Automated Design of Corrugated Feeds by the Adjoint Network Method

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***Abstract*— Automated full-wave design of corrugated feeds is generally accomplished by repeated numerical analysis of different feed geometries as obtained by slightly varying the geometrical dimensions of the corrugations. Since a corrugated feed contains hundreds of discontinuities, the above procedure is very time-consuming. In order to reduce the numerical effort, the adjoint network method (ANM) has been applied to the design and sensitivity analysis of circular corrugated feeds radiating into free space. By using the ANM, the return loss sensitivities with respect to variations of *all* geometrical dimensions are obtained with *just one* analysis of the entire feed. When a geometrical parameter is varied, only the discontinuity containing that parameter need to be analyzed; the overall sensitivities being computed by means of a simple formula. Corrugated feeds with more than 100 corrugations have been designed by using the ANM. They have been built and measured demonstrating the efficiency of the proposed approach.**

***Index Terms*—Adjoint network method, corrugated feeds sensitivities, modal analysis, tolerance analysis.**

I. Introduction

Satellite communication antennas require keen performances in terms of return loss, polarization purity, high power handling capability, and low intermodulation products [1]–[3]. As a consequence, all the relative subsystem, including the feed, must be designed so as to satisfy the antenna specifications. A severe control is also required for the shape of the feed radiation pattern, in terms of amplitude, phase, cross-polar peak, and return loss, often over a band more than 30% wide.

Given this scenario, it is not surprising that efficient full-wave electromagnetic simulators, rigorously accounting for all the electrical phenomena, are employed in order to analyze and design the feed structure. Recently, an automated design environment of this kind (i.e., including modal analysis of conical corrugated feed, free-space radiation, appropriate optimization techniques, and yield analysis of manufacturing tolerances) has been set up and tested for several cases, allowing a considerable reduction of design time and costs.

This paper presents the procedures developed in order to design feeds and the techniques used for optimizing their performances toward prescribed values. Of fundamental importance in this context is the use of the Cohn's sensitivity theorem applied to the full-wave analysis of microwave circuits. As noted in [4, p. 80], Cohn established and used in [5] what amounts to be the Tellegen theorem [6], [7] two years before Tellegen. Later, thanks to the work of Director and Rohrer [8] the latter theorem became a basic tool in the computer-aided sensitivity analysis of electrical circuits.

The pioneering work of Bandler [9]–[12] has paved the way to the application of sensitivity analysis and optimization of large microwave systems [13]. Although the sensitivity theorem has found wide applications for electrical circuits [4], its use in the full-wave analysis of complex microwave circuits is rather new. Up to this present time, a few applications have been made in [14]–[16] by considering common microwave components such as filters, multiplexers, etc.

In this paper, the authors apply the adjoint network method (ANM) to radiating structures, by introducing a way to account for radiation losses. Despite its importance, this subject has received modest attention thus far. In fact, historically, a great interest has been devoted to the calculation of radiation properties of hollow pipes and horns (see [17]–[21]). However, the problem of the efficient computer-aided design (CAD) of corrugated horns has not been addressed, apart from a few exceptions, as in [22]–[24].

In [14], the ANM has been used in conjunction with the generalized admittance matrix (GAM) analysis method in order to develop efficient optimization routines for filters in rectangular waveguides. In this paper, the authors apply the sensitivity theorem together with the more commonly used approach based on the generalized scattering matrix (GSM) to the design of corrugated circular feeds. For example, with the proposed method, return loss sensitivities with respect to the variation of *all* geometrical parameters can be computed with *just one analysis* of the entire network, irrespective of the number of geometrical parameters. Note that on the contrary, in standard approaches based on numerical evaluation of the derivatives, each derivative requires a distinct analysis of the entire feed.

The results obtainable by the proposed approach are illustrated by the example of a corrugated horn operating in the frequency range of 10.70–14.50 GHz. This feed, which is shown in Fig. 1, has been designed, manufactured, and measured, providing excellent agreement between theoretical and measured data, as well as very good performances in terms of low return loss (less than −34 dB) and low cross-polarization (better than −41 dB) over the band of interest.

In Section II, the overall design procedure is briefly outlined, while Section III is devoted to a formulation of the sensitivity theorem suitable for antenna feeds. Finally, the theory is applied to the solution of a practical case for which experimental and numerical results are compared and discussed.

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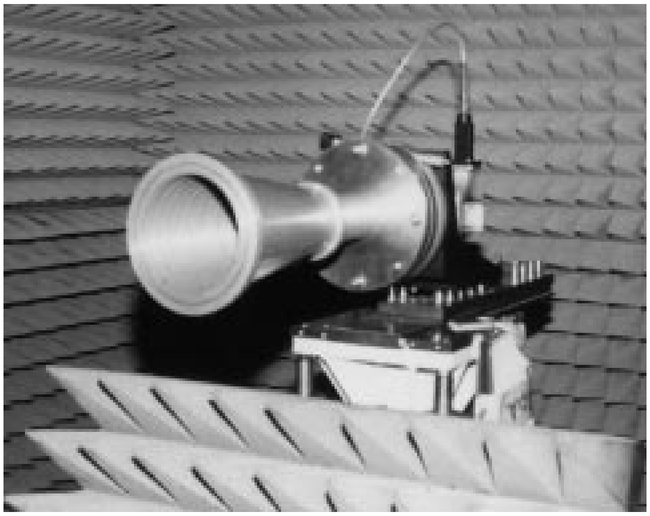

Fig. 1. Photograph of the conical corrugated feed.

II. Automated Design Procedure

For reference convenience, the automated design procedure may be divided into the following three main parts.

1) Preliminary determination of the dimensions of the feed, which are evaluated by using analytical methods (surface impedance approximation, space harmonic analysis). At this time, an error function relative to the desired performance is also defined.
2) Optimization of the dimensions of the inside corrugations. This optimization is based on the full-wave characterization of the various discontinuities as obtained by standard modal analysis technique. The optimization algorithm is a quasi-Newton search method for the minimum of the error function. It is possible to optimize either all the corrugations or only a limited number of them. It is also possible to optimize the corrugation depth only, its thickness, or both quantities.
3) Overall evaluation of effects of the manufacturing tolerances by a sensitivity analysis and by a statistical method.

The first part provides the dimension of the aperture, the type of feed (either narrow flared, wide flared, multiflared, profiled, dual depth, axially corrugated, etc.) and the length of the feed. The initial number of corrugations are also chosen according to analytical considerations.

The initial optimization acts on a small number of parameters such as flare angles, aperture diameter, number of corrugations, groove depths, groove-ridge ratio for the throat, and flared section.

A subsequent optimization starts from the geometry previously obtained and considers all the dimensions of the corrugations by using the GSM of the various discontinuities. Finally, a sensitivity analysis with respect to changes of the geometrical dimensions is performed.

From the above description it is apparent that optimizations and sensitivity analyses (i.e., the evaluation of how the response changes when one geometrical parameter is altered) play a fundamental role in the design procedure. The key factor in order to efficiently accomplish these evaluations is the use of the Cohn's sensitivity theorem joined with the overall description of the circuit by the GSM. This is described in the next section.

III. Application of the Sensitivity Theorem to the Feed Design

A. External Ports

Before applying the ANM it is necessary to define the quantities with respect to which one needs to perform optimization and tolerance analyses. For a typical feed these quantities are:

- return loss;
- radiation pattern.

In order to extract information on these quantities one needs to define the so-called *external ports*.

The external port relative to return loss is that port connecting the input guide, see Fig. 4, with the feed structure. It is noted that just one electrical port is needed (i.e., just one mode) provided the reference plane is placed far enough away from the feed discontinuities.

Radiated power depends on both the field distribution on the aperture and the current distribution on the outer wall of the feed. In order to analyze the feed a combined fields integral equation is used, as proposed in [22], which allows to optimize both the current distributions on the outer wall of the feed and the electric field distribution on the aperture. For ease of exposition, the authors will refer in the following to only the electric field on the aperture, the extension to radiation from currents being straightforward. The aperture electric field, $\mathbf{E}$, may be expressed as a modal sum; by denoting with $\mathbf{e}_n$ the nth mode of the circular waveguide on the aperture, it may be written as

$$\mathbf{E} = \sum_{n=1}^{N} V_n \mathbf{e}_n \tag{1}$$

where the V_n are the amplitudes of the modal components and the sum has been truncated to N terms. Each mode generates a radiated field; hence, by indicating with $\mathbf{f}_n$ the far-field transform of the mode $\mathbf{e}_n$, the radiated electric field $\boldsymbol{\mathcal{E}}$ is given by

$$\boldsymbol{\mathcal{E}} = \sum_{n=1}^{N} V_n \mathbf{f}_n. \tag{2}$$

Note that since the aperture dimensions are considered as fixed, the variation of geometrical parameters inside the feed only affects the amplitude coefficients V_n. In order to evaluate the sensitivities of the radiated field, one needs to calculate the sensitivities of V_n with respect to variations of the geometrical parameters. To this end, one needs to place external ports on the radiating aperture. The voltages at these external ports are those appearing in (1) and (2). The network performing the task of collecting the voltages on the aperture has been called the "output reference" network; it is simply made by open-circuited ports. The use of this network when applying the ANM will become clearer in the following two subsections.

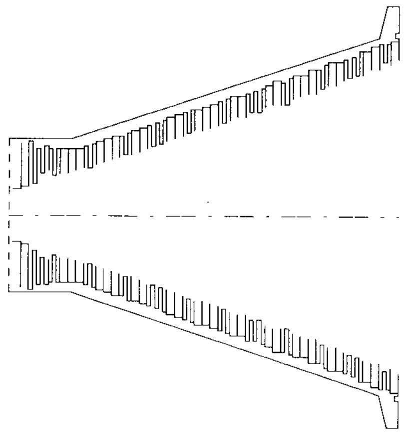

Fig. 2. Cross section of a corrugated horn. Although the design is not in scale, the number of corrugations is that effectively used.

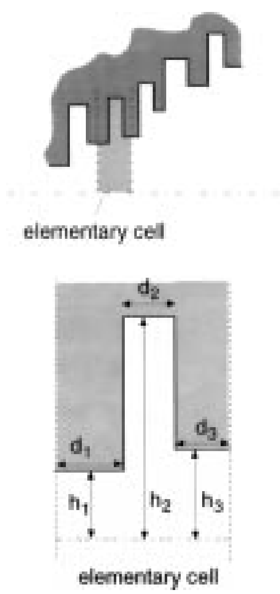

Fig. 3. A section of the corrugated feed showing the definition of the elementary cell is plotted on the left side. On the right side, the geometry of the elementary cell is shown. As is apparent, there are six geometrical parameters with respect to which optimization is possible. d_1, d_3 are half the distance between two adjacent stubs; h_1, h_2, h_3 are the radii of the circular waveguides.

B. Circuit Analysis

A corrugated circular feed, as shown in Fig. 2, is entirely made by step discontinuities in circular waveguides and by sections of waveguide. As will be apparent in the following, it is convenient to consider as *elementary cell* the structure shown in Fig. 3 (i.e., two step discontinuities and three sections of waveguide). Note that each elementary cell may be represented by a network, with ports corresponding to the selected accessible modes. As a consequence, the feed, together with input waveguide and the radiating aperture, is represented by the cascaded networks shown in Fig. 4. Observe that the output reference network is just made by open-circuited ports in standard analysis; however, as one will see, for the ANM computations sources and matched loads are connected to it.

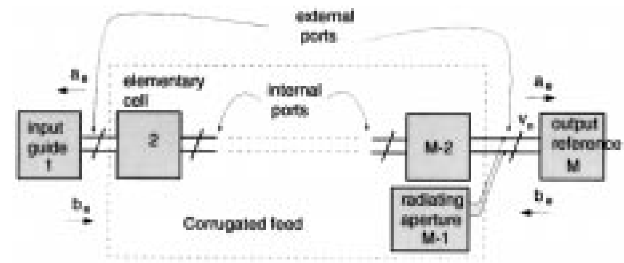

Fig. 4. Equivalent network for the application of the ANM to a radiating corrugated feed. For each network, the $\mathbf{a}^{(k)}$ represents the wave impinging on it and $\mathbf{b}^{(k)}$ the relative outgoing waves. Note that for the external ports, the external networks are taken as reference.

The relationship between incoming and outgoing waves for the kth network are given by

$$\mathbf{b}^{(k)} = \mathbf{S}^{(k)}\mathbf{a}^{(k)} + \mathbf{c}^{(k)} \tag{3}$$

where $\mathbf{a}^{(k)}$ represents the waves impinging on the kth network and $\mathbf{b}^{(k)}$ the relative outgoing waves. The term $\mathbf{c}^{(k)}$ takes into account possible generators present inside the kth network; in this case, it can be different from zero only for $k = 1$, i.e., for the input waveguide, and for the Mth network, which corresponds to the output reference network.

In order to make use of the sensitivity theorem, the basic idea is *to avoid solution of the network by cascading the various elements*. On the contrary, it is expedient to consider the *entire* network by introducing the arrays

$$\mathbf{a} = \begin{bmatrix} \mathbf{a}^{(1)} \\ \mathbf{a}^{(2)} \\ \vdots \\ \mathbf{a}^{(M)} \end{bmatrix} \qquad \mathbf{b} = \begin{bmatrix} \mathbf{b}^{(1)} \\ \mathbf{b}^{(2)} \\ \vdots \\ \mathbf{b}^{(M)} \end{bmatrix} \qquad \mathbf{c} = \begin{bmatrix} \mathbf{c}^{(1)} \\ \mathbf{c}^{(2)} \\ \vdots \\ \mathbf{c}^{(M)} \end{bmatrix} \tag{4}$$

and the global GSM given by

$$\mathbf{S} = \begin{bmatrix} \mathbf{S}^{(1)} & & & \\ & \mathbf{S}^{(2)} & & \\ & & \ddots & \\ & & & \mathbf{S}^{(M)} \end{bmatrix}. \tag{5}$$

By using the above definitions one may write

$$\mathbf{Sa} + \mathbf{c} = \mathbf{b}. \tag{6}$$

In order to solve for the amplitudes of the waves present in this actual circuit one has also to consider the *interconnection matrix* $\mathbf{\Gamma}$ (see [26, Sec. 3.2.1]) which describes the relationship between incoming and outgoing waves at the ports of the networks connected together. Such a matrix is sparse, made by 0 and 1 only, and provides a relationship of the type

$$\mathbf{b} = \mathbf{\Gamma a}. \tag{7}$$

The last two equations relate the amplitudes of the waves at each port of the whole network to the excitations provided by the generators, as

$$\mathbf{c} = (\mathbf{\Gamma} - \mathbf{S})\mathbf{a}. \tag{8}$$

Hence, in order to find the wave amplitudes at *all* ports in this circuit one needs to solve the above system for the given excitations. However, since the matrix $\mathbf{\Gamma} - \mathbf{S}$ is highly sparse, very efficient algorithms can be used for the system solution (see e.g., [26, Appendix II]). It is also interesting to note that although one is solving the entire network at once in order to expedite sensitivities' computations, the numerical efficiency of this type of analysis is the same as that obtained by cascading subnetworks.

C. Waves Sensitivities

In order to compute the sensitivities one makes use of the distinction between *internal* and *external* ports as shown in Fig. 4. For the external ports one takes as reference the external networks; thus incident and reflected waves are as illustrated in Fig. 4. By suitably numbering the various ports one may write the vectors $\mathbf{a},\ \mathbf{b},\ \mathbf{c}$ as

$$\mathbf{a} = \begin{pmatrix} \mathbf{a}_e \\ \mathbf{a}_i \end{pmatrix} \qquad \mathbf{b} = \begin{pmatrix} \mathbf{b}_e \\ \mathbf{b}_i \end{pmatrix} \qquad \mathbf{c} = \begin{pmatrix} \mathbf{c}_e \\ \mathbf{c}_i \end{pmatrix} \tag{9}$$

where the subscripts $e,\ i$ refer to external and internal ports, respectively. It is noted that, in the case considered, no generators are placed inside the feed so that $\mathbf{c}_i = 0$.

The quantities relative to the adjoint network are now introduced. For a reciprocal network, as in this case, the latter corresponds to the original one; hence, one may write the Tellegen theorem as [26, p. 125]

$$(\mathbf{b}_e)_j^T \left(\frac{\partial \mathbf{a}_e}{\partial p} \right)_i = \sum_{k=2}^{M-1} [\mathbf{a}^{(k)}]_j^T \frac{\partial \mathbf{S}^{(k)}}{\partial p} [\mathbf{a}^{(k)}]_i. \tag{10}$$

In the above, M is the number of networks, while p is the generic variable, e.g., it may be the guide height, the length of a corrugation, etc. The indices $i,\ j$ refer to the quantities calculated during the i and j analysis, respectively. A few words are in order to explain how to use (10).

One external port with a unit amplitude wave while matching all the other external ports is excited. Hence, the $(\mathbf{b}_e)_j^T$ is an array with all zero elements apart for the jth element whose value is 1 (this is equivalent to saying that one has placed a generator at the jth port, $c_j = 1$). By solving the system (8) for this particular excitation one finds, for all the subnetworks, the arrays $(\mathbf{a}_k)_j^T$. This process is repeated by exciting, in turn, all the external ports.

By following this approach, the left-hand side (LHS) of (10) is the derivative of the scattering parameter s_{ij} of the feed when the parameter p is changed. In this way, when considering N modes on the aperture and one input mode, all the sought sensitivities are obtained by performing just $N+1$ analyses of the entire network.

D. The Elementary Cell

However, in the application of (10), it is also important to recognize that when changing one geometrical parameter only a few of the scattering matrices of the M sub-networks depend on that parameter; that is, most of the terms $\partial \mathbf{S}^i / \partial p$ appearing in (10) are zero, thus significantly simplifying its numerical evaluation.

It is particularly convenient to use, as the elementary cell, the structure shown in Fig. 3. From the latter it is clear that for each cell one has six geometrical parameters, namely the three heights and the three lengths. A variation of the height or length of the central section ($d_2,\ h_2$ with reference to Fig. 3) of the cell affects only the GSM of that particular cell. A variation of the geometrical parameter corresponding to the input/output sections, i.e., of $h_1,\ h_3,\ d_1,\ d_3$, also affects the adjacent cell.

It is now clear what the considerations to follow are when choosing the elementary cell. From one side it is convenient to deal with single discontinuities, which results in the necessity to evaluate less terms in the sum in (10). On the other side, the latter choice also provides a larger number of internal ports, thus making the solution of the system (8) slower. It is obvious that the final choice is the result of a compromise. Note that as the number of modes in the subsections are greater than the number of modes in the adjacent sections, since $h_2 > h_1$, h_3, it is more convenient to choose the modes in the narrower sections as this basis.

E. Summary of the ANM as Applied to the Full-Wave Analysis of Microwave Feeds

The above discussion can be summarized in the following procedure.

- Instead of calculating the scattering matrix of the overall circuit by cascading the various elementary GSM's one considers the entire network and solves the system (8) for $N+1$ excitations provided one has $N+1$ external ports.
- The terms $\partial \mathbf{S}^k / \partial p$ are readily determined by numerical differences.
- All the elements $\partial s_{ij} / \partial p$ for $i,\ j = 1, \cdots, N+1$ are now computed by using (10).

F. Additional Remarks

One can compare the proposed approach with the standard one by briefly summarize the latter. In the standard approach, the derivative of a scattering parameter with respect to the geometrical dimension p is evaluated by performing the analysis of the entire feed. Most of the computer time is spent by cascading the scattering matrices, which apart from a few of them, have not been changed by the variation in the parameter p. In this approach, the entire feed is analyzed for a few excitations. In order to compute the derivative of the scattering parameter with respect to the variation of the parameter p, only the GSM relative to that parameter has to be calculated. In this respect, as noted in [14], the efficiency of this approach is remarkably better.

IV. Results

Several feeds have been designed by using the described procedure. As an example of the results, some data concerning a feed designed so as to satisfy the following requirements have been reported: return loss less than 33 dB over the bandwidth 10.95–14.5 GHz and cross-polar less than 42 dB over the same bandwidth. The approximate formulas reported in [21] have been used in order to obtain a suitable starting point. In this way, a feed geometry consisting of 108 discontinuities, total length of the feed being 292 mm, while the diameter of the input guide is 17.66 mm, and the diameter of the aperture is

TABLE I
COMPARISON OF MEASURED AND THEORETICAL VALUES FOR THE DIRECTIVITY AND RETURN LOSS OF A CORRUGATED CIRCULAR FEED

frequency (GHz)	Direct. meas.	Direct. theory	Return loss meas.	Return loss theory
10.70	19.34	19.33	-26.8	-26.6
10.95	19.49	19.52	-33.6	-35.0
11.85	20.18	20.21	-35.0	-35.5
12.75	20.85	20.82	-42.1	-48.7
14.00	21.54	21.58	-37.8	-36.8
14.50	21.79	21.78	-33.5	-38.0

TABLE II
COMPARISON OF MEASURED AND THEORETICAL VALUES FOR CROSS-POLARIZATION AND HPBW OF A CORRUGATED CIRCULAR FEED

frequency (GHz)	Cross meas.	Cross theory	HPBW meas.	HPBW theory
10.70	-39.92	-41.09	20.72	20.92
10.95	-43.76	-45.92	20.34	20.36
11.85	-46.65	-45.25	18.82	18.94
12.75	-45.21	-46.37	17.28	17.42
14.00	-43.69	-47.16	15.98	15.94
14.50	-46.05	-47.97	15.46	15.41

100.26 mm, has been obtained. The manufacturing tolerances required for the various sections, with reference to Fig. 3, are 3/100 of mm for d_1, d_2, d_3, h_1, h_3, and of 1/10 of mm for h_2. For optimization purposes a scalar functional obtained by summing over 20 frequency points has been used. For each frequency point the functional is obtained as the weighted sum of the squared differences of actual and desired directivity, return loss, cross-polar peak, and nine different beamwidths.

In Table I, measured and theoretical values for directivity and return loss have been reported. On the average, about 40 modes (TE + TM) at each sides of the elementary cells have been used; hence, since there are 52 cells, the required memory for storing all GSM's is about 2 MB per frequency. It is noted that the modest differences between experimental and computed results may be ascribed to manufacturing tolerances. In Table II, a similar comparison is shown for the cross-polarization and the half-power beamwidth (HPBW). Again, good agreement is observed.

In order to provide an example of the radiated field, measured and theoretical values have been plotted in Figs. 5 and 6. It is apparent that by using the automated design process, excellent results are obtained. In Figs. 7 and 8, measured and theoretical behavior of the phases of the radiated field is shown. Also in this case, a noticeable agreement is found; however, the measured phases are different from the computed ones only for very small amplitudes (below 40 dB). This is in accordance with the amount of reflections due to the nonperfect absorbing panels, which typically provide a reflection coefficient for normal incidence of about 45–50 dB (see, e.g., *eccosorb VHP-NRL,* Emerson & Cumming).

It is interesting to note that the ANM allows tolerance analyses to be performed with modest computer effort. For example, the degradation of the return loss when using a

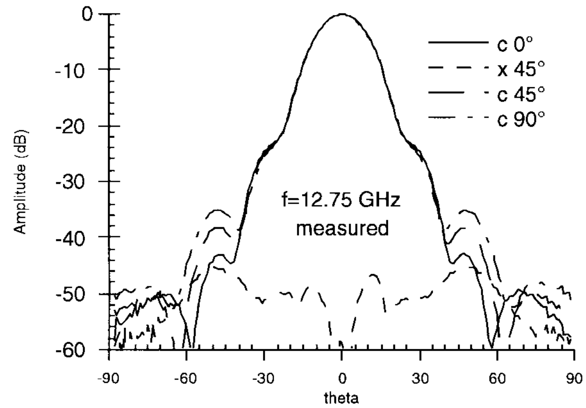

Fig. 5. Measured radiation pattern at the frequency of 12.75 GHz. Plotted are the co-polar (c) pattern for three different angles and the cross-polar (x) pattern at an angle of 45°.

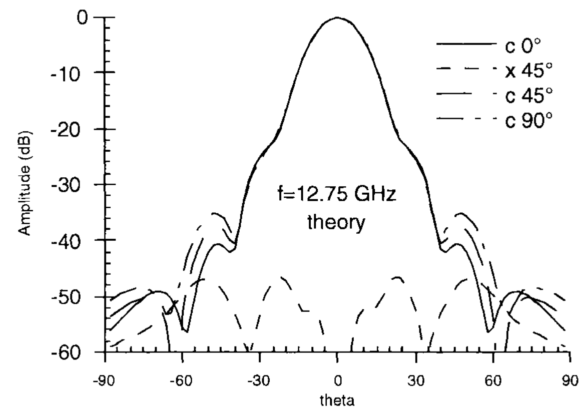

Fig. 6. Theoretical radiation pattern at the frequency of 12.75 GHz. Plotted are the co-polar (c) pattern for three different angles and the cross-polar (x) pattern at an angle of 45°.

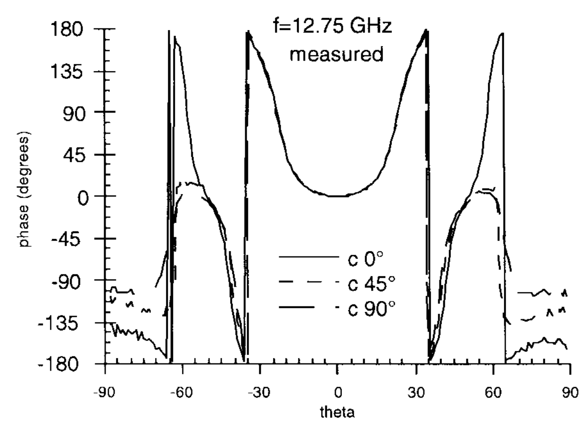

Fig. 7. Measured phase of the radiated field at the frequency of 12.75 GHz. Reported are the results for the co-polar (c) fields for three different angles.

tolerance of 0.03 mm for the internal dimensions of the corrugations and of the ridges has been investigated, while a tolerance of 0.1 mm for depth of the ridge was used. In order to compute the manufacturing tolerances, all dimensions have been changed in a random way by following a Gaussian distribution with variance equal to the above tolerances or to 1/2 and 1/3 of this value. This criteria defines a probability of 68.27%, 95.45%, and 99.73%, respectively, that the error

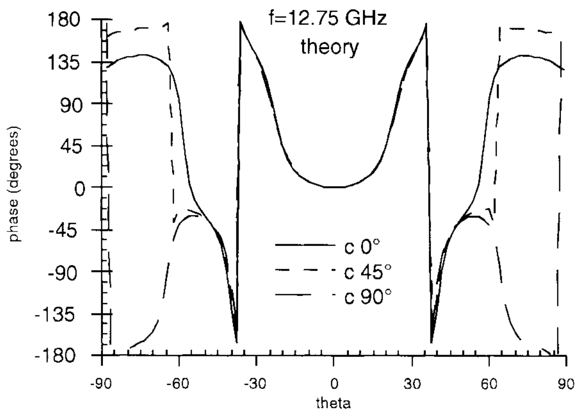

Fig. 8. Computed phase of the radiated field at the frequency of 12.75 GHz. Reported are the results for the copolar (c) fields for three different angles.

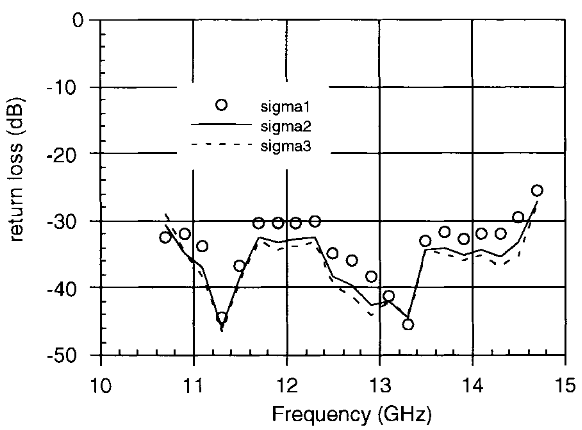

Fig. 9. Computed return loss of the corrugated feed for three different values of the variance of manufacturing tolerances. The plotted curves are the envelopes of all statistically determined responses. The curve "sigma1" refers to a variance of 0.1 mm; the curve "sigma2" refers to a variance of 0.05 mm; the curve "sigma3" refers to a variance of 0.03 mm.

on the horn dimensions is less than the value of the tolerance. From the latter analysis, shown in Fig. 9, it is apparent that by using the above tolerances the component satisfies the desired requirements in the band of interest.

V. Conclusion

An environment for the automated design of corrugated circular feeds has been developed by employing an electromagnetic simulator and the ANM. The electromagnetic full-wave simulator makes use of efficient modal analysis for the evaluation of the generalized scattering matrices of the step discontinuities in circular waveguides. The ANM has been implemented so as to include radiative effects.

By using this environment it is feasible to design a corrugated feed at a fraction of the time generally required by standard approaches. Moreover, it also allows a tolerance analysis to be performed in order to verify the robustness of the proposed design.

As an example of application, a corrugated horn has been designed, built and measured, with more than 100 discontinuities. The agreement between measured and theoretical values has been found to be excellent, and a sensitivity analysis has also provided the manufacturing tolerances necessary to meet specifications.

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