Digitally Controlled Crystal Oven

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Signion

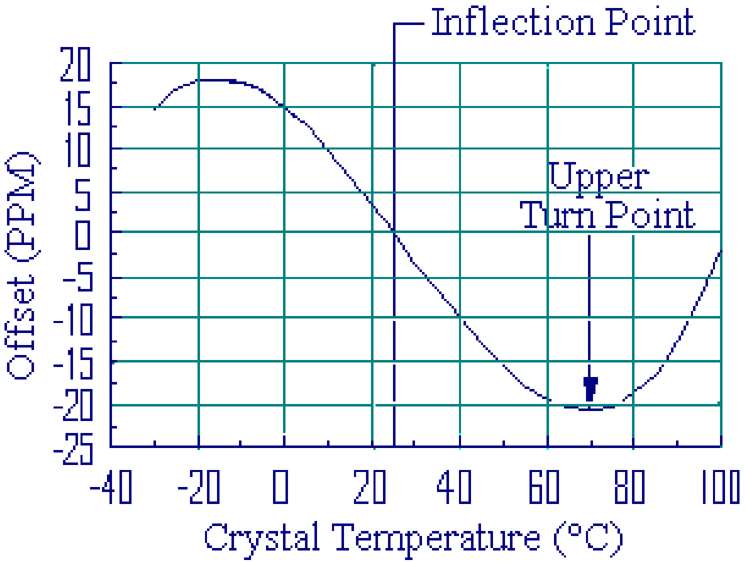
Attributes of widely-used frequency references

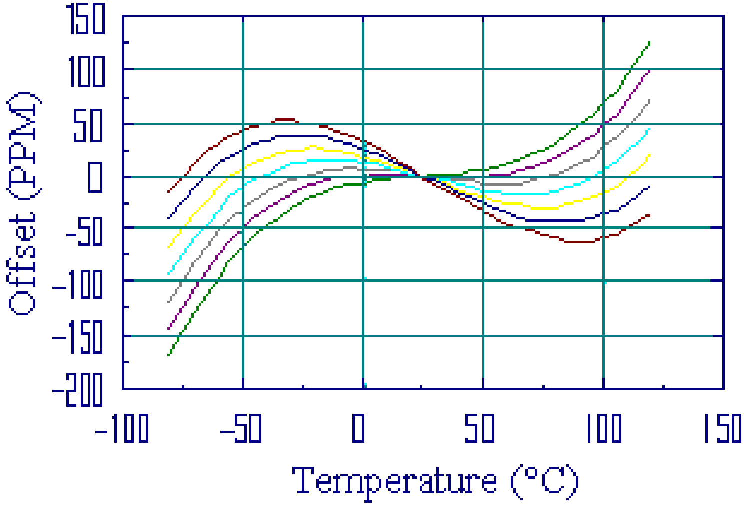
	Description	Stability/ accuracy	Price	Power	Warm-up time to rated operation	Applications
XO, VCXO	Crystal oscillator	10^{-4}-10^{-5}	<$1	50mW	<10s	Watches, phones, TV, PC, toys
TCXO	Temperature compensated crystal oscillator	10^{-5}-10^{-6}	<$10	50mW	<10s	Wireless, GPS
OCXO (AT-cut)	Ovenized Crystal oscillator	10^{-7}-10^{-9}	<$200	600mW (peak)	<100s	Instruments, telecom, radar, satcom
Rubidium	Rb Frequency Standard	10^{-10}-10^{-12}	<$5000	20W	<300s	SONET/ SDH, calibration, test, GPS base stations
Cesium	Cs Frequency standard	10^{-11}-10^{-12}	<$50,000	30W	<2000s	SONET/ SDH, calibration, test

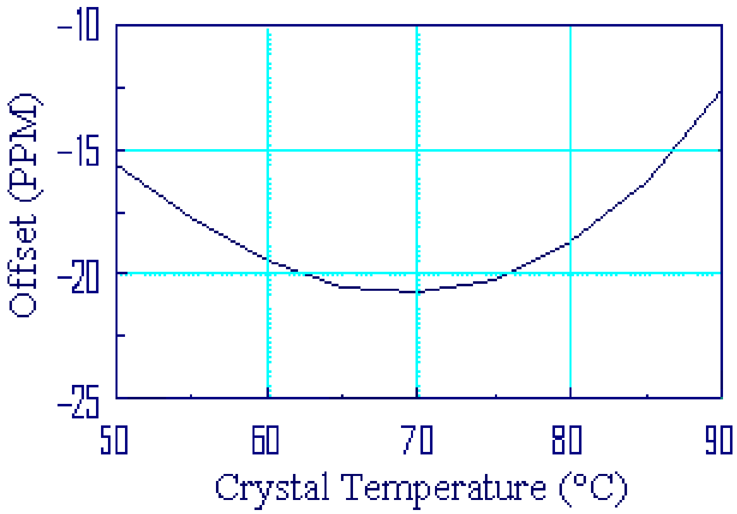
Ovenized crystal oscillators (OCXOs)

- Stability of low-end (10^{-8} to 10^{-9}) frequency standards
- Reduced steady-state power consumption
- Reduced warm-up time
- Priced at $50, much of the cost is in manufacturing process and tuning/ calibration (rather than raw material)
- Our focus is on reducing tuning/ calibration costs by replacing analog components with digital technology

Temperature vs. Frequency







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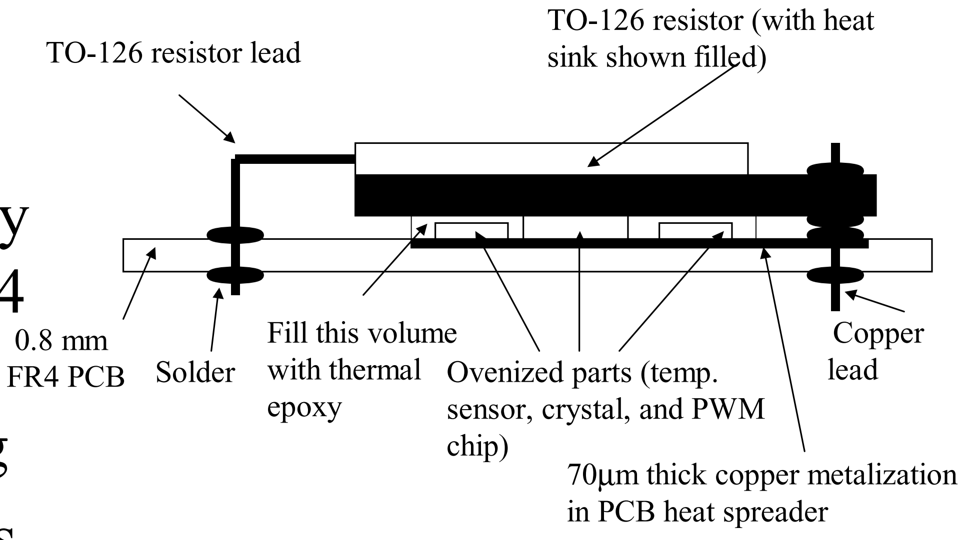
Use mass-produced oven materials

- Standard power resistors (rather than thermofoil heaters)
- Thermal mass of (electrically isolated) metalization of FR4 PCB heat spreader may be increased by nickel cladding
- Copper lead/ solder provides thermal connection from heater to metalization


TO-126 resistor lead

TO-126 resistor (with heat sink shown filled)

0.8 mm FR4 PCB

Solder

Fill this volume with thermal epoxy

Ovenized parts (temp. sensor, crystal, and PWM chip)

Copper lead

70µm thick copper metalization in PCB heat spreader

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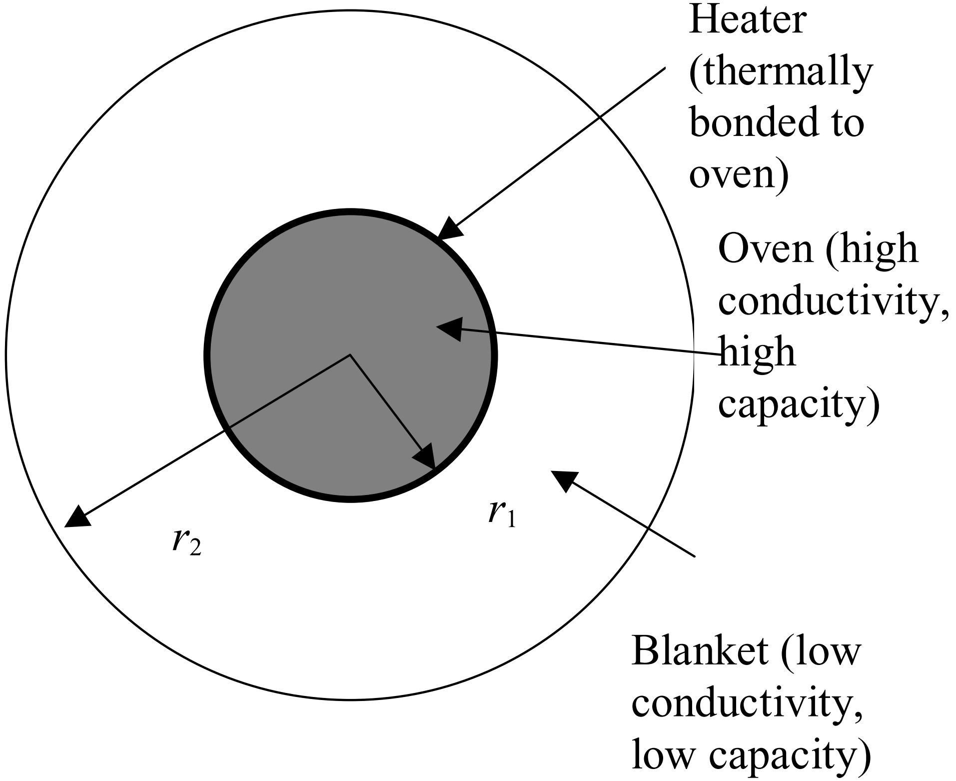
Relative oven/ blanket dimensions

- Oven $C \propto r_1^3$
- Oven R (wrt ambient)$\propto(r_2-r_1)/r_1^2$
- Oven $RC \propto r_1 \cdot (r_2-r_1)$
- Maximized at $r_1=r_2/2$ (independent of oven/ blanket materials!)
- At this r_1 (for a given r_2), high frequency variations of ambient temperature are filtered out
- Similarly, heater $RC \propto r_1$
- (Oven lag/ heater lag)$\propto$ (r_2-r_1). Increase for better control.
- Steady-state heater power$\propto(\theta_h-\theta_a)\cdot r_1^2/(r_2-r_1)$



In practice, reducing the oven size based purely on mechanical considerations, may reduce oven controllability because of self heating!

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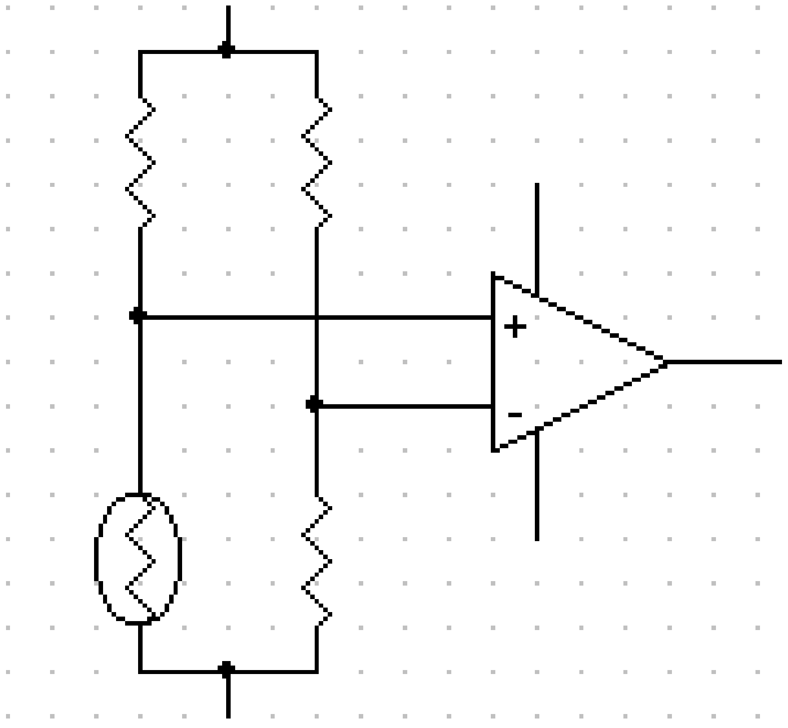
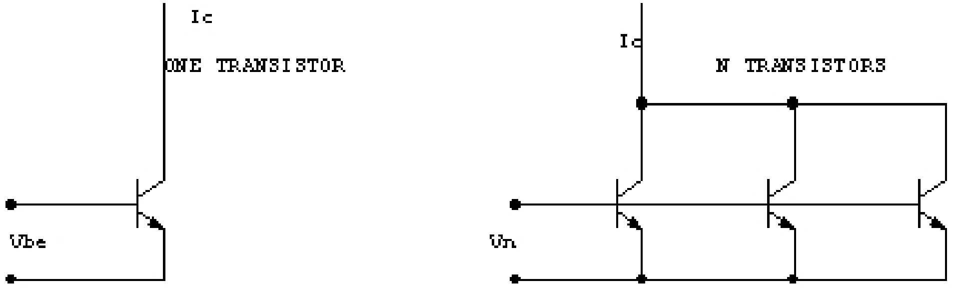
Traditional Oven Controller

- Use thermistor (resistor with –ive tempco) bead, bonded to heat sink, in otherwise resistive bridge
- Aging effects behavior of all components, but most severe is the drifts of the OP Amps (usually 3) in controller
- Need to tune controller before encapsulation (i.e., assumes that this is a repeatable process)
- Tuning potentiometers are effected by aging/ shock



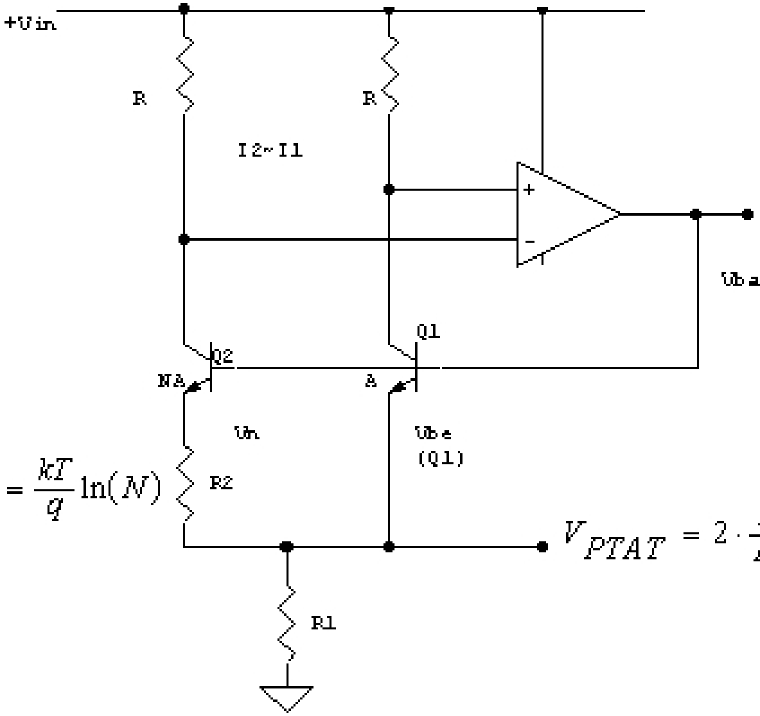
Semiconductor Temperature Sensor

- Typical non-linearity: ±0.1°C over -40°C-105°C
- ±0.5°C maximum error at a given temperature
- Drift with aging <0.2°C over 10,000 hours operation



$$V_{BE} = \frac{kT}{q}\ln\left(\frac{I_c}{I_s}\right) \qquad V_N = \frac{kT}{q}\ln\left(\frac{I_c}{N \cdot I_s}\right)$$

$$V_{BE} - V_N = \frac{kT}{q}\ln(N)\text{, Independent of } I_c, I_s$$



$$V_{BE} - V_N = \frac{kT}{q}\ln(N)$$

$$V_{PTAT} = 2 \cdot \frac{R1}{R2} \cdot \frac{kT}{q}\ln(N)$$

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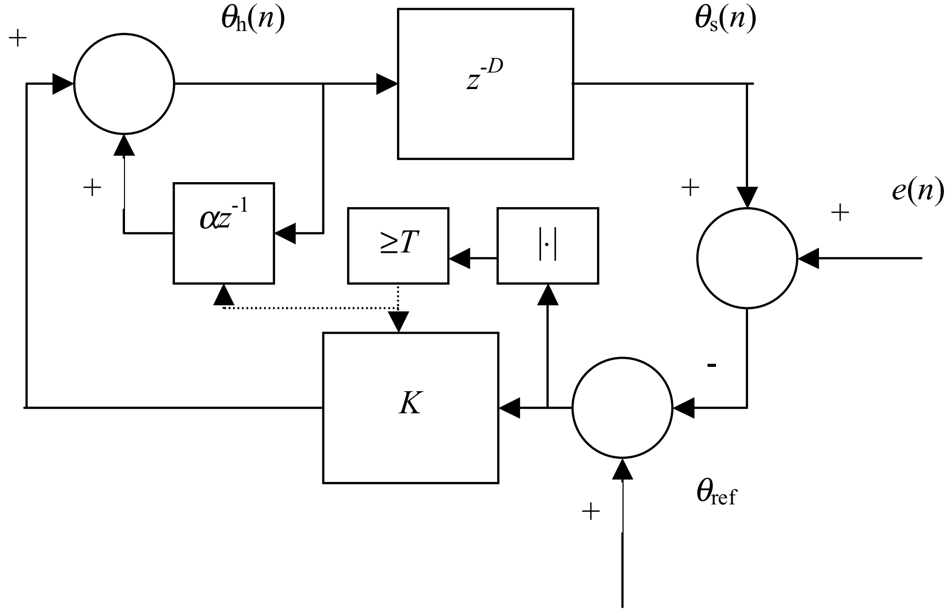
Proportional plus derivative controller with feed-forward

- Feed-forward to compensate for oscillation at thermal lag
- Lack of integral term (which would add to thermal lag and be prone to “wind-up”) gives rise to a steady state “droop”
- Derivative term expands proportional range and reduces overshoot (which may harm electronic circuits over time)
- Can control to 0.0625°C



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Compensation for supply voltage variations

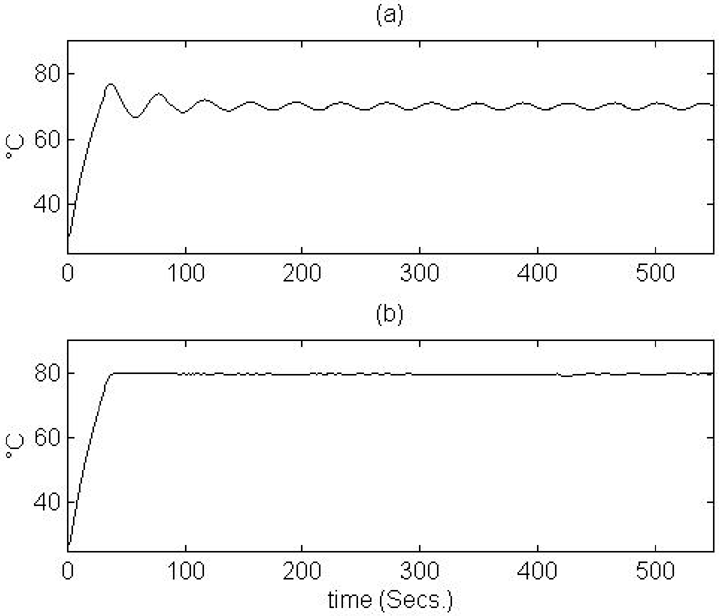
- Regulation adds uncontrolled hot-spot in enclosure
- $\rho(n) = \rho(n-1) + \rho(n-1) \cdot [V^2(n-1) - V^2(n)] / V^2(n)$
- Executed frequently (compared to the oven time constant)
- Anti-aliasing filter to reject high-frequency noise
- Use an inexpensive PWM chip to sense supply voltage

Implementation

- 8-PIN SOIC low-profile PIC12CE519-04I/SN micro-controller
- 16-byte EEPROM stores temperature/ frequency set-points and controller constants
- No interrupts!
- 8-bit timer has insufficient resolution to implement PWM (requires 16-bit accuracy)
- Use quantization to 8-bits and first order quantizer feed-back
- Communicate temperature to PC (every 1.2 seconds) and allow changes to set-points (temperature/ frequency/ controller constants)
- Use digital potentiometer to set varactor diode bias (for frequency tuning)

Oven response tuning

- Variant of the Ziegler-Nichols method
- Set K_d=0, α=1 and then increase K to K_u, where continuous cycling, with period P_u seconds, around a lower-than nominal temperature occurs (Fig. *a*)
- K, K_d and α are set to $0.75K_u$, $4P_u/\Delta T$ and $1-(\Delta T/P_u)$ respectively (ΔT is sampling time in seconds).
- For example oven, K_u =31, P_u=36 seconds; setting K=24, K_d =128 and α=31/32 yields a rise time and settling time of 41 and 93 seconds respectively. Droop is 0.28°C. The overshoot from the drooped temperature is 0.41°C.
- Then set temperature to desired target (response in Fig. b)



(a) Continually cycling response at 70°C set-point with K=31 (b) Oven response: during the settling period, from 0-300 secs, the supply voltage is 5.25V; from 300-420 seconds, the supply voltage is 4.75V; while in the remaining time the supply is once again 5.25V

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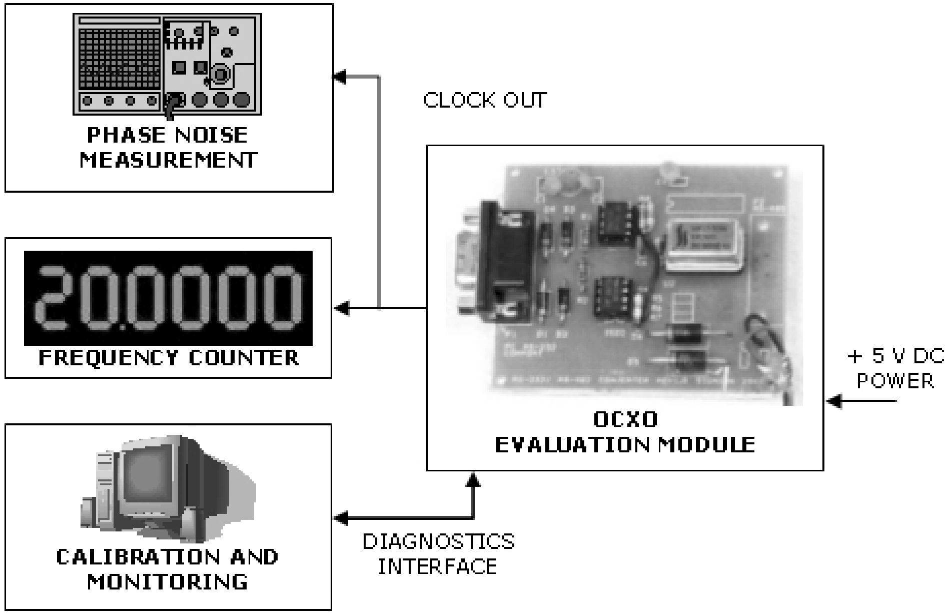
Temperature set-point and frequency tuning

- Modified Allan variance (for phase noise) is:

$$\mathrm{mod}\,\sigma_y^2(\tau) = \frac{2}{n^4\pi^2\tau_0^2}\int_0^{f_h}\frac{S_y(f)\sin^6(\pi\tau f)}{f^2\sin^2(\pi\tau_0 f)}\,df$$

- Rather than specifying Allan variance, it is typical to specify the maximum value of the noise spectrum, S_y, at specified offsets from the center frequency
- Adjust the temperature set-point to obtain lowest phase noise curve
- Adjust the center frequency through the varactor diode bias
- Repeat the previous two steps until desired phase noise and center frequency are obtained



Signion

We have described:

- Oven construction
- Oven electronics
- Digital control algorithm
- Oven parameter tuning
- Temperature set-point and frequency tuning

Realizing a high performance and compact OCXO is a function of several other factors (in crystal manufacturing process) that have not been described!