EFFICIENT FULL-WAVE CAD OF WAVEGUIDE DIPLEXERS

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ABSTRACT

The paper presents an efficient CAD algorithm for the design of waveguide front-end diplexers. Three different types of junctions can be employed: E-plane T-junction, H-plane T-junction and E-plane bifurcation. Channel filter configurations currently include - but are not limited to - waveguide stub filters and inductive-iris filters.The diplexer design is performed in three basic steps: synthesis, analysis and optimization. In order to improve the computing efficiency of the design algorithm, highly accurate transmission line models are used in the initial component design and optimization stages. The final optimization and the analysis of the entire diplexer makes use of a full-wave mode-matching model, which can include waveguide transformers at all ports.

The CAD routine is verified against measurments, and excellent agreement between predicted and measured results is obtained.

I. INTRODUCTION

Waveguide front-end diplexers are typically used in fixed satellite service (FSS) antenna systems with common transmit and receive feeds. The diplexers are employed behind each feed in order to separate Tx and Rx channels.

While it is well known that waveguide diplexers can be optimized on the basis of full-wave models, e.g. mode matching, and additional matching elements [1] - [3], such a component design is often tedious and time-consuming due to the extremely high CPU-time required. Equivalent-circuit models [4], [5], on the other hand, produce results much faster, but their applications are limited to certain dimensional constraints, due to proximity effects, where the degree of validity of such models is practically uncertain. For waveguide cross-section ratios around b/a=0.1 to 0.15, excellent diplexer designs are usually obtained by equivalent-circuit modelling of E-plane T-junctions [4] and waveguide stub filters [1]. Although such designs have been used for many years, power levels and multipactor specifications of modern satellite communication systems no longer permit reduced-height rectangular waveguide components. However, already at a ratio of 0.2 - 0.25, equivalent-circuit designs no longer produce reliable designs, hence demanding full-wave methods to be employed.

Therefore, this paper focuses on an efficient diplexer design which combines the advantages of the equivalent circuit approach with full-wave mode-matching algorithms. The software package currently contains subroutines for the following configurations (Fig. 1):

Waveguide Junctions:	- E-plane T-junctions - E-plane bifurcations - H-plane T-junctions
Rx and/or Tx Filters:	- Inductive-iris filters - Single-sided stub filter - Double-sided stub filters

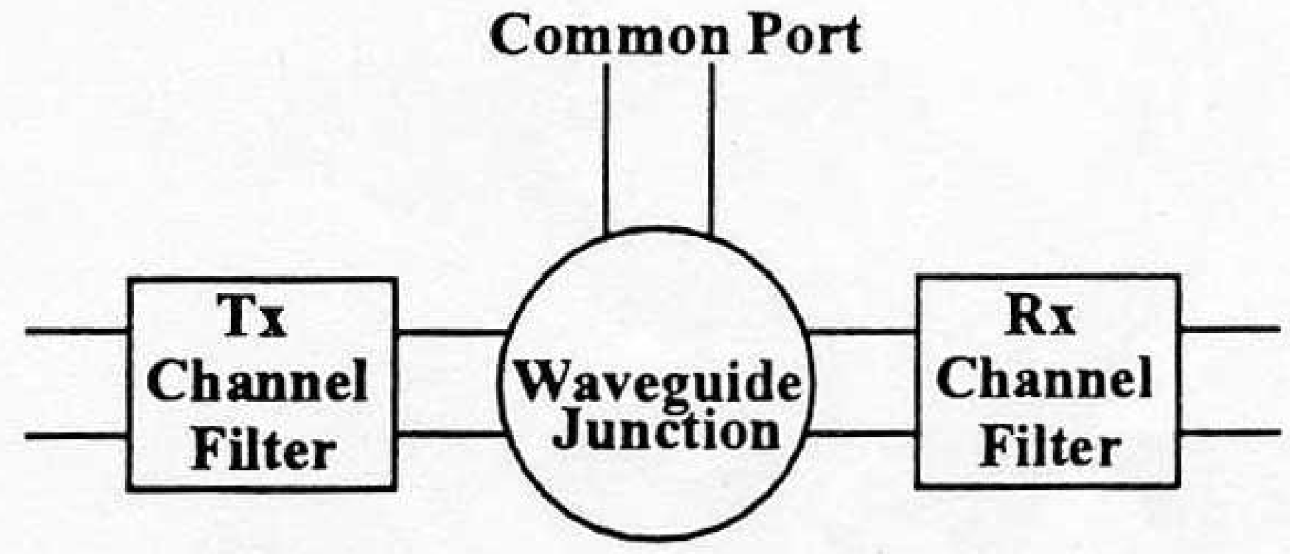

Fig. 1: *Block diagram of waveguide diplexer.*

II. ANALYSIS

The engine of the software package is a mode-matching based analysis for various discontinuities that are required in the diplexer assembly. Compared to standard mode matching algorithms, the CPU-time efficiency is significantly increased due to two measures. Firstly, the TE_{xmn} - mode approach is utilized, which has a proven record of successful designs with single- or double-plane step discontinuities and junction blocks involved [1], [6]. Secondly, the number of modes used in individual combinations of discontinuities automatically adapts to the problem at hand. For discontinuity calculations, the number of modes is selected according to the cross-section ratios of the connected waveguides. Although one of these numbers is usually high, the connection of this discontinuity with others over a finite distance of waveguide requires only a few modes.

In each different cross-section of rectangular waveguide, the x-component of a magnetic vector potential component is written as

$$A_{hx} = \sum_{q=1}^{Q} \sqrt{\frac{\omega \mu_o / k_{zq}}{A\left[k_o^2 - k_{xm}^2\right]}} \quad T_{mn}(x,y) \cdot [F_q exp(-jk_{zq}z) - B_q exp(jk_{zq}z)] \quad (1)$$

where F_q and B_q are the wave amplitudes travelling in the positive and negative z direction, respectively, and A is the cross-section of the individual region. T_{mn} (=T_q), where index q is related to combinations (m,n) with respect to increasing cutoff frequencies, are the cross-section functions satisfying the boundary conditions.

$$T_{mn}(x,y) = \sin\left[\frac{m\pi}{a}(x-e)\right]\frac{\cos\left[\frac{n\pi}{b}(y-d)\right]}{\sqrt{1+\delta_{0n}}} \quad (2)$$

δ_{0n} is the Kronecker delta, a and b the waveguide cross-section dimensions, and e and d distances to the origin.
In case of a T-junction, e.g. in the E-plane with cross-section dimensions $a \times c$ (I) and $a \times b$ (II,III), the vector potential is obtained from a superposition of functions

$$T^I_{mn} = C^I_{mn}\sin\left(\frac{m\pi}{a}x\right)\frac{\cos\left(\frac{n\pi}{c}z\right)}{\sqrt{1+\delta_{0n}}}\cos(k^I_{ymn}y) \quad (3)$$

$$T^{II}_{ik} = C^{II}_{ik}\sin\left(\frac{i\pi}{a}x\right)\frac{\cos\left(\frac{k\pi}{b}y\right)}{\sqrt{1+\delta_{0k}}}\cos(k^{II}_{zik}z) \quad (4)$$

$$T^{III}_{jl} = C^{III}_{jl}\sin\left(\frac{j\pi}{a}x\right)\frac{\cos\left(\frac{l\pi}{b}y\right)}{\sqrt{1+\delta_{0l}}}\cos\left[k^{III}_{zjl}(z-c)\right] \quad (5)$$

where superscript I identifies the common port, II and III follow clockwise, and k_z^i are the phase constants in waveguide i with the remaining two ports shorted. For further details, especially the derivations of single-junction and cascaded scattering matrices, the reader is referred to [1].
If the entire diplexer component comprises exclusively E-plane (H-plane) discontinuities, the mode spectra are reduced to those of TE^x_{1n} (TE^x_{m0}) modes. In case of both discontinuities being present in the component, a combination of modes is used as outlined in [6]. Good agreement between theory and measurements is already obtained for three to five modes in the matrix-connecting algorithms. Individual discontinuities are analyzed with up to 45 modes.
A loss prediction is carried out on the basis of the fundamental-mode attenuation constant and the resonator unloaded Q-efficiency in the design frequency range.

III. DESIGN

The design is carried out in three steps. First, the channel filters are synthesized for given diplexer specifications. Standard filter synthesis and a combined equivalent-circuit / mode-matching approach is used to ensure filter performance. Secondly, if the b/a ratio permits the T-junction to be represented by an equivalent circuit, the diplexer is pre-optimized with the equivalent-circuit approach. Thirdly, a subsequent analysis based entirely on mode matching either confirms the equivalent-circuit results or identifies a need for further optimization using mode-matching routines exclusively. At this point, waveguide transformers, if required, at all three ports can be incorporated, and all dimensions can be individually selected as optimization parameters. The optimazation strategy itself is based on a minimax algorithm [7]. Note that, contrary to comparable diplexer configurations in [1] - [3], additional matching elements such as inductive irises are not required. Therefore, this design concept leads to more compact diplexer configurations.
The entire software package is operational on personal computers. Depending on diplexer specifications of various degrees of difficulty and restrictions, with which the software has been tested, complete designs of diplexer components take between five minutes and four hours on a Pentium 90 computer.

IV. RESULTS

The excellent agreement between mode-matching analysis and measurements is demonstrated in Figs. 2 for two different diplexer configurations. Fig. 2a shows an E-plane T-junction diplexer with waveguide stub filters. For interface purposes with standard waveguide equipment, impedance transformers have been added at all three ports.
Fig. 2b shows a similar comparison for an E-plane T-junction diplexer with inductive-iris filters. Again, excellent agreement is obtained within the 70dB-dynamic range of the measurement equipment.
A comparison between the equivalent-circuit approach and mode matching is demonstrated in Fig. 3 for an E-plane T-junction single-sided stub-filter diplexer (similar configuration as in Fig. 2a, but without transformers) with a waveguide height-to-width ratio of b/a=0.13. Excellent agreement is observed, and a mode-matching analysis is used simply to confirm the results. In certain high-power applications, it is necessary to design the diplexer with maximum height. In this situation, the diplexer stub dimensions become very small and are not manufacturable.
A solution to this problem is depicted at the top of Fig.4. The stub-filter synthesis based on the equivalent-circuit approach is still used, but it is applied to only half the actual structure and, therefore, uses only half the waveguide height. By mirroring such a stub-filter design, the original waveguide height is restored, and double-sided stub filters are obtained. The mode-matching software currently developed includes the double-sided stub-filter diplexer design. The options for the stub location are: 1) pointing towards the common port, 2) pointing away from the common port as shown in Fig. 2a, and 3) the double-stub approach in Fig. 4.

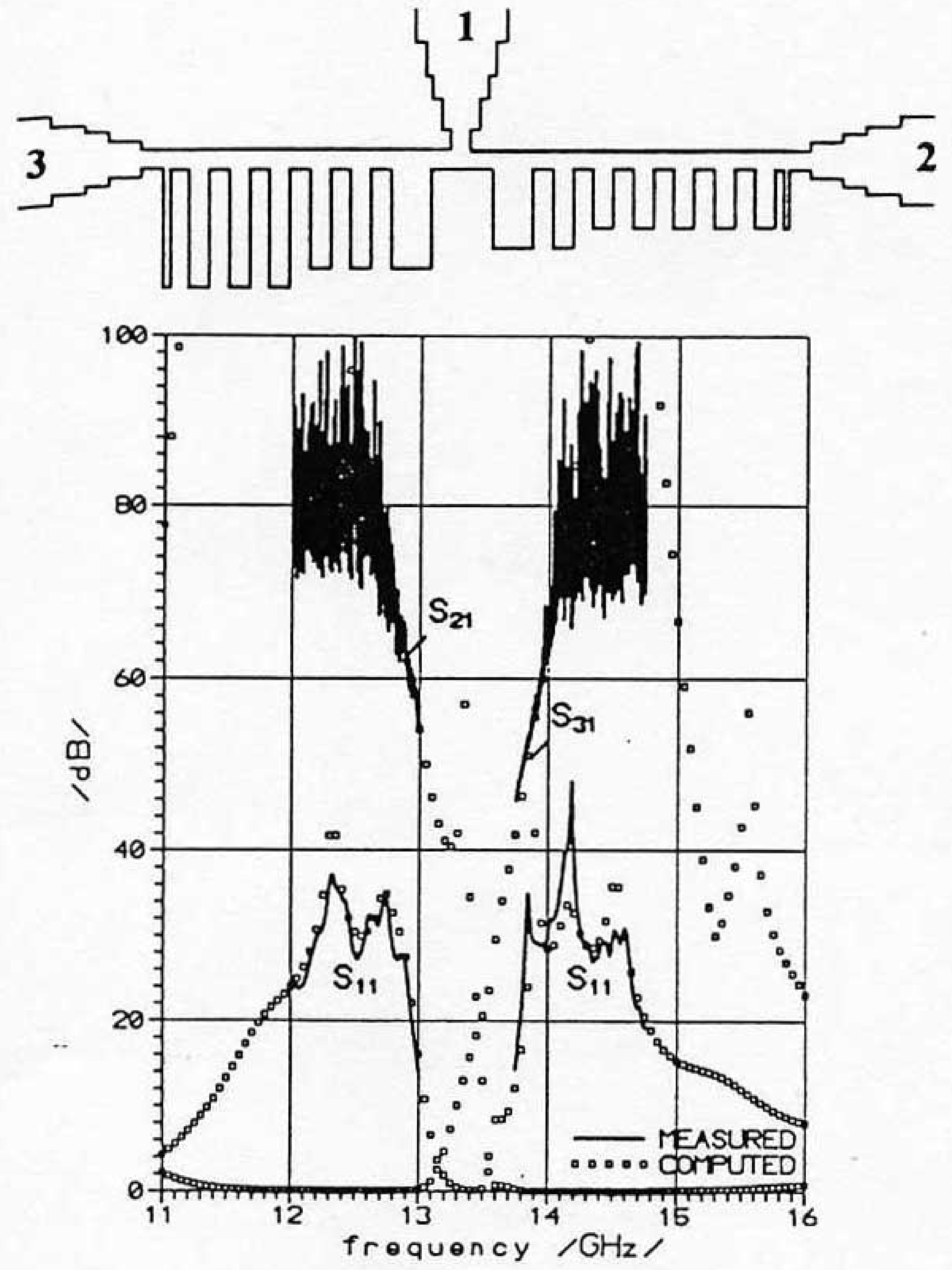

Fig. 2a: *Measured and computed performances of E-plane T-junction diplexer with single-sided stub filters and transformers.*

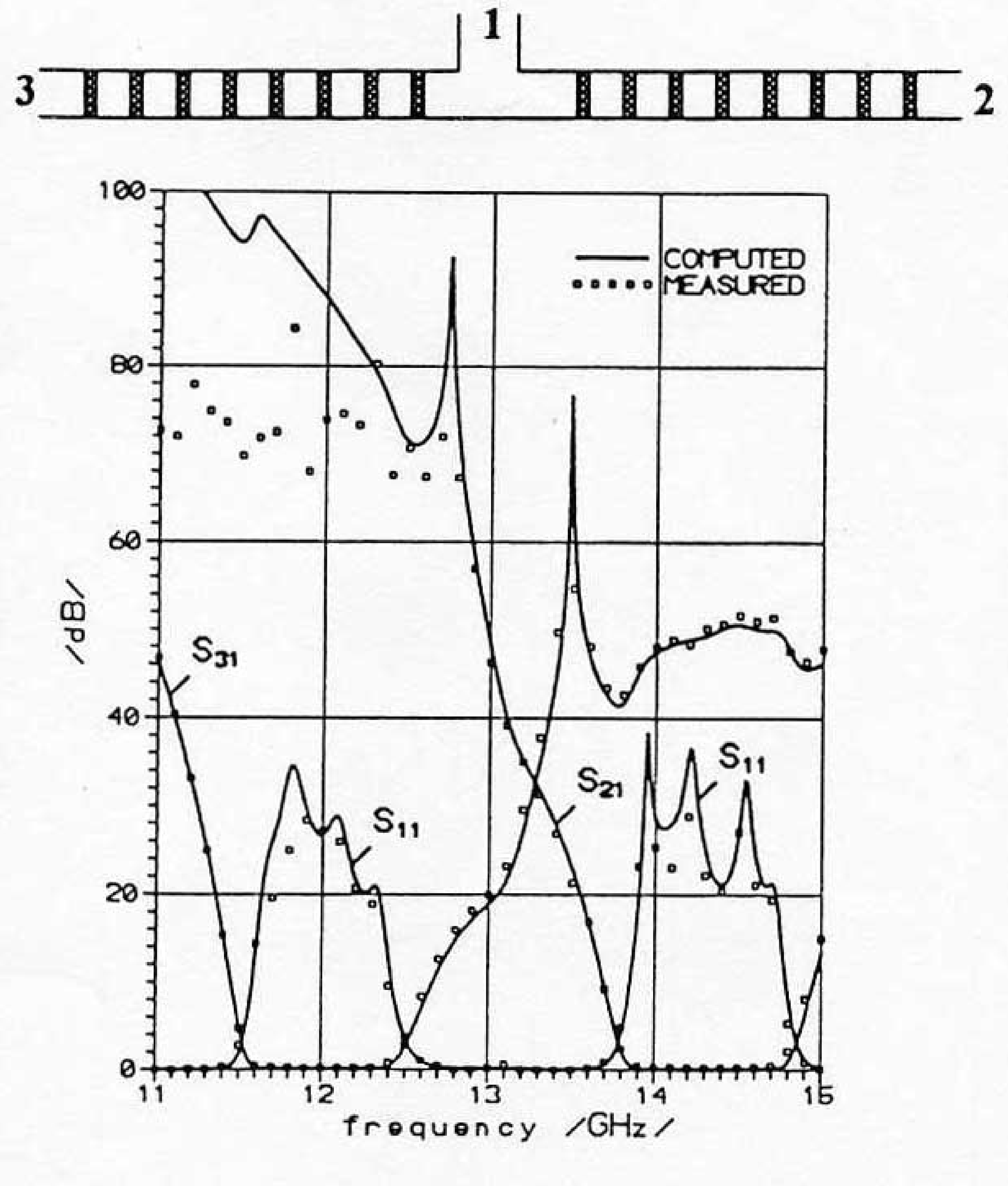

Fig. 2b: *Measured and computed performances of E-plane T-junction diplexer with inductive-iris filters.*

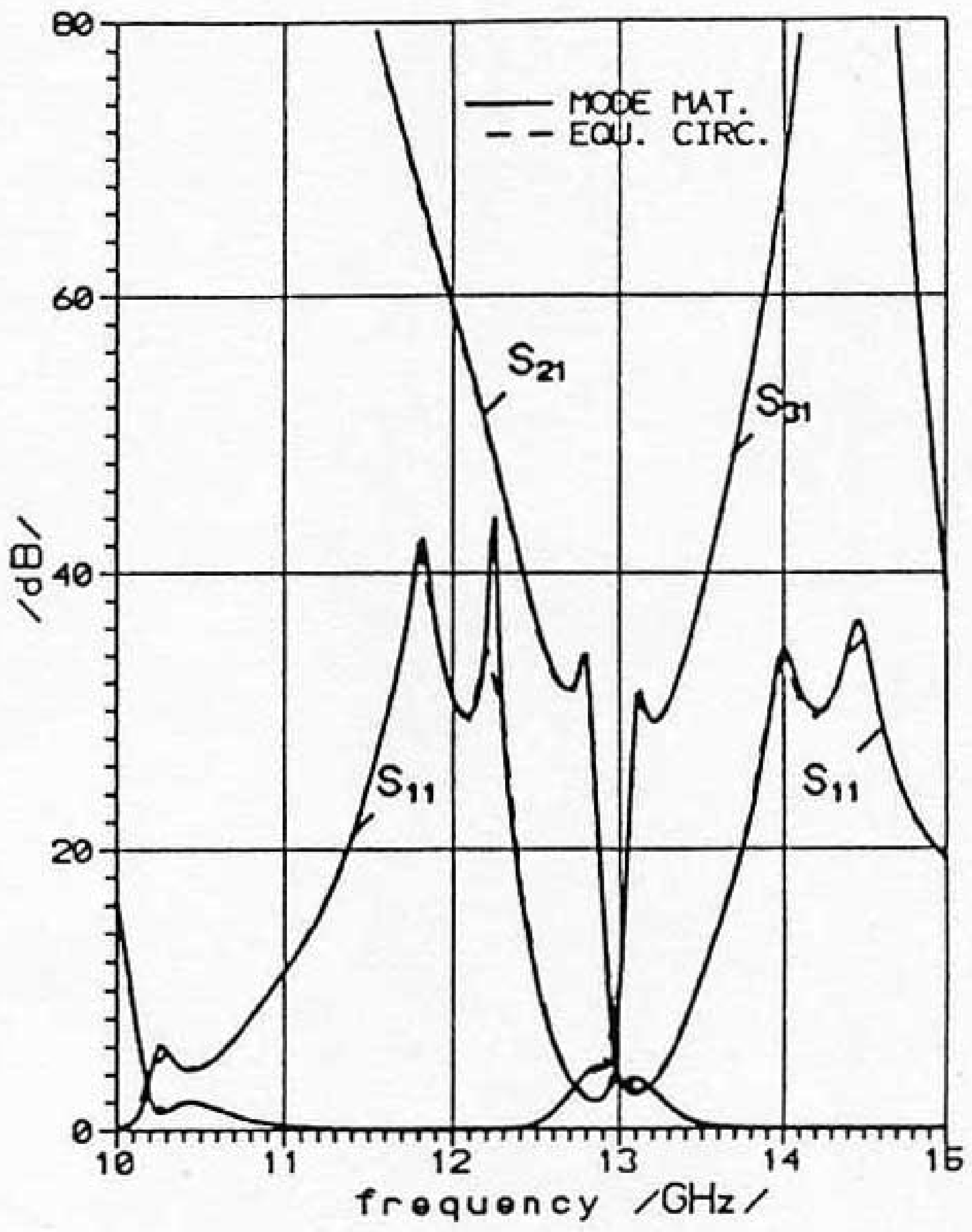

Fig. 3: *Comparison between equivalent-circuit approach and mode matching for E-plane T-junction single-sided stub-filter diplexer at b/a=0.13.*

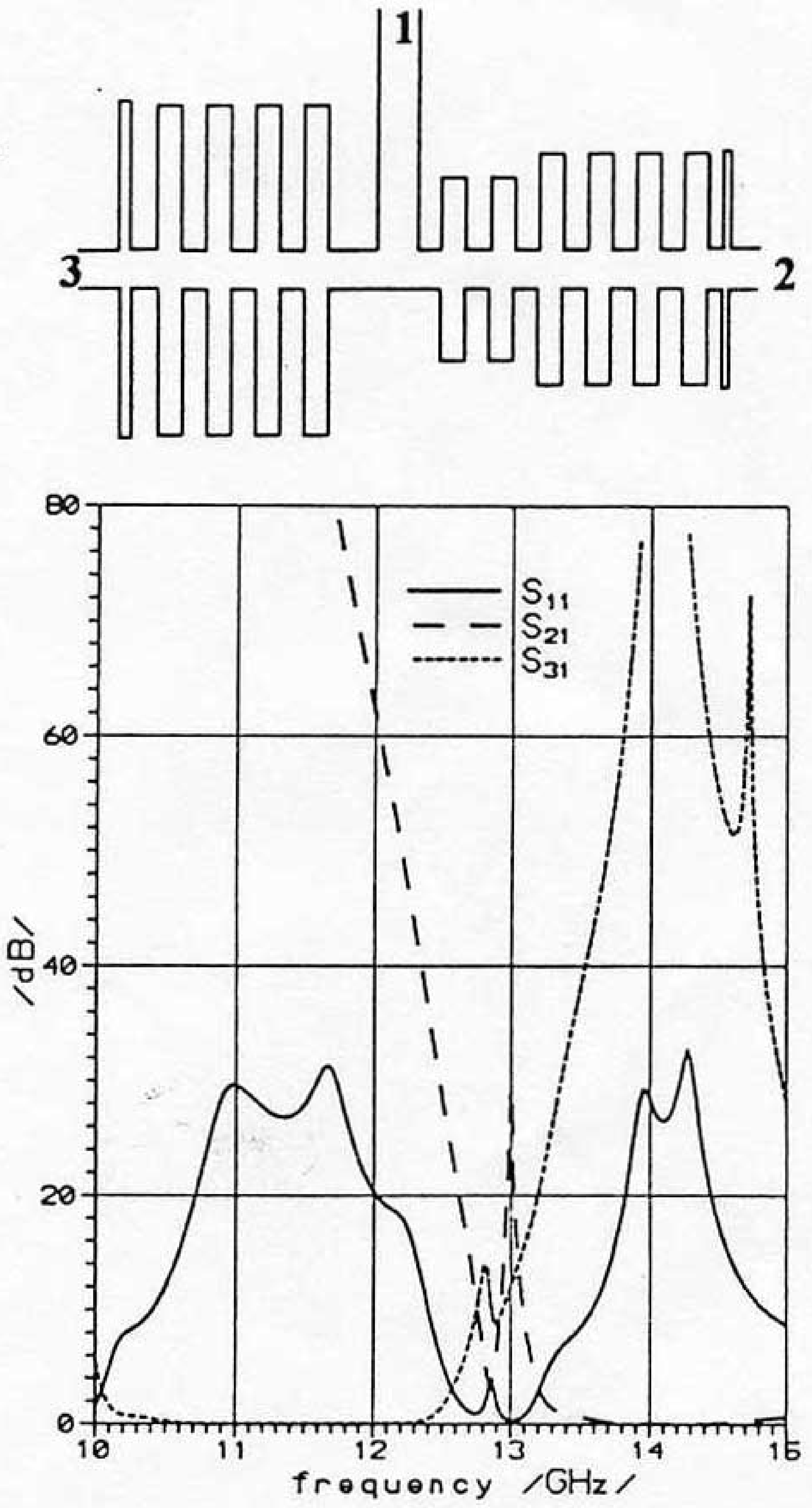

Fig. 4: *Computed performance of E-plane T-junction double-sided stub-filter diplexer (b/a=0.27).*

Once the stub filters are synthesized, the optimization of the entire diplexer is carried out with mode-matching analysis routines only. The performance of the optimized design is shown in Fig.4. Note that specifications required unequal Rx and Tx bandwidths. The design goal for optimization was set to 26dB return loss and 60 dB isolation.

For even higher ratios of *b/a*, stub filters are no longer recommended, and inductive-iris filters are used in the current software setup. The E-plane bifurcation diplexer with inductive-iris as shown in Fig. 5 provides good performance up to the full regular waveguide height (*b/a*=0.5). The input power divider and channel filters are synthesized according to [1], and the optimization software varies the transformer profile and filter dimensions for optimum performance. Alternatively, an H-plane configuration as shown in Fig. 6 can be used. This design is independent of the waveguide height.

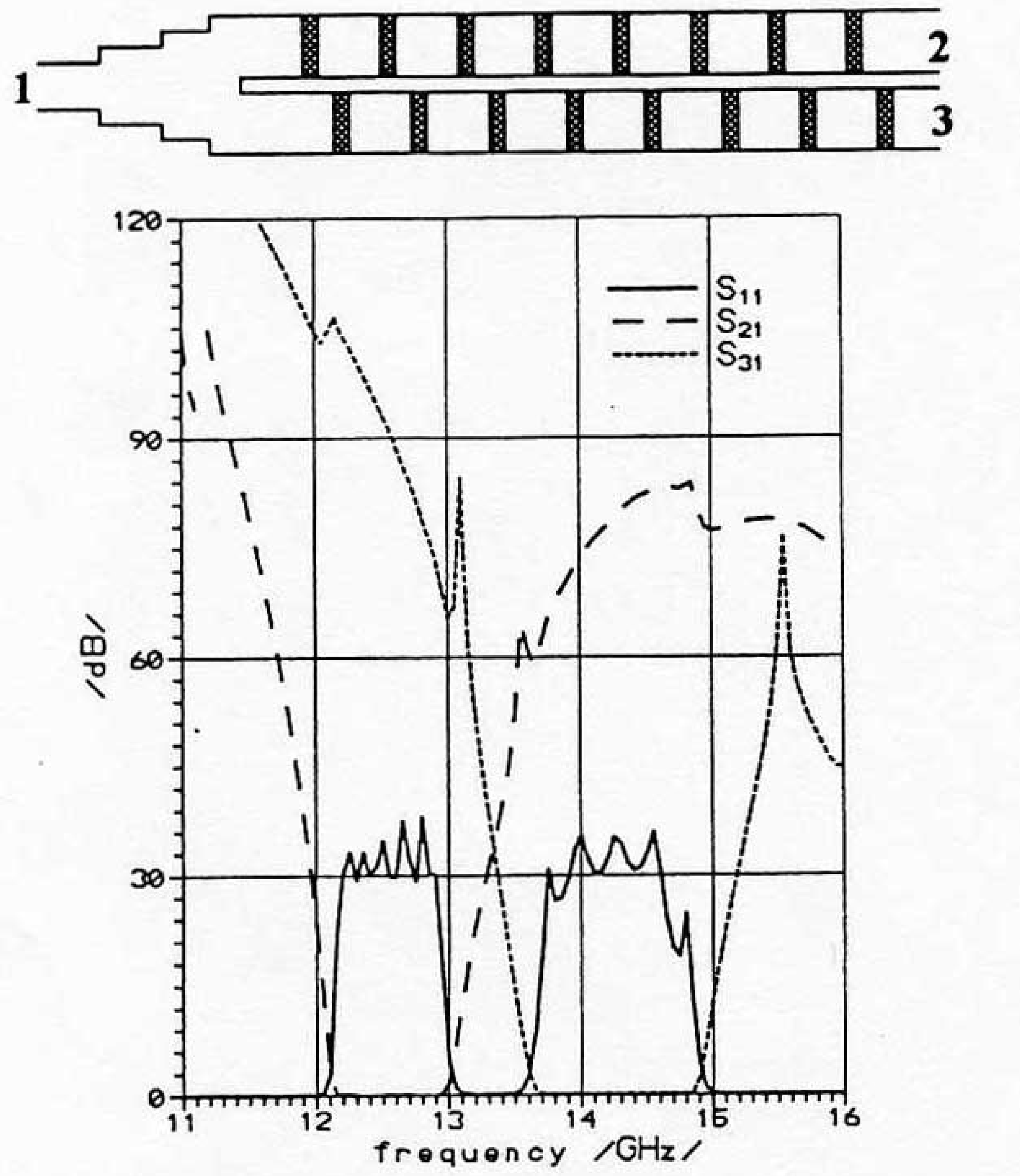

Fig. 5: *Computed performance of E-plane bifurcation diplexer with inductive-iris filters (b/a=0.5).*

V. CONCLUSIONS

An efficient CAD strategy for waveguide front-end diplexers in fixed satellite service antenna systems is presented. Channel filter and junction components are presynthesized by equivalent-circuit or mode-matching routines. In order to provide the design engineer with a fast and reliable design, a minimax optimization scheme and mode-matching analysis is used in the final step of the design process. Waveguide height restrictions can be efficiently overcome, and an option for trans formers at all three ports is included. The final design is compact as additional tuning elements are not required. The software is operational on standard Pentium personal computers.

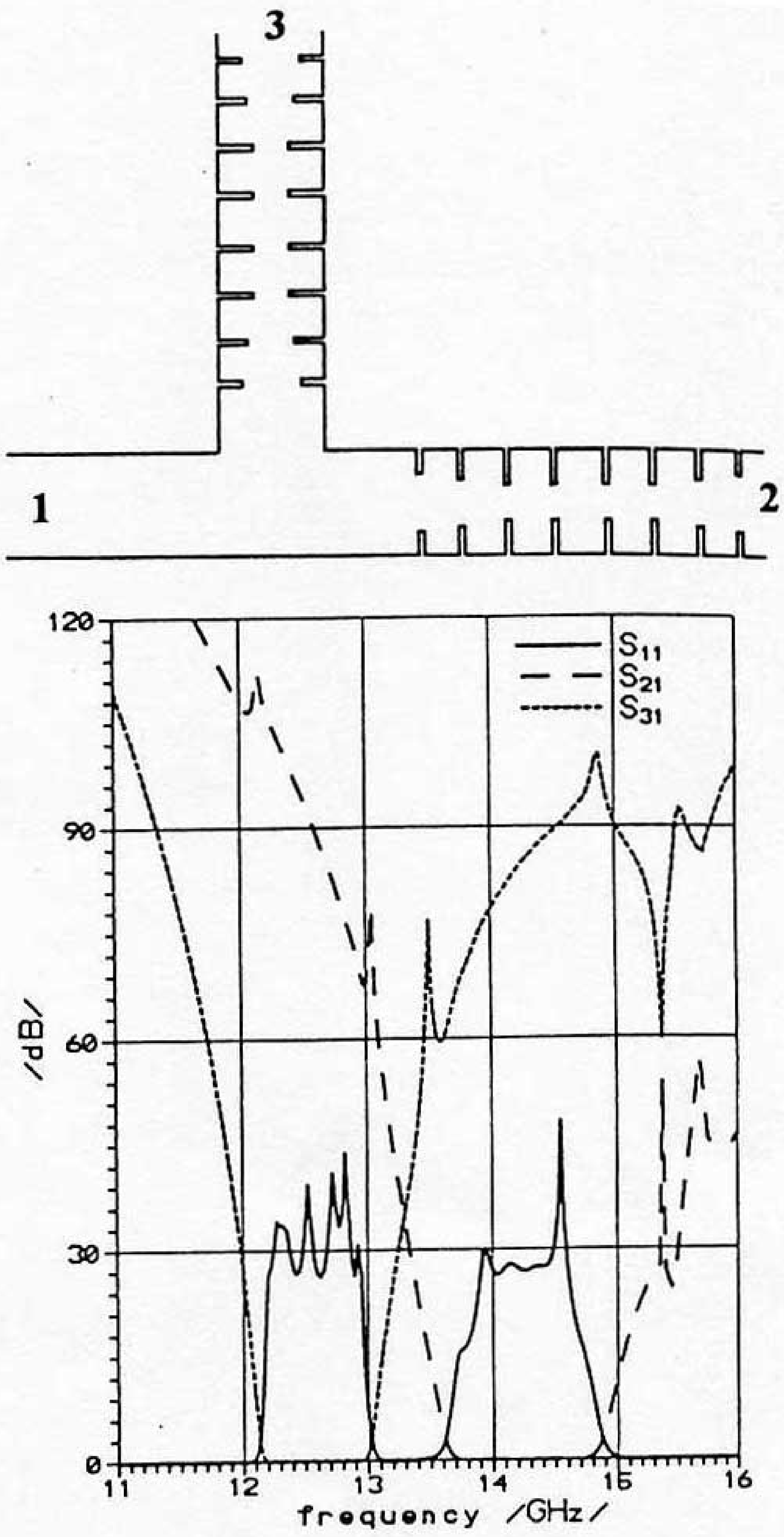

Fig. 6: *Computed performance of H-plane T-junction diplexer with inductive-iris filters (b/a=0.5).*

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