NARROW-BAND HAIRPIN-COMB FILTERS FOR HTS AND OTHER APPLICATIONS*

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ABSTRACT

The folded half-wavelength resonators in hairpin-comb filters all have the same orientation whereas the orientations of the resonators in conventional hairpin filters alternates. Hairpin-comb filters have attractive properties for design of compact, narrow-band filters such as are often desired for high-temperature-superconductivity and other applications.

INTRODUCTORY CONCEPTS

In many applications keeping filter structures to a minimum size is very important. This is particularly true of high-temperature superconductor (HTS) filters where the available size of usable substrates is quite limited. In the case of narrow-band microstrip filters (say, with bandwidths of the order of 1 percent or less) this problem can become quite severe because the substantial difference between the even- and odd-mode wave velocities when the substrate dielectric constant is large can create relatively large forward coupling between the resonators. This presents a need for large spacings between the resonators in order to obtain the required narrow bandwidth [1]. This may make the overall structure unattractively large, or perhaps impractical, for some situations. Hairpin-comb filters provide a possible way around this problem. Of course the use of hairpin resonators also reduces the size of a filter since the folded half-wavelength resonators are somewhat less than a quarter wavelength long.

Figure 1 shows a two-resonator comb-line filter. For the present we will assume it to be realized in stripline so the even- and odd-mode velocities on the coupled lines will be equal, thus preventing forward coupling. The two resonators are grounded at the crosshatched sidewall, and in this example the input and output couplings are provided by tapped-line connections. It turns out that this structure would have no passband at all if it were not for the "loading" capacitors Cr. From the equivalent circuit for a combline filter [2] it can be seen why this happens. Since the resonators are shorted at one end, with Cr = 0 they are resonant when they are a quarter-wavelength long. As seen from their open-circuited ends, they look like shunt-connected, parallel-type resonators which would yield a passband at this frequency. However, there is also an odd-mode resonance in the region between the lines which acts like a bandstop resonator connected in series between the two shunt resonators. This creates a pole of attenuation at the same frequency that a passband would otherwise occur. Thus, the potential passband is totally blocked. However, if loading capacitors Cr are added at the ends of the resonators, the resonator lines must be shortened in order to maintain the same passband frequency. This shortens the length of the slot between the lines and causes the pole of attenuation to move up in frequency away from the passband. In general, the more capacitive loading that is used, the further the pole of attenuation would be above the passband and the wider the passband of the filter can be. If only small loading capacitors Cr are used a very narrow passband can be achieved even though the resonators are physically quite close together. Similar operation also occurs if more resonators are present. If the structure in Fig. 1 is realized in microstrip the performance is considerably altered because of the different even- and odd-mode velocities, though some of the same properties exist in modified form.

Figure 2 shows a "hairpin-comb" filter of the type treated by this paper. This filter is somewhat analogous to the comb-line filter in Fig. 1. (In this case series-capacitance input and output couplings are shown, though tapped-line couplings as in Fig. 1 could be used in this filter also.) The resonator lines are roughly a half-wavelength long but are folded back on themselves so the height of the resonators is a little less than a quarter wavelength. Note that, unlike the combline filter in Fig. 1, the structure in Fig. 2 has no ground connections. However, since the opposite sides of a hairpin resonator have opposite potentials, there is a virtual ground running down through the center line of symmetry of the resonator. Thus, we might expect the filter in Fig. 2 to have properties similar to those of a combline filter. It turns out that the hairpin-comb filter does have similarities to a combline filter, but the hairpin-comb behavior is more complex. In a stripline hairpin-comb structure with C12 = 0 and with equal even- and odd-mode velocities a pole of attenuation is created at the frequency for which the parallel-coupled region d in Fig. 2 is a quarter-wavelength long (assuming couplings beyond nearest-neighbor lines are

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negligible). The optional capacitor C12 in Fig. 2 can be included to add further control over the location of the adjacent pole of attenuation (or of multiple poles in structures with more resonators) and also to help adjust the bandwidth of the filter. The filter structure in Fig. 2 can likewise be made to be extremely narrowband even though the resonators may be very close together. As for microstrip combline filters, microstrip hairpin-comb filters are more complicated to analyze and design than are analogous filters in homogeneous stripline but have many similar properties. One difference between the microstrip and stripline cases in the examples that we have tried is that the pole of attenuation near the passband occurs below the passband in the microstrip case rather than above the passband.

HAIRPIN-COMB VS HAIRPIN FILTERS

Figure 3(a) shows a well known form of hairpin-resonator bandpass filter [3]. It can be thought of as an alternative version of the parallel-coupled-resonator filter first introduced by Cohn [4], except that here the resonators are folded back on themselves. Note that the orientations of the hairpin-resonators alternate. This results in quite strong coupling and this structure is capable of considerable bandwidth. However, in the case of narrow-band filters, particularly for microstrip filters on a high-dielectric substrate, this structure is undesirable as it may require quite large spacings between the resonators in order to achieve the desired narrow bandwidth.

The hairpin-comb type of filter as in Fig. 2 differs from the hairpin filter in Fig. 3(a) primarily in that the orientation of the resonators in a hairpin-comb filter is always the same. This difference is of major importance. Resonances that occur in the coupling regions between resonators greatly reduce the coupling between resonators, and with the addition of a small capacitance C12 between resonators as is shown in Fig. 2, it is possible to eliminate the passband entirely even though the resonators are quite closely spaced.

Figure 3(b) shows another common form of hairpin-resonator filter[5] which might at first be thought to be fundamentally the same as the hairpin-comb filter in Fig. 2, whereas, actually, it is quite different. In this case the open-circuited ends of the resonator have been considerably foreshortened and a strongly capacitive gap is added to bring the remaining structure to resonance. The resonators are then semi-lumped, the lower part being inductive and the upper part being capacitive. The coupling between resonators is almost entirely inductive, and it makes little difference whether adjacent resonators are inverted with respect to each other or not. Hence, they are usually made to have the same orientation. This structure will also require quite large resonator spacings for small bandwidths.

From the above examples it can be seen that the hairpin-comb type of filter differs from the hairpin filter structures in Figs. 3(a) and 3(b) in that the hairpin resonators all have the same orientation while the coupling regions between resonators are sufficiently long so as to have resonance effects which can greatly reduce the coupling between resonators at frequencies in the range of the desired passband. It will also be noted that the hairpin-comb structure in Fig. 2 uses rounded sections at the bottoms of the resonators, rather than rectangular sections as in Figs. 3(a),(b). This is not fundamental to this type of filter but we have used these round sections to prevent regions with unnecessarily high current density which can cause nonlinear effects in a superconductor.

SOME DESIGN EXAMPLES

Herein we will focus on examples of narrowband microstrip hairpin-comb filters. In such cases the couplings beyond nearest neighbor resonators is much more important than it would be in relatively wideband hairpin filter structures as in Figs. 3(a),(b). This is because for a hairpin-comb filter the direct coupling between adjacent resonators is relatively small so that the stray couplings beyond nearest neighbor line sections becomes much more important. In order to obtain accurate designs it is important to include couplings beyond nearest neighbors. This makes the use of the more common design procedures based on network synthesis techniques impractical. As a result, we used what might be called "educated cut and try" to obtain the desired responses. We used an in-house CAD program which handles multiple lines using the "method of lines" (MoL) [6] and which will also treats single or multiple curved line sections using the methods in Ref. [7]. This program obtains the quasi-static capacitance and inductance matrices for multiple lines and uses these data for computing frequency responses. Structures like the semi-lumped capacitors were designed with the aid of the planar full-wave analysis program EM [8].

A two resonator microstrip filter as in Fig. 2 was designed using a $LaAlO_3$ substrate h = 0.267 mm thick having $\varepsilon_r = 24.1$. The dimensions in the figure were d = 8.504, sa = 1.0, w = 0.30, and sb = 0.20, all in mm. The coupling capacitance Cc was about Cc = 0.216 pf, though a pi equivalent circuit for the coupling capacitor was actually used. Accurate analysis of the coupling capacitor C12 as designed turned out to be a problem. This is because the two ports for the capacitor were adjacent and so close together as to interact, and the capacitor finger structure was not symmetrical as viewed from these ports. (If the finger structure had been symmetrical as seen from the ports an accurate analysis could have been obtained using even- and odd-mode excitation.) A final value for C12 (0.076 pf) for use in computing the theoretical response was obtained by varying the value of C12 used in the program until the computed frequency of the pole of attenuation below the passband closely agreed with the measured frequency for that pole (1.865 GHz). Then the computed passband width at points 1-dB down from the minimum attenuation was $\Delta f = 14.8$ MHz and the passband center frequency was computed to be $f_o = 1.97$ GHz. This compares with measured values of $\Delta f = 14.2$ MHz and $f_o = 1.955$ GHz. This is an approximately 0.73 percent bandwidth. Figure 4 shows the measured passband response of this filter. The measured minimum loss in the passband was approximately 0.33 dB including the loss of the normal metal connectors. .

A four-resonator trial microstrip hairpin-comb filter as shown in Fig. 5 was also designed, fabricated, and tested. Using dimension definitions as in Fig. 2, in this case d = 8.626, sa = 1.5, w = 0.5, and the spacing between the resonators at the center of the filter was 1.45, all in mm. The substrate was 0.283-mm-thick $LaAlO_3$. Some minor modifications of the upper ends of the end resonators was needed to obtain synchronous tuning. Also, slight tuning of the two inner resonators was accomplished by insertion of dielectric material near the resonators. Figure 6(a) shows the measured and computed transmission response of the filter while Fig. 6(b) shows the measured and computed return loss. The passband width at points 1-dB-down from the minimum loss point was 17.2 MHz, and the measured passband was centered at 1.8360 GHz. The percentage bandwidth is 0.94. The minimum passband loss was approximately 0.41 dB including the loss of the normal metal connectors.

CONCLUSIONS

The hairpin-comb type of filter holds promise for the fabrication of compact narrowband filters. This can be useful for planar filters designed using normal metal conductors but may be particularly helpful for HTS filters. It can be shown that this general type of structure is potentially useful for either stripline or microstrip realizations, though the designs will come out rather different for given design specifications.

REFERENCES

[1] G. L. Matthaei and G. L. Hey-Shipton, "Concerning the Use of High-Temperature Superconductivity in Planar Microwave Filters," *IEEE Trans. on MTT*, vol. 42, pp. 1287-1293, July 1994.

[2] G. L. Matthaei, L. Young, and E. M. T. Jones, *Microwave Filters, Impedance-Matching Networks, and Coupling Structures*, Artech House Books, Dedham, MA, 1980, pp. 497-506 and 516-518.

[3] E. G. Cristal and S. Frankel, "Hairpin-Line and Hybrid Hairpin-Line/Half-Wave Parallel-Coupled-Line Filters," *IEEE Trans. MTT*, vol. MTT-20, pp. 719-728, November 1972.

[4] S. B. Cohn, "Parallel-Coupled Transmission-Line-Resonator Filters," *IRE Trans. PGMTT*, vol. MTT-6, pp. 223-231, April 1958, or see pp. 472-477 of Ref. [2] above.

[5] M. Sagawa, K. Takahashi, and M. Makimoto, "Miniaturized Hairpin Resonator Filters and Their Application to Receiver Front-End MIC's," *IEEE Trans. MTT*, vol. 37, pp. 1991-1997, December 1989.

[6] R. Pregla and W. Pascher, "The Method of Lines," in *Numerical Techniques for Microwave and Millimeter-Wave Passive Structures*, T. Itoh, Editor, Wiley, New York, 1989.

[7] H. Diestel, "A Quasi-TEM Analysis for Curved and Straight Planar Multiconductor Systems," *IEEE Trans. MTT*, vol. 37, pp. 748-753, April 1989.

[8] EM is a full-wave field solver for planar circuits and is produced by Sonnet Software, Suite 100, 101 Old Cove Road, Liverpool, NY 13090.

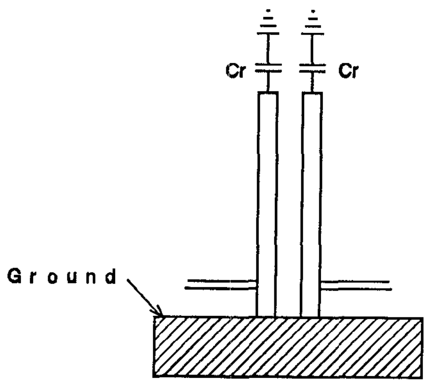

Fig. 1. A stripline two-resonator comb-line filter with tapped-line couplings at the input and output.

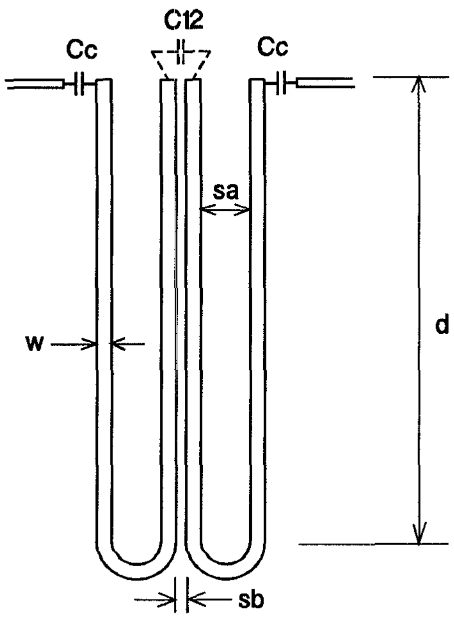

Fig. 2. A two-resonator hairpin-comb filter with capacitance couplings at the input and output.

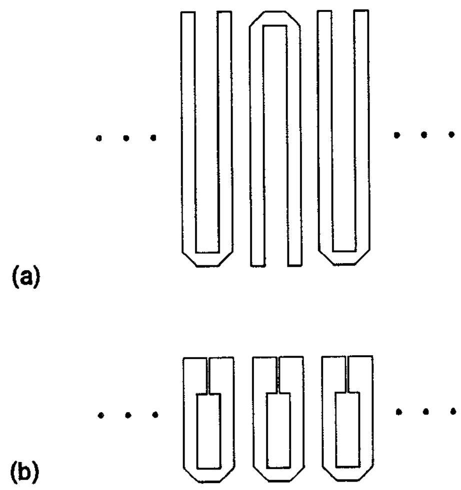

Fig. 3. At (a) is shown a common form of hairpin-resonator filter structure. Note the alternating orientations of the resonators. At (b) is shown another common form of hairpin-resonator filter which uses resonators which have reduced height by virtue of capacitance loading. In this case the orientations of the resonators make no difference.

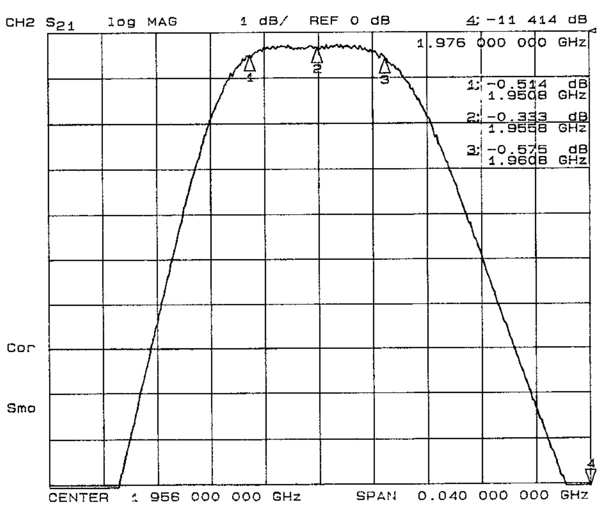

Fig. 4. A measured response for a trial, microstrip two-resonator hairpin-comb filter of the form in Fig. 2.

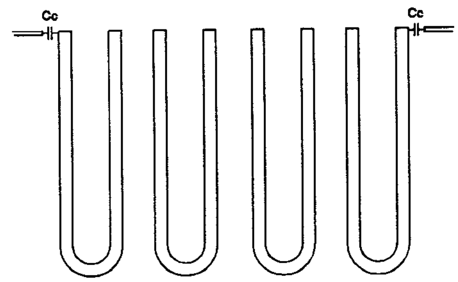

Fig. 5. A four-resonator hairpin-comb filter with capacitance couplings at its ends.

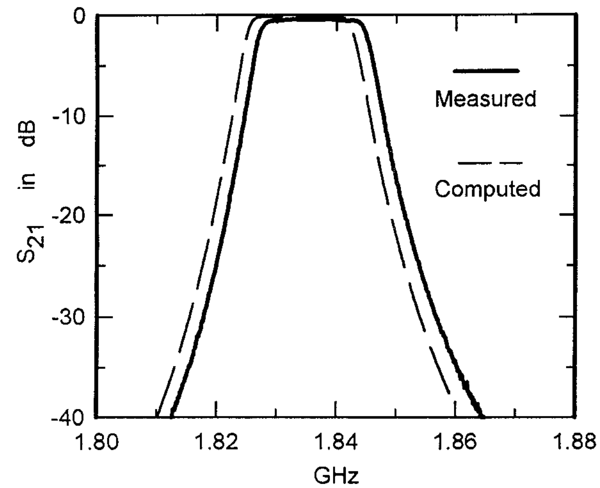

Fig. 6(a) Computed and measured transmission responses for a trial, microstrip four-resonator filter of the form in Fig. 5.

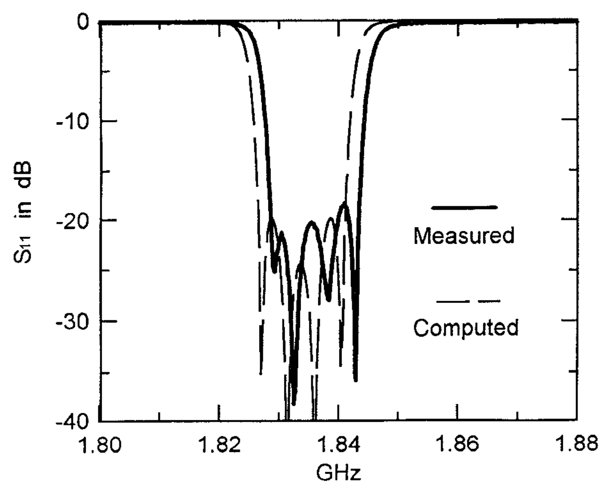

Fig. 6(b) Computed and measured return loss for the trial four-resonator filter.