FERRITE TUNABLE MILLIMETER WAVE PRINTED CIRCUIT FILTERS

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ABSTRACT

New designs of millimeter wave magnetically tunable E-plane integrated circuit filters are described. The filters combine the advantages of printed circuit technology with those of the high power capability of ferrite-slab loaded waveguides. Computer optimized design data based on the rigorous modal S-matrix method are given for Ka-band tunable metallic and finline type filters. The theory is verified by measured results in Ku-band.

INTRODUCTION

Tunable bandpass filters where the resonant frequency is controlled by a d.c. biasing magnetic field have found many applications, [1] - [5]. Common techniques utilize ferrimagnetic YIG resonators [1] - [3], or ferrite slabs in resonating below-cutoff waveguides [4], [5]. This paper describes new designs of millimeter wave magnetically tunable E-plane integrated circuit filters.

Based on E-plane metallic filters with additional lateral ferrite slabs (Fig. 1a), and large-gap finline filters on a ferrite substrate (Fig. 1b), the design combines the advantages of low-cost millimeter wave printed circuit technology [6] - [10], with those of high power capability of tunable ferrite-slab loaded waveguide filters [4], [5]. Moreover, the exact design theory enables the high-precision manufacturing by etching techniques without the necessity of post assembly 'trial-and-error' adjustment methods. Furthermore, these types of filters, which are suitable also for a large number of resonators, may complement advantageously the more narrow-band YIG filters [5], when relatively large bandwidth designs combined with moderate tuning ranges are required. These features suggest the appropriate application of the filters e.g. for receiver preselectors in radar, troposcatter, navigation, and communication systems [5].

Analogous to the rigorous computation of printed E-plane circuit filters without ferrite inserts [8] - [10], and of ferrite-slab loaded waveguide components [11], the computer-aided design of the tunable filters in this paper (Fig. 1) is based on the modal-S-matrix method. Therefore, higher-order mode coupling effects as well as the finite thickness of the metallic and ferrite inserts are taken into account.

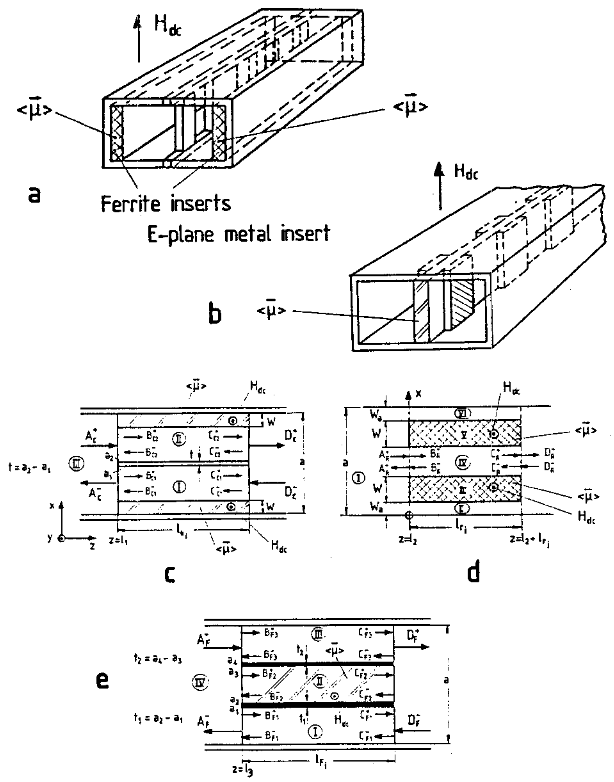


Fig. 1: Ferrite tunable millimeter wave printed circuit filters
a) E-plane metal insert filter with lateral ferrite slabs; b) Large-gap finline filter on a ferrite substrate; c) Coupling section of the metal insert type; d) Resonator region of the metal insert type; e) Coupling section of the finline type

THEORY

For the field theory treatment, the filter structures (Fig. 1) are decomposed into appropriate key building blocks: ferrite-slab loaded septate waveguide coupling section (Fig. 1c), and the double ferrite-slab loaded resonator region (Fig. 1d), for the metal-insert filter type; ferrite-slab loaded double septate coupling section (Fig. 1e), and the single ferrite-slab loaded resonator region (Fig. 1e, with metallization of thicknesses t_1, t_2 removed), for the finline filter type. The overall scattering matrix of the total filter component is calculated by suitable direct combination [8], [10], [11] of all single modal scattering matrices of the key-building blocks and homogeneous waveguide sections involved. This procedure preserves numerical accuracy, and the number of modes at the discontinuities may be adapted to the specific requirements of each individual step junction, as no symmetry of modes is necessary.

For each homogeneous subregion, ν = I to IV (Figs. 1c, 1d, 1e), the field equations [12] of the resulting TE_{n0} wave, if a TE_{m0} wave is incident,

$$\nabla \times \vec{H} = j\omega\epsilon\,\vec{E}\,,\quad \nabla \cdot (\langle\vec{\mu}\rangle\,\vec{H}) = 0$$
$$\nabla \times \vec{E} = -\,j\omega\langle\vec{\mu}\rangle\,\vec{H},\qquad \nabla \cdot \vec{E} = 0 \tag{1}$$

are derived from the electric field component $\vec{e}_y E_y^{(\nu)}$ expressed as a sum of N eigenmodes [11] satisfying the vector Helmholtz equation and the boundary conditions at the discontinuities in the x direction. The permeability tensor is given e.g. in [13].

The propagation factor γ_n in the waveguide sections is determined via field matching [11], [12] of the transverse field components along the boundaries in the x direction, together with the relations for the single wavenumbers in the cross-sectional subregions. The requirement that the system determinant be zero results in a transcendental equation for γ_n which is solved numerically [11]. The influence of small lateral air gaps of width w_a (cf. Fig 1d), due to fabrication tolerances, on the filter response, which has been observed at evanescent mode filters as well [5], is adequately taken into account.

Matching of the transversal field components at the corresponding interfaces of Fig. 1c at $z = l_1$ yields

$$\sum_{m=1}^{M} (A^+_{Cm} + A^-_{Cm})\, T_{Cm}\, u_{Cm} = \sum_{n=1}^{N}(B^+_{C1n}e^+_{1n} + B^-_{C1n}e^-_{1n} + B^+_{C2n}e^+_{2n} + B^-_{C2n}e^-_{2n});$$

$$\sum_{m=1}^{M} (A^+_{Cm} - A^-_{Cm})\, T_{Cm}\, Y_{Cm}\, u_{Cm} = \begin{cases} \sum\limits_{n=1}^{N} (B^+_{C1n}h^+_{1n} - B^-_{C1n}h^-_{1n}) & x \in (\mathrm{I}) \\ \sum\limits_{n=1}^{N} (B^+_{C2n}h^+_{2n} - B^-_{C2n}h^-_{2n}) & x \in (\mathrm{II}) \end{cases} \tag{2}$$

where T_{Cm} is the normalization factor so that the power carried by a given wave is 1W for a wave amplitude of $1\sqrt{W}$ [12]. Y_{Cm} is the wave admittance, and u_{Cm} is the cross-section function determined by the given boundary conditions. The normalized eigenfunctions of the forward (+), or reverse (-) n-th mode, e^+, e^-, h^+, and h^-, respectively, are given via (1) by the eigenmode expressions for $E_y^{(\nu)}$ analogeously to [11]. The modal scattering matrix (S^C) of the coupling structure of finite length l_{ki} (Fig. 1c) is obtained by suitably arranging the still unknown normalized amplitude coefficients involved:

$$\begin{bmatrix} (A^-_C) \\ (D^+_C) \end{bmatrix} = \begin{bmatrix} (S^C_{11}) & (S^C_{12}) \\ (S^C_{21}) & (S^C_{22}) \end{bmatrix} \cdot \begin{bmatrix} (A^+_C) \\ (D^-_C) \end{bmatrix} \tag{3}$$

Matching of the the transversal field components at the interfaces at $z = l_2$ (Fig. 1d), and at $z = l_3$ (Fig. 1e) yields equations which are similar to (2). The scattering matrices (S^R) of the resonator region of length l_{ri}, and (S^F) of the coupling region of length l_{Fi} are found analogeously. For computer optimization [11] of the filters, the expansion into up to ten eigenmodes at each discontinuity has turned out to be sufficient. The final design data are proven through an expansion of 30 eigenmodes. The convergence behaviour of the modal method used for ferrite loaded waveguides has already been demonstrated in [11].

RESULTS

Fig. 2 shows the calculated filter response of a computer-optimized three-resonator magnetically tunable metal insert filter with lateral ferrite TT86-6000 slabs (Transtech Inc.) of widths w = 0.5mm for two different d.c. field strengths (curves 1, 2). The operating midband of the filter may be tuned within about 29.7 and 30.4 GHz. The calculated

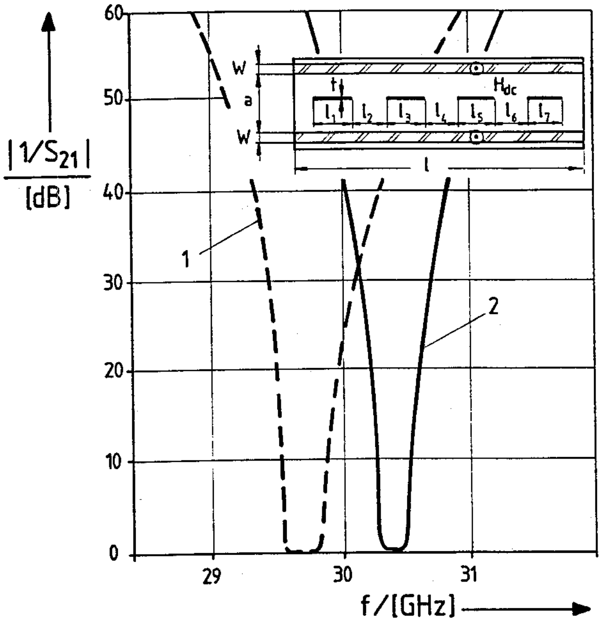


Fig. 2: Computer-optimized Ka-band magnetically tunable E-plane metal insert filter
Design data: Ferrite TT86-6000, w = 0.5mm waveguide a=7.112mm, b=a/2; t = 0.51mm;
$H_1 = 0$, $H_2 = 2\cdot10^5$A/m.

filter response of a computer-optimized magnetically tunable five-resonator large-gap finline is presented in Fig. 3 for two different d.c. field strengths providing a tuning range from about 29.1 to 30.0 GHz. The good temperature stability of the two filter types presented may be demonstrated by plotting the related relative midband frequency variation $f_{CT} = [f_0(0^{\circ}C) - f_0(40^{\circ}C)]/f_0(20^{\circ}C)$ against the d.c. field strength (Fig. 4). The curves (a) for the metal insert type (cf. Fig. 2), and (b) for the finline type (cf. Fig. 3) are calculated by including the corresponding data of the ferrite material for the parameters (temperature and H_0) in the analysis of the frequency behaviour of the optimized filters.

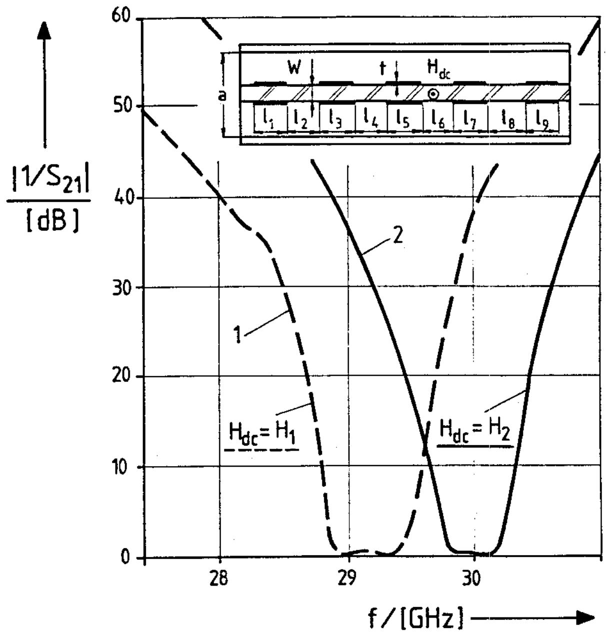


Fig. 3: Computer-optimized Ka-band magnetically tunable large-gap finline filter on a ferrite substrate
Design data: Ferrite TT86-6000, w = 0.5mm waveguide same as in Fig. 2; t = 10μm;
$H_1 = 0$, $H_2 = 2\cdot10^5$A/m.

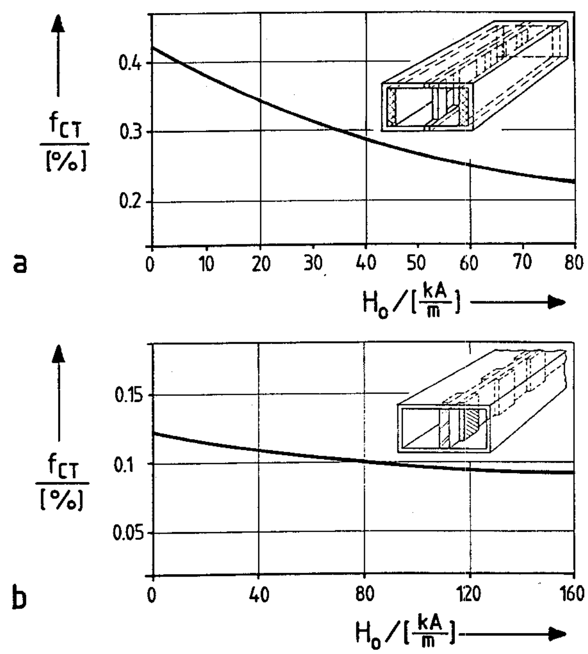
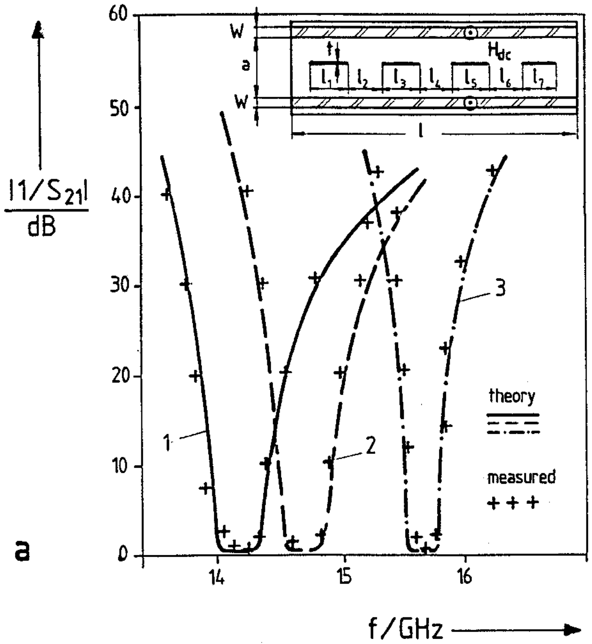


Fig. 4: Relative midband frequency variation with temperature
$f_{CT} = [f_0(0^{\circ}C) - f_0(40^{\circ}C)] / f_0(20^{\circ}C)$
plotted against the d.c. field strength:
a) Tunable metal insert filter (Fig. 2).
b) Tunable finline filter (Fig. 3).

The theory presented is verified by measured results of an optimized magnetically tunable three-resonator Ku-band metal insert filter (Fig. 5a). As all relevant parameters, like higher-order mode interactions and the influence of an additional air gap between ferrite slabs and the waveguide walls, are included in the design theory, the theoretically predicted values agree well with measured results. The components of the fabricated filter are shown in Fig. 5b: the R140 waveguide housing (15.799mm × 7.899mm) together with the biasing magnet, the photoetched 0.19 mm thick metal insert (99.9% pure copper), and the two lateral TTI-2800 ferrite slabs of standard width w = 1mm.

a



b

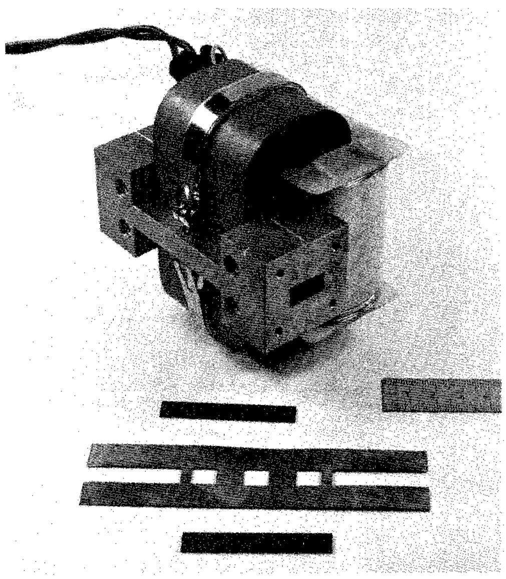


Fig. 5: Experimental verification
a) Filter response of a tunable three-resonator metallic E-plane filter. Design data: Ferrite TTI-2800, w = 1mm; waveguide: a = 15.799mm, b = a/2; t = 0.19mm; $H_1 = 0$ (curve 1), $H_2 = 4.8 \cdot 10^4$ A/m (curve 2), $H_3 = 1.72 \cdot 10^5$ A/m (curve 3); + + + measured; -----, - - - , - · · - ·· , theory. b) Components of the fabricated filter: R140waveguide housing together with the biasing magnet, the photoetched 190μm thick metal insert, and the two lateral ferrite slab inserts.

Acknowledgement: This work was financially supported under contract N. Ar138/6-1 by the DFG (German Research Society).

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