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RIGOROUS DESIGN OF EVANESCENT-MODE E-PLANE FINNED WAVEGUIDE BANDPASS FILTERS

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ABSTRACT

This paper presents a new design of compact, low-cost and low-insertion loss evanescent-mode waveguide bandpass filters with bilateral metallic E-plane fins. Based on the modal scattering matrix method, the rigorous design takes into account the influences of both, the finite fin thickness and the higher-order mode interaction at all discontinuities. Computer optimized design data are given for filters with passbands in the X- and the E-band with wide stopbands. The theory is verified by measurements.

INTRODUCTION

Evanescent-mode microwave bandpass filters have found many applications in satellite communication systems, as preselectors or in multiplexers, [1] - [5], [8], due to several advantages over the conventional coupled resonator filter types, such as, for instance, compactness and wide stopbands. Common techniques utilize capacitive screw obstacles [1] - [3], round capacitive posts [4], [5], bilateral or unilateral ridge waveguide sections for lowpass filter structures [6], [7], and, more recently, non-touching unilateral E-plane fins of negligible thickness with and without a dielectric layer [8]. Capacitive screws, round posts and ridge waveguide elements are often difficult to fabricate at low cost and to mass-produce [1] - [6]. Dielectric layers cause additional losses, and, hence, the low-insertion loss design potential inherent to the technology may not be fully utilized. Thin unilateral fins may lead to small ridge gaps and, therefore, may achieve low power handling capability [7], [8]. This paper describes a new design of millimeter wave printed circuit evanescent-mode waveguide bandpass filters (Fig. 1) which avoids these disadvantages.

Based on bilateral all-metal E-plane fins (Fig. 1), the design combines the well-known properties of the waveguide E-plane integrated-circuit technology [9] with the advantages of the evanescent-mode concept [1] - [8] and of the low-insertion loss quality resulting from the complete absence of supporting dielectrics, [6] - [10]. The proposed structure where the finite fin thickness is included in the design achieves relatively large gap widths of about one quarter of the waveguide height in the below cutoff section and leads to filter characteristics with high skirt selectivity and wide stopbands.

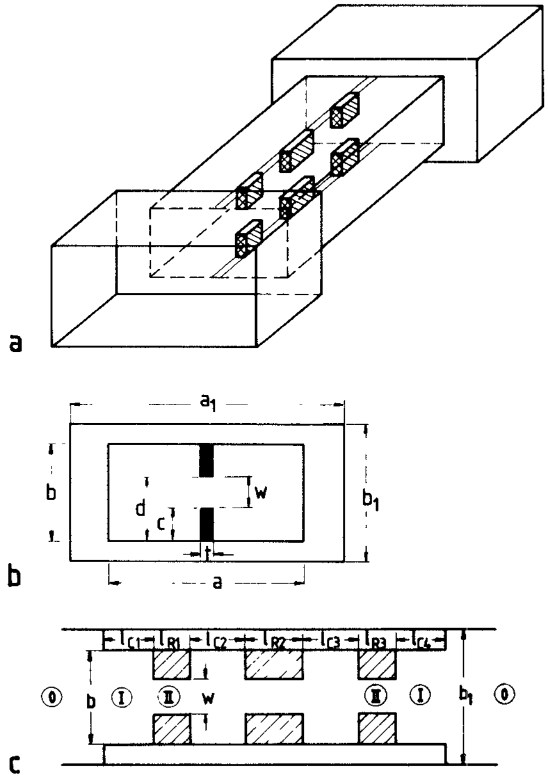

Fig. 1: Evanescent-mode bilateral E-plane finned waveguide bandpass filter
a) Input- and output waveguide, below cutoff waveguide with E-plane fins of thickness t; b) Cross-sectional dimensions c) Longitudinal section dimensions in the filter region

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Usual design methods for evanescent-mode filters are based on empirical studies [1], [2], equivalent circuit techniques [3] - [7], and on scattering matrix techniques in conjunction with the spectral domain approach [8]. The equivalent circuit technique neglects the coupling effects of higher order modes which are of great significance for a reliable prediction of the characteristic of this kind of filters. The spectral domain approach omits the influence of the finite thickness of the E-plane fins which has turned out to be of increasing importance, especially at millimeter wave frequencies [9], [10]. To ensure good overall performance, however, it may be desirable to include rigorously all actual effects of the fin elements as well as the higher order mode interactions between them.

The computer-aided design method in this paper, therefore, is based on field expansion into normalized eigenmodes [9] - [11], which yields directly the modal S-matrix of the appropriate key building blocks, the double-step discontinuity and the transition waveguide to the E-plane finned waveguide with finite thickness. The immediate modal S-matrix combination of all interacting structures includes the higher-order mode coupling effects and allows the stopband characteristics of the filters to be included in the filter design.

THEORY

For the computer-aided design of the evanescent-mode E-plane finned waveguide bandpass filter (Fig. 1), the modal S-matrix method [9] - [11] is applied. The filter structure is decomposed into two key building block discontinuities: double step junction from the input waveguide above cutoff to the waveguide below cutoff filter section, step discontinuity from the rectangular waveguide to the E-plane finned waveguide. Combination with the known scattering matrices of the corresponding intermediate homogeneous waveguide sections of finite lengths yields the total scattering matrix of the filter. As the modal scattering matrices of the key building block structures have already been derived in [10], [11], the theory is given here in abbreviated form only.

The electromagnetic field in the subregions i = 0, I, II (Fig. 1c)

$$\vec{E}^{i} = \nabla \times (A^{i}_{Hz}\vec{e}_{z}) + \frac{1}{j\omega\epsilon} \nabla \times \nabla \times (A^{i}_{Ez}\vec{e}_{z})$$
$$\vec{H}^{i} = \nabla \times (A^{i}_{Ez}\vec{e}_{z}) - \frac{1}{j\omega\mu} \nabla \times \nabla \times (A^{i}_{Hz}\vec{e}_{z}) \qquad (1)$$

is derived from the z-components of two vector potentials

$$\vec{A}^{i}_{Hz} = \sum_{q=1}^{\infty} (\sqrt{Z^{i}_{Hq}}) \cdot T^{i}_{Hq}(x,y) \cdot [V^{i}_{Hq}\exp(-jk^{i}_{zHq}z) + R^{i}_{Hq}\exp(+jk_{zHq}z)] \qquad (2)$$

$$\vec{A}^{i}_{Ez} = \sum_{p=1}^{\infty} (\sqrt{Y^{i}_{Ep}}) \cdot T^{i}_{Ep}(x,y) \cdot [V^{i}_{Ep}\exp(-jk^{i}_{zEp}z) - R^{i}_{Ep}\exp(+jk_{zEp}z)],$$

with the wave impedances

$$Z^{i}_{Hq} = (\omega\mu_0)/(k^{i}_{zHq}) = 1/Y^{i}_{Hq},$$
$$Y^{i}_{Ep} = (\omega\epsilon_0)/(k^{i}_{zEp}) = 1/Z^{i}_{Ep} \ . \qquad (3)$$

$V^{i}_{H,E}$, $R^{i}_{H,E}$ are the TE-, and TM-mode wave amplitudes of the forward and backward waves, respectively, to be related to each other. This will yield the corresponding scattering matrix relations, cf. (4); k_z are the propagation factors, and T^{i}_{Hq}, T^{i}_{Ep} are the cross-section eigenfunctions of the corresponding waveguide structures under consideration, [10], [11].

Matching the tangential field components of, for instance, regions I and II at the common interface yields the modal scattering matrix of the related discontinuity, e.g. waveguide to finned waveguide [10]

$$\begin{bmatrix} (R^{I}) \\ (V^{II}) \end{bmatrix} = (S) \begin{bmatrix} (V^{I}) \\ (R^{II}) \end{bmatrix} \qquad (4)$$

The series of step discontinuities, for a complete filter structure, is calculated by direct combination of the single modal scattering matrices, [9] - [11]. As with metal insert filters and finned transformers [9], [10], the computer aided design is carried out by an optimization program applying the evolution strategy method. An error function is minimized with respect to a parameter vector which contains the coupling and resonator lengths as well as the slot widths (Fig. 1c). In the optimization process, seven TE-modes together with three TM modes have been used which provides sufficient convergence behaviour of the scattering parameters. The final design data are verified by considering twelve TE- and seven TM-modes together with nine expansion terms [10] in the finned waveguide section. As all symmetries are advantageously taken into account, one computer run with fifty frequency sample points takes about 10 min on a IBM 370 computer.

RESULTS

In order to verify the theory given, Fig. 2b shows the calculated and measured input reflection coefficient $|S_{11}|$ in decibels as a function of frequency of a very simple, non-optimized filter structure with four bilateral E-plane fins in a single WR-62 waveguide (15.799mm × 7.899mm) housing (Fig. 2a). The thickness of the fins is t = 0.9 mm (the gap width is w = 3.1mm). The mechanical tolerances of the structure (which have been measured by a measuring microscope) are taken into account in the analysis. Excellent agreement between theory and measurements may be stated.

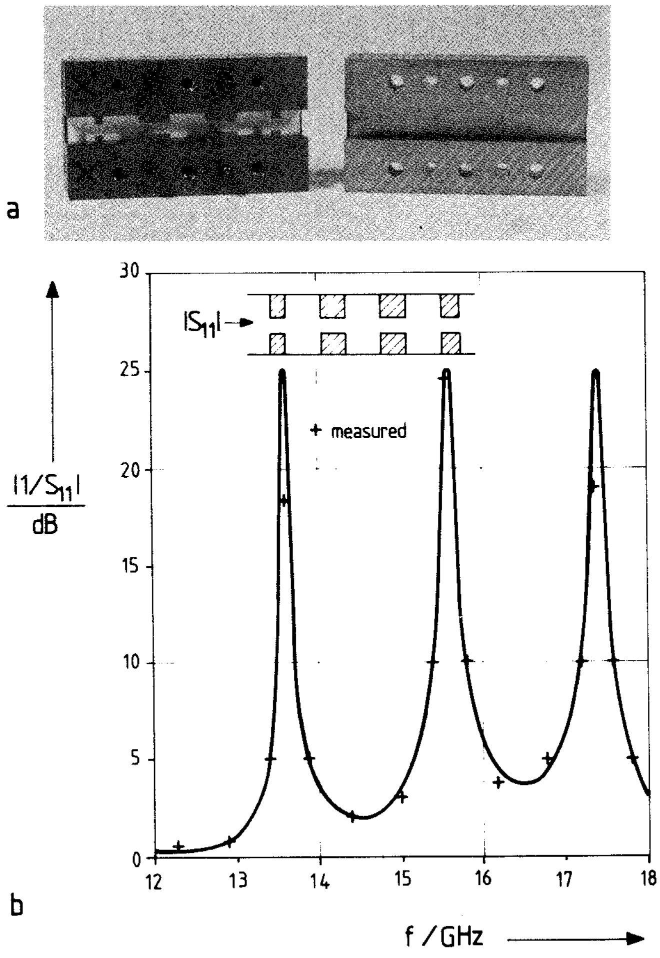

Fig. 2: Non-optimized simple filter structure
Verification of the theory; four bilateral E-plane fins in a single WR 62 waveguide housing (15.799mm × 7.899mm), fin thickness t = 0.9mm, gap width w = 3.1 mm. a) Photograph of the realized structure; b) Calculated and measured (+) input reflection coefficient $|S_{11}|$ in decibels versus frequency;

A computer optimized X-band evanescent-mode E-plane finned waveguide bandpass filter design example with passband at about 11 GHz is shown in Fig. 3. A WR 90 (22.86mm × 10.16mm) waveguide housing is chosen for the input and output waveguide, the filter section utilizes a WR 42 (10.668mm × 4.318mm) waveguide below cutoff. The optimized design with five E-plane fins of thickness t = 1mm achieves a minimum stopband attenuation of more than 60 dB for the whole Ku-band. The comparison with the characteristics of a corresponding E-plane metal-insert coupled resonator filter [9] with five resonators (dashed line) demonstrates the significant improvement of the rejection quality by the E-plane printed-circuit evanescent-mode filter technique. Moreover the skirt selectivity compares very favourable with that of the conventional metal-insert filter.

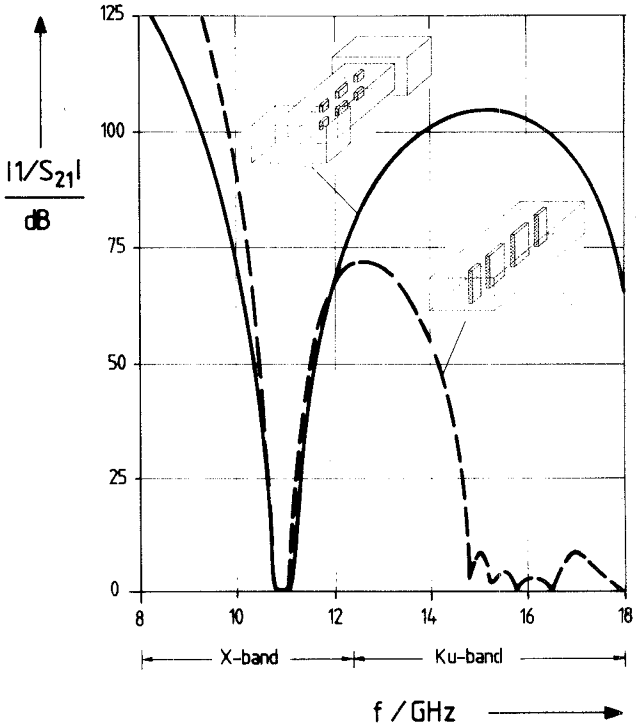

Fig. 3: Computer optimized X-band evanescent-mode E-plane finned waveguide bandpass filter
WR 90 (22.86mm × 10.16mm) waveguide input and output housing, WR 42 (10.668mm × 4.318mm) below cutoff waveguide. Fin thickness t = 1mm, gap width w = 0.975mm. Design with 5 E-plane fins

Fig. 4 shows the results of a computer optimized E-band evanescent-mode E-plane finned waveguide bandpass filter design example with a WR 12 (3.098mm × 1.549mm) input and output waveguide and with a WR 7 waveguide reduced in height (1.651mm × 0.668mm) below cutoff filter section. This design with three E-plane fins of thickness t = 150 µm achieves a minimum stopband attenuation of more than 40 dB up to about 110 GHz (the end of the next higher waveguide band, the W-band). The sensitivity of the performance of the optimized E-band filter to dimensional tolerances is demonstrated by the dashed curve (Fig. 4) which shows the insertion loss for a fin gap width increased by only 2 µm. This may illustrate the necessity for a reliable design theory which takes all relevant parameters into account.

CONCLUSION

The modal S-matrix method presented achieves the exact computer-aided design of novel evanescent-mode bilateral E-plane finned waveguide bandpass filters with wide stopbands. Since the theory includes the finite thickness of the fins as well as higher-order mode interactions at all discontinuities, the design achieves the reliable precision manufacturing without the necessity of post assembly adjustments, and allows the stopband characteristic of the filter to be taken into account in the optimization process. Moreover, this design leads to relatively wide gap widths which may help to meet high power handling requirements. Measurements verify the theory given by excellent agreement.

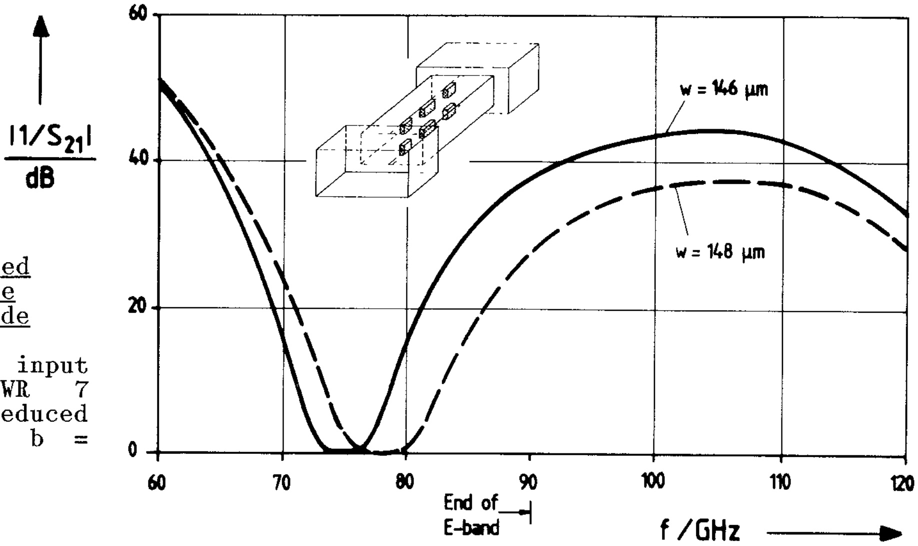

Fig. 4: Computer optimized E-band evanescent-mode E-plane finned waveguide bandpass filter
WR 12 (3.098mm × 1.549mm) input and output waveguide, WR 7 below cutoff waveguide reduced in height (a = 1.651mm, b = 0.668mm); t = 150 µm.

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