High-quality Crystal Filter – Design and Realization

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***Abstract* — Analog oscillators and filters are still very important devices in modern telecommunication and measurement equipment. Quartz crystal units are used for high-quality oscillators and filters, due to their extremely stable resonant frequency and Q-factor. In this paper the design and realization of a high-quality bandpass quartz crystal filter with a possible application to antenna circuitry is described.**

***Keywords* — Crystal units, crystal filters, filter design, filter realization, communications, digital communications.**

I. Introduction

CRYSTAL units are electromechanical devices, based on piezoelectricity. When cutting them in an appropriate way regarding crystal axes, they are characterized by an extremely stable resonant frequency and a very high quality factor (Q-factor). Once designed, crystal units have advantages of high-quality performances and relatively low cost production [1] – [9].

An approximate equivalent model of a crystal unit, which is valid at frequencies near to crystal resonant frequency, is depicted in Fig. 1 [3]. Mechanical vibrations are modeled with serial elements, R_m, C_m, L_m, which are internal parameters. Capacitance C_0 comes from crystal electrodes and parasitic capacitances and even can be added externally.

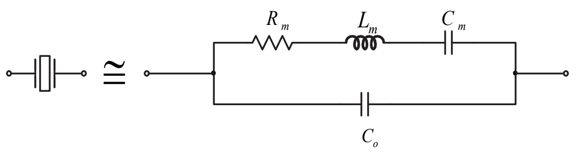

Fig. 1. Equivalent model of a crystal unit.

A typical plot of the reactance vs. frequency, of the circuit in Fig. 1, is depicted in Fig. 2. Serial (resonant) frequency, f_S, is determined by parameters L_m and C_m and has the following value:

$$f_S = \frac{1}{2\pi\sqrt{L_m \cdot C_m}} \quad (1)$$

Parallel (antiresonant) frequency, f_P, is defined by:

$$f_P = \frac{1}{2\pi}\sqrt{\frac{C_m + C_0}{L_m C_m C_0}} \cong f_S(1 + C_m / 2C_0)\Big|_{C_0 >> C_m} \quad (2)$$

Internal losses described by serial resistance, R_m, are small, leading to an extremely high Q-factor of the order of 10^6 [4]. Since parallel capacitance C_0 is significantly greater than C_m frequencies f_S and f_P are very close, as indicated in Fig. 2. Crystal units operate in the range between f_S and f_P, when the reactance has an inductive nature. Manufacturers of crystal units usually cut and handle crystals in such a way that the resonant frequency of unloaded crystal is higher than required. By adding external parallel capacitance C_P the frequency can be fine tuned to a desired (lower) frequency.

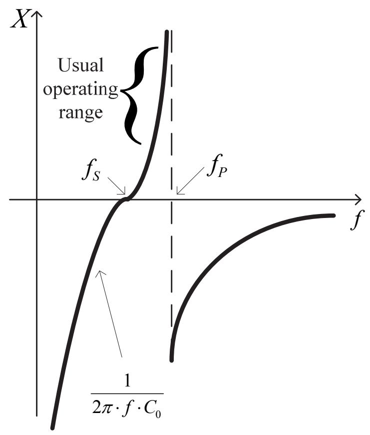

Fig. 2. Typical plot of the reactance of crystal unit vs. Frequency.

II. Basics of Crystal Filter Design

Crystal units are normally used in band pass and band reject filters. The extremely high Q-factor of unloaded crystal unit permits a very narrow bandwidth and sharp separation between passband and stopband. The simplest scheme of a filter with a single crystal unit (denoted as A) is depicted in Fig. 3. By several filter sections, usually in a cascade connection, a desired transfer function can be realized.

When designing crystal filters one needs to pay attention to several important requirements [10] combining electrical and mechanical demands. Electrical demands relate to the choice of filter function (Butterworth,

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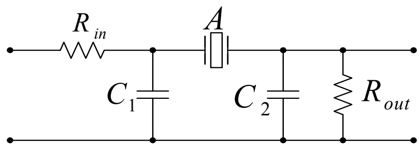

Fig. 3. Basic filter section realized with single crystal unit.

Chebyshev, etc.) and the filter order for satisfying given specifications: required attenuation limits in passband (max attenuation) and stopband (min attenuation), permitted ripple in the passband, lowest and highest frequencies in the passband (or stopband) region, the width of transition regions, phase and delay requirements, etc. Also, input and output resistances (impedances) should be matched with the source and the load, for satisfying VSWR or return loss requirements.

Regarding mechanical demands, note that crystal units are electromechanical devices with a precise (mechanical) resonant frequency. Due to that they are very sensitive to external vibrations and shocks, so special attention should be addressed to the mounting and housing. Also, some interharmonical modes of vibrations may occur producing "spurious" responses – very narrow responses, generally located at high frequencies, which considerably differ from desired values. If they appear in the stopband, the attenuation is decreased, while in the passband they will introduce an unwanted notch. Fortunately, spurious responses are very narrow and they usually don't cause a serious problem unless for signals at just these frequencies.

Additional requirements may be addressed to environmental conditions, such as temperature range, humidity, etc., in which the crystal filter has to operate.

The number of crystal units is dictated by a desired filter order, because each crystal unit is characterized by one complex pole (see Fig. 2). Therefore, the filter with *N* crystals is often referred to as a filter with *N* poles.

Parallel capacitances, denoted as C_0 in Fig. 1, reduce the bandwidth, but this effect can be minimized by adding low-loss parallel inductances. By adding serial capacitances between crystal units their coupling and impedance matching can be obtained.

Actually, there are only a few global manufacturers that offer the possibility of crystal filters realization satisfying specific customer's requirements. More often, manufacturers produce standard (typical) crystal units and filter types.

By following previous theoretical considerations [11] and rich professional experience of researchers at the School of Electrical Engineering and the Institute Mihajlo Pupin in Belgrade [12] – [15], we have derived a procedure for the design and realization of the high-quality crystal filter QFA2106, which will be described in the following sections.

III. Requirements for Filter QFA2106

A band-pass filter QFA2106, suitable for a high frequency range [1] – [10] (as in antenna circuits), was designed and realized, according to strict requirements that meet the specifications for basic and special conditions, which are set by the customer.

One of the important demands was to achieve as high as possible attenuation in the stop-band, and to reduce spurious responses in the range of interest. Regarding the desired attenuation, an appropriate filter order (the number of crystal units) was determined, while the reduction of spurious responses was obtained by choosing the optimal diameter of the crystal unit [2] and by an appropriate arrangement of components on the printed circuit board.

The filter central frequency of 126.95 MHz in the passband provides relative attenuation smaller than 3 dB in the frequency range of ±7.5 kHz and attenuation greater than 40 dB outside the band of ±40 kHz. In the range within ±50 kHz, the relative decline is more than 40 dB.

In Table I, we present technical characteristics of the proposed filter QFA2106, required by our customer.

Minimal transducer attenuation in the passband should be less than 6dB. Input and output filter impedances are 50Ω. Operating temperature range is -20 ºC to +70 ºC, while storage temperature range is -40 ºC to +85 ºC. The filter should be placed in the housing G10 BNC of the size 61x26x2 (dimensions in mm).

The manufacturing process applied to filters QFA2106 can be used for the production of all the types of crystal filters, which have strict requirements regarding the level of guaranteed attenuation in the stopband and strictly defined ripple and phase characteristic of the passband.

Table 1: Required technical characteristics of the filter QFA210.

Parameter	***Value***
Reference frequency	126.95 MHz
Bandwidth at 3 dB	± 7.5 kHz min
Pass band ripple	1 dB max
Transition band to attn. 20dB	± 30 kHz max
Transition band to attn. 40dB	± 60 kHz max
Relative attenuation (min)	40 dB
Min. transducer attenuation	6 dB max
Input impedance	50 Ω
Output impedance	50 Ω
Values of spurious responses	10 dB max
Operating temperature range	-20 ºC to +70 ºC
Storage temperature range	-40 ºC to +85 ºC
Maximum drive level	+ 10 dBm
Housing	G10 BNC

IV. Design of the Crystal Filter QFA2106

The whole filter design has been performed through two basic parts: the circuit design and design of crystal units. Circuit design relates to electrical requirements (approximation function, filter order, the number of crystal units, etc.), after that particular design of crystal units is performed. Both designing parts are mutually dependent in some way and design process should be derived through several iterations, which needs high designers' experience.

A. Circuit design

The circuit is designed by using transformation techniques for the cascade of lattice sections. The transfer function and filter topology are determined according to specified requirements.

Based on the specifications of the amplitude response in stop- and pass-band, the approximation function, filter order and corresponding filter topology are determined (Fig. 4). The circuit is designed under the assumption of real (non-ideal) filter elements. Circuit design defines the requirements for the crystal unit [1], [7], [9], [11]. As an assistant tool for testing filter design we used computer program developed for such purposes [15].

The filter order determines the number of crystals required. As depicted in Fig. 4, the filter is composed of four quartz resonators in a semi-lattice network, with two types of crystal units, denoted as *A* and *B*. The choice of crystal unit has a major impact on the overall filter performances. For instance, inappropriate choice of crystal unit may produce high spurious response, then, units having a low Q-factor may degrade amplitude and/or phase response, etc. After determining filter order and topology, the next step is to choose crystal units (usually called crystal resonators) having parameters which are well suited to given requirements.

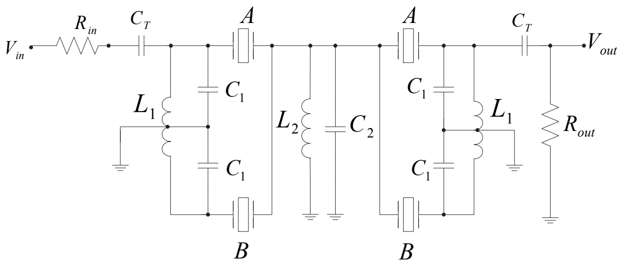

Fig. 4. Electrical scheme of the crystal filter QFA2106.

Furthermore, it is very important to design the layout of printed circuit board (PCB). The position of components in the PCB is essential, due to parasite effects, electromagnetic noise and other internal and external influences.

B. Design of crystal units

For the given project, we decided to use crystal units with AT-cut, of 66 μm thickness which operate in the 5th overtone mode. Realization of crystal units corresponds to the preliminary list of technical characteristics and requirements for such crystal units (given in Table II).

In crystal units design it is very important to make an appropriate selection of electrodes and the coating film. Here we used electrodes with thickness of d=0.89mm. For realizing such electrodes we developped a new technology, based on aluminium as an appropriate material regarding electromechanical demands. Frequency adjustment is done with a sodium chemical process (maximal deviation after group evaporation is less than -35kHz), and with anode oxidation (max +60kHz) which provides very stable Al_2O_3 films. After this process and cementation, all crystal units are being treated for 24 hours on air for making a thin film of stable oxide. Crystal units are plan-parael (PP) with a diameter of Φ=5mm in a cold welded (CW) housing (HC-45 type). For assuring high rejection of spurious responses, extremely high plan parallelism of crystal plates is necessary [11] – [14]. This is a very challenging technology problem and only a few manufacturers in the global market can resolve it.

TABLE 2: REQUIRED TECHNICAL CHARACTERISTICS FOR CRYSTAL UNITS USED IN FILTER QFA2106.

Item	***Value***
Housing	HC-45
Crystal unit frequency	f_A=126938.830kHz f_B=126961.160kHz
Q-factor	> 60,000
Dynamic capacity	C_m = 0.083 mpF±10%
Parallel capacity	C_0 = 0.9 pF±5%
Dynamic resistance	R_1 < 190Ω
Frequency adjustment	df/f = ±10ppm
Frequency tolerance	df/f = ±15ppm
Aging	df/f = 1ppm/yr
Spurious frequencies (f_n)	A. f_0 +80kHz, without f_n B. f_n>35dB, f_0 ±1MHz
Operating temperature range	-20 ºC to +70 ºC
Storage temperature range	-40 ºC to +85 ºC

Notes: Frequencies f_A and f_B are crystal unit frequencies (unit *A* and *B*). Both units have the same Q-factor. Capacitance C_m, C_0 and resistance R_1 are from the equivalent scheme depicted in Fig 1. and they were assumed the same for both crystal unit types. Matching, deviation, and spurious frequencies are typical data required for design of crystal units.

V. FINAL REALIZATION

A. Production

The final step was the production of designed filter. This process is also very demanding, which includes preparation of all processes which are necessary for each production phase. The production consists of two global phases: production of filter units and the encapsulation of filters.

Production of crystal filter units is realized by applying all necessary mechanical, chemical and testing (adjusting) processes. It includes crystal cutting, rounding, grinding, polishing, deposition of thin Al film electrodes, and finally mounting the units into the housing, cementing and vacuum enclosing. Between all processing steps a number of different control measurements and correction processes are applied, assuring high quality and high precision of realized units.

After the production of crystal units, special attention is devoted to the choice of additional electronic components: resistors, capacitors and inductors, regarding their tolerances, temperature dependence, aging, dimensions and quality, in general. Some components, like inductors, have to be realized and tuned manually.

The second production phase consists of mounting and soldering components on the PCB. After that, the connecting input/output access points are mounted and the complete PCB is encapsulated into the housing.

The final step is adjusting the encapsulated filter by fine tuning of variable components, by using a high precision network analyzer. When filter characteristics satisfy a required specification, filter housing will be hermetically closed. Since the filter QFA2106 is designed for outdoor purposes, the housing G10 BNC was used. In Fig. 5. the technical drawing of the housing G10 BNC is depicted, while the photo of final product, the realized filter FA2106, is presented in Fig. 6.

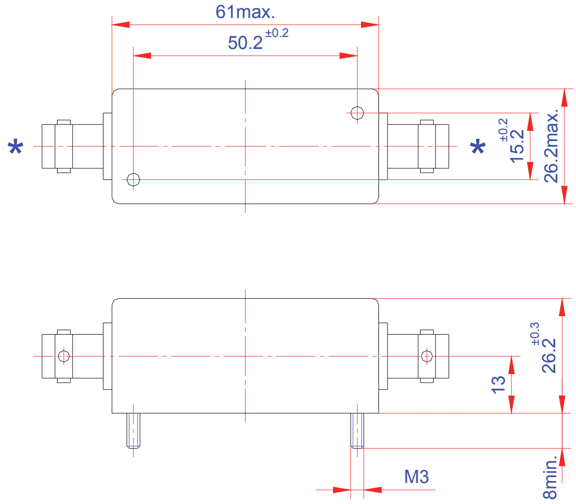

Fig. 5. Housing G10 BNC for filter QFA2106.

Fig. 6. Final product: filter QFA2106.

Crystal filter QFA2106 was produced using the newest technologies in crystal units realization, derived as joint work of Institute Mihajlo Pupin and Innovation Center and School of Electrical Engineering, University of Belgrade.

B. Measurement results

Requirements are completely satisfied and they are approved by measurement results. In Fig. 7. the measurement results for realized band-pass filter QF 106 are presented. In the upper part of Fig. 7. the measured values of most relevant filter parameters are presented, such as nominal centre frequency, bandwidth, etc. In the bottom of Fig. 7. transfer the function is presented in the narrower frequency range (upper diagram) and in the wider range (lower diagram).

VI. Conclusion

A new band-pass crystal filter was designed, according to severe requirements assuming special conditions. Testing results performed on realized filters confirm their quality and potential application in high-quality professional devices.

In the world market there are only a few global manufacturers producing high-quality crystal filters based on specific requirements for a specific consumer. For such type of production, highly qualified, educated and experienced researchers, designers and manufacturers are required.

Nowadays, in view of economic aspects, it is necessary to establish collaboration between more institutions and manufacturers. The Institute Mihajlo Pupin, Belgrade, has a long tradition and great experience in the realization of these types of electronic components based on specific requirements. From cooperative work with the Innovation Center and the School of Electrical Engineering, University of Belgrade, it is expectable to realize even better results in the future.

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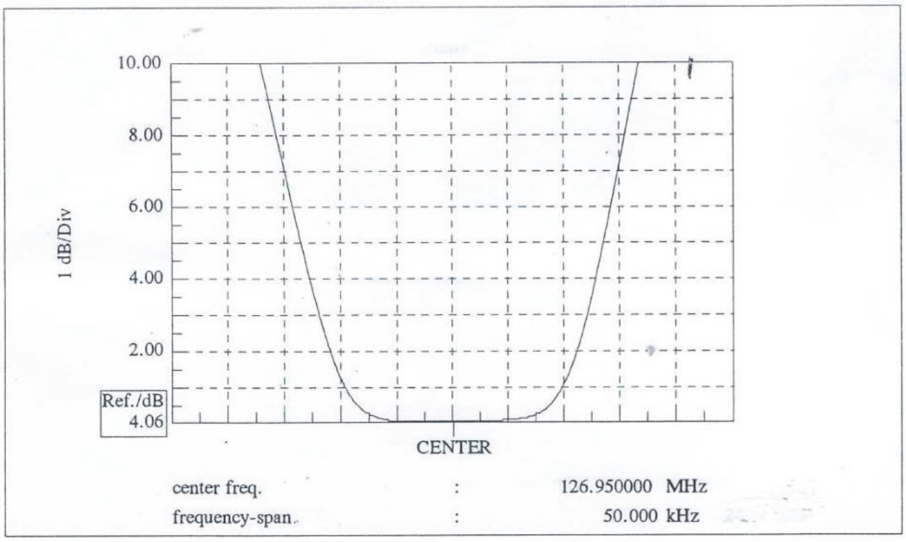
FILTER - TEST RECORD

1. nominal centre freq.	fc :	126.950000 MHz	
2. delta fc	:	+114 Hz	
3. bandwidth	at 3.0 dB :	24.112 kHz	
	w.r.t. fc :	-11.942 kHz	+12.170 kHz
4. ripple	:	0.00 dB	in fm +/- 7.500 kHz
5. transducer attenuation	:	4.1 dB	
6. attenuation at fc	:	4.1 dB	
7. stop bandwidth	at :	20.0 dB	
	at fc :	- 24.786 kHz	+ 24.169 kHz
	at :	40.0 dB	
	at fc :	- 53.220 kHz	+ 48.919 kHz
8. ultimate attenuation	>= :	69.4 dB	
	from :	125.950000 MHz	to 126.890000 MHz
	>= :	67.7 dB	
	from :	127.010000 MHz	to 127.950000 MHz



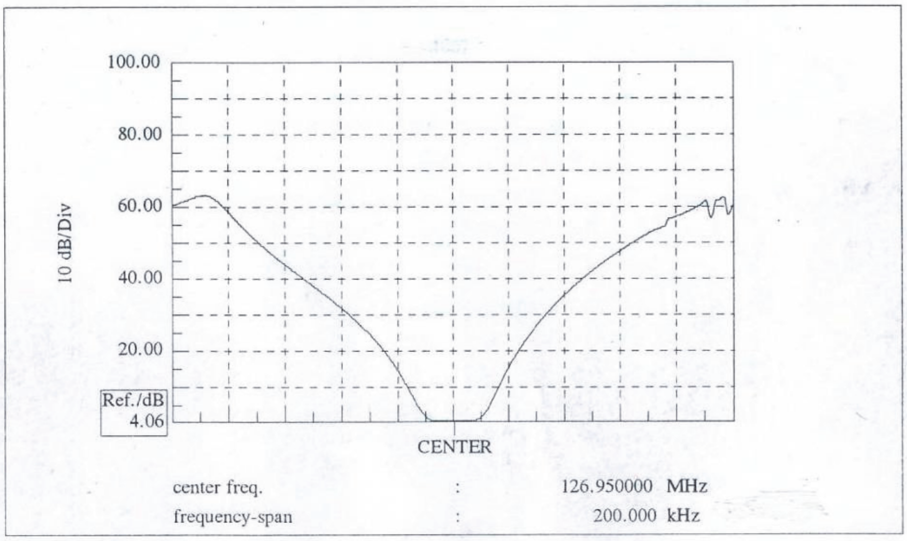


Fig. 7. Measurement results for realized crystal filter QFA2106.