DESIGN AND TUNABILITY OF FERRITE-LOADED
E-PLANE BANDPASS FILTERS

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Abstract
A class of magnetically tunable microwave and millimeter-
wave filters utilizing E-plane integrated circuit technology
is presented. The investigated configurations include large-gap
ferrite-substrate finline filters as well as double and multiple
ferrite-slab loaded metal insert filters. The computer-aided
design procedure involves the evolution strategy method for
optimization and a rigorous modal scattering matrix field theory
treatment for the analysis. Calculated results are verified
by measurements of Ku-band prototypes utilizing ferrite ma-
terials TTVG-1200 or TTI-2800. Excellent tuning characteristics
providing a constant filter response shape and 0.8-1.0
dB insertion loss within the tuning range are achieved.

Kurzfassung
Es wird eine Klasse magnetisch abstimmbare Mikrowellen-
- und Millimeterwellenfilter in integrierter E-Ebenentechnik
vorgestellt. Die untersuchten Konfigurationen umfassen
Fensterfilter mit hoher Schlitzbreite auf Ferritsubstrat
sowie Metallstegfilter mit doppelten und mehrfachen Ferrit-
einsätzen. Das rechnerunterstützte Entwurfsverfahren bein-
haltet die Evolutionsstrategie für die Optimierung und eine
feldtheoretisch strenge, modale Streumatrixmethode als Ana-
lyse. Die berechneten Resultate werden durch Messungen an
Ku-Band-Prototypen überprüft, die Ferritmaterialien TTVG-
1200 oder TTI-2800 enthalten. Excellente Abstimmungscha-
rakteristika mit einer konstanten Filterkurve und 0.8-1.0 dB
Einfügungsdämpfung im Abstimmungsband werden erzielt.

Figure 1. Ferrite-loaded E-plane bandpass filters. a) finline filter on ferrite substrate;
b) double ferrite-slab loaded metal insert filter; c) single-sided multiple ferrite-
slab loaded metal insert filter; d) double-sided multiple ferrite-slab loaded metal
insert filter.

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I. INTRODUCTION

Nearly constant bandpass characteristics in the tuning range, low insertion losses, and high-power capabilities are the desired properties of tunable waveguide filters. Being of considerable practical interest for many applications [1], these components have been realized using different technologies, e.g., sliding waveguide walls [1], varactor diodes [2], single crystal ferrite resonators such as YIG, spinels and hexagonal ferrites [1, 3, 4] and ferrite-slab loaded evanescent-mode waveguide sections [5]. Although YIG-tuned filters provide wide tuning ranges, their application may often be restricted by the narrow-band selectivity and by low-power handling capabilities. The use of hexagonal ferrites still leads to relatively high insertion losses [e.g., 4]. Ferrite-slab evanescent-mode filters require capacitive posts, screws and fine tuning adjustments [5], which lead to a difficult and cost-intensive fabrication process, especially at millimeter-wave frequencies.

Recently, a new class of magnetically tunable filters utilizing E-plane integrated circuit technology has been introduced [6,7]. Based on the rigorous field theory design methods presented in [8-10], large-gap fineline filters (on ferrite substrates) and double ferrite-slab loaded metal insert filters have been described.

This paper summarizes the results obtained so far, and introduces new designs utilizing multiple ferrite-slab loading. Constant bandwidth in the tuning range, stopband characteristics comparable with unloaded filters, and insertion loss values below 1.5 dB enable the commercial application in high-power microwave systems.

Since the rigorous field theory design procedure takes into account all relevant circuit parameters, calculated values are in extremely close agreement with data obtained from Ku-band measurements. The proposed method is suitable for filter designs up to 60 - 70 GHz where the relatively low magnetic saturation of the hitherto available ferrite materials leads to limitations in the tuning ranges.

II. THEORY

The frequency responses of the four different filter structures in Fig. 1 are calculated by combining the modal scattering matrices of the appropriate key building blocks (Fig. 2), e.g. use Figs. 2a, d to obtain the finline filter of Fig. 1a, or use Figs. 2b, f to get the configuration in Fig. 1d. Since the modal S-matrices of both, the ferrite-loaded waveguide/coupling section and the finline/metal insert filter have already been treated in [10, 6] and [8, 9], respectively, the theoretical description given here may be reduced to the fundamental steps.

Provided that an incident wave is of the $\text{TEm}_m$ mode spectrum and the ferrite is magnetized in $y$-direction, the electromagnetic field in each homogeneous subregion $i = I, IIa-IIe, IIIa-IIIc, IV$ (c.f. Fig. 2)

\[
\begin{align*}
\nabla \times \vec{H} &= j \omega \epsilon \vec{E} \\
\nabla \cdot (\mu_r \vec{H}) &= 0 \\
\n\nabla \times \vec{E} &= -j \omega \mu_r \vec{H} \\
\n\nabla \cdot \vec{E} &= 0
\end{align*}
\]

is calculated from the corresponding electric field component $E_m$ which is expressed as a sum of eigenmodes [10]. In non-ferrite subregions, the Polder tensor $< \vec{S} >$ reduces to the scalar free-space permeability $\mu_r$, whereas in ferrite regions, its components for the saturated ferrite material

\[
< \vec{\mu} > = \begin{bmatrix}
\mu_1 & 0 & -j \kappa \\
0 & \mu_r & 0 \\
j \kappa & 0 & \mu_1
\end{bmatrix}
\]

are calculated from well known formulas [11]. The scalar permeability of a demagnetized ferrite may be determined using experimental relations given in [12].

In non-homogeneous waveguide cross-sections, e.g. region II in Figs. 2a-c and region III in Fig. 2e, the propagation constants are computed by matching the tangential field components $E_m, H_m$ at the common interfaces and solving the resulting transcendental equation in the complex plane [10].

Figure 2. Key building blocks. a) single ferrite insert (symmetrical); b) double ferrite insert (symmetrical); c) single ferrite insert (asymmetrical); d) finline filter coupling section; e) double ferrite-slab loaded coupling section; f) single metal insert.
Although the ferrite slabs are placed close to the waveguide sidewalls (Fig. 1b-d), the influence of small lateral air gaps on the filter response, which has also been observed in [5], is adequately taken into account by introducing subregions IIa, e, IIC, and IIa, IIIC in Figs. 2b, c, and 2e, respectively.

Matching the transversal field component $E_y$, $H_z$ at $z = 0$ and incorporating the finite lengths 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.

$$\begin{bmatrix} S_1 \\ \vdots \end{bmatrix} = \begin{bmatrix} (S_{11}) & (S_{12}) \\ (S_{21}) & (S_{22}) \end{bmatrix}$$

In (3), $(S_{23})$ is the submatrix containing the complex modal transmission coefficients. Hence the insertion loss if given by

$$\frac{1}{S_{21}} = \frac{-20 \cdot \log(|S_{21}(1,1)|)}{dB}$$

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

III. DESIGN

Ferrite materials with low losses and relatively constant thermal characteristics are suitable for high-power applications. Subsidiary resonance effects may be circumvented by limiting the biasing magnetic d.c. field according to the spinwave linewidth of the material [13-15].

For the computer-aided design, the filters are preoptimized assuming a demagnetized ferrite and using the design strategies outlined in [8, 9]. With all remaining parameters kept constant, the tuning range of the filter curve towards higher frequencies is analyzed. A final optimization run fine tunes the lengths of the key building blocks to provide low losses and a fairly constant response shape throughout the tuning range.

IV. RESULTS

Fig. 3 shows the calculated and measured response of a Ku-band magnetically tunable finline filter, which offers the most elegant manufacturing possibility among the structures investigated. However, increasing the tuning range with the thickness $w$ of the ferrite substrate leads to higher insertion losses because the maximum field intensity is concentrated in the lossy ferrite material of the resonator regions. A tuning efficiency of 2.7 MHz/KA/m and minimum insertion losses from 1.3 to 2.3 dB seem to be an acceptable compromise in this case. Since the electrical lengths of both, the coppercladded coupling sections and the resonator regions, equally depend on the biasing magnetic field, the bandwidth cannot be kept constant within the tuning range.

This also holds for the double-slab filled metal insert filter (Fig. 4). However, the configuration takes advantage of the fact that additional ferrite material can be utilized when placed near the waveguide sidewalls instead of the center. Hence the tuning efficiency is increased to 9 MHz/KA/m, and the measurements show a fairly constant insertion loss value of 1 dB. On the other hand, the use of thick ferrite slabs can lead to a significant reduction of the cutoff frequencies within the coupling sections. As a result, an undesirable narrow-stopband characteristic is obtained (Fig. 4) that causes a second passband to occur even within the waveguide's monomode range.

Figure 3. Measured and calculated response of a magnetically tunable Ku-band finline filter. Ferrite TTVG-1200, $w = 0.7$mm, $t = 16$μm, $H_1 = 0$, $H_2 = 230$KA/m.

Figure 4. Measured and calculated response of a double-slab loaded metal insert filter. Ferrite TTS-2800, $w = 1$mm, $t = 0.19$mm, $H_1 = 0$, $H_2 = 172$KA/m.
This problem may be circumvented by merely loading the resonator sections with ferrite material instead of using two lateral slabs. Calculated and measured filter responses of the single-sided and double-sided multiple ferrite-slab-loaded metal insert filters are shown in Figs. 5a and 5b, respectively. Since the coupling sections do not contain any ferrite material, the cutoff frequencies remain high in this region, which is essential for a good stopband behavior. The operating midband frequency of the single-sided type (Fig. 5a) may be tuned from 14.65 to 15.55 GHz. The tuning efficiency of 4.3 MHz/KA/m is almost linear up to 16.6 GHz. The upper tuning range limit, however, is caused by increasing ferrimagnetic losses with higher magnetic bias. The insertion loss of 0.8-1.0 dB is extremely low, and the bandwidth variation is less than three percent throughout the tuning range. An improved tuning efficiency of 7.6 MHz/KA/m is achieved by double-sided multiple ferrite-slab loading of the resonator sections (Fig. 5b). However, the insertion loss increases to 1.0 - 1.5 dB for this filter variant.

Figs. 6 show the filter responses of computer-optimized Ka-band versions corresponding to Figs. 5. These designs provide tuning efficiencies of 3.25 and 4.75 MHz/KA/m.

Higher magnetic bias is required for efficient tuning with progressing frequencies. Therefore, hexagonal ferrites with the highest magnetic saturation available are recommended in the millimeter-wave range beyond 60-70 GHz, even at the expense of higher losses. Photographs of the finline and double-slab loaded metal insert filter prototypes including the biasing magnets are shown in Figs. 7a and 7b, respectively.

V. CONCLUSIONS

A class of magnetically tunable microwave and millimeter-wave filters has been presented utilizing E-plane integrated circuit technology and rigorous field theory design concepts. Multiple-slab loaded metal insert filters with ferrite material merely mounted at the sidewalls of the resonator sections provide nearly constant bandpass characteristics in the tuning range, low insertion losses and reasonable tuning efficiency. Moreover, all different structures presented are suitable for high-power applications. Since the rigorous field theory analysis and design routine considers higher-order mode interactions, finite metallization thickness and lateral air gaps, the theoretically predicted values are in extremely close agreement with measured results.

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REFERENCES

Figure 5. Measured and calculated responses of multiple ferrite-loaded metal insert filters. Data as in Fig. 4, except $H_2 = 210$ KA/m. a) single-sided ferrite loading; b) double-sided ferrite loading.


Figure 6. Calculated responses of optimized magnetically tunable Ka-band metal insert filter. a) single-sided ferrite loading; b) double-sided ferrite loading.
Figure 7. Photographs of magnetically tunable E-plane filter prototypes. a) finline type; b) metal insert type.