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POLYLITHIC CRYSTAL FILTERS WITH LOSS POLES AT FINITE FREQUENCIES*

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ABSTRACT

This paper describes a design investigation of polylithic crystal filters with finite frequency loss poles, and in particular, loss poles in both the lower and upper stopbands obtained by bridging capacitors across the coupled resonators. Practical design considerations and experimental results are also reported.

INTRODUCTION

Polylithic crystal filters (filters consisting of more than one crystal wafer where at least one wafer contains acoustically coupled resonators) have been in successful production for almost 5 years. The physical properties of the quartz resonators make them suitable for operation between 1-100 MHz and they are especially suitable for use in narrow band filters. One of the largest applications of polylithic filters is in the communications industry where they are used in single-sideband frequency-division-multiplexing systems.[1-4] They are superior for this type of application because of their small size, excellent frequency stability characteristics and low manufacturing cost. They also require no power.

Most of the polylithic filters now in production are of the "all-pole" type or those with loss poles in the lower stopband only. Each of these loss poles is produced by a single crystal resonator in a shunt branch of a ladder structure. Occasions arise where more system attenuation is required in the upper stopband. One method of accomplishing this is to use a lowpass filter following baseband demodulation. Another method would be to increase the degree of the single-sideband filter by increasing the number of loss poles at infinite frequency. However, both of these methods are costly and the latter would also increase the dissipation and the delay distortion in the passband, which is undesirable for data transmission. These factors lead to the interest in the investigation of crystal filters with finite loss poles, especially loss poles in the upper stopband. There are several means of obtaining finite loss poles in a crystal filter[5-8] but the technique of bridging a capacitor across a coupled resonator is especially suitable for polylithic crystal filters. Very narrowband filters, such as pilot-pick-off filters, have been made using this technique. Most filters of this type have been designed by trial and error by perturbing an exact non-bridged design. This paper will describe some results on an exact synthesis of a complex channel filter using network transformations that were developed for this purpose.

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DESIGN METHOD

Fig. 1 shows the equivalent circuit of a coupled crystal resonator[2] with an external capacitor, C_b, bridged across the two non-grounded terminals. In this circuit, C_o represents the stray capacitances. L_a, L_d and C_a, C_d are the motional inductances and capacitances, respectively. The coupling capacitor, C_c, may be positive or negative depending on the connection of the resonator electrodes.

Fig. 2 shows an equivalent ladder circuit[9] of the bridged network in Fig. 1. The circuits are equivalent if, and only if, the following constraint on the elements of the network in Fig. 2 is satisfied:

$$L_1(C_3+C_4)+L_2(C_4+C_5)=0 \tag{1}$$

For ease of manufacturing, the value of L_a is required to be the same as that of L_d. This imposes a further constraint on the elements:

$$L_1C_3^2=L_2C_5^2 \tag{2}$$

It is clear from eqn. (1) that, for positive inductances, some of the series capacitors in Fig. 2 must be negative and thus one of the loss poles is necessarily in

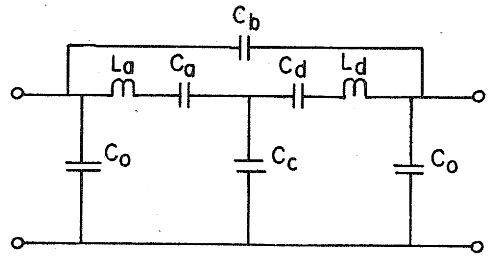


Fig. 1. Equivalent circuit of coupled resonator with bridging capacitor.

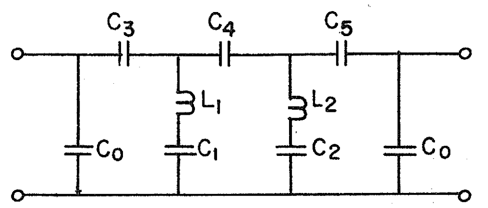


Fig. 2. Equivalent ladder circuit of Fig.1.

the upper stopband. If the above two constraints are satisfied, the element values of the circuit in Fig. 1 are given directly by

$$C_b=1/(1/C_3+1/C_4+1/C_5) \tag{3}$$

$$L_a=L_d=2/(1/L_1+1/L_2)$$

$$C_c=(1+L_1/L_2)^2/((L_1/L_2)^2(1/C_2+1/C_5)$$
$$+(L_1/L_2)(1/C_3+1/C_5-1/C_1-1/C_2)+1/C_1+1/C_3)$$

$$C_a=\tfrac{1}{2}(1+L_2/L_1)^2C_5/((L_2/L_1)(C_5/C_1-C_3/C_1)$$
$$-(1+L_2/L_1)(C_4/C_2+1))$$

$$C_d=\tfrac{1}{2}(1+L_1/L_2)^2C_3/((L_1/L_2)(C_3/C_2-C_5/C_2)$$
$$-(1+L_1/L_2)(C_4/C_1+1))$$

To obtain a polylithic bandpass filter with finite loss poles, a ladder network without any bridging is first designed. The loss poles are realized by shunt branches and the sections to be bridged should have the form shown in Fig. 2. Norton transformations (Fig. 3) are applied to this network to obtain a structure satisfying the above constraints. Eqn. (3) is then used to obtain the bridged sections. The detailed design procedure is illustrated in the following example.

DESIGN EXAMPLE

A 20th degree equal-ripple-passband polylithic filter was designed, with one pole of loss at zero frequency, five poles of loss at finite frequencies and nine poles of loss at infinite frequency. The preliminary design was done with a conventional ladder synthesis program.[10] The ladder structure is shown in Fig. 4.

Four loss poles, two in each stopband, are realized

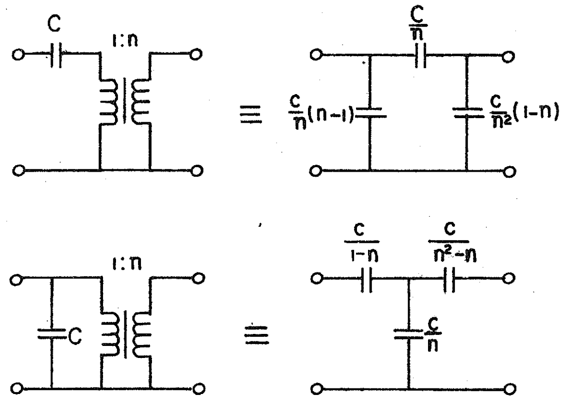


Fig. 3. Impedance transformations used in crystal filter design.

by two bridged sections. Each bridged section realizes two loss poles, one in the lower stopband and the other in the upper stopband. To obtain a physically symmetrical filter, the two finite poles in the upper stopband are at the same frequency. The same is true for the two lowest finite frequency loss poles in the lower stopband. The remaining loss pole, which is the one closest to the lower cutoff frequency, is to be realized by a single shunt resonator. The single resonator is put at the center of the filter with one bridged-coupled resonator on each side. Since the filter is symmetrical, it can be developed by concentrating the design on a half section taken about the center components.

Impedance transformations are made as shown in Fig. 5 to obtain elements in the ladder structure such as to satisfy the constraints in eqns. (1) and (2). Note that, as shown in the figure, the transformations are not unique. By suitably choosing the transformer turns ratios, a physically realizable filter is possible. Eqn. (3) is applied to obtain the bridged sections. Finally, impedance transformations are made on the end resonators (those without bridging capacitors) to equalize the inductances. The final configuation of the filter is shown in Fig. 6.

The calculated response of this filter is shown in Fig. 7. Note that there is substantially more attenuation in the lower stopband than in the upper stopband. The pole frequency locations have been optimized to give the best physical element values. The pole locations have a considerable effect on the impedance levels

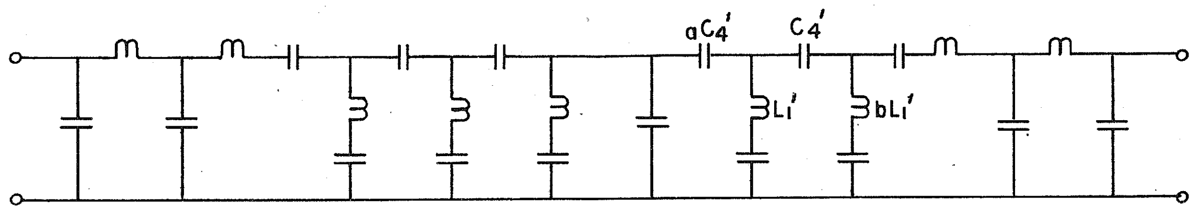
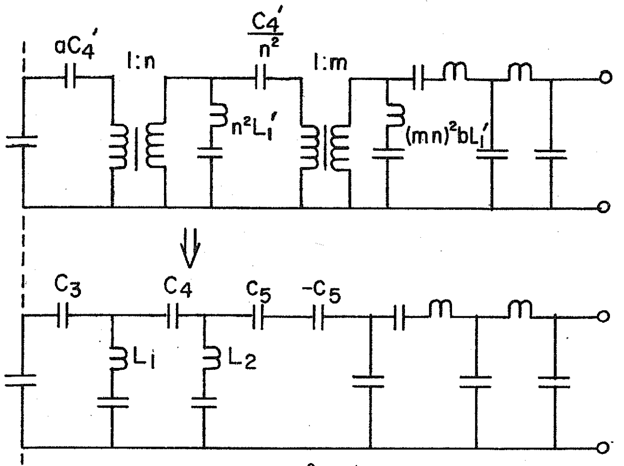


Fig. 4. Initial ladder circuit design used in example.



$$n = \frac{(a+1)^2 + b}{a((a+1) \pm \sqrt{b})}$$

$$m = \frac{1}{1+a(1-n)}$$

Fig. 5. Transformation for the bridged resonator section.

in the filter. There are constraints on the inductance values that depend on the physical size of the quartz blank and the frequency of operation. For the 8 MHz frequency range where this is used, the lower limit is approximately 5 mH and the upper limit is approximately 50 mH. The sections which are bridged by capacitors may also be selected to obtain the best element values. An acceptable design should have an inductance ratio of less than 2 : 1 in the coupled resonators. It is this that imposes the most critical constraint in the design of crystal filters.

EXPERIMENTAL RESULTS

The above example was built with one single resonator and four coupled resonators. NPO ceramic chip capacitors were used. The crystal resonators were tuned by evaporating more metal on the electrodes to to decrease the frequency to $\pm$ 10 Hz of the desired value. Tuning was done before mounting the capacitors. No tuning was needed on the bridging capacitors. The capacitor tolerance used was $\pm$ 2%. The filter response was relatively insensitive to the bridging capacitors and it was found that there was very little change in the passband and stopband responses when the capacitors were changed by 10% from their nominal values. This can be explained by looking at the sensitivity for a stopband loss pole with respect to its corresponding bridging capacitor. The sensitivity is given by

$$S_{Cb}^{\omega_0} = \pm 1/(2\,\omega_0^{\,2} L C_b C_c ((1/C_a - 1/C_d)^2 + 4(1/C_c - 1/C_b)/C_c)^{\frac{1}{2}}) \tag{4}$$

where the positive sign is used for the upper stopband pole and the negative sign is used for the lower stopband pole. Note also that C_c is negative and $L_a = L_d = L$. Eqn. (4) shows that the pole frequencies move closer to the passband as the the value of the bridging capacitor, C_b, is increased. The sensitivity in this example is in the order of 10^{-4}. From this it is not surprising that the bridging capacitors are the least sensitive elements in the filter.

The resistive terminations have to be adjusted slightly to compensate for the uncertainty in the impedance of the experimental model of the filter. The designed passband ripple is 0.13 dB. and the measured passband ripple on two samples is about 0.5 dB. Stopband attenuation is well above 70 dB and spurious responses are not observable. The measured response is shown in Fig. 8.

CONCLUSION

An equivalent network for a bridged-coupled resonator is described in this paper. This facilitates the synthesis of high-grade polylithic filters suitable for use in SSB FDM systems. It was found, both by experiment and by calculation, that the frequency response of a polylithic filter is very insensitive to the bridging capacitors. This, in conjunction with the well-known good temperature and aging characteristics of the AT-cut quartz crystal, allows the production of good quality crystal filters with finite loss poles. This can be done with little modification to the present technology used in polylithic crystal filter production.

Since polylithic filters are mass production items, every aspect of design and production must be given very careful consideration before going into the production stage. There are many areas in the field of crystal filters that are worthy of further investigation by either university or industrial researchers. Some of these will now be mentioned. Since very tight impedance ratios are required within a polylithic filter,

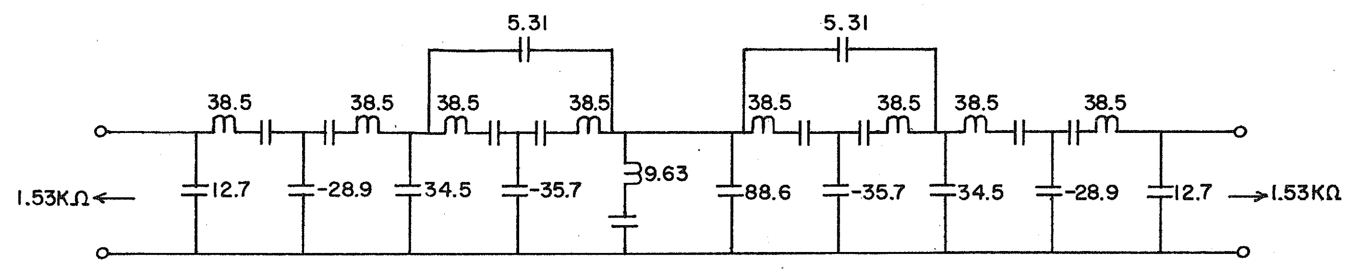


Fig. 6. Final design of example polylithic crystal filter (capacitance values in pF, inductance values in mH).

equal-ripple responses in the passband and stopbands are normally traded-off for better element values. It would be useful to find the approximation that gives the best set of element values. The Q of a crystal resonator is about 200,000 , which is much lower than the Q of the intrinsic crystal. This should be able to be improved. This in itself is a large topic worthy of much investigation. Another possibility is to predistort the filter to compensate for the finite Q characteristics. Another area of interest is the application of multiple bridgings (by bridging a capacitor across two or more resonators to produce multiple loss poles) to crystal filters. This technique has been applied successfully to mechanical filters and in a similar fashion to microwave filters.

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REFERENCES

1. D. F. Sheahan, "Single sideband filter for short-haul systems," Proc. Mexico, Int., 1971, pp.744-748.

2. D. F. Sheahan and C. E. Schmidt, "Coupled resonator quartz crystal filters," WESCON, Session 8, August 1971.

3. S.W. Anderes, "A polylithic filter channel bank," IEEE Trans. Comm., Vol. COM-20, Feb. 1972, pp. 48-52.

4. D. F. Sheahan, "Channel bank filtering at GTE Lenkurt," Proc. IEEE ISCAS,April 1974, pp.115-119.

5. H. Yoda, Y. Nakazawa and N. Kobori, "High frequncy crystal monolithic (HCM) filters," Proc. 23rd Annual Sym. Freq. Cont., 1969, pp.76-92.

6. A. A. Simpson, E. D. Finch, Jr. and R. K. Weeman, "Composite filter structures incorporating monolithic crystal filters and LC networks," Proc. 25th Annual Sym. Freq, Cont., 1971, pp.278-296.

7. Y. Masuda, I. Kawakami and Kobayashi, "Monolithic crystal filter with attenuation poles utilizing 2 dimensional arrangement of electrode," Proc. 27th Annual Sym. Freq. Cont., 1973. pp.227-232.

8. D. F. Sheahan and R. A. Johnson, "Crystal and mechanical filters," IEEE Trans. Circuits and Systems, vol. CAS-22, Feb. 1975, pp. 69-89.

9. M. S. Lee, "Equivalent network for bridged crystal filters," Electronics Letters, Vol. 10, No. 24, Nov.1974, pp. 507-508.

10. H. J. Orchard and G. C. Temes, "Filter design using transformed variables," IEEE Trans. Circuit Theory, Vol. CT-15, Dec. 1968, pp.385-408.

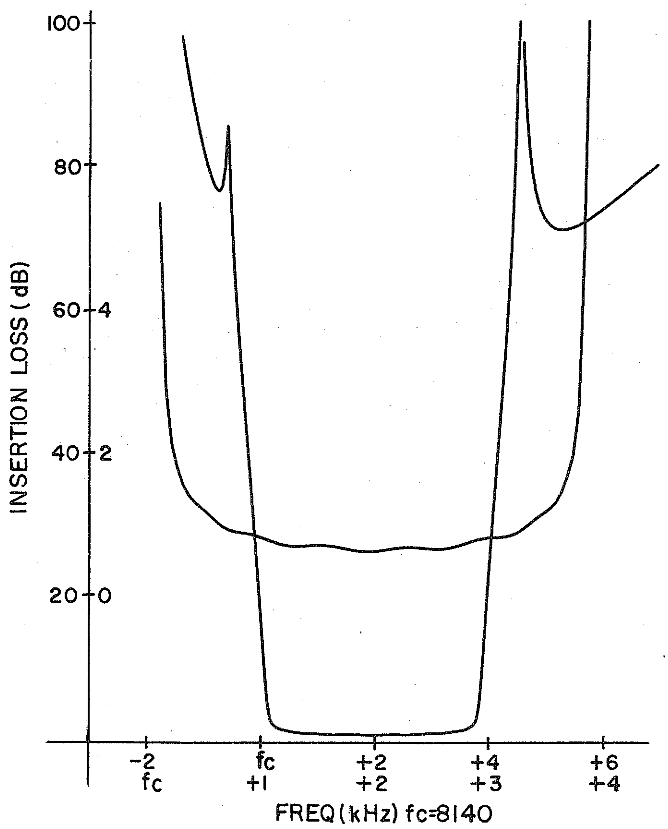

Fig. 7. Calculated response of example filter.

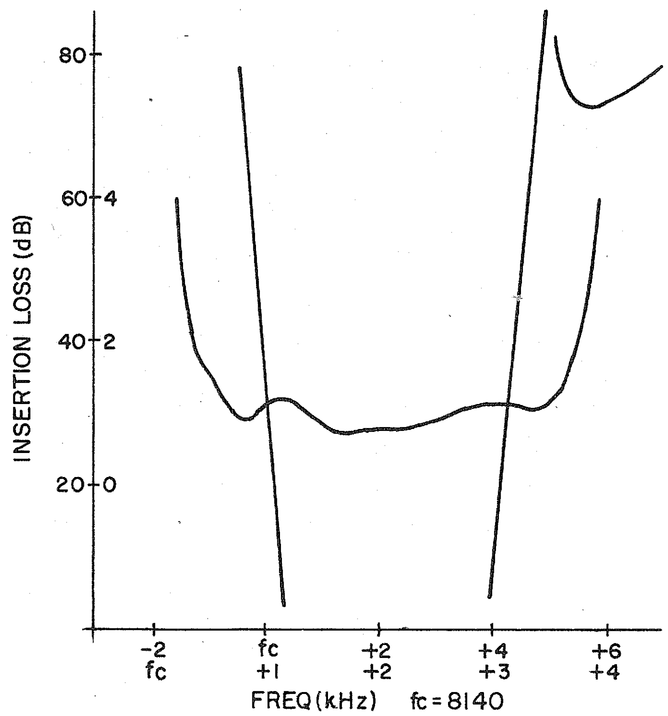

Fig. 8. Measured response of example filter.