Design of Highly-Selective Bandpass Filters with Non-Uniform Dissipation.

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Abstract

With the exception of predistortion most design methods for microwave filters are based on lossless prototype networks, with the effects of loss generally being considered afterwards, by analysis rather than synthesis. This paper presents new techniques, which either utilize existing losses, or add losses, to improve the performance of microwave bandpass filters. Experimental prototype filters have been designed and the measured results demonstrate improved performance compared with that previously reported.

Keywords: Filter, predistortion, dissipative elements.

Introduction

Filters play an important role in many microwave systems, where they serve to suppress unwanted signals. As the characteristics of a single filter can have a significant impact on the overall system performance, it is desirable to achieve the most ideal response possible. One of the major performance limitations is the unloaded quality factor (Q) of the resonators. High performance filters generally require high-Q resonators, which are often physically large and may necessitate the use of an expensive technology such as dielectric resonators.

Design methods are needed to help design filters which meet the increasingly stringent demands of modern communication systems. In order to realize optimum performance, resonator losses cannot be ignored. Unfortunately, most conventional design techniques do not take losses into account. One exception is the classical method of predistortion [1]. With this technique, the poles of the transfer function are shifted to the right of the complex plane. A lossless filter is then synthesized. The addition of uniform dissipation loss results in S12 of the network having an ideal response, other than for increased absolute insertion loss. This technique is useful for applications where the increased passband insertion loss can tolerated, such as in a satellite IMUX [2] or alternative receiver architectures [3], [4]. The disadvantage of predistortion is that the selectivity increase is realized by reflecting power in the passband, which results in decreased in-band return loss. As a result predistorted filters usually require the use of an isolator in practice. It should be noted that since the dissipation loss of a network with uniform dissipation (i.e. constant resonator Q) is proportional to its group delay, then the only way to compensate for losses in such a network is to differentially reflect energy at certain frequencies.

In this paper new methods of designing filters with non-uniform dissipation will be discussed. These methods produce more selective filter transfer functions than either conventional designs or uniform-Q predistorted filters. In contrast to predistortion, power is largely absorbed to increase selectivity rather then reflected. In section II the theory of the design techniques will be outlined. In section III the design of a prototype filter, realized in microstrip, is presented as a demonstration of the new design techniques. Experimental results for the filter are given, showing significant improvements compared to other approaches.,

Theory

This technique is based on work described in [5], which demonstrated that by adding a complementary pole-zero pair to a lossy transfer function where K<1:

$$S_{12} = K\left(S_{12(Lossless)}\right)\left(\frac{p-\alpha}{p+\alpha}\right) \qquad (1)$$

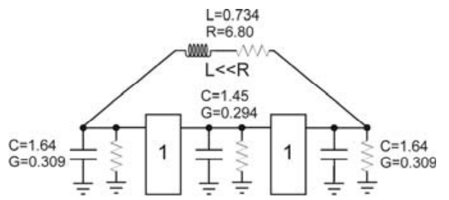
(1

The amplitude response remains unchanged, but allows loss to be distributed when synthesized using the technique demonstrated in section IIA. The return loss is also improved. The added pole/zero pair creates a new transmission path in the form of a low-*Q* cross-coupled resonator. This method becomes mathematically very complex for higher-order filters, and a simplified method utilizing computer optimization is given in [3]. In the simplified method, a transmission zero on the real axis is added to the transfer function:

$$S_{12} = K\left(S_{12(Lossless)}\right)\left(p-\alpha\right) \qquad (2)$$

(18)

This real-



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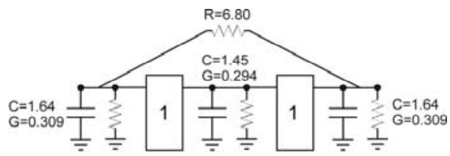

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Fig. 3. (a) Lossy 3rd-order Butterworth with resonant resistive cross-coupling (b) Non-resonant approximation of the resistive cross coupling.

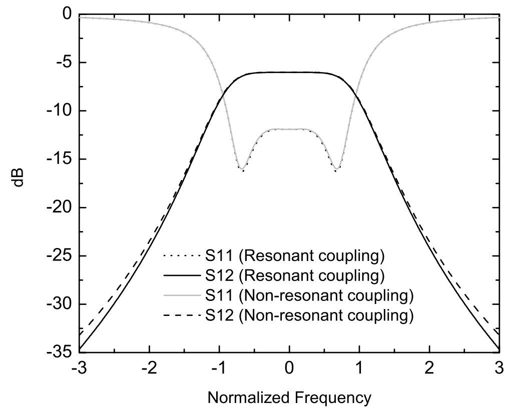


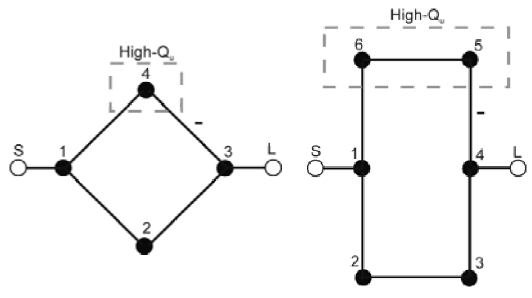
Fig. 4. Responses of lossy third-order Butterworth filters with resonant and non-resonant resistive cross couplings.

axis transmission zero effectively flattens out the passband, and is realized by simply placing a resistor across any three consecutive resonators. This gives a response almost identical to that of (1), the difference being a slightly reduced selectivity. A lossless filter is first synthesized, then the resonator loss and coupling resistors are added. Component values are then optimized.

The network shown in Fig. 3a is the result of the synthesis of (1), with

$$S_{12(Lossless)} = \frac{1}{\left(p^3+2p^2+2p+1\right)} \qquad (3)$$

(a third-order Butterworth transfer characteristic), K=0.5, and $\alpha = 9$. Loss has successfully been introduced into the central resonator. The *Q* of the outer resonators is 5.3 and the *Q* of the central resonator is 4.9. The *Q* of the cross-coupling resonator is 0.11. Shown in Fig.3b is the same network with the non-resonant approximation of (2). Shown in Fig. 4 is a comparison of the responses of the two networks. The network with a resonant cross coupling gives an ideal Butterworth response shifted down 6 dB, with 12-dB return loss. The response of the network with the non-resonant cross



(a) (b)

Fig. 5. Filter topologies consisting of a high-Q path and a low-Q path. (a) 4th-order giving one asymmetric transmission zero. (b) 6th-order giving two symmetric transmission zeroes.

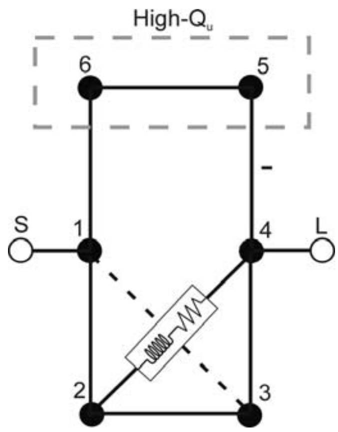


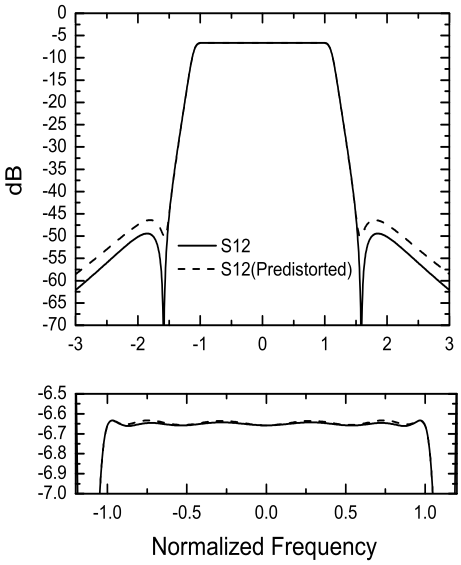
Fig. 6. 6th-order filter with multi-path loss distribution and resistive cross-coupling (hybrid).

coupling is virtually identical, save for a slightly lower selectivity.

In this section filter topologies are identified which, when loss is distributed appropriately, the dependence of ΔIL on group delay is effectively reduced. This allows for an increase in selectivity. These topologies consist of two signal paths: one path forming the response at the band edges (where the group delay peaks), and the other forming the response at the center of the passband, similar in concept to active channelized filters[6]. If the former is made of high-*Q* resonators and the latter of low-*Q* resonators, increased selectivity can be achieved at the expense of increased insertion loss for a given average *Q*. Two such topologies are shown in Fig. 8.

Shown in Fig. 5 is an asynchronously tuned 4th-order cross-coupled filter and a synchronously tuned 6th-order cross-coupled filter. Both have a "high-*Q*" path and a "low-*Q*" path. The asymmetric topology produces one zero either below or above the passband, depending on how resonator 4 is tuned. The use of this topology to produce a single real-frequency transmission zero was first suggested in [7], and can be designed using the matrix rotation techniques described therein. In this configuration the *Q* of resonator 4 has a great effect on band edge adjacent to the transmission zero. In the 6th-degree symmetric topology, the two symmetric transmission zeroes are controlled by the split resonant modes of the coupled resonators 5 and 6. This topology can be realized using matrix rotations. As in the asymmetric case, increasing the *Q* of resonators 5 and 6 sharpens the band edges. This is illustrated in Fig. 5a. Shown in Fig. 5b are the individual responses of the two transmission paths. The path containing resonators 1-4 forms a lossy Chebychev response. The path containing resonators 1,4,5,6 provides a peak at each band edge. Since resonators 1 and 4 possess effectively infinite *Q* (the losses contributing mainly to absolute insertion loss) increasing the *Q* of resonators 5 and 6 relative to the other three resonators is an effective way of sharpening the band edges. The order of both topologies can be increased by adding an even number of resonators to the low-*Q* path. The 6th-order topology is the most interesting as it can be readily used in conjunction with the resistive cross-coupling technique described in the next section.

An effort was made to design a filter using resistive coupling and multi-path loss



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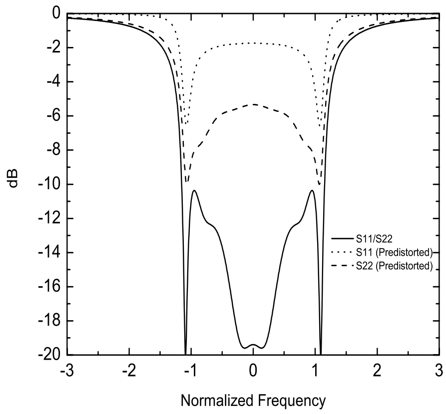


(b)

Fig. 7. Simulated responses of a symmetric hybrid filter vs. a predistorted filter. (a) S_{12}. (b) S_{11}.

distribution techniques which gives equivalent selectivity to a predistorted filter. For convenience, an example taken from recent literature [2], a 6th-degree predistorted filter with 6.7-dB insertion loss and transmission zeroes at +/-j1.5522. The predistorted response is shown in Fig. 7, along the response of a symmetric hybrid filter of the form shown in Fig. 6. The transfer responses are essentially identical, with the symmetric hybrid filter giving ideal transmission zeroes and a slightly deeper stopband. The hybrid filter also gives improved return loss. The group delay performance is equivalent.

The return loss at both ports of the symmetric hybrid filter is 10.36 dB, while the predistorted filter gives a return loss of 1.73 dB at the input and 5.33 dB at the output. The average *Q* of the hybrid filter is 26% lower then the predistorted filter. To achieve a stopband performance comparable to predistortion, two resonant resistive cross couplings are used.

The prototype *Q* of the resonant resistive cross couplings in the symmetric hybrid filter is 0.56. If this filter was to be realized using resonators possessing a *Q* of 2000 (coaxial for example) forming the low-*Q* path, the resonant resistive cross couplings would possess a *Q* of 176, easily realized with microstrip resonators. Decreasing resistive cross-coupling *Q* results in decreased out of band attenuation. The effect on the response out to the transmission zeroes is negligible.

Microstrip Prototype

A microstrip prototype was designed with performance similar to the symmetric hybrid filter just described, but with allowances in performance given due to the low-*Q* of microstrip resonators, i.e. choosing a realizable bandwidth and a practical amount of passband loss. Also, only one resonant resistive cross coupling is realized due to layout limitations. Shown in Fig. 8 is the fabricated circuit. The substrate is *Rogers RT Duroid* 6010 with a thickness of 1.27 mm and dielectric constant of 10.2. The high-*Q* resonators are 2.94 mm wide. The low-*Q* resonators are 1.16 mm wide, with 0Ω chip resistors (the required value of 0.3Ω was found difficult to accurately implement; pieces of microwave absorber were used to tune the *Q* values) placed at the center. A 0.35 mm wide line with a 35Ω chip resistor provides

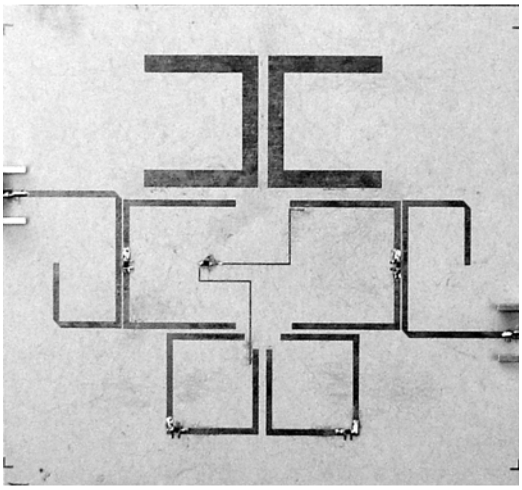
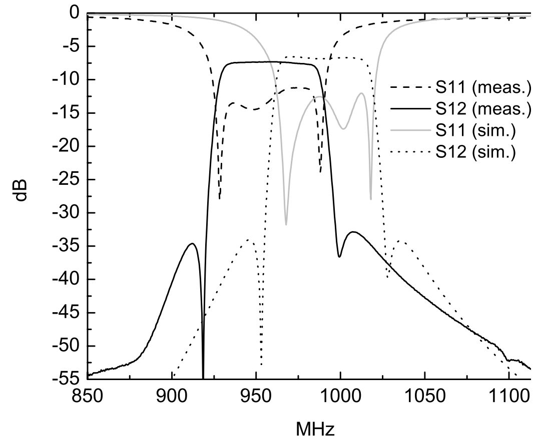


Fig. 8. 6th-degree hybrid filter microstrip prototype.

the resistive cross-coupling.

The measured results along the simulated results from *ADS Momentum* are shown in Fig. 9a. The measured responses of the high- and low-*Q* paths are shown in Fig. 9b. The filter did require tuning to accommodate tolerances in the fabrication process, which was accomplished with copper tape and microwave absorber. The center frequency is 958.4 MHz, with a 3-dB bandwidth of 60 MHz, giving a fractional bandwidth of 6.2%. The passband insertion loss is 7 dB and the return-loss ripple level is 11 dB. In both the *ADS Momentum* simulation and during tuning it was found that the recovery of both transmission zeroes could not be achieved simultaneously. This was not the case with the initial transmission-line schematic model, which leads us to the conclusion that this is due to the effects of unwanted cross couplings. The difference in center frequency between the simulated and measured responses is due to manufacturing tolerances and effects of tuning elements. The high- and low-*Q* resonators possess a *Q* of approximately 250 and 80, respectively, giving an average *Q* of 137. The shape of the measured response is equivalent to that



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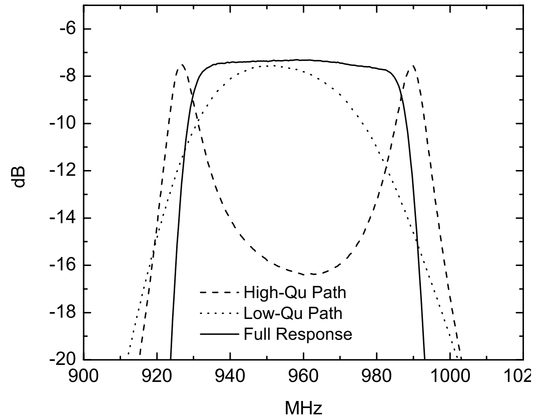

(b)

Fig. 9. 6th-degree hybrid filter microstrip prototype results. (a) Measured vs. simulated results. (b) Measured low- and high-*Q* path responses.

of a conventional filter with a uniform *Q* of 750.

Conclusion

Excellent results on the design of bandpass filters with non-uniform *Q* resonators are obtained using techniques based on resistive cross coupling, matrix rotations, and multi-path loss distribution, together with a degree of computer optimization. These filters give superior performance over a predistorted filter in terms of return loss and average *Q*. These techniques have been experimentally verified with a microstrip prototype. These types of filters are readily applicable to the design of high-performance coaxial, waveguide, and dielectric resonator filters. This is the first time that bandpass filters with non-uniform *Q* resonators have been reported. There is further scope to extend this work to exact synthesis techniques.

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