NONRECIPROCAL EFFECTS IN AN OPEN DIELECTRIC WAVEGUIDE WITH GRATING STRUCTURES

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Abstract

Nonreciprocal phenomena in a grating structure created on an open waveguide containing anisotropic media are studied. Experimental investigations based on the theory predict that new nonreciprocal devices can be developed for millimeter-wave integrated circuits.

1. Introduction

This paper proposes a novel nonreciprocal device for microwave and millimeter-wave circuits made of dielectric waveguides. Recently, a considerable attention has been paid to the development of millimeter-wave integrated circuits based on the dielectric waveguide. One important problem is the development of nonreciprocal devices such as isolators and circulators. Little has been reported on this subject. Nanda[1] reported a field displacement type isolator which consists of a ferrite rod and a resistive film. Its performance is not very good mainly because the resistive film cannot be placed in such a way that it absorbs energy of the wave propagating in one direction only and does not affect the one in another direction.

We propose here the use of a periodic grating in conjunction with a dielectric waveguide containing anisotropic media. Although grating structures created on an open waveguide have been analyzed and used for developing leaky wave antennas and distributed Bragg reflectors[2-7], no attempt has yet been made to use them for nonreciprocal devices.

The fundamental principle of operation is as follows: When a slab material with an anisotropic permeability (e.g. ferrite) or permittivity (e.g. plasmon) is sandwiched between two different isotropic media, the field displacement effect is created by applying a dc magnetic field. Hence, the surface waves propagating in the structure in the opposite directions have different propagation constants β_+ and β_-. Now a periodic grating is created in the guide, and choose the grating period d so that at least one space harmonic for β_- wave is in the radiating region; whereas, all harmonics for β_+ wave are in the non radiating region. Hence, the device works as a leaky wave antenna for the wave traveling in one direction and eventually most input energy is consumed by radiation; whereas, for the wave traveling in the opposite direction, no leakage loss results. It is expected that a highly efficient isolator may be built by this structure, because we can introduce a selective loss mechanism unlike in the conventional structure with a resistive film.

2. Theory

Let us consider the structure in Fig. 1. In the present case, the material is assumed to have a tensor permeability $[\mu_f]$. A static magnetic field H_{DC} is applied in the y direction. We will analyze only the TE modes because the TM modes do not exhibit any nonreciprocity for this arrangment.

When there is no grating, the propagation characteristics of such a waveguide may be analyzed readily from the equivalent transmission line model in the z direction. For instance for the $[\mu_f]$ layer, the transmission line model provides

$$\begin{bmatrix} e_y(0) \\ h_x(0) \end{bmatrix} = \begin{bmatrix} \cos\theta + \frac{\kappa\beta}{\mu k}\sin\theta & -j\frac{\omega\mu_e}{k}\sin\theta \\ -j\frac{\omega^2\mu\varepsilon-\beta^2}{\omega\mu k}\sin\theta & \cos\theta - \frac{\kappa\beta}{\mu k}\sin\theta \end{bmatrix} \begin{bmatrix} e_y(-t_f) \\ h_x(-t_f) \end{bmatrix} \quad (1)$$

where $k^2 = \omega^2\mu_e\varepsilon - \beta^2$, and $\theta = kt_f$ and $\mu_e = (\mu^2 - \kappa^2)/\mu$. e_y and h_x are tangential electric and magnetic fields at the interfaces $z = 0$ and $-t_f$, respectively. An eigenvalue problem for the propagation constant β is obtained by the application of transverse resonance condition readily derivable from the transmission line matrices like the one in (1). Owing to the anisotropy of magnetized ferrite, a propagation constant of surface wave traveling along the (+x) direction differs from the one for the wave along the (-x) direction, viz., $\beta_+ \neq \beta_-$.

Therefore, a nonreciprocal leakage phenomena will occur if the grating period d is suitably chosen such that

$$k_s > \beta_- - \frac{2\pi}{d} > -k_s > \beta_+ - \frac{2\pi}{d} \quad (2)$$

where $k_s = \omega\sqrt{\varepsilon_s\mu_0}$ is the bulk wavenumber of the substrate. This condition signifies that only the -1st space harmonic of the wave along the (-x) direction will lead away. Fig. 2 shows the mechanism schematically.

Now, this grating ferrite waveguide will become an isolator. This planar type of isolator is similar to the field-displacement type. The grating in the anisotropic waveguide will provide a loss mechanism to the (-x) directed wave but no loss for the (+x) wave. This is an important and very desirable characteristic of this isolator. If two grating ferrite waveguides are placed parallel as shown in Fig. 3, a 4-port circulator action is expected. Nonreciprocal leakage and coupling are used in this circulator.

The equivalent transmission line method may be modified to apply to a structure with a grating. The attenuation constant of the wave propagating in the structure is

$$\alpha = \sum_n P_n/P \quad (3)$$

where P is the power flow in the structure without a grating and P_n is the power leaking into the n-th space harmonic. The summation is over the traveling type harmonics only. Table I shows some numerical results of attenuation constant.

3. Experiment

As a preliminary test, we created an anisotropic waveguide consisting of a ferrite slab placed on a Stycast HiK substrate. Experiments have been conducted at X-band to demonstrate feasibility of the device before a full scale test at higher frequencies is conducted. Instead of a notch type grating in Fig. 1, we placed metal strips periodically at the interface between the ferrite and substrate. This is for ease of fabrication and for providing stronger perturbation than in the notch type because our ferrite sample is relatively short to obtain leakage in the measurable amount if the latter is used.

Fig. 4 shows the difference of transmitted energy from one port to another when the direction of H_{DC} is switched.

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This is equivalent to the forward and reverse transmission with a fixed direction of H_{DC}. It is seen that about 14 dB forward-to-reverse ratio is obtained with H_{DC} of 5.4 K gauss at 9.9 GHz. A relatively strong peak appears around 10.5 GHz in the upward direction. This may be explained as follows. Around this frequency, waves traveling in both directions are leaky and the difference in transmission coefficients should be zero (0 dB level). However, the level of signals received is low and loss mechanisms due to the grating and other junctions can affect more strongly to the β_+ wave.

4. Conclusions

We proposed and analyzed wave guiding characteristics in an open dielectric waveguide containing anisotropic media and a grating structure. A feasibility experiment indicates this structure is useful for developing nonreciprocal devices for microwave and millimeter-wave dielectric integrated circuits.

References

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Table I. Calculated Attenuation Constants

t_g/λ	$\alpha\lambda$ (dB)
1.67×10^{-2}	3.95×10^{-2}
3.33×10^{-2}	8.68×10^{-2}
5.00×10^{-2}	12.01×10^{-2}

$\varepsilon_f = 16$, $\varepsilon_s = 9.6$, $\mu = 1$, $k = 0.3$, $d/\lambda = 0.164$, $t_f/\lambda = 0.1$

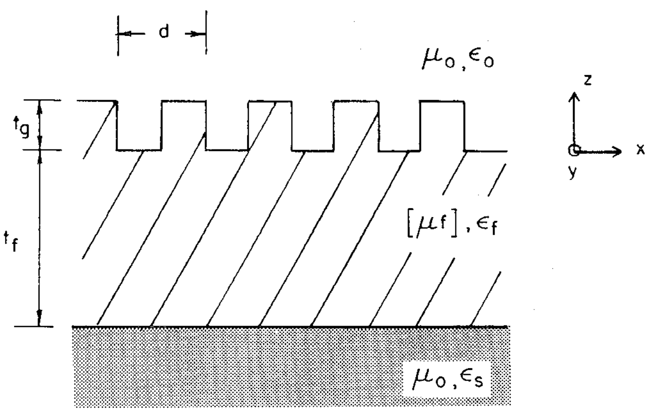


Figure 1. Grating ferrite slab waveguide $\varepsilon_f > \varepsilon_s > \varepsilon_0$

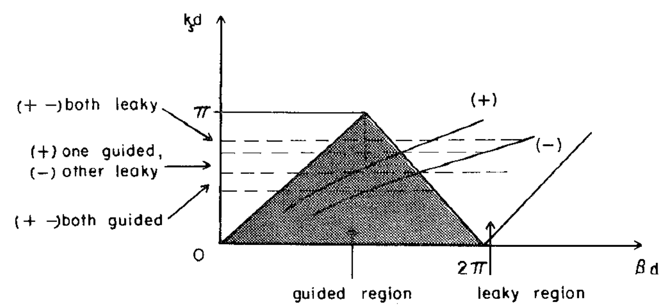
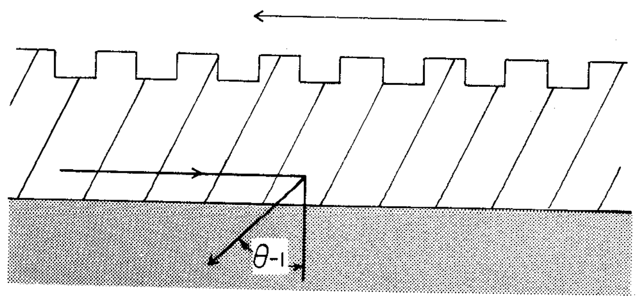
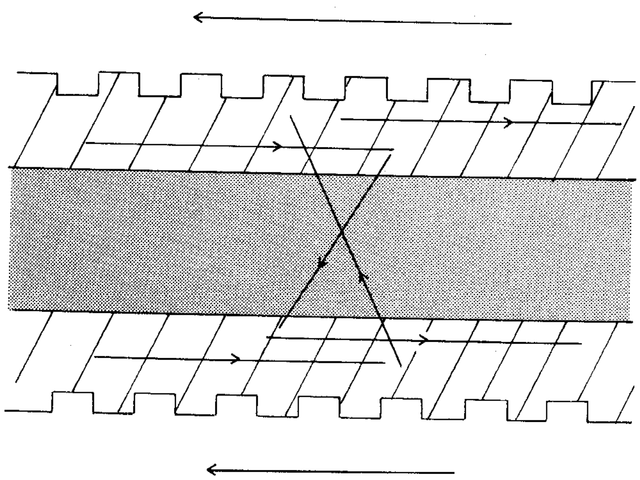


Figure 2. Brillouin diagram for periodic structures



(a) ISOLATOR



(b) CIRCULATOR

Figure 3. Grating type isolator and circulator

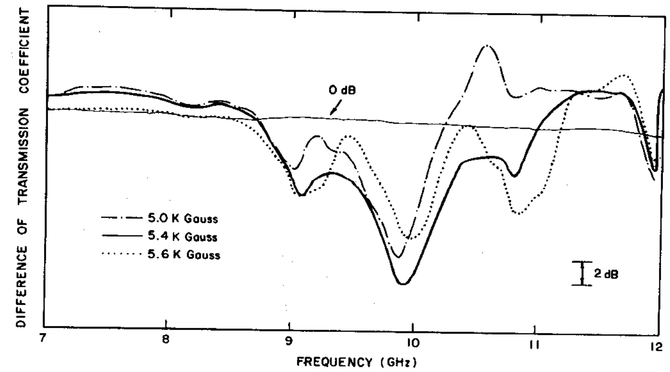


Figure 4. Measured nonreciprocity of transmission coefficients