Electromagnetic Study of a Ferrite Coplanar Isolator Suitable for Integration

Bernard Bayard, Didier Vincent, Constantin R. Simovski, and Gérard Noyel

***Abstract*—The transmission coefficient of a nonreciprocal coplanar waveguide (CPW) using ferrite rods is studied. A new approximate method is proposed to evaluate the propagation constant of such a perturbed waveguide, which is based on the use of numerical data referring to the nonperturbed waveguide. We have estimated the value of the nonreciprocity effect and settled the condition of the validity of our theory. Some experimental data of a CPW with ferrite inclusions are also presented.**

***Index Terms*—Anisotropic media, coplanar waveguides (CPWs), ferrite isolator, nonreciprocal wave propagation.**

I. Introduction

SOME nonreciprocal microwave components such as isolators and circulators are based on the gyromagnetic properties of ferrites. The ferrite bulk substrate is magnetized by a constant magnetic field, which makes this kind of device noncompatible with monolithic microwave integrated circuit (MMIC) technology and only available in discrete packages. On the other hand, the active components that are completely integrated show a higher noise level, insertion losses, and a lower frequency range (approximately 5 GHz) than the passive devices. Consequently, the development of devices integrating a ferrite on a semiconductor chip is a major focus of current research. A coplanar ferrite isolator is adopted because it is built with coplanar strips on a dielectric substrate and needs only a small quantity of ferrite material in the slots.

A theoretical explanation of the operation of such an isolator is given. An approximate method is then proposed to evaluate the propagation constant of a coplanar waveguide (CPW) with magnetic inclusions in the slots. Finally, some simulation data are compared to experimental results.

II. Coplanar Ferrite Isolator

Some time ago, Wen [1] made a nonreciprocal isolator using two ferrite rods placed at the dielectric interface between strips (Fig. 1). In these rods $(0.01 \text{ in} \times 0.005 \text{ in} \times 0.6 \text{ in})$, the magnetostatic wave (MSW) was excited in the 5.5–6.5-GHz frequency band. This isolator provided 37-dB isolation at a center frequency of 6 GHz and 2-dB insertion losses. However, such performances using this structure has never been reproduced since this date. In this paper, we propose a theoretical model

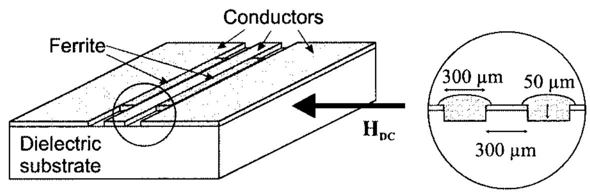

Fig. 1. CPW cell with ferrite inclusions.

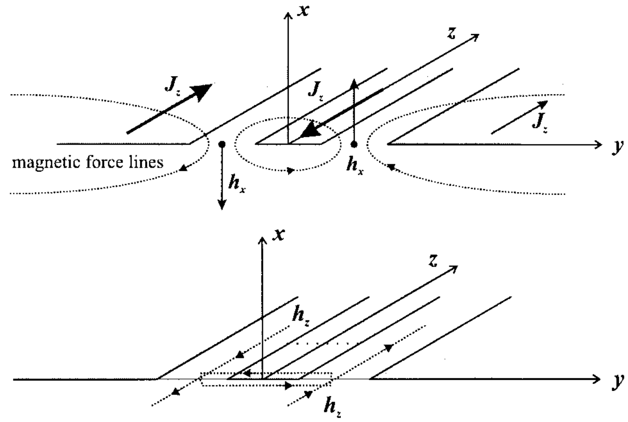

Fig. 2. MFLs in the CPW and microwave magnetic field $\mathbf{h}$ at the interface.

clarifying the operation of a similar isolator and predicting its technical characteristics.

The magnetic force line (MFL) is not closed inside the ferrite sample and the transversal distribution of the microwave magnetic field $\mathbf{h}$ is assumed to be practically uniform for frequency bands and rod sizes like those mentioned above. When the applied magnetic-field direction is horizontal (along the y-axis in Fig. 2), the plane of the spin precession excited by a microwave magnetic field is the vertical (xz)-plane.

If the $\mathbf{h}$ vector at a given point in the rod rotates in the same direction as the inner magnetization vector $\mathbf{m}$, the wave energy is absorbed by spins. In the opposite case, there is no spin–wave interaction (Fig. 3). Therefore, the physical foundation of the isolator studied in [1] is based on the different $\mathbf{h}$ vector rotations for forward [see Fig. 3(a)] and backward propagation [see Fig. 3(b)]. Unperturbed microwave magnetic field $\mathbf{h}_0$, existing in the same CPW (without a ferrite), is applied to the rods and is concentrated near the interface air–substrate. At this interface, one has

$$\mathbf{h_0} = h_{0x}\hat{\mathbf{x}} + h_{0z}\hat{\mathbf{z}}. \quad (1)$$

Here, h_{0x} is produced by the longitudinal current in the strips and is maximal between them [see Fig. 2(a)]. From Fig. 2(b), it

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B. Bayard, D. Vincent, and G. Noyel are with the Devices and Instrumentation in Optoelectronics and Microwaves Laboratory, University of Saint-Etienne, Saint-Etienne 42023, France (e-mail: bayard@univ-st-etienne.fr.).
C. R. Simovski is with the Physics Department, St. Petersburg State Institute for Fine Mechanics and Optics, St. Petersburg 197101, Russia.
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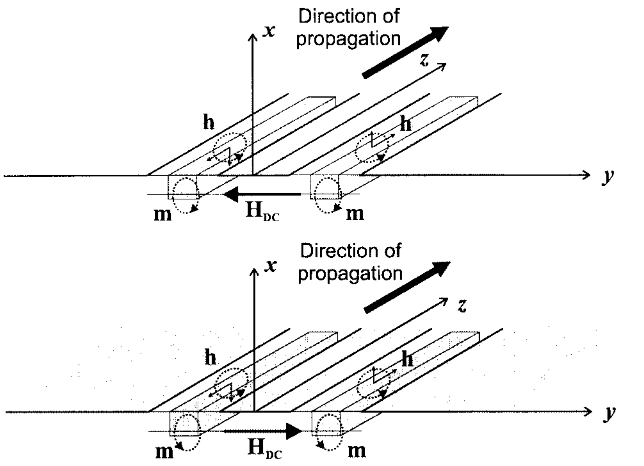

Fig. 3. Spin–wave interaction for each direction of propagation (for reverse direction $\mathbf{H}_{\mathrm{DC}}$ is inverted).

is clear that the longitudinal component h_{0z} vanishes at the interface if the substrate permittivity ϵ equals unity. Anyway, the absolute values of h_{0z} are smaller than the values of h_{0x}. The location of rods on the surface $x = 0$ (rods are centered over it), as chosen in [1], does not seem to be quite optimal since h_{0z} values are smaller in the air over the interface than the values of h_{0z} under the interface (since the displacement currents are mainly concentrated in the substrate). The nonreciprocal effect becomes maximal when the $\mathbf{h}$ vector polarization is circular; thus, the best results are obtained when h_{0z} and h_{0x} values are approximately equal to each other. In the general case of an elliptical polarization, it can be decomposed in two (a left and right) circular polarizations of different magnitudes. The circular polarization that coincides with the magnetization of the ferrite will be absorbed at the resonance, while the other one will not be perturbed. The total wave will be mostly absorbed according to a direction of propagation or a direction of the applied field and weakly absorbed in the other one. Therefore, the value h_{0z} must be made as large as possible, and it seems to be better to submerge ferrite rods into the substrate.

III. Theory

The CPW behavior (without rods) is well known and the propagation constant of the main mode can be calculated by a spectral-domain approach (SDA) method [2]. The corresponding $\mathbf{h}$ field polarization is elliptical at the interface. Consider the $\mathbf{h}$ vector when the mutual coupling of the ferrite rods is negligible or the structure contains only one rod. At first, we give the theoretical explanation of the operation of reference isolator, then we evaluate the propagation factors and calculate the transmission coefficients.

A. One Rod Case

Let a single ferrite rod be centered at an arbitrary point of the waveguide cross section. Hence, the RF applied field $\mathbf{h}_a$ to this rod is the field taken at the same point of an unperturbed CPW

$$\mathbf{h_a} = \mathbf{h_0}. \tag{2}$$

Assuming $\mathbf{h}_0$ is known over the ferrite rod cross section (assumed to be very small compared to the wavelength), we may write the well-known magnetostatic relation for internal field $\mathbf{h}$ generated in the rod by external field $\mathbf{h}_0$ [3]

$$\mathbf{h_0} = (\bar{\bar{1}} + \bar{\bar{N}}\bar{\bar{\chi}})\mathbf{h}. \tag{3}$$

Here, $\bar{\bar{N}}$ and $\bar{\bar{\chi}}$ are, respectively, the demagnetizing tensor (dyadic) and susceptibility tensor (dyadic), which take the form

$$\bar{\bar{\chi}} = \chi(\hat{\mathbf{x}}\hat{\mathbf{x}} + \hat{\mathbf{z}}\hat{\mathbf{z}}) - j\kappa(\hat{\mathbf{x}}\hat{\mathbf{z}} - \hat{\mathbf{z}}\hat{\mathbf{x}}) \tag{4}$$

$$\bar{\bar{N}} = N_x\hat{\mathbf{x}}\hat{\mathbf{x}} + N_y\hat{\mathbf{y}}\hat{\mathbf{y}} + N_z\hat{\mathbf{z}}\hat{\mathbf{z}} \tag{5}$$

where $\hat{\mathbf{x}}$, $\hat{\mathbf{y}}$, and $\hat{\mathbf{z}}$ are unit vectors along the x-, y-, and z-axes, respectively. We obtain from (3)

$$h_x = \frac{(1+\chi N_z)h_{0x} + j\kappa N_x h_{0z}}{1 + \chi(N_x + N_z) + (\chi^2 - \kappa^2)N_x N_z} \tag{6}$$

$$h_z = \frac{(1+\chi N_x)h_{0z} - j\kappa N_z h_{0x}}{1 + \chi(N_x + N_z) + (\chi^2 - \kappa^2)N_x N_z}. \tag{7}$$

The demagnetizing and susceptibility tensors get complex values at the resonance band. The rod is extended along the z-axis so we can set $N_z \simeq 0$ and may write

$$h_x = \frac{h_{0x} + j\kappa N_x h_{0z}}{1 + \chi N_x} \tag{8}$$

$$h_z = h_{0z}. \tag{9}$$

It is possible then to rewrite these equations as a relation between the external ellipticity factor $h_{0z}/h_{0x} = j\xi$ and the internal one $h_z/h_x = j\zeta$

$$\frac{h_z}{h_x} = j\zeta = j\xi\frac{1 + \chi N_x}{1 - \kappa N_x \xi}. \tag{10}$$

When the demagnetizing factor N_x vanishes, we have, of course, $\mathbf{h} = \mathbf{h_0}$. The ellipticity factor $j\xi$ of the external magnetic field $\mathbf{h_0}$ is a complex number depending on frequency. It is, however, a small value, and the polarization is closer to a linear one than to a circular one. At low frequencies (the transversal size of CPW is small compared to λ), h_{0x} has almost the same phase as that of the longitudinal currents in the strips, and the h_{0z} phase is close to that of the displacement current between them. Therefore, the phase shift between these components is close to the $\pi/2$ radian and $j\xi$ is almost purely imaginary.

Using the SDA method to simulate the electromagnetic response of the structure, we effectively find an ellipticity factor as only an imaginary number.

We can now calculate the microwave internal magnetization $\mathbf{m} = \bar{\bar{\chi}}\mathbf{h}$, and find for each direction of propagation

$$m_x^{\pm} = \chi h_x \mp j\kappa h_z = (\chi \pm \kappa\zeta)h_x \tag{11}$$

$$m_z^{\pm} = \chi h_z \pm j\kappa h_x = j(\chi\zeta \pm \kappa)h_x \tag{12}$$

(for the reverse direction, κ must be replaced by $-\kappa$).

Near the resonance frequency, κ is close to χ and we can, therefore, express the polarization of the magnetization

$$\left(\frac{m_z}{m_x}\right)^{\pm} = j\frac{\pm\left(\dfrac{\kappa}{\chi}\right) + \zeta}{1 \pm \left(\dfrac{\kappa}{\chi}\right)\zeta} \simeq \pm j. \tag{13}$$

When the previous ratio is j, both magnetic field and magnetic moments rotate in the same direction, and the energy of the propagating wave is absorbed. Otherwise, the spin–wave interaction is very weak. This case corresponds to the optimal operation of the isolator.

B. Two Rods Case

Now two infinitely long ferrite rods are placed at the interfaces of the CPW. The field $\mathbf{h_a^l}$ applied to the left rod is the sum of the unperturbed field $\mathbf{h_0^l}$ and the additional field $\mathbf{h_r^l}$ is produced by the magnetization of the right rod $\mathbf{m^r}$. To take into account these interactions, we can write

$$\mathbf{h_a^l} = \mathbf{h_0^l} + \mathbf{h_r^l} = \mathbf{h_0^l} + \bar{\bar{F}}\mathbf{m^r} \quad (14)$$

$$\mathbf{h_a^r} = \mathbf{h_0^r} + \mathbf{h_r^r} = \mathbf{h_0^r} + \bar{\bar{F}}\mathbf{m^l}. \quad (15)$$

The upper indexes mean left and right rods in these formulas, where

$$\int\int\int \bar{\bar{F}}(x,y) = F_x\hat{\mathbf{x}}\hat{\mathbf{x}} + F_z\hat{\mathbf{z}}\hat{\mathbf{z}} \quad (16)$$

describes the spatial distribution of the field created by a thin rod in the presence of metallic strips. The internal field in both rods is expressed via an applied one in the same way as shown in (3)

$$\mathbf{h^{l,r}} = \mathbf{h_a^{l,r}} - \bar{\bar{N}}\mathbf{m^{l,r}} \quad (17)$$

$$\mathbf{m^{l,r}} = \bar{\bar{\chi}}\mathbf{h^{l,r}}. \quad (18)$$

From these relations, we obtain

$$\mathbf{m^l} = [\bar{\bar{1}} + \bar{\bar{\chi}}\bar{\bar{N}}]^{-1}\bar{\bar{\chi}}\left[\mathbf{h_0^l} + \bar{\bar{F}}\mathbf{m^l}\right] \quad (19)$$

$$\mathbf{m^r} = [\bar{\bar{1}} + \bar{\bar{\chi}}\bar{\bar{N}}]^{-1}\bar{\bar{\chi}}\left[\mathbf{h_0^r} + \bar{\bar{F}}\mathbf{m^r}\right]. \quad (20)$$

This system determines the magnetostatic eigenmodes in the pair of ferrite rods. In our configuration, the rods are positioned symmetrically with respect to the plane xz. Therefore,

$$\mathbf{h_0} = \mathbf{h_0^l} = -\mathbf{h_0^r} \quad (21)$$

and the only mode

$$\mathbf{m} = \mathbf{m^l} = -\mathbf{m^r} \quad (22)$$

is excited. Thus, we have

$$\mathbf{m} = \left[\bar{\bar{1}} + \bar{\bar{\chi}}(\bar{\bar{N}} + \bar{\bar{F}})\right]^{-1}\bar{\bar{\chi}}\mathbf{h_0} \quad (23)$$

$$\mathbf{h} = \left[\bar{\bar{1}} + \bar{\bar{\chi}}(\bar{\bar{N}} + \bar{\bar{F}})\right]^{-1}\mathbf{h_0}. \quad (24)$$

From these relations and putting $N_z = 0$, we obtain

$$h_x = ah_{0x} + jbh_{0z} \quad (25)$$

$$h_z = jch_{0x} + dh_{0z} \quad (26)$$

with

$$a = \frac{(1+\chi F_z)}{1+\chi(N_x+F_x+F_z)+(\chi^2-\kappa^2)(N_x+F_x)F_z} \quad (27)$$

$$b = \frac{\kappa(N_x+F_x)}{1+\chi(N_x+F_x+F_z)+(\chi^2-\kappa^2)(N_x+F_x)F_z} \quad (28)$$

$$c = \frac{-\kappa F_z}{1+\chi(N_x+F_x+F_z)+(\chi^2-\kappa^2)(N_x+F_x)F_z} \quad (29)$$

$$d = \frac{\left(1+\chi(N_x+F_x)\right)}{1+\chi(N_x+F_x+F_z)+(\chi^2-\kappa^2)(N_x+F_x)F_z}. \quad (30)$$

These relations generalize (6) and (7) by taking into account the rods' mutual coupling. However in this paper, we assume that the coupling is negligible and we set $\bar{\bar{F}} = 0$. We simply add the effect of each rod when we evaluate the propagation constant. The rods' mutual coupling effect $\bar{\bar{F}}$ will be considered in our subsequent works.

C. Evaluation of the Propagation Constant

In this section, we propose a new approximate method for evaluating the propagation constant. Though the method is applied here for the cases of ferrite rods, it can be easily rewritten in terms of arbitrary inclusion (dielectric or magnetic) whose transversal size is small in comparison to the wavelength and when the characteristic transversal sizes of the waveguide are also sufficiently small compared to λ. Since this method is approximate, it involves some necessary conditions for its applicability in agreement with experimental results.

Let the mode with propagation constant $j\beta$ propagate in the perturbed waveguide. Then

$$\mathbf{e}(x,y,z) = \mathbf{E}(x,y)\exp(-j\beta z) \quad (31)$$

$$\mathbf{h}(x,y,z) = \mathbf{H}(x,y)\exp(-j\beta z) \quad (32)$$

$$\mathbf{m}(x,y,z) = \mathbf{M}(x,y)\exp(-j\beta z) \quad (33)$$

respectively, the microwave electric, magnetic, and bulk magnetization fields. From Maxwell's equation

$$\nabla \times \mathbf{e} = -j\omega\bar{\bar{\mu}}\mathbf{h} \quad (34)$$

we write

$$\frac{\partial e_z}{\partial y} - \frac{\partial e_y}{\partial z} = -j\omega\mu_0\left[\left(\bar{\bar{1}} + \bar{\bar{\chi}}\right)\mathbf{h}\right]_x \quad (35)$$

or

$$\frac{\partial E_z}{\partial y} + j\beta E_y = -j\omega\mu_0(1+\chi)H_x - \omega\mu_0\kappa H_z. \quad (36)$$

If the ferrite permittivity is close to the dielectric one and if the frequency is low, the transversal distribution of the electric field is weakly perturbed by the ferrite rod insertion and we can put

$$\nabla_y E_z \simeq \nabla_y E_{0z} \quad (37)$$

$$E_y \simeq E_{0y}. \quad (38)$$

Relation (36) then becomes

$$\frac{\partial E_{0z}}{\partial y} + j\beta E_{0y} = -j\omega\mu_0(1+\chi)H_x - \omega\mu_0\kappa H_z. \quad (39)$$

When there is no ferrite rod, the propagation constant is known $(j\beta_0)$ and it is possible to calculate $\partial E_{0z}/\partial y$ from

$$\frac{\partial E_{0z}}{\partial y} + j\beta_0 E_{0y} = -j\omega\mu_0 H_{0x}. \quad (40)$$

After substituting from (6), (7), and (39) into (40), we finally write (when the rods coupling is negligible)

$$\beta \simeq \beta_0 - \omega\mu_0\frac{1-N_x}{1+\chi N_x}\left(\chi\frac{H_{0x}}{E_{0y}} - j\kappa\frac{H_{0z}}{E_{0y}}\right). \quad (41)$$

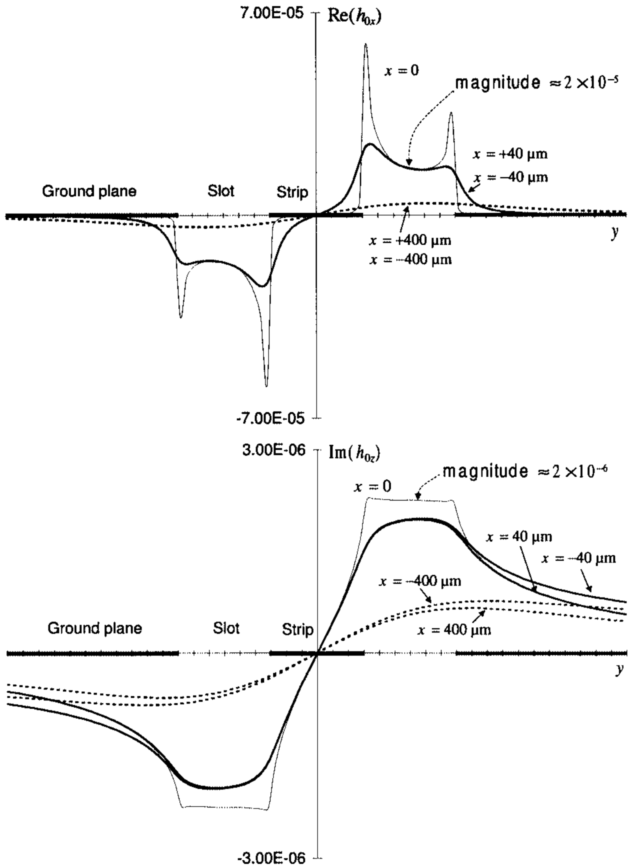

Fig. 4. Microwave magnetic field $\mathbf{h}$ at the interface of a CPW without inclusions simulated with a SDA ($f = 10$ GHz).

When the propagation direction of the microwave signal is inverted, the sign of the fields components along the y- and z-axes must be changed. On the other hand, when the applied field direction is inverted, κ must be substituted by $-\kappa$. These two situations are equivalent and lead to a set of two propagation constants, which may be written as

$$\beta^{+} = \beta_0 - \omega\mu_0\psi(\chi + \kappa\xi)\frac{H_{0x}}{E_{0y}} \quad (42)$$

$$\beta^{-} = \beta_0 - \omega\mu_0\psi(\chi - \kappa\xi)\frac{H_{0x}}{E_{0y}} \quad (43)$$

with

$$\psi = \frac{1 - N_x}{1 + \chi N_x} \quad (44)$$

$$\frac{H_{0z}}{H_{0x}} = j\xi \quad (45)$$

The conventional definition of demagnetizing factors is valid under the assumption that the applied field is uniform. As shown in Fig. 4, the microwave longitudinal field h_{0z} of the CPW without magnetic inclusions is constant across the slots; on the contrary, h_{0x} shows great variation. Therefore, the magnitude and polarization of the applied field ($\mathbf{h_a} = \mathbf{h_0}$) are not uniform in the rods along the y-direction, but the demagnetizing factors have been used as an approximation to calculate the internal field $\mathbf{h}$. Considering the linearity of the demagnetizing factors, the nonuniformity of the external field implies a nonuniformity of the internal field according to (3). To take each point in the rods into account, we average these relations on the rods' section. Considering the uniformity of the fields along the thickness of the rods (x-axis), it implies the only integration on the y-axis

$$\int_0^W \beta^{\pm} dy = \int_0^W \left[\beta_0 - \omega\mu_0\psi(\chi \pm \kappa\xi)\frac{H_{0x}}{E_{0y}}\right] dy. \quad (46)$$

Finally, since β and β_0 are constant and the effect of one rod is added to the other, we average β over the slot width W and we obtain

$$\beta^{\pm} = \beta_0 - \omega\mu_0\psi\frac{2}{W}\int_0^W \left[(\chi \pm \kappa\xi)\frac{H_{0x}}{E_{0y}}\right] dy. \quad (47)$$

This relation shows the influence of the anisotropic properties of the ferrite (κ) and the ellipticity of the microwave magnetic field (ξ) on the nonreciprocity of the device ($\beta^{+} - \beta^{-}$).

IV. Calculations and Experimental Results

From the SDA method, we have calculated the electric and magnetic fields on the interface air–substrate of the CPW without magnetic inclusions (Fig. 4). The dimensions of this CPW are 300-μm wide for the strip and the slots (Fig. 1), the conductors are supposed to be infinitely thin, the thickness of the substrate is $h = 635$ μm, and its permittivity is $\epsilon_r = 10.2 - j0.035$. The computation of the electromagnetic fields are performed at $f = 10$ GHz, and transversal and longitudinal components (h_{0x} and h_{0z}) of the microwave magnetic field are plotted Fig. 4. The combination of a real component h_{0x} and an imaginary component h_{0z} leads to an elliptic polarization of the magnetic microwave field (the imaginary and real parts of h_{0x} and h_{0z}, respectively, are negligible). The relative magnitudes $|h_{0x}| \simeq 2 \times 10^{-5}$ and $|h_{0z}| \simeq 2 \times 10^{-6}$ at the center of the slots correspond to an ellipticity $\xi = 0.1$ of the microwave field.

A. Calculations

The CPW propagation factor has been calculated from (47) and the propagation constant has been obtained as that depending on the applied field value. The transmission losses (in decibels per centimeter) for both forward and backward propagations have been plotted (Fig. 5). The Polder tensor model [3] is chosen to calculate χ and κ as follows:

$$\chi = \frac{(\omega_r + j\alpha\omega)\omega_M}{(\omega_r + j\alpha\omega)^2 - \omega^2} \quad (48)$$

$$\kappa = \frac{\omega\omega_M}{(\omega_r + j\alpha\omega)^2 - \omega^2} \quad (49)$$

with

$$\omega_r = \gamma\mu_0 H_{\mathrm{DC}} \quad (50)$$

$$\omega_M = \gamma\mu_0 M_S \quad (51)$$

where γ is the gyromagnetic ratio, α is the damping factor, M_S is the saturation magnetization of the ferrite, and H_{DC} is the applied constant magnetic field.

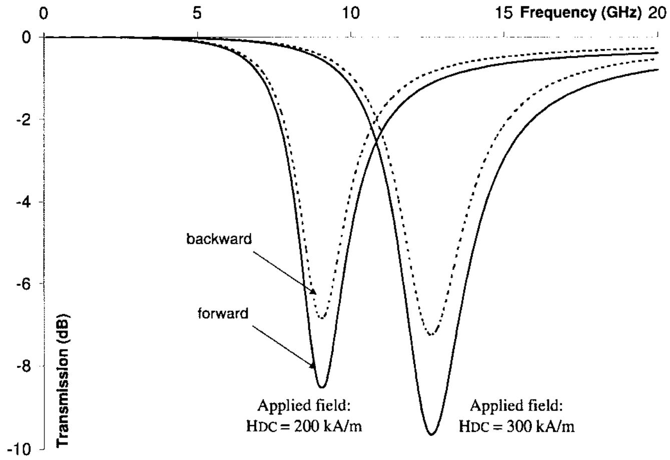

Fig. 5. Simulated transmission magnitude of a CPW with two ferrite rods for 200 and 300 kA/m applied.

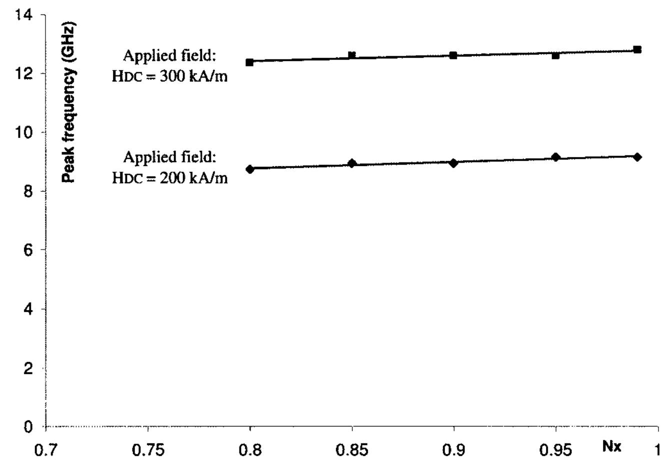

Fig. 6. Simulated peak frequency for different shape factor N_x values.

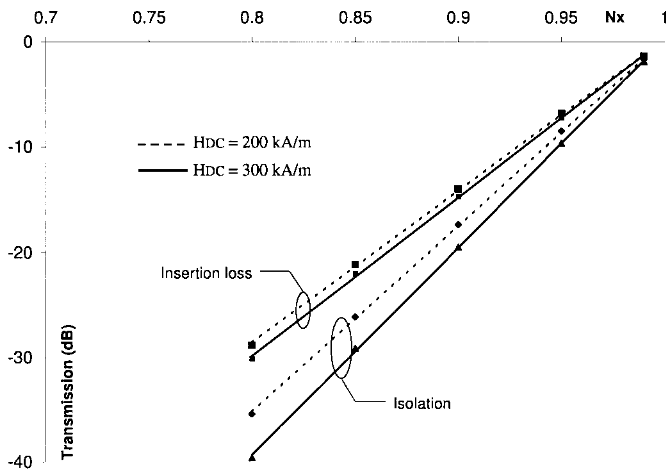

Fig. 7. Simulated transmission magnitude for different shape factor N_x values.

Numerical results are shown in Fig. 5, which have been computed using the following values:

1) $\alpha = 0.1$;
2) $M_S = 140$ kA/m;
3) $\gamma = 2\pi.28.10^9$;
4) $\epsilon_r = 10.2 - j0.035$;
5) $N_x = 0.95$;
6) $H_{\rm DC} = 200$ kA/m and 300 kA/m.

Significant nonreciprocal transmission magnitude has been predicted in the CPW with magnetized ferrite rods. This effect increases with the ferrite magnetization [4].

Fig. 6 shows the weak influence of the shape factor N_x on the frequency of the magnitude peak. Isolation (forward transmission) and insertion loss (backward transmission) increase if the shape factor is lower than one (Fig. 7), i.e., for thick films. High simulated values are obtained with a small shape factor, but our evaluation method of the propagation constants is only available for thin films (N_x close to one).

B. Experimental Results

A mag-hematite ferrite powder has been placed at the interfaces of a CPW (Fig. 1) and the transmission scattering parameters S_{21} (direct) and S_{12} (reverse) were measured with an HP 8510 network analyzer in the 2–20-GHz frequency band. Experimental results are shown in Fig. 8. The ferrite powder was made from mag-hematite nanoparticles (10-nm mean diameter). The dielectric substrate was a commercial 635-μm-thick RO3010 ($\epsilon = 10.2$, $\tan\delta < 0.0035$) with 17-μm-thick copper. We assume volume powder concentration is close to 30% and the magnetization of bulk material is 336 kA/m.

The physical meaning of the curves in Fig. 5 and 8 is the same. However, it is not possible to compare exactly theoretical and experimental curves because, at the present time, we still do not have an exact electromagnetic model for the tensor permeability of this granular material, and we cannot, for the moment, simulate its behavior in a CPW. We need to determine effective permittivity and permeability to calculate the transmission coefficients S_{21} and S_{12}. However, the qualitative agreement between calculated and experimental curves is visible from comparing the corresponding curves in Fig. 5 and 8. The same nonreciprocal phenomenon occurs and increases with the applied magnetic field in our theory, as well as in our measurements.

C. Wen's Configuration

The isolator proposed by Wen [1] is made of a CPW with both 762-μm-wide slots and a strip on a 635-μm-thick rutile substrate ($\epsilon_r = 130$). Two Trans-Tech G1000 gadolinium–aluminum-doped garnet ($M_S = 80$ kA/m, $\Delta H = 5.25$ kA/m, $\epsilon_r = 14.7$) rods are placed in the slots and a 170-kA/m dc magnetic field is applied. The device is 20.32-mm long.

The microwave electric and magnetic fields of the CPW without rods are calculated from the SDA. The results are similar to the ones showed in Fig. 4, but they differ in magnitude. Relative magnitudes as high as $|h_{0x}| \simeq 4 \times 10^{-5}$ and $|h_{0z}| \simeq 2.36 \times 10^{-5}$ are obtained at the center of the slots at 6 GHz, i.e., an ellipticity $\xi = 0.6$ of the microwave field. This value, higher than that of the previous case, can be explained by a non-TEM propagation under one of these conditions: a higher frequency, wider strip and slots dimensions, or a higher permittivity.

The influence of the magnetic rods on the propagation coefficient has been calculated from (47). Approximately 10-dB

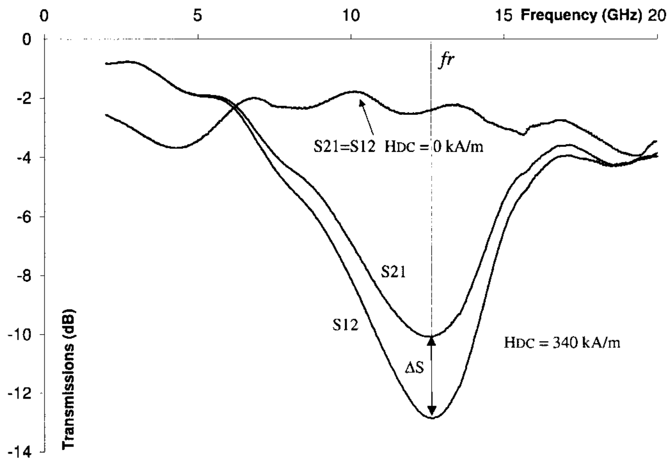

Fig. 8. Experimental results with a nanometric powder of mag-hematite, transmission magnitude with or without applied field.

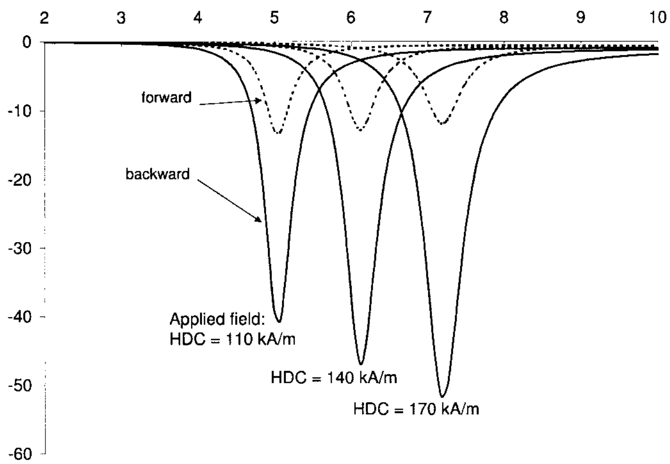

Fig. 9. Simulated transmission magnitude of Wen's isolator.

transmission losses and 50-dB isolation are obtained (Fig. 9). High insertion losses values are the consequence of an ellipticity different to one.

These results differ in magnitude with ones of Wen's experiments [1] because some parameters cannot be taken into account in our method. On one hand, the thickness of the rods is approximately 127 μm and cannot be approximate to a thin film. On the other hand, the permittivity of the rods is ten times higher than that of the substrate. As a consequence, the inclusion of the rods causes a great perturbation of the electromagnetic-field configuration.

V. Conclusion

A simple and explicit method for evaluating the propagation constants and transmission losses of a nonreciprocal coplanar isolator has been presented. From the data obtained by a SDA method for the unperturbed CPW, we calculate propagation constants for the forward and backward propagation directions of the isolator (a perturbed CPW). Nonreciprocal transmission in our theoretical model turns out to be significant, as well as in our experimental results. Although some rough approximations have been made in our model, the experimental and theoretical curves are in qualitative agreement. In order to compare quantitatively the theoretical results with the experimental data, we need to get an appropriate electromagnetic model of the material to determine its permeability and scattering parameters. The approximate theory presented above can be improved by taking into account the coupling between the ferrite rods.

The approximate method presented here has the advantage of simplicity, saves much computation time, and highlights the parameters that have to be improved. It could be used to design nonreciprocal microwave passive components made of thin magnetic films [5]. It may also be the root of a new diadic characterization method of anisotropic magnetic materials.

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Bernard Bayard was born in France, in 1972. He received the Engineer degree and Ph.D. degree in electronics from the Superior Institute of Advanced Technologies (ISTASE), Saint-Etienne, Saint-Etienne, France, in 1997 and 2000, respectively.

He is currently an Assistant Professor at the University of Saint-Etienne, Saint-Etienne, France. His research activities concern the integration of magnetic microwave components and the deposition and characterization of ferrimagnetic thin films.

Didier Vincent was born in France, in 1959. He received the Ph.D. degree in electronics from the University of Saint-Etienne, Saint-Etienne, France, in 1995.

He is currently an Assistant Professor at the University of Saint-Etienne. His research activities concern the integration of magnetic microwave components.

Constantin R. Simovski was born in Russia, in 1957. He received the degree from the Leningrad Polytechnic Institute (LPI), Leningrad, Russia, in 1980.

From 1980 to 1992, he was with the Soviet scientific and industrial firm Impulse, where he was involved with antenna systems for special communications and in the domain of special ionosphere physics. Since 1992, he has been with the St. Petersburg State Institute for Fine Mechanics and Optics, St. Petersburg, Russia, where he is currently a Full Professor. His current scientific interests are photonic crystals, high-impedance surfaces, nonreflective shields, polarization transformers, and frequency-selective surfaces.

Gérard Noyel was born in Saint-Etienne, France.

He was a Docteur d'état ès Sciences with the University Jean Monnet, Saint-Etienne, France, in 1987. He was engaged with instrumentation and research on insulating materials, initially on organic liquids, then on magnetic liquids and finally on solid magnetic structures. He developed dielectric and magnetic characterization methods from very low up to very high frequencies. The aim of these studies was the applications of these materials in electronics. Since 1998, he has been the Director of the Devices and Instrumentation in Optoelectronics and Microwaves (DIOM), University of Saint-Etienne, Saint-Etienne, France, and Director of the Engineer School, Superior Institute of Advanced Technologies (ISTASE), Saint-Etienne, Saint-Etienne, France.