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LOW CONSUMPTION BVA RESONATORS

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In this paper the author studies several possibilities to reach low consumption of electrical power in the maintaining of BVA resonator at its turnover. Heatings by dielectric losses, by deposited resistors, by infrared radiations and by acoustic losses are examined. The results of calculations and experiments are presented and discussed. Two solutions are rejected because no convenient for low consumption or for weak aging. The retained solutions could open a new way for manufacturing of minature ovenized resonators.

1. Introduction

Concerning quartz crystal oscillators designed for low consumption, low power and low volume applications, the commercially available devices correspond to both following areas:

— first, the temperature compensated crystal oscillators (TCXO) providing, in the case of the best, a frequency stability equal to $\pm 3 \cdot 10^{-7}$ on the range $-40° + 70°$C, with an aging of $\pm 10^{-8}$/day and a required power usually equal to 70 mW at all temperatures.

— second, the miniature ovenized oscillators (OCXO) which provide a frequency stability of $\pm 5 \cdot 10^{-9}$ on the range 0°C to +50°C, with aging of $\pm 5 \cdot 10^{-10}$/day and power about 300 mW at 25°C.

Today a new need appears demanding the same requirements what the last one, but with aging of $\pm 5 \cdot 10^{-11}$/day. In this paper we examine the possibilities to reach the previous goal using BVA resonators, those being known for their weak aging. The possibilities are first a microwave ovenized resonator, second a resonator directly heated by conduction, third a resonator heated by infrared radiations and at last a resonator using an internal heating provided by acoustic losses.

For all these devices only the heart of the resonators is ovenized. Indeed, in the area of low consumption, the available heating power is very weak. So, heating is applied inside the can and not outside the can like is the case for usual ovens.

2. Microwave ovenized resonator

A basic idea is the quartz material can be heated by the means of dielectric loss. That last one occurs inside the bulk material in an homogeneous process and independently from thermal conductivity of the quartz crystal. First indication of that principle has been proposed by BESSON and DECAILLIOT [5]. The frequency range choosen is 2 to 4 GHz because of the commercial avaibility of microwave sources. For that frequency range the loss angle corresponds to $\operatorname{tg}\delta = 2.5 \cdot 10^{-4}$. The power P delivered per unit volume is given by

$$P = \pi f \varepsilon_r \varepsilon_0 \operatorname{tg}\delta E^2 \tag{1}$$

where f is the frequency, $\varepsilon_r \varepsilon_0$ the permittivity and E the electric field. The value of E can be calculated by the relation (1), P being equal to 300 mW (see Introduction) for a volume of half a cubic centimeter (central part and condensors of BVA resonator), f being 3 GHz and $\varepsilon_r = 4$. We obtain $E = 100$ kV/m. That result proves the faisability of a microwave ovenized resonator using an electromagnetic cavity and, particularly, a reentrant high Q cavity. That last one is schematically shown Figure 1. The crystal quartz resonator is set up inside central gap, the gaps of top and bottom providing thermal and electric isolations. If the dimensions of the cavity are correctly calculated, an intense microwave field is provided inside the gaps.

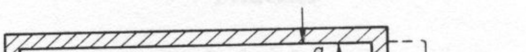

FIG. 1. Reentrant three gaps cavity

The design of the Fig. 1 is equivalent to four identical cavities with the same gap g for each cavity, under the condition the dielectric material is the same for all cavities. If a crystal quartz is set up inside the central gap, the quartz permittivity occurs and the central gap must be divided by ε_r.

In the case of a single cavity (high = h; radius = a), the TM_{mnp} general solution of the Maxwell's equations written in cylindrical coordinates (r, θ, z) is given by [4]:

$$H_r = -j\sqrt{\frac{\varepsilon}{\mu}\frac{\lambda_c}{\lambda}}\frac{J_m\left(\frac{2\pi r}{\lambda_c}\right)}{\frac{2\pi r}{\lambda_c}} m E_0 \sin m\theta \cos p\pi\frac{z}{h} \tag{2}$$

$$H_\theta = -j\sqrt{\frac{\varepsilon}{\mu}\frac{\lambda_c}{\lambda}} J'_m\left(\frac{2\pi r}{\lambda_c}\right) E_0 \cos m\theta \cos p\pi\frac{z}{h} \tag{3}$$

$$H_z = 0$$

$$E_r = -\frac{\lambda_c}{\lambda_g} J'_m\left(\frac{2\pi r}{\lambda_c}\right) E_0 \cos m\theta \sin p\pi\frac{z}{h} \tag{4}$$

$$E_\theta = \frac{\lambda_c}{\lambda_g}\frac{J_m\left(\frac{2\pi r}{\lambda_c}\right)}{\frac{2\pi r}{\lambda_c}} m E_0 \sin m\theta \sin p\pi\frac{z}{h} \tag{5}$$

$$E_z = J_m\left(\frac{2\pi r}{\lambda_c}\right) E_0 \cos m\theta \cos p\pi\frac{z}{h} \tag{6}$$

$$\text{and } \frac{X_{mn}}{a} = \frac{2\pi}{\lambda_c}$$

where H_r, H_θ, H_z, E_r, E_θ and E_z are the magnetic and electric components of the magnetic field H and electric field E. J_m is the Bessel's function of first kind and m order, and X_{mn} the nth no null root of $J_m(x) = 0$. The derivative of J_m is noted J'_m.

The reentrant cavity of the Fig. 1 can be decomposed in single elements where fields are expressed by series of solutions like the equations (2) to (6), the continuity being assumed by the boundary conditions at bonds between those single elements. Only the Oz axisymmetrical solutions are kept, providing an homogeneous electric field inside the central gap. Same calculations has been developed by JAWORSKI [9]. The theoretical and numerical analysis has been performed by RAULIN [11]. One important of obtained results is shown Fig. 2. They are the electric field lines corresponding to the three gaps cavity of the Fig. 1.

It appears areas where the electric field is null. They will be advantageously used for setting the electrodes wires. That field configuration corresponds to the fondamental mode. For its, the electric field is more homogeneous inside the central gap and it presents the best efficiency to heat quartz crystal resonators. The total energy stored is located at half in the central gap. But it can be seen that the energy dissipated by dielectric losses inside the quartz crystal with respect to the energy dissipated by Joule effect in the metallic sides of the cavity is weak. Indeed that ratio is about 15% in the best case.

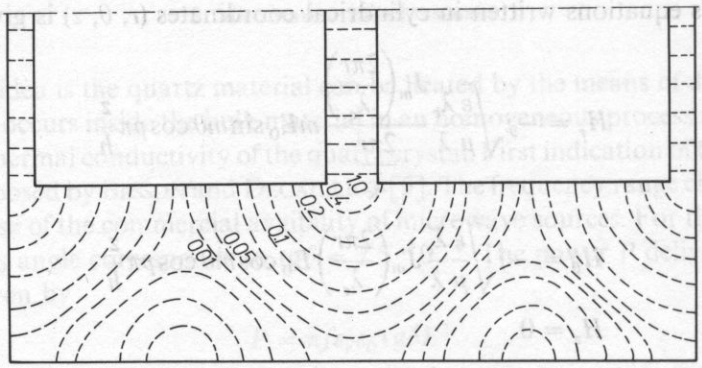

FIG. 2. Electric field of the three gaps cavity (fondamental mode)

Our experimental set-up [17] works up a V.C.O. type generator working between 2 and 4 GHz used together with an amplifier delivering a power of 2 W. A circulator separes incident wave from wave reflected by the cavity. Control is obtained by detection of reflected wave (see Fig. 3).

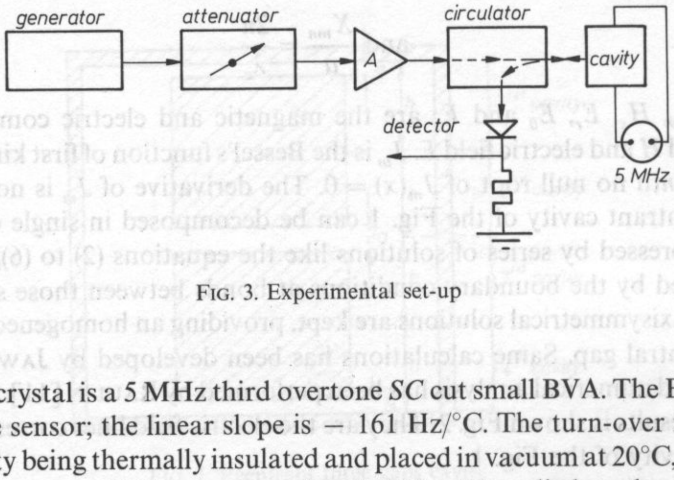

FIG. 3. Experimental set-up

The used crystal is a 5 MHz third overtone *SC* cut small BVA. The B mode is used as temperature sensor; the linear slope is -161 Hz/°C. The turn-over is obtained at 70°C. The cavity being thermally insulated and placed in vacuum at 20°C, the turn-over is reached for a power of 2 W corresponding to 240 mW applied on the quartz crystal. So, the theoretical analysis is confirmed. It is pointed out the weak ratio of energy usable for heating of the quartz crystal with respect to energy losses in the cavity sides. Let us precise the cavity sides were gilded with a gold thickness of two micrometers, i.e. greater than the skin effect thickness. The observed limitation of that ratio cannot be performed because of the very weak factor tgδ of the quartz material. There is the intrinsic limit of the principle of heating by dielectric losses.

3. Resonator heated by conduction

The principle of quartz crystal heating by resistors directly deposited on the edge of the crystal is for long time known [3], [10]. For BVA resonators BESSON [1] has proposed to deposite the heating resistors on the external sides of the BVA condensors. In 1989 GALLIOU and MOUREY [6] realize prototypes where the heaters are resistive paste printed on the condensors, on the opposite surfaces of the electrodes. The two condensors and the resonator are sandwiched together by insulating pieces manufactured in polytetrafluoroethyl. The whole is set up inside an evacuated enclosure.

The resistors are deposited on the condensors by serigraphy. It is not possible to serve the usual resistive pastes of electronic hybrid technology. Indeed, those mineral pastes must be heated at 800°C, temperature no convenient for quartz crystals. Only the pastes with carbon can be served, their baking temperature being 250°C. The thickness of the deposited resistors is 15 μm and procures a maximal power of 50 mW/mm^2.

In a first step the resonator temperature was measured with a thermistor sticked on the heaters and in a second step by the means of the B mode, for *SC* cut resonators.

The thermal study of the BVA resonator has been carried out by VALENTIN in 1985 [13]. The part of the radiative transfer heating was pointed out. For an usual BVA resonator the part of the radiative transfers is about one third by two thirds for the conductive transfers.

The Figs. 4 and 5 show the warmup and the heater power consumption for a BVA resonator heated by two resistors deposited on the condensors. Those results have been obtained for a 10 MHz *SC* cut resonator.

The previous results are very interesting for fast warmup and low consumption devices. The inconvenience of that heating method is the degazing of the heaters, which limites the aging performances about 10^{-9}/day. There is hard difficulty to perform that

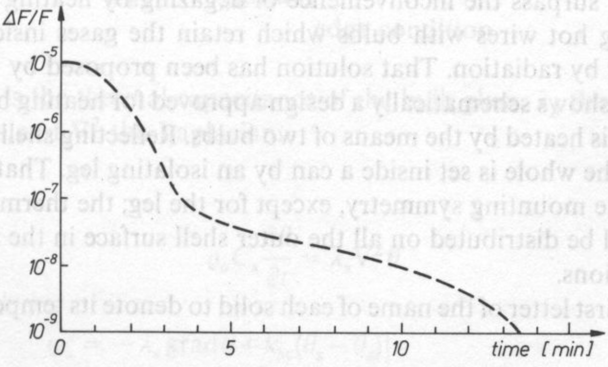

FIG. 4. Warmup for BVA resonator

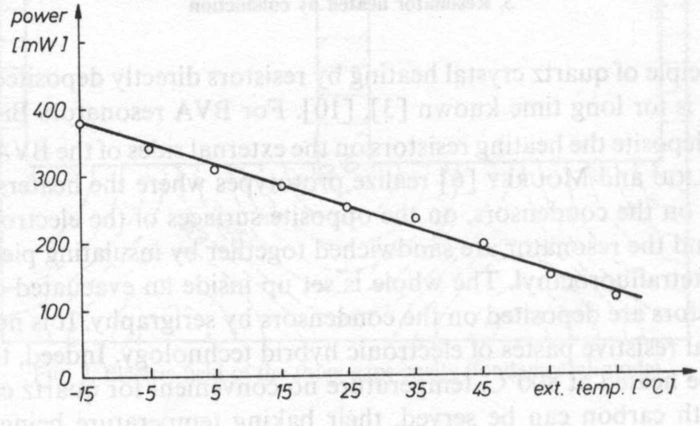

FIG. 5. Heater power consumption for BVA resonator

last aging because of the absorbing layer of the quartz crystal presents a thickness of two angströms for a frequency variation of one hertz (1 mm corresponds to 5 MHz for an *SC* cut, 3rd overtone). Now, two angströms are about the thickness of a monomolecular layer. Under those conditions it is preferable to research other solutions for low consumption heating of BVA resonator, particularly if we will turn to account its weak aging.

4. Infrared radiations oven

In order to surpass the inconvenience of degazing by heating layers, a solution consists in using hot wires with bulbs which retain the gases inside. Then the heat transfers appear by radiation. That solution has been proposed by VALENTIN in 1983 [14]. The Fig. 6 shows schematically a design approved for heating by radiation where a quartz crystal is heated by the means of two bulbs. Reflecting shell surrounds quartz and bulbs and the whole is set inside a can by an isolating leg. That simplified design clearly shows the mounting symmetry, except for the leg; the thermal conductance of this last one will be distributed on all the outer shell surface in the following thermal exchange equations.

Using the first letter of the name of each solid to denote its temperature (see Fig. 6), we can write:

for the hot wire

$$P = k_{wc}(\theta_w - \theta_c) + S_w \varphi_w \tag{7}$$

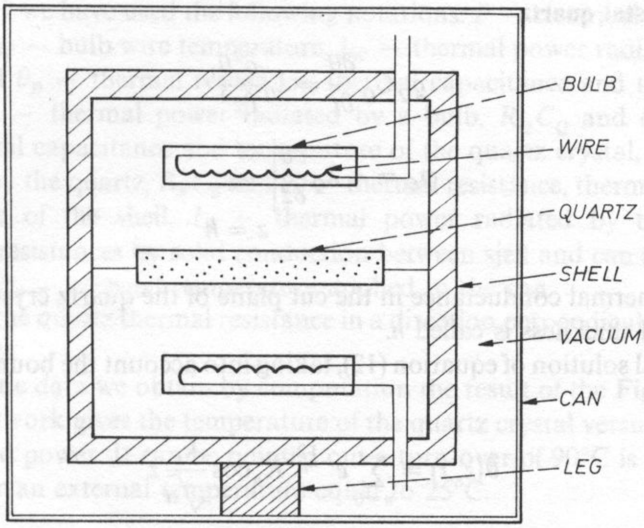

FIG. 6. Schematical infrared radiations oven

where P is the electrical power applied to the wire, k_{wc} the thermal conductance by solid conduction between the wire and the can, θ_i are temperatures, S_w the wire surface and φ_w the surfacic flux radiated by the wire. Here the thermal capacitance of the wire is neglected.

for the bulb glass

$$\varrho_B C_B \frac{\partial \theta}{\partial t} = \lambda_B \nabla^2 \theta \tag{8}$$

$$\varphi_B = -\lambda_B \operatorname{grad} \theta \Big|_{\text{edge condition}} \tag{9}$$

where $\varrho_B C_B$ is the thermal capacitance of the bulb glass, λ_B the thermal conductivity of the glass and ∇^2 the Laplacian.

for the shell

$$\varrho_s C_s \frac{\partial \theta}{\partial t} = \lambda_s \nabla^2 \theta \tag{10}$$

$$\varphi_s = -\lambda_s \operatorname{grad} \theta + k_{sc}(\theta_s - \theta_c) \Big|_{\text{edge condition}} \tag{11}$$

where the used notations are homogeneous with the previous.

for the crystal quartz

$$\varrho_Q C_Q \frac{\partial \theta}{\partial t} = \lambda_Q \frac{\partial^2 \theta}{\partial z^2} \tag{12}$$

$$\varphi_Q = -\lambda_Q \frac{\partial \theta}{\partial z}\bigg|_{z=h} \tag{13}$$

Here the thermal conductance in the cut plane of the quartz crystal is neglected. The half crystal thickness is called h.

The general solution of equation (12), taking into account the boundary condition (13), is given by

$$\theta(z, t) = \sum_{n=0} e^{-k_n^2 t} K_n \cos \frac{k_n}{\sqrt{a}} z \tag{14}$$

$$\text{where } a = \frac{\lambda_Q}{\varrho_Q C_Q} \tag{15}$$

the constants k_n and K_n being calculated from the conditions at $t = 0$.

The main problem is the calculation of the radiated flux, according with the transparency of bulb glass and quartz in the range of wavelengths zero to four micrometers. The radiated flux expressions are strongly non-linear and depend on the fourth power of the temperatures. So it is convenient to use the electrical analogy for computer-aided analysis. Figure 7 shows the electrical equivalent circuit of thermal transfers [7].

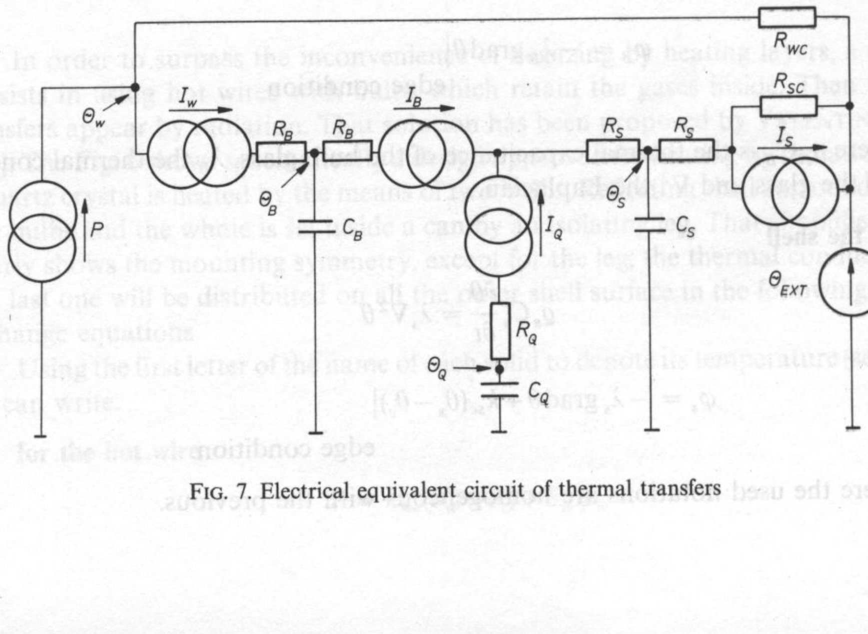

FIG. 7. Electrical equivalent circuit of thermal transfers

On the Fig. 7 we have used the following notations: P – electrical power applied to a bulb wire, θ_W – bulb wire temperature, I_W – thermal power radiated by a bulb wire, R_B, C_B and θ_B – thermal resistance, thermal capacitance and temperature of a glass bulb, I_B – thermal power radiated by a bulb, $R_Q C_Q$ and θ_Q – thermal resistance, thermal capacitance and temperature of the quartz crystal, I_Q – thermal power radiated by the quartz, $R_S C_S$ and θ_S – thermal resistance, thermal capacitance and temperature of the shell, I_S – thermal power radiated by the shell, R_{SC}, R_{WC} – thermal resistances by solid conduction between sjell and can (R_{SC}) and wire and can (R_{WC}), θ_{ext} – external temperature applied to the can.

R_Q denotes the quartz thermal resistance in a direction perpendicular to the plane of the crystal cut.

Using realistic data we obtain by computation the result of the Fig. 8, where the shown curves network gives the temperature of the quartz crystal versus the time and versus the applied power. It can be pointed out a turn-over of 90°C is obtained with only 200 mW for an external temperature equal to 25°C.

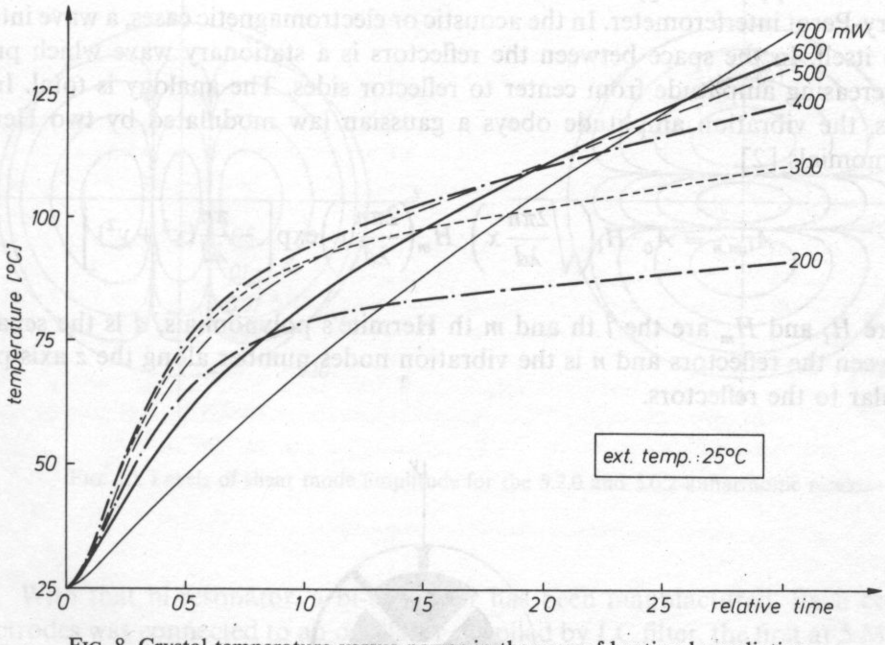

FIG. 8. Crystal temperature versus power in the case of heating by radiation

So, the simulation of heating by radiation shows it is possible to obtain low consumption for high turn-over. More, the heating is very homogeneous because of the thermal flux flows through the whole surfaces of the crystal and not only by two points (the holders). So the thermal dynamic effects are reduced. At last, the thermal resistance in the direction perpendicular to the cut plane is about thousand times less than the thermal resistance in the cut plane. So, if a large heating step is applied on a cold crystal, the break down risk is very reduced. A precise study of oscillators heated by infrared radiations was exhibited in a recent paper [7].

5. Internal heating by acoustic losses

The internal heating of coated resonators and BVA resonators has been proposed by VALENTIN in 1980 [15]. The internal heating comes from the electrical energy dissipated by acoustic losses. The efficiency of that transformation is greater than 99%. Then, the thermal power equals the drive power. For heating by acoustic losses it is necessary to use a specific mode (overtone or anharmonic) providing a low coupling factor with the main mode and supporting high drive levels. Of course, the trapped energy resonators can be used for internal heating, and BVA resonators are particularly designed for that, since they accept very high levels, till several hundreds of milliwatts.

The trapped energy bulk wave acoustic resonators use the spherical mirror Fabry-Perot interferometer. In the acoustic or electromagnetic cases, a wave interferes with itself. In the space between the reflectors is a stationary wave which presents a decreasing amplitude from center to reflector sides. The analogy is total. In both cases, the vibration amplitude obeys a gaussian law modulated by two Hermite's polynomials [2].

$$A_{l,m,n} = A_0 \cdot H_l\left(\sqrt{\frac{2\pi n}{\lambda d}}\, x\right) \cdot H_m\left(\frac{2\pi n}{\lambda d}\, y\right) \exp\left[-\frac{\pi n}{\lambda d}(x^2+y^2)\right] \tag{16}$$

where H_l and H_m are the l th and m th Hermite's polynomials, d is the separation between the reflectors and n is the vibration nodes number along the z axis perpendicular to the reflectors.

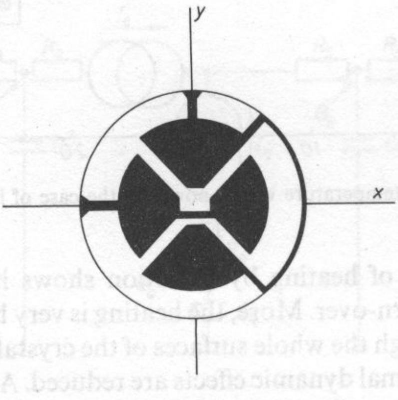

FIG. 9. Double electrodes system

WILSON in 1974 [18], next TIERSTEN and SMYTHE in 1977 [12] have proposed similar results in the case of trapped energy acoustic resonators. In the usual case, the vibration is located at the resonator central part and in peripheric spots corresponding to the Hermite's polynomials extrema. The energy is trapped inside these spots and inside the central part.

In a first step, we have realized a resonator provided a double electrodes system deposited on the condensors of a fifth overtone 5 MHz BVA resonator, *AT* cut. This work has been carried out by GILLET [8]. The double electrodes system is shown Fig 9.

Figure 10 shows the curves with same levels of shear vibration amplitude in the main plane of the resonator. These curves are obtained by computation in the case of the 5.2.0. and 5.0.2. modes. The subscripts l and m indicate the nodal lines number in the directions x and y. It can be pointed out the phase change of the amplitude is very fast, and in respect to that observation, the manufacturing of electrodes system must be realized with great care.

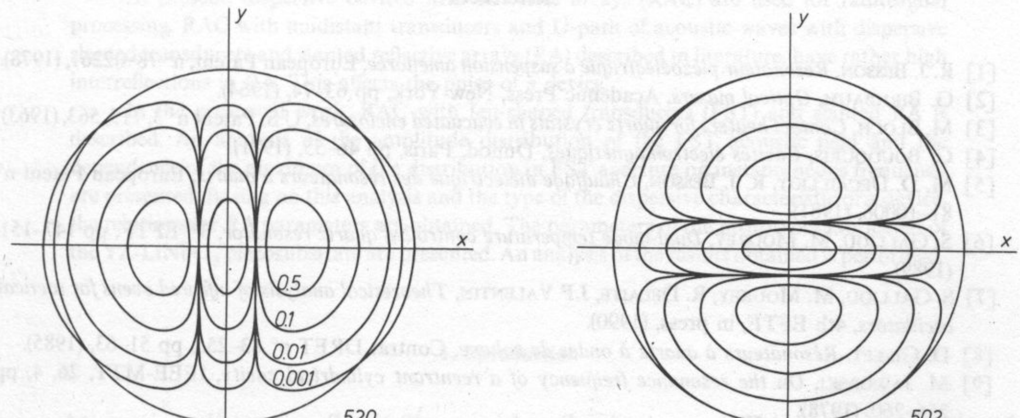

FIG. 10. Levels of shear mode amplitude for the 5.2.0 and 5.0.2 anharmonic modes

With that bi-resonator, a bi-oscillator has been manufactured. Each couple of electrodes was connected to an oscillator supplied by LC filter, the first at 5 MHz, the second at 7 MHz. Two signals were obtained. The frequencies were 5.1131 MHz for the 5.2.0. mode and 7.0878 for the 7.0.2. mode. The indirect amplitude frequency effect is minimized using anharmonics of different overtones [16].

The second step of that work is not realized today. The question is to know how to serve such a bi-resonator for providing a main mode and an internal heating mode. We consider this experiment is important. A success would open the way for a new miniature ovenized resonator.

6. Conclusions

We have examined four different possibilities to obtain low consumptions for BVA resonators.

By the means of the dielectric losses the necessary electrical power remains more high. The resistors deposited on the condensors bring on an unacceptable degazing, providing an aging largely greater than the usual aging of the BVA resonator. Probably the heating by infrared radiations is the best solution for low consumption; it could be turned to account in the future. The internal heating by acoustic losses is the more smart solution; it needs two very well uncoupled vibrations. In order to obtain such a result, it is possible to serve an even mode of vibration excited by parallel electric field. Then the even mode is very little affected by the vibrating state of the central part of the resonator and the discoupling between the modes can reach a nearly null value.

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