RIGOROUS DESIGN OF SEPTATE E-PLANE MULTIPLEXERS WITH PRINTED CIRCUIT ELEMENTS

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ABSTRACT

A new design of compact, low-cost and low-insertion loss millimeter wave multiplexers is introduced utilizing metallic E-plane filters integrated in the septate waveguide sections of wide-band E-plane n-furcated power dividers. A rigorous simulation technique, which is based on the modal scattering matrix method, comprises the complete component including the E-plane transformer, the septum as well as the filter sections, and takes the influences of the higher-order mode interaction at all discontinuities into account. Computer optimized data are given for Ku- and E-band di- and triplexer design examples with five-, or seven-resonator metal-insert filters, respectively.

INTRODUCTION

Recent advances in the design of channelized receivers have stirred the need for compact, low-cost and low-insertion-loss millimeter wave diplexers and multiplexers. Common designs utilizing printed circuit filter technology [1] - [7] include hybrid, [1] - [3], E-plane T-junction, [4], H-plane T-junction, [3], [5], and suspended probe coupling techniques, [6], [7]. Hybrid and probe coupling methods require additional structures and, hence, may cause additional costs and losses, [1] - [3], [6] - [8]; T-junction feeds are relatively narrow-band and it is often difficult to compensate for the rapid reactance variation, [3] - [5].

In this paper, we will describe a new design of a millimeter wave multiplexer (Fig. 1) which is capable to avoid these disadvantages by utilizing the wide-band low-insertion loss properties of E-plane n-furcated power dividers [9]. The design is well compatible with metallic E-plane filters providing low insertion losses because of the absence of supporting dielectrics, [10], [11]. Moreover, the technique leads to very compact and low-cost multiplexer performances as the metal-etched filters may be directly integrated in the septate E-planes of a common split-block waveguide housing (Fig. 1).

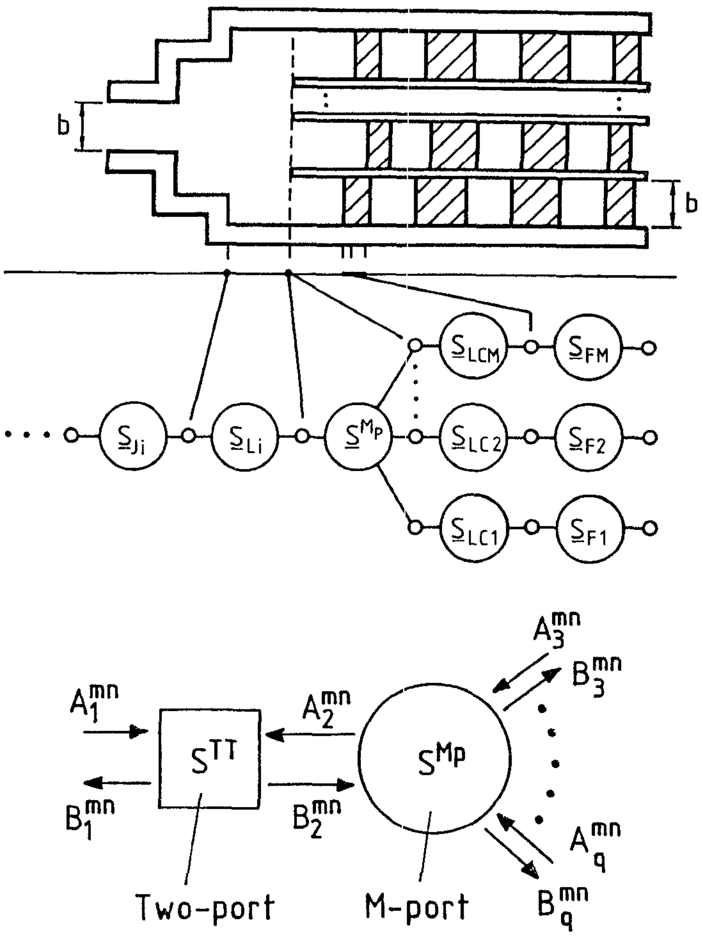

Fig. 1: Septate E-plane multiplexer with metallic E-plane filters

Usual design methods of millimeter wave multiplexers are based on empirical studies [1], equivalent circuit techniques [2], [3], [12], or approximate theories for the transitions [6], [7]. However, loading effects of the filter structures as well as the higher-order mode interactions between them and the feeding transition must be rigorously included in the design of the multiplexer to ensure good overall performance, especially for millimeter wave designs. Moreover, it may be desirable to take advantage of the full low-insertion loss and mutual compensation potential inherent to the technology by utilizing adequate exact simulation and optimization theories for the total millimeter wave multiplexer structure.

This paper presents a rigorous modal scattering matrix method for the design of the complete multiplexer component comprising the E-plane transformer, the septum and the filter section (Fig. 1). As higher-order mode interactions at millimeter waves have turned out to be of increasing importance, already for designing single filters [11], these effects, as well as the septum and metallization thicknesses, are taken into account for the complete component. Relevant influences, such as the transformer step heights and lengths, the septum distance to the transformer section, as well as the individual distances of the filters to the power divider section, are utilized for the optimization process as additional design parameters. Moreover, the exact design theory enables the high-precision manufacturing by computer controlled milling machines and etching techniques without the necessity of post assembly 'trial-and-error' adjustment methods.

THEORY

For the computer-aided design of the complete multiplexer structure (Fig. 1), the modal S-matrix method [9], [11], [13], is applied. The combination of all individual structures (E-plane and H-plane step discontinuities), including the higher-order mode interaction of the cascaded structures, requires all six field components to be considered, at each discontinuity. For a general homogeneous waveguide subregion under consideration, the fields

$$\vec{E} = \frac{1}{j\omega\epsilon}\nabla \times \nabla \times (\vec{Q}_{ez}) + \nabla \times (\vec{Q}_{hz}) \qquad (1)$$
$$\vec{H} = -\frac{1}{j\omega\mu}\nabla \times \nabla \times (\vec{Q}_{hz}) + \nabla \times (\vec{Q}_{ez})$$

are derived from the z-components of the electric (e) and magnetic (h) vector potentials

$$Q^{o}_{ez} = \sum_{i^{o}} N^{o}_{i^{o}} \cdot T^{o}_{ei^{o}} \cdot (A^{o\pm}_{ei^{o}} \cdot e^{\mp jk^{o}_{ze_{i^{o}}} z})$$
$$Q^{o}_{hz} = \sum_{i^{o}} N^{o}_{i^{o}} \cdot T^{o}_{hi^{o}} \cdot (A^{o\pm}_{hi^{o}} \cdot e^{\mp jk^{o}_{zh_{i^{o}}} z}) \qquad (2)$$

where $o = 1,2,3,\ldots,M_s$ (M_s = total number of subregions), i^o is the index for all TE-, and TM-modes in each subregion, N are the normalization factors due to the complex power, and T are the eigenfunctions in the corresponding subregions, [9], [11], [13]; $A^{\pm}$ are the amplitude coefficients of the forward and backward waves, and k_z are the wavenumbers of the corresponding TE- and TM-modes.

By matching the tangential field components at the common interfaces at the individual step discontinuities, the wave amplitude coefficients of (2) can be related to each other after multiplication with the appropriate orthogonal function, [9], [11], [13]. This yields the key building block two-port modal scattering matrices (S_{Ji}), (S_{Fi}) of the transformer and filter sections, respectively (cf. Fig. 1), and the M-port modal scattering matrix (S^{Mp}) of the n-furcated waveguide section [9].

In order to preserve numerical accuracy, the direct combination of the modal scattering matrices of all step discontinuities and of the intermediate homogeneous waveguide sections is used. The advantage of this procedure has already been demonstrated for two-port structures, cf. [11], [13]. The more general relations, which may also be used iteratively, for multi-port structures, e.g. including the transformer section two-port modal scattering matrix (S^{TT}), and the M-port modal scattering matrix (S^{Mp}), to calculate the scattered wave vectors B of the mn modes considered at the ports 1, s, (s=3,4,...,q), cf. Fig. 1, are given by

$$B_1 = [S^{TT}_{11} + S^{TT}_{12} \cdot W \cdot S^{Mp}_{11} \cdot S^{TT}_{21}] \cdot A_1 + S^{TT}_{12} \cdot W \cdot K\ ,$$
$$B_s = S^{Mp}_{s-1,1} \cdot [S^{TT}_{21} + S^{TT}_{22} \cdot W \cdot S^{Mp}_{11} \cdot S^{TT}_{21}] \cdot A_1 + S^{Mp}_{s-1,1} \cdot S^{TT}_{22} \cdot W \cdot K + P, \qquad (3)$$

with

$$W=(U-S^{Mp}_{11}S^{TT}_{22})^{-1},\quad K=\sum_{r=2}^{q-1} S^{Mp}_{1,r}\cdot A_{r+1},$$

$$P=\sum_{p=2}^{q-1} S^{Mp}_{s-1,p}\cdot A_{p+1},$$

and where the indices denote the related submatrices.

A computer program was written using the preceding relations and utilizing the evolution strategy method, cf. [13], for optimizing the geometrical parameters for given specifications. Sufficient asymptotic behaviour has been obtained by consideration of 15 TE- and TM-modes for the E-plane transformer and n-furcated waveguide section, and up to 40 TE_{m0}-modes for the filter sections.

RESULTS

A computer optimized Ku-band diplexer design example with two five-resonator metallic E-plane filters in the septate waveguide regions is shown in Fig. 2. Due to the inclusion of all relevant design parameters in the optimization process, only a one-step transformer is required to provide the desired pass-band return loss of about 26 dB. This holds also for thicker septa thicknesses as is demonstrated by a design example with t = 3mm. For higher frequencies, cf. the E-band diplexer design example in Fig. 3, a two-step transformer section has been chosen. The efficiency of the design method, also for more complicated structures, is demonstrated by the E-band triplexer design example shown in Fig. 4.

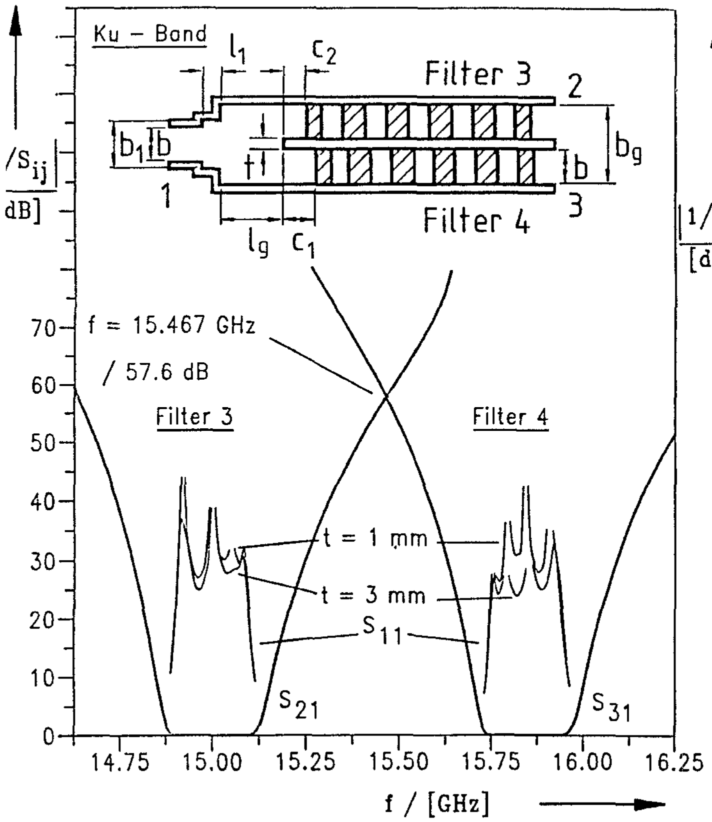

Fig. 2: Computer-optimized septate E-plane diplexer for Ku-band with two 5-resonator metallic E-plane filters.
Filter 3: f_{03} = 15.00 GHz,
filter 4: f_{04} = 15.85 GHz.

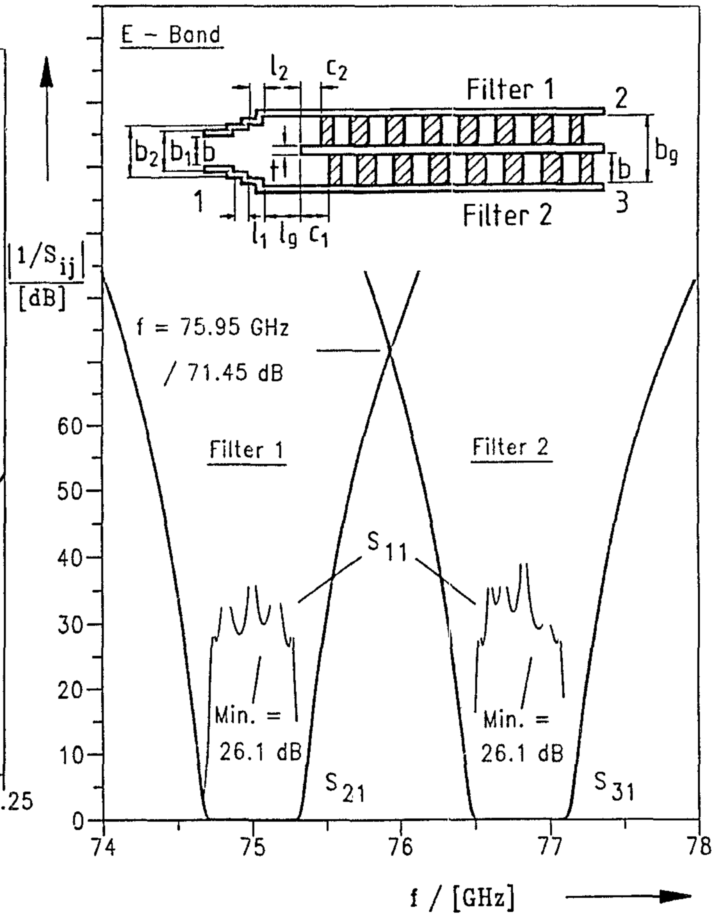

Fig. 3: Computer-optimized septate E-plane diplexer for E-band with two 7-resonator metallic E-plane filters.
Filter 1: f_{01} = 75.00 GHz,
filter 2: f_{02} = 76.80 GHz.

Measurements are available for the typical single components. The metallic E-plane filters have been fabricated and measured up to 144 GHz [11], [13], and the n-furcated waveguide power dividers have already been utilized for practical antenna feeding networks in the R120 waveguide-band (10 - 15 GHz), [9]. Excellent agreement between theory and measurements verifies the modal S-matrix design method. For diplexer designs with metallic E-plane filters, based on E-plane T-junction feeds, measured pass-band insertion losses of typically about 0.5 - 0.8 dB in the R120-band have been reported [4]. The E-plane diplexers designed may be fabricated utilizing computer controlled milling machines for the split-block housing of the filters and the transformer section, and using metal-etching techniques for the filter elements.

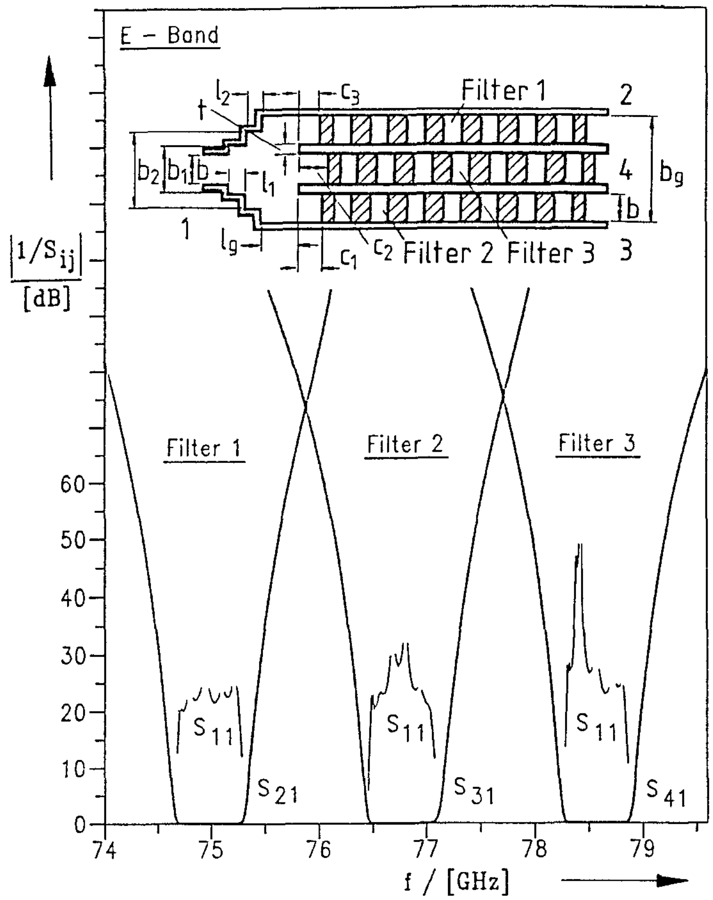

Fig. 4: Computer-optimized septate E-plane multiplexer for E-band with three 7-resonator metallic E- plane filters.
Filter 1: f_{01} = 75 GHz,
filter 2: f_{02} = 76.8 GHz,
filter 3: f_{03} = 78.6 GHz.

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