AXTAL ADVANCED XTAL PRODUCTS

Comparison Of The Characteristics Of Quartz, Langasite and Gallium Phosphate Bulk Acoustic Wave Resonators

Bernd Neubig*

*AXTAL, Buchfinkenweg 8, D-74931 Lobbach, E-Mail: BNeubig@axtal.com

Content

- Scope
- Langasite (LGS) and $GaPO_4$ Material
- Comparison of Resonator Characteristics
- Temperature Compensation for Sensors
- VCXO and OCXO application
- Summary & Conclusions

Scope

- LGS and $GaPO_4$ are rather thoroughly characterized piezoelectric crystal materials
- Both materials are now commercially available
- Both materials are excellent candidates for applications as sensors and frequency control components beyond the limitations given by quartz

LGS and $GaPO_4$ Material

Langasite (LGS) $La_3Ga_5SiO_{14}$

Courtesy FOMOS Moscow / Russia

LGS and $GaPO_4$ Material

Gallium Phosphate $GaPO_4$

Courtesy PIEZOCRYST Graz / Austria

LGS and $GaPO_4$ Material

- Why use these materials ?
  - Higher coupling factor k than quartz,
    while high Q-factor and good temperature stability

	k_{max}
Quartz	**8 %**
Langasite	**14.8 %**
$GaPO_4$	**15.8 %**

$$k \approx \sqrt{\frac{C_1}{C_0 + C_1}}$$

- allows wider frequency pulling for VCXO
  (Voltage Controlled Crystal Oscillator)
- allows sufficient pulling for higher overtones (OCXO)
- allows higher sensitivity for capacitor/resonator sensor systems

LGS and $GaPO_4$ Material

- Why use these materials ?
  - Lower frequency constant $N = f \cdot t$ than quartz

	N
Quartz (AT cut)	**1660 kHz mm**
Langasite (Y-cut)	**1380 kHz mm**
$GaPO_4$ ($Y^{-17°}$ cut)	**1270 kHz mm**

    - allows smaller resonators at lower frequency
  - Application at very high temperatures

	Limiting factor
Quartz	**Twinning >350°C, $\alpha \rightarrow \beta$ phase transition @ 573°C**
Langasite	**Melting point @ 1470°C**
$GaPO_4$	**$\alpha \rightarrow \beta$-cristobalite phase transition @ 970°C**

LGS and $GaPO_4$ Material

- What are the limiting factors?
  - Manufacturing cost

Quartz	Cheap raw material, cost-effective hydrothermal growth
Langasite	High Gallium price, low-cost & fast Czochrasky growth
$GaPO_4$	High Gallium price, expensive & slow hydrothermal growth, yield limitations

  - Available wafer size

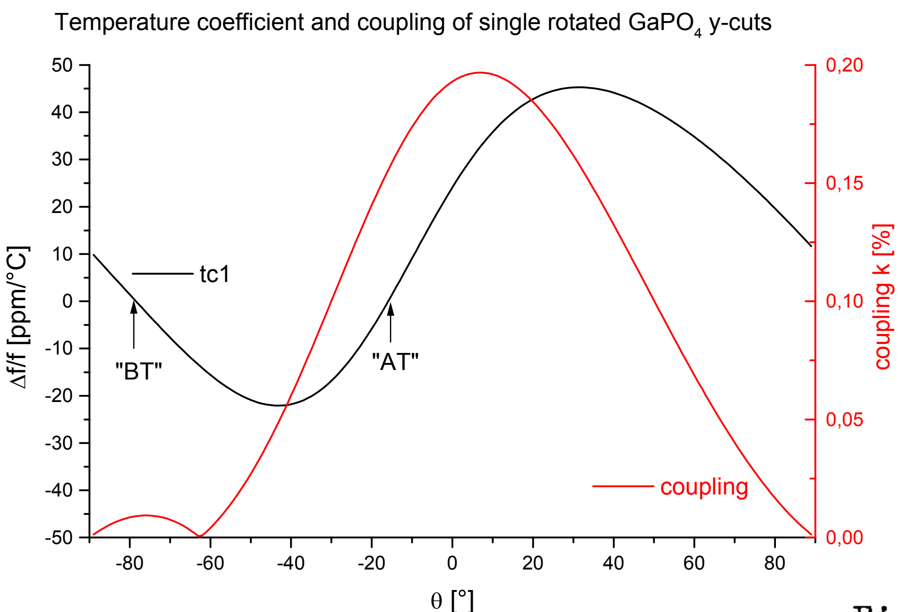
Quartz	4'' wafers commercially available in high volume
Langasite	3'' and 4'' wafers commercially available
$GaPO_4$	Blanks with dislocation-free areas of 2~4 cm^2

LGS and $GaPO_4$ Material

- Some Characteristic Parameters

		Quartz	Langasite	$GaPO_4$
Moh's hardness		7	6,6	5
Density / $kg \cdot m^{-3}$		2650	5750	3570
Thermal expansion	α_{11}	13,7	5,1	12,8
in $ppm \cdot K^{-1}$	α_{33}	7,5	3,6	3,7
Dielectric permittivity	ε_{11}^{S}	4,43	18,9	5,8
	ε_{33}^{S}	4,63	50,7	6,6
Piezoelectric coefficient	d_{11}	2,3	6,2	4,5
in $pC \cdot N^{-1}$	d_{14}	0,57	5,3	1,9

LGS and $GaPO_4$ BAW Y'-Cuts



from: Krispel, F. et al., FCS 2003

$GaPO_4$

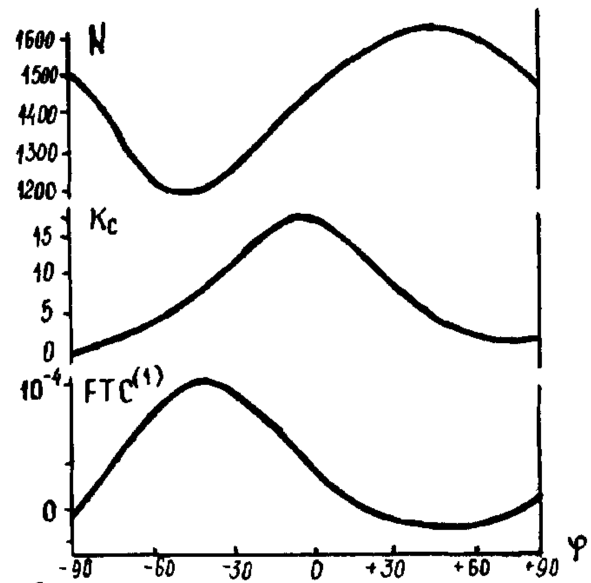
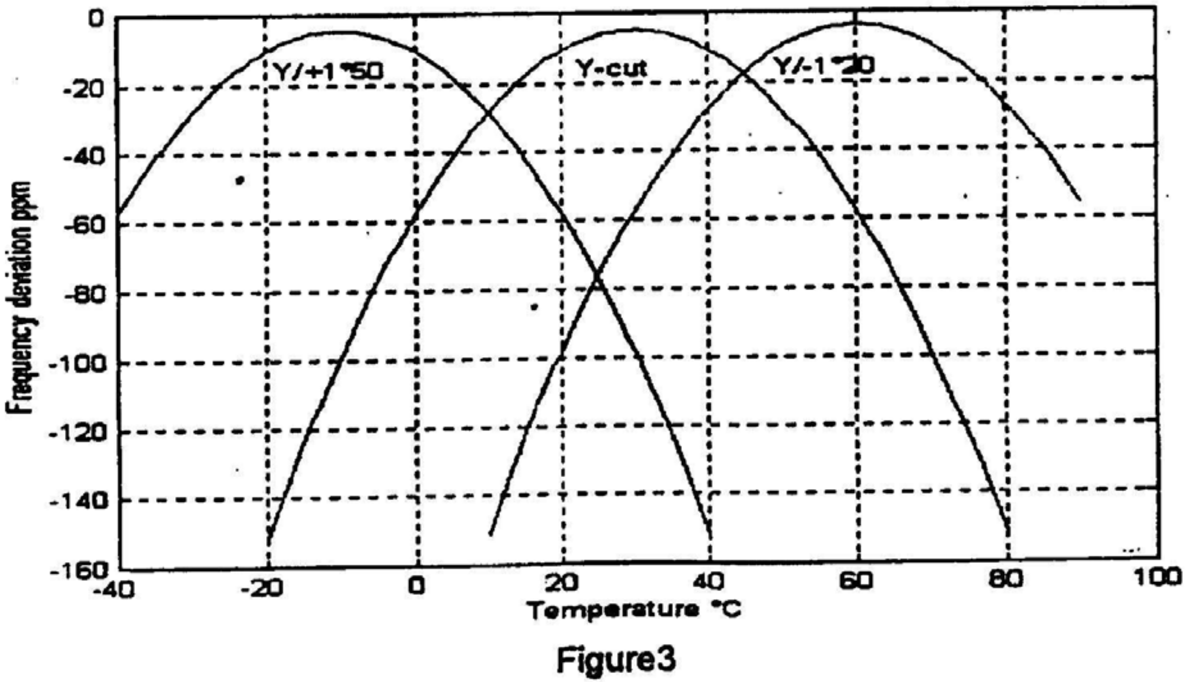


Fig. 6: Frequency constant N, electromechanical coupling coefficient k_s and the first order frequency temperature coefficient $FTC^{(1)}$ vs the rotation angle

from: Sakharov, S.A. et al., FCS 1992

LGS

f(T) for LGS Y'-Cuts



$$\boxed{\frac{df}{f}(T) = a_2 \cdot (T - T_0)}$$

with

$a_2 = -0{,}059\ ppm \cdot K^{-2}$

Angle sensitivity for TOT:

$-0{,}4\ K \cdot arcmin^{-1}$

from: Grouzinenko, V.B. et al., FCS 2001

f(T) for $GaPO_4$ Y'-cuts

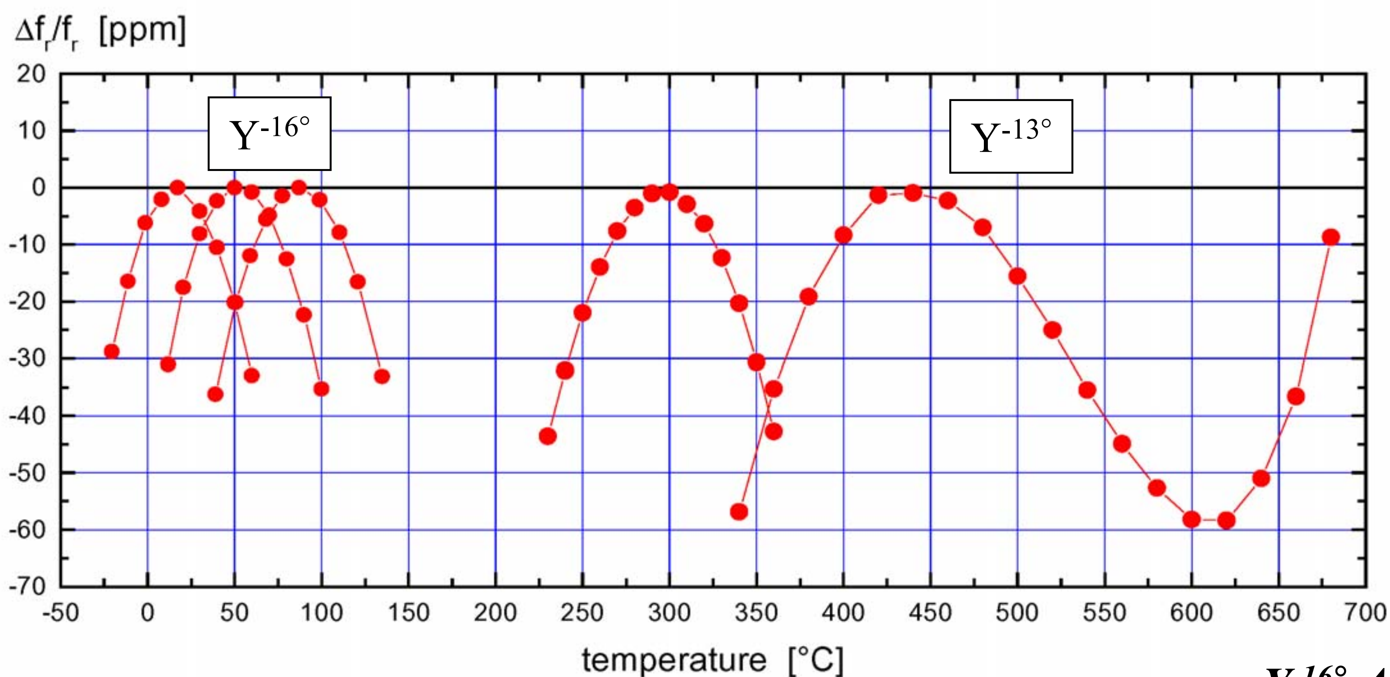


Figure 2: Temperature compensation in $GaPO_4$ thickness shear resonators

Y-16° Angle sensitivity: -0,8 K·arcmin^{-1}

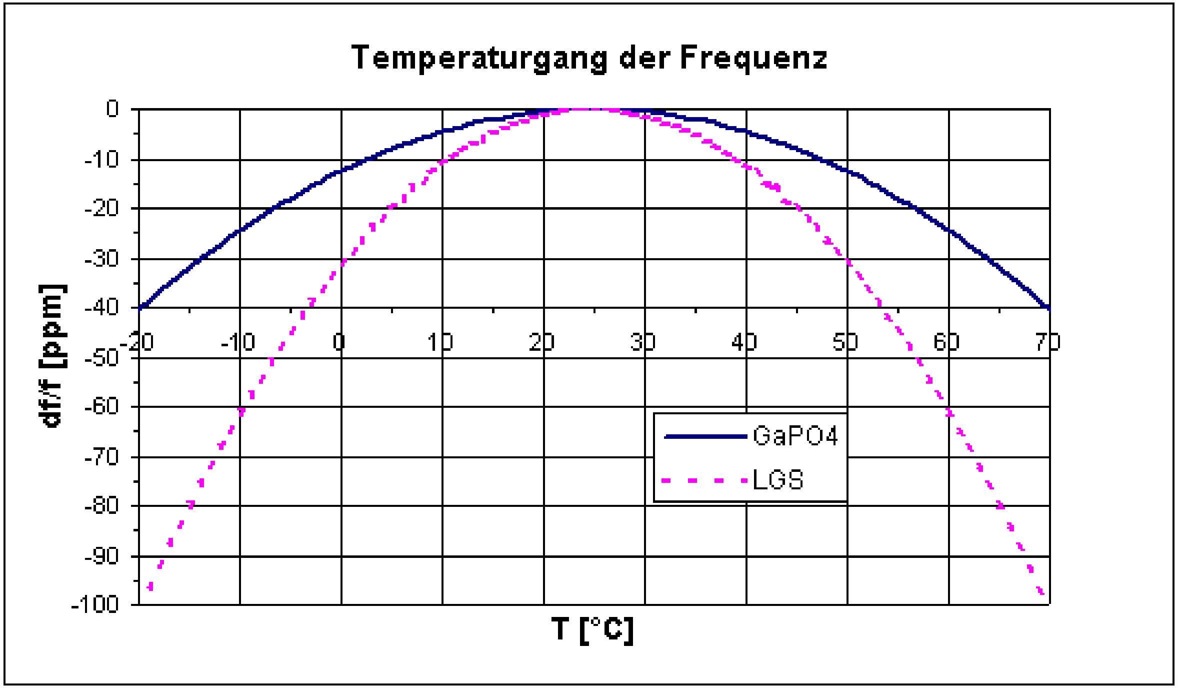
from: Worsch, P.M. et al., Munich (2001)

$$\frac{df}{f}(T) = a_2 \cdot (T - T_0)$$

a_2 ***= -0,019 ppm·K^{-2}***

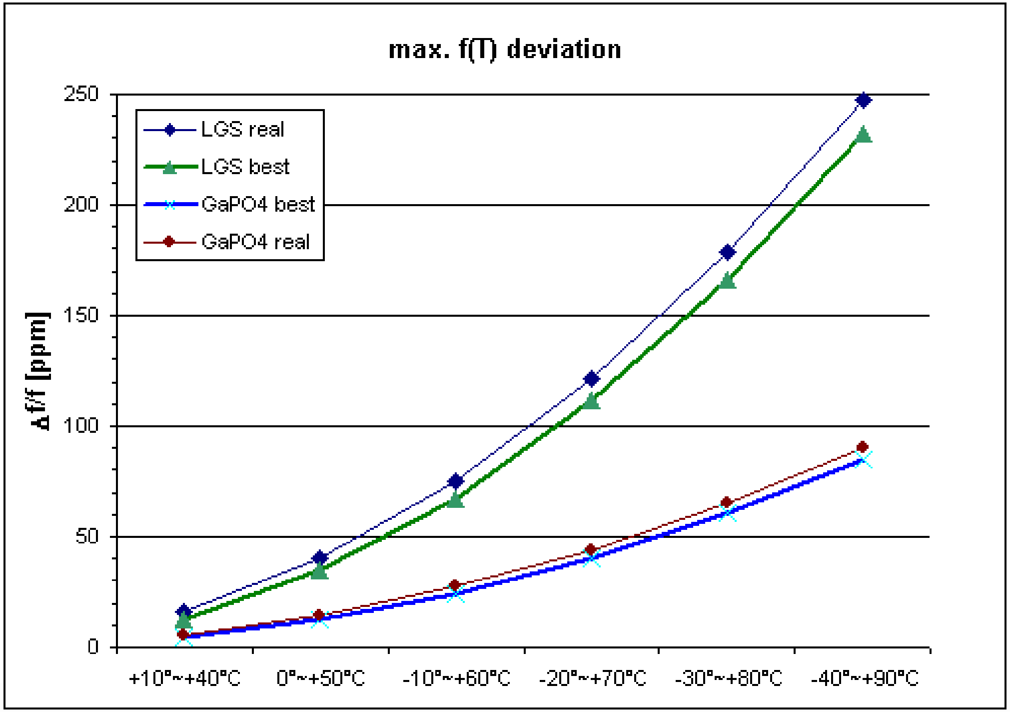
Temperature Stability

- f(T) - Comparison LGS vs. $GaPO_4$



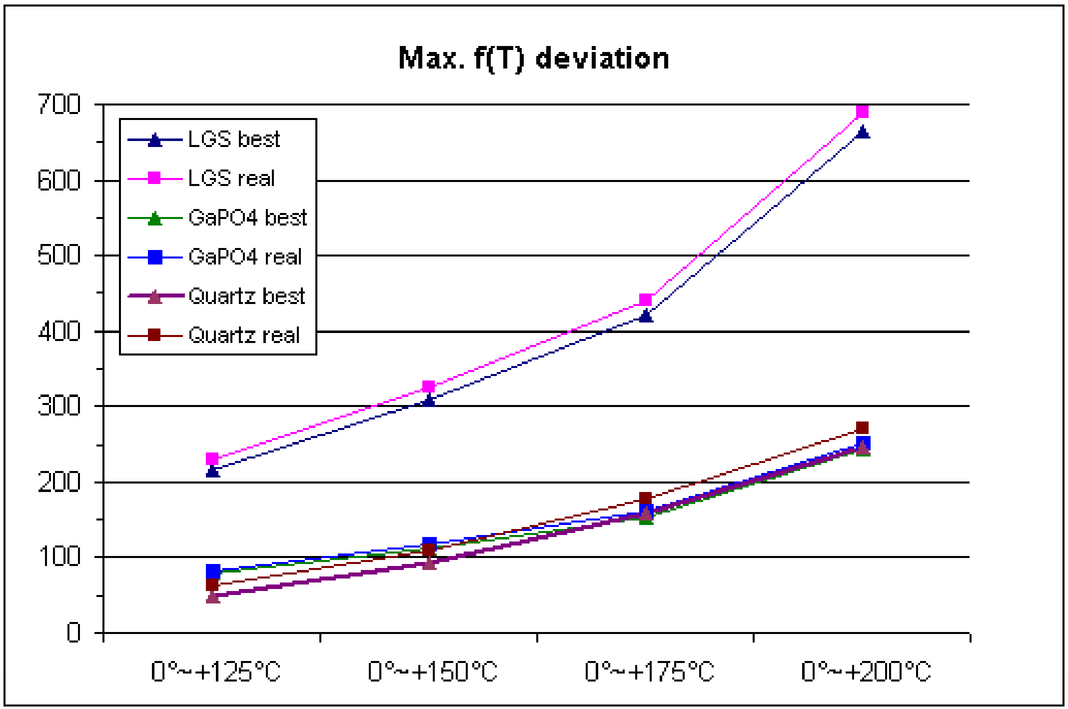
Temperature Stability

- Overall temp. stability LGS vs. $GaPO_4$



Temperature Stability

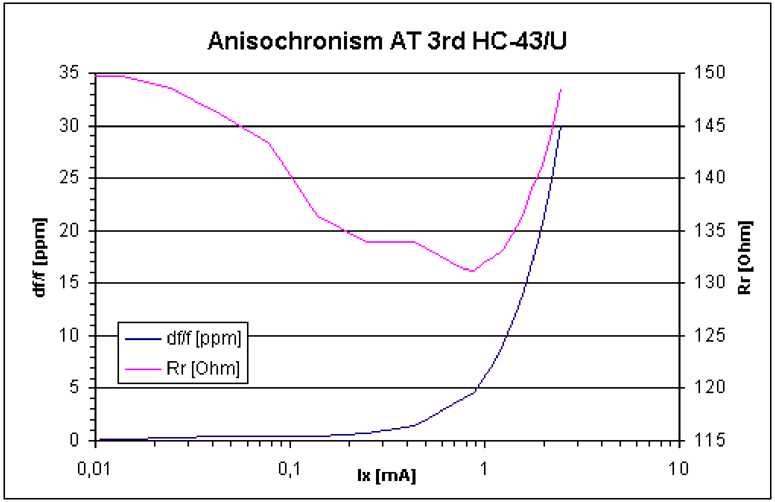
- Hi-Temperature f(T) LGS vs. $GaPO_4$

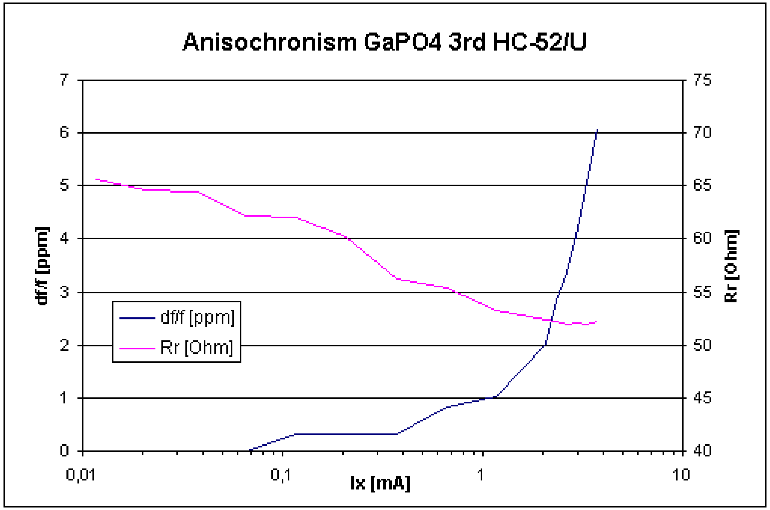


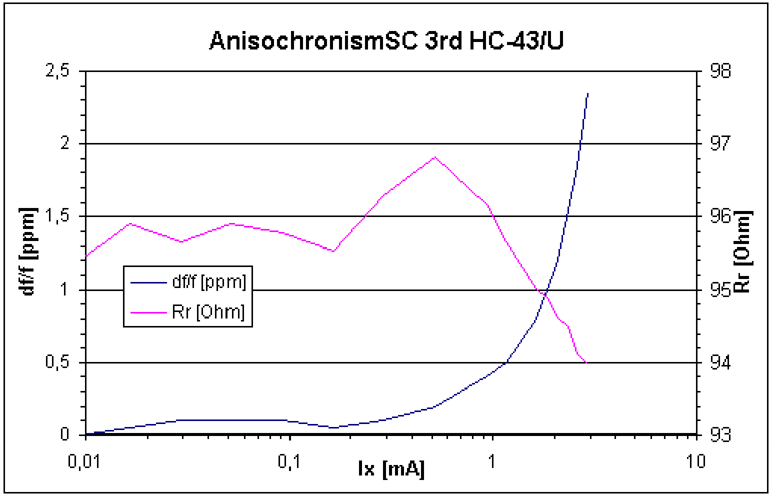
Other features

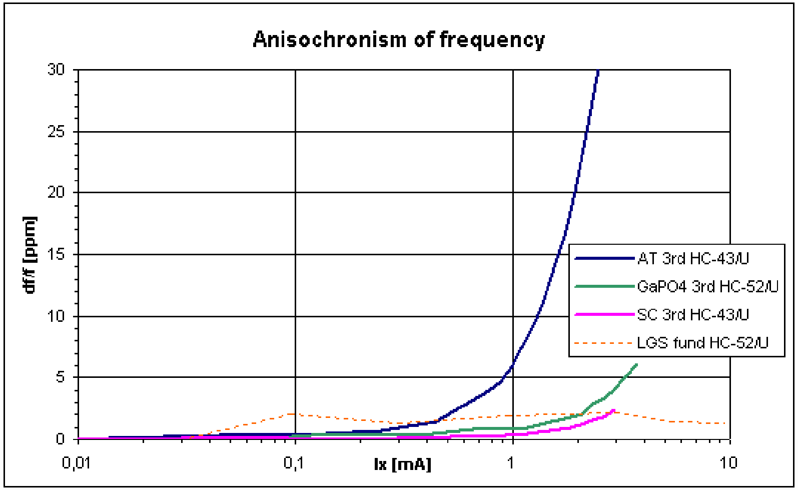
- Drive level dependence (Anisochronism)
  - Non-Linearity starts at higher vibration amplitudes than in quartz AT cut resonators
  - Comparable ($GaPO_4$) or superior (LGS) to quartz SC-cut, while easier to manufacture due to single rotation
  - Allows to drive resonators harder
    - Lower (phase) noise
    - Advantage in some sensor / actor applications

Anisochronism Results



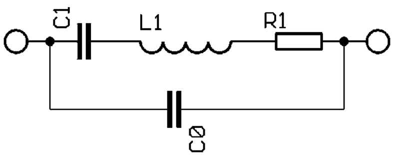


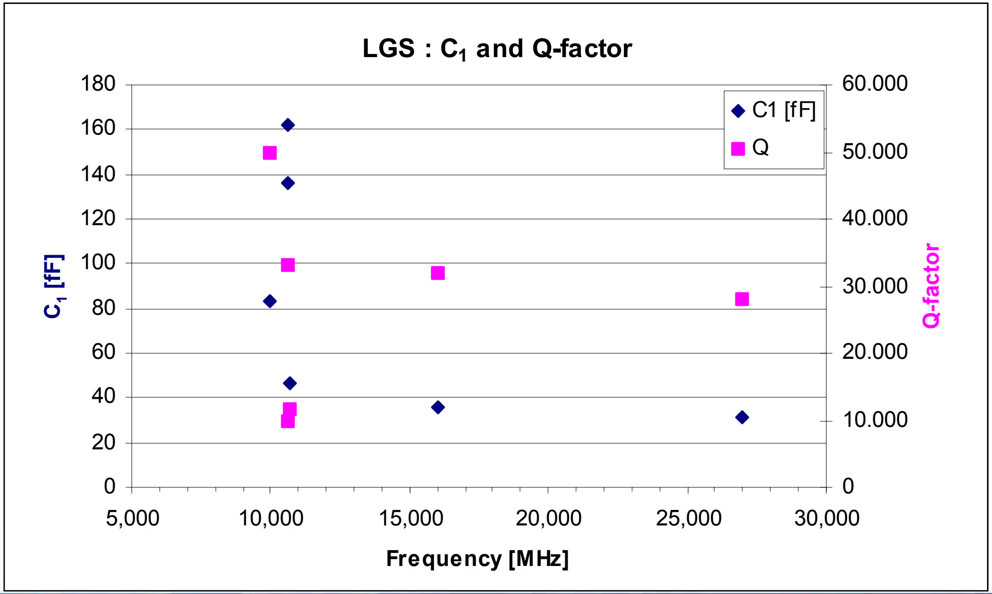




LGS : Resonator Parameters

Freq [MHz]	R_1 [Ohm]	C_1 [fF]	C_0 [pF]	r	Q
10,000	3,9	83	5	60	50.000
10,650	3,3	136	81	59	33.000
10,650	9,4	162	9,7	60	9.800
10,700	28,0	47	3,9	83	11.700
16,000	9,5	36	2,4	67	32.000
27,000	8,2	31	2,3	75	28.000

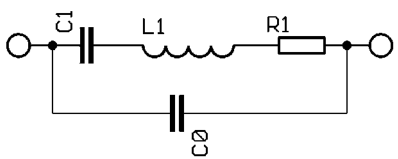


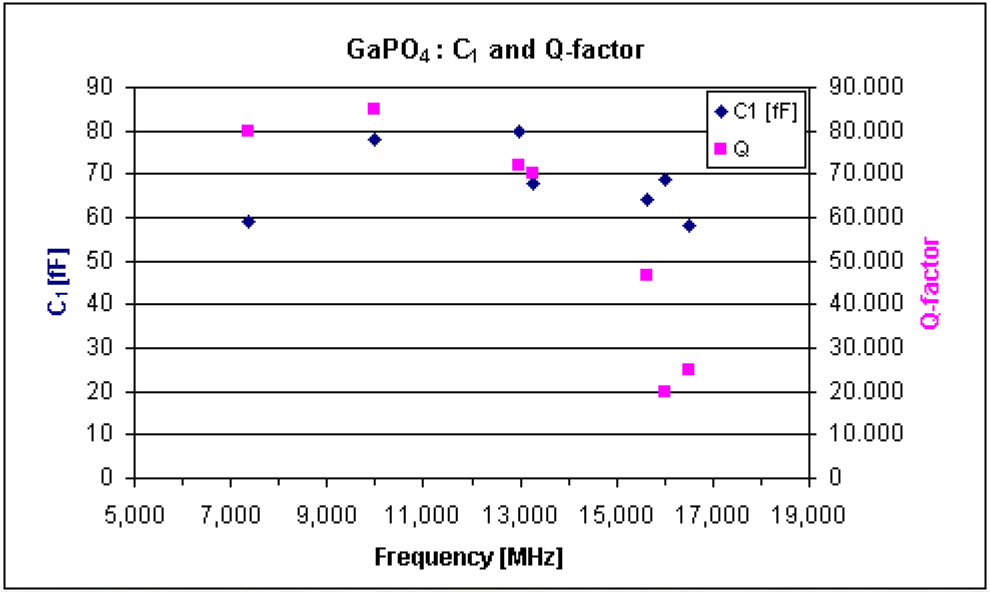


Enclosure:
HC-52/U

$GaPO_4$: Resonator Parameters

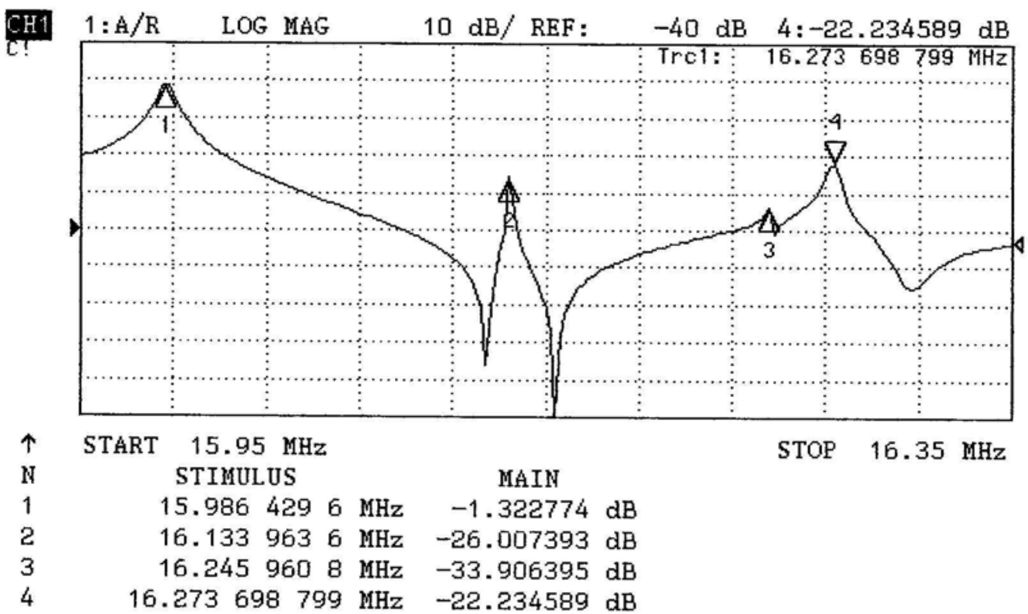
Freq [MHz]	R_1 [Ohm]	C_1 [fF]	C_0 [pF]	r	Q
7,375	4,6	59	3,4	58	80.000
10,000	2,4	78	4,4	56	85.000
12,966	2,2	80	4,6	57	72.000
13,280	3,0	68			70.000
15,625	3,7	64	5,2	83	46.600
16,000	7,4	69	3,8	54	20.000
16,500	8,0	58			25.000
9,85/ 3rd OT	62	1,1	1,8	1719	244.000





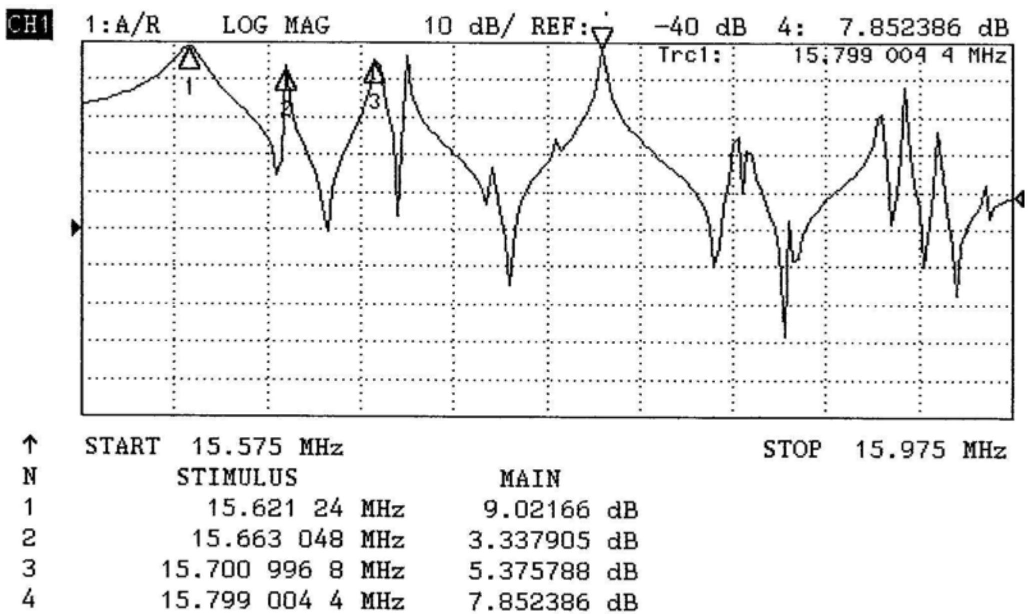
Enclosure:
HC-52/U

LGS : Spurious Resonances



Enclosure:
HC-52/U

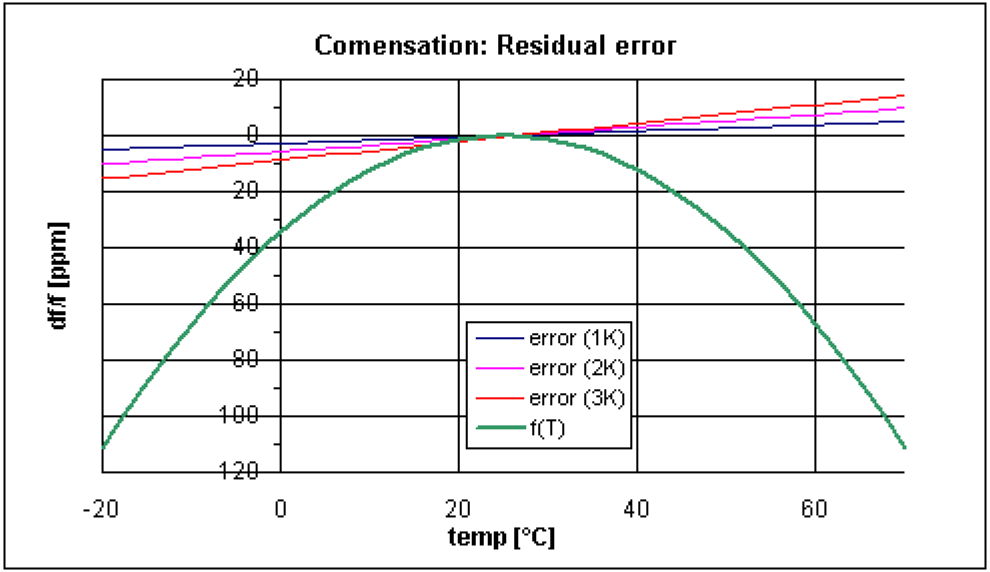
$GaPO_4$: Spurious Resonances



Enclosure: HC-52/U

Temperature Compensation

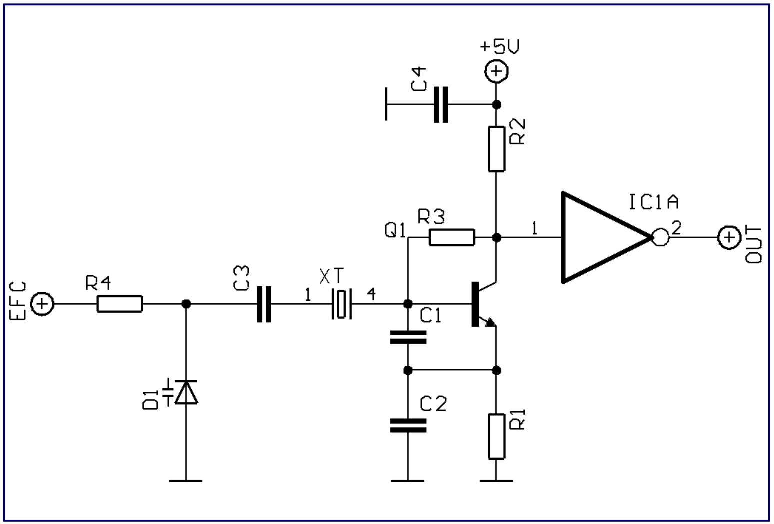
Compensation of f(T) error (sensor applications)
by using 2 resonators and subtracting the frequencies



Green:
f(T) of reference resonator

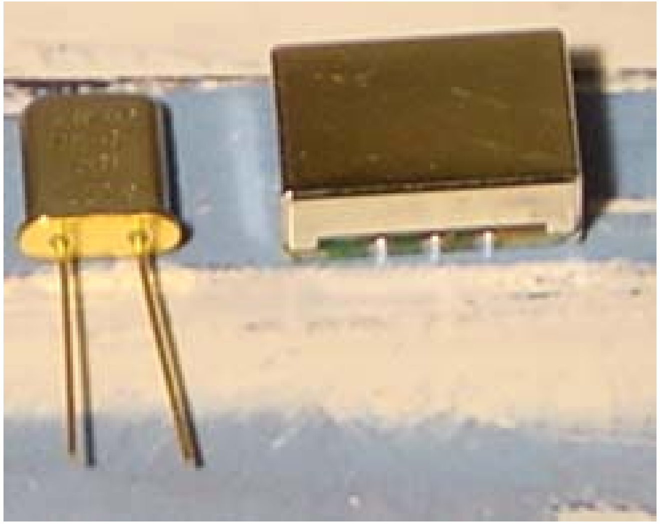
others:
residual f(T) error for TOT-difference of 1 K, 2K and 3K

LGS and $GaPO_4$ VCXO



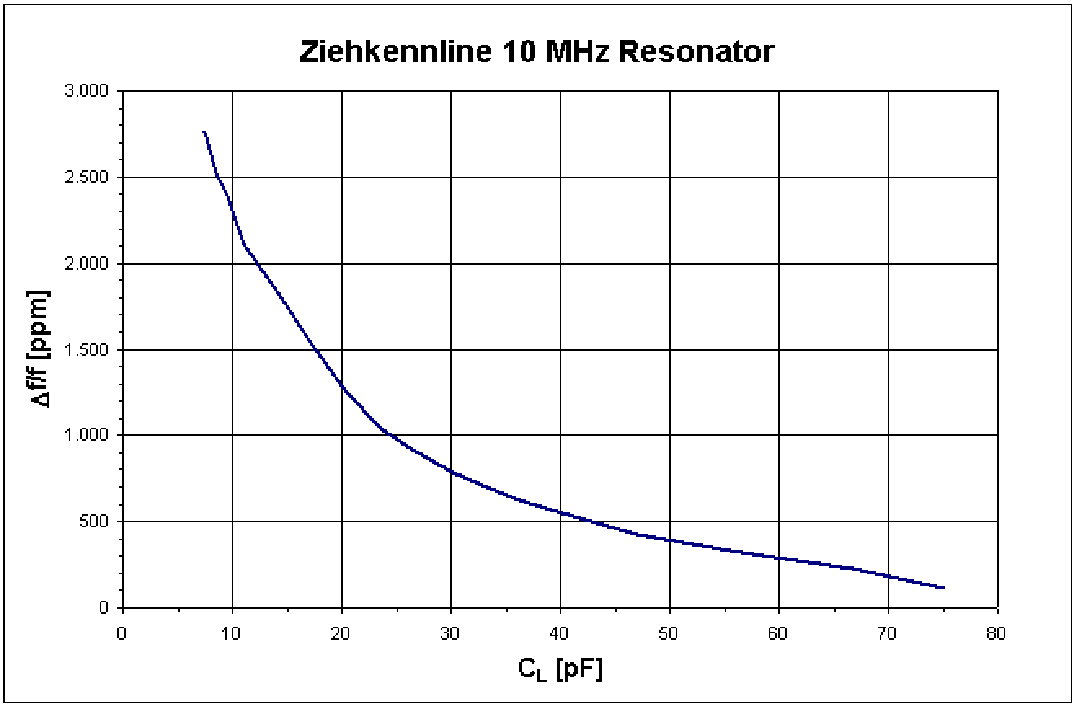
D1 = hyperabrupt varactor

VCXO schematic

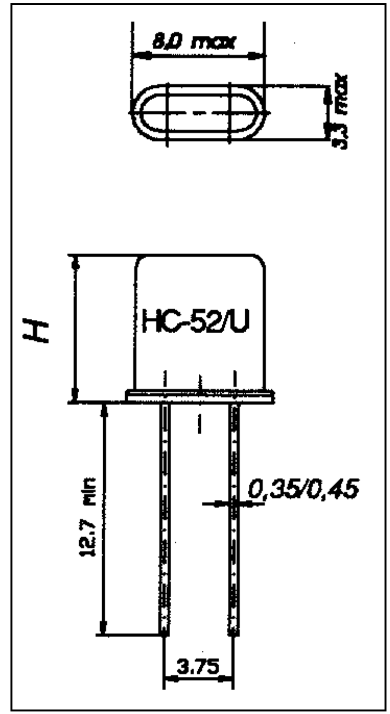


HC-52/U resonator &
9x14 mm VCXO

Pullability & Size

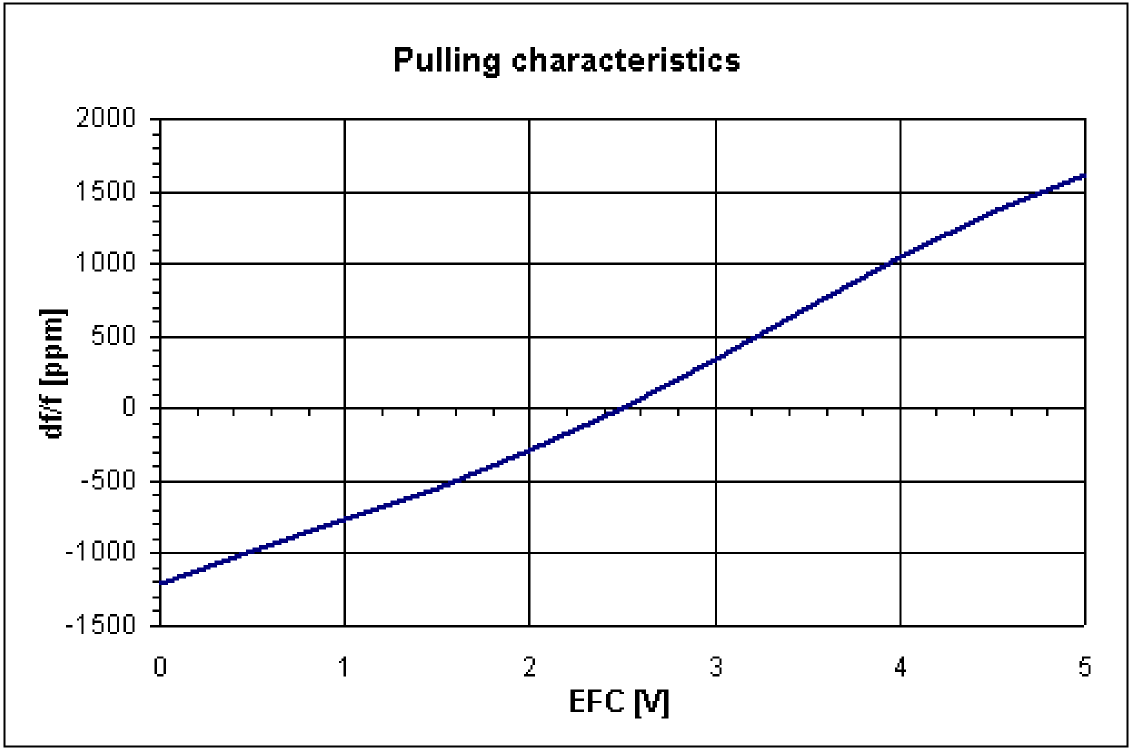


Typical Pulling Characteristics $f(C_L)$ of a 10 MHz LGS resonator in HC-52/U



Package HC-52/U
(H = 8.0mm)

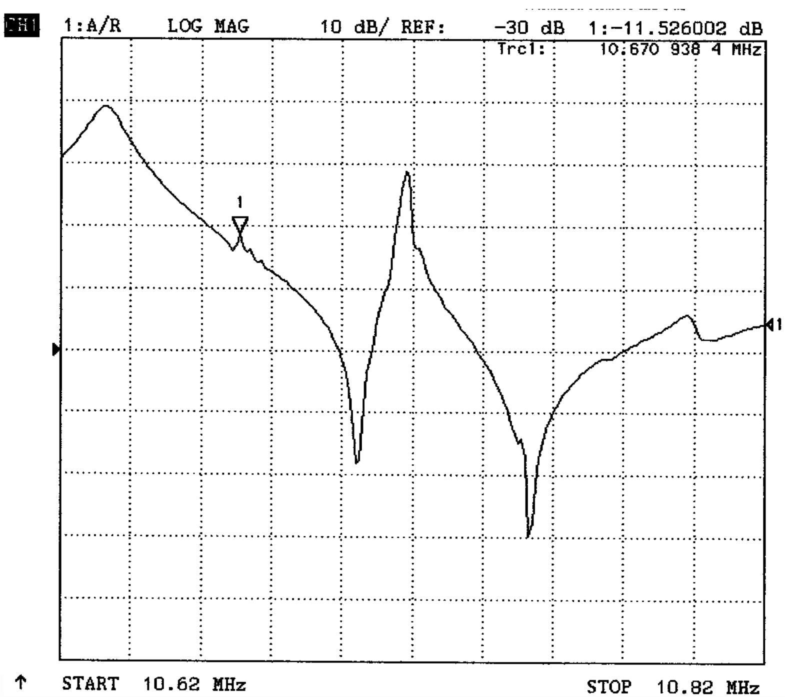
VCXO Pulling characteristics



Resonator:
$GaPO_4$
16 MHz
HC-52/U

VCXO Pulling characteristics

- PR Limitation by spurious resonances

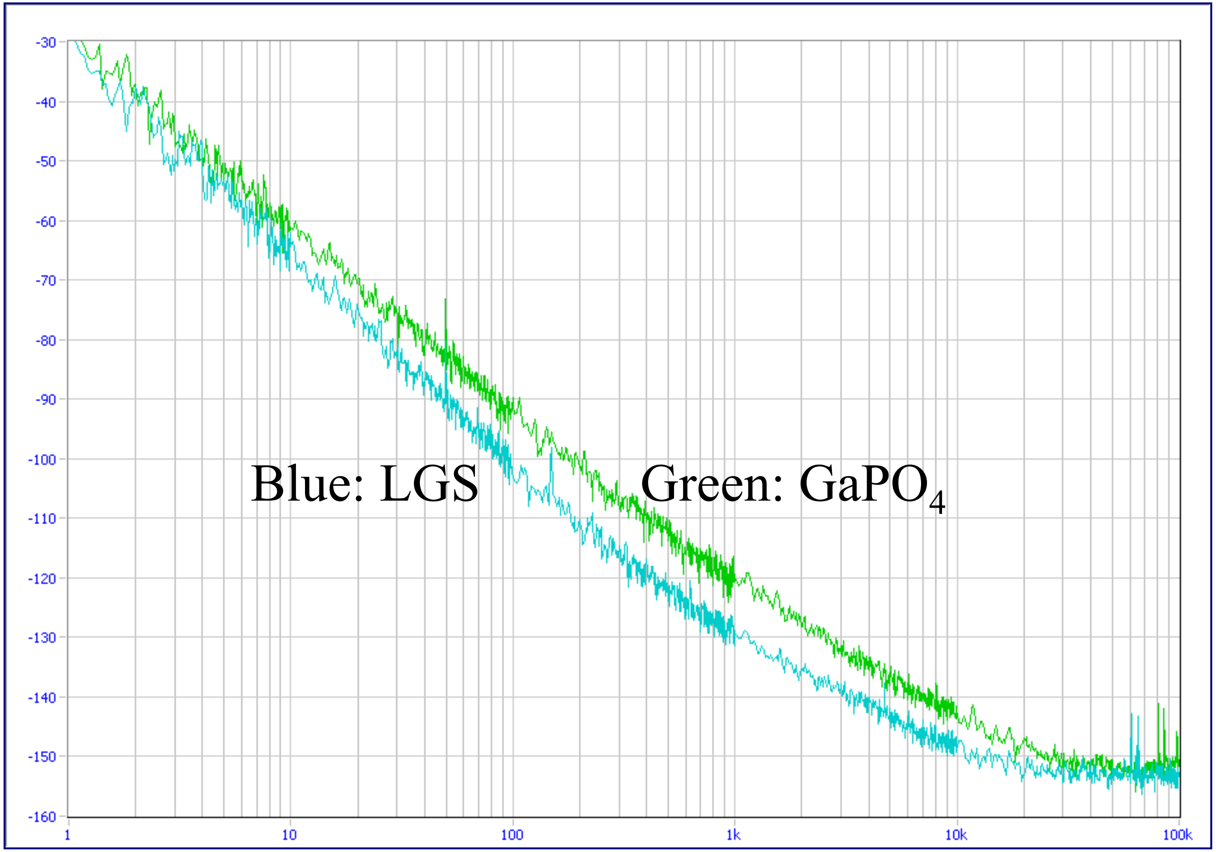


Even small spurious resonances distort the pulling characteristic.

Spurious resonances increase with larger electrode size and with electrode thickness.

Resonator design must take care of energy trapping.

VCXO Phase Noise

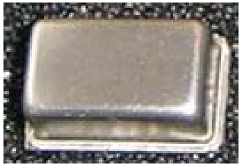


<u>VCXO 16 MHz</u>

LGS:
C_1= 36 fF
Q=32 000

$GaPO_4$:
C_1= 69 fF
Q=20 000

$GaPO_4$ and Quartz OCXO

- OCXO in 4 pin DIL14 package  requires a HC-52/U size resonator or smaller
- 10 MHz / 3rd overtone not realizable in HC-52/U with Quartz AT and SC
- $GaPO_4$ allows 10 MHz / 3rd due to lower frequency constant
- LGS would also allow 10 MHz / 3rd, but is not evaluated yet

$GaPO_4$ and Quartz OCXO

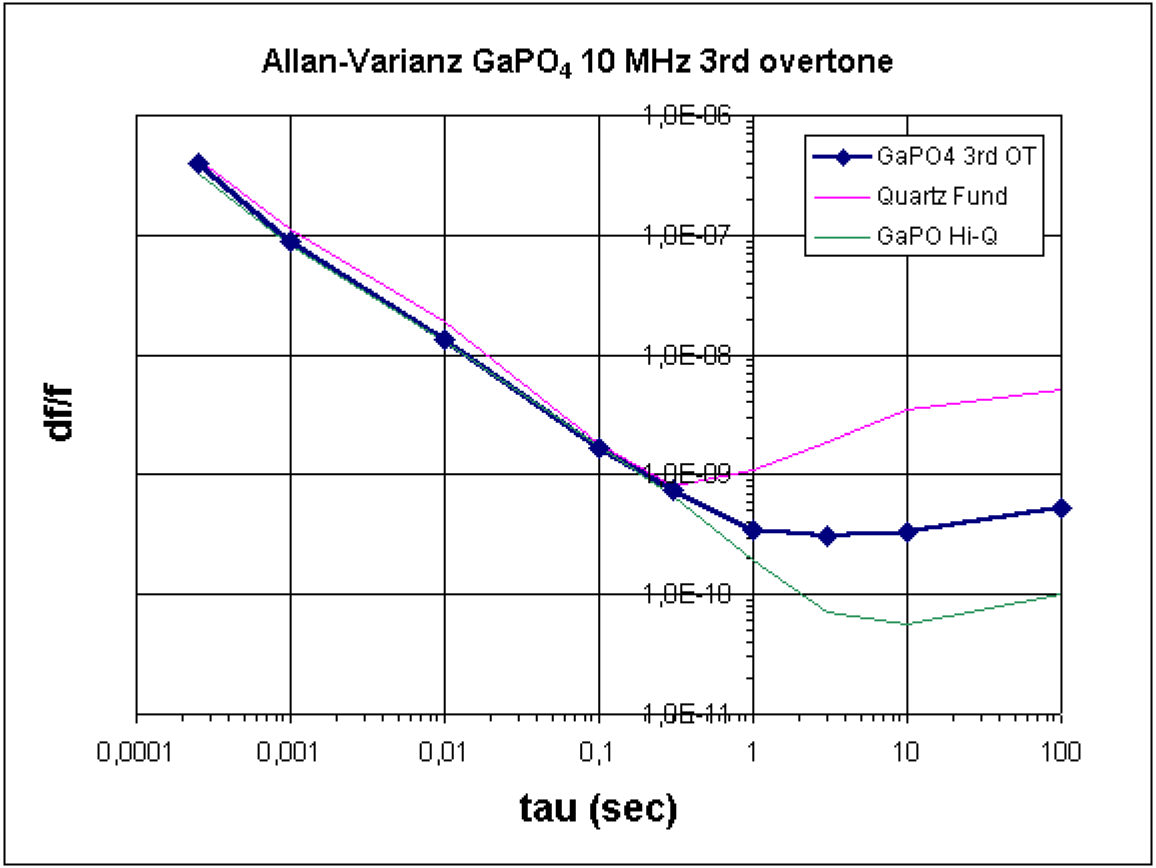
- $GaPO_4$ vs. Quartz AT & SC

Type	Parameter	Value
$GaPO_4$ 3rd overtone Y-16° - cut HC-52/U	Frequency	9.85 MHz
	R_1	62 Ω
	C_1	1.06 fF
	C_0	1.83 pF
	Q	244 000
	r	1719
Quartz Fundamental AT – cut HC-52/U	Frequency	12 MHz
	R_1	10.4 Ω
	C_1	11.5 fF
	C_0	2.54 pF
	Q	111 000
	r	220

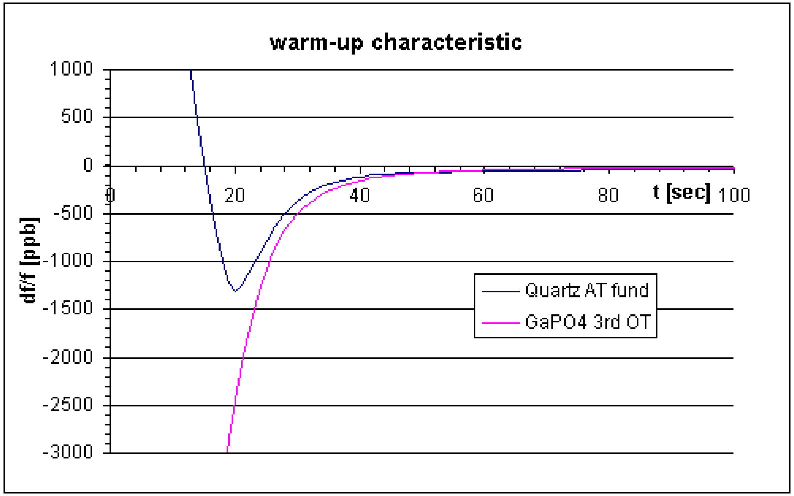
Type	Parameter	Value
Quartz 3rd overtone SC - cut HC-43/U	Frequency	10 MHz
	R_1	100 Ω
	C_1	0.145 fF
	C_0	2.17 pF
	Q	1 120 000
	r	15 000
Quartz 3rd overtone AT - cut HC-43/U	Frequency	10 MHz
	R_1	140 Ω
	C_1	0.30 fF
	C_0	4.15 pF
	Q	390 000
	r	14 000

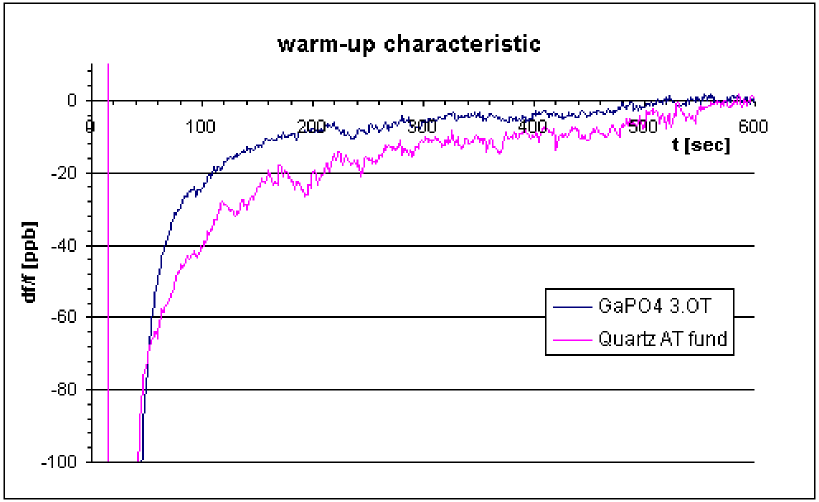
used

DIP OCXO Allan Variance



DIP OCXO Warm-up





OCXO with $GaPO_4$ resonator shows no overshoot, and is faster on frequency (after 60 sec), similar to SC-cut quartz crystal

Summary & Conclusions

- LGS and $GaPO_4$ show interesting capabilities for VCXO, OCXO and sensor applications
- VCXO in 9x14 mm size with high pulling range and low phase noise
- OCXO in DIP14 size using low-frequency 3rd overtone resonators

Summary & Conclusions

- VCXO in 9x14 mm size
  - Pulling range limited by spurious responses
    - Trade-off C_1 vs. Spurs
    - Energy trapping must be considered
  - $GaPO_4$ offers better f(T) stability than LGS
  - $GaPO_4$ shows in average higher Q value than LGS, close to Q-factors of quartz AT cuts
  - Low anisochronism allows higher drive level

Summary & Conclusions

- OCXO 10 MHz in DIP14 size
  - $GaPO_4$ $Y^{-16°}$ cut is a good candidate for miniature OCXO with overtone resonators
  - short-term stability is superior to quartz (AT fund) resonator of same size
  - Warm-up time of $GaPO_4$ based OCXO is shorter and shows no overshoot as a quartz AT-cut
  - OCXO performance of LGS not studied yet