Simulation and design of RF filters

A unique filter simulation technique designed to make that ladder SSB filter work the first time.

By M. I. Dieste

The demand for precise frequency control and frequency discrimination is inherent in the field of communications. Many efforts have been made to develop highly stable oscillators and extremely selective electrical filters. For this purpose, quartz crystals are used in numerous applications because of their intrinsic quality factor and their highly sensitivity frequency characteristic.

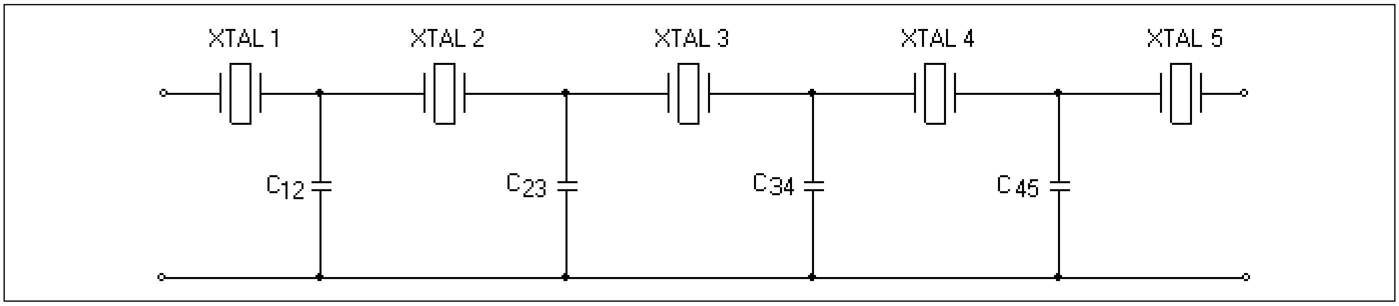


Figure 1. A ladder network filter configuration.

Piezoelectric filters are universally employed for filtering in radiocommunication systems because of their excellent selectivity. Present technologies allow designers to obtain fundamental frequencies in the range from 60 MHz to 250 MHz. At these frequencies it is possible to design filters with reduced dimensions by the integration of several resonators. More important uses of crystal filters are in all classes of mobile two-way, as well as in point-to-point radiocommunications, electronic navigation systems and frequency synthesizers.

Xtal	R1(Ω), max	L_1(mH)	C_0(pF)	f_r(MHz)
1, 5	12	3.25	2.65	29.992560
2, 4	12	3.40	2.62	29,998601
3	12	3.30	2.42	29.991651

Table 1. Crystals parameters and series-resonance frequency values.

Discrete vs. monolithic filters

Most crystal filters are bandpass networks. A division can be made between discrete resonator filters, in which a resonator is a separate device, and monolithic crystal filters, in which some of the resonator are coupled acoustically[1]. As such, discrete crystal filters can be classified as narrowband, intermediate bandpass filters, wideband filters and extra-large bandwidth filters.

For narrow or very wide bandwidth, discrete resonator filters may be preferable to monolithic designs. Also, the discrete crystal filter allows more flexibility in the choice of schematic design. Narrowband crystal filters can be designed so that the crystal static capacitances can be accommodated without the use of inductors[2].

They can be realized as either a ladder or a bridge circuit. The advantages and disadvantages of both forms of realization are a result of the physical nature of the quartz element and the properties of the schematics[3].

In this article, the design of a discrete crystal filter with center frequency of 30 MHz, and strict specifications relating to bandwidth, frequency stability, and attenuation is presented. The structure chosen in the design is a ladder filter where the crystals are functioning in their fundamental mode, with a frequency versus temperature stability of ±70 ppm. Also, simulation is employed to verify the design and to determine the thermal behavior of the filter.

Filter design requirements

The filter has been designed in order to meet the following specifications: center frequency of 30 MHz; a 3dB bandwidth of ±10 kHz; maximum ripple of 1 dB; infinite attenuation frequency located twelve half-bandwidth from the center

C_{12}	C_{23}	C_{34}	C_{45}
25.57	29.90	29.90	25.57

Table 2. Coupling capacitor references and values (in pF).

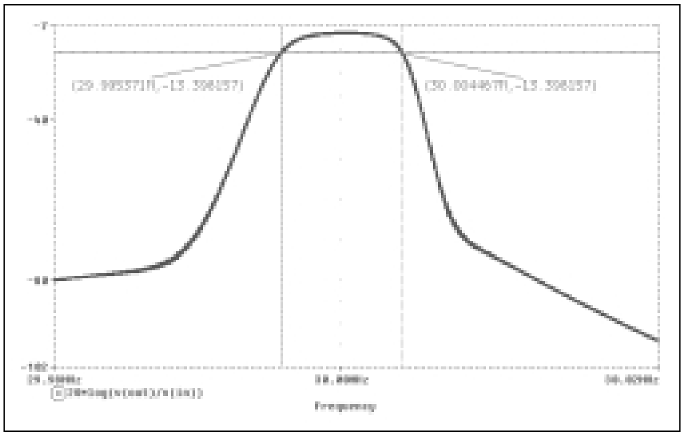


Figure 2. The simulated responses of a five-crystal filter around the center frequency.

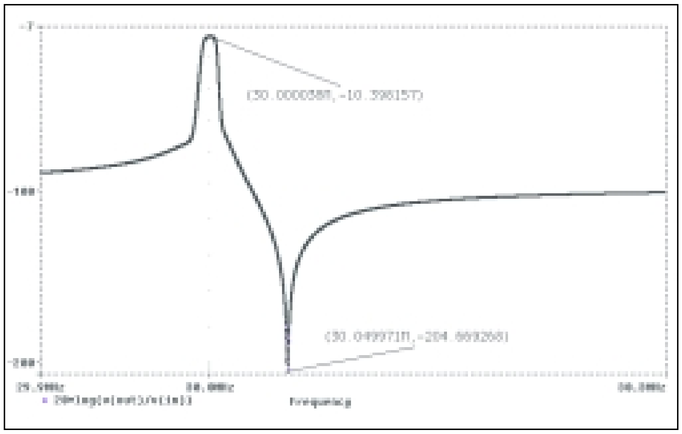


Figure 3. The SSB filter response.

frequency; operating temperature range from –20° C to +70° C and frequency stability of ±85 ppm.

Crystal characteristics

In order to achieve the specifications, the structure chosen is a ladder filter (see Figure 1) where the crystals are functioning in their fundamental mode. AT-cut crystals are used. The crystal has been cut at an angle of about 35° 15', in reference to the optical axis of the crystal. Quartz resonators are used in order to achieve high frequency stability within the temperature range. Using quartz crystals, stabilities of around ±20 ppm are easily obtained with a wide range of temperatures (–20° C to +70° C) if an appropriate crystal is chosen.

The most important consideration in the design is crystal realizability so that the capacitance ratio, ie., the ratio of the parallel to the series capacitance of the crystals can be a minimum of about 200. This is possible only if AT-cuts have been employed.

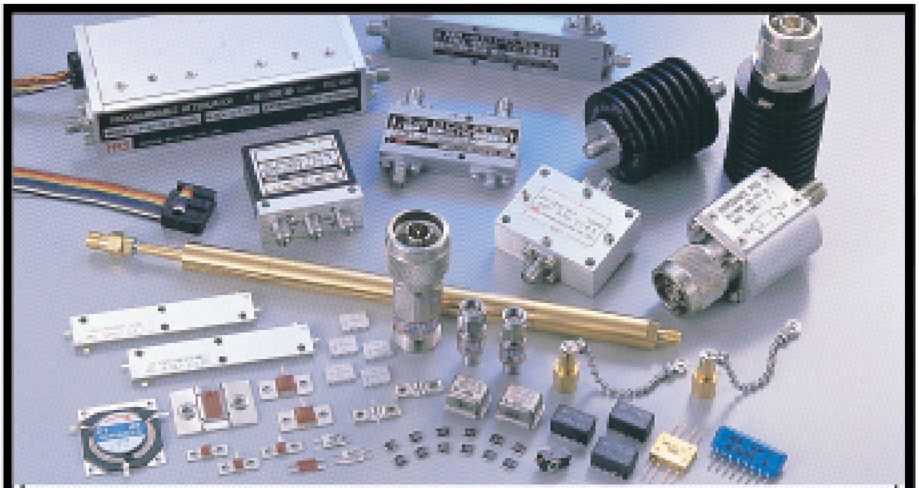
Circuit description

This network has been selected because it provides a narrow and stable bandwidth and because the slight dissymmetry, inherent to this configuration, is not critical. The series crystal circuit sets the passband with the crystal series resonance and for this application the crystals may be manufactured close to the requirements so that it is not necessary to use trimmers in the circuit.

The parallel resonance frequency produces the peak of attenuation expected from the filter. Thus, if all the peaks are not precisely coincident owing to variations of parallel capacity, there is no degradation in the performance of the filter. Moreover, the problem of spurious response in the crystals has less influence in this configuration since each crystal tends to reject the spurious of the others.

The structure used combines the stopband attenuation advantage of a multisection filter with the ability of the lattice to allow resonators of similar impedance level to be used throughout. The method for the synthesis of this filter in ladder form was given by Haine[4]. Values obtained from this method are shown in Tables 1-2.

The crystals can be represented close to the resonance frequency by a series resistance R_1, an inductance L_1 and a capacitance C_1 connected in series, in addition to a capacitance C_0 connected



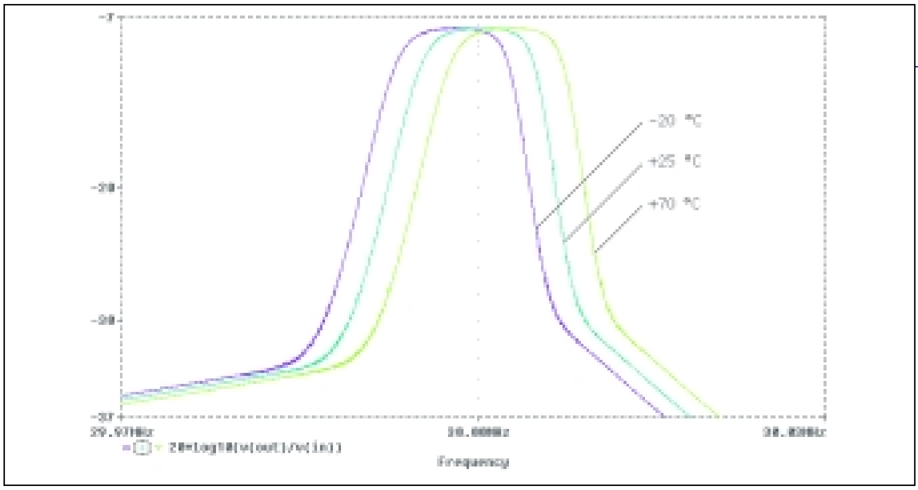


Figure 4. The thermal behavior of the filter.

in parallel. C_1 may be evaluated from the values shown in Table 1[5]. These values are typical for AT-cut crystals working at frequencies close to 30 MHz.

From Tables 1 and 2 can be observed that the structure is symmetrical about the center. That is, the same values of components are seen from either end.

Filter simulation

Before constructing a prototype, it is important to determine its characteristics by using a simulation program. Although other specific programs can be used, in this case PSpice is used as a simulation tool for the analysis of the filter.

As can be observed in Figure 2 and Figure 3, with this configuration it is possible to accomplish the overall specifications desired. Inspection of the response shown in Figure 2 reveals that the 3 dB bandwidth is slightly narrower than the required bandwidth. Also, a slight dissymmetry is observed. For the configuration shown in Figure 1, the capacitance ratio of the resonator equivalent circuit determines a maximum bandwidth of ±15 kHz.

Figure 3 shows that the infinite attenuation frequency is located around twelve half-bandwidths from the center frequency.

Thermal behavior

The crystals used in this design have a frequency stability of around ±80 ppm in the operating temperature range so that specifications can be realized. Nevertheless, when attempting to design quartz crystals filters with more stringent specifications, related to frequency stability, it is important to determine, a priori, the variations in frequency of the filter when the temperature changes. A temperature analysis can be done from using a temperature model of the electrical equivalent circuit parameters of the quartz crystal.

To determine the thermal behavior of the filter, a parametric analysis has been performed in the circuit shown in Figure 1. For that it is necessary to include the thermal behavior of the equivalent circuit parameters of the crystals[5]. Figure 4 shows the frequency variation of the filter employing crystals with a frequency versus temperature stability of ±80 ppm in the operational temperature range from –20° C to +70° C. For clarity, Figure 4 shows only the thermal behavior of the filter in the temperature limits (–20° C, +70° C) and the nominal value has been included. For this last temperature (+25° C) the center frequency value (+30 MHz) and its corresponding bandwidth can be observed.

Figure 5 shows the deviations, expressed in ppm, of the center frequency of the filter when the temperature changes within the temperature range. Also, it shows the thermal behavior of the crystal.

As can be observed in Figure 4, for the design of the filter employing quartz crystal with a frequency temperature stability of ±80 ppm, the filter stability gets worse with regard to the crystals being approximately of ±85 ppm.

For the rest of the cases studied a similar behavior has been observed. The case shown in Figure 4 is the most adverse one.

Conclusions

In this paper the design of a single side band filter using AT-cut quartz crystal resonators has been presented. To

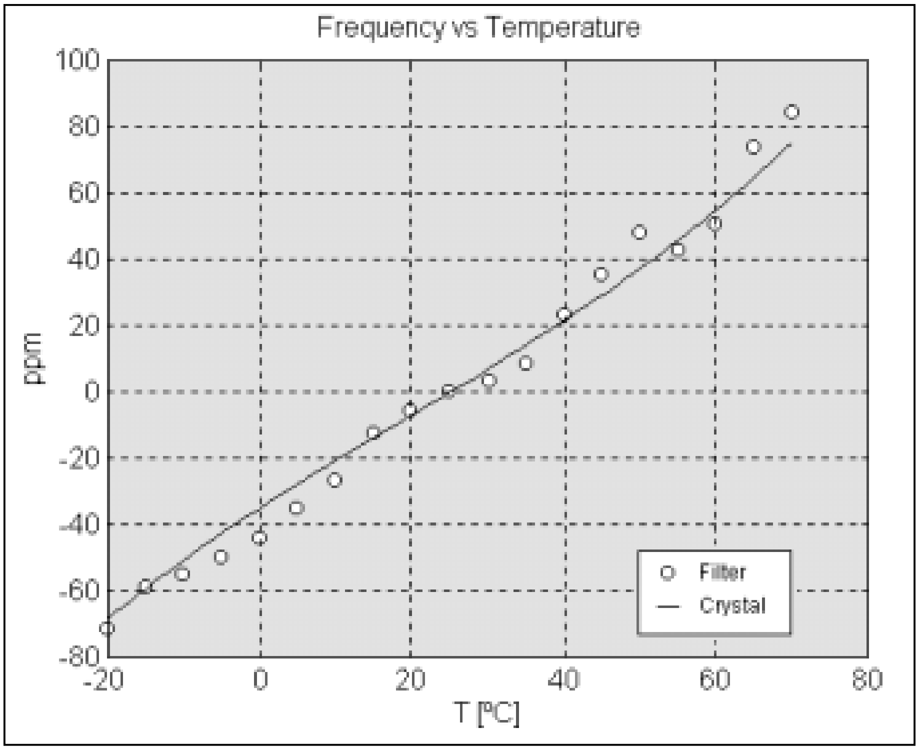


Figure 5. Comparison of the thermal behavior of the crystal and filter.

meet the design criterion, a ladder configuration was chosen. This type of network has been selected because it provides a narrow and stable bandwidth.

From the results obtained it is possible to say that the temperature stability of the filter is given mainly by the temperature stability of the crystals, and that the filter exhibits bigger temperature variations than the crystals. Therefore, in order to obtain a filter with a given temperature stability, it is necessary to select crystals with better stability than the filter.

RF

References

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About the author

M. I. Dieste received her BS degree in physics (electronic and computer science) and MSc from the University of Valladolid, Spain. She has worked for six years in the area of RF and communication systems, where she has been involved in the development of many RF systems such as high-Q oscillators, filters, etc. She is currently employed as Associated Professor in the University of Burgos where she teaches and does research in the field of electronics. She can be reached at +34 47 258915, e-mail: *midieste@ubu.es.*