A NOVEL NONRECIPROCAL FERRITE IMAGE GUIDE

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***Abstract* — A single ferrite/dielectric image line is analyzed using the effective permittivity method, adapted for ferrites. E_{pq}^{x} modes are used in association with a transverse bias direction to obtain nonreciprocal behavior. It is shown that the required conditions can be obtained that enables the composite image line to guide in one direction and leak in the other. Thus, the structure behaves as a "leaky-wave isolator." Dispersion diagrams showing this behavior in the frequency range 14-30 GHz are obtained for a 2x2 mm^2 ferrite rod with adjacent dielectric loading with ε_r=11.**

I. INTRODUCTION

The increased interest in millimeter-wave systems presents challenges in the design of ferrite components. Assuming that all other ferrite-related parameters remain constant, an inherent problem is the reduction in gyrotropy as the signal frequency is increased, i.e. the off-diagonal component of the ferrite permeability approaches zero as the frequency is increased well above ferrimagnetic resonance. A second problem is the increase in conductor loss as the frequency is increased. Therefore, it is helpful if a component can be devised that minimizes the use of conductor and requires only weak gyrotropy. This paper describes a new type of isolator that combines these features i.e. a nonreciprocal ferrite image guide. It is the ferrite equivalent of a dielectric image guide but it guides in one direction and leaks in the other direction.

A dielectric image guide can be visualized as half the cross-section of an optical fibre, on a conducting ground plane, scaled up to millimetric wavelengths. Dielectric waveguides have been described by a number of authors [1]-[4], and Mc^Levige et al [4] also considered insulated image line as well as grounded image line. The "effective permittivity" method is used in [5] and also used in our paper but is modified to analyze our structure that includes ferrites

Assuming propagation in the z-direction, rectangular dielectric waveguides and image lines can support E_{pq}^{x} and E_{pq}^{y} modes. These modes are commonly referred to as being hybrid in nature because they do not possess the simpler field distributions of either TM or TE modes. Since E_{pq}^{x} modes have principal field components of E_x, H_y and H_z we choose the direction of bias as x which makes the best use of precessional motion of ferrite dipoles and exhibits nonreciprocal behavior.

Ferrite image guides have been investigated by several authors [6]-[8], principally in the context of ferrite-controlled coupling between dielectric image guides. In [5], based on earlier analysis in [9], an isolator was described based on nonreciprocal coupling between two dielectric image guides. The coupling was through a transversely magnetized ferrite layer placed over the image guides. In [7] the use of a ferrite with the bias field applied in the x, y or z direction was investigated to control the coupling between two dielectric image guides. Non reciprocal behavior was found with all three orientations but large bias fields were found to be necessary. The analytical approach in our paper and in those cited above is similar, but this work investigates the properties of a single guiding structure, does not involve coupling between two structures, and selects the modes and bias direction required to enhance the nonreciprocal behavior.

II. THE FERRITE STRUCTURE

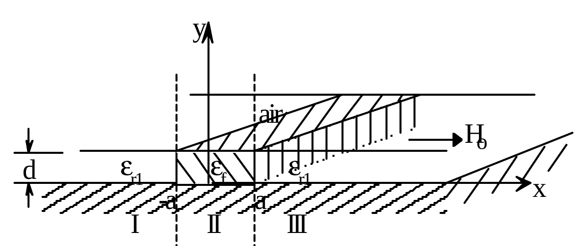

Fig. 1. Ferrite image guide structure

The ferrite image guide is shown in Fig 1. It consists of a rectangular ferrite rod (relative permittivity ε_f width 2a, and height d) on a metallic ground plane with identical dielectric slabs on both sides extending to infinity. The rod and the slabs have the same height and the region above them has a low permittivity, typically air. The dielectric slabs have a relative permittivity ε_{r1} where $\varepsilon_{r1}<\varepsilon_f$. Propagation is in the z-direction and the ferrite is biased in the plane of the structure and transverse to the direction of

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propagation. In the first stage of the "effective permittivity" method, each of the regions I II, and III (=II) shown in Fig 1 is considered separately as a horizontal slab (thickness d) of infinite extent on a ground plane, as shown in Fig 2 and Fig 3. These slabs will support TE or TM modes that are dependent on the dimensions, material parameters and frequency. The propagation constants of infinite slabs in these new models can be found by matching tangential electric and magnetic fields at the boundaries. The TE and TM solutions have E-field orientations that are related to E_{pq}^{x} and E_{pq}^{y} modes of the initial image guide. However the TE modes are required for this application. Then each region can be replaced by homogeneous regions, this time infinite in y direction, and having effective dielectric constants that are defined analytically by using propagation constants of structures of Fig 2 and Fig 3. The final structure to analyze is that shown in Fig 4. The propagation constants of the original structure can be approximated using this new hypothetical model. With this orientation of the layers, the TM modes are required for this application so that the overall solutions correspond to E_{pq}^{x} modes of the original structure.

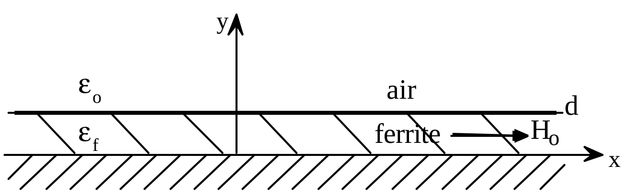


Fig. 2. Infinite ferrite slab on a ground plane

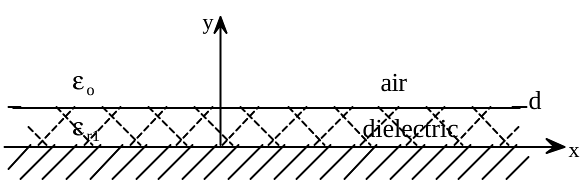


Fig. 3. Infinite dielectric slab on a ground plane

If $\varepsilon_{eff2} > \varepsilon_{eff1}$ the central rib will guide a wave, and if $\varepsilon_{eff2} < \varepsilon_{eff1}$ it will not. The novel feature of this structure is that this inequality can be controlled because, due to the transverse bias field, the TE modes of the conductor-backed infinite ferrite slab shown in Fig. 2. exhibits nonreciprocal field displacement. [10]. This means that $\beta^{+} \neq \beta^{-}$ and consequently the effective permittivity, $\varepsilon_{eff2}^{+} \neq \varepsilon_{eff2}^{-}$. Thus it becomes possible to create the required conditions to guide waves one way but not the other. Such a device is a "radiative, or leaky-wave, isolator" and it has not been observed previously in the microwave literature.

II. The Derivation of Propagation Constants

Matlab m files are written for all three structures and transcendental equations related to each case are solved numerically. The ferrite is type TT1-390 with saturation magnetization of $4\pi M_s = 2150$ G and $\varepsilon_f=12.7$. It is biased in ± x direction with H_o=500 Oe. All losses are ignored. The thickness d=2 mm and the width a=4 mm. The dielectric constant of the dielectric layers is $\varepsilon_{r1}=10$. We will first start with Fig 2 considering solutions where fields are guided by the ferrite region and field components are being derived from magnetic potential ϕ_h.

$$\phi_h = \psi_x = \begin{cases} A_1 e^{-k_1(y-d)} & y \geq d \\ A_2 \sin k_2 y & d > y \geq 0 \end{cases} \qquad (1)$$

$$k_1^2 = k_z^2 - k_o^2$$
$$k_2^2 = \varepsilon_f \mu_{eff} k_o^2 - k_z^2 \qquad (2)$$

$$h_y = \frac{k_z \psi_x - \frac{\kappa}{\mu}\frac{d\psi_x}{dy}}{\omega\mu_{eff}} \qquad h_z = \frac{\frac{d\psi_x}{dy} - \frac{\kappa}{\mu} k_z \psi_x}{j\omega\mu_{eff}} \qquad (3)$$

Where $\mu_{eff}=(\mu^2-\kappa^2)/\mu$, the effective permeability and k_z is the propagation constant and $k_o=\omega^2\mu_o\varepsilon_o$. All the definitions of the parameters appeared in the field expressions have well known definitions and can be found in [11]. The effective dielectric constant of the overall structure is given by;

$$\varepsilon_{eff2} = \varepsilon_f \mu_{eff} - (k_2 / k_o)^2 \qquad (4)$$

Similarly for the structure of Fig 3 (1)-(3) can be modified for the dielectric slab and effective dielectric constants can be obtained from propagation constants using the boundary conditions.

$$\phi_h = \begin{cases} A_2 e^{-k_a^{'}(y-d)} & y \geq d \\ A_1 \sin k_2^{'} y & d > y \geq 0 \end{cases} \qquad (5)$$

$$k_2^{'2} = \varepsilon_{r1} k_o^2 - k_z^{'2}$$
$$k_a^{'2} = k_z^{'2} - k_o^2 \qquad (6)$$

$$e_x = wm_o k_z' f^h \quad (7)$$

$$h_z = -jk_z' \partial f_h / \partial y \quad (8)$$

$$e_{eff1} = e_{r1} - (k_2' / k_o) \quad (9)$$

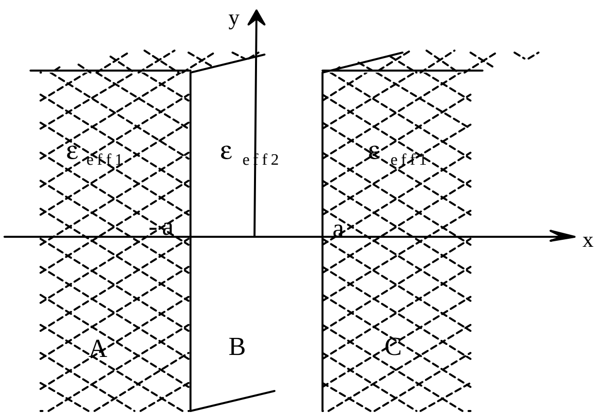


Fig. 4. Hypothetical model to approximate the propagation constants of the original structure

It is well known that TE modes in grounded ferrite slabs biased in the plane in a direction transverse to the direction of propagation exhibit nonreciprocal behavior [10]. Nonreciprocity is observed as having different propagation constants and different field distributions for positive and negative going waves. As the propagation constants differ with respect to the direction of propagation (this is same as changing the bias direction) it is possible to obtain two different effective dielectric constants for the two different directions.

Table 1 shows the propagation constants with respect to frequency obtained for the structures of Fig 2 and Fig 3. There are two different propagation constants for two bias directions for the infinite ferrite slab (as bias(+) and bias(-)). The fourth column, beta (diel) on the other hand shows the propagation constants of the dielectric slab. It can be seen that even though ε_{eff2}(-) is always greater than ε_{ef1}, ε_{eff2}(+) is smaller at lower frequencies and greater at higher frequencies due to the difference in the propagation constants of the ferrite slab with different bias directions. So, for the structure shown in Fig 4 in which the effective constants will be used, it becomes possible to create the required conditions to guide the waves in one direction (where $\varepsilon_{eff2} > \varepsilon_{eff1}$) and not in the other (where $\varepsilon_{eff2} < \varepsilon_{eff1}$). If the region II of Fig 2 were a simple dielectric with the same dielectric constant of the ferrite used, there would always be reciprocal propagation in both directions. However due to the nonreciprocal behavior, the ferrite slab acts as if it has a smaller dielectric constant in one direction and much higher in the other. This is the key idea we propose to build a new type of isolator.

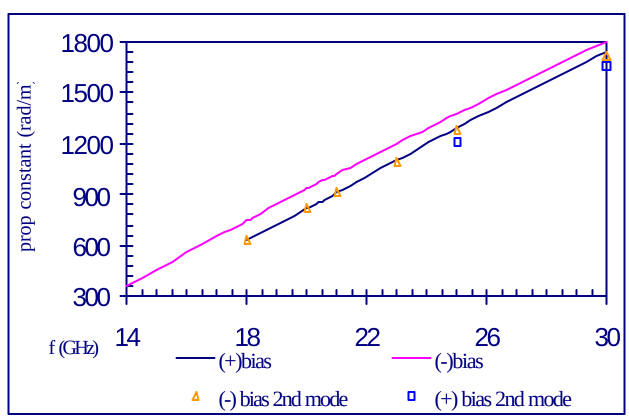
Having determined the effective dielectric constants we can write the field solutions for Fig 4 assuming a sinusoidal variation in Region B and exponential decays in A and C. Analysis is not given here due to lack of space. Fig 5 shows a plot of propagation constants of the structure of Fig 4, which approximates the propagation constants of the original structure. It can be seen that the dispersion curves for two different propagation directions do not start from the same frequency.

TABLE I
PROPAGATION AND EFFECTIVE DIELECTRIC CONSTANTS OF STRUCTURES IN FIG 3 AND FIG 4

freq	bias (+)	bias (-)	beta (diel)	Eeff 1	Eeff 2 (+)	Eeff 2 (-)
14	293.22072	419.95325	326.7625	1.2419128	0.99994	2.0512972
15	355.057	521.3	393.304	1.567317	1.27731	2.75344
16	445.56431	618	467.8859	1.949497	1.76792	3.401102
17	543.469	711.1771	546.2428	2.3537285	2.32988	3.9897
18	643.4318	862.0635	626.26158	2.7596201	2.91301	4.52642
20	842.705	979.46	787.5	3.53446	4.0473	5.467593
21	940.8026	1066.705	867.87729	3.8936851	4.575527	5.8821059
23	1133.125	1239.245	1027.27453	4.54778726	5.5332812	6.6182238
25	1320.4085	1409.792	1184.5738	5.183148	6.35944	7.24957
30	1770.34	1829.6108	1568.939	6.23522	7.93877	8.47925

Fig 5 shows that it is possible to have propagation in one direction and not in the other for about 4 GHz (from 14 to 18 GHz). This numerical example is only a preliminary study and it is possible to improve the bandwidth of the isolation by changing either the bias strength or the $\varepsilon_f/\varepsilon_{r1}$ ratio.

Fig. 5. Approximated propagation constants of the



original structure showing an isolation of about 4 GHz

By setting H_0=0, and ε_{r1}=11 and a=1 mm we obtained a second set of propagation constants as can be seen in Fig 6. The "isolation bandwidth" has increased to 7 GHz (from 14 GHz to 21 GHz), and the reduced width eliminated the higher order modes that were shown in Fig 5.

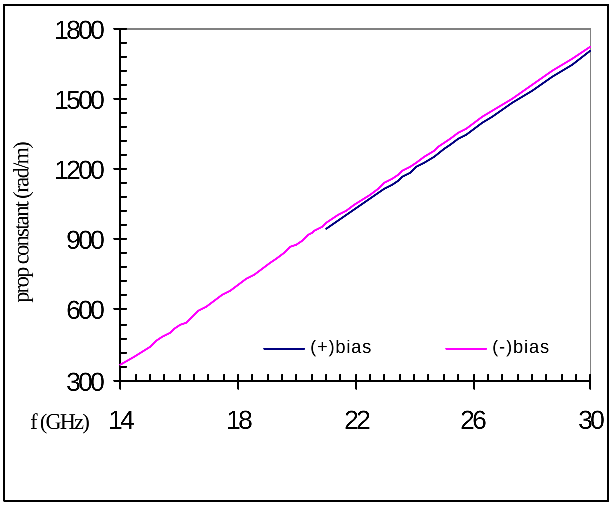


Fig. 6. Approximated propagation constants of the original structure showing an isolation of about 7 GHz

V. CONCLUSION

It has been shown that by selecting the correct modes and bias direction a simple method exists to obtain a leaky-wave ferrite image guide isolator. With an appropriate choice of dimensions, bias strength and constitutive parameters we obtained leaky-wave behavior for approximately 7 GHz over the frequency range of 14-30 GHz, and eliminated higher order modes. These structures are being simulated using Ansoft HFSS and experimental work is in hand.

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