monolithic crystal filters

Introducing the MCF, a new and improved development in crystal-filter technology — a report on its applications in communications electronics

When high selectivity in electronic circuits is a must, mechanical filters, ceramic filters, or crystal filters are used. A new type of crystal filter is becoming popular: the monolithic crystal filter (MCF). It replaces the conventional crystal filter and leads to new applications for this new product, because the MCF shows comparable electrical features but is smaller and can be made more economically in large-scale production. What is a monolithic crystal filter, and what is the difference between it and conventional crystal filters?

conventional crystal filter

Conventional crystal filters consist of one to ten single quartz crystals coupled together by inductors, capacitors, and resistors in a distinct way to yield the filter characteristics required by the design specifications. As a typical example, **fig. 1**, shows the internal circuit of the well-known XF-9B bandpass filter of KVG* which is a standard filter for single-sideband applications. It's an eight-pole filter, which means it includes eight crystals. The bandwidth is ±1.2 kHz at −6 dB attenuation (related to the passband) at a center frequency of 9 MHz.

Each stage consists of tuned half-lattice bridges with one crystal in each branch. The stages are coupled through *C4* and *C5*. For matching the filter impedance to 500 ohms, the input and output circuits have stacked windings. To compensate for strays, both resonate circuits are tuned to a higher frequency. With external trimming capacitors the filter can be aligned to the exact center frequency, which is also the point of minimum passband ripple.

monolithic two-pole (dual) filter

Instead of single crystals, the monolithic crystal filters use multiple resonators, which consist of several vibrating systems plated onto one common crystal blank. Typically, these vibrators are of the thickness shear type (AT cuts) with a frequency range from 5-30 MHz in the fundamental mode (plano-parallel crystal blanks). Most types of multiple resonators work in the fundamental mode, but the same principle can be applied to overtone resonators as well.

The simplest arrangement of multiple resonators is the monolithic two-pole filter, referred to as "dual." What is its difference compared with single crystals?

The equivalent electrical circuit of a single crystal is shown in **fig. 2.** It involves a high-Q series-resonant circuit consisting of the motional parameters $L1$, $C1$, $R1$ and the static capacitance, C_0, in parallel. The Q is greater than 50,000.[1,2]

The series-resonant frequency is

$$f_s = \frac{1}{2\pi\sqrt{L_1 C_1}} \tag{1}$$

and parallel-resonant frequency above f_s is

$$f_p = \frac{1}{2\pi\sqrt{L_1\left(\frac{C_0 C_1}{C_0 + C_1}\right)}} \tag{2}$$

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*Kristallverarbeitung Neckarbischofsheim, West Germany; available in the United States and Canada from Spectrum International, Post Office Box 1084, Concord, Massachusetts 01742.

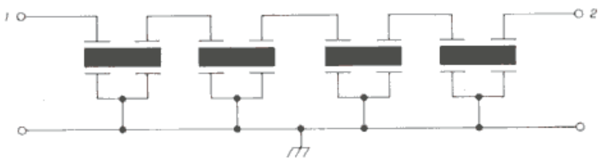

fig. 11. Internal circuit of KVG-Monolithic filter XFM-107S03.

plification of the structure of multipole crystal filters. Instead of discrete crystals, MCFs contain multiple crystal systems on a common quartz blank, which are mechanically coupled between each other by the quartz blank.

The typical application is in the frequency range of AT-cut crystals, most in the fundamental mode, but with increasing importance also as third or higher overtone monoliths. However, bandwidth is somewhat reduced in overtone applications.

The most usual forms of MCFs are dual resonators and series configurations of duals-to-high-pole filters. Beyond this, there are new interesting applications for duals as i-f preselectors, simple noise filters, or f-m demodulators.

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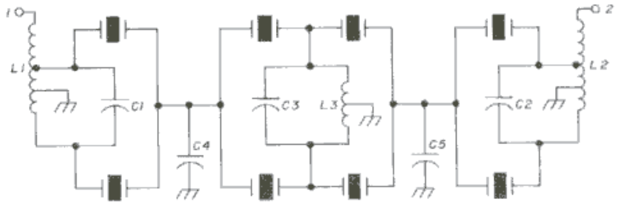

fig. 1. Internal circuit of KVG filter XF-9B.

The monolithic two-pole filter has two pairs of electrodes, which are plated onto one common crystal so that both resonators are mechanically coupled to each other by the crystal blank in a well-defined magnitude. This leads to the equivalent electrical circuit shown in **fig. 3**.

Both resonators consist of the motional quantities $L1$, $C1$, $R1$ and $L1'$, $C1'$, $R1'$. The static capacitances across each pair of electrodes are C_0 and C_0'. The four-pole in **fig. 3** (dashed lines) involving C_k and the negative capacitances $-C_k$ — a so-called impedance inverter configuration[3] — represents the mechanical coupling between both systems.[4]

The coupling factor, k is

$$k = \frac{C_1}{C_k} \tag{3}$$

and has an order of magnitude of 10^{-4} - 10^{-3} in fundamental-mode duals. Overtone duals have smaller coupling factors. The coupling factor of a particular dual is determined by the configuration of the electrodes, the gap between them, the crystallographic direction of coupling, the mass of the electrode plating, and the thickness of the quartz blank.[5]

The resonant frequencies of both resonator pairs are normally equal or very close to each other:

$$f_1' \approx f_1 = \frac{1}{2\pi\sqrt{L_1C_1}} \tag{4}$$

Because of the coupling effect these frequencies can't be measured directly. For example, between pin A and pin B, with pin C open (**fig. 3**), you can measure a frequency f_1^* that's lower than that obtained with **eq. 4**.*

Two new resonant frequencies occur, which are the characteristic vibration modes of monolithic dual resonators. These frequencies are of great significance for the application of duals as filter components:

1. When both resonator systems are connected in parallel, as shown in **fig. 4A**, series resonance appears at the so-called "symmetric frequency":

$$f_{sym} = f_1\sqrt{1-k} \tag{5}$$

In this circuit both systems vibrate in equal phase. This means that the mechanical displacement (of the thickness-shear motion of the crystal) takes place in the same direction in both systems.

2. Connecting both resonators as shown in **fig. 4B**, series resonance appears at the "antisymmetric frequency," f_{asym}, which is above f_{sym}:

$$f_{asym} = f_1\sqrt{1+k} \approx f_{sym}\,(1+k) \tag{6}$$

In this configuration both systems vibrate in phase opposition.

Additionally, both frequencies, f_{sym} and f_{asym}, can be measured between pins A and B with short circuited output pins (B and C). In this case, symmetric and antisymmetric frequencies are the frequencies of maximum input admittance of the four pole.[6]

The frequency difference between both characteristic frequencies — often called "mode spacing" — increases with higher coupling factor, k, as you can see in **eq. 6**.

monolithic multipole resonators

The principle of the monolithic dual resonator can be expanded and leads to monolithic multipole resonators with up to eight or ten resonator systems on the same crystal disc.

The mathematical synthesis of such vibrators is complex. Also measuring and production techniques are difficult. Each type of filter needs a certain configuration of the resonators. This restricts the feasibility of economically producing a large number of filter specifications in smaller quantities. Furthermore, with a larger number of resonators, the problem of spurious responses increases. This is why the multipole monolithic crystal filter hasn't become popular except for special applications such as channel filters.[7] The tendency is to obtain multipole crystal filters by stacking several dual resonators, as explained below.

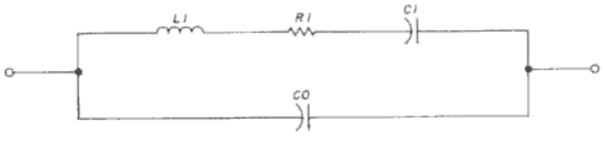

fig. 2. Equivalent electrical circuit of a crystal.

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*More precisely, two frequencies exist:

$$f_{1,2}^* = f_1\sqrt{1 + \frac{C_1}{2C_0} \pm \sqrt{k^2 + \left(\frac{C_1}{2C_0}\right)^2}}$$

The lower frequency is between f_{sym} and f_{asym}, where f_{sym} and f_{asym} are the "symmetric frequency" and "antisymmetric frequency" as described in the following text.

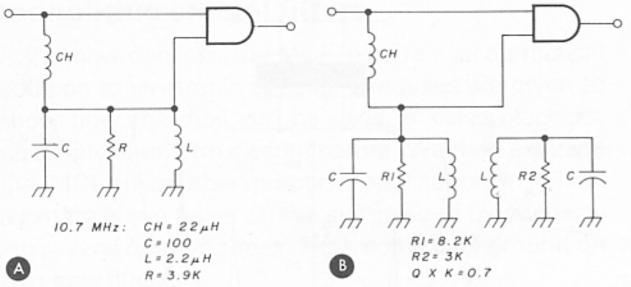

fig. 8. Schematics of f-m quadrature detectors — (A) with single resonant circuit; (B) with bandpass filter.

well as high audio yield. The demodulator response is the typical S-shaped characteristic. The two peaks are approximately at the symmetric and the antisymmetric frequencies.

Fig. 9 shows a circuit working on this principle. It consists of the RCA integrated circuit CA3089E. Both terminating resistors, $R1$ and $R2$, are chosen for best phase linearity (*i.e.*, constant group delay) in the passband between the two peaks. Their values depend on the motional parameters, L_1C_1, and the mode spacing of the dual.

This principle can be generalized for other quadrature detector ICs such as ULN2113A (Sprague), TAA661 (Signetics), or TBA120S (Siemens).

multipole filters with n>2

Monolithic crystal filters with more than two poles can be synthesized by connecting several dual resonators in series whereby they are coupled to each other by capacitors to ground (*i.e.*, the common electrode). As an example, **fig. 10** shows the internal circuit of the KVG monolithic filter XFM-107B (bandwidth ±7.5 kHz at 10.7 MHz). Input and output are terminated with tuned circuits, which transform the filter impedance to a standard value of 910 ohms (with $C_{ext} = 25\,pF$ in parallel).

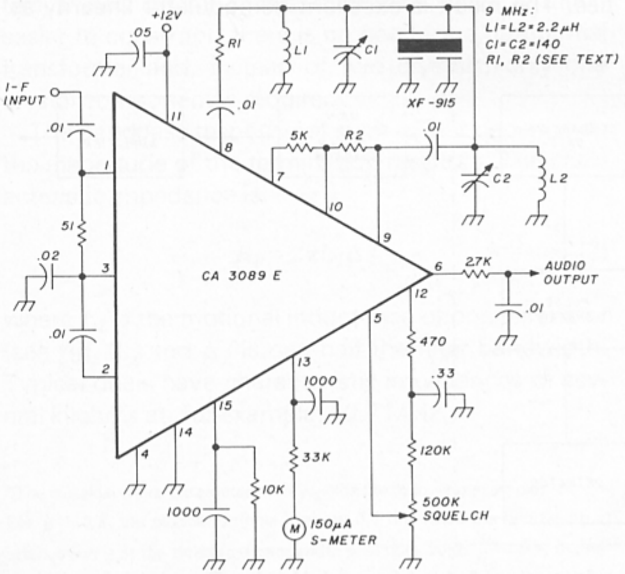

fig. 9. F-m demodulator with dual as discriminator.

As with single duals, such composite filter structures can be terminated directly with a pure ohmic resistance given by the filter synthesis. In this case both tuned circuits can be omitted.

Furthermore, with increasing bandwidth up to about 1 per cent (*i.e.*, 1 part in 100) of the center frequency, the coupling capacitors become so small that they are realized by the static input and output capacitances of the coupled duals plus stray capacitances alone. Then the simplest structure of a monolithic crystal filter can be achieved. It consists only of a chain of directly coupled duals, as you can see in **fig. 11** for the KVG monolithic filter XFM-107S03 (10.7 MHz bandwidth ±10.6 kHz).

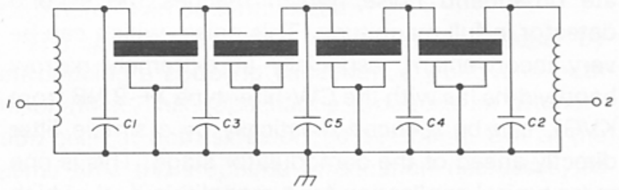

fig. 10. Internal circuit of KVG-Monolithic filter XFM-107B.

Comparing this circuit with that of a discrete crystal filter as in **fig. 1**, the simplification is evident. Further, the half-lattice filters with more than five crystals usually need a third tuned circuit (see L_3, C_3 in **fig. 1**), which gives additional insertion losses that can't be compensated for by the termination. This isn't necessary with monolithic filters because they present much smaller amounts of insertion loss than conventional crystal filters.

The electrical properties of monolithic crystal filters are equivalent to those of crystal filters with discrete components. That's why you can realize all known filter responses in monolithic structures, but with an upper limit for the bandwidth. Generally, filters with monolithic crystals vibrating in the nth overtone mode can be obtained with relative bandwidths smaller by the factor $\frac{1}{n^2}$.

The theoretical filter curves for ideal (lossless) filters — that means, the responses of attenuation and phase *vs.* frequency — are cataloged in normalized representation in the literature on the subject.[9,16]

summary

Monolithic crystal filters (MCFs) stand for the sim-

We now consider the MCF in its role as a practical addition to electronic circuits. Examples are given to show how the dual can be used in noise blankers, noise filters, and fm discriminators. We then examine the MCF in another practical application in which more than two poles can be synthesized by connecting several duals in series. First, some background on two-pole filters.

Two-pole filter characteristics. As shown by the theory of network synthesis and by the theorem of Bartlett,[8] the equivalent electrical circuit of a dual (**fig. 3**) can be transformed into an equivalent half-lattice bridge with a differential transformer, which has the same response of amplitude and phase *versus* frequency.[9]

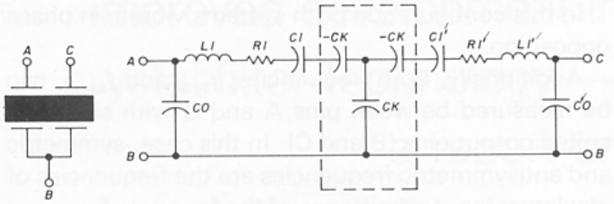

fig. 3. Configuration and equivalent electrical circuit of a dual resonator.

When a dual is terminated at its input and output with an impedance value, $Z_{in} = Z_{out}$, the elementary form of a two-pole crystal filter results. The identical selectivity curve is shown as the equivalent half-lattice, two-pole filter with single crystals terminated with the same impedances (**fig. 5**).

Comparing the number of components in both filters shows clearly that a monolithic filter is much easier to construct: there is no need for a differential transformer and, instead of two crystals, only one crystal component is required.

The bandpass response of such a filter depends on the magnitude of the termination resistors. The characteristic impedance is

$$R_0 = 2\pi L_1 \Delta f \tag{7}$$

where L_1 is the motional inductance of one resonator (see **fig. 3**), and Δf is one-half the filter bandwidth. Typical duals have characteristic impedances of several kilohms at, for example, 10.7 MHz.

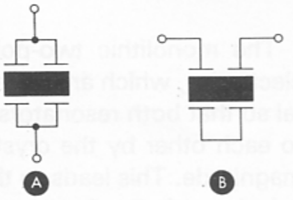

fig. 4. Pin configurations for measuring symmetric (A) and antisymmetric (B) frequencies.

Reasonable bandpass filter responses (with curves having a near-rectangular passband characteristic) can be achieved with terminating impedances of $R = Z_{in} = Z_{out}$ smaller than R_0. The smaller the R value, the higher the passband ripple, but the skirts of the filter characteristic will be steeper.*

By proper selection of the termination impedances and characteristic frequencies of the dual, every filter response known from the filter theory of effective parameters (*i.e.*, Chebyshev, Gaussian, Bessel, Legendre)[9] can be synthesized.

The skirts of this filter can be made steeper by introducing a coupling capacitor, C_A between both resonators. This capacitance produces an attenuation peak at both sides of the passband. But at the same time the stopband attenuation decreases, as shown in **fig. 6**, for several values of C_A (as multiples of C_0).[10]

To fulfill the total selectivity demands of a special device (*e.g.*, a receiver), such a two-pole filter will surely not be sufficient. Despite this disadvantage, there are some interesting application examples for this simple filter component.

Dual as an i-f preselector in noise blankers. Noise blankers are designed to blank out short-duration noise pulses with high amplitude, especially in shortwave or mobile receivers. The best point at which to insert a noise blanker in a receiver is ahead of the i-f stages before the crystal filter, which provides the main selectivity. This is because narrow-bandwidth filters produce ringing, which distorts the signal.[11]

The block diagram of a typical noise blanker is shown in **fig. 7**. It includes two alternatives to obtain the noise information. Version A derives it from the i-f signal; version B obtains it from a separate noise receiver tuned to a "silent" frequency.[12]

Following the mixer a broadband i-f filter must be

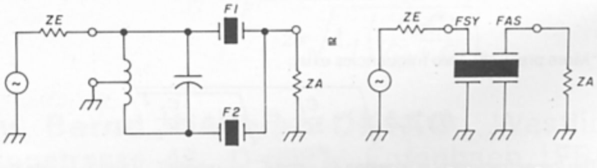

fig. 5. Two-pole crystal filter with differential transformer and equivalent monolithic crystal filter.

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*The classical wave-parameter theory yields the following example: For $\frac{R}{R_0} = 0.8$, the passband ripple is about 0.1 dB, while the bandwidth at attenuation is at the three-fold bandwidth a −3 dB. With $\frac{R}{R_0} = 0.5$, the ripple increases to 0.22 dB, while the −20-dB bandwidth is only 2.8 times the −3-dB bandwidth.

inserted, one narrow enough to cut off strong out-of-band signals but broad enough to avoid ringing. A monolithic dual is a unique device for this i-f preselector, as it can be inserted directly with pure ohmic termination and without any alignment effort — if the dual spurious responses are negligible.

For the well-known 9-MHz crystal filter line, KVG offers its dual type XF-912 for a bandwidth of ±7.5 kHz (at −3 dB). It is housed in a 3-pin HC-18 case and needs terminating resistances of 4.0 kilohms for a Chebyshev response. Different types with other bandwidths are available on request.

Dual as a noise filter. Normally, the main selectivity of commercial receiver i-f strips is produced by a high-performance (*e.g.*, eight-pole-type crystal) filter ahead of the i-f amplifier stages. But usually the following broadband high-gain amplifier stages generate broadband noise, which reaches the second detector in full magnitude. This noise, which can be very inconvenient, especially at extremely narrow bandwidths (as with the CW-filter type XF-9 NB from KVG), can be reduced drastically by a simple filter directly ahead of the demodulator stage. This is one more typical application for a monolithic dual, which can be easily inserted without any adjustments. For example, the type XF-912 can be used again. Similar duals exist also for other i-fs such as 10.7 MHz or 21.4 MHz.

Dual as an fm discriminator. IC quadrature detectors are frequently used to demodulate fm signals. The principle on which these demodulators work is as follows.

The frequency-modulated i-f signal is applied to one port of an AND gate; the other port is connected to a phase-delayed portion of the same signal. The phase delay depends on the frequency. The gate output yields the demodulated audio-frequency signal if followed by an integrating RC lowpass filter.

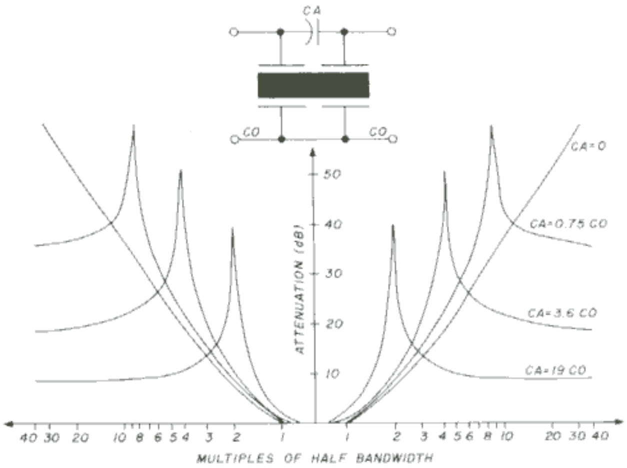

fig. 6. Frequency response of a dual with attenuation poles achieved by an additional capacitor, C_A.

The phase-delay circuit is a parallel-resonant circuit, which is coupled through a choke or a small capacitor, as shown in **fig. 8A**. This circuit provides a phase delay that increases or decreases linearly with frequency changes in the vicinity of the resonant frequency.[13] Higher slopes of the phase *vs* frequency curves, and thereby higher recovered audio, can be realized by using a bandpass filter with a coupling coefficient of about $Q \cdot k = 0.7$. This is shown in **fig. 8B**.[14]

The bandpass-filter can be substituted with a conventional dual resonator, which is designed as a Bessel-function filter with linear phase characteristics. The result is excellent demodulator linearity as

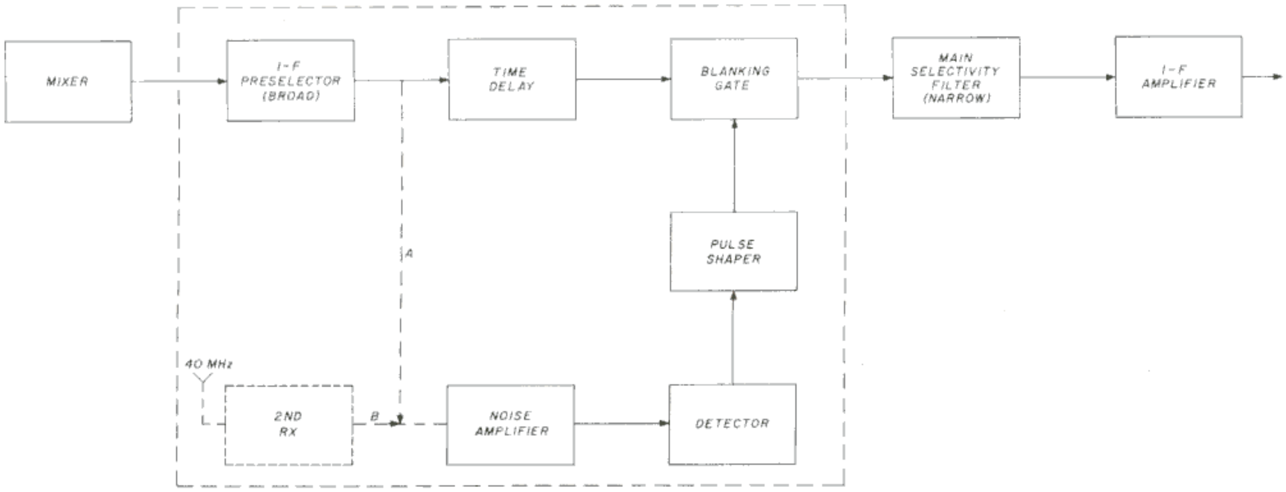

fig. 7. Block diagram for a typical noise blanker. Version A: noise information derived from i-f. Version B: noise information derived from separate noise receiver.