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Correction of Manufacturing Deviations in Waveguide Filters and Manifold Multiplexers without Tuning Screws

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Microwave filters and multiplexers commonly employ tuning screws to compensate for small errors occurring during the fabrication process. Nevertheless, the use of tuning screws has some disadvantages, because the small gaps between the screws and the holes are prone to create unwanted effects when dealing with high power signals, specially for space applications, and are also the source of potential radiation losses. In this paper, an alternative technique to correct manufacturing deviations is presented, in which tuning screws are replaced by fixed metal insertions. In this case, the correction is made by means of designing new insertion pieces that will be able to correct those small deviations. In order to find the dimensions of the new pieces, a space mapping technique is applied. For verification purposes, the method has been applied over a circular-waveguide dual-mode filter, and later over a manifold multiplexer containing the same type of filters. However, the technique can be directly extended to any type of waveguide filters and multiplexers where tuning screws are also employed.

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I INTRODUCTION

Tuning screws are often used in waveguide filters and multiplexers to compensate for small errors produced during the fabrication process. However, the use of tuning screws has some disadvantages. First of all, they may cause problems dealing with high power signals, specially in space applications, since the small gaps along the threads between the screws and the holes, together with the contamination (metal shavings, dirt, etc.) on the surface of the screws, are likely to create passive intermodulation (PIM) and multipaction effects [1]. These gaps may also create potential radiation losses in the structure. Besides, it is known that, for space applications, fixed structures are generally preferred against others with mobile parts, because non-fixed parts can be moved due to vibration effects (i.e. those generated during the launching operation). Furthermore, the tuning process of these screws is usually a time consuming task, and must be carried out by an expert operator. For all these reasons, many authors have tried to avoid the use of tuning screws in the design and manufacturing of dual-mode filters [1–3].

In this work, an alternative technique has been developed to correct manufacturing deviations, avoiding the use of tuning screws. Here, the correction is made by means of substituting some pieces of the fabricated devices for new ones, which are able to correct those deviations. These pieces are quite cheap and easy to manufacture.

In order to find the dimensions of the new pieces, an space mapping (SM) technique is going to be applied. Space mapping (SM) techniques were originally introduced to design microwave components in [4]. Since then, the idea has been successfully applied in different works with some specific variations [5–9]. Space mapping algorithms are usually employed to design microwave devices in a more efficient way, by combining the efficiency of circuit models with the accuracy of electromagnetic (EM) models. A low-accuracy model which is very fast (usually a circuit model) is used as a “coarse model”, while a high-precision model (usually obtained with an EM simulator) is employed as a “fine model”. The final aim is to obtain an optimal design given by the fine model without performing direct optimization over such expensive model. Instead, many simulations of the coarse model are combined with a few simulations of the fine model, thus establishing a relationship (mapping) between both models.

Here, the space mapping technique is going to be applied in an alternative way. It will be used to calculate the dimensions of a new set of pieces containing the fixed insertions. The difference between the dimensions of the new pieces and the dimensions of the old ones will be able to compensate for the manufacturing deviations in the whole structure. Therefore, the space mapping will take place between the measurements of the manufactured device (fine model), and the response simulated by the full-wave EM solver. Hence, by comparing the simulated responses with the measured ones, we will be able to recover the desired measured response using suitable insertion pieces found with the full-wave EM simulator.

In [10], this procedure was particularized for a specific type of filter, the circular-waveguide dual-mode (CWDM) filter. Here, the correction process is going to be generalized for any type of waveguide filter with tuning screws, in which they can be replaced by fixed insertions. The only requirement is that these pieces must be liable to be fabricated as separate pieces. In a similar way, the process will also be extended to correct manufacturing deviations in manifold multiplexers containing channel filters with the same characteristics, where the mentioned filters must also be liable to be fabricated independently of the rest of the structure (which is indeed the most usual way to fabricate waveguide multiplexers).

The rest of the document is organized as follows. In section II, the procedure to correct manufacturing deviations in any type of waveguide filters is going to be introduced, thus explaining how the dimensions of the new pieces are calculated through an SM technique. In section III, the method will by applied to correct manufacturing deviations in a specific filter structure, in particular a CWDM filter. After that, in section IV, the technique will be extended to a more complex case, consisting on a manifold multiplexer whose channel filters are CWDM filters. Finally, after critically discussing the limitations of the proposed method and giving some practical advises in section V, the main conclusions will be reviewed in section VI.

II METHODOLOGY

A) Problem Overview

Let us consider a typical situation in which a waveguide filter has been designed, providing a good simulated response, and then, once it is manufactured, the measured response is different from the desired one. Assuming that the full-wave EM solver employed for the design was accurate enough, the deviation in the response will be due to the manufacturing tolerances, which are small errors in the dimensions of the fabricated device, due to inaccuracies in the fabrication process.

If the manufactured filter has tuning screws, this would be the time when they would be would be used to tune the response. This would be done by moving all the available screws while observing the measured response provided by the network analyzer. If fixed insertions are considered instead of the tuning screws, this correction process is performed in an alternative way, but the final idea will be very similar, since the aim is to obtain the dimensions of the fixed insertions that achieve a response as close as possible to the desired one. In order to find the dimensions of these pieces, more than one iteration (but usually quite a few) may be necessary, as it usually happens with the SM techniques. The whole design procedure is going to be detailed below.

B) Space Mapping Models and Parameters

In the proposed SM application, the coarse model will be a full-wave EM solver. The fine model responses are the measurements of the manufactured filter, which can be obtained with a vector network analyzer.

The SM parameters that are going to be modified during the correction process are the dimensions of the fixed pieces replacing the tuning screws. For example, if each tuning screw is substituted by a rectangular metal insertion, the SM parameters will be the penetrations of these insertions (thus emulating the tuning process of the screws). In that case, there would be as many SM parameters as the number of fixed metal insertions (which is equal to the number of tuning screws in the traditional structure).

C) Formulation

In this case, the aggressive space mapping (ASM) technique has been employed [5]. The ASM is a version of the classical SM technique [4] where less simulations of the fine model are needed, thus resulting in a very efficient algorithm.

Following the method explained in [5], the dimensions of the fixed insertions (normally the penetration lengths) to be fabricated in each iteration are calculated as follows

$$\mathbf{L}_f^{(j)} = \mathbf{L}_f^{(j-1)} + \mathbf{h}^{(j)} \tag{1}$$

where $\mathbf{L}_f^{(j)}$ is a vector with the penetration lengths of the fine model in the j-th iteration, and $\mathbf{h}^{(j)}$ is the new increment for each new iteration that can be obtained as indicated next

$$\mathbf{h}^{(j)} = -(\mathbf{B}^{(j)})^{-1}\mathbf{f}^{(j)} \tag{2}$$

In the previous equation, $\mathbf{B}^{(j)}$ denotes the corresponding Jacobian matrix, also described in [4], that can be obtained by means of the classical Broyden update

$$\mathbf{B}^{(j)} = \mathbf{B}^{(j-1)} + \frac{\mathbf{f}^{(j)}\mathbf{h}^{(j-1)T}}{\mathbf{h}^{(j-1)T}\mathbf{h}^{(j-1)}} \tag{3}$$

and $\mathbf{f}^{(j)}$ can be calculated as

$$\mathbf{f}^{(j)} = \mathbf{L}_c^{(j)} - \mathbf{L}_c^{(0)} \tag{4}$$

where $\mathbf{L}_c^{(j)}$ and $\mathbf{L}_c^{(0)}$ are the dimensions in the coarse model for the j-th iteration and for the optimal solution (the insertion dimensions of the originally designed filter), respectively.

For the particular case of the first iteration, given that there is no information available to build the Jacobian matrix, the identity matrix is used instead.

D) Correction Process

Once the original filter has been designed and fabricated, its response is measured. When this response is different from the desired one, the correction process starts. In order to perform the first iteration, the first step is to obtain the new dimensions of the coarse model ($\mathbf{L}_c^{(1)}$). This is done by obtaining, with the full-wave EM software code, a response that matches the previously measured response. This can be done by optimizing the original design, only modifying the penetration lengths of the metal insertions. The new penetrations of the coarse model $\mathbf{L}_c^{(1)}$ obtained after the optimization process are introduced in (1)-(4) to obtain the new penetration values of the fine model $\mathbf{L}_f^{(1)}$, which correspond with the dimensions of the new pieces that will be manufactured.

The next step is to measure the filter response after substituting the original insertion pieces with the ones obtained after the first SM iteration. If the new measured response is not close enough to the desired one, a second SM iteration can be performed. In this case, the response measured after the first SM iteration will be matched with the optimizer to obtain $\mathbf{L}_c^{(2)}$. The whole process can be repeated until the desired response is achieved, or until there are not significant improvements between iterations (see section V).

III CORRECTION OF MANUFACTURING DEVIATIONS IN CWDM FILTERS

Circular-waveguide dual-mode (CWDM) filters are widely used in payload systems of communication satellites, due to their reduced weight, compact size and electrical performance [11–14]. One of the main problems of these filters is their high sensitivity to manufacturing deviations, which usually involve important degradations of the measured response. This drawback is commonly alleviated by means of tuning screws.

Here, the correction process explained in section II is going to be particularized to this type of filters. More specifically, a four-pole CWDM filter with two cavities has been considered, whose structure is depicted in Fig. 1. As it can be seen, it has three fixed rectangular-shaped insertions placed inside each cavity, instead of tuning and coupling screws.

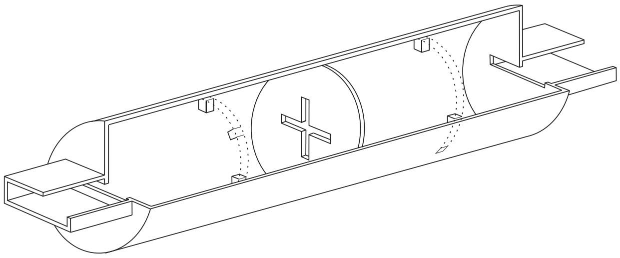

Figure 1: Proposed structure for a four-pole dual-mode filter in circular waveguide. The tuning and coupling screws have been replaced by fixed rectangular-shaped metal insertions.

After designing the filter using an EM solver, it was manufactured. For the fabrication process, the filter was divided into 5 separate pieces (see Fig. 2), to allow the replacement of two pieces containing the fixed insertions. The manufactured filter can be seen in Fig. 3, while the disassembled device is shown in Fig. 4.

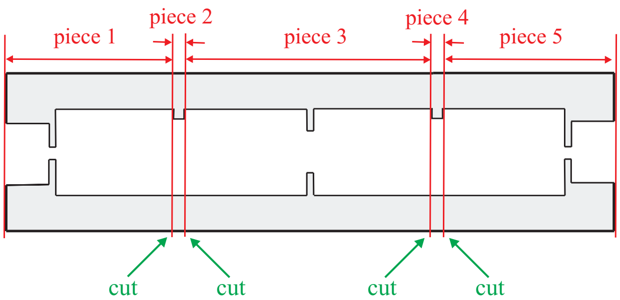

Figure 2: Side cut of the manufactured CWDM filter structure divided into 5 pieces.

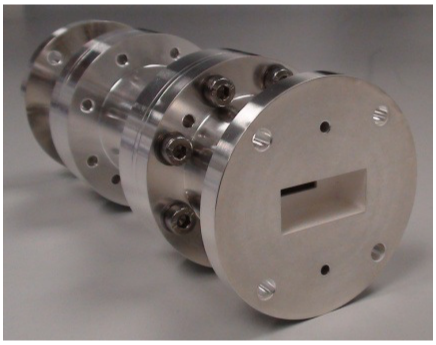

Figure 3: Manufactured CWDM filter with all its pieces assembled together.

The ideal response of the filter, obtained with a full-wave EM solver, is shown in Fig. 5 (solid line). After measuring the manufactured filter, the response shown in Fig. 5 (dashed line) was obtained. As it can be seen, due to the manufacturing tolerances, the response of the fabricated filter is quite different from the simulated one.

In order to improve the response of the manufactured filter, two new insertion pieces (corresponding with pieces 2 and 4 in Fig. 2) need to be designed. The SM technique is going to be applied to calculate the penetrations of the three insertions of each piece.

Figure 4: Detailed view of the pieces composing the CWDM filter in Fig. 3.

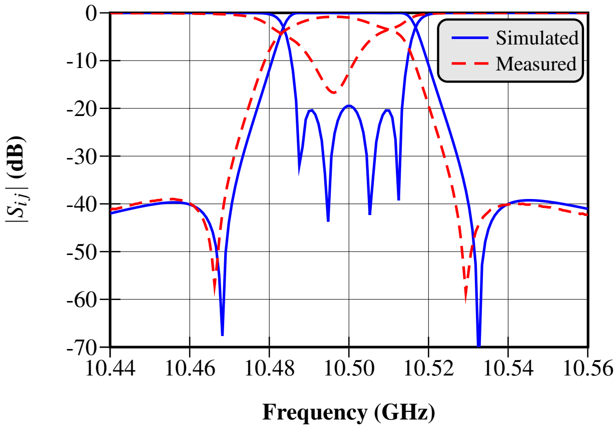

Figure 5: Ideal response obtained with a full-wave EM solver (FEST3D) compared with the measured response of the manufactured CWDM filter.

Therefore, the only parameters that are going to be modified during the SM process are the penetration depths (L variables in Fig. 6) of the 6 rectangular-shaped metal insertions.

In this case, the full-wave EM solver FEST3D [15] has been used as a coarse model, but any other software capable of coping with the full-wave EM analysis of the proposed complex structures, within reasonable CPU times, could be used instead. The fine model was the measurement obtained with a vector network analyzer (Agilent E8364B, 10 MHz to 50 GHz). A total of 3 SM iterations have been performed. After each iteration, the length of the 6 insertions were obtained as indicated in the previous section, and the corresponding two pieces were fabricated. The penetration lengths obtained in the different iterations are detailed in Table 1.

The measured responses of the filter with the pieces obtained after each iteration are shown in Figure 7. As it can be seen, the improvement of the response of the first iteration, with regard to the one of the original manufactured prototype, is already considerable. The differences between iterations one and two are also quite important, achieving a better return loss value after the second iteration. Finally, the last iteration has been able to correct almost perfectly the existing frequency shift, thus achieving a response that is very

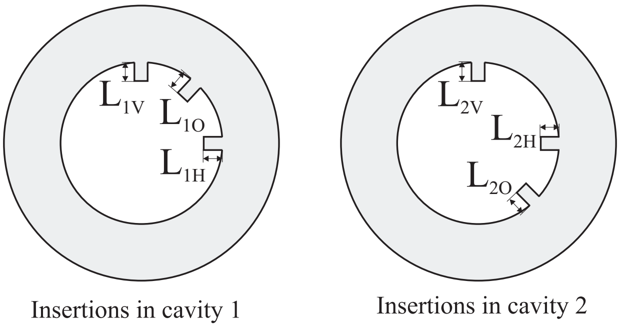

Figure 6: Pieces with insertions allocated in the middle of each cavity in the CWDM filter.

	Iteration 0		Iteration 1		Iteration 2		Iteration 3	
	$L_c^{(0)}$	$L_f^{(0)}$	$L_c^{(1)}$	$L_f^{(1)}$	$L_c^{(2)}$	$L_f^{(2)}$	$L_c^{(3)}$	$L_f^{(3)}$
L_{1V}	2.0000	2.0000	2.2754	1.7246	2.1328	1.5218	1.9758	1.5589
L_{1H}	3.1449	3.1449	3.2264	3.0634	3.1720	3.0220	3.1226	3.0421
L_{1O}	2.2505	2.2505	2.3596	2.1414	2.2526	2.1382	2.2062	2.1704
L_{2V}	2.0000	2.0000	1.9709	2.0291	2.0772	1.9112	1.9070	1.9895
L_{2H}	3.1345	3.1345	3.1194	3.1496	3.1542	3.1195	3.1072	3.1421
L_{2O}	1.7071	1.7071	1.6422	1.7720	1.7387	1.7237	1.7573	1.6923

Table 1: Penetration lengths obtained during the correction process of the CWDM filter.

close (almost identical) to the ideal one.

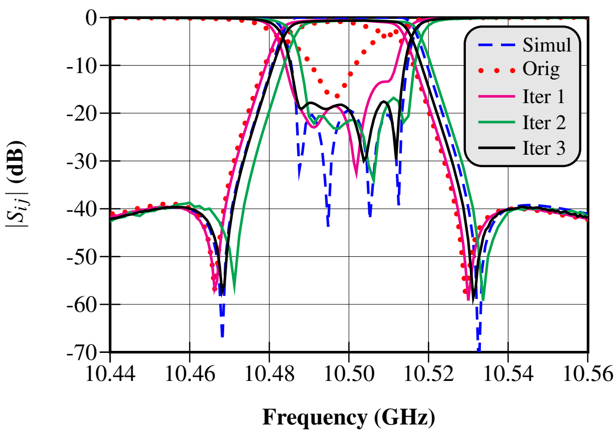

Figure 7: Measured responses after each iteration, compared with the simulated response, and the original fabrication of the CWDM filter.

In order to better verify the effectiveness of the method, the final response has been represented together with the ideal EM simulated response and the measurements of the original prototype (see Fig. 8). The improvement between the response of the original manufactured prototype and the response of the last SM iteration is clearly observed.

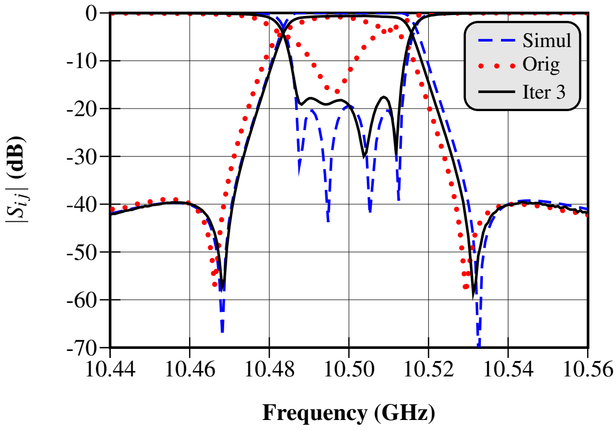

Figure 8: Comparison between the responses of the measured original prototype and the last SM iteration, together with the desired ideal response of the CWDM filter.

IV CORRECTION OF MANUFACTURING DEVIATIONS IN MANIFOLD MULTIPLEXERS

The correction procedure here proposed can also be applied to multiplexers containing channel filters that traditionally have tuning screws. In this section, the method is going to be extended to a manifold waveguide multiplexer with CWDM filters, although the technique could be directly employed with other multiplexer configurations. In particular, a multiplexer with 8 contiguous channels has been considered, whose structure can be seen in Fig. 9.

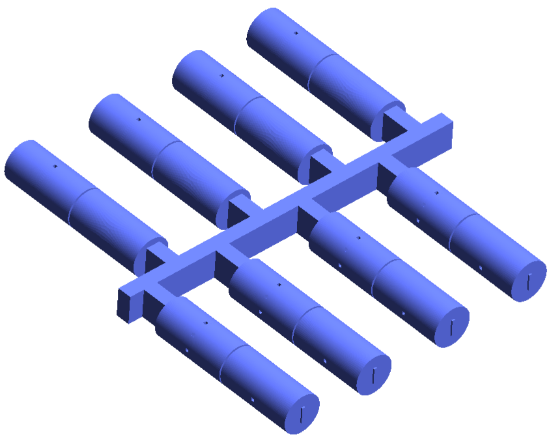

Figure 9: Physical structure of the contiguous 8-channel multiplexer with herringbone configuration, and whose filters are four-pole CWDM filters.

In this case, due to the complexity of the device, a prototype has not been manufactured. Instead, the errors in the dimensions occurring during the fabrication process have been considered with a full-wave EM-solver. To do so, aleatory deviations of about 10 microns (which is a typical value specified by manufacturers) have been introduced in the dimensions of all the channel filters, manifold waveguide sections, and waveguides connecting the manifold with the filters. Hence, in this example, the coarse model is the ideal EM model (without errors), and the fine model is the EM model with errors in its dimensions, that models what we would obtain by measuring the fabricated device with a network analyzer. Fig. 10 shows the simulated response of the ideal multiplexer (solid line) in comparison with the response of the multiplexer with the simulated errors (dotted line). In order to make the visualization more clear, only the common port return loss (CPRL) and the transmission of one of the channels have been displayed in such figure.

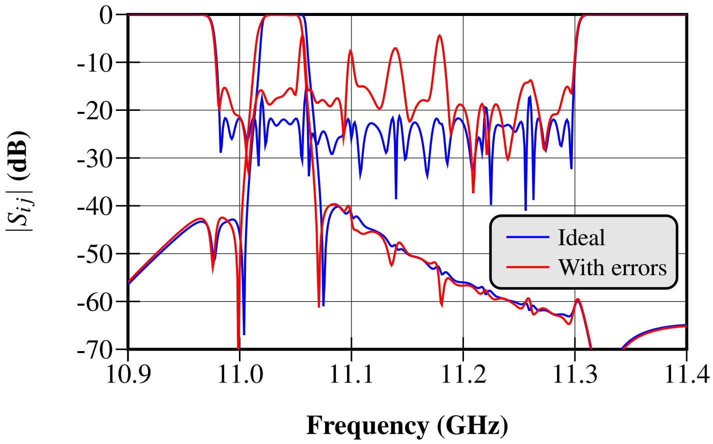

Figure 10: Ideal response of a contiguous 8-channel multiplexer obtained with a full-wave EM solver (FEST3D), compared with the response of the same multiplexer considering manufacturing deviations.

The next step would be to disconnect all the channel filters from the manifold and measure (in our case simulate considering deviations) each of them separately. After that, following the same procedure as for individual filters, the measured responses of the individual channel filters should be matched with the corresponding ideal simulated prototypes, by optimizing the penetrations of the metal insertions. This is done filter by filter, for the 8 channel filters. Now, it is important to assure that not only the module of the simulated response perfectly matches the measured one, but also the phase must be exactly the same, since in multiplexer design the phase of the channel filters matters, in order to achieve a certain response of the whole device. Figures 11 and 12 show the responses (module and phase) of the second channel filter with errors compared with the corresponding optimized responses.

Once the simulated isolated responses of all the channel filters perfectly match (in module and phase) the corresponding measured ones, a new EM model of the multiplexer is created. The next step is to perform a slight general optimization, considering the penetrations of the insertions of all the involved channel filters, in order to match the measured response of the whole multiplexer. That way, the manufacturing errors in the manifold can also be accounted for.

After that, two new insertion pieces for each channel filter are designed, filter by filter, using the formulation detailed in section II. These pieces are manufactured, and then introduced in the manufactured multiplexer. In our case, we have simulated this step by introducing the dimensions of the new insertion pieces in the EM model of the multiplexer considering manufacturing errors. The CPRL and transmission (second channel) responses

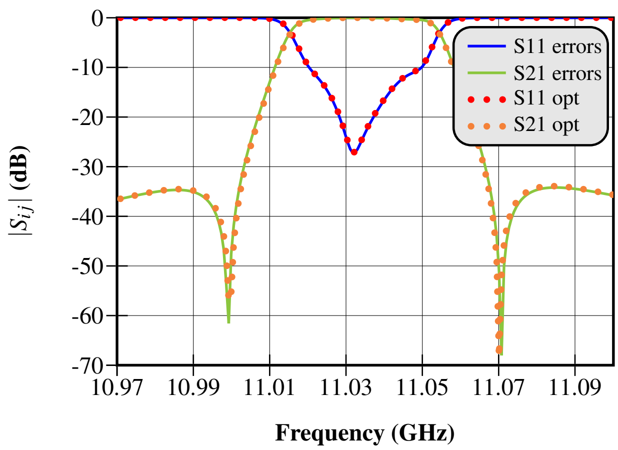

Figure 11: Optimization of the EM model to match the module of the response of the second channel filter with manufacturing deviations.

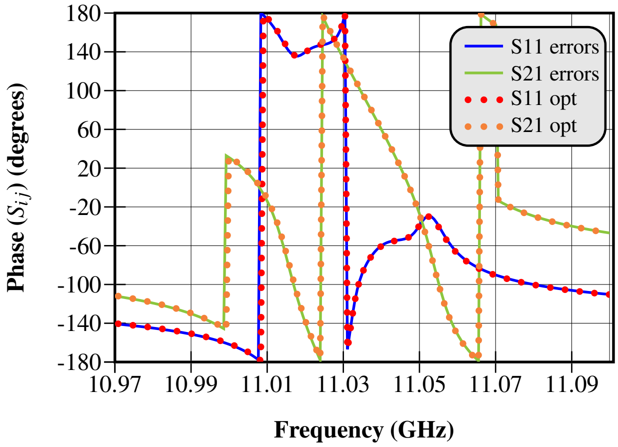

Figure 12: Optimization of the EM model to match the phase of the response of the second channel filter with manufacturing deviations.

of the corrected multiplexer have been shown in figures 13 and 14, respectively, together with the response of the ideal multiplexer, and the one of the original multiplexer with simulated manufacturing deviations. As it can be seen, with just one iteration it has been possible to significantly improve the response of the multiplexer to be manufactured. Nevertheless, as it was done before for the individual filters, successive iterations could also be applied, in order to achieve a more accurate response, but from the results shown it is expected that a few number of iterations will be needed.

V PRACTICAL CONSIDERATIONS

The proposed method is mintended for the correction of the filter response, which has been deteriorated due to the manufacturing deviations in the whole structure. However, the insertion pieces fabricated in each iteration are not perfectly fabricated either. Because of that, a totally perfect response is never going to be achieved (except for a matter of

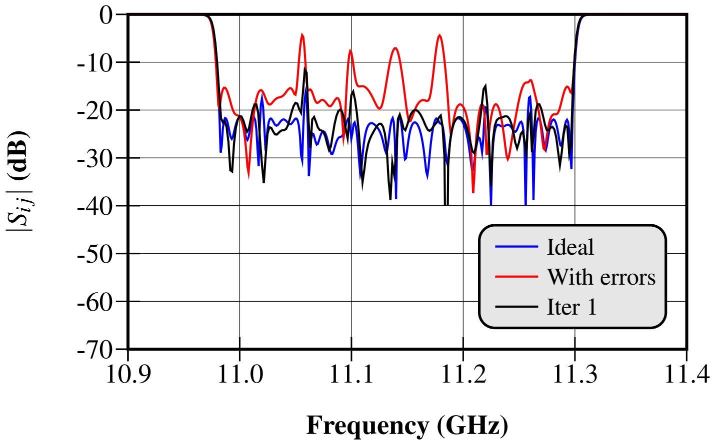

Figure 13: CPRL response of the corrected multiplexer (including manufacturing errors), compared with the simulated response of the original design, and the one of the multiplexer with the simulated errors.

chance). Nevertheless, due to mechanical reasons, the accuracy that can be obtained in the fabrication of the pieces with insertions is significantly higher than the accuracy that can be achieved in the rest of the structure, so the final result, if not perfect, can be very close to the ideal one.

Apart from that, this technique will only be able to correct those manufacturing problems that can be compensated with the circuit parts considered in the process (in this case the rectangular metal insertions). Therefore, the best achievable result will be similar to the one obtained in the tuning process of a filter or multiplexer, where real tuning and coupling screws are used instead of fixed insertions. This means that if, for example, there are important errors in the fabrication of the irises, which could lead to a significant variation of the bandwidth, it may not be possible to correct the related response deviations perfectly. Nevertheless, given that case, the technique would be able to significantly improve the initial response of the original manufactured device.

VI CONCLUSIONS

A novel technique to correct manufacturing tolerances in the production of waveguide filters and manifold multiplexers has been proposed, which allows to avoid the inclusion of tuning screws, replacing them by fixed rectangular-shaped metal insertions. In this case, the tuning process of the screws is substituted by the manufacturing of these insertion pieces in an iterative process. The aggressive space mapping technique is employed to design these pieces, thus being able to finally achieve the desired response.

The procedure has been initially validated with a CWDM filter. A total of three space mapping iterations have been performed. A significant improvement has been observed between the measurements of the original prototype and the measured results corresponding to the third space mapping iteration. Additionally, the correction process has also been applied to a manifold multiplexer with 8 CWDM filters, showing very good results after performing just one iteration. The same technique could be easily extended to other type of waveguide filters and multiplexers.

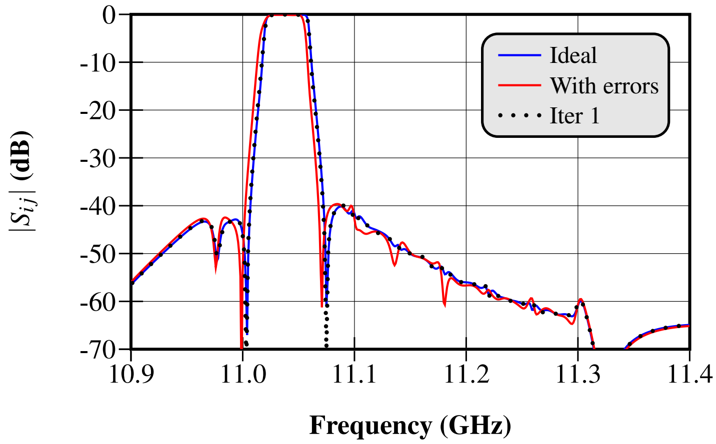

Figure 14: Transmission response of the second channel of the corrected multiplexer (including manufacturing errors), compared with the simulated response of the original design, and the one of the multiplexer with the simulated errors.

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