Proceedings of the 2003 IEEE International Frequency Control Symposium and PDA Exhibition
Jointly with the 17th European Frequency and Time Forum

GALLIUM PHOSPHATE PLANE RESONATORS AND FILTERS

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Abstract: -***Gallium phosphate is a quartz analogue that possess much more intense piezoelectric properties. Here, we report a study made to determine more accurately the properties of filters that can be made using gallium phosphate AT cu resonators. The energy trapping properties of such resonators are first studied using computations and experiments; important differences with quartz are found. The computed and experimental vibrations modes are compared using synchrotron radiation X-ray topography determination. Using these results, we examine in detail the possibilities to build filters or diplexers with large bandwidth. Several topologies are considered (Jaumann filters including or not inductances, ladder filters,…) and an experimental example is given. The obtained results demonstrate the large potential of this material for filtering applications.***

Keywords Gallium phosphate, quartz homeotypes, crystal resonators, crystal filters, duplexers.

I. INTRODUCTION

Gallium ortho-phosphate is a quartz-homeotypic piezoelectric crystal that presents simultaneously a much larger coupling coefficient (k^2 is nearly four times that of quartz) and a large thermal stability of its properties.

The potential interest of this material is appeared nearly 20 years ago when several considerations based upon theoretical approaches have indicated that it should present more intense piezoelectric properties than quartz and berlinite. These predictions were confirmed by the first constants measurements made using crystals hydro thermally grown in phosphoric acid, on spontaneous nucleations [1-3]. Some time after, it was demonstrated that larger and better crystals could be obtained using epitaxial growth on berlinite ($AlPO_4$) in sulphuric acid solutions [4-6]. High temperature growth in both the direct solubility region [5] and in the retrograde solubility region [7-8] was then demonstrated. It was then shown that these growth conditions lead to a low OH concentration. Growth on quartz seed was then demonstrated [9]. More recently new fundamental investigations concerning several crystal growth processes were made. New solvents were tried and optimized growth conditions giving a good crystalline quality and a good purity at moderate growth temperature were established together with methods to lengthen the crystals. Further refinements in the crystal growth method starting from a quartz seed were performed and have led to large crystals presenting a very small dislocation density [7][9 to 16].

Many sets of constants of the gallium phosphate were measured [2][9 to 15]. They allow now to predict quite accurately the properties of devices. From computations made using these constants and from direct experiments [16 to 18], it was shown that this material presents compensated cuts from very low to very high temperatures. Several studies were made to determine experimentally the exact orientation of the main compensated Y rotated cut [16-17]. The first results obtained with crystals with different purity and perfection have indicated that this cut was situated between $\theta = -14°$ and $\theta = -17°$. The most recent determinations, made using much better crystals, have shown that this cut (the equivalent of the AT cut of quartz) is situated in the range from Y-15° 30' to about Y-16°15' depending on the geometry of the resonator, the overtone rank, and the exact inversion temperature.[20-21].

Several recent studies have indicated that the devices made with such orientations have attractive propertie in term of temperature stability or of Q factor [15].

From all the previous results, it may be induced that this cut should present large advantages over AT quartz for filter or VCXO applications. The purpose of this contribution is to discuss in more details the application of AT gallium phosphate to filters.

II ENERGY TRAPPING IN AT CUT GAPO4 PLANE RESONATORS.

A. Computations.

Filter resonators need to have, as far as possible, a monomode response. The apparition of additional modes (anharmonics) in plane resonators is governed by the energy trapping phenomena. They appears typically when some design parameters of the resonator (the electrodes dimensions or the mass loading) exceed certain values. In a communication to the 1997 IEEE International Frequency Control Symposium [18] we have studied in some depth the energy trapping phenomena occurring in plane resonator made using gallium phosphate and langasite. In figure 1, we present some of the results then obtained for resonator using elliptical electrode having an axis ratio simply related to the values of two essential theoretical parameters (two coefficients of the partial derivative equation governing the energy trapping) appearing in the theory of Tiersten [19] which was used for these computations. In the following figures we use a reduced expression of the resonance frequencies (f) of the mode situated near the fundamental one:

$$\Omega_n = \sqrt{\frac{f^2 - fce^2}{fcl^2 - fce^2}}$$ where :fce is the cut off frequency of the electroded part of the resonator, fcl is the cut frequency of the unelectroded region. We use also a reduced electrode dimension which allow to compare different electrode geometry:

$$r_r = \frac{\sqrt{S}}{2h}$$, here S is the electroded surface and 2h the thickness of the plate.

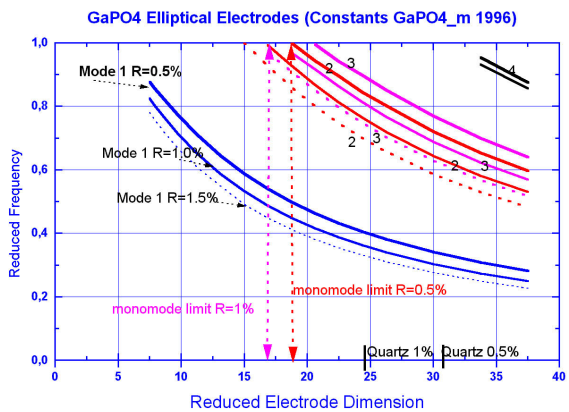

Figure 1: Apparition of anharmonics in AT GaPO4

In figure 1 we can observe, for the three different mass loading considered, that a 2nd mode appears for values of the reduced electrode dimension that are much smaller than for the corresponding cases in AT quartz. This means that gallium phosphate filter type resonators must have much smaller electrodes than quartz filter type resonators. Even if new constant measurement where made after 1997, the quantitative data appearing in figure 1, and the conclusions then made are extremely similar to what can be obtained with the more recent sets of constants.

The case of the particular elliptical electrodes considered here is theoretically, by far, the most favourable one, but, it was observed previously (and it is still observed), that the computed material anisotropy upon which is based the excentricity of the particular elliptical electrodes chosen above, was not confirmed experimentally. Having no new elements to consider optimal elliptical electrodes, we have decided to consider resonators with a low mass loading and circular electrodes. In figure 2, the result of new computations made for this case are represented (same definition for the reduced frequency and electrode dimension). The results are quite similar to the previous one but with a somehow less favorable limit for the monomode region. These computations were made using several recent sets of constants [14-15-17]. They have given extremely similar results for the resonance frequencies independently of the set of constants used.. We have chosen to represent those obtained with the constants of reference [17], because they give somehow better values for the inductance of the equivalent scheme (closer to the experimental ones, see below). On figure 3, we have represented a quantity related to the effective dimension of the mode (the value of the largest semi- axis of the mode for which the displacement is 1% of those existing in the center of the resonator for a given excitation); this value is normalized by the thickness of the resonator. It is possible to observe that this quantity is not very dependant of the electrode geometry (elliptical or circular electrodes) and that it presents a minimum for relatively small electrodes. When the electrode diameter is further reduced the mode becomes larger and larger in the plate before to extends infinitely at the lower cut-off frequency (Ω=1).

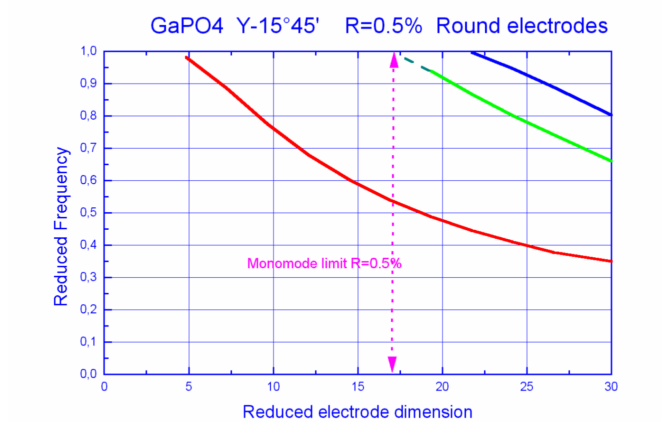

Figure 2: Apparition of anharmonics (round electrodes).

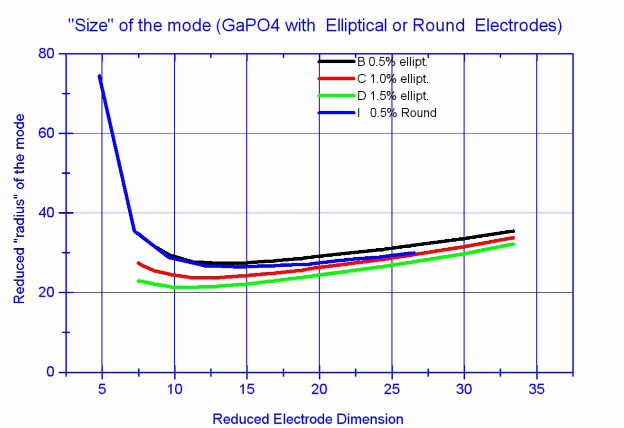

Figure 3: Reduced effective size of the fundamental.

This has the consequence that the (computed) inductance increases sharply for the smallest electrode dimensions (before cut-off). Despite, the large sensitivity to electrode dimension and to mass loading, this property can find interesting applications. This fact can be observed in figure 4 that was computed for plates with a thickness corresponding to those used in one of the experiments (2h=0.1835µm).

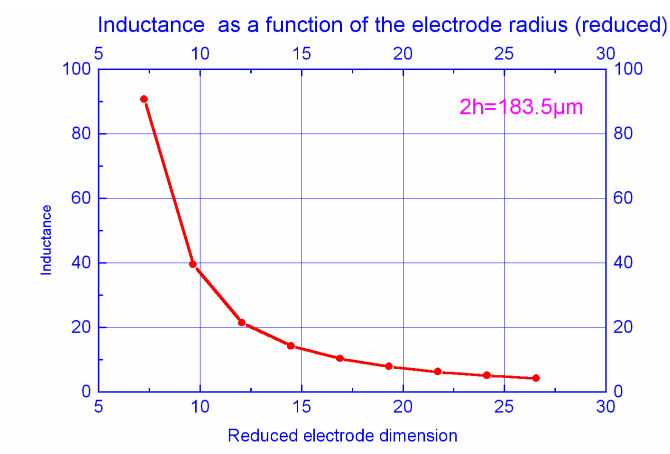

Figure 4: Computed inductance for round electrodes.

B. Experimental results:

Several series of resonators were made to measure the equivalent scheme and the coupling coefficient and also in the view of building filters. In a first attempt, resonators having a frequency around 5.080 Mhz were prepared following a quite conventional pin lap process using abrasive of decreasing size. It was found that a combination using successively garnets and alumina abrasives ending with alumina of mesh 800 allowed to achieve a good parallelism with a visually good surface appearance. No etching was used in this first try. The metallised resonators (R=0.5%, Phi=3.0mm) were measured at different excitation levels (respectively between about –16dBm and about 1 dBm). An important effect of the excitation level on the equivalent resistances was detected. In all cases and particularly at low excitation, the Q factors where found significantly lower than expected from previous experiments, despite the (known) very good quality of the material used. Some of the results obtained with minimum and maximum excitation are presented in table 1 and 2.

Table 1: Measurements at a low excitation level (#-16dBm)

Plate No	1	2	3	4	5
Funda-mental	R=33.0 L=30.9mH C1=32.1fF	R=50.4 L=35.3mH C1=29.2fF	R=59.0 L=31.3mH C1=34.2fF	R=59.4 L=28.3mH C1=36.8fF	R=43.9 L=36.5mH C1=29.4fF
3rdOver-tone	R=116. L=33.mH C1=3.25fF	R=197. L=34.8mH C1=2.96fF	R=100. L=33.3mH C1=3.43fF	R=159. L=30.3mH C1=3.30fF	R=91.9 L=35..9mH C1=3.30fF

Table 2: Measurements at an high excitation level (#1dBm).

PlateNo	1	2	3	4	5
Funda-mental	R=33.0 K=15.6% K'=15.6%	R=30.4 K=14.7% K'=14.8%	R=58.5 K=15.0% K'=15.1%	R=29.4% K=15.0% K'=15.1%	R=17.6 K=14.9% K'=15.0%
3rdOver tone	R=65.9 K=14.0% K'=14.0%	R=129. K=12.3% K'=12.4%	R=51.5 K=15.5% K'=15.5%	R=87.9 K=15.0% K'=15.0%	R=52.0 K=14.3% K'=14.3%

Table 3: Characteristics of the first series of resonators.

mean fundamental frequency = 5078.7kHz , electrode diam.=3mm. mean thickness =.2484 mm mean mass loading=0.59% mean inductance=32.51mH mean k' =15.14 % (8 samples)

The coupling coefficients were computed using the resonance and antiresonance frequencies according to the conventional approximate formula or to the exact formula for one dimensional modes (k'). No correction were made for the parasitic capacitances. The mean characteristics of these resonators are given in table 3.

Since the dependence to the excitation level was attributed to surface defects created in the lapping process, it was chosen to make a second series of resonators in using after the lapping operation, a deep etching in a concentrated solution of phosphoric acid containing a significant amount of gallium and aluminium phosphates at a temperature of 80°C. In table 4 we have represented the properties of some of the 6.9 MHz resonators obtained after an etching of about 400 to 450 kHz. One plate was further etched to about 800kHz (No 9) with the visible effect to achieve a further decrease of the resistance of this resonator.

Table 4: Resonator for filter experiments

No	**2**	**4**	**10**	**1**	**3**	**7**	**9***
Fr(MHZ)	6.909	6.909	6.909	6.962	6.962	6.962	7.420*
A(dB)	1.60	2.11	1.93	1.11	1.25	1.20	0.86
R(Ohm)	20.2	27.5	24.9	13.5	15.4	14.8	10.4
L(mH)	9.82	9.12	11.0	8.71	11.1	8.95	8.35

In table 5, we compare the observed properties of the resonators with computed ones. The agreement is good except for the inductance which is found quite lower in the experiments than in the computation. The coupling coefficient is in most case higher than 15.5% and exceed sometimes 16% (without any correction for the parasitic capacitance in parallel with Co). This indicate that the computed value may underestimate some how the actual coupling coefficient for this cut.

Table 5: Experimental (nine 6.9 MHz resonators in HC6u holder) and computed properties of the resonators.

Mean plate thickness=0.1835µm, Electrode diameter 3.0±0.05mm Mean resonance frequency:=6936.07 kHz (7pièces); Initial mass loading = 0.5% Mean final mass loading #0.60%(with the frequency adjustements) Mean inductance= 9.7mH (±1.4mH), Mean Co* =1.95 (±0.15pF) Mean parasitic capacitance Cp=1.25pF (±0.20pF).

Computed resonance frequency =6937680Hz Computed inductance =14.11 mH Computed Co=1.995pF (Parameters used Thickness=0.1835µm, R=0.6%, cut Y-15°45')

*It is suspected that Co include a certain part of parasitic capacitance

C. X-ray topography study of the resonators.

Several plates were studied with a Laue transmission setting [7][8] using the white X-ray beam delivered by the LURE DCI synchrotron at Orsay (France). Some of the topographs obtained with a <-2 1.0> diffraction vector and a (mean) wavelength near 0.7 Å are represented in figures 5 to 8. Without excitation, the contrasts observed (figure 5 and 7) are related to bulk or surface defects or to static deformations of the plate (bending by the HC6 fixtures in figure 5). Shallow contrasts, typical of growth bands, are observed in figure 5 they are perpendicular to the growth direction (z);: they are absent in figure 7. No macroscopic dislocations are clearly observable in both plates that may still contain surface defects related to the lapping operation (despite the large chemical etching).

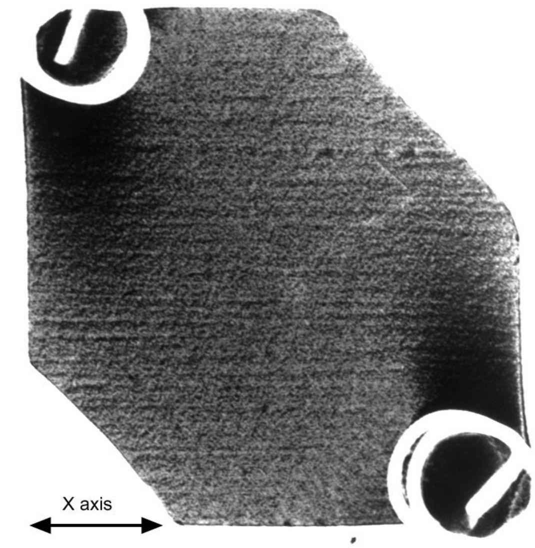

Figure 5: X-ray topograph of resonator No 9 (no excitation).

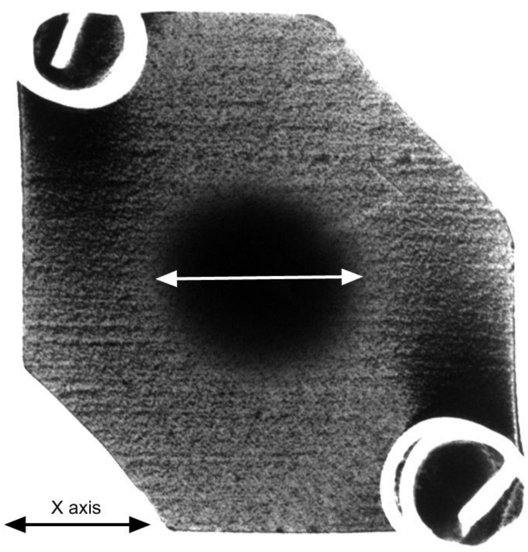

Figure 6: Experimental mode shape determined by synchrotron radiation topography (resonator No 9).

In figure 6 and 8, it possible to observe that the mode shape of the fundamental is slightly elliptical (more elongated in the x direction as expected from the theory) but the observed anisotropy is much lower than those predicted by the theory (figure 9).

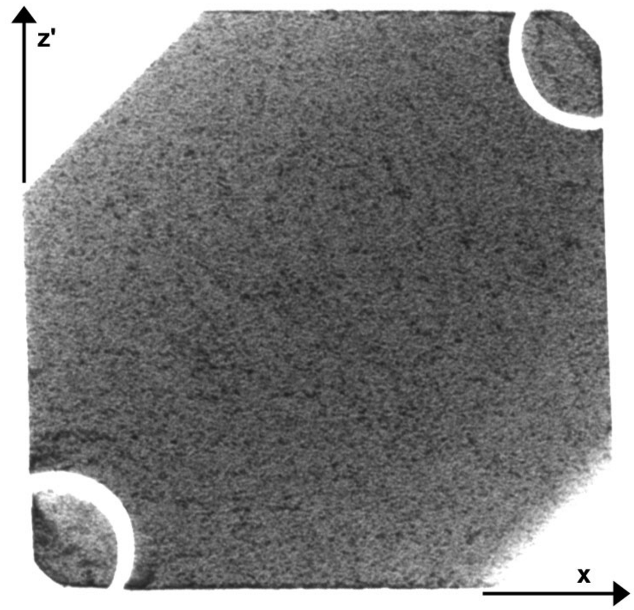

Figure 7: X-ray topograph of resonator No 1 (no excitation).

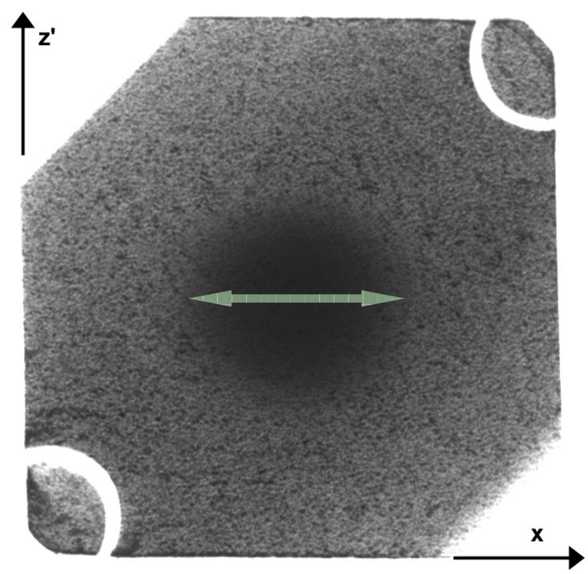

Figure 8: Experimental mode shape determined by synchrotron radiation topography (resonator No 1).

Quite similar results concerning the computed anisotropy of the mode are found using all recent sets of constants. A similar observation was also made in the case of plano-convexe AT GaPO4 resonators [20]. It is suspected that this difference between the computed and the observed modes results of uncertainties on several minor elastic constants as the calculation of the coefficients of the Tiersten partial derivative equation include the calculation of difference of function of such constants and may be quite sensitive to their accuracy.

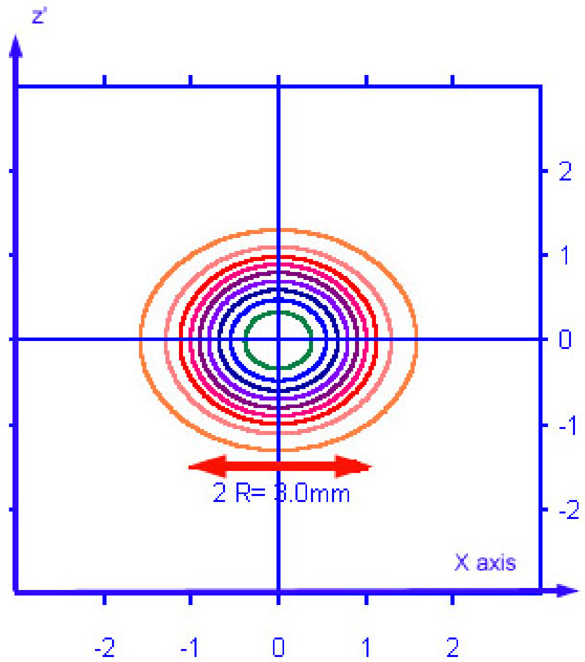

Figure 9: The computed mode shape for comparison with figure 8 (same scale as in fig.8).

III JAUMANN (UN-ENLARGED) FILTERS USING GAPO4.

Using rounded values of the elements of the equivalent scheme previously given (see figure 5) we have computed four crystals Jaumann filters (figure 6) with Tchebitchev response having bandwidth ranging from 30 to 100kHz at a center frequency of 6950kHz. No enlargement of the bandwidth (using extra inductances) was attempted at this stage, and the parasitic capacitances (Cp) were included in the design (in Ca and Cb) [22].

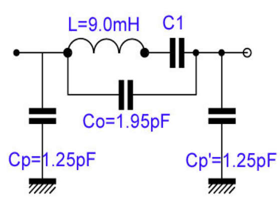

Figure 10: Equivalent scheme considered in the synthesis.

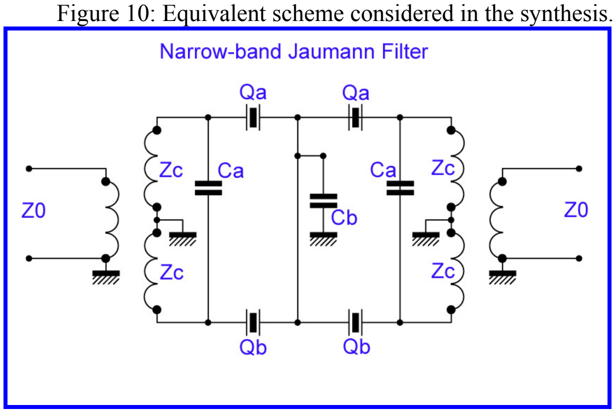

Figure 11: Jaumann narrow band filter.

Above a bandwidth of the order 85kHz the impedance Zc becomes quite high (figure 7) but still realizable at this frequency; however, the factor which in fact limits the achievable bandwidth are the parasitic capacitances of the crystals (and of the transformers) (figure 8). For the experiments, a bandwidth of 77.5 kHz was chosen in considering that Ca have to include the parasitic capacitance of the transformers.

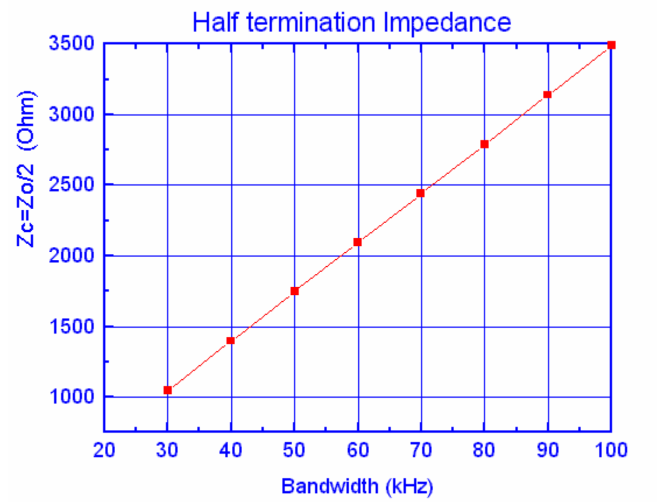

Figure 12: Half termination impedance as a function of B.W.

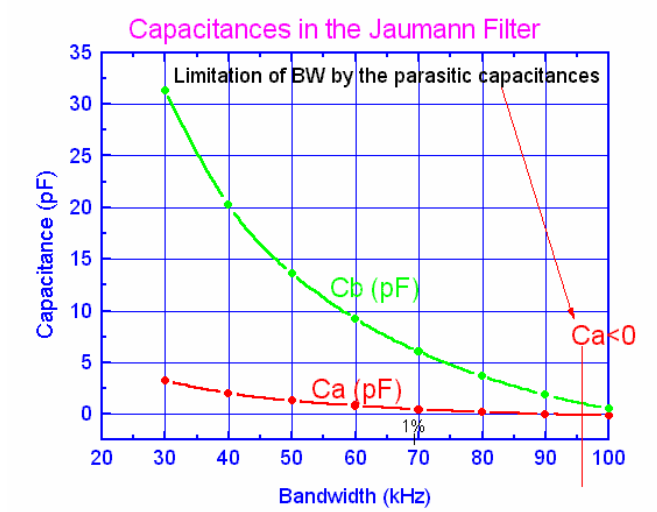

Figure 13: Capacitances of the Jaumann filter.

The computed response of the Jaumann filters (no losses) are represented in figure 14, whereas the experimental response is represented in figure 15. On this figure, it is possible to observe that one of the low frequency resonator has unwanted anharmonics that disturb the response of the filter in the higher transition band and probably reduce some how the band width (in fact this resonator has also a weak parasitic mode (most probably a symmetrical anharmonics) situated between the resonance and the antiresonance that give also a weak anomaly in the pass-band. These modes were probably produced by an non-uniform etching of the plate. However this first experiment demonstrate clearly that quite large bandwidth can be achieved with gallium phosphate. For quartz, it is usually the condition of a non-negative value of the Cb capacitance that limits the achievable bandwidth. In this experiment we have set Ca to zero while Cb was adjusted to a value near 4 pF. It is probably possible to reduce some how the Cp capacitance of the resonators (for example in using different crystal holders) and to obtain some how larger bandwidth without using enlarging inductances.

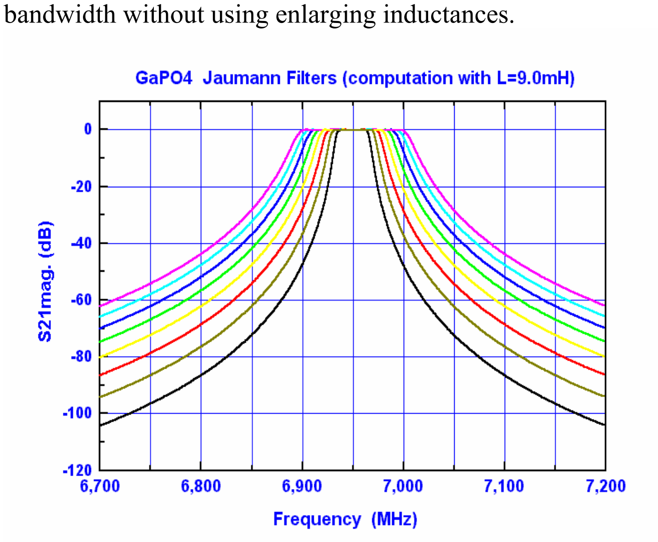

Figure 14: Computed response of the Jaumann filters.

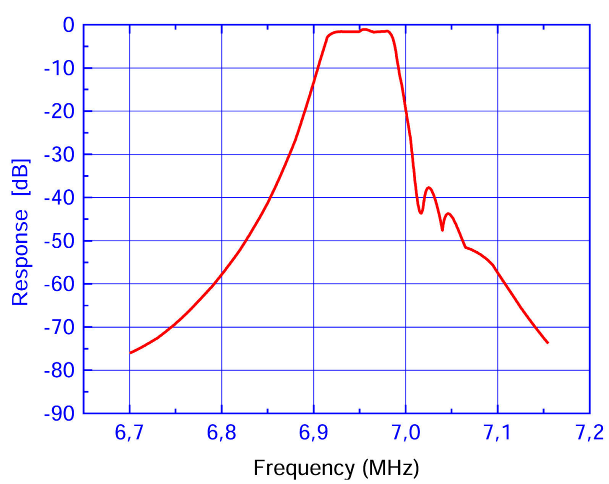

Figure 15: Experimental response (3dB bandwidth#74 kHz).

IV. Lattice and Jaumann filters enlarged using inductances.

Several lattice or Jaumann (or bridged T) filter topologies are known to allow to obtain much larger bandwidth with crystals of a given coupling coefficient than those considered in §III. Among them we have chosen to consider the lattice filters containing one serial or a parallel inductance and several crystals per arm. They were proposed and discussed a very long time ago, by Masson [23] and particularly by Andrieux [24]. We naturally prefer their Jaumann equivalents (see figure 16).

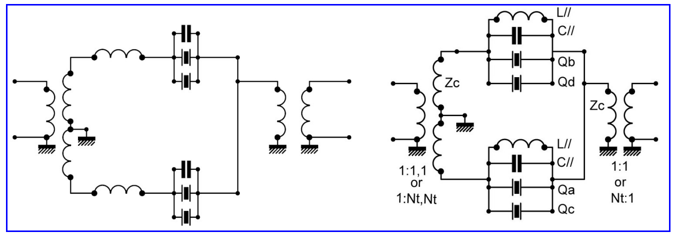

Figure 16: Jaumann filter using inductances
to increase the bandwidth.

These topologies present the important advantage that the equal inductances can in fact be moved toward the access of the filter (conventional lattice transformation) and/or be included in a (real) transformers situated at the access, so that a large part of their dissipation can be eliminated in the termination resistances. Here we will mostly consider the case with a parallel inductance and two resonators per arm since it is more directly comparable to the previous one (in fact, the case of a serial inductance can give nearly exactly the same responses, except for frequencies near f=0 or near infinity).

To discuss this case, we have used of the image parameter synthesis of these filters that was proposed by Andrieux in his book and we have considered that near 7 MHz an inductance of the order of 8mH can be realized quite easily without parasitic response. This kind of filter requires to employ crystals with quite different values of the equivalent inductances, on the basis of the results given in figure 4, we have also considered that values ranging up to more than 30 mH near 7Mhz will be achievable (may be with some progress in the plate preparation, since such resonators with large inductances will probably have equivalent schemes more sensitive to the parallelism of the plates). In table 6, we give the computed values of the elements of the filter. Nt is the transformation ratio to achieve 50 Ohm terminations. No particular remarks have to be made about the values of the elements (except those previously made about the ratio (here of the order of 3) required for the inductances of the two resonators of each arm).

Table 6: Elements of the enlarged Jaumann filters using AT GaPO4

BW (kHz)	La (mH)	Ld (mH)	Lc (mH)	La (mH)	L// (µH)	Ct//* (pF)	Zc (Ω)	Nt (50Ω)
50	8.01	21.43	21.48	8.00	0.151	3476.	654	3.61
100	8.01	22.46	22.57	8.00	0.611	857.	1325	5.15
150	8.02	23.72	23.90	8.00	1.386	375.	2018	6.35
200	8.04	25.12	25.36	8.00	2.488	208.	2731	7.39

*Ct=C//-Coi-Coj includes the two static capacitances of the two resonators of each arm.

The computed response including likely losses for the crystals and for the inductances are represented in figure 17. It should be noticed that the response is not equi-ripple either in the band-pass or in the stop band. This kind of response appear to be quite resistant to the dissipation in the inductance (no modification of the termination values were made) and to lead to a favorable phase response. For each bandwidth, 3 curves are given, they correspond to slightly different value of a parameter chosen to account for the fact that the image impedance are not real (except at some frequencies).

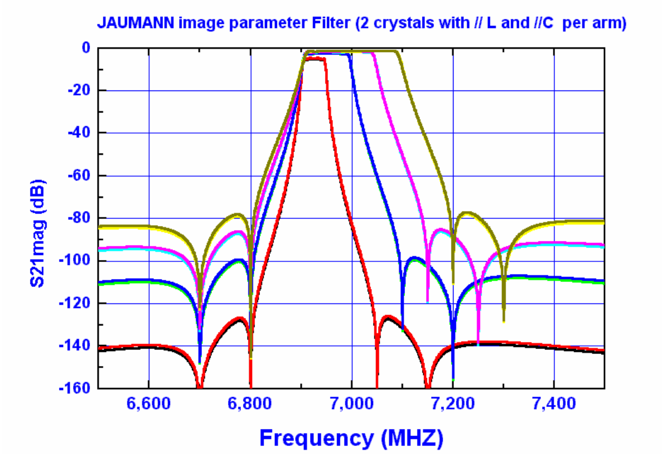

Figure 17: Computed responses of enlarged Jaumann filters using AT GaPO4.

On the whole, the results given in figure 17, indicates the large potential of gallium phosphate for filter applications.

IV Sophisticated ladder filters and duplexer obtained using transformations.

In this paragraph, we will present the results of a work made to obtain high performance filters and duplexers[25]. As an example, we will consider here elliptical filters in which a transformation is made to introduce resonators with prescribed characteristics (inductances and capacitance ratio). The method presented can be used for of most of the bandpass filter topologies, it is particularly adapted to the "minimum inductance" topologies were many crystals can be used, they include the "true" zigzag filters constituted only of 3 elements dipoles. The first step of the example is quite conventional, we use the efficient method propose by Amstutz [26] for the synthesis of the elliptical filter and then the Saal & Ulbricht transformation to obtain a minimum inductance form of the filter (figure 18). A direct extraction under this form would also have been possible. This lead to a topology where all the dipoles of the filter except those at each end are three element dipoles (with only one inductance like piezoelectric resonators). Then a quite complexe transformation is made to transform these three elements dipoles so that they present each (preferably all, from an economic point of view) a given capacitance ratio and a given inductance, so as to be realizable with a given material (and preferably with the same process). The inductances of the two element dipoles could also be transformed to more favorable values or to ensure given termination resistances. The principle used to achieve this result is to divide the capacitances of the dipoles and to use as many Norton simultaneous transformation as there is inductances.

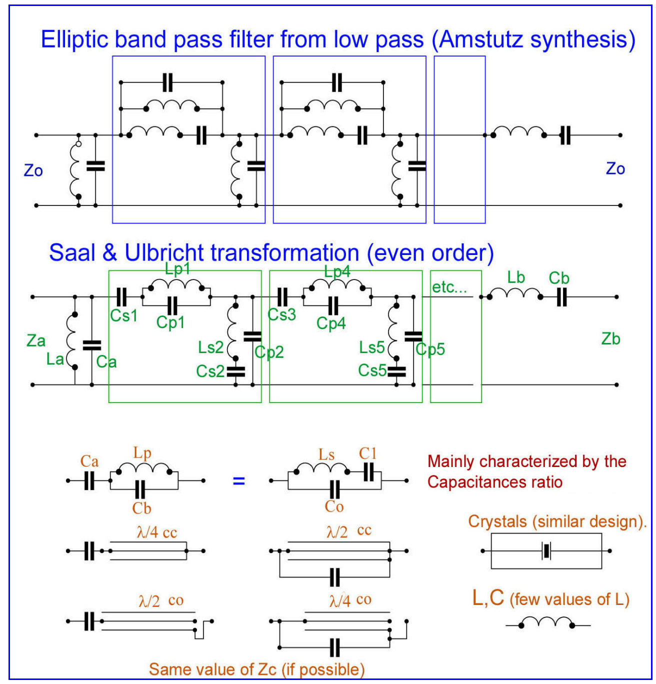

Figure 18: Elliptical filter (

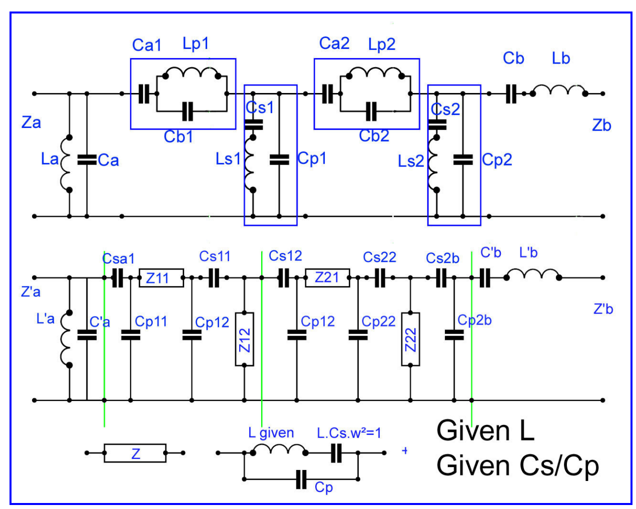

Figure 19: The result of the transformation.

This introduce a number more than sufficient of degree of freedom to achieve the wanted result (the remaining degree of freedom can be used for other purposes such as to chose some standard values for the capacitances)[25]. As known for all crystal filters, there is no solutions above a certain relative bandwidth when given values of the capacitance ration are chosen. In figure 20 an example of elliptical filter using GaPO4 is given (scheme of figure 19, C1/Co=1/37 L=6mH for all resonators). The fractional bandwidth chosen is very nearly the maximum realizable with this material, this filter degree and this topology (some capacitances becomes quite low). This bandwidth is already very appreciable for a ladder filter that give a very good selectivity with only 4 crystals.

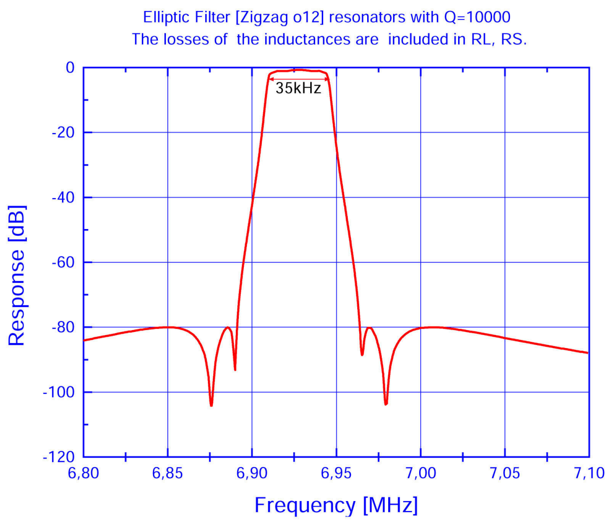

Figure 20: Response of an elliptical filter using four GaPO4 resonators.

Table 7: Elliptical filter: Values of the elements

	Name	Node	Node	Value	Q factor
RES	RST	0	1	12.5 nominal	#Reduced
IND	LBT	1	2	0.74393E-10	0.250E+03
CAP	CBT	2	3	0.74393E-10	
CAP	CPT	3	0	0.76537E-11	
CAP	CST	3	4	0.33138E-12	
IND	LS4	4	5	0.60000E-02	0.100E+05
CAP	CS4	5	0	0.88932E-13	
CAP	CP4	4	0	0.33794E-11	
CAP	CST	5	6	0.21696E-10	
CAP	CPT	6	0	0.68395E-11	
CAP	CP3	6	8	0.33938E-11	
CAP	CS3	6	7	0.89310E-13	
IND	LS3	7	8	0.60000E-02	0.100E+05
CAP	CPT	8	0	0.13014E-11	
CAP	CST	8	9	0.12229E-11	
IND	LS2	9	10	0.60000E-02	0.100E+05
CAP	CS2	10	0	0.89296E-13	
CAP	CP2	9	0	0.33932E-11	
CAP	CST	9	11	0.29788E-11	
CAP	CPT	11	0	0.50134E-11	
CAP	CS1	11	12	0.88946E-13	
IND	LS1	12	13.	0.60000E-02	0.100E+05
CAP	CP1	11	13	0.33800E-11	
CAP	CPT	13	0	0.17236E-12	
CAP	CST	13	14	0.87248E-11	
CAP	CAT	14	0	0.19526E-8	
IND	LAT	14	0	0.27006E-06	0.300E+03
RES	RLT	14	0	3.0E+3Nominal	#Reduced

It should be noticed that further transformations could be made for example to modify the termination impedances (in table we have chosen to show very different termination impedances that are quite “natural” for this topology). It is easy, to achieve practically any termination using a conventional narrow band transformation (addition of two capacitances).

One other important interest of this filter topology is that it makes very easy the constitution of crystal multiplexers. The scheme used to compute multiplexers is represented in figure 21. The optimisation is much easier than in many other cases since very few change in the values of the elements are needed. The optimisation is conducted numerically (using a least square, a least p-th or a minimax criterion).It is generally preferable to end the process by the transformation of the termination impedances, as indicated above. An example based on the filter considered previously (figure 20) and an other one with the same bandwidth is given in figure 22.

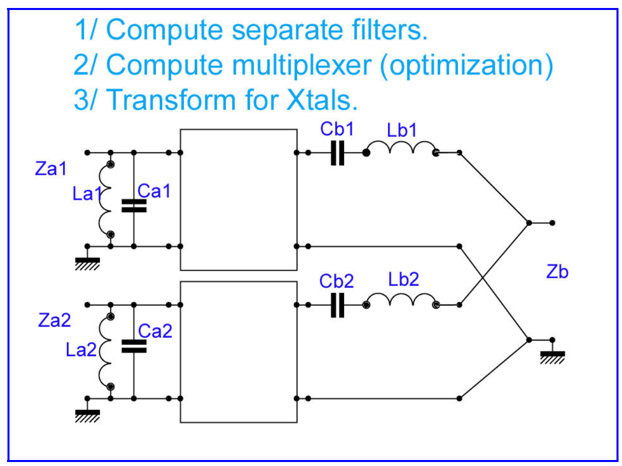

Figure 21: Computation of a duplexer.

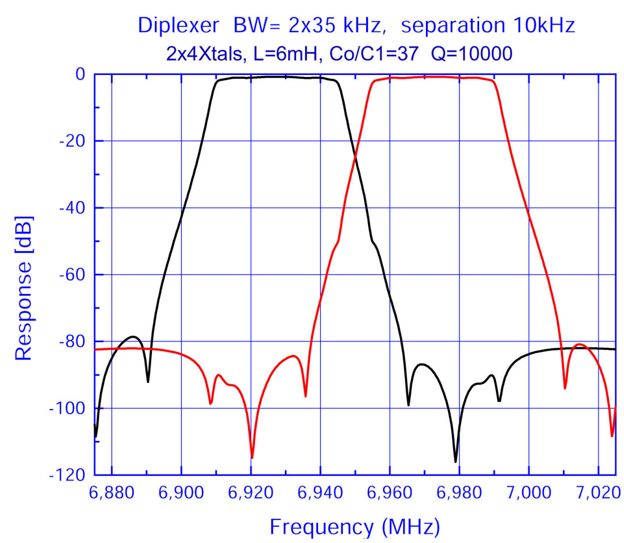

Figure 22: Computed example of duplexer using gallium phosphate resonators.

CONCLUSION

Gallium phosphate resonators where shown to have very interesting energy trapping properties. The published material constants allow to predict accurately the resonance frequencies and their thermal variations. The measured inductance and most probably the effective coupling coefficients of AT plane resonators seems some how better than predicted by the calculations. The material is now of good quality, it is much more sensitive to hard abrasives than quartz. Several filter topologies can be found to realize filters with much wider band than with quartz. Crystal filters and multiplexers achieving better performances and much easier manufacturability than those using more conventional topologies can be made using sophisticated network transformations. One the whole, gallium phosphate appears as a very interesting material for filter applications.

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