The method of moments in the spectral domain is applied to the rigorous full-wave analysis of coupled line microstrip filters fabricated on magnetized ferrites. The results show that the center frequency of the filters can be tuned over a wide range by adjusting the magnitude of the bias magnetic field of the ferrite substrates. However, the filters bandwidth is reduced as the tuning frequency increases. This bandwidth reduction is explained in terms of the behavior of the resonant frequencies and quality factors of the resonators included in the filters.

Index Terms—Bandpass filters, magnetic tuning, microstrip resonators, microwave ferrites.

I. INTRODUCTION

Numerical and experimental results have shown that the resonant frequencies of microstrip patch resonators fabricated on magnetized ferrites can be adjusted over a wide range by varying the magnitude of the DC bias magnetic field [1], [2]. Bearing in mind this idea, tunable bandpass filters containing microstrip resonators on ferrite substrates have been fabricated and measured [3]. Although simple models can be used for predicting the resonant frequencies of straight microstrip resonators fabricated on magnetized ferrites [1], [3], the performance of complex microstrip circuits on ferrite substrates can only be predicted via a rigorous full-wave electromagnetic analysis [4]. In the current letter the authors apply the method of moments (MoM) in the spectral domain [4] to the numerical determination of the frequency-dependent scattering parameters of coupled line microstrip bandpass filters fabricated on magnetized ferrite substrates. The results presented show that the pass band of these filters can be tuned by varying the magnitude of the bias magnetic field of the ferrites, which is in agreement with the experiments carried out in [3]. However, the results obtained also show that the tunability of the filters is achieved at the expense of a bandwidth reduction.

II. OUTLINE OF THE NUMERICAL PROCEDURE AND RESULTS

Figs. 1(a) and 1(b) show the side and top views of a coupled line microstrip filter printed on a magnetized ferrite. The ferrite substrate is assumed to be magnetically saturated, and the DC bias magnetic field inside the ferrite substrate is assumed to have no component along the y axis, which ensures that the feeding microstrip lines of the filter are bidirectional [5] (and therefore, standard circuit theory can be used in the determination of the filter scattering parameters). The permeability tensor of the ferrite can be obtained in terms of the gyromagnetic ratio, \( \gamma = 1.759 \times 10^{11} \) C/Kg, the frequency, \( f \), the saturation magnetization of the ferrite material, \( M_s \), the magnitude of the internal bias magnetic field, \( H_0 \), the linewidth, \( \Delta H \), and the angle between the z axis and the bias field, \( \theta_b \) (see [2] and references therein). In order to obtain the scattering parameters of the filter of Fig. 1, the de-embedding technique described in [6] has been followed. The two feeding microstrip lines have been fed by means of delta-gap generators. Then, an electric field integral equation (EFIE) for the current density on the filter and the feeding lines has been obtained, and the EFIE has been solved by means of the Galerkin’s version of the MoM. As explained in [6], the scattering parameters of the filter have been determined in terms of the currents on the feeding lines via matrix pencil technique. Rooftop basis functions have been used in the approximation of the current density, and the entries of Galerkin’s matrix have been efficiently computed in the spectral domain as shown in [2].

In order to check the validity of the algorithm for the analysis of the coupled line filter of Figs. 1(a) and 1(b), in Fig. 2 the numerical results obtained via the commercial package “Ensemble” for a coupled line filter on conventional dielectric substrate are compared with our numerical results in the nonmag-
Very good agreement is found between the two sets of results.

Fig. 3 shows our numerical results for a coupled line microstrip filter fabricated on normally biased ferrite substrate. Note that the filter can be tuned by about 21% as the magnitude of the bias magnetic field is varied from $\mu_0 H_0 = 0.01$ T to $\mu_0 H_0 = 0.14$ T. However, this tuning is carried out at the expense of a bandwidth reduction. In fact, the 3 dB bandwidth of the filter is about 11% when $\mu_0 H_0 = 0.09$ T, and about 4.5% when $\mu_0 H_0 = 0.14$ T. Fig. 4 helps to explain this behavior. In this figure, the authors plot the relative difference between the two fundamental resonant frequencies of the coupled resonators appearing in the filter ($\Delta f/\bar{f} = 2(f_1 - f_2)/(f_1 + f_2)$ where $f_1$ and $f_2$ are the two resonant frequencies), and the quality factors of these two resonances. The resonant frequencies and quality factors have been computed by means of the method described in [2]. In Fig. 4 the relative difference $\Delta f/\bar{f}$ decreases as $\mu_0 H_0$ increases, which indicates that the coupling between the two resonators of the filter of Fig. 3 decreases with increasing $\mu_0 H_0$. This coupling reduction provides an explanation for the bandwidth reduction noticed in Fig. 3. Concerning the quality factors plotted in Fig. 4, they suffer a reduction as $\mu_0 H_0$ increases, which is attributed to the increasing effect of ferrite losses on the resonances (when $\mu_0 H_0$ increases, the resonant frequencies are closer to the ferrite gyromagnetic resonance, and ferrite losses become more important as shown by the reduction of $|S_{12}|$ in the pass bands of Fig. 3). The reduction in the quality factors with increasing $\mu_0 H_0$ makes less severe the bandwidth reduction of Fig. 3, but does not suffice to prevent that bandwidth reduction.

In Fig. 5 the authors analyze a coupled line filter on longitudinally biased ferrite. The dimensions of this filter have been chosen in such a way that its operating frequency range is similar to that of the filter of Fig. 3. In the case of the filter of Fig. 5,
a tuning range of about 27% is achieved as $\mu_0 H_0$ is varied from 0.01 T to 0.09 T, which is slightly larger than that obtained in Fig. 3 for the filter on normally biased ferrite. As it happens with the filter of Fig. 3, the filter on longitudinally biased ferrite of Fig. 5 suffers from bandwidth reduction as $\mu_0 H_0$ increases but this bandwidth reduction is more pronounced than that observed for the filter of Fig. 2. In fact, the 3 dB bandwidth of the filter analyzed in Fig. 4 is about 3% when $\mu_0 H_0 = 0.01$ T, and about 0.5% when $\mu_0 H_0 = 0.06$ T. When $\mu_0 H_0 = 0.09$ T the behavior of the two-pole filter of Fig. 4 is completely degraded and resembles that of a single resonator (this fast degradation of the filters on longitudinally biased ferrites is also visible in the experimental results published in [3]). By analogy with Fig. 4, Fig. 6 shows that the coupling between the resonators of the filter of Fig. 5 decreases as $\mu_0 H_0$ increases, which justifies the bandwidth reduction observed. However, in Fig. 6 the quality factors of the coupled resonators remain basically unaffected as $\mu_0 H_0$ varies, and therefore, their behavior cannot alleviate the bandwidth reduction of the filter of Fig. 5. The different behavior of the quality factors in Figs. 4 and 6 may help to explain why the bandwidth reduction of the filter of Fig. 5 is more pronounced than that of Fig. 3.

If Figs. 3 and 5 are compared, one notices that although the two filters operate in similar frequency bands, the filter on normally biased ferrite provides a much larger bandwidth than the filter on longitudinally biased ferrite (Figs. 4 and 6 show that this is due to the fact that the coupling between resonators is larger in the normally biased configuration than in the longitudinally biased configuration). Also, we have already seen that the bandwidth reduction suffered by the filter on normally biased ferrite is less pronounced than that of the filter on longitudinally biased ferrite. Therefore, we can state that although the filters on both normally and longitudinally biased ferrites show similar tuning capabilities, the bandwidth performance of the filter on normally biased ferrite is much better than that of the filter on longitudinally biased ferrite.

Finally, it should be pointed out that in all the results presented in this Section the authors have deliberately worked above the range of frequencies in which magnetostatic wave propagation is allowed [2]. This is because magnetostatic waves have a deleterious effect on the performance of the resonators appearing in the filters [2].

### III. Conclusions

The method of moments in the spectral domain has been used for determining the scattering parameters of coupled line microstrip filters on ferrite substrates with both normal and longitudinal bias magnetic fields. The authors have found that in the two bias configurations the center frequency of the filters can be tuned by varying the magnitude of the bias magnetic field, but the bandwidth is reduced as the tuning frequency increases. In spite of bandwidth reduction, the filters on normally biased ferrites have proven to have a much better performance than that of filters on longitudinally biased ferrites.

### References


