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VCXOs with wide pull-in range using alternatives to quartz

Frequency generation using a quartz crystal oscillator offers a high degree of stability over a relatively wide range of temperature. However, alternative materials to quartz offer a wider pull-in range with similar stability, making it possible to create VCXOs with ten times the pull-in range.

1. Introduction

Quartz crystal oscillators are distinguished by a high degree of stability, but the pull-in range for VCXOs (Voltage Controlled Crystal Oscillators) is relatively narrow, typically ±50 ppm to ±150 ppm.

The author described the various circuit techniques that can be used to increase the pull-in range [1]. To do this, high-inductance coils must be used in series and/or parallel with the crystal. The higher the series inductance, the wider the pull-in range. But the quality, and therefore the stability, falls drastically, since the characteristics of the coil become more and more important in specifying the frequency.

Research has been going on into alternatives since quartz started to be used to generate frequencies, but no material has been found to date that can really replace quartz. In recent years great progress has been made with research and development projects involving piezo-electric crystals. These are almost as stable as quartz, but allow for wider pull-in ranges (and/or wider bandwidths in filters). Also much progress has been made into the industrial production of these crystals. Here are some of these alternative materials to quartz:

- berlinite (aluminium phosphate $AlPO_4$)
- gallium phosphate(V) ($GaPO_4$), together with the lanthanum compounds
- langasite (LGS, lanthanum gallium silicate $La_3Ga_5SiO_{14}$)
- langanite (LGN, lanthanum gallium niobate $La_3Ga_5NbO_{14}$) and langatate (LGT, lanthanum gallium tantalate $La_3Ga_5TaO_{14}$).

Some of the materials listed are nowadays commercially available as synthetically pulled crystals (Fig 1) [2], [3].

Resonators made from these crystals have a considerably higher pulling capability than quartz with an identical or similar crystal structure. Thus voltage-controlled oscillators can be manufactured which have ten times the pull-in range of a quartz VCXO, also broadband filters.

Fig 1: Gallium Phosphate crystal. Photgraph from AVL List [2].

2. Basic principles

The pulling capability of a piezo-electrical resonator is determined by the so-called coupling factor, *k*. Its value is pre-set by the physical characteristics of the material, and it varies depending on the angle of cut. Table 1 shows the maximum value of *k* for various materials.

The equivalent circuit diagram of a piezo-electric resonator is shown in Fig 2. C_1, L_1 and R_1 form the frequency-determining dynamic branch and C_0 the static inherent capacitance.

The coupling factor, k, is related to the equivalent circuit components by the relationship:

$$k^2 \approx \frac{C_1}{C_0 + C_1} \approx \frac{1}{r}$$

Where: $r = C_0/C_1$ described as the capacity ratio.

For high frequency stability combined with greater pulling capability, the resonator disc must be cut out of the crystal at an angle at which the temperature coefficient of the frequency is as low as possible, and simultaneously the coupling factor is relatively high. The most favourable situation is when a temperature coefficient, TK_f , of zero is present in the middle of the working temperature range.

In contrast to the working temperature cutting of quartz, the most favourable temperature coefficient curve for thickness shear oscillators using $GaPO_4$ and the lanthanum compounds LGS, LGN and LGT is a second-order parabola with the form:

$$\frac{\Delta f}{f_0} = b \cdot (T - T_0)^2$$

Where: T_0 is the arrest point temperature ($TK_f = 0$) and *b* the parabolic coefficient. The latter is negative, i.e. the parabola is “opened downwards”.

An arrest point at $T_0 \approx 25°C$ can be attained using $GaPO_4$ with a cutting angle of $\theta \approx -16°$ and using LGS with a Y cut ($\theta = 0°$).

The parabolic coefficient, *b*, for $GaPO_4$ is approximately $2x10^{-8}$ K^{-2}, and for LGS approximately $6x10^{-8}$ K^{-2}. In practice, this means that for $GaPO_4$ a frequency stability of ± 20ppm can be attained in the temperature range from 20°C to +70°C and ± 40ppm in the range from 40°C to +85°C.

The possibilities for resonators and VCXOs using alternatives to quartz can be shown through two examples at 5MHz and 10MHz.

Table 1: Maximum values of coupling factor k for various materials.

Material	k
Quartz	7%
Langasit (LGS)	15.8%
Gallium Phosphate ($GaPO_4$)	19%

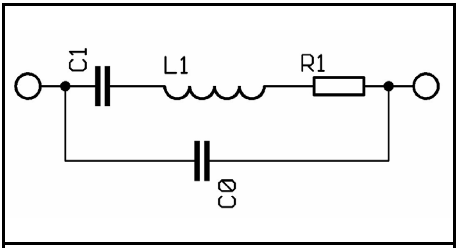

Fig 2: Equivalent circuit diagram of a piezo-electric resonator.

3. Example 1: 10MHz resonators

Resonators were manufactured in the HC-52/U housing, using gallium phosphate ($GaPO_4$) with a Y-16° cut, and the following typical data were obtained:

- Dynamic capacitance C_1 = 80fF
- Static capacitance C_0 = 4.3pF
- Resonant impedance Rr = 2.3Ω
- Quality Q = 87,000

In contrast, quartzes with the same frequency and size display the following typical values:

- Dynamic capacitance C_1 = 10fF
- Static capacitance C_0 = 2.8pF
- Resonant impedance Rr = 14Ω
- Quality Q = 114,000

The capacity ratio is thus 5.3 times greater for the $GaPO_4$ resonator than for a quartz oscillator. In addition, the former has considerably lower impedance, though the quality is somewhat less.

The frequency-temperature characteristic of the $GaPO_4$ resonator is represented in Fig 3. The frequency stability is better than ± 20ppm / 20°C to +70°C, the typical stability for an oscillating quartz in the same temperature range being ± 10ppm.

The pulling characteristic measured with the $GaPO_4$ resonators, i.e. the frequency change plotted against the load capacitance, C_L , is shown in Fig 4. The curve demonstrates a possible pull-in range of 2,500ppm, without the use of coils in the pull-in circuit, which is 10 times the range of a normal quartz crystal VCXO! (Fig 4)

With an additional coil in series with the $GaPO_4$ resonator, a pull-in range of 5,000ppm or more can be obtained.

For comparison purposes, resonators made from langasite (LGS) were measured, which display the following properties:

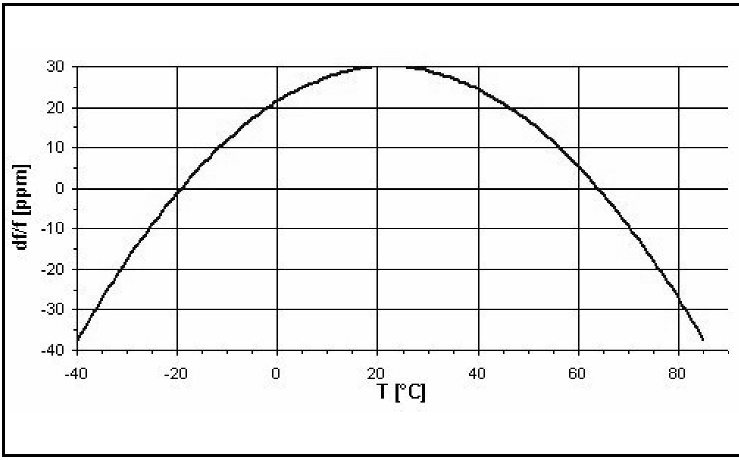

Fig 3: Temperature coefficient of a 10MHz $GaPO_4$ resonator.

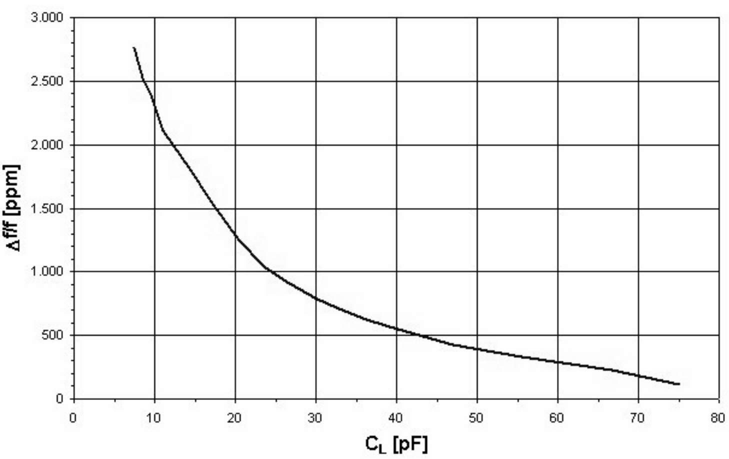

Fig 4: Frequency change plotted against load capacitance for a 10MHz resonator.

- Dynamic capacitance C_1 = 4 fF
- Static capacitance C_0 = 3.3pF
- Resonant impedance Rr = 25Ω
- Quality Q = 12,500

The capacity ratio of the LGS resonator is four times as high as that of the quartz crystal, but it is 32% lower than that of the $GaPO_4$. The resonators have a higher impedance and a markedly lower quality than the comparison materials.

4. Example 2: 5MHz VCXO with 1300ppm pull-in range

Below 10MHz, quartz crystals in a small housing such as the HC-52/U are more difficult (and thus more expensive) to manufacture, since the quartz resonators must be formed as convex discs in order to obtain sufficient quality and stability. However, this is associated with a reduction in the dynamic capacitance, C_1, and thus with a reduced pulling capability.

Alternative materials to quartz such as $GaPO_4$ have a thinner resonator disc at the same frequency, which can be manufactured with parallel faces and can thus deliver a more favourable capacity ratio.

The following equivalent circuit data was obtained using $GaPO_4$ resonators in Y-16° section at 5MHz:

- Dynamic capacitance C_1 = 58fF
- Static capacitance C_0 = 2.8pF
- Resonant impedance Rr = 6Ω
- Quality Q = 90,000

The capacity ratio, *r* , amounts to approximately 48; with fundamental crystals of the same frequency and size, *r* has values approximately 7 or 8 times greater.

These resonators were used to manufacture VCXOs in a miniature SMD housing with dimensions of 9mm x 14mm. The frequency / voltage characteristic obtained with commercially available capacitance diodes and without coils is shown in Fig 5. For a pull-in voltage range of 0.25V to 4.75V, a pull-in range of approximately 1,300ppm was obtained.

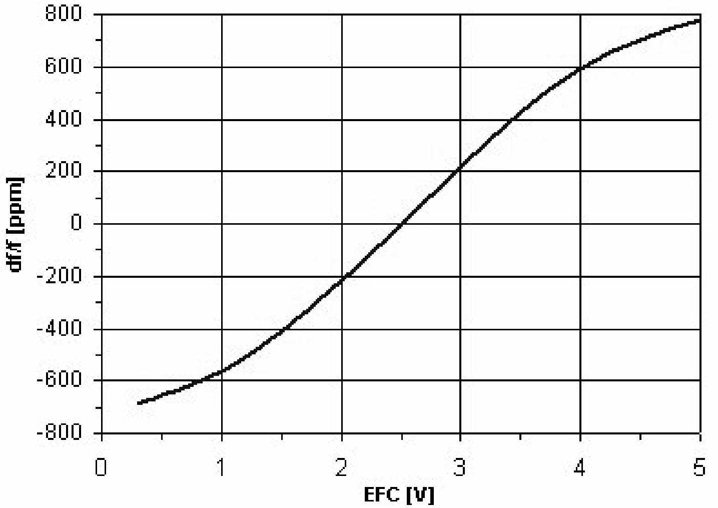

Fig 5: Frequency change versus voltage using a capacitance diode on a 5MHz VCXO.

5. Summary

Piezo-electric crystals are now industrially produced that can be used to manufacture oscillators that exceed the limits of quartz crystal oscillators. Thus frequency stable VCXOs can be manufactured with pull-in ranges up to 10 times greater than those of quartz crystal oscillators.

Using such resonators and oscillators, made from alternative materials to quartz, opens up new possibilities both for professional applications and for amateurs wishing to experiment. Wide range VCXOs in SMD format are already commercially available today [4]. Resonators can also be obtained from the same source.

6. Literature

[1] Neubig, B.: Design of crystal oscillator circuits, VHF Communications, issues 3 and 4/1979; downloadable from the authors website, www.qsl.net/dk1ag

[2] $GaPO_4$ website of AVL List web site www.gapo4.com

[3] Website of Roditi International Corp. www.roditi.de

[4] Website of AXTAL Advanced XTAL Products www.AXTAL.com: AXIS30 range.