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Design of broadband passive components based on distributed-parameters synthesis techniques

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Abstract. Advanced design techniques are needed in high-performance applications of waveguide passive components. For this reason, the concept of a design procedure based on synthesis techniques is introduced. With this strategy the geometry of the device is directly obtained from the specifications on the frequency response, without the aid of optimization algorithms. Experimental results, concerning waveguide filters and polarizers, are also reported in comparison with the theory.

1. Introduction

In the most demanding application of waveguide passive devices (Uher et al. 1993) for antenna feed systems, concerning both the telecommunication and the astrophysical communities, the specifications are becoming ever more stringent. In particular, devices with broadband behavior are mandatory for high capacity communication channels and for high-sensitivity and reconfigurable radiotelescope receivers.

The basic specifications always concern the return loss and the insertion loss of the structure and its overall geometrical dimensions. Moreover, in the case of waveguide filters, one or more high-rejection bands (low transmission coefficient) are required, whereas, in the case of waveguide polarizers, a very precise 90° differential phase shift between the transmission coefficients corresponding to the two principal polarizations is necessary in order to obtain a very low cross-polarization coefficient. For brevity, other feed-system components are not discussed in this paper.

To design these components, the available electromagnetic analysis tools are not suitable on their own, since they can only provide the frequency response from a given input geometry. On the contrary, in a design process, the geometry must be obtained from a desired frequency behavior. Hence, the design process is an inverse one.

In the literature, several consolidated design methods (Arndt et al. 1997) make use of optimization algorithms to find the solution. A typical scheme of this procedure is depicted in Fig. 1.

At first, an initial guess for the geometry (obtained from previous designs or from the literature) is analyzed by means of a full-wave tool (Itoh 1989). Then, since the response of the device will not generally satisfy the specifications, the input geometry will be modified by an optimization algorithm (according to the differences between the desired frequency response and the current one, properly arranged in a cost function) and subsequently analyzed.

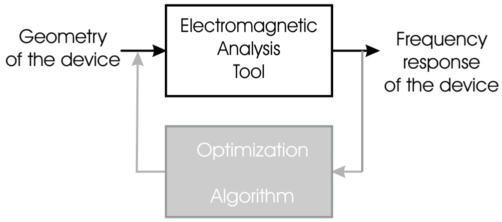

Fig. 1. Scheme of a design procedure based on an optimization algorithm.

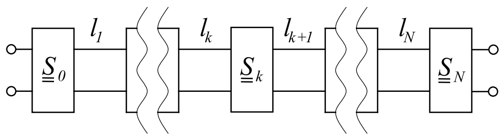

Fig. 2. Single-mode distributed-parameter model of the passive component under design, exploiting the scattering matrices of the overall discontinuities.

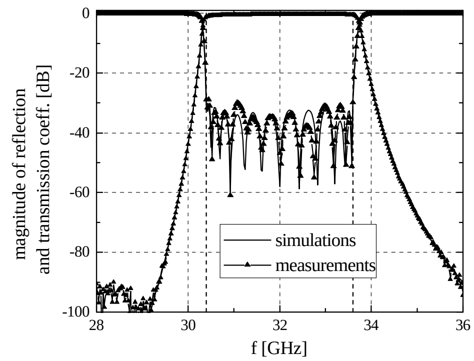

Fig. 3. Frequency response of a 12-cavity E-plane septum filter in a WR28 waveguide.

In general, this scheme must be iterated several times in order to find a solution. Therefore, this procedure becomes very time consuming, especially when general-purpose commercial software for electromagnetic analysis is used. Moreover, the presence of local minima in the cost function often leads to less than optimum solutions, which could be far from the optimum design configuration.

In order to avoid the above-mentioned problems a new design strategy has been developed (Tascone et al. 2000). This method does not make use of optimization algorithms but relies on an analytical model of the device (with a corresponding parameter extraction procedure), and on the identification of the relationship between this model and the accurate full-wave one by means of an abstract linear system.

In its original form, the developed method is suitable for the design of filters, multiplexers and transitions. More recently, it has been generalized for dual-polarization (dual-mode) structures (Virone et al. 2005) such as waveguide polarizers and directional couplers.

In this paper an overview of the overall synthesis technique is presented and relevant results are reported in comparison with measurements.

2. Synthesis technique

For the sake of simplicity, the synthesis technique will be presented for single-polarized devices. Subsequently, the generalization to dual-polarized devices will be considered.

As a starting point, the circuit model depicted in Fig. 2 is introduced.

This model, which consists of cascading the scattering matrices $\underline{\underline{S}}_k$, representing the discontinuities (for example, irises for a filter or steps for a transition) which form the component (l_k are the spacings between them), is a single-mode one. However, differently from the models employed in the other consolidated design techniques (with lumped elements), it is a distributed-parameter one, so that, still being analytical, it better represents the frequency behavior of the structure.

The frequency response can be efficiently described by the element $T_{21}(\omega)$ of the transmission matrix $\underline{\underline{T}}(\omega)$, where ω is the angular frequency. This parameter is related to the reflection S_{11} and transmission S_{21} coefficients of the structure by the following relationship:

$$T_{21} = \frac{S_{11}}{S_{21}}. \quad (1)$$

Thanks to this representation, both the specifications on reflection and transmission coefficients can be described with this unique parameter. In particular, in the case of a reciprocal lossless structure, assuming a non-dispersive

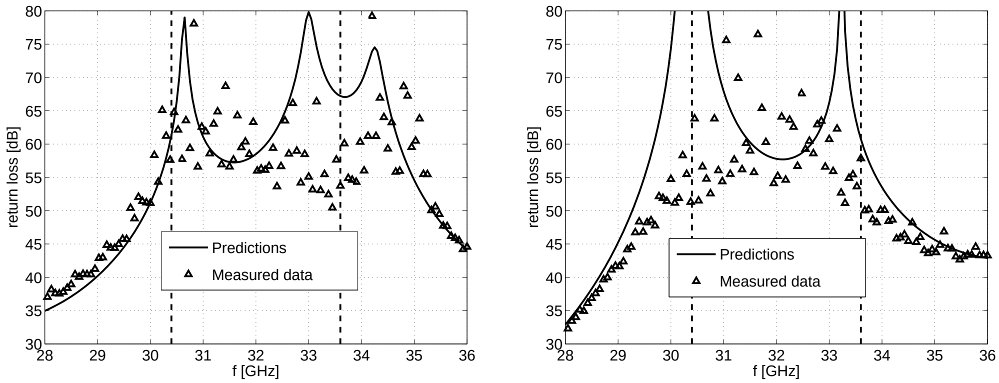

Fig. 4. Return loss of an 8-iris circular-waveguide Ka-band polarizer, corresponding to the two principal polarizations.

behaviour for the magnitude of the $\underline{\underline{S}}_k$, the T_{21} has the following polynomial form (Tascone et al. 2000):

$$T_{21}(\omega) = \sum_{k=0}^{N} b_k z^k.$$

where $N + 1$ is the number of discontinuities, b_k are complex coefficients and z is a complex variable related to the frequency.

This polynomial form is very appealing and useful because, in this way, the specifications on the frequency response of the structure are easily introduced by positioning the zeros of the polynomial T_{21} (from (1), notice that the T_{21} zeros correspond to the reflection zeros).

Starting from the desired frequency response, a proper extraction procedure is exploited (Tascone et al. 2000), so that the transmission coefficients (S_{21k}) of the discontinuities are evaluated. Then, from these quantities, their geometrical parameters (for example iris apertures, step heights, etc.) and the spacings between them (l_k) are obtained. In other words, the geometry of the device is directly obtained from the frequency response and at this time, a first designed device is available.

In order to predict the real behaviour of the structure, the obtained device is analyzed by means of full-wave techniques (Peverini et al. 2004). Obviously, because of the above-mentioned hypothesis, it will not completely satisfy the specifications. For this reason, a compensation procedure is introduced (Tascone et al. 2000). In particular, the full-wave frequency response is interpolated with the polynomial $A_{21}(\omega)$. Thanks to this, it is possible to look at the whole synthesis procedure like a unique system with T_{21} (the desired frequency response corresponding to the single-mode model) as input and A_{21} (the full-wave frequency response corresponding to the real behaviour of the device) as output. Then, according to the control theory, under the hypothesis of small variations, this system is identified with a linear one and its transfer function is used to compensate for the discrepancies between the single-mode model and the full-wave one.

As far as the dual-polarized components are concerned, their design is more complicated because two frequency responses, one for each polarization (mode), have to be controlled simultaneously, and furthermore, also the value of the phase shift between the two transmission coefficients has to be adjusted to a precise value (for example, 90° for polarizers and 3-dB directional couplers). The first problem has been solved by developing an algorithmic relationship (Virone et al. 2005) between the polynomial frequency responses corresponding to the two polarizations. In particular, starting from the interpolated full-wave response for one polarization, the geometry is obtained

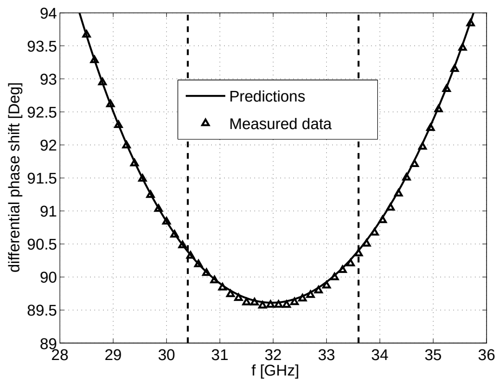

Fig. 5. Differential phase shift between the transmission coefficient for the principal polarizations of an 8-iris circular-waveguide Ka-band polarizer.

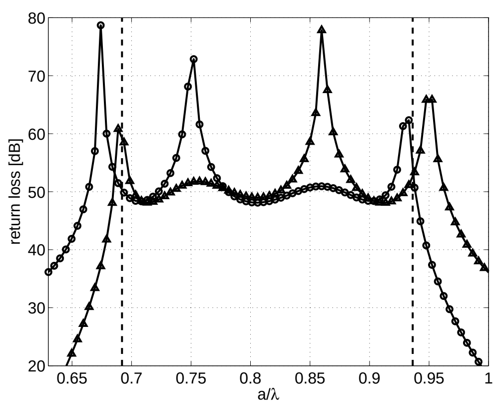

Fig. 6. Return losses of a 7-iris square-waveguide polarizer, corresponding to the two principal polarizations. a is the waveguide dimension and λ is the free-space wavelength.

by means of the above-mentioned extraction and identification procedures. Subsequently, the full-wave response for the other polarization is efficiently computed by exploiting another linear system identification. The latter problem has been overcome by dynamically controlling the maximum degree coefficient of the polynomial responses. In particular, since this coefficient exhibits a monotonic relationship with respect to the total differential phase shift, its value is automatically adjusted in order to obtain the correct phase shift value.

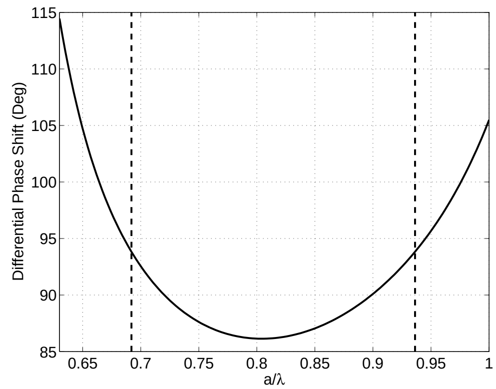

Fig. 7. Differential phase shift between the transmission coefficient for the principal polarizations of a 7-iris square - waveguide polarizer. a is the waveguide dimension and λ is the free-space wavelength.

3. Results

In order to verify the potentiality and the reliability of the proposed design strategy, some design examples are provided in this section.

Figure 3 shows the frequency response of a Ka-band WR28-waveguide filter realized with 12 cavities, coupled by means of E−plane septum discontinuities. Thanks to the developed design technique, the device exhibits a reflection coefficient lower than −30 dB in a 10% frequency band and very steep attenuation slopes in very good agreement with measurements. Another example consists of a Ka-band polarizer, designed with 8 irises. Figure 4 shows the return losses, corresponding to the principal polarizations, which are better than 50 dB in the operative band, in good agreement with measurements. As for the differential phase shift shown in Fig. 5, the maximum deviation with respect to 90° is 0.°42, in optimum agreement with the experimental results, corresponding to a cross-polarization level of −48 dB.

Finally, a very compact broadband polarizer with 7 irises in a square waveguide is also reported. As shown in Fig. 6, the return loss is higher than 48 dB in the 30% frequency band for both polarizations and, as reported in Fig. 7, the maximum deviation from 90° is 3.°8, corresponding to a maximum cross-polarization level of −29.5 dB.

4. Conclusion

A design strategy for waveguide passive components, based on distributed-parameter circuit models and on a linear system identification of the relationship between these circuit models and the full-wave ones, has been presented.

With this procedure, also the waveguide transitions (if present in the feed-system) can be designed in conjunction with the devices themselves, in order to obtain more compact and reliable structures.

The reported designed devices show the capabilities of the method and the experimental results confirm its validity.

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