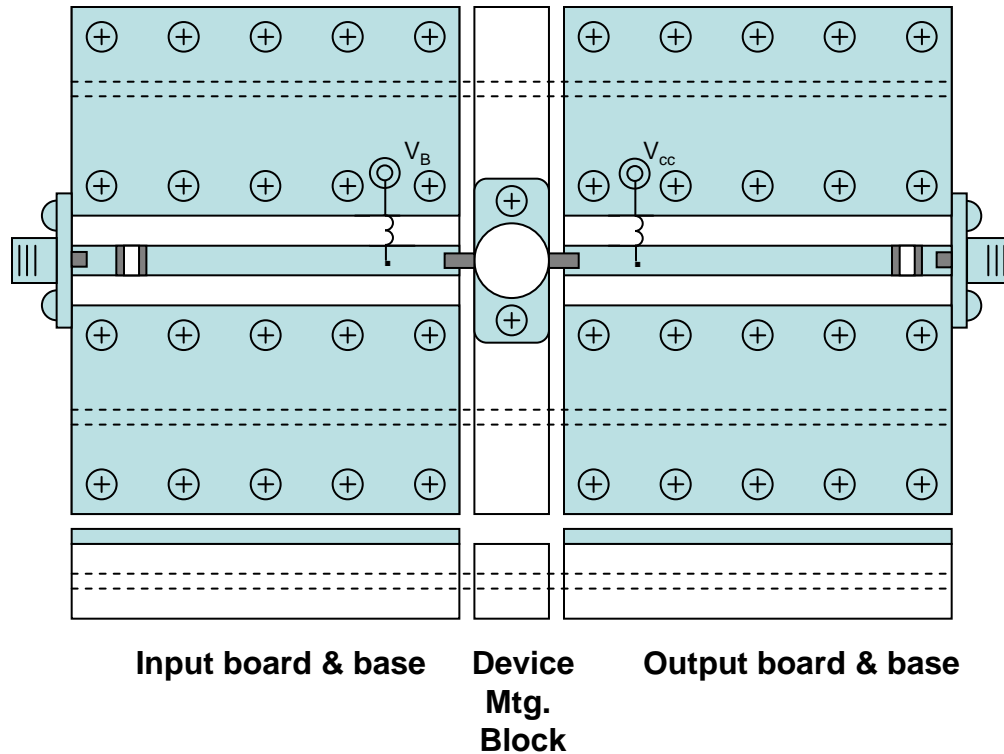
NEGATIVE RESISTANCE OSCILLATOR: OPEN LOOP



Equation (Workspace: NegR VCO)
USING Linear1.NegR
InverseS11 = 1/.RECT[S11]

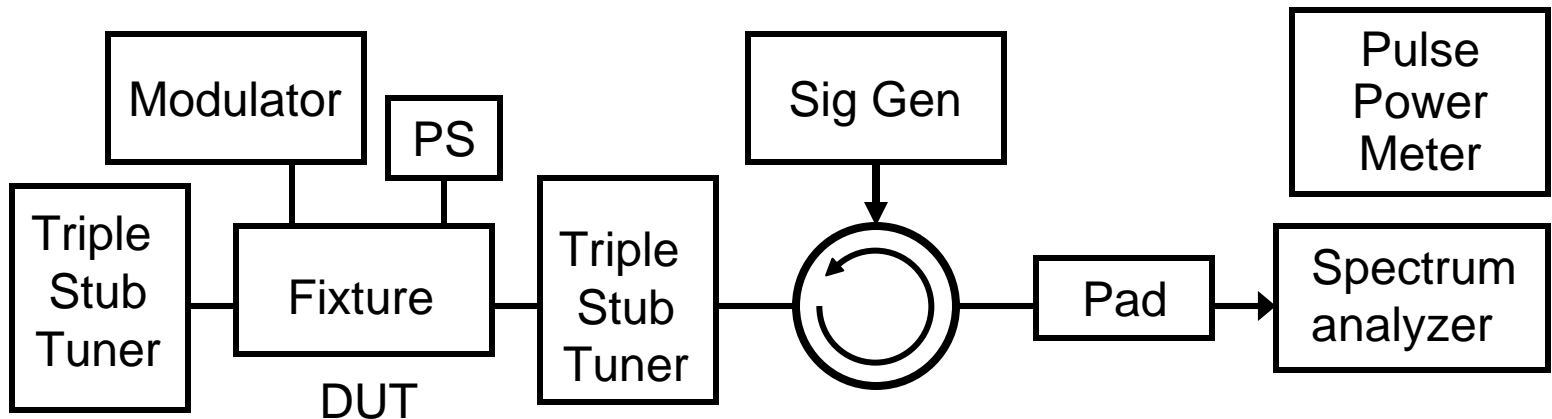


Development Fixture for 60 Watt Pulsed Osc.

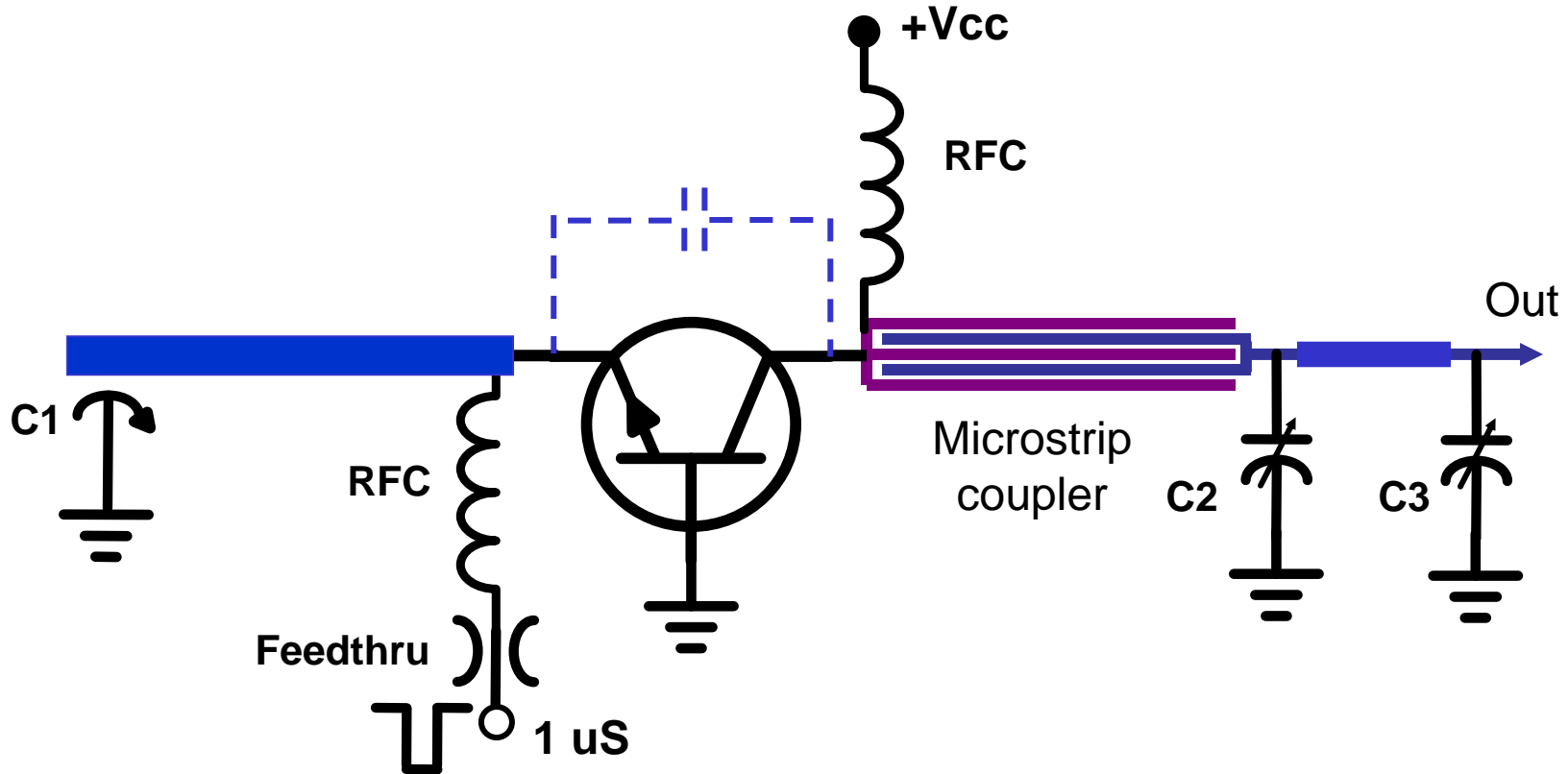


Fixture:

- Provides transistor mtg.
- Provides for bias, DC blocks
- Allows separation for impedance measurements



1.2 GHz Pulsed Power Oscillator



- Custom 60 watt pulsed power transistor originally from *MSC*
- Microstrip substrate bonded on aluminum plate for heat transfer
- Emitter and collector resonators intended to stabilize frequency
- Oscillator fed a dual transistor quad hybrid amplifier for impedance stability.

Good Practice for Oscillators

1. Use a well regulated and/or post filtered power system
2. Maximize high loaded Q for best performance
3. Try to swamp variable device parasitics with stable capacitors
4. Incorporate several dB of extra loop gain in feedback oscillators
5. Control/minimize the gain at off frequencies, consider high-pass feedback
6. Buffered oscillators and oscillator buffering is/are highly desirable
7. Don't parallel bypass capacitors, break up with beads
8. Use high stability caps everywhere if possible (glass, ceramic, porcelain):
 - NPO or sometimes N for resonate circuits
 - Higher stability bypass caps
9. Uses sealed thermistors for temperature comp.
10. Series mode crystal oscillators are more deterministic, "try series R"
11. Provide a good thermal and mechanical environment, watch shock & vib.
 - Use mechanically/electrically stable tuning components
 - Ground and/or isolate the correct (human) end of tuning elements

Good Practice: Testing

1. Run the oscillator off of a bare power supply (system):
 - a. See that it starts and runs properly over a good range
 - b. See good start up with “AC and DC” power up
 - c. Retest under the real power and load conditions
2. Look for noise peaks at other frequencies for instabilities
3. For production oscillators (establish and keep all data!):
 - a. Try different date codes of amplifier devices
 - b. Test over temperature (*last resort: judicious quick freeze and soldering iron, limit temperature shock*)
 - c. Monitor XCO's weekly at constant temp for several months or more, at least sample