Efficient Analysis of Magnetostatic Surface Waves in Printed and Suspended Ferrite Loaded Strip Lines

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***Abstract*—This paper analyzes the guidance of magnetostatic surface waves (MSSW) by a metallic strip printed on a ferrimagnetic slab or on a dielectric/ferrimagnetic structure (suspended configuration) in the frame of the magnetostatic approach. An integral spectral domain analysis (SDA) is used for this purpose. Shielding upper and/or lower ground planes are also considered. Some interesting new physical effects, such as backward and complex MSSWs in the suspended configuration are reported. Good agreement with previously published experimental and computed results confirms the validity of our approach.**

***Index Terms*—Magnetostatic waves, microstrips, microwave ferrites.**

I. Introduction

THE propagation of MSSWs along multilayer dielectric-ferrite-metal structures is a well understood topic (see [1] and references therein). But usually, metallizations of infinite width are considered. However, the width of the metallization of a practical structure must be finite, being the strip line a more realistic model in such case. Moreover, magnetostatic strip lines may be of technological interest due to the field confinement in the region below the strip. Recently new magnetostatic devices using strip-guided forward volume magnetostatic waves (FVMSW) have been proposed [2]. Strip-guided MSSWs may be also an alternative. Strip-guided MSSWs can be excited by placing a suspended metallic strip over a conventional MSSW transducer between the input and output antennas [3]. Excitation of strip-guided FVMSWs by direct feeds has been reported in [2]. A similar configuration could be useful for the excitation of strip-guided MSSWs, although the feed should be designed taking into account that the first strip-guided MSSW is an odd mode, as it will be shown later.

Propagation of MSSWs along strip lines printed over a ferrite slab with magnetic bias field perpendicular to the strips and parallel to the slab interface has been analyzed in [4]. In the present paper we apply an integral SDA to obtain the MSSWs guided by strip lines printed or suspended over a ferrite slab. The magnetic biasing field is chosen parallel to the ferrite surface and making an arbitrary angle with the strip orientation. The main advantage of the proposed method is that it can account for any possible ferrite loaded multilayer configuration, containing any kind of dielectric/air layers, with arbitrary magnetization. However, in this paper, we restrict ourselves to the study of magnetization parallel to the interfaces, which is the orientation causing MSSW propagation [1]. The main physical effects resulting from the finite strip width, the existence of a dielectric layer between the strip and the ferrite slab and/or the orientation of the magnetic bias field, are analyzed. Unidirectionality, propagation of forward and backward waves, presence of bounded complex modes and strong variations of the phase and group velocity with the strip width and dielectric thickness are some meaningful effects that we have encountered.

II. Analysis

It is a well known fact that both, dielectric-ferrite (DF) and metal- ferrite (MF) magnetized interfaces can support MSSWs. The frequency range for MSSW excitation along a DF interface is $f_1 < f < f_2$ whereas $f_1 < f < f_3$ is the frequency range of excitation of such waves along a MF interface ($f_1 = \sqrt{f_0(f_0+f_m)}$, $f_2 = f_0 + (1/2)f_m$, $f_3 = f_0 + f_m$, $f_0 = (1/2\pi)\gamma\mu_0 H_0$, $f_m = (1/2\pi)\gamma\mu_0 M_s$, γ is the gyromagnetic ratio [1], H_0 is the internal biasing magnetic field and M_s is the magnetization at saturation). This fact suggests that *non-radiating* (bounded) MSSWs can be guided by a metallic strip placed on a ferrite slab in the frequency range $f_2 < f < f_3$, since in this range the MF interface allows propagation but the DF interface precludes it. In fact, in [4] it is shown that unidirectional MSSWs are guided by strips printed on ferrites in the whole range $f_1 < f < f_3$, although in the range $f_1 < f < f_2$ unbounded MSSWs can be also guided by the DF interface. In this paper we are interested in studying the guidance of bounded MSSWs along the more general structure in Fig. 1. We will assume the field dependence $\exp(-jk_z z + j\omega t)$ in the following. A *current* function is defined at each point x on the strip by

$$I(x) = \int_{-w/2}^{x} J_{s,z}(x')\,dx' \quad (1)$$

where $\mathbf{J}_s$ is the strip surface current density. For magnetostatic modes the total current supported by the strip must vanish, i.e., $I(-w/2) = I(w/2) = 0$. This fact can be understood from both the magnetostatic [4] and the full-wave analysis [5] and implies that the usual definition of line characteristic impedance, $Z = 2P/|I|^2$, does not apply to the analysis of strip-guided magnetostatic waves, since it yields $Z \to \infty$. Also, the line voltage is a meaningless concept for MSSWs (is for this reason that MSSWs can be guided by the ungrounded structure of Fig. 1 with $h_1 = h_4 \to \infty$). This does not mean that strip-guided

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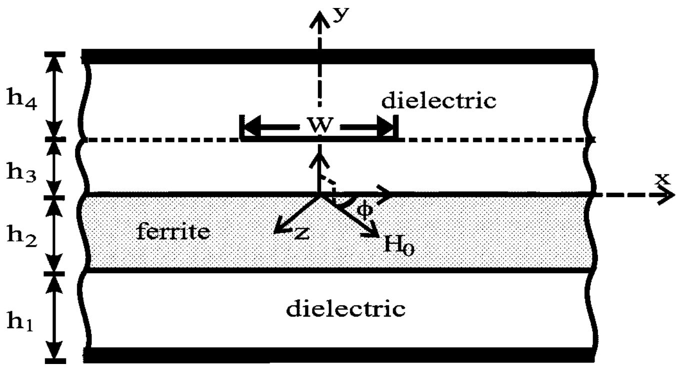

Fig. 1. Cross section of the guiding structure analyzed in this paper.

TABLE I
COMPARISON BETWEEN OUR MAGNETOSTATIC RESULTS AND THE FULL-WAVE RESULTS IN [6] FOR THE STRUCTURE OF FIG. 1 WITH $h_1 = 2$ mm, $h_2 = 0.254$ mm, $h_3 = 0$, $h_4 = 0.254$ mm, $w = 1.016$ mm, $\mu_0 H_0 = 0.0275$ T, $\mu_0 M_s = 0.275$ T, Freq $= 5$ GHz

$k_z(\mathrm{mm}^{-1})$					
mode 1	mode 2	mode 3	mode 4	mode 5	
1.521	3.104	4.951	6.903	8.915	Ref.[6]
1.506	3.097	4.959	6.902	8.861	This method

MSSWs could not be excited in practice, but only that the conventional transmission line circuit model does not apply to this kind of waves.

The magnetic field is derived from the magnetostatic potential, ψ, as follows: $\mathbf{H} = -\nabla\psi$ and $\mathbf{B} = \overline{\boldsymbol{\mu}} \cdot \mathbf{H}$, where $\overline{\boldsymbol{\mu}}$ is the magnetic permeability tensor of the medium. An integral equation can be readily formulated for the y-component of the magnetic flux density along the strip interface

$$B_y(x;\, y = h_3) = \int_{-w/2}^{w/2} G(x - x';\, k_z,\, \omega) I(x')\, dx' \qquad (2)$$

where $G(x - x')$ is a scalar Green's function. The spectral version of this Green's function is obtained in closed form by solving the equation for ψ, i.e., $\nabla \cdot \overline{\boldsymbol{\mu}} \cdot \nabla\psi = 0$, in the spectral domain, and enforcing the appropriate boundary and jump conditions for ψ and B_y at the interfaces. Finally, the phase constants of the magnetostatic modes propagating along the structure in Fig. 1 are obtained by applying the Galerkin method in the spectral domain. Triangular subsectional basis functions are used to approximate $I(x)$ on the strip.

III. NUMERICAL RESULTS

In order to validate the accuracy of the magnetostatic approach, Table I compares our results for the first five magnetostatic modes in a shielded printed strip line with those computed using the full wave approach in [6]. A similar good agreement is found in Fig. 2, where our results for a printed unshielded strip line are compared with those reported in [4]. The MSSW modes in Table I and Fig. 2 are alternatively odd and even and form an infinite set of *unidirectional* modes with increasing phase constant. Fig. 2 also shows how the phase constant and time delay of the MSSWs can be substantially increased by reducing the strip width, an effect of potential practical interest. The disper-

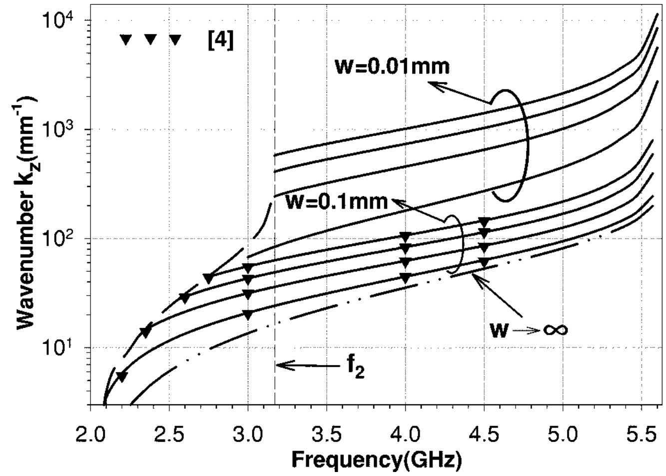

Fig. 2. Dispersion curves for the phase constant of the first four magnetostatic modes of the structure in Fig. 1 with $h_1 = h_4 \to \infty$, $h_2 = 0.01$ mm, $h_3 = 0$, $\phi = 0$, $\mu_0 H_0 = 0.0251$ T, and $\mu_0 M_s = 0.1760$ T. Curves are plotted for $w = 0.1$ mm, $w = 0.01$ mm (solid lines) and for the infinite unmetallized slab (dashed lines) and the infinite metallized slab ($w \to \infty$; dash-dotted lines). Comparison with the results in [4] is also shown.

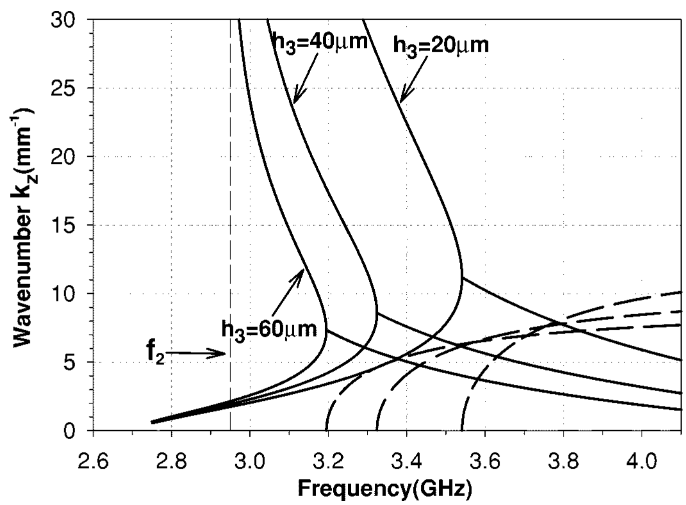

Fig. 3. Dispersion curves for the propagation constant of the first magnetostatic mode of the structure in Fig. 1 with $h_1 = h_4 \to \infty$, $h_2 = 100$ μm, $w = 1$ mm, $\phi = 0$, $\mu_0 H_0 = 0.0632$ T, and $\mu_0 M_s = 0.0840$ T. Curves are plotted for $h_3 = 20,\ 40,\ 60$ μm. Solid lines: phase constant ($\mathrm{Re}(k_z)$). Dashed lines: attenuation constant ($|\mathrm{Im}(k_z)|$).

sion curve for the MSSW guided by the non metallized ferrite slab is also shown in Fig. 2. It can be seen that, for $f > f_2$, the bound strip-guided MSSWs are the unique magnetostatic waves guided by the structure. This fact can be useful for technological applications, because excitation of nondesired magnetostatic slab modes is not present at those frequencies.

The effect of the magnetizing field orientation has been also analyzed and it has been found that for moderate values of the angle ϕ (see Fig. 1), the mode phase constant decreases and the time delay, $(\partial\beta)/\partial\omega$, increases with ϕ. However, for values of ϕ roughly above 20°, strip guided MSSWs were not found. It seems that this kind of modes are closely related to magnetization mainly perpendicular to the strip. In any case, if $\phi \neq 0$, the MSSW modes are neither even or odd.

The consequences of inserting a dielectric layer between the ferrite slab and the metallic strip is illustrated in Fig. 3. The main

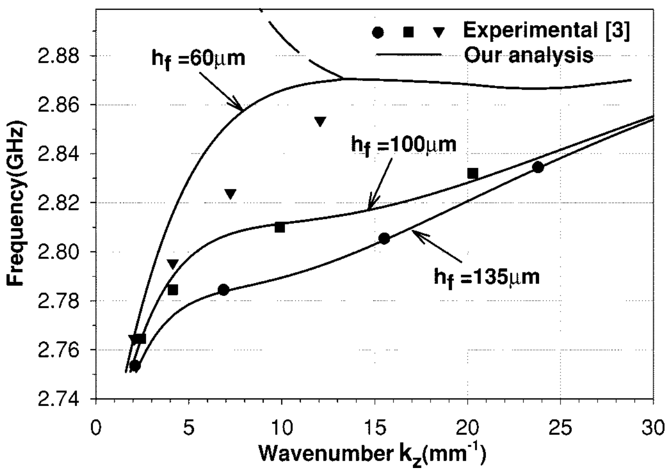

Fig. 4. Phase constant for the first magnetostatic mode of the structure in Fig. 1 with $h_1 = h_4 \rightarrow \infty, h_2 = 16\ \mu$m, $w = 2$ mm, $\phi = 0, \mu_0 H_0 = 0.0632$ T, $\mu_0 M_s = 0.0840$ T, $\Delta H_0 = 3 \times 10^{-5}$ T, and $h_3 = 135, 100, 60\ \mu$m (solid lines are propagating modes and dashed lines complex modes). Dots, squares, and triangles are experimental measures [3].

effect is the appearing of forward and backward modes, which combines at a given frequency yielding complex modes. Forward and backward MSSW modes are well known solutions for infinite ($w \rightarrow \infty$) ferrite-dielectric-metal structures [1]. Propagation of unbounded complex modes along these structures was also reported in [7]. Thus, the presence of forward, backward and complex MSSWs guided by suspended strips could be expected from those results. However, the numerical values of the propagation constant depends on the strip width and our method provides, for the first time, a simple procedure to compute them. At the starting point of complex modes the group velocity vanishes, giving rise to a resonant absorption in the line. This phenomenon has been experimentally observed in [3]. In Fig. 4, our results for the phase constant of MSSWs guided by suspended strips are compared with the experimental data provided in [3] (there are no numerical computations in [3]). The agreement between our simulated data and experiment is excellent for $h_3 = 135$ and $100\ \mu$m. Some disagreement appears for the smallest value, $h_3 = 60\ \mu$m, but experimental errors in the determination of h_3 together with the high sensitivity of the measured parameter for small values of h_3 can provide an explanation. A complex mode appears in our computed results for $h_3 = 60\ \mu$m. Notice that experimental results qualitatively agree with this fact, because modes with higher values of the phase constant should be backward and, therefore, they could not be detected by the experimental setup used in [3]. This is explicitly quoted in [3]. Complex solutions in Figs. 3 and 4 correspond to bound modes. The computation of bound complex waves in open structures of finite size is a noticeable fact, because these modes have been typically found in closed waveguides [8]. Magnetostatic suspended strip lines could find application in tunable rejection band filters and resonators. These devices would take advantage of the narrow-band resonant absorption at the starting point of the complex modes, where the group velocity vanishes.

IV. Conclusions

A method for the numerical analysis of MSSWs guided by ferrite loaded multilayer strip lines has been presented. Computed results agree quite well with previous analytical and experimental published data. From these results it can be concluded that some of the main features of MSSW propagation along infinite multilayer ferrite-dielectric-metal waveguides also appear in strip lines in a multilayer ferrite-dielectric medium. These features include unidirectionality as well as the existence of backward and complex modes. In contrast with infinite width structures, strip guided MSSWs are bound modes with the field confined in the region below and around the strip. In addition, the existence of an *infinite set of modes*, which are alternatively even and odd if the biasing field is perpendicular to the strip, is a distinctive feature of ferrite loaded finite width strips. Another noticeable feature of strip guided MSSWs is that both, the wave phase constant and the time delay can be substantially increased by reducing the strip width. These features can find application in the design of new delay lines, filters, and other magnetostatic-wave devices. Our analysis provides a simple, fast, and reliable method for the quantitative characterization of those finite width strip lines. Moreover, strip guided complex modes have been computed for the first time in open stripline structures. In addition to its theoretical interest, these waves show potentially useful resonances at the starting point of these complex modes.

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