Analysis, Design, and Experimental Verification of Microwave Filters for Safety Issues in Open-Ended Waveguide Systems

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***Abstract*—Safety issues must be seriously considered in the practical implementation of microwave industrial systems with open ports. To preserve the radiation of these open-ended waveguide systems into permissible levels, bandstop microwave filters are widely used. In this paper, the accurate analysis, design, and experimental verification procedure of such filters are extensively studied. A singly and a doubly corrugated filter for continuous flow microwave industrial systems are designed. Two prototypes of such devices have been manufactured and experimentally verified.**

***Index Terms*—Admittance matrix representation, bandstop filters, filter design, microwave measurements, safety.**

I. Introduction

MICROWAVE energy is currently used in many widespread applications, such as medicine, radar based systems, mobile communications, and industrial processes [1]. In many of these applications, open-ended waveguide systems are usually employed since microwaves must interact dynamically with the matter to be processed. A major concern in such systems is the hazardous effect of microwave energy leakage on human tissues [2]. Attempts to maintain this radiation effect into permissible levels have been proposed in the technical literature [3]. A very effective solution already proposed in [4], and commonly used in many practical systems, is based on corrugated reactive filters (see Fig. 1). These structures reflect back the energy escaped from the microwave applicator by offering an open circuit to such energy; thus, also improving the efficiency of the system.

The analysis and design of corrugated filters have traditionally been performed by an approximate method based on monomode equivalent circuits [5], [6]. Provided that the validity restrictions of the monomode representation are satisfied, the method is accurate enough for singly corrugated filters. However, it does not give very precise results for more complex structures, such as the doubly corrugated configurations [4]. In this paper, a multimode analysis method based on the generalized admittance matrix (GAM) representation, recently reported in [7], is proposed for the accurate analysis of singly and doubly corrugated filters. Additionally, a more precise design technique of such structures is also described. This technique exploits the accuracy and efficiency of the new analysis method proposed in order to refine the initial solution provided by the traditional design method.

In the design procedure of microwave filters for safety issues, a very important aspect is the accurate verification of the electrical specifications by the proposed structure. For instance, the precise measurement of the electrical response of corrugated filters cannot be fully accomplished with a network analyzer since the measuring configuration does not reflect the real working conditions of such filters (the effect of free-space radiation is not considered). Furthermore, conventional calibration techniques of network analyzers require standard dimensions for the input and output ports of the filters to be measured, and also requires that only the fundamental mode propagates at the measurement reference planes [8]—conditions that are not always satisfied in many practical applications. An alternative solution that overcomes the previous limitations is based on measurements performed in anechoic microwave chambers. This measuring technique has recently been proposed in [9] for the particular case of guided-mode resonance transmission filters. In this paper, a novel verification procedure of open-ended waveguide filters in anechoic microwave chambers is also presented.

This paper is organized as follows. In Section II, the new analysis method proposed for corrugated filters is fully described, whereas the more effective design technique based on such analysis method is outlined in Section III. Next, the novel experimental verification procedure in anechoic microwave chambers is detailed in Section IV. Section V first validates the analysis method previously described by considering two application examples already reported in the literature. A CPU time comparative study between the new analysis technique proposed and a commercial simulator is also included. The design and experimental verification procedure of a singly and a doubly corrugated filter for microwave industrial systems are then presented. Two prototypes of such devices have been manufactured and measured, thus confirming the validity of the analysis, design, and measuring techniques proposed in this paper.

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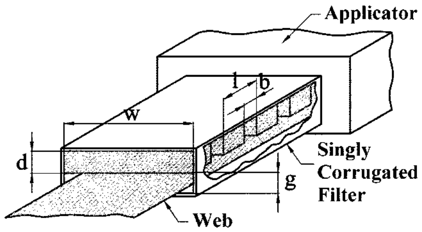
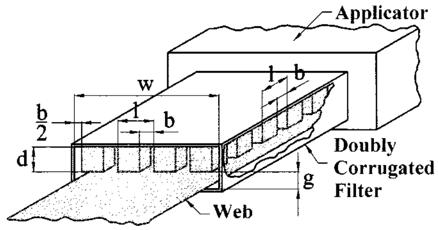


(a)



(b)

Fig. 1. (a) Singly and (b) doubly corrugated filter under consideration.

II. Analysis Method

The structures under consideration are the singly and doubly corrugated filters shown in Fig. 1(a) and (b), respectively. To analyze these filters, they are decomposed into planar waveguide junctions and sections of uniform waveguide interconnecting them. For the accurate and efficient characterization of these two basic building blocks, the GAM formulation is chosen.

Any planar waveguide junction can be easily modeled by a GAM representation following the efficient method recently proposed in [7]. As a result, the admittance matrix elements take the following form:

$$Y_{m,n}^{(1,1)} = (-j)Y_{0n}^{(1)} \cot(\beta_m^{(1)} l_{\mathrm{ref}})\delta_{m,n} \tag{1}$$

$$Y_{m,n}^{(2,1)} = Y_{n,m}^{(1,2)} = jY_{0n}^{(1)} \csc(\beta_n^{(1)} l_{\mathrm{ref}})\langle \mathbf{h}_n^{(1)}, \mathbf{h}_m^{(2)} \rangle \tag{2}$$

$$Y_{m,n}^{(2,2)} = (-j) \sum_{r=1}^{\infty} Y_{0r}^{(1)} \cot(\beta_r^{(1)} l_{\mathrm{ref}})\langle \mathbf{e}_r^{(1)}, \mathbf{e}_n^{(2)} \rangle \langle \mathbf{h}_r^{(1)}, \mathbf{h}_m^{(2)} \rangle \tag{3}$$

where $\mathbf{e}_p^{(\delta)}$ and $\mathbf{h}_p^{(\delta)}$ are, respectively, the transverse electric and magnetic normalized vector-mode functions of the pth mode in region δ ($\delta = 1$ for the waveguide with bigger cross section or $\delta = 2$ for the smaller waveguide in the junction), $\beta_p^{(\delta)}$ and $Y_{0p}^{(\delta)}$ represent the propagation constant and characteristic admittance of the pth mode in region δ, l_{ref} is a reference length in the bigger waveguide, and $\delta_{m,n}$ represents the Kronecker delta. All the TE and TM modes in (1)–(3) are sorted according to their increasing cutoff wavenumber.

From (1) to (3), it is obvious that the main computational effort comes from the evaluation of the $Y_{m,n}^{(2,2)}$ elements because they involve series to be evaluated at each frequency point. The number of terms to be considered in such series is determined through convergence studies. For the planar waveguide junctions involved in the structures considered in this paper, practical studies have revealed that 400 terms are required to obtain convergent results. This computational effort can be reduced dramatically following the acceleration technique proposed in [10], which consists on extracting the frequency dependence of the aforementioned series. Using this technique, the frequency computations required to evaluate the $Y_{m,n}^{(2,2)}$ elements are essentially reduced to adding, at most, ten terms.

As is evident from (1)–(3), the proposed analysis technique requires to know the modal spectrum of both waveguides involved in any planar junction, as well as the modal coupling coefficients between these two sets of modes. This modal information can be obtained analytically for waveguides with standard cross section, such as the rectangular ones. Unfortunately, the junctions present in the doubly corrugated filters always imply multiridged waveguides. The modes of such waveguides and the coupling integrals required are obtained efficiently implementing the method fully described in [11] and [12]. This procedure consists essentially of rewriting the Helmholtz equation in a form that gives rise to a linear matrix eigenvalue problem once the Galerkin method is used to obtain the modal solution. After some post-processing of the matrices already used to find the modes, the algorithm then also allows to compute straightforwardly the coupling integrals required.

The sections of uniform waveguide connecting the planar waveguide junctions of the structure are also characterized by a GAM representation. According to [13], the admittance parameters are given by the well-known expressions

$$Y_{m,n}^{(1,1)} = Y_{m,n}^{(2,2)} = (-j)Y_{0n}^{(1)} \cot(\beta_n^{(1)} l_{\mathrm{wg}})\delta_{m,n} \tag{4}$$

$$Y_{m,n}^{(2,1)} = Y_{m,n}^{(1,2)} = jY_{0n}^{(1)} \csc(\beta_n^{(1)} l_{\mathrm{wg}})\delta_{m,n} \tag{5}$$

where l_{wg} now represents the waveguide section length.

After cascading the admittance matrices, which represent the basic building blocks of the structure considered, and applying the corresponding load conditions, a banded linear system is finally obtained. For the solution of this system, a very efficient iterative technique, which fully exploits its banded nature, has been implemented (see explicit details in [14]).

The efficiency of the analysis technique proposed also depends on the number of interacting modes chosen at the waveguides of the structure. Such a number must be determined in order to obtain accurate results, and it is practically derived from convergence studies of the S-parameters of the whole structure. In Section V, the number of interacting modes required by each one of the filters considered in this paper can be found.

III. Design Technique

As can be seen in Fig. 1(a), a singly corrugated filter is a periodic cascade of pure capacitive steps in rectangular waveguide, which allows to eliminate only the radiation of open-ended waveguide systems related to the fundamental mode (i.e., TE_{10}). For the design of these devices, the traditional method described, for instance, in [6], is initially chosen since it provides good results in most practical situations.

The traditional design method is based on a monomode equivalent representation of all the elements integrating the structure. Therefore, the E-plane T-junctions of the structure are modeled by the monomode equivalent circuit proposed in [15], whereas the rectangular waveguides interconnecting such T-junctions are represented by a simple transmission line related to the fundamental mode. Exploiting the periodicity of the monomode equivalent circuit of the filter, the image method described in [16] is then used to determine a simple expression for the attenuation response

$$\alpha(\mathrm{dB}) = 8.686\, n\, \mathrm{acosh}\left(\left|\cos(\beta l') - \left(\overline{X}_T + m_T^2 \frac{b}{g}\tan(\beta d')\right) \cdot \frac{\sin(\beta l')}{2}\right|\right) \tag{6}$$

where n represents the number of sections (i.e., E-plane T-junctions) of the filter, β is the propagation constant of the fundamental mode, b and g are physical parameters of the filter shown in Fig. 1(a), and l', $\overline{X}_T$, m_T, and d' are electrical parameters derived from the equivalent circuit of a filter section [3], [15].

In order to maximize the attenuation response given by (6), it can be simply deduced that the d- and l-parameters must take the following values:

$$d = \left.\frac{\lambda_{g,TE_{10}^z}}{4}\right|_{f=f_0} - d_T \tag{7}$$

$$l = \left.\frac{\lambda_{g,TE_{10}^z}}{4}\right|_{f=f_0} + 2l_T \tag{8}$$

where f_0 is the central frequency of the stopband and d_T, l_T are again electrical parameters of the monomode equivalent circuit of the T-junctions, whose explicit expressions can be found in [15]. From such expressions, it is concluded that the values of d_T and l_T depend on the physical parameters g, w, and b. The g- and w-parameters are fixed by the material dimensions. With regard to the value of the b-parameter, it must be chosen in order to optimize (6), but taking care of not violating the validity range of the monomode equivalent circuit (a higher value of b implies a shorter distance between consecutive T-junctions, thus exciting higher order modes not considered in the model).

Finally, as can be deduced from (6), the number of sections n of the filter determines the level of attenuation, and it is, therefore, suitably chosen in order to fulfill the electrical specifications of the filter.

The values of the physical parameters given by the design technique are then inserted into the electromagnetic (EM) simulator based on the theory reported in Section II, and the response of the filter is finally refined with regard to specifications. This last step of the design technique can be of paramount importance in those cases where the validity restrictions of the monomode equivalent circuit of the structure are not satisfied.

On the other hand, a doubly corrugated filter has an additional set of longitudinal slots cut through the transverse corrugations, as can be seen in Fig. 1(b). If the center-to-center spacing of the resulting teeth is small in terms of the free-space wavelength, this structure will be essentially isotropic, and will have nearly the same characteristics for TEM waves propagating through it in any direction parallel to the web [5], [6]. Since any TE_{m0}^z mode can be decomposed into two of such TEM wave components, a doubly corrugated filter designed to reflect back these TEM waves can avoid the leakage of energy related to all TE_{m0}^z modes, which allows wider system ports very useful in many practical applications. Traditionally, the design procedure just explained for singly corrugated filters has also been employed for the doubly corrugated case, once the fundamental mode wavelength ($\lambda_{g,\mathrm{TE}_{10}^z}$) is replaced by the free-space wavelength (λ_0) corresponding to TEM waves [4]. Unfortunately, this design procedure of doubly corrugated filters is based on rough approximations and does not usually provide very accurate results. However, the physical dimensions given by such a design procedure can be used as a good starting point to optimize [with the help of a very accurate and efficient simulation tool (see Section II)] the geometry of the structure in order to fulfill the electrical specifications.

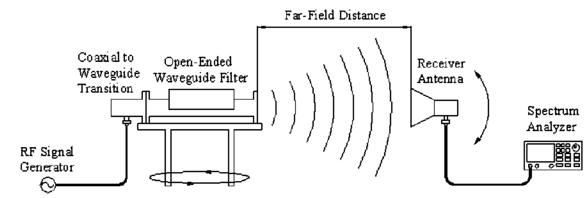


Fig. 2. Experimental setup for transmission measurements of open-ended waveguide filters in anechoic microwave chambers.

IV. New Experimental Verification Procedure

The new experimental setup implemented to characterize the transmission behavior of open-ended waveguide filters inside microwave anechoic chambers is depicted in Fig. 2. As we can see in this figure, the filter to be measured is fed by a coaxial-to-waveguide transition connected to an RF signal generator, which sweeps the whole frequency range of interest. The energy not reflected by the waveguide filter is radiated at free space through its open aperture. The receiver antenna, which is placed in the far-field region of the system aperture, must explore the power radiated by the filter in any space direction, and delivers it to a spectrum analyzer synchronized with the RF signal generator. In order to define a transmittance response of the filter, it is required that the experimental value be measured in the direction of maximum radiated power, which, for safety issues, must be kept within permissible levels.

To remove the systematic errors caused by the measurement system just described, a reference calibration standard must be chosen and measured. The calibration standard proposed is a uniform waveguide section whose aperture dimensions are the same ones of the entry and exit ports of the filter to be measured. The length of the reference waveguide must be equal to the total length of the waveguide filter, so as to keep the same distance between the radiating aperture and the antenna in both measurements. The power radiated by the calibration standard must be measured again in all space directions, and the maximum value obtained is used to normalize the power emitted by the filter in its direction of maximum radiation. The resulting value is the transmittance response of the open-ended waveguide filter, which provides the attenuation level introduced by the filter structure under more "real" working conditions.

For those open-ended waveguide filters that only support the fundamental mode, it is obvious that the directions of maximum radiated power by the filter and the calibration standard will agree (normal to the aperture), thus simplifying the measuring procedure previously described. Furthermore, in such cases, the measured transmittance response should be similar to the well-known S_{21}-parameter. This property has been used in Section V to validate the new verification procedure proposed in this paper. Moreover, this procedure could be effectively used to measure the transmission behavior of the aforementioned filters with nonstandard dimensions for the input and output ports.

On the other hand, if higher order modes are supported by the system, the directions of maximum radiated power by the filter and the calibration standard can be different, and none of them has to be normal to the aperture. Nevertheless, the previous definition of the transmittance response of the filter is also meaningful since it provides the effective reduction on the maximum radiated power by the open-ended system.

V. Results

The goal of this section is to fully validate the analysis method, design technique, and new experimental verification procedure proposed in this paper. To accomplish this objective, we first consider a singly and a doubly corrugated filter already studied in the technical literature. Secondly, the property of modal independent stopband response of doubly corrugated filters for any TE^z_{m0} excitation is proven. Next, a singly and a doubly corrugated filter for safety issues in open-ended microwave industrial systems are designed, manufactured, and finally measured.

A. Validation Results

The first structure considered is the pure capacitive filter in WR75 waveguide illustrated in Fig. 3(a). The simulated response of the reflection coefficient provided by our simulation tool is shown in Fig. 3(b), where it is compared with numerical and experimental results from [17]. An excellent agreement between our results and those of [17] can be observed, thus fully validating the analysis tool developed for singly corrugated filters. Note, even that the narrow transmission resonance produced at about 14.75 GHz is only predicted correctly by our analysis technique.

In order to obtain the very accurate results of Fig. 3(b), only the TE^z_{1n} $(n = 0, 1, \ldots, 7)$ and TM^z_{1n} $(n = 1, 2, \ldots, 7)$ modes have been considered at each waveguide of the filter. The full-wave analysis of this structure has required 0.0034 s per frequency point on a Cray Silicon Graphics Origin 2000 platform.

The second validation structure is a doubly corrugated filter composed of five rows of three blocks affixed to the upper wall of a WR340 waveguide. The physical parameters of the structure are given in Table I. In Fig. 4, we compare the results given by our analysis method with the theoretical and experimental results reported in [4]. As can be seen in this figure, a very good agreement between our results and the measurements is obtained in the whole band of interest, whereas a certain misalignment between such measurements and the theoretical results from [4] is detected in the higher frequency range. These results reveal the necessity of using analysis methods such as

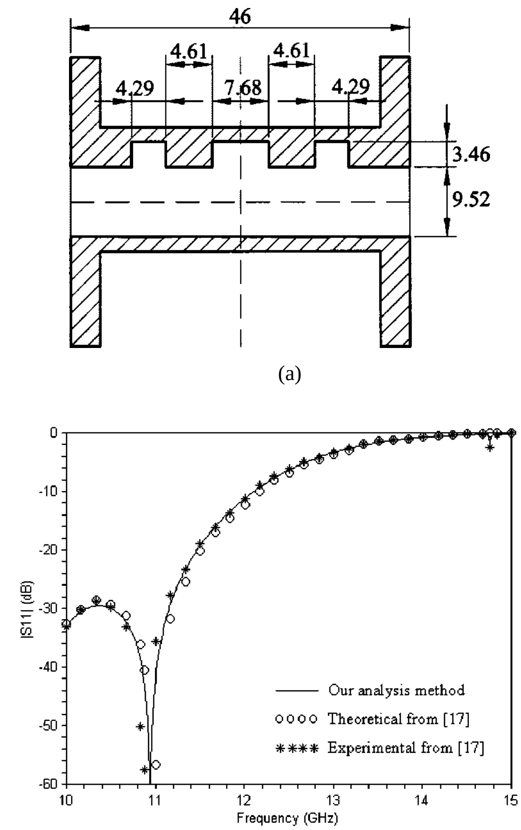


Fig. 3. Reflection coefficient (S_{11}-parameter) of the pure capacitive waveguide filter in (a). The solid line represents our simulated results, while the stars and circles reproduce the experimental and numerical responses from [17], respectively. All dimensions in (a) are in millimeters.

TABLE I
GEOMETRY OF THE DOUBLY CORRUGATED FILTER CHOSEN AS A VALIDATION EXAMPLE IN FIG. 4

blocks	3x5	w (mm)	86.36
g (mm)	14.88	l (mm)	28.79
d (mm)	28.30	b (mm)	9.74

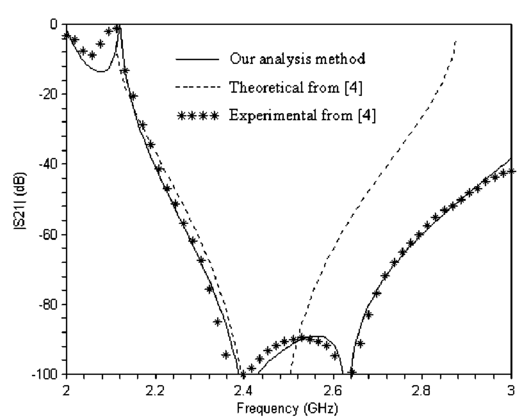


Fig. 4. Transmission coefficient (S_{21}-parameter) of the doubly corrugated filter described in Table I. The solid line indicates our results, with dashed lines and stars representing the theoretical and experimental results from [4], respectively.

TABLE II
GEOMETRY OF THE DOUBLY CORRUGATED FILTER THAT REJECTS THE ENERGY RELATED TO THE TE^z_{10} AND TE^z_{20} EXCITATION

blocks	10x5	w (mm)	172.72
g (mm)	13.97	l (mm)	17.27
d (mm)	29.21	b (mm)	6.29

the one proposed in this paper for the accurate full-wave characterization of doubly corrugated filters.

For obtaining the accurate numerical results of Fig. 4, the first 60 TE^z and TM^z modes (sorted according to their increasing cutoff wavenumber) have been considered in each waveguide of the filter. The numerical computations were performed again on a Cray Silicon Graphics Origin 2000 platform. The full-wave analysis of the whole structure only required a CPU time of 0.288 s per frequency point.

Next, the property of modal independent stopband response of doubly corrugated filters is verified. For that purpose, a filter with the geometry described in Table II is considered, which has been designed to reject the energy related to the TE^z_{10} and TE^z_{20} modes propagating through the access ports in the band of interest. In Fig. 5, our simulated results for the magnitude of the transmission responses of the filter for both modes are plotted. As can be seen in this figure, the curves for both modes exhibit a very similar shape, and the transmission zeros and poles are placed at very close frequency points. The responses mainly differ in the attenuation level, which can be attributed to the different incident angles of the TEM waves related to the TE^z_{10} and TE^z_{20} modes. In fact, the higher the order of the mode, the higher the incident angle, thus increasing the number of corrugations to be crossed. The authors would like to remark that they have also numerically proven that there is no transmission coupling between the two aforementioned modes.

The previous example has also been simulated with the commercial software HFSS[1] and, for comparative reasons, the results obtained have been included in Fig. 5. The comparison reveals a good agreement between our results and the HFSS data, although a slight deviation in frequency is observed between both responses. Such deviation can be due to the fact that the results provided by the finite-element commercial simulator are still not accurate enough. Nevertheless, the authors have observed that the results provided by HFSS converge slowly to their results if higher accuracy is requested.

A final study in terms of the computational effort required to solve the last example has also been performed. To obtain the very accurate results of Fig. 5, our software tool has considered again the first 60 TE^z and TM^z modes in each waveguide of the structure, thus giving place to a CPU time of 0.888 s per frequency point on a Silicon Graphics Origin 2000 platform. On the other hand, the HFSS results required a CPU cost of 789 s per frequency point on a Sun Enterprise 3000 workstation. This impressive result allows us to conclude that the code developed in this paper can be suitably used not only for analysis purposes, but also for real-time design procedures, where the use of very efficient analysis tools is a critical requirement.

[1]HFSS, HP-EEsof, Hewlett-Packard Company, Santa Rosa, CA 1998.

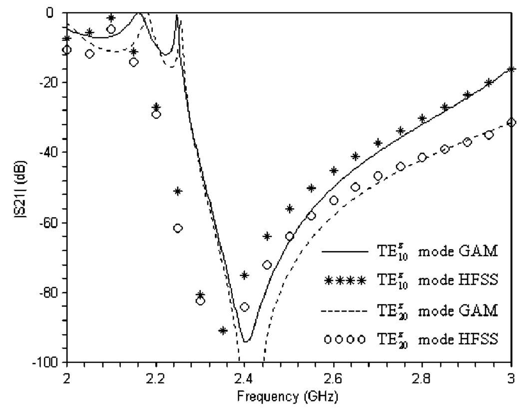


Fig. 5. Transmission coefficient (S_{21}-parameter) of the doubly corrugated filter described in Table II. The solid and dashed lines represent our transmission responses for the TE^z_{10} and TE^z_{2} modes, respectively. The stars and circles represent the same responses provided by the commercial software HFSS.

TABLE III
GEOMETRY OF THE SINGLY CORRUGATED FILTER MANUFACTURED

sections	3	w (mm)	86.36
g (mm)	20.00	l (mm)	48.46
d (mm)	41.64	b (mm)	24.00

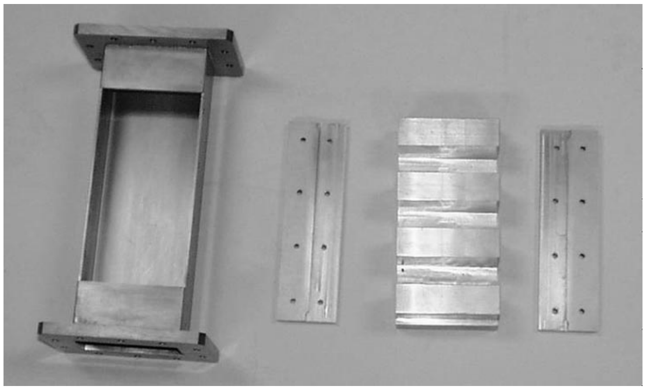
B. Design and Experimental Verification of a Singly and Doubly Corrugated Filter

A singly and doubly corrugated filter for open-ended microwave industrial systems have been designed. The electrical requirements for both filters are a high attenuation level (greater than 60 dB) and a wide (about 150 MHz) stopband response centered at 2.45 GHz. The dimensions of the material to be processed fix the values of 20 and 86.36 mm for the g- and w-parameters, respectively. These dimensions of the system gap (see Fig. 1) only allow the propagation of the fundamental mode (i.e., TE^z_{10}) at the access ports of the filters in the operating frequency range.

The design procedure of singly corrugated filters explained in Section III provides the optimum section length and corrugation height (l- and d-parameters) once the remaining physical parameters (g, w, and b) are known. Since the g- and w-parameters are fixed by the material dimensions, the key point of the design procedure is the correct determination of the b-parameter. After performing an optimization strategy of the filter response, a final value of 24.00 mm was obtained for the b-parameter. Finally, three corrugated sections was revealed to be enough in order to satisfy the electrical specifications. The final values of all the design parameters are shown in Table III.

The singly corrugated filter designed has been manufactured and terminated with standard WR340 waveguides for measuring reasons (see pieces and final aspect of the manufactured filter in Fig. 6(a) and (b), respectively). In Fig. 6(c), the simulated response of the filter is compared with measurements performed with a network analyzer. From such a figure, it can be concluded that the analysis and design techniques of singly corrugated filters proposed in this paper are extremely accurate.

For the doubly corrugated filter, the traditional design procedure is used to determine an initial approach of the physical



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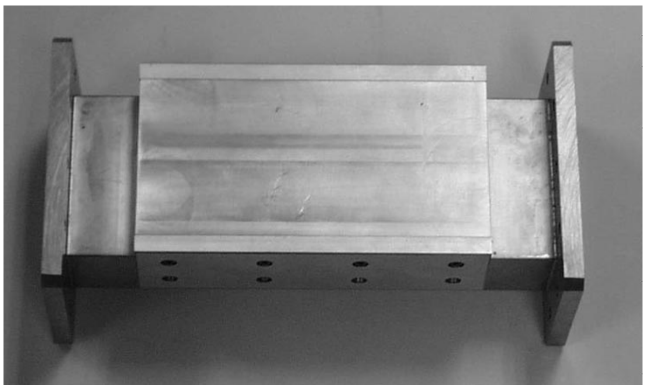

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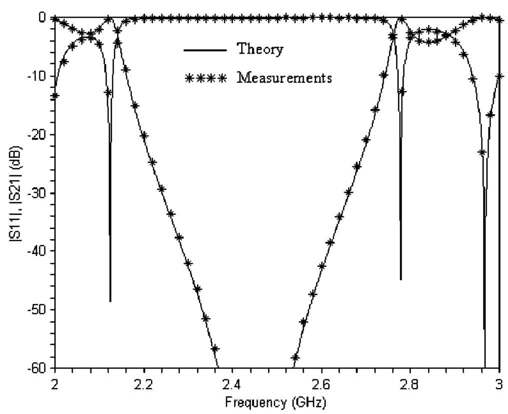


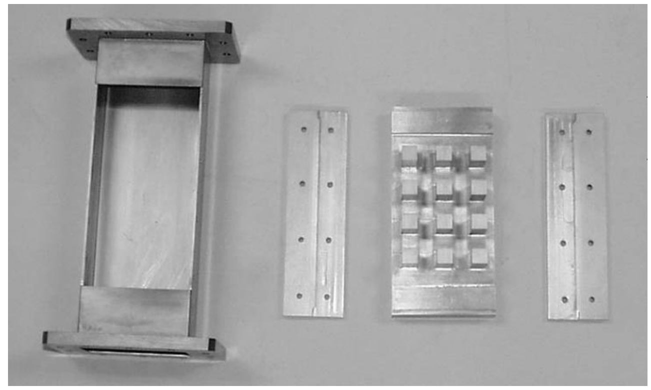
(c)

Fig. 6. Magnitude of the scattering parameters of the singly corrugated filter manufactured. (a) Pieces of the filter. (b) General view of the whole structure. (c) Solid lines indicate our simulated results, and the stars are our own measured results.

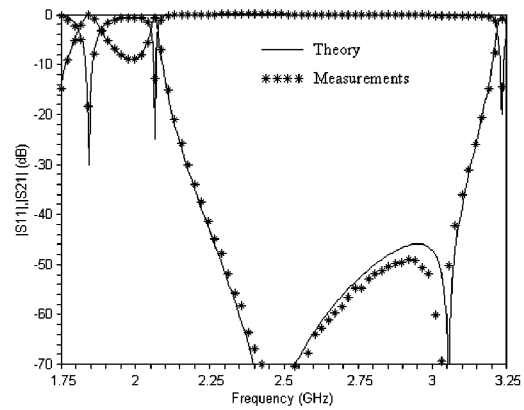
TABLE IV
GEOMETRY OF THE DOUBLY CORRUGATED FILTER MANUFACTURED

blocks	3x4	w (mm)	86.36
g (mm)	20.00	l (mm)	28.79
d (mm)	28.39	b (mm)	16.00

parameters. Using a refined optimization procedure, the final geometry defined in Table IV is then obtained. The designed device has been manufactured and also terminated with two standard WR340 waveguides, now located at a distance of 16 mm from the first and last row of bosses. A top view of the pieces integrating the filter is shown in Fig. 7(a). The simulated re-



(a)



(b)

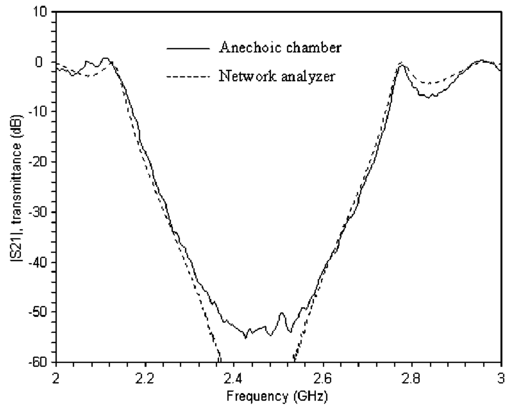
Fig. 7. Magnitude of the scattering parameters of the doubly corrugated filter manufactured whose pieces are shown in (a). (b) Solid lines indicate our simulated results, and the stars are our own measured results.

sults for the magnitude of the scattering parameters of the filter are shown in Fig. 7(b), where they are compared with measurements performed in the laboratory. As can be seen in this figure, simulated and measured results agree quite well, thus fully con-firming the accuracy of the analysis tool and design technique employed.

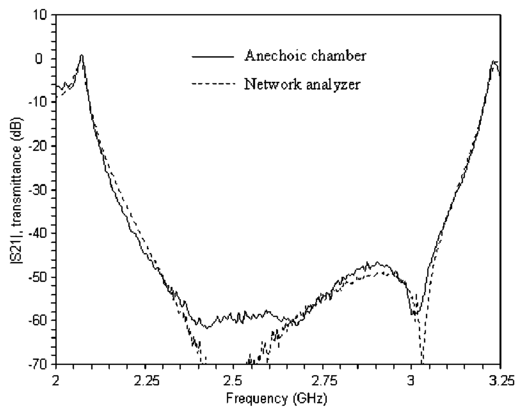
In order to know a more "real" transmission response of the two previous filters, that is taking into account the effect of the radiation into free space, both manufactured filters were measured inside an anechoic microwave chamber following the experimental verification procedure previously proposed in Section IV. In Fig. 8(a) and (b), a comparison between the transmittance response obtained in the anechoic chamber and the S_{21}-parameter provided by the network analyzer is presented for the singly and doubly corrugated case, respectively. Although, in both cases, the two experimental results were obtained under nonidentical load conditions, the agreement between them is indeed very good. These results confirm the good behavior of both filters even under more "real" working conditions, and additionally allow to validate the new experimental procedure in anechoic chambers proposed in this paper.

VI. Conclusion

In this paper, the very important topic of microwave filters for safety issues in open-ended waveguide systems has been



(a)



(b)

Fig. 8. Measured responses of the: (a) singly and (b) doubly corrugated filters. (a)–(b) Solid lines represent the measurements obtained in the anechoic microwave chamber, and the dashed lines represent the measured results with the network analyzer.

studied. For the most widely used structures, i.e., the singly and doubly corrugated filters, a full-wave analysis method based on the GAM representation has been proposed. The accuracy and efficiency of this analysis technique have been verified with two application examples already considered in the technical literature, and with a third example also characterized with a commercial simulator (HFSS). Next, a more accurate design technique based on traditional strategies and the new analysis method has been fully described. The effectiveness of such procedure has been validated with the practical design of a singly and a doubly corrugated filter for continuous flow microwave industrial systems, which have finally been manufactured and measured. Furthermore, a novel experimental verification procedure of open-ended waveguide filters in anechoic microwave chambers is proposed and successfully proven. The value of this paper is that the analysis, design, and experimental verification techniques proposed can be effectively applied to future guided solutions for reducing the leakage of microwave energy.

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