Tolerance analysis of bypass-, cross- and direct-coupled rectangular waveguide band-pass filters

J. Bornemann, U. Rosenberg, S. Amari and R. Vahldieck

Abstract: Tolerance analyses of bypass-, cross- and direct-coupled rectangular waveguide filters are presented. It is found that, contrary to common belief, standard direct-coupled waveguide filters are not less sensitive with respect to their passband behaviour than filters with cross or bypass couplings. Moreover, they are considerably larger than bypass-coupled TM_{110}-mode cavity designs, which always present the shortest solution and allow a simple implementation of transmission zeros. The general approach of the tolerance analysis is verified through measurements of a large number of fabricated direct-coupled seven-pole inductive-iris filters. It is concluded that both the path and the radius of the manufacturing end-mill cutter influence the return loss and passband spread of the fabricated filter components.

1 Introduction

Direct-coupled, elliptic and pseudo-elliptic waveguide filters find widespread application in modern communication systems where specifications for efficient spectral power utilisation demand both sharp cutoff skirts and acceptable passband return-loss performance. Owing to the narrow-band characteristics of such filters, their sensitivity to fabrication tolerances is of fundamental importance to the design engineer. Therefore, following the theoretical design process and verification, a tolerance analysis must be performed. It is usually based on Monte Carlo simulations [1] or similar statistical techniques in order to test the robustness of the design with respect to variations dictated by the manufacturing process, e.g. [2].

The purpose of this study is to display and compare the variations of different types of rectangular waveguide filters with respect to manufacturing tolerances. In particular, we investigate inline TM_{110}-mode filters with TE_{10}-mode bypass coupling [3], an inline dual-mode filter with cross-coupling [4] and a folded H-plane filter with cross-coupling [5] and compare their sensitivities to those of direct-coupled inductive-iris filters [6–8]. Other factors in this study are the actual size of the individual components and, the variations of path and radius dimensions, which account for the machining of the structure with an end-mill cutter.

It is not the purpose of this paper to introduce new filter structures, as waveguide filter designers are aware of these topologies, nor are we trying to introduce new numerical concepts. The numerical procedures in this investigation are based on modal analysis within the coupled-integral-equations technique (CIET) [4]. The correctness of the associated codes has been extensively verified by measurements and comparison with independently developed and/or commercially available software packages. Moreover, the number of modes and basis functions have been chosen to be high enough to prevent convergence issues influencing the tolerance analysis. Neither these verifications nor the details of the techniques will be repeated here. Instead, the reader is referred to [3, 6, 9] for further details.

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2 Numerical results

A number of bypass-coupled, cross-coupled and direct-coupled filters are presented, which have been designed for operation at 12.5 and 12.3 GHz. In the following, they are subjected to:

(i) manufacturing tolerances of $\pm 12.5\,\mu m$;

(ii) one hundred trials with different dimensions generated by statistical variation (using a random number generator) within the above limits;

(iii) volume (length, height and width) comparison using 5 mm of added material for outer walls and flanges.

The first example is a TM_{110}-mode filter with TE_{10}-mode bypass coupling. It is based on so-called singlets in which each single-mode cavity creates its own transmission zero [3]. The design features a 280 MHz bandwidth at 12.5 GHz (2.24%) and transmission zeros at 11.37, 11.83, 13.09 and 13.81 GHz. Figure 1 shows the optimised (dark lines) and tolerance-related performance (grey lines). It is observed that whereas the bandwidth and transmission zeros are well maintained, the return loss drops from 23 to 18 dB in the worst case. (Note that the nearly horizontal lines in this and the following Figures are caused by the trace back from the last point of analysis i to the first point of analysis $i+1$.) The overall volume of this filter is only $28.8 \times 28.1 \times 29.1\,mm^3$ (length, width, height).

A cross-coupled four-pole filter with four transmission zeros requires source-load (input–output) coupling and, therefore, is usually realised by structural folding. For comparison with Fig. 1, a folded H-plane filter with cross-couplings 1-to-4 and source-to-load was designed for the same bandwidth and is shown in the inset of Fig. 2. The lower right cavity is designed for a TE_{102}-mode in order to achieve negative coupling between resonator 1 and 4 and positive coupling between source and load as dictated by the coupling scheme, e.g. [10]. It is interesting to note that in this case, the outermost transmission zeros could not be positioned at the same locations as those in Fig. 1 without severely sacrificing the in-band return-loss performance. Similarly, the bypass-coupled design in Fig. 1 will not allow the leftmost transmission zero to be lowered to that of Fig. 2. The tolerance performance of the folded cross-coupled filter is shown in Fig. 2. With transmission zeros at 10.81, 11.90, 13.12 and 14.16 GHz, a return loss of 27 dB was achieved (dark lines). This value drops to just below 20 dB when the tolerances are considered. Otherwise, the tolerance performance is comparable with that of the bypass-coupled filter in Fig. 1. However, the folded cross-coupled filter requires 2.8 times the volume of the one with bypass coupling.

Design engineers are often faced with a choice between a complicated filter design involving transmission zeros and a simple design process using a slightly higher-order standard inductive-iris filter. In this context, it is commonly believed that a filter without transmission zeros is less sensitive to manufacturing tolerances. Figure 3 demonstrates that, as far as the passband is concerned, this is not necessarily the case. A standard inductive-iris filter with six direct-coupled resonators was designed for the same passband as those displayed in Figs. 1 and 2. Figure 3 shows that the return loss of the direct-coupled design deteriorates in much the same way as those observed for the bypass- and cross-coupled designs in Figs. 1 and 2. Therefore, direct-coupled standard inline rectangular waveguide filters cannot be regarded as less sensitive with respect to their passband behaviour than filters with bypass or cross couplings. Moreover, the component volume of $102.1 \times 19.5 \times 29.1\,\text{mm}^3$ for the six-resonator design in Fig. 3 places this filter at a disadvantage when compared to the design in Fig. 1.

As the bandwidth decreases, filter performances become more sensitive to manufacturing tolerances. Figure 4 shows the design of a four-pole bypass-coupled singlet filter similar to that in Fig. 1 but for a bandwidth of 1% at 12.3 GHz. In order to suppress two of the transmission zeros shown in Fig. 1, the centre iris is aligned vertically (cf. [3]). The design was optimised for a 21 dB return loss and transmission zeros at 12.08 and 12.59 GHz. The overall

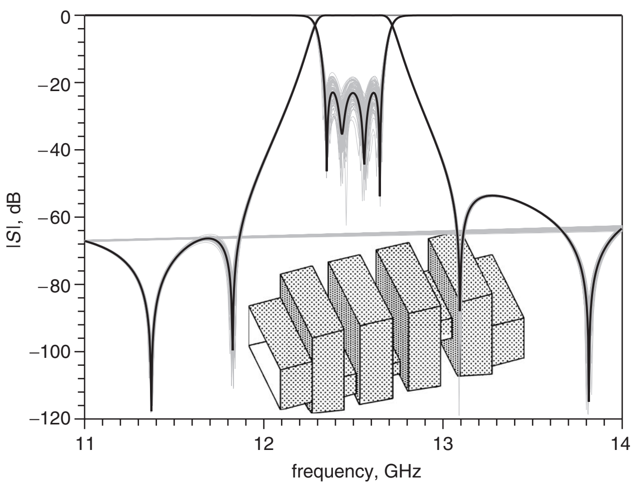

Fig. 1 *Tolerance analysis of a four-pole singlets (bypass-coupled) filter with four transmission zeros*
$V = 28.8 \times 28.1 \times 29.1\,\text{mm}^3$

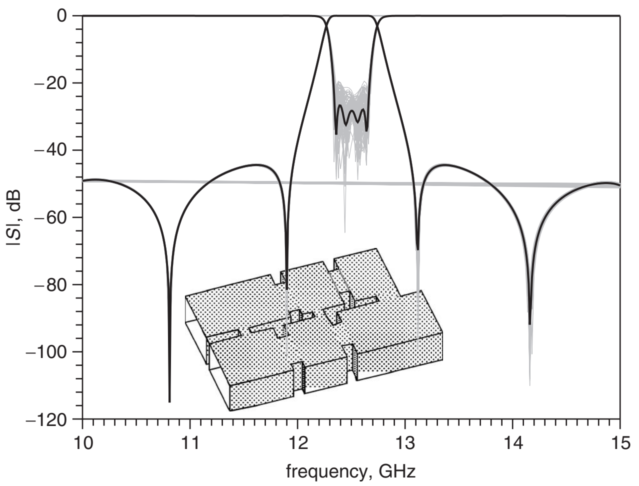

Fig. 2 *Tolerance analysis of a folded four-pole (cross-coupled) filter with four transmission zeros*
$V = 68.8 \times 19.5 \times 49.1\,\text{mm}^3$

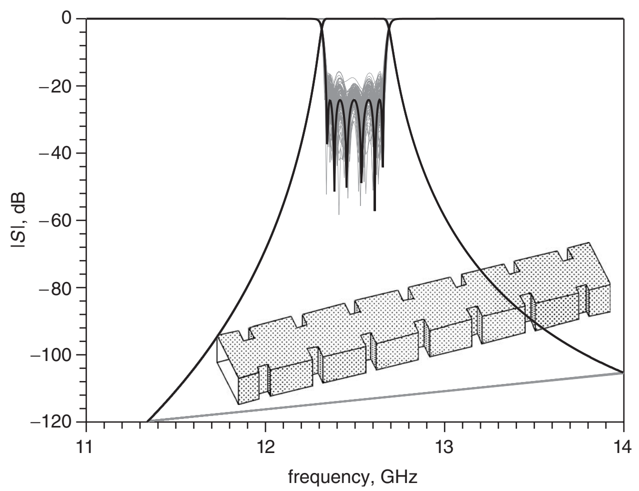

Fig. 3 *Tolerance analysis of a six-pole direct-coupled inductive-iris filter for comparison with Figs. 1 and 2*
$V = 102.1 \times 19.5 \times 29.1\,\text{mm}^3$

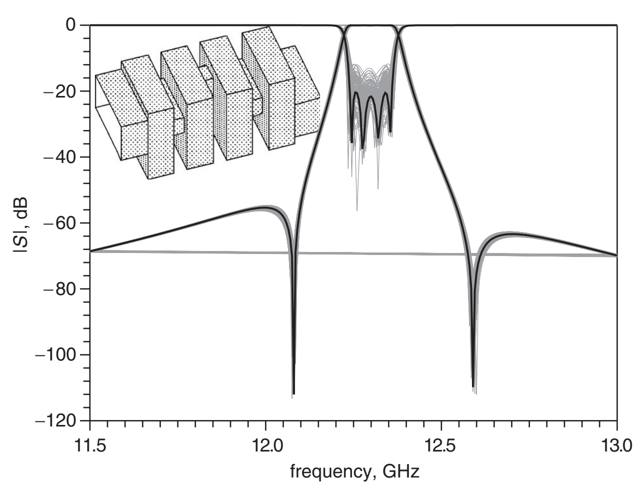

Fig. 4 *Tolerance analysis of a four-pole singlets (bypass-coupled) filter with two transmission zeros*
$V = 32.3 \times 33.4 \times 30.7\,\text{mm}^3$

component volume is $32.3 \times 33.4 \times 30.7\,mm^3$. As shown in Fig. 4, the tolerance analysis shows a reduction in bandwidth to below 0.9%. Moreover, a return loss of only 12 dB is retained.

For comparison with Fig. 4, Fig. 5 shows an inline dual-mode filter with 1-to-4 cross-coupling according to [4]. As expected, the tolerance performance of this filter is similar to that of Fig. 4. However, in spite of the dual-mode operation, this filter occupies 1.3 times the volume ($55.2 \times 27.0 \times 29.1\,mm^3$) compared to that of Fig. 4.

Again, the narrowband designs of Figs. 4 and 5 are compared with a direct-coupled inductive-iris filter. A five-pole structure (cf. Fig. 6) is used to achieve a slope, which is more comparable with the bypass-coupled and cross-coupled structures (Figs. 4 and 5). Although the optimised return loss in Fig. 6 is better than 30 dB, the available bandwidth and return loss after tolerance analysis are very similar to those of the structures in Figs. 4 and 5. However, the overall component volume of $90.6 \times 19.5 \times 29.1\,mm^3$ places this five-pole direct-coupled design at a disadvantage.

Although the tolerance analysis covers the entire frequency response, we have mainly discussed the passband return loss performances of the different filter arrangements. In the stopbands, direct-coupled filters are indeed less sensitive (e.g. compare Fig. 3 with Figs. 1 and 2 and Fig. 6 with Figs. 4 and 5). For filters with transmission zeros, the stopband sensitivities demonstrated in Figs. 1, 2, 4 and 5 are usually acceptable for practical implementations. However, when the exact positions of the transmission zeros is critical, i.e. when it comes to tuning the stopbands (transmission zeros) of the assembled filters to compensate for the manufacturing tolerances, then modular designs (such as those based on cascaded singlets, doublets, triplets and quadruplets) are more advantageous. In modular designs, specific transmission zeros are generated and controlled by specific blocks, which is not the case for folded canonical configurations where one coupling term may affect all of the transmission zeros. Nevertheless, this information does not significantly affect the tuning of the passband as the results of this investigation show. It is rather the bandwidth of the filter, which determines the complexity of tuning the passband.

3 Application and measurements

The tolerance analysis technique was applied to the fabrication of an inductive-iris filter. The design was performed for a 22 dB return loss and a bandwidth of 750 MHz at 20.664 GHz, taking into account that, after mass production, a 15 dB return loss and a 500 MHz

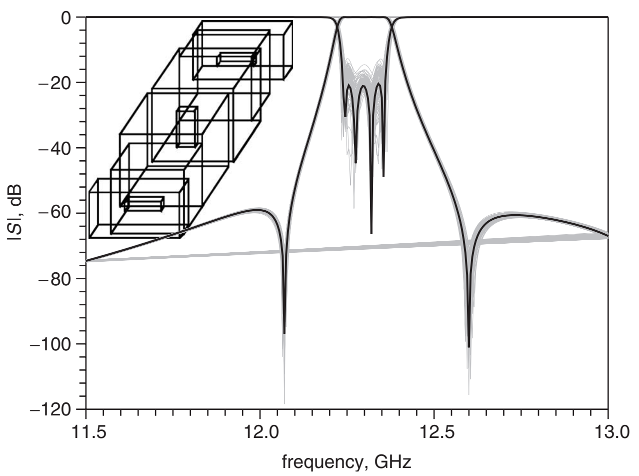

Fig. 5 *Tolerance analysis of an inline four-pole (cross-coupled) filter with two transmission zeros*
$V = 68.8 \times 19.5 \times 49.1\,mm^3$

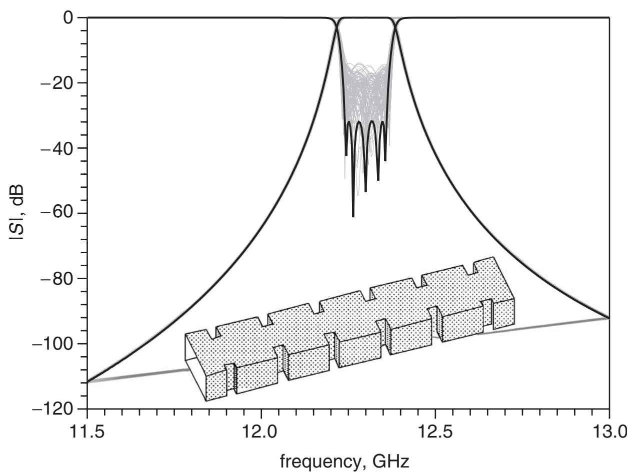

Fig. 6 *Tolerance analysis of five-pole direct-coupled inductive-iris filter for comparison with Figs. 4 and 5*
$V = 90.6 \times 19.5 \times 29.1\,mm^3$

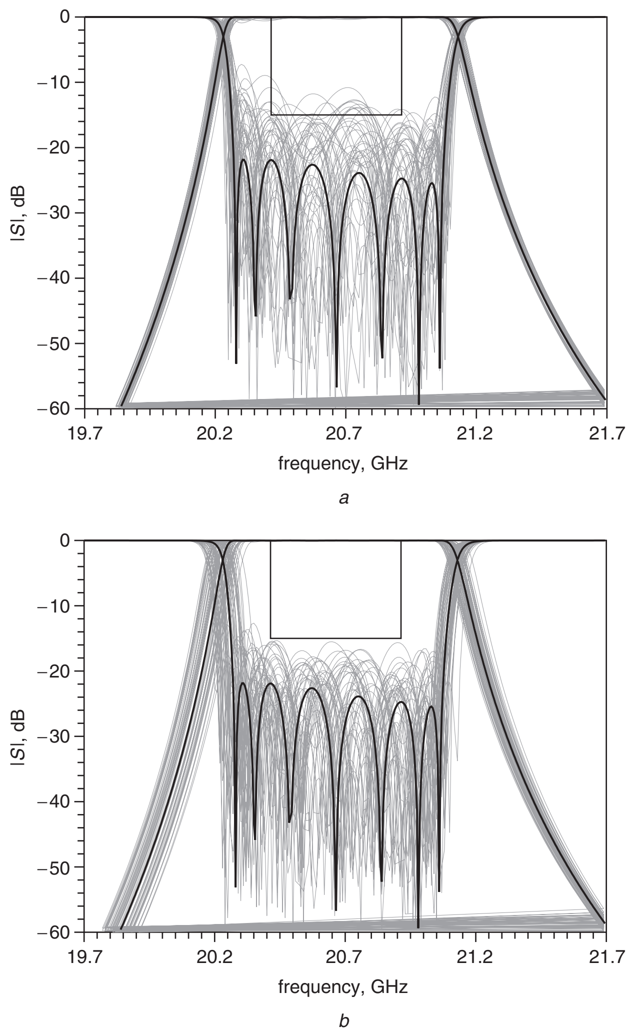

Fig. 7 *Performance of seven-pole direct-coupled inductive-iris filter (cf. Fig. 9)*
a Tolerance analysis assuming $\pm 20\,\mu m$ statistical variation of dimensions
b Tolerance analysis assuming $\pm 10\,\mu m$ statistical variation of the cutter path plus $\pm 10\,\mu m$ variation of the cutter radius

bandwidth were to be retained (cf. rectangular function in Fig. 7). Stopband specifications dictated a seven-order filter function. The design of the filter structure considered an end-mill cutter radius of 1.55 mm to accommodate low-cost production aspects. The design was performed using the commercial software package μWave Wizard©.

The filter was then subjected to a tolerance analysis using the mode-matching package of [9] and assuming a statistical variation of the dimensions of $\pm 20\,\mu m$. This analysis in shown in Fig. 7*a* where the solid black lines resemble the original design for a 22 dB return loss and a bandwidth of 750 MHz. It is obvious that the target of a 15 dB return loss cannot be achieved with this statistical variation of dimensions.

Since the component was to be manufactured using a CNC machine, the $\pm 20\,\mu m$ tolerances were divided between the path ($\pm 10\,\mu m$) and the radius ($\pm 10\,\mu m$) of the end-mill cutter. It is obvious that the statistical variation of the end-mill cutter will lead to a deterministic variation of the dimensions. For an increasing radius, the cavities will be wider and longer whereas the irises are thinner with their apertures increased. Such a tolerance analysis, involving both the path and the radius, is shown in Fig. 7*b*. Over the 500 MHz bandwidth, the return loss is better than the required 15 dB. Note that the wider spread of the insertion loss curve (compared to Fig. 7*a*) is due to the variation of the cutter radius.

After fabrication of a large number of filter components, 20 filters were arbitrarily selected and measured. The measurements are shown in Fig. 8. They validate the tolerance analysis in Fig. 7*b* including the spread of curves due to the variation of the cutter radius. Figure 9 shows a photograph of one of the manufactured filter components. Owing to the long connection lengths to the input and output ports as specified by the topology of the entire system, the overall volume of this filter was of no immediate concern.

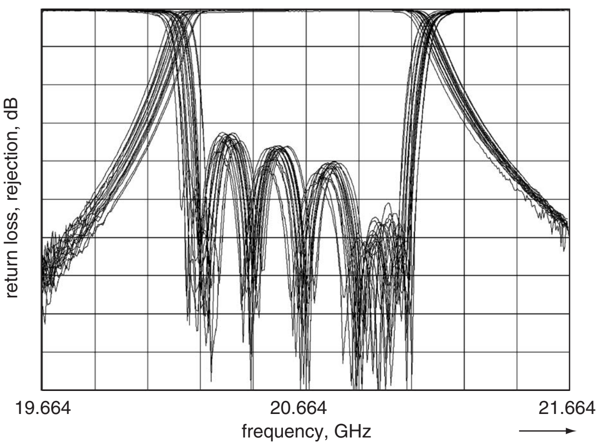

Fig. 8 *Measurements on 20 seven-pole inductive-iris filters*
Note that the scales for return loss and rejection are 5 dB and 10 dB, respectively, per division

4 Conclusions

Monte-Carlo-based tolerance analyses of rectangular waveguide filters reveal that as far as the passband is concerned, bypass-coupled, cross-coupled and direct-coupled topologies follow a very similar dependence on manufacturing tolerances. It was found that the use of higher-order direct-coupled waveguide filters without transmission zeros presents no significant sensitivity advantage compared to filters with transmission zeros. On the contrary, they are usually longer and not as compact. Among the designs investigated, filters based on TM_{110}-mode cavities are the most compact ones and exhibit sensitivity to fabrication tolerances very similar to other filter components. The tolerance analysis is verified through measurements on 20 seven-pole inductive-iris filters, which confirm that a combination of variations of both the path and the radius of the end-mill cutter needs to be considered for mass-producible filter components.

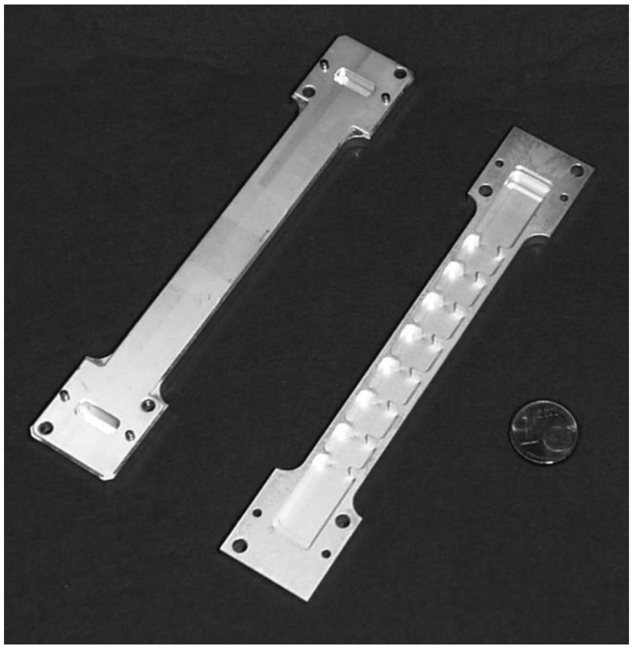

Fig. 9 *Photograph of one of the 20 seven-pole inductive-iris filters and size comparison with a Euro 1 cent coin*

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