ANALYSIS AND TUNING EFFICIENCY OPTIMIZATION OF MAGNETICALLY TUNED PRINTED E-PLANE CIRCUIT FILTERS

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ABSTRACT

The tuning efficiency of metal insert filter loaded with ferrite slabs is defined and analysed. Three parameters which dominate the filter tunability (ferrite slab thickness, distance to narrow waveguide wall and ferrite saturation magnetization) are discussed. An optimum combination of these parameters has been found and new filter design based on modal scattering method is presented. The improved filters can be tuned over 60-70% of a standard waveguide band with an insertion loss between 1 and 3 dB, depending on frequency.

INTRODUCTION

The technology of microwave tunable filters may involve several different tuning techniques such as mechanical tuning (e.g. sliding waveguide walls [1]), electronic tuning (e.g. varactor diode controlled filters [2]) and ferrimagnetic resonance coupling (YIG-filters [3], hexagonal ferrite resonators [4]). Waveguide filters, which are tuned by changing the permeability of ferrite slabs in the resonators were introduced recently in several papers [8], [9],[10]. These devices have excellent band pass filter characteristics (low insertion loss, high rejection attenuation, wide stop-band separation, high selectivity), high power handling capability,can be designed accurately, manufactured at low cost and do not require adjustment after assembly . In this respect they rival the customary YIG-filters. However, their principal drawback is the limited tuning range (about 30% of a waveguide band).
In the following we will describe how this tuning range can be doubled by carefuly analysis and optimizing the parameters which determine the tuning efficiency.

THEORY

The tuning efficiency of a magnetically tuned filter may be defined as

$$\eta[\Delta fo] = \frac{fo[H dc2] - fo[H dc1]}{Hdc2 - Hdc1} \qquad (1)$$

where fo[H dc2] and fo[H dc1]are the frequencies corresponding to the dc-magnetic field strenghts Hdc2 and Hdc1 ,respectively. This definition of tuning efficiency is generaly valid and thus may be apllied to the particular structure shown in Fig. 1a. In this filter design, the resonator sections are partially filled with ferrite material. Such an arrangement appears to be superior to the structures described in [10], which contain two lateral ferrite plates extending across the entire filter, including the coupling sections.

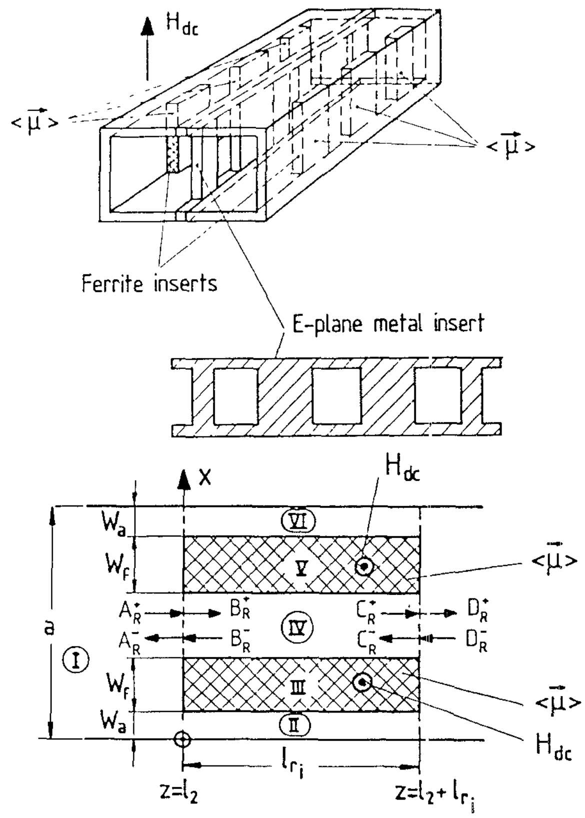

Fig. 1: Magnetically tunable band-pass filter
a) E-plane tuned metal insert filter with multiple ferrite slabs; b) key building blocks for field theory treatment : resonator region

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In order to ensure similar tuning conditions for different ferrite materials, the starting value for the dc magnetic field will always be set to H_{dc1} =0. The upper value depends on frequency; for Ku-band it is about $H_{dc} = 10^5$ A/m. Hence the tuning region is quasi -linear for all possible materials. The demagnetized ferrite (H_{dc} =0) may be characterized by a scalar permeability, with approximate values given by the experimental relations in [7].

For the field theory treatment of the investigated structures the modal S-matrix method is applied [8]. The S-matrix expressions for the septated waveguide coupling sections and symetrically loaded resonator regions (Fig. 1b) are described in [5] and [9], respectively. Matching the transversal field components at z=0 and incorporating the finite lenghts of the sections leads to the modal two-port scattering matrices of the related key-building blocks which are appropriately cascaded to form the overall S-matrix of the filter structure:

$$[S] = \begin{bmatrix} (S_{11}) & (S_{12}) \\ (S_{21}) & (S_{22}) \end{bmatrix} \qquad (2)$$

In (2), (S_{21}) is the submatrix containing the complex modal transmission coefficients. The filter response is obtained as an expression for the frequency-depedent insertion loss:

$$\frac{1/S_{21}}{dB} = -20 \log [S_{21}(1,1)] \qquad (3)$$

where element (1,1) denotes the TE_{10} mode on either side of the component.

The midband frequencies fo[H_{dc1}], fo[H_{dc2}] may be determined directly from the filter responses. The parameters which dominate the tuning efficiency are (see Fig. 1b): relative ferrite slab thickness w_f /a , relative distance between narrow waveguide wall and ferrite insert, w_a /a , and the relative saturation magnetization of the ferrite material ω_m / ω , where a = waveguide width, f= operating frequency, $\omega = 2\pi f$, $\omega_m = \gamma M_s$. The influence of these parameters on the wavelenght, in the ferrite loaded E-plane resonators has been discussed previously [11]. The proper choice of the ferrite saturation magnetization is of major importance for desired operation of each ferrite device in a given frequency range. For optimal tuning range, Ms should be large enough to provide a steep permeability slope, yet the lossy resonance region should be sufficiently far away. The importance of the air gaps between ferrite and narrow waveguide walls was discussed in previous papers [10], [12]. Snyder [12] pointed out the existence of small lateral air gaps due to waveguide fabrication tolerances, but he did not take them into account in his analysis. We know now that they can cause great differences between theory and experiment. This small distance, usually estimated to be of the oreder of the waveguide corner radius, may be increaseed on purpose and thus become an additional parameter with considerable influence on the filter tuning efficiency.

The ferrite slab thickness is of similar importance for efficient tunability. It was shown in [8] that the filters loaded with slabs thinner than 0.035 times the waveguide width, can not be tuned over a satisfactory range. However, when resonators are filled with too large amount of high permittivity ferrite material the higher order modes may propagate and the energy absorption even outside the resonance region may become critical.

RESULTS

In the following figures the functional dependency between tuning efficiency and various tuning parameters will be shown. Fig. 2 shows how the ferrite slab thickness affects the filter tunability. The tuning efficiency grows almost exponentially with increasing slab thickness up to a value of w_f /a =0.75. Beyond this limit, higher order modes start to propagate and drastically alter the characteristics of the filter. Fig. 3 demonstrates a guasi-linear growth of the filter tuning efficiency with increasing saturation magnetization. The optimum M_s for a given frequency range lies usually below the maximum value for commercially avaiable materials (5000 Gs). Fig.4 shows the effect of the distance separating slabs and waveguide wall, on the tuning efficiency. Again the characteristics becomes meaningsless beyond w_a /a > 2 10^{-2} due to the onset of higher-order mode propagation.

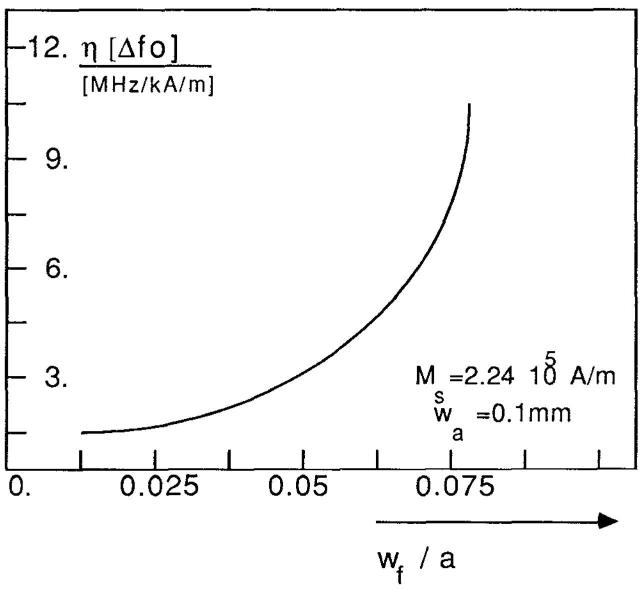

Fig. 2 Tuning efficiency as a function of normalized ferrite slab thickness.

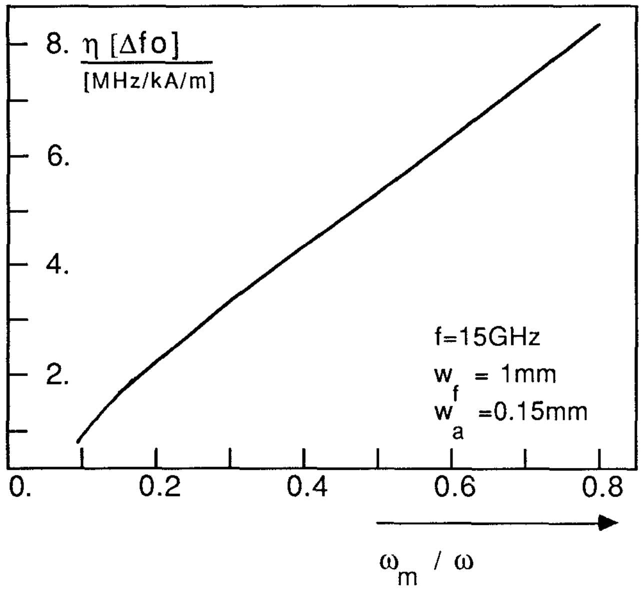

Fig. 3 Tuning efficiency as a function of normalized saturation magnetization.

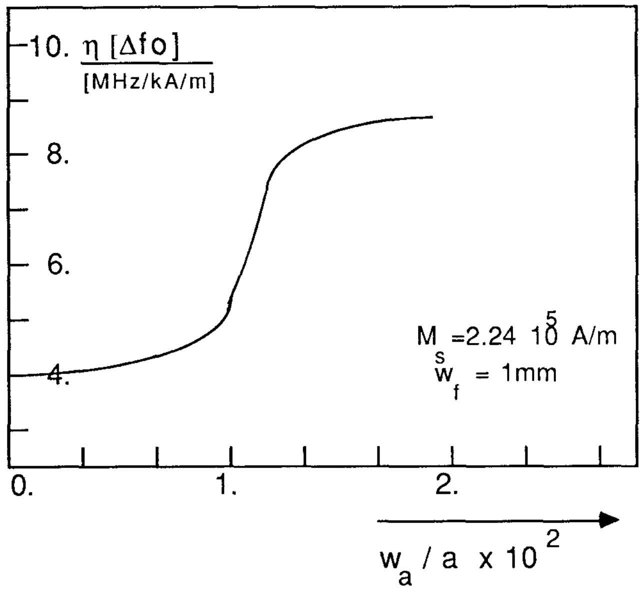

Fig. 4 Tuning efficiency as a function of normalized slab-waveguide wall distance.

Having thus obtained the effect of the various tuning parameters on tuning efficiency, we were able to select an optimum combination of these parameters and to maximize the tuning range of the magnetically tunable filters. To demonstrate the dramatic increase in tuning range obtained with our new approach, we have compared two Ku-band filters in Fig. 5. The first (Fig. 5.a) was presented in [9] and provided the best results published so far. Its tuning range goes from 14.25 to 16. GHz. The saturation magnetization of the ferrite material is 2.24 10^5 A/m. The second filter (Fig. 5b) was designed using our tuning range optimization which calls for an optimal saturation magnetization of $2.8 \cdot 10^5$ A/m and the dimensions specified in Fig. 5b. The new filter can be tuned from 13 to 17 GHz without sacrifice in overall filter performance.

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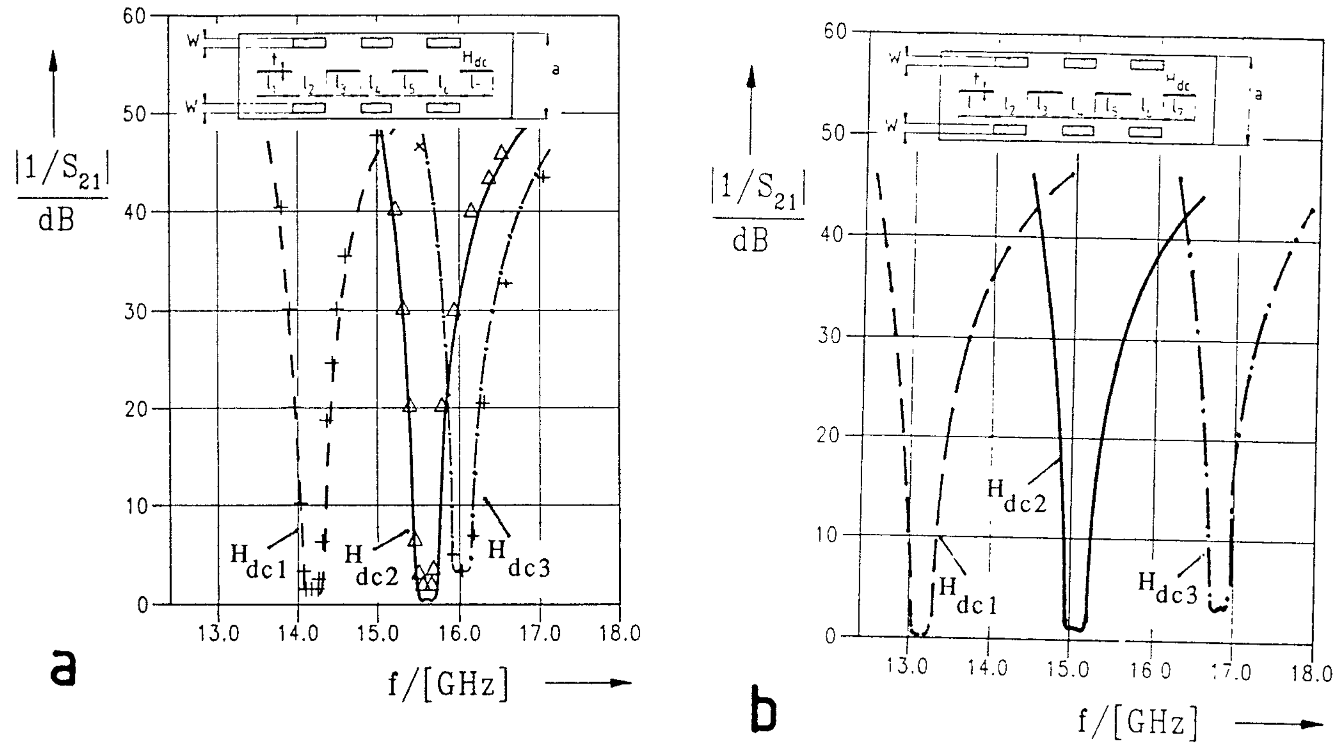

Fig. 5 Magnetically tunable E-plane metal insert filter for Ku-band.

a) design without tuning efficiency optimiztion steps, design data: Ferrite TTI-2800, a=2b=15.799mm, t=0.19 mm w_a = 0.1mm, w_f =1mm, $l_1 = l_7$ = 3.59mm, $l_2 = l_6$ =8.916mm, $l_3 = l_5$ = 9.417mm, H_1 = 0., H_2 = 1.75 10^5 A/m, H_3 = 2.4 10^5 A/m

b) extended tuning range design
design data: Ferrite TT2-3500, a=2b=15.799mm, t=0.19mm, w_f = 1.15mm. w_a = 0.17mm, $l_1 = l_7$ = 2.238mm, $l_2 = l_6$ = 10.504 mm, $l_3 = l_5$ = 8.915mm, l_4 = 10.548mm, H_{dc} -field like in Fig. 5 a.