Hybrid Circuit-Full-Wave Computer-Aided Design of a Manifold Multiplexers Without Tuning Elements

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***Abstract*—A hybrid procedure is introduced for computer-aided design (CAD) of manifold multiplexers without tuning elements. The procedure is based on: 1) a standard initial design with a simple network prototype; 2) a hybrid optimization with the multiplexer manifold rigorously described by a full-wave model and filters still described in terms of their network prototype; and 3) a final full-wave optimization of the entire structure. The proposed approach drastically reduce computer time while making it feasible to perform a very accurate full-wave optimization which in turn allows the avoidance of using tuning elements. An example illustrates and validates the CAD procedure.**

***Index Terms*—Filters, modal analysis, multiplexers, optimization.**

I. Introduction

MANIFOLD multiplexers are currently used for combining a number of channels or signals into a single output waveguide. They find application both in satellite communication systems [1] and for combining several high-power signals for measurement purposes. When high-power signals are handled, the presence of tuning screws may become undesirable, as they increase losses and are a possible source of passive intermodulation.

Several multiplexers' design techniques, which work with equivalent network representation of the relevant discontinuities, have been presented thus far [2]–[7]. Other researchers have developed methods based on computer-aided optimization approaches [8]–[12], which, starting from a simple network prototype of the multiplexer consisting of a manifold and filters, vary all the parameters in such a way so as to obtain the prescribed specification.

In practice, all these techniques still require tuning elements due to their limited accuracy. In order to avoid the presence of tuning elements it is, therefore, necessary to perform an accurate full-wave optimization of the entire multiplexer. The direct full-wave optimization of the latter, when considering the necessarily high number of expansion modes is, on one hand, highly exposed to local minima and, on the other, even by using sophisticated techniques as the adjoint network method [13], [14], hardly within actual computer capabilities.

These difficulties are related to the use of just two types of representations: one in terms of a simple and fast equivalent network (but not very accurate) and the other in terms of a full-wave analysis, which is accurate, but very computer intensive and prone to local minima problems.

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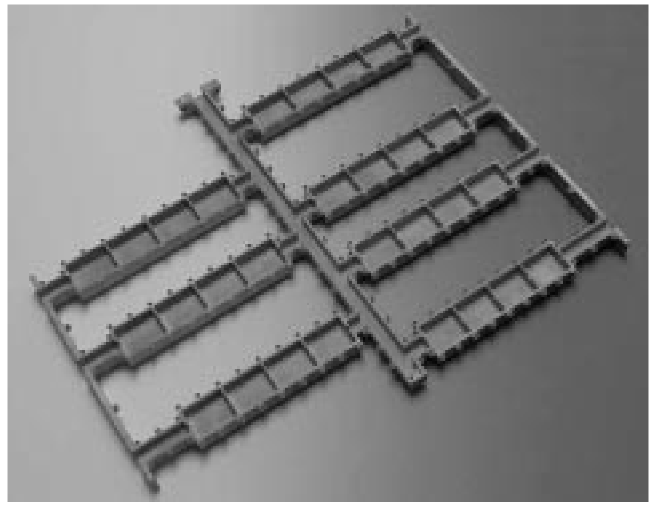

Fig. 1. Seven-channel Ku-band multiplexer for high-power signal measurement realized without tuning screws. This photograph shows the component half-structure manufactured with clam-shell technology.

To circumvent these difficulties, in the next section, we introduce a hybrid optimization procedure, which solves the problem by using network and full-wave models at the same time. Such a procedure, due to its efficiency and accuracy, enables the design of a multiplexer without tuning screws entirely at a computer level.

In particular, to illustrate the design procedure, we refer to the device shown in Fig. 1, i.e., a seven-channel multiplexer working in the 11–12-GHz band having four-pole channel filters of 100-MHz bandwidth spaced 160 MHz between each other. A comparison between measured and theoretical results is presented in Section III.

II. Multiplexer Design Procedure

A typical manifold multiplexer is composed of a number of narrow-band channel filters branched along a waveguide manifold. The filters may be placed on either side of the guide or, when required by size constraints, be all on the same side. The computer-aided design (CAD) procedure for manifold multiplexers is based on the following three steps.

- Step 1) A standard initial design with a network prototype.
- Step 2) A hybrid optimization with the multiplexer manifold rigorously described by full-wave analysis and filters still described in terms of their equivalent networks.
- Step 3) A final full-wave optimization of the entire structure.

The above steps, and the advantages of adopting such a procedure, are discussed below.

A. Initial Design With a Network Prototype

As usual, the procedure starts by using standard approaches for the filters and manifold design; this provides an initial starting point. Unfortunately, such a starting point is not yet suitable for the accurate full-wave optimization necessary for avoiding post-manufacturing tuning. By starting the accurate full-wave optimization at this time, it is likely to fall into the trap of local minima and, in any case, the optimization time will be too long.

In practical cases, most of the computer effort is required for the accurate analysis of the narrow-band filters, often realized by using double step discontinuities. On the other hand, the full-wave analysis of the manifold is significantly less computer intensive. In fact, by using modal techniques, it reduces to a simple two-dimensional problem.

B. Hybrid Optimization of Multiplexer

The basic idea is, therefore, to perform a hybrid-network full-wave optimization; we make use of the full-wave model for representing the manifold behavior, while the filters responses are still described in terms of their equivalent circuits.

In this way, we recover the correct multiplexer response by adjusting the positions of filters along the manifold, the branched lengths of each channel, and the internal parameters of filters (couplings, detunings, external Q's).

At this time, our parameter space is composed by the *geometrical* dimensions of the manifold and by the *electrical* parameters of the filters.

Note that there is a one-to-one correspondence between the network parameters (coupling coefficients, detunings) of filters and the geometry of their cavity structure (irises and cavity length, respectively). Hence, it is possible to map a change of a coupling coefficient to a change in the relative iris dimension; similarly, a detuning only reflects in a change of the cavity length. This procedure results in a starting-point geometry configuration that is suitable for the final full-wave optimization.

The hybrid optimization procedure has several advantages: not only does it allow a consistent reduction of computer times, but it also avoids local minima related to second-order effects present with the full-wave representation of the entire structure.

The hybrid optimization result, shown for the present example in Fig. 2, is obtained by analyzing the channel filters with their equivalent network and the manifold by a full-wave (modal) technique.

The same geometrical structure, when analyzed entirely by a full-wave technique, provide the result shown in Fig. 3, which is the starting point for the final full-wave optimization.

C. Final Full-Wave Optimization

In order to produce a set of geometrical dimensions for the multiplexer manufacturing, a final full-wave optimization of the entire structure is performed.

The most direct way to evaluate the objective function and its derivatives consists in changing each parameter and performing a new analysis of the entire multiplexer. It is readily observed that this process is largely redundant since, most of the time, it is wasted in computing blocks that have not been changed at all. As an example, the calculation of the sensitivity of the

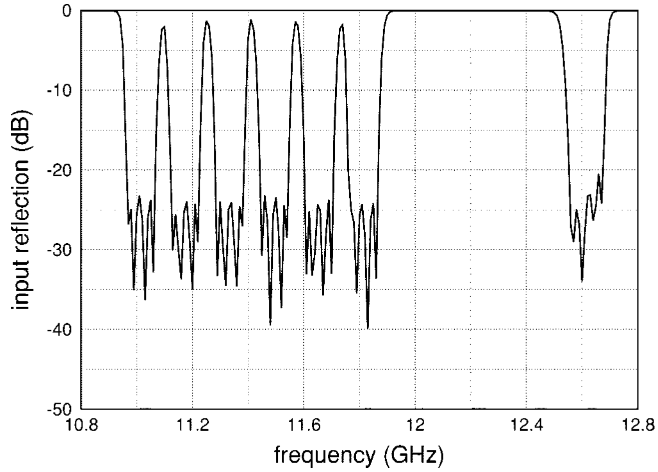

Fig. 2. Multiplexer response as a result of the hybrid optimization (with the channel filters simulated at network level and the manifold by rigorous full-wave modal approaches).

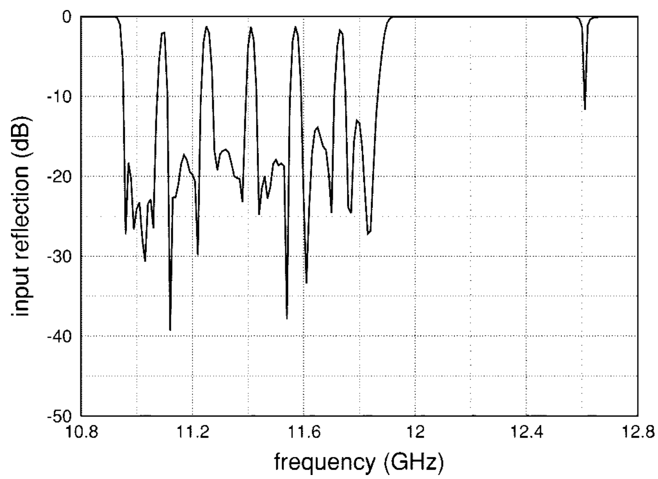

Fig. 3. Rigorous full-wave analysis of the multiplexer with geometry as in Fig. 2.

reflection coefficient at the common port with respect to the length of the second cavity of the ith filter requires calculation of the response of all other $N-1$ filters that are unchanged. In order to avoid such a waste of time, a modification of the adjoint network method has been implemented. In particular, a save–retrieve option has been used, which allows a remarkable reduction of the number of operations. In this way, by using efficient modal techniques and the above save–retrieve option, the global computer-aided optimization of the entire structure with an accuracy adequate to avoid further postmanufacturing tuning becomes a feasible task.

In a first optimization cycle, each channel is individually optimized. This process is rather fast, as most of the structure is not changed and, hence, needs not be recalculated. The number of variable involved is up to ten. During the final optimization cycle, all channels are simultaneously considered and computation become intensive with up to 70 variables involved; however, since the first cycle has already brought all channels to a return loss better than 18 dB, the total computing time remains within reasonable limits.

The error function requires the return loss of each channel to be better than a prescribed value over a specified bandwidth;

TABLE I
SPECIFICATIONS DETAILS OF THE SEVEN-CHANNEL MULTIPLEXER

channel frequency (GHz)	Operating Specifications	Design Specifications	Measured Results
1	11.00	11.00	11.00
2	11.16	11.16	11.16
3	11.32	11.32	11.32
4	11.48	11.48	11.48
5	11.64	11.64	11.64
6	11.80	11.80	11.80
7	12.60	12.60	12.60
Useful Bandwidth	± 40MHz	± 50MHz	> ± 40MHz
Return loss over usefull bandwidth (dB)	18	22	> 20
Channel to channel Isolation (at c.f.) (dB)	25	32	> 30

it also requires that the isolation at the center frequency of the adjacent channel satisfies a given value.

The basic algorithm used in the optimization is the pattern search method of Hooke and Jeeves (see [16]), which is a direct search technique with no calculation of derivatives.

III. RESULTS

By using the hybrid optimization procedure, a seven-channel multiplexer operating in the 11–12-GHz frequency band has been designed, built, and measured. Detailed specifications, design requirements, and measured results are summarized in Table I. The input–output ports are standard WR75 waveguides. The component has been fabricated in aluminum in two symmetrical parts by using the clamshell technology (see Fig. 1). The manufacturing has been carried out by means of numerically controlled milling and spark-eroding techniques with a specified goal accuracy of ±0.01 mm in the manifold region and ±0.005 mm for cavity and iris dimensions. This high degree of accuracy has been estimated as adequate in order to get from the experimental multiplexer most of the computed performances. It is further noted that this accuracy has only required a moderate increase of manufacturing costs.

A. Channel Filters Design

Channel filter requirements results in the selection of a four-pole Chebyshev filter response with 24-dB return loss to be implemented in a rectangular waveguide by a cascade of single-mode cavities. In order to reduce the losses, the TE_{102} resonant mode has been considered, allowing a significant increase of the quality factor. Accordingly, the cavities have a cross section of 23×23 mm and an approximate length of 30 mm; the external irises have a fixed height, a thickness of 2 mm, an approximate width of 10 mm, and finally, the inner irises have a fixed height of 3 mm, a thickness of 1 mm, and an approximate width of 6 mm.

An accurate design of channel filters is of particular relevance for realization of multiplexers without tuning screws. The required accuracy refers both to numerical computation and to manufacturing tolerances.

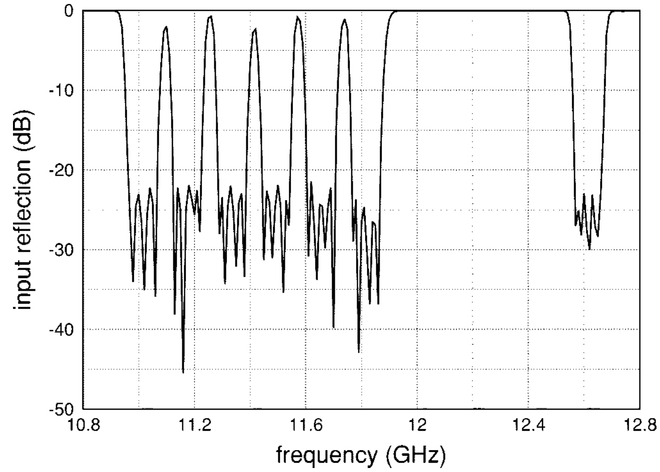

Fig. 4. Computed input reflection after the final full-wave optimization.

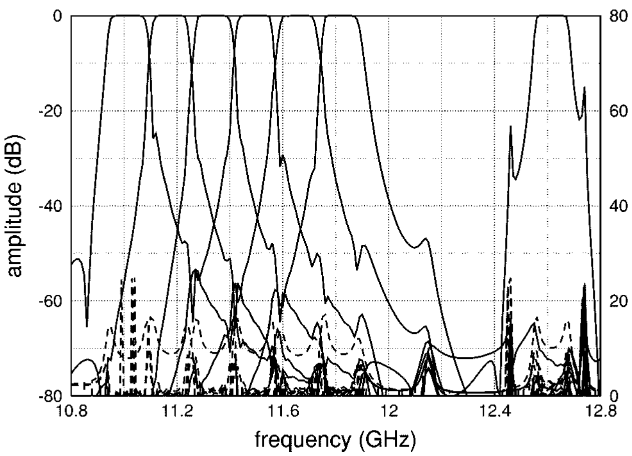

Fig. 5. Computed channel transmission after the final full-wave optimization.

The above dimensions illustrate that the single-filter structure is essentially a cascade of rectangular waveguides with different cross sections in both directions (i.e., double step discontinuities). Hence, in order to analyze such a structure, it is convenient to adopt efficient modal techniques; naturally, the problem dimensionality requires the use of both TE and TM modes. Moreover, as is possible to observe from the relative dimensions of the cavity with respect to the irises, an adequate number of modes (of the order of several hundreds) should be considered in order to avoid convergence ambiguities.

B. Manifold Design

The manifold structure is a branched rectangular waveguide with E-plane T-junctions. This type of discontinuity is advantageous both for mechanical realization and modeling purposes. In particular, for modeling, a scattering superposition technique has been used [15]; the problem dimensionality has allowed consideration of only the LSE_{1n}^{x} modal family. As a consequence, the accurate full-wave analysis of the manifold is extremely fast.

C. Measured Results

Theoretical results are shown in Fig. 4 for the input reflection and in Fig. 5 for the transmission of all channels. The response of the experimental multiplexer, measured with the HP 8510 Nework Analyzer in conjunction with a precise homemade thru-

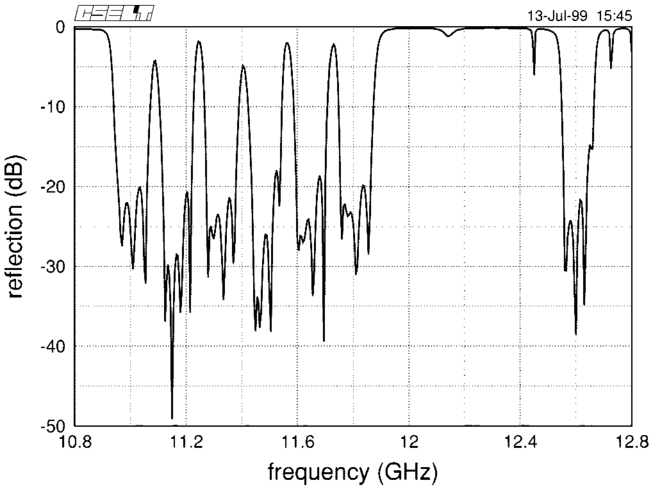

Fig. 6. Measured input reflection.

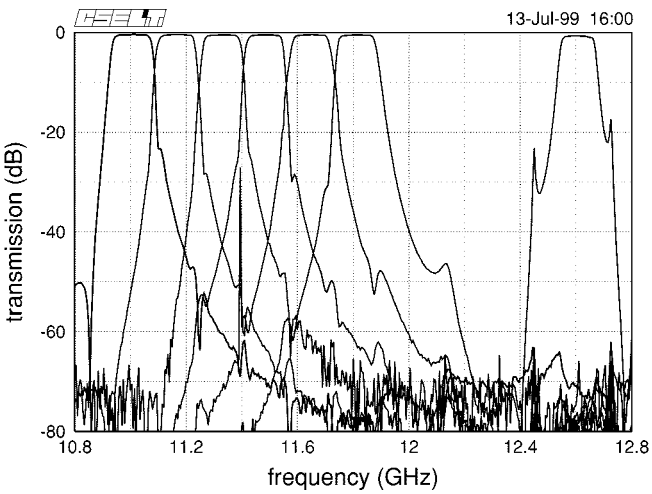

Fig. 7. Measured channel transmission.

reflect line (TRL) calibration, is reported in Figs. 6 and 7 and shows a favorable agreement with computer calculations.

IV. Conclusion

A hybrid-network full-wave optimization procedure for the efficient CAD of a wide-band semicontiguous channel multiplexer has been presented.

The manifold design consists of interconnected E-plane T-junctions that are joined to separately designed filters via an hybrid optimization procedure, which combines the advantages of full-wave optimization and the efficiency of network representation.

The hybrid optimization provides a starting point for a global full-wave optimization, which leads to the sought final result.

This procedure has allowed the design of a Ku-band seven-channel multiplexer without tuning screws by using currently available manufacturing tolerances.

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References

[1] C. Kudsia, R. Cameron, and W. C. Tang, "Innovations in microwave filters and multiplexing networks for communications satellite systems," *IEEE Trans. Microwave Theory Tech.*, vol. 40, pp. 1133–1149, June 1992.
[2] R. G. Egri, "A contiguous-band multiplexer design," in *IEEE MTT-S Int. Microwave Symp. Dig.*, Boston, MA, 1983, pp. 86–88.
[3] R. Tong *et al.*, "An 11 GHz contiguous band output multiplexing network for INTELSAT VI spacecraft," in *IEEE MTT-S Int. Microwave Symp. Dig.*, Dallas, TX, 1982, pp. 405–407.
[4] G. Matthaei, L. Young, and E. M. T. Jones, *Microwave Filters, Impedance Matching Network and Coupling Structures*. New York: McGraw-Hill, 1965.
[5] G. Matthaei and E. Cristal, "Theory and design of diplexers and multiplexers," in *Advances in Microwaves*. New York: Academic, 1967.
[6] J. D. Rhodes and R. Levy, "A generalized multiplexer theory," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-27, pp. 99–111, Feb. 1979.
[7] ——, "Design of general manifold multiplexers," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-27, pp. 111–122, Feb. 1979.
[8] A. E. Atia, "Computer-aided design of waveguide multiplexers," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-22, pp. 332–336, Mar. 1974.
[9] D. Rosowsky, "Design of manifold type multiplexers," in *Proc. Eur. Space Agency Microwave Filters Workshop*, June 1990, pp. 145–146.
[10] J. Uher, J. Bornemann, and U. Rosemberg, *Waveguide Components for Antenna Feed Systems*. Norwood, MA: Artech House, 1993.
[11] L. Accatino and P. Carle, "Computer aids for designing and simulating microwave multiplexers for satellite applications," presented at the GlobeCom, Atlanta, GA, 1984.
[12] J. W. Bandler, S. Daijavad, and Q. J. Zhang, "Exact simulation and sensitivity analysis of multiplexing networks," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-34, pp. 93–102, Jan. 1986.
[13] A. Morini, T. Rozzi, and M. Mongiardo, "Efficient CAD of wideband contiguous channel multiplexers," in *IEEE MTT-S Int. Microwave Symp. Dig.*, San Francisco, CA, 1996, pp. 1651–1654.
[14] F. Alessandri, M. Mongiardo, and R. Sorrentino, "New efficient full wave optimization of microwave circuits by the adjoint network method," *IEEE Microwave Guided Wave Lett.*, vol. 3, pp. 414–416, Nov. 1993.
[15] E. Kuhn, "A mode-matching method for solving field problems in waveguide and resonator circuits," *Arch. Elektr. Ubertragung*, pp. 511–518, 1973.
[16] J. W. Bandler, "Optimization methods for computer-aided design," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-17, pp. 533–552, Aug. 1969.

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