Implementing Transmission Zeros in Inductive-Window Bandpass Filters

Marco Guglielmi, Fabrizio Montauti, Luca Pellegrini, and Paolo Arcioni

Abstract—**Transmission zeros are usually implemented in microwave filters as extracted poles, or with cross couplings between nonadjacent cavities. Recent work, however, indicates that, for inductive band-pass filters, higher order-mode excitation can be usefully exploited for the purpose of creating transmission zeros. In this paper we describe a new cavity configuration that can be used to introduce transmission zeros in the electrical performance of microwave filters based on thick inductive windows in rectangular waveguides using the higher order-mode interactions. One transmission zero per filter cavity can be introduced and its frequency location can be easily controlled adjusting suitable geometrical parameters. The basic principle is discussed in detail and a computer aided design procedure is also presented. Finally, several application examples are included indicating how the new cavity design can indeed be used to improve the performance of this class of filters.**

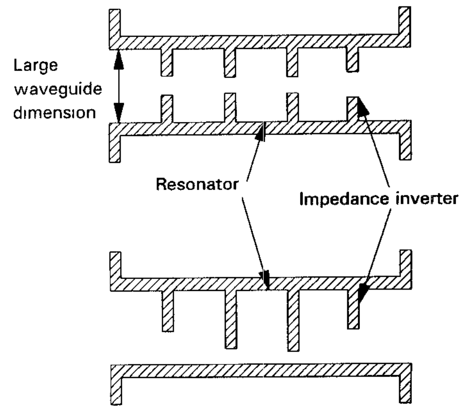

Fig. 1. Typical geometry of a microwave filter based on thick inductive windows. Centered implementation in (a) and offset implementation in (b).

I. INTRODUCTION

MICROWAVE bandpass filters composed of thick inductive windows in rectangular waveguide, like the one shown in Fig. 1(a), have been the subject of a very large number of publications and are still used extensively in microwave systems both for space and ground applications. The basic behavior of the structure is very well understood. Centered, thick, inductive windows are used as impedance inverters, and lengths of uniform waveguides are used as half-wavelength resonators. Recently, a very similar filter structure has been proposed [Fig. 1(b)], where the impedance inverters are implemented with offset windows [2]. More recently, another technical contribution appeared describing a detailed sensitivity analysis for the centered implementations [3]. The classical design procedure for this type of filter is well known and is described, for instance, in [1] allowing for the synthesis of bandpass filters of the Chebycheff type.

In most of the contributions that can be found in the technical literature, however, the basic filter function is obtained using essentially only the fundamental mode of the rectangular waveguide. Although in [2] and [3], the effects of higher order modes excited by the irises are included, their presence is actually not exploited in the filter design itself.

The state of the art for this type of filters has been further extended by a recent contribution where the excitation of higher order modes is used to introduce a transmission zero in the insertion loss characteristic of the filter [4]. The structure proposed, uses in-line cavities with asymmetric inductive windows as coupling elements, so that even and odd higher order-modes are excited, and their interference produces transmission zeros. The authors of [4] clearly identify the physical effect that is responsible for the presence of the zero but do not indicate how to control its position in terms of the filter geometry nor discuss the inherent limitations of the structure.

In this paper, we demonstrate how, with the in-line structure, the position of the zero can be controlled independently from the bandpass behavior only within a limited range. We then propose a new "corner" cavity configuration that can overcome some of the limitations identified. A simple computer aided design procedure is then discussed to use the new cavity configurations, and finally, as an example of application, several filter designs are discussed showing how the new corner cavity can indeed be used to improve the performance of this class of filters.

II. TRANSMISSION ZEROS

The implementation of transmission zeros in the insertion loss response of a microwave filter can be obtained using the well known "extracted pole" technique [5] or by introducing couplings between nonadjacent resonators (cross couplings) (see [6] for instance). Using the extracted pole technique, two cavities can be designed to produce at the same time two transmission poles (return loss minima) and one transmission zero. Using cross couplings, what is actually done from a physical point of view in order to generate a transmission zero, is to provide two paths to the signal with the proper phasing so that cancellation can occur at a given frequency (one path

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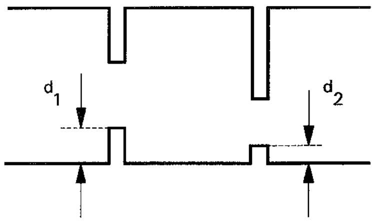
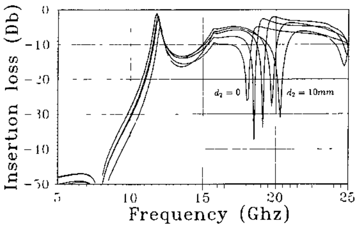
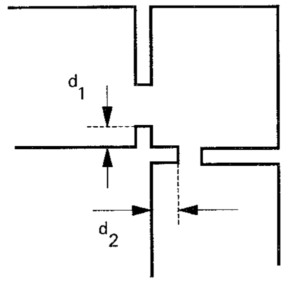


(a)

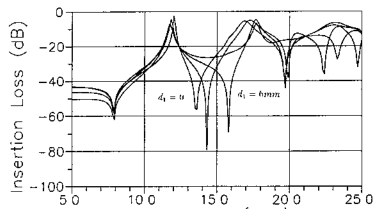


(b)

Fig. 2. Single cavity with offset coupling windows in 2(a). One aperture offset is kept equal to zero (d_1) while the other isvaried (d_2) to control the position of the transmission zero in 2(b). The first resonance at 12 GHz is the fundamental resonance of the cavity (bandpass). The curve showing the zero in the left-most position in 2(b) corresponds to $d_2 = 0$, while the right-most curve corresponds to $d_2 = 10$ mm (2 mm steps).



(a)



(b)

Fig. 3. Example of corner cavity configuration in (a) and electrical performance in b) (the offset d_1 is used as a parameter). The left-most transmission zero location corresponds to $d_1 = 0$ mm, while the curve without zero corresponds to $d_1 = 6$ mm (steps of 2 mm).

is the main signal path while the other is the *cross coupling*, the stronger the cross coupling the closer the zeros to the filter bandpass). This is routinely done in circular waveguide using dual-mode resonators and does not require the use of additional cavities. The only limitation is that to have one transmission zero at a finite frequency a minimum number of three electrical resonances is required (usually called triplet or trisection), while to implement a pair of zeros symmetrically about the passband a minimum of four electrical resonances is required (quadruplet).

With respect to rectangular waveguides, it appears that the most common implementation reported so far in the technical literature is for filters with extracted poles. However, an alternative possibility which has been reported recently is the use higher order modes for the implementation of the two signal paths required for the generation of a zero. It has in fact been shown in [4] that, using offset inductive windows as impedance inverters, an additional signal path could be introduced via the interaction between the even and odd modes thus generating a transmission zero above the passband of the filter. For practical implementations, however, it is necessary to identify which physical parameter of the structure can be used to control the position of the transmission zero.

In this context, it was shown in a previous publication that the extent of the coupling between even and odd higher order modes could be easily changed by adjusting the offset of the inductive window [7]. This effect can in fact be used to change the position of the transmission zero, as shown in Fig. 2, where the offset of one of the apertures (d_2) is used as a parameters. The first peak at about 12 GHz in the insertion loss curve in Fig. 2 is the main resonance of the cavity while the transmission zero (18 to 20 GHz) is produced by the offset.

Using the in-line configuration, however, the zero can only be located relatively far-away from the band-edge of the filter, as it is clearly shown in Fig. 1, where the closest transmission zero achieved is located at 18 GHz, corresponding to $d_2 = 0$ mm in Fig. 2(a). The situation can be partially improved using the *corner cavity* described in the next section.

The results shown in Fig. 2, as well as all the other simulation results shown later, have been obtained with the full-wave CAD tool FEST [8], including all higher order-mode effects. FEST is based on Multimode Equivalent Network representation (MEN) of the structure being studied. The detailed description of such a MEN, however, is beyond the scope of the present paper.

III. Corner Cavity Implementation

Using the in-line implementation, the strength of the *additional* coupling that can be introduced between input and output is limited because the apertures are located at opposite sides of each cavity. The higher order modes excited by the offset are below cutoff and can only interact weekly. As a result, the transmission zero that is obtained can not be placed very close to the resonance frequency of the cavity. To place the zero closer, a stronger coupling is required. A stronger coupling between the higher order modes excited can be obtained if the input and output apertures are placed on adjacent walls of the cavity, as shown in Fig. 3(a). With this implementation (corner cavity), the strength of the coupling is significantly increased and transmission zero can now be implemented closer to the passband of the cavity. The strength of the coupling, and hence the position of the zero, can be controlled by changing the distance of the apertures from the common corner, as shown in Fig. 3(b), where the closest zero is now at 1.5 GHz from the main resonance of the cavity [$d_1 = 0$ in Fig. 3(a)].

IV. Application Examples

In the previous sections, we have shown how transmission zeros can be implemented in rectangular cavities using the

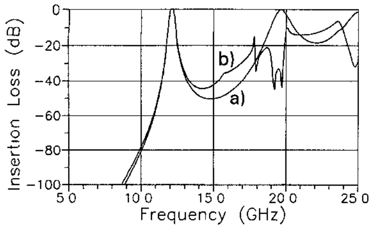
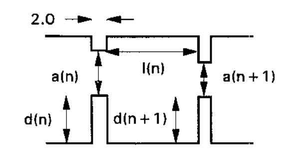


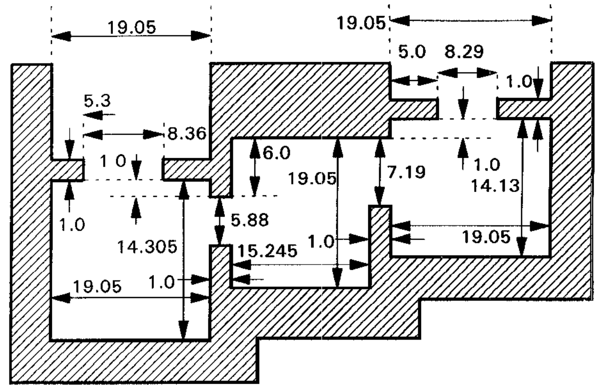
Fig. 4. Simulated electrical performance of a three-pole filter. Centered window implementation in a), and offset implementation on b). The offset has been optimized to suppress the second passband of the filter.

TABLE I
PHYSICAL DIMENSIONS OF THE MICROWAVE FILTERS IN FIG. 4A) AND B)

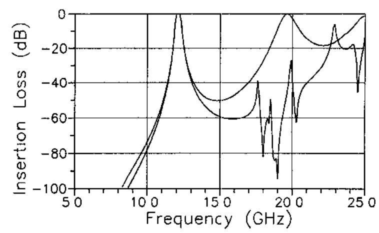
Centered	Offset
a(0) = 9.194 a(1) = 5.859 a(2) = 5.859 a(3) = 9 194	a(0) = 10.86 a(1) = 6.14 a(2) = 6 79 a(3) = 10.86
l(1) = 13.62 l(2) = 14.969 l(3) = 13.62	l(1) = 13.74 l(2) = 15.047 l(3) = 13 756
All dimensions in mm	d(0) = 0 0 d(1) = 8.5 d(2) = 2.0 d(3) = 0 0



a = 19.05 b = 9.525

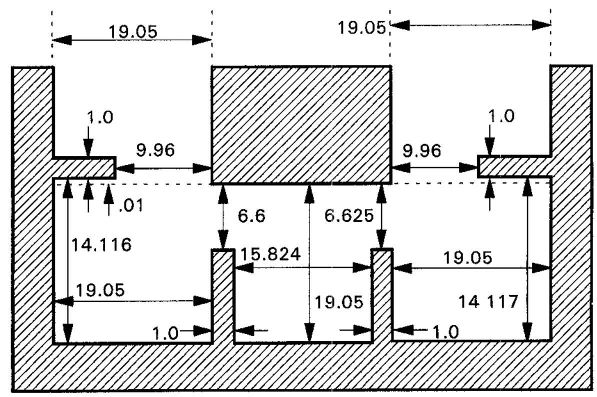


(a)

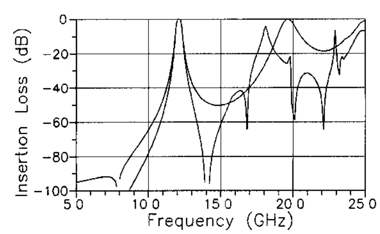


(b)

Fig. 5. Example of three-pole filter using two corner cavities in 5(a). Electrical performance in 5(b). The corner cavity offsets have been optimized to suppress the second passband of the filter. To facilitate the evaluation of the results, the response of the centered window implementation in Fig. 4 a) is reproduced here as well.



(a)

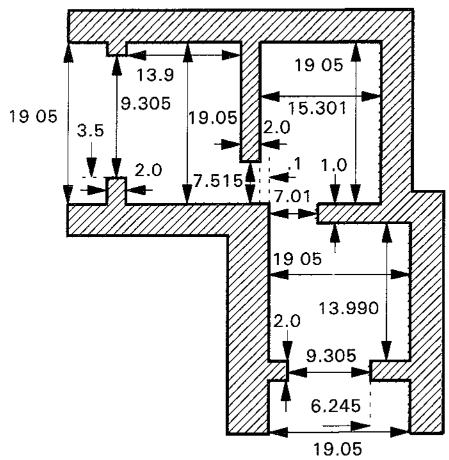


(b)

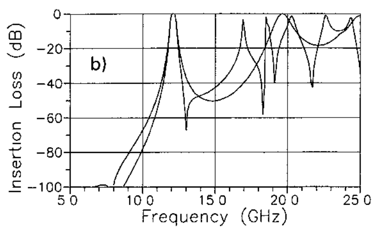
Fig. 6. Example of three-pole filter using two corner cavities in 6(a). Electrical performance in 6(b). The corner cavity offsets have been optimized to increase the selectivity of the filter. To facilitate the evaluation of the results, the response of the centered window implementation in Fig. 4 a) is reproduced here as well.

interactions between the fundamental and the higher order modes. In order to use effectively this feature, however, we must be able to design a microwave filter with prescribed passband and transmission zero location. This can be easily accomplished using the procedure described in [9]. Following [9], in fact, one can obtain the final dimensions of a filter structure sequentially adding one cavity at the time. If we now use one of the cavity geometries described in this paper, the procedure to be followed is essentially identical. The only difference is that we now start with fixing the initial location of the transmission zero by adjusting the offset of the coupling apertures and then we proceed to adjust the parameters of the cavity as required (coupling aperture widths and cavity length). Once the cavity is nearly optimized, we fine tune the offset again in order to obtain the proper zero location and we conclude with the final adjustment of the cavity parameters. The recursive optimization of the transmission pole (resonant cavity) and of the transmission zero is very rapidly convergent so that it does not change significantly the simplicity of the original procedure as described in [9]. This is essentially due to the fact that the transmission zeros generated are not close enough to the edge of the bandpass to significantly interact with the transmission poles of the filters (insertion loss minima) so that a pure Chebycheff filter response can still be achieved.

The first application example that we discuss is for the in-line configuration. Fig. 4 shows the computed performance of two three pole filters, one implemented with centered apertures in Fig. 4 a), and the other with the offset configuration in Fig. 4 b). The offsets have been optimized to suppress the second passband of the filter. Table I gives the complete dimensions of the two structures. As it is evident from Fig. 4 b), the offset implementation has a better out-of-band response due to the



(a)



(b)

Fig. 7. Example of three-pole filter using one corner cavity in 7(a). Electrical performance in 7(b). The corner cavity offsets have been optimized to increase the selectivity of the filter. To facilitate the evaluation of the results, the response of the centered window implementation in Fig. 4 a) is reproduced here as well.

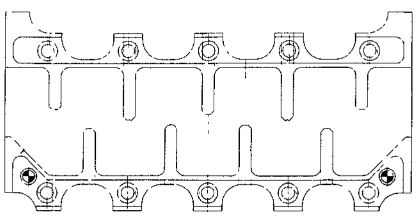
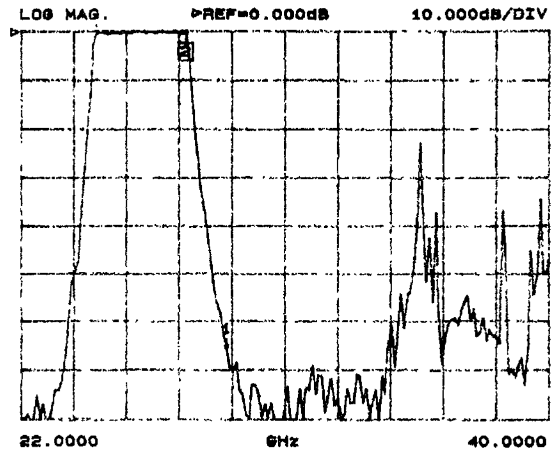
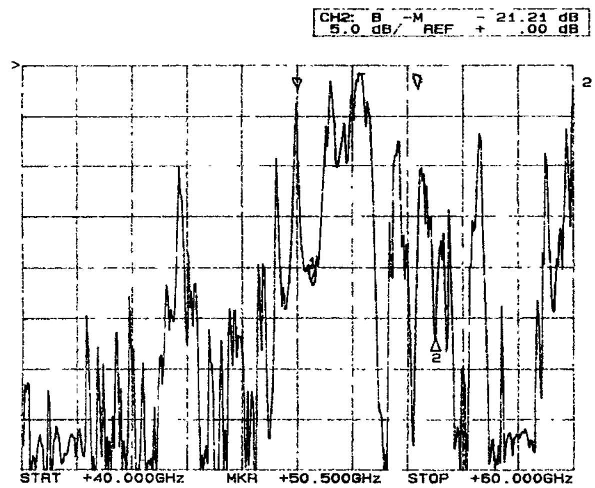


Fig. 8. Structure of a microwave filter realized taking advantage of the additional transmission zeros.



(a)



(b)

Fig. 9. Measured inband (a) and out-of-band (b) response of the filter in Fig. 8.

presence of the transmission zeros (three zeros can be clearly identified between 18 and 20 GHz).

A much better result is obtained using a combination of in-line and corner cavities. Fig. 5(a) shows a sketch of a three pole filter, and Fig. 5(b) shows its computed performance. Again the structure has been optimized to suppress the second passband. As we can see from Figs. 4(b) and 5(b), using the corner cavities the cancellation is much more effective than using the in-line cavities (again the three zeros can be clearly identified between 18 and 21 GHz).

Using again a combination of in-line and corner cavities, we have then designed another three pole filter placing the two transmission zeros generated by the corner cavities close to the passband of the filter. Fig. 6(a) gives a sketch of the filter, and Fig. 6(b) shows its computed performance. As we can see, then presence of the two zeros has increased the selectivity of the filter and generated a deep null in the insertion loss performance at about 14 GHz (the third pole can still be identified at about 17 GHz).

As previously discussed, the distance in frequency between the transmission zero and the resonance frequency of the cavity that generates the zero itself depends on the relative strength between the input/output coupling on the fundamental-mode resonator (transmission pole) and of the extra input/output coupling introduced by the higher order modes (cross coupling). To decrease the distance in frequency between the pole and the zero we must increase the relative strength of the cross coupling. In the previous example, corner cavities are used at the input and at the output of the filter where the strongest resonator couplings are required. If the corner cavity is used internally in the filter (the second resonator for instance) a weaker resonator coupling is required so that the zero can be placed closer to the center frequency of the filter. The resulting structure is shown in Fig. 7(a), and its computed performance is shown in Fig. 7(b). As we can see comparing Fig. 7(b) with Fig. 6(b), using the corner cavity in the center of the filter allows to place the transmission zero closer to the passband of the filter.

As a last application example we present measured results of a nine-pole microwave filter that takes advantage of the extra transmission zeros to suppress the second passband. This

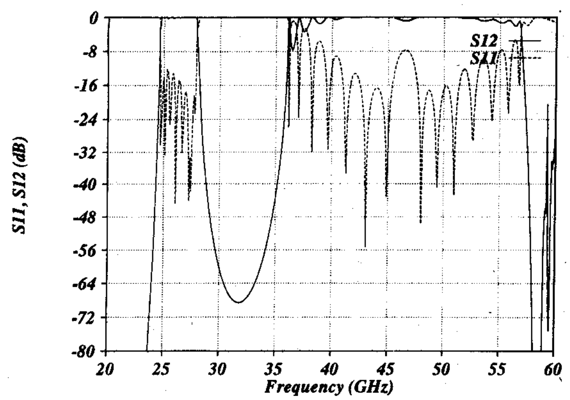


Fig. 10. Simulated performance of a microwave filter designed with the same target specifications as the one in Fig. 8, but realized with the standard *in line* implementation.

filter has been manufactured for the satellite ARTEMIS of the European Space Agency and its structure is shown in Fig. 8 while, the measured results are shown in Fig. 9. The result shown in Fig. 10 represents the simulated performance of a filter with the same inband specifications as the one in Fig. 8 but realized with in-line cavities and centered inductive steps. As it is evident from the comparison between Figs. 9 and 10, the presence of the extra transmission zeros has improved significantly the out-of-band rejection of the filter.

V. Conclusion

In this paper we have described an alternative procedure to implement transmission zeros in the insertion loss performance of microwave filters based on thick inductive windows in rectangular waveguide. The transmission zeros are generated using the interactions between the fundamental and the higher order modes excited by the inductive apertures in each individual filter cavity. Two types of cavity configuration have been discussed, namely the in-line configuration and the corner configuration. For both cavities the actual location of the transmission zero can be controlled independently from the other cavity parameters (bandwidth and resonance frequency). The frequency of the transmission zero introduced is always higher than the passband of the filter and one transmission zero per cavity can be implemented without increasing the physical size (or the mass) of the filter.

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Paolo Arcioni, for a photograph and biography, see this issue, p. 1855.