Quartz Crystals, Oscillators & Filters

Walter Salden VE7WRS

Adam Farson VA7OJ

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Quartz Crystals, Oscillators & Filters

- Outline
  - Introduction
  - History
  - The Decision
  - Packaging
  - Frequency Measurement
  - Oscillators
  - Uses
  - Crystal Filters
  - References

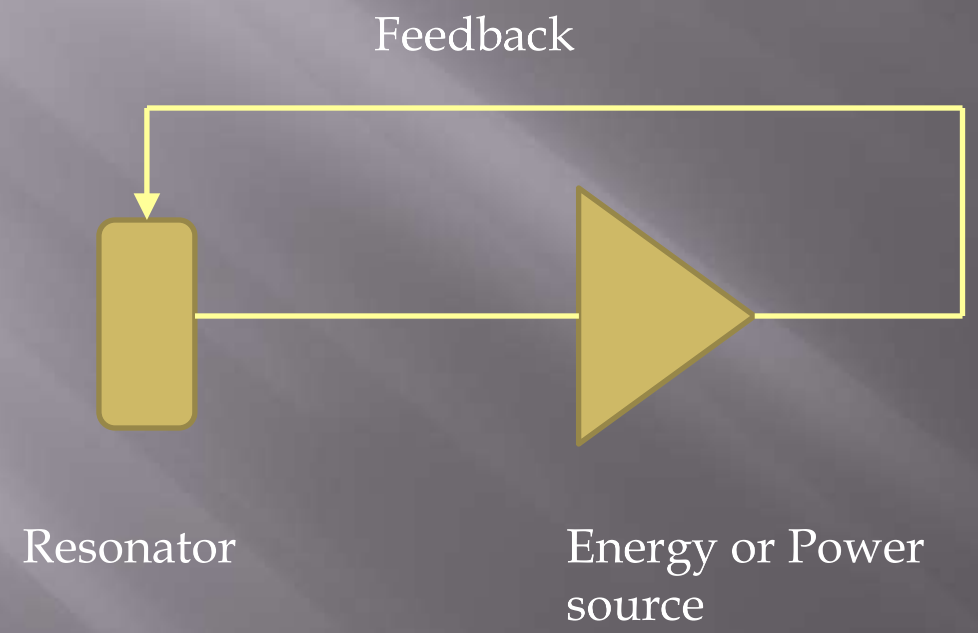
Everywhere

- Crystals and oscillators are everywhere
  - Appliances
  - Cars
  - Electronics
  - Watches and clocks
  - Computers
  - Test and measurement

  and of course…
  - Radios!

Resonator, Energy and Feedback

- Elements of an oscillator



Examples

Resonator	Energy Source
Child on swing	parent pushing
Grandfather clock	wind up spring
Metronome	battery or spring
Crystal	amplifier with feedback

Why Quartz as the Resonator?

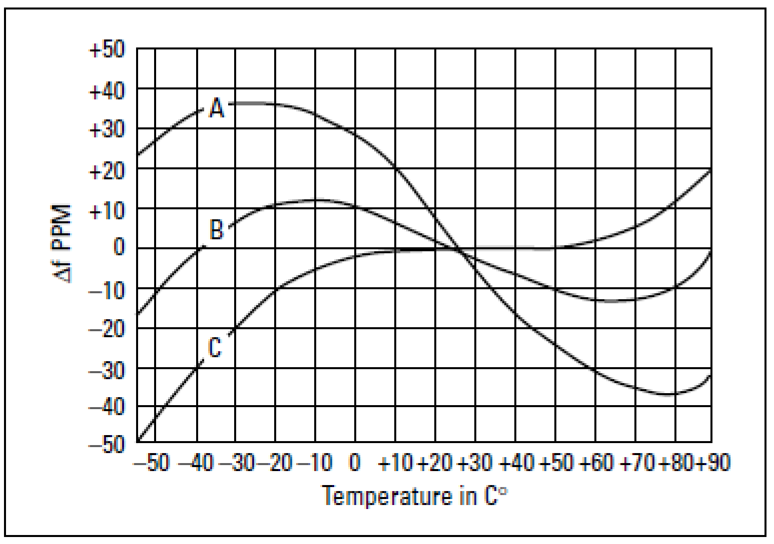
- Piezoelectric properties
  - Flex it and it will produce electricity – BBQ lighter
  - Apply electricity and it will flex – crystal oscillator
  - Not unique to quartz
    - (also some ceramics, Rochelle salt)
- Exceptional mechanical properties
  - Many g's when used in typical oscillator
  - Typically $0.2 - 5 * 10^{-10}/g$
- SiO_2
  - Interesting and useful crystal structure
  - Hexagonal crystal habit

Crystallography

- Crystal Structure
  - Si and Oxygen atoms different sizes
  - Nature finds the most efficient packing
  - n/2 n/4 etc
  - X-ray analysis determines optimum cutting angles

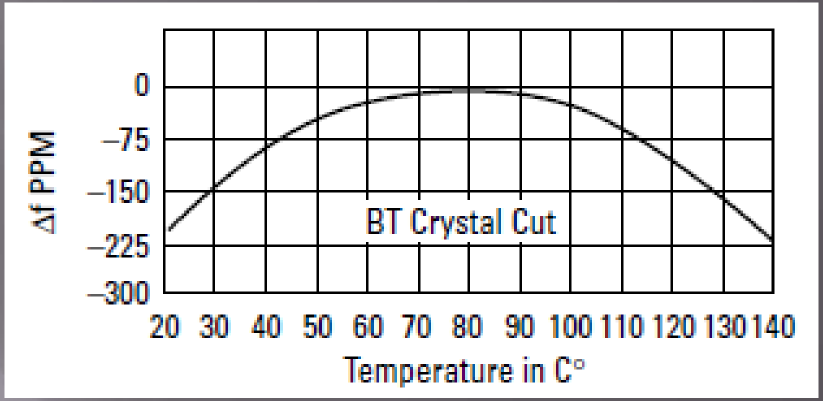
- Many 'cuts'
  - Each with unique properties
  - Optimize for specific need
  - Each cut has specific freq/temp characteristic
  - AT, BT, SC, etc.

Freq/temp curves for various cuts



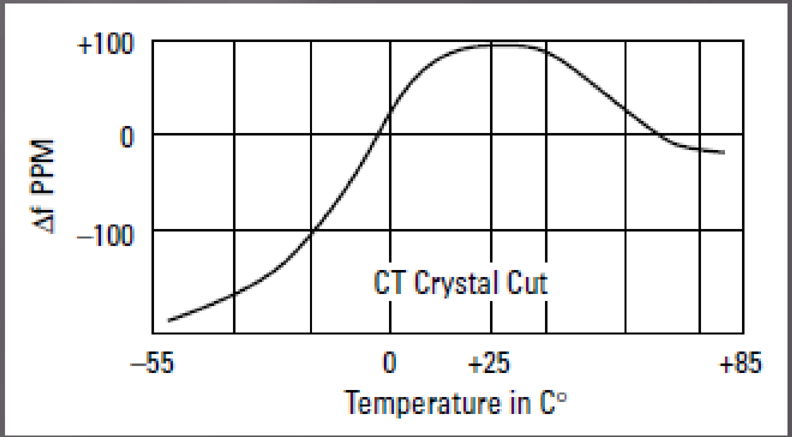
AT-cut

A, B, and C are temperature vs. frequency plots of AT cuts which have been varied by a few seconds of angle rotation.



BT-cut

best suited for ovened crystals



CT-cut

It started with us Hams

- First adopters were ham radio operators
- Allowed unprecedented frequency stability
  - No more 'chasing each other around the bands'
  - Frequency markers
- Cottage industry of hams and friends (optical) grinding quartz crystals developed
- Learn by doing, secretive, trial and error
- Ad's in QST
- Production estimated at 100K/year (1939)

World Quartz Production

- From naturally occurring quartz mines
  - Didn’t learn to grow in labs until the late 1940’s
- World’s #1 supplier was Brazil
  - Abundant
  - High quality
    - Few Defects
  - Large size crystals
    - Early techniques very wasteful
      - This improved over time
  - Inexpensive – until the demand skyrocketed

Start of WWII

- 'war games' demonstrated the advantage of crystal controlled radio:
  - Temperature Stability
    - airplanes
  - ease of use (channels not dial settings)
    - Try adjusting VFO dial in a bouncing tank!
- Limited to frequencies you actually have crystals for
  - Many lives lost due to lack of compatible crystals
  - Can't dial in a new frequency like a VFO
- Extremely risky 'high tech' venture at the time
  - Could enough be produced?
  - Could they solve 'sudden crystal death' syndrome?

The Big Gamble

- Could it be done?

  Would the quartz supply last?

  Might the Axis turn off the supply?

  Could crystals be produced in quantities required?

  estimates of projected need kept growing:

  10 thousands

  100 thousands

  into millions of units

- Became a national priority almost on the scale of the Manhattan Project (Atom Bomb)
- What if it doesn’t work? – nothing to fall back on

Keep Control

- Every effort made to keep any quartz from getting to Axis powers
  - Bribery, spies, hijackings, etc
  - Black market – buy direct from miners
  - Major intelligence effort
  - USN sank U-boat laden with quartz in mid-Atlantic
  - *Also limit British access to quartz*

Making it work

- Mass production
  - Consolidate production
  - Contracts to over 150 companies
  - Synthetic quartz growing processes developed in US, Germany
    - German process too slow (3 weeks to grow 20 cm crystal bar)
    - Bell Labs started growing quartz for FDM carrier filters during WW2
  - Overcome trade secrets; technology/process sharing
  - Egos and conflict !!!!
- Solved the ‘sudden death syndrome’
  - One company had almost no failures, didn’t want to share the knowledge
  - Etching of the surface after grinding removed stress fractures
- Eventually portable grinders
  - Make custom crystals at the front

Axis Powers

- Germany forced to develop complex VFO based radios
  - Have seen examples in presentations by VA7OJ
  - USA and Britain unable to match workmanship
  - 3.2 x 10^{-5} VFO frequency stability achieved
- Limited crystal supply for calibrators, IF filters
  - Extremely valuable and in short supply
  - Crystals assigned to special units who went from site to site
  - Japan also had very limited access to quartz
    - Japanese crystals even inferior to German parts
      - Compare today's superb Japanese crystals, filters, SAW etc.

Packaging

- FT-243 – standard from WWII
  - Standardization was critical
  - Gasketed but not in vacuum
  - ‘Tweak’ frequency with a pencil
  - Field re-work possible
    - Automotive valve-grinding paste used in some cases!

- HC – hermetically sealed holders
- Watch crystals
- Surface mount crystals & crystal filters

Crystal Holders

FT-243 (WW2)

HC-6/U*

HC-18/U *

HC-49/U *

*Current types

HC-6/U interior

100 kHz reference crystal in glass tube

Frequency measurement

- A critical problem prior to and during WW2
  - Frequency counters did not exist prior to 1950's
  - Precision-made LC absorption wavemeters: $f = 1/(2\pi LC)$
  - Crystal calibrator in HF receiver
    - injects harmonic-rich output of 100 kHz crystal osc. into front end
    - "pips" at 100 kHz intervals
    - interpolation dependent on accuracy of dial calibration
  - German receivers e.g. FuG 10, E52 were so accurate that British SIGINT/COMINT sites used them as frequency meters!
  - Accuracy of frequency-measuring instruments a critical problem for crystal manufacturers prior to US BC-221, LM
  - Coventry bombing raid succeeded due to inaccurate measurement of German navaids' tone frequencies by British

BC-221 Frequency Meter

BC-221 Freq Meter (US Navy equivalent: LM)

- The BC-221 (SCR-211) is a heterodyne frequency meter
  - It has 4 stages: a VFO with a precision vernier dial, a 1 MHz crystal calibrator, a mixer and an audio amplifier.
  - Each meter has a unique, computer-generated calibration book.
  - First, the VFO is calibrated against a harmonic of the 1 MHz crystal calibrator.
  - Next, the VFO is tuned for zero-beat with the unknown signal.
  - The vernier dial is then read carefully and the frequency obtained from the calibration book in the cover of the instrument.
  - 2 fundamental freq. ranges: 100 - 250 kHz (LOW), 2 - 4 MHz (HIGH).
- Frequency accuracy:
  - Max. error: $3.4 * 10^{-4}$ (1.355 kHz) at 4 MHz (worst-case: 250 Hz on 80/40m achievable.) Stability: ± 60 Hz/1 hour. BC-221 usable as TX drive unit.
- Arrival of Lend-Lease BC-221's in UK (1941-42) enabled British SIGINT to avoid repetition of the Coventry disaster.
- BC-221 remained in use until 1960's, when **frequency counters** became cost-effective and "semi-portable".

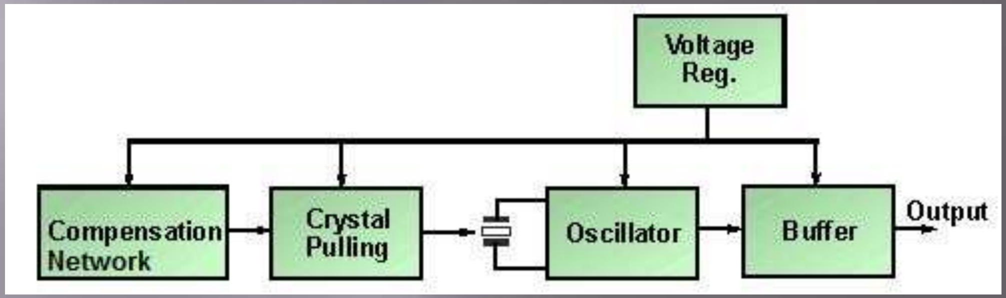
Crystal Oscillators

- Discrete – PC board
  - High quality, e.g. Wenzel
- Modularized
  - TCXO – temperature compensated
  - OCXO – oven stabilized – 60-85°C
    - Single and double oven
  - VCXO – good for cleaning up PLL
    - ‘tweak’ frequency with control voltage

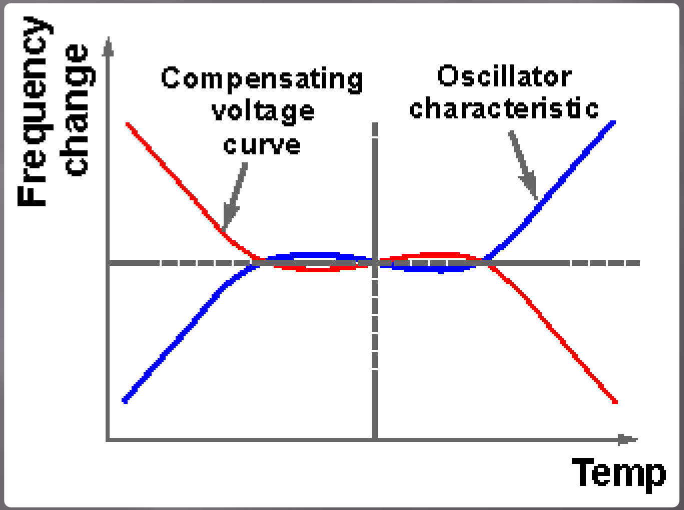
10 MHz OCXO

- Many manufacturers – variable quality

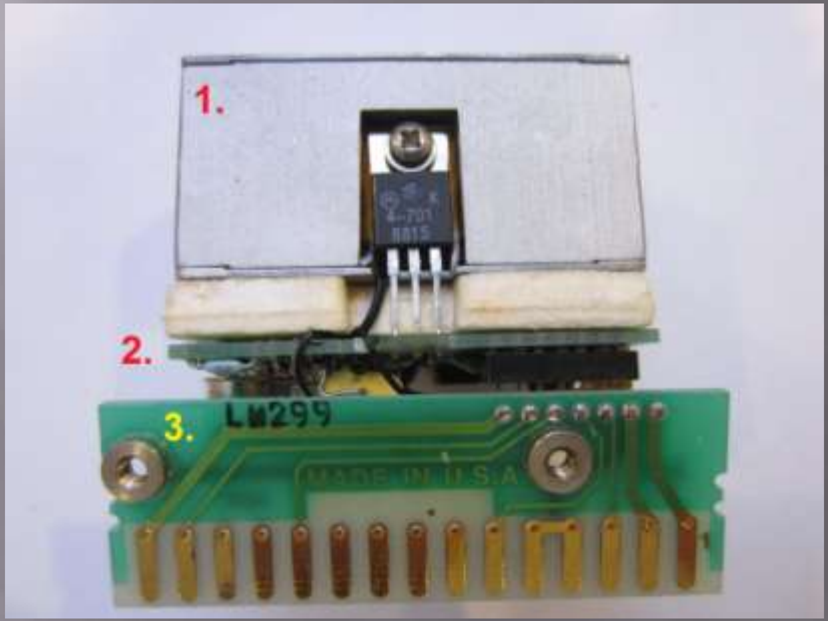
TCXO (Temp. Compensated Xtal Oscillator)



- Compensation network: R's, C's and thermistors
- Crystal pulling: varactor diode
- Network generates curve equal & opposite to crystal freq/temp curve



OCXO (Oven Controlled Xtal Oscillator)



- Example: HP 5350B OCXO
- Thermistor in enclosure senses crystal temperature

1. Crystal enclosure with heater transistors on front & back
2. Oscillator/oven controller board below crystal enclosure
3. Connector board.

Performance

- Specs:
- Accuracy
  - $1 * 10^{-6}$ (HC-18/U at ambient) to $1 * 10^{-8}$ (OCXO)
  - Oscillator circuits can be trimmed on freq.
- Drift (typ. range -40 to +85°C)
  - $2.5 * 10^{-5}$ (simple osc.) to $3 * 10^{-8}$ (top-grade OCXO)
- Ageing
  - Crystalline structure changes slowly over time
  - Ageing spec: typ. $< 3 * 10^{-6}$ after 10 years
    - Mfr. pre-ages crystals for ≈ 10 days prior to shipping

Uses of Crystal Oscillators

- Radios
  - Modern radios clock synthesizer from crystal master osc.
    - "1 or 2 crystals per channel" obsolete since 1970's
  - Often TCXO option for improved stability
  - Watch spurs and phase noise if using external oscillator

- Test Equipment
  - -04 High-accuracy option
  - At one time very much in demand on used market
  - Mostly superseded by low cost GPS disciplined oscillators
    - Synchronize all equipment to one oscillator

Beyond Quartz Oscillators

- GPS Disciplined Oscillators (GPSDO)
  - Synchronize ovenized quartz oscillator to the atomic clocks on GPS satellites
  - Surplus telecom market $125 - 500
- Rubidium (Rb) Oscillators
  - Recently on eBay $50
  - Good accuracy – poor phase noise
  - Used surplus units may have limited life
- Cesium (Cs) Oscillators for private use
  - Are you a ‘time nut’ ?
- *Future presentation:* Precision Frequency Sources

Typical precision sources

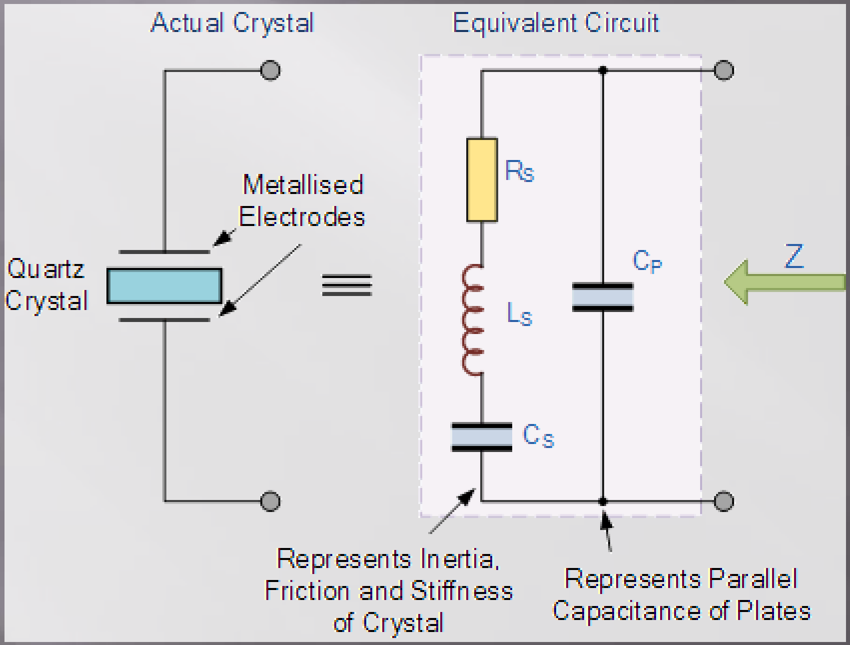
HP Z3805A GPSDO

Rubidium Oscillator

HP 5061A Cesium Oscillator

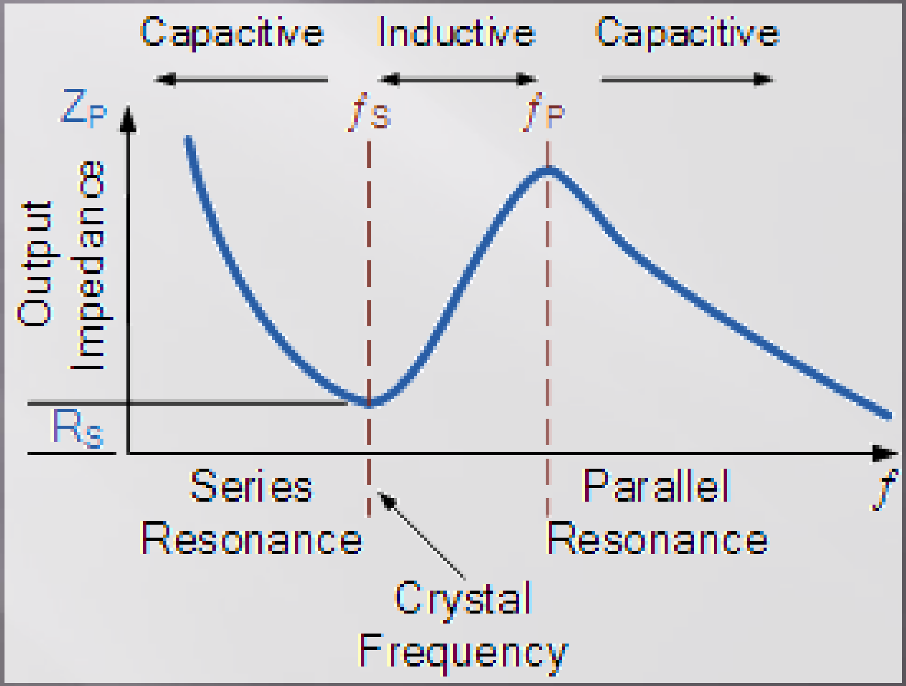
Crystal Filters

- A single crystal exhibits series & parallel resonances
  - L_S/C_S: series (bandstop); L_S/C_S: parallel (bandpass).



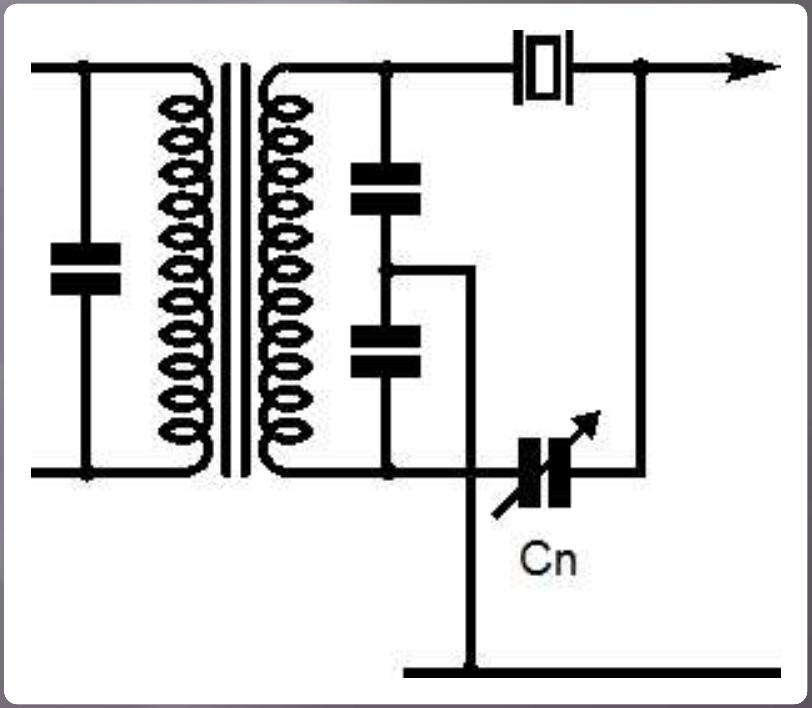
Freq. response of crystal

- A single crystal can be a bandstop or bandpass filter
- $f_0 = f_S$: bandstop; $f_0 = f_P$: bandpass.



The “Lamb” Crystal Filter

- This simple filter was patented by J.J. Lamb in 1939 and fitted to many early HF receivers (e.g. National HRO series). Its bandwidth is 100 Hz or less.
- Cn is the front-panel “crystal phasing” control, which shifts f_P to place the signal at the peak of the crystal’s passband.

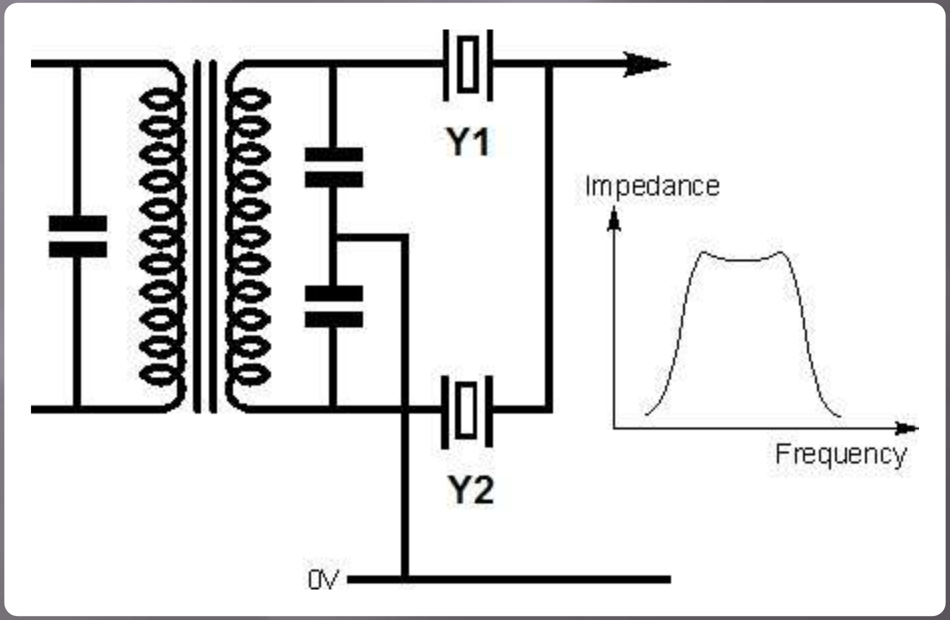


Multi-Pole Crystal Filters

- Two (or more) are definitely better than one!
  - Filter sections can be cascaded just as LC circuits can, to yield a narrower filter with better out-of-band rejection.
  - The individual sections must be impedance-matched to one another and to the source and load impedances.
  - There are two popular topologies, **half-lattice** and **ladder**.
  - The crystal parameters are calculated via a software program and cut to these parameters.
  - Alternatively, the home constructor can purchase a large quantity of inexpensive "generic" crystals and hand-select them for his filters using a VNA.
  - Multi-pole crystal filters are used in radio receivers and transmitters, test equipment and telecom transmission systems.

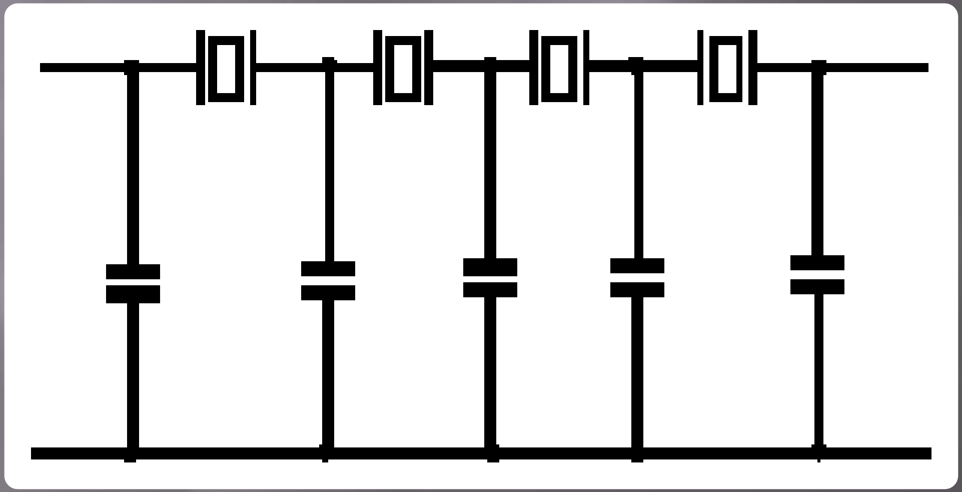
Half-Lattice Filter

- f_P of Y1 = f_S of Y2. Sections can be cascaded for better selectivity.
- Passband has some ripple (variation between centre & edges).
- One section (2 poles) has ≈ 20 dB rejection (stopband attenuation).
- 4 poles: 50 dB. 6 poles: 70 dB. 8 poles: 90 dB (best for RX IF filter).



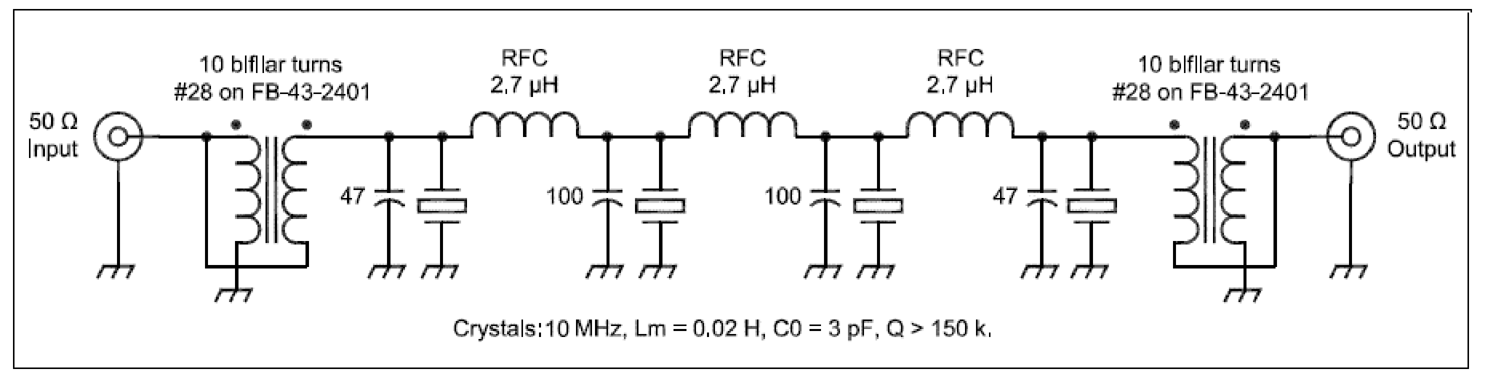
Ladder Filter

- The ladder filter is a π-section filter.
- All the crystals are cut to the same frequency.
- Shunt capacitors provide inter-crystal coupling.
- A bandpass filter is shown; in a bandstop filter, the series elements are inductors and the crystals are the shunt elements.



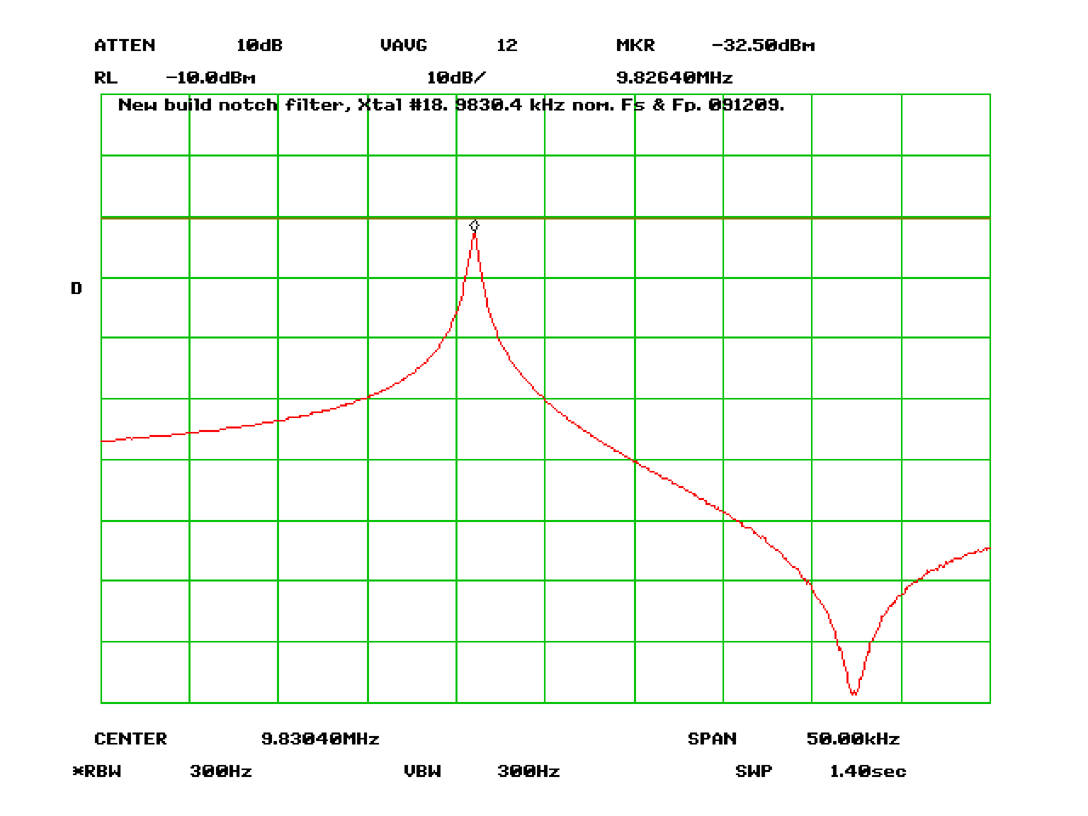
Homebrew Ladder Filter

- The authors needed a bandstop filter for phase noise measurements. The filter suppresses the close-in phase noise of the test signal source.
- We designed and built our own filter.
  - Our crystals were 9.83MHz.



Crystal Selection

- First, we characterized the individual crystals on a spectrum analyzer & tracking generator.



Filter Board Assembly

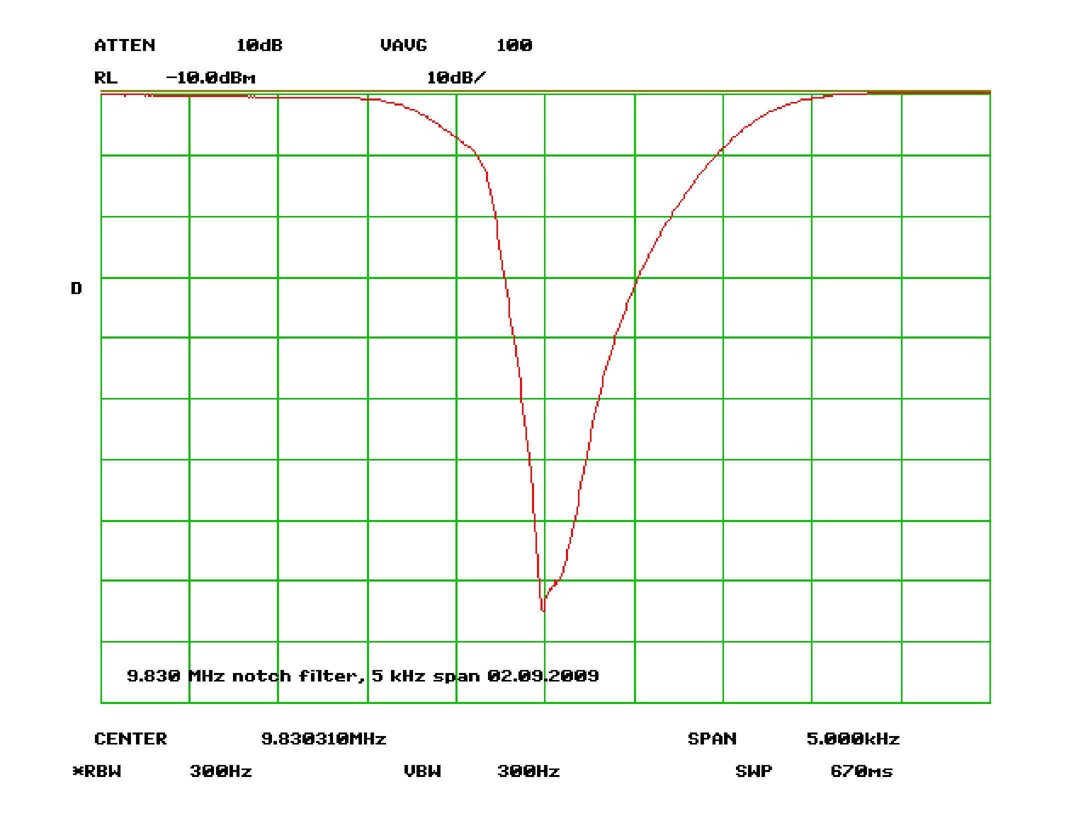
- Next, we built the filter on a W8DIZ board.
- The bifilar-wound toroidal transformers match the filter's Z_0 (200Ω) to 50Ω.

Final Assembly

- We then mounted the completed filter in a Hammond die-cast enclosure with male SMA connectors.
- Next step: testing.

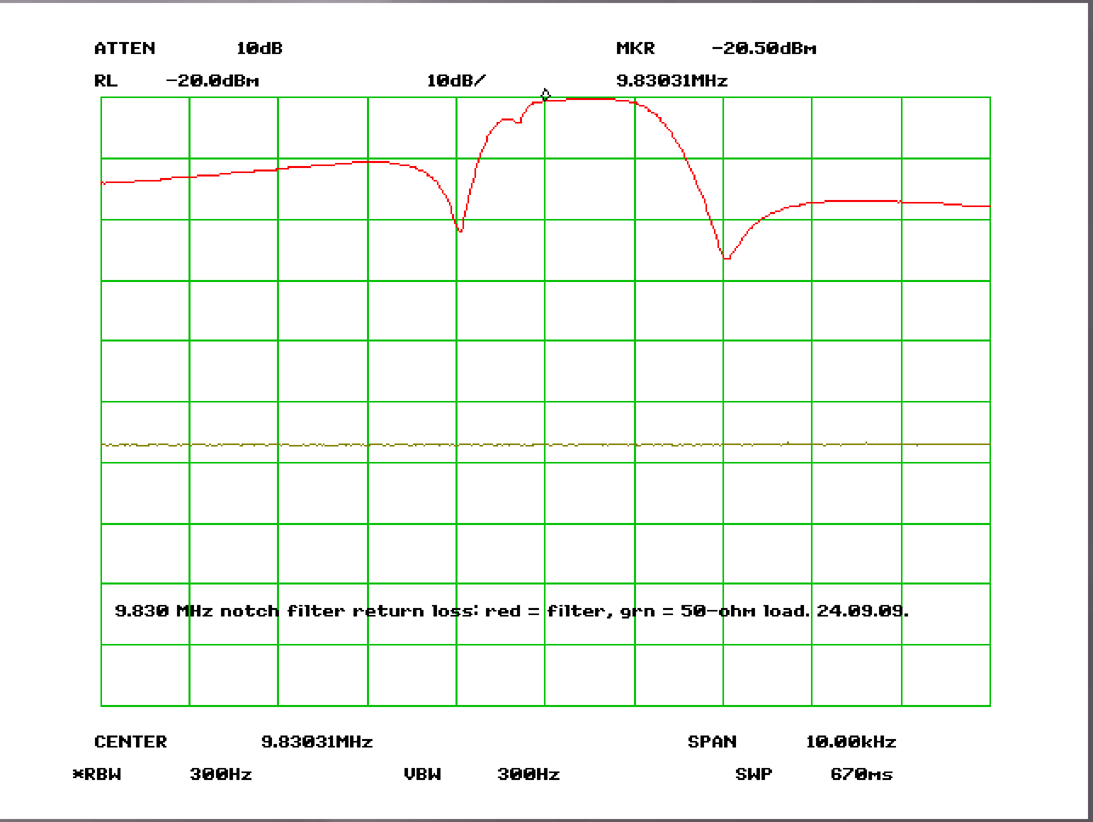
Testing our Filter

- This is the frequency response of the completed 9.83 MHz bandstop filter.
- Stopband attenuation 85 dB at 9830.3kHz.
- Passband insertion loss: 0.6 dB.



How's the match?

- Adequate, but not brilliant. 3 dB pads at input & output will help.
- Here is the return loss curve (filter vs. 50Ω test termination).



References

- Books:
  - "Crystal Clear", by Richard J. Thomson Jr.
  - "Most Secret War", by R.V. Jones
- Internet
  - A History of the Quartz Crystal Industry in the USA (IEE-UFFC)
  - History of the Crystal Industry in the Carlisle PA Area
  - A History of Crystal Filters (IEEE-UFFC)
  - Fundamentals of Quartz Oscillators (HP App Note 200-2)
  - Quartz Crystal Theory (Jauch Quartz GmbH, Germany)
  - Quartz Crystal Overview (KVG, Germany)
  - Quartz Crystal Oscillator Tutorial
  - Quartz Crystal Bandpass Filters
  - TM 11-300, BC-221 Technical Manual (PDF)
  - BC-221 Frequency Meter Calibration Method
- YouTube videos & tutorials:
  - The Manufacture of Synthetic Quartz Crystals (Bell Labs Archives)
  - Introduction to Quartz Crystal Resonators (DigiKey/Crystek PTM)
  - Crystals Go to War (1943)