ANALYSIS OF ANISOTROPIC NONRADIATIVE DIELECTRIC (NRD)-GUIDES USING COUPLED-MODE THEORY

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ABSTRACT

The combined effect of uniaxial dielectric and magnetic anisotropies on the performance of nonidentical asymmetric NRD-guides is investigated using the conventional coupled-mode theory (CMT). The modal characteristic equations of structures containing several slabs of anisotropic materials can be relatively complicated to manipulate. Otherwise, the CMT approach is adequately accurate and its use is simple. The propagation characteristics obtained by the presented formulation are compared with those obtained by the exact theory. Numerical results for some common uniaxial materials such as sapphire and epsilam-10 indicate that the wave propagation characteristics can deviate significantly from the corresponding isotropic case, particularly at millimeter-wave.

INTRODUCTION

The nonradiative dielectric (NRD) waveguide was proposed by Yoneyama and Nishida [1] for millimeter-wave applications. The NRD technology is able to offer attractive features such as simplicity, easiness of fabrication, low transmission losses and radiation suppression at discontinuities and curved sections. A wide set of devices have been reported [2] and recent practical applications of NRD millimeter-wave circuits include transceivers for local area networks (LAN) and car collision-avoidance radars [3]. However, most of the reported devices have been fabricated using isotropic or ferrite materials [4], [5]. Recently, the interest in the use of other anisotropic materials for NRD-guides has increased, especially in those exhibiting pseudochiral characteristics [6] and uniaxial dielectric and magnetic anisotropies [7], [8]. The investigation of wave propagation properties in devices containing anisotropic materials is of great importance, particularly at millimeter-waves frequencies.

Otherwise, couplers play an important role in millimeter-wave technology as part of useful devices such as filters, power dividers and mixers. Coupled structures in NRD technology using straight and curved guides have been proposed and investigated [9], [10]. Structures based on symmetric coupled straight guides can be easily analyzed by means of the well-known even and odd modes approach. However, if the slab materials are nonidentical and/or the structure is asymmetric, the modes of the composed structure can be analyzed by means of full-wave approach [11]. In these cases, after applying the boundary conditions a homogeneous system of equation for the propagation constant is produced. If the structure consists of several slabs of anisotropic materials, such as dielectric uniaxial, biaxial and/or ferrites, the terms composing the equations can be very complicated to manipulate. On the other hand, the CMT approach is adequately accurate and its use is easier [11]. The two needed propagation constants are obtained from the single slab case, which only requires the solution of an analytical characteristic equation. Recently, Watanabe and Yasumoto [12] investigated the propagation characteristics of NRD couplers using coupled-mode formulation based on singular perturbation technique, comparing results with those obtained by means of exact theory, conventional and improved CMT. Therefore, only coupled NRD using isotropic materials were investigated.

In this work, the combined effect of uniaxial dielectric and magnetic anisotropies on the performance of nonidentical and asymmetric NRD-guides is investigated. The conventional CMT approach applied to the solution of anisotropic wave guiding is based on the procedure proposed by Awai and Itoh [13], whose investigation was concerning only planar structures with ferrites at millimeter-wave frequencies. The performance of NRD-guides based on straight slabs made of sapphire and epsilam-10 is here investigated. The effect of magnetic uniaxial anisotropy is also considered. The propagation characteristics obtained by the presented formulation are compared with those obtained by the exact theory. Numerical results show that in some investigated cases the effect of such anisotropies cannot be neglected, particularly at millimeter-waves.

THEORY

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The cross-sectional view of the NRD coupled slabs is shown in Fig.1a. The anisotropic materials are assumed lossless and the propagation is along z-direction. The dielectric and magnetic anisotropies are characterized by the relative permittivity and permeability tensors

$$[\varepsilon_{ri}],[\mu_{ri}] = \begin{bmatrix} \varepsilon_{1i},\mu_{1i} & 0 & 0 \\ 0 & \varepsilon_{2i},\mu_{2i} & 0 \\ 0 & 0 & \varepsilon_{2i},\mu_{2i} \end{bmatrix}, \tag{1}$$

where *i=1,2* represents the guides 1 and 2. The fundamental mode of interest in NRD-guide is the LSM_{10}, which has five components ($H_x=0$). Both guides are assumed single mode.

The conventional CMT is based on the overlap integrals of the evanescent fields. In order to perform the analysis, the anisotropic NRD coupler is divided into two single slab base structures, as shown in Fig.1b. The coupled electric and magnetic fields can be written as [13]

$$\overline{E} = c_1\overline{E_1} + c_2\overline{E_2}\ ,\ \overline{H} = c_1\overline{H_1} + c_2\overline{H_2}\ , \tag{2}$$

where $\overline{E_i}$ and $\overline{H_i}$ ($i=1,2$) are the modal fields in two basis structures, and c_1 and c_2 are coefficients to be determined. In single slab, the principal electric field of the LSM modes is given by $E_x = [A_1\cos(qx) + B_1 sin(qx)]\, sin(k_y y)$, where A_1 and B_1 are constants to be determined. The modal characteristic equations results from the application of the boundary conditions and are given by

$$\varepsilon_{1i}\, p k_{1c}^2 = q k_{1a}^2 \tan(qW/2),\ \varepsilon_{1i}\, p k_{1c}^2 = -q k_{1a}^2 \cot(qW/2), \tag{3}$$

for even and odd modes, respectively. The terms in (3) are defined by: $k_{1c}^2 = \varepsilon_{2i}\mu_{2i}k_0^2 - q^2$, $k_{1a}^2 = p^2 + k_0^2$, $k_0 = 2\pi/\lambda_0$, λ_0 is the free space wavelength. The propagation constant is given by $\beta^2 = \varepsilon_{1i}\mu_{2i}k_0^2 - (\varepsilon_{1i}/\varepsilon_{2i})\, q^2 - k_y^2$, where $k_y = m\pi/h$, $m = 1,2,3,\ldots$

NUMERICAL RESULTS

Since several conventional NRD devices are fabricated using isotropic materials as polystyrene ($\varepsilon_r = 2.56$), fused quartz ($\varepsilon_r = 3.8$), or alumina ($\varepsilon_r = 9.5$), it is reasonable to design a coupler utilizing anisotropic material in such way that at least one of the slabs is made of conventional isotropic material. For instance, one branch of the coupler can be fabricated with isotropic material to keep the line homogeneity, acting as the principal line and interconnecting other devices. The other coupler branch, made with anisotropic material, would be used to improve the device performance. In order to demonstrate the usefulness of the CMT, directional coupler using two different dielectric anisotropic materials is presented. In the design of a directional coupler using nonidentical straight slabs, the phase synchronism can be achieved by adjusting the material parameters and/or slab widths. Sapphire ($\varepsilon_1 = 11.6$ and $\varepsilon_2 = 9.4$) and epsilam-10 ($\varepsilon_1 = 10.3$ and $\varepsilon_2 = 13.0$) were chosen to compose the coupled structure analyzed since the values of the permittivity tensor elements are not significantly different from each other, resulting in close values for the slab widths.

First, the two slab widths for a given value of propagation constant (phase synchronism) are chose. To facilitate the design, the dispersion diagram of the principal mode (LSM_{10}) and the first higher-order mode (LSM_{20} in the analyzed case) for epsilam-10 and sapphire are plotted as a function of the single slab width for 50 GHz and h=2.7 mm, as shown in Fig.2. The first choice of slab thickness should be the intersection point of the LSM_{10} curves for sapphire and epsilam-10. However, at that point (W_3=1.642 mm) the guides become multimode. Thus, an appropriate choice would be W_1=1.050 mm for the sapphire slab and W_2=0.938 mm for the epsilam-10 slab thickness. The corresponding propagation constants are $\beta_1 = 1.598539$ mm^{-1} and $\beta_2 = 1.598537$ mm^{-1}, respectively, which are adequately close values.

The coupling length of the device can be obtained by means of the analysis of the wave amplitudes in the two guides. The wave amplitudes of guides 1 (sapphire) and 2 (epsilam-10) versus propagating distance are plotted for h=2.7 mm for two coupling spacing, s=0.9 mm and s=1.0 mm, as shown in Fig.3. The corresponding coupling lengths are about 18.8 mm and 22.2 mm, respectively.

The combined effect of uniaxial dielectric and magnetic anisotropies on the wave amplitudes of guides 1 (sapphire) and 2 (epsilam-10) versus propagating distance is also analyzed for 50 GHz, s=0.9 mm, and h=2.7 mm, as shown in Fig.4. In this case, the values of the permittivity tensor elements are those corresponding to sapphire and epsilam-10, but a magnetic anisotropy was introduced in the material characteristics of guide 1 ($\mu_{11} = 1.0$ and $\mu_{21} = 1.1$). Both cases, with and without magnetic anisotropy, are shown in Fig.4 for the sake of comparison. A 10% variation in parameter μ_{21} of guide 1 (LSM_{10} mode are not affected by μ_{11}) is enough to strongly deteriorate the phase synchronism. In order to restore phase synchronism, the coupler has to be redesigned. A new dispersion diagram must be drawn to include the effect of magnetic anisotropy. For instance, the width of guide 1 is kept the same, but the corresponding propagation constant is now $\beta_1 = 1.886416$ mm^{-1}. The thickness of guide 2 is now W_2=1.028 mm and the corresponding propagation constant is $\beta_2 = 1.886404$ mm^{-1}. For the same coupling spacing, s=0.9 mm, the coupling length changes from 18.8 mm (without magnetic anisotropy) to about 32.7 mm (including magnetic anisotropy). In this case, the magnetic anisotropy had the effect of strongly affect the directional coupler performance, deviating it from the case of nonmagnetic anisotropy.

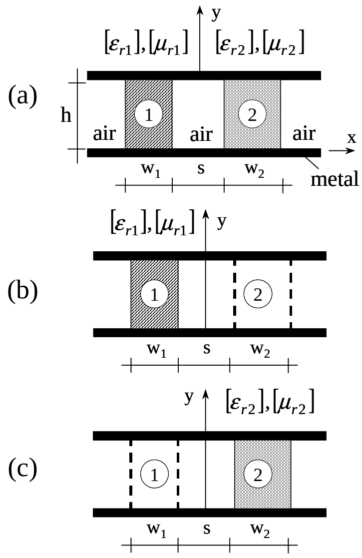

Figure 1. NRD cross-sectional view. (a) Coupled anisotropic guides; (b), (c) base structures.

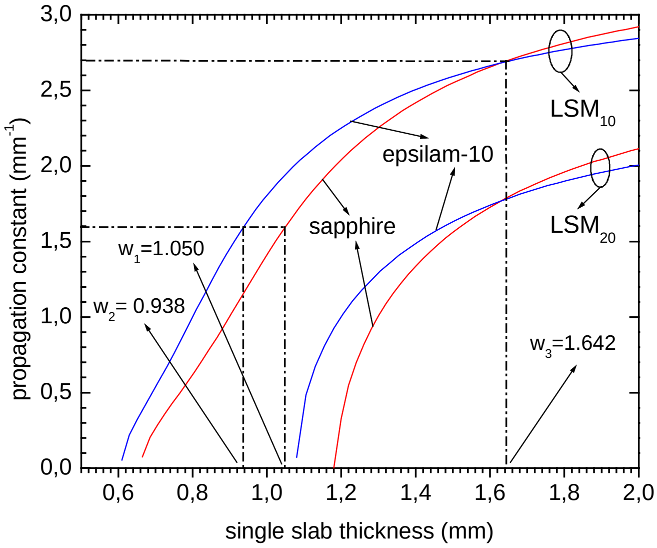

Figure 2. Dispersion diagram for the principal mode (LSM_{10}) and the first high-order mode (LSM_{20}) for epsilam-10 ($\varepsilon_{12} = 10.3; \varepsilon_{22} = 13$) and sapphire ($\varepsilon_{11} = 11.6; \varepsilon_{21} = 9.4$). The frequency is 50 GHz. Magnetic anisotropy is not considered in this case ($\mu_{11} = \mu_{12} = \mu_{21} = \mu_{22} = 1$).

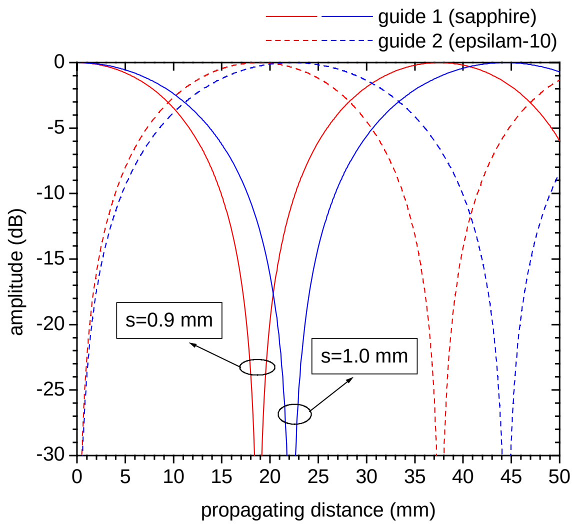

Figure 3. Wave amplitudes of guides 1 and 2 versus propagating distance for two coupling spacing. The frequency is 50 GHz.

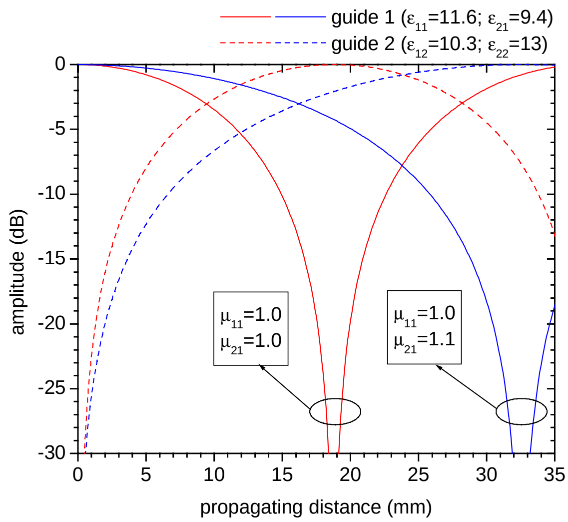

Figure 4. Combined effect of uniaxial dielectric and magnetic anisotropies on the wave amplitudes of guides 1 and 2 versus propagating distance. The frequency is 50 GHz and the coupling spacing is s=0.9 mm.

The comparison of propagation characteristics of coupled NRD-guides evaluated by exact solution and conventional CMT for some values of the coupling spacing, *s*, is shown in Table 1. For very low values of the coupling spacing (strong coupling), the differences between the coupling lengths are relatively high, as it is expected for the conventional CMT approach. In the *s* value region about 1.0 mm, the results by the CMT approach exhibit good agreement with those obtained by exact solution.

Table 1. Comparison of propagation characteristics of coupled NRD-guides evaluated by exact solution and conventional CMT for some values of coupling spacing. Propagation constants and coupling lengths are, respectively, β_{even} , β_{odd} , L_π^e (exact solution), k_1 , k_2 , L_π^{CMT} (conventional CMT). Guide 1: sapphire, W_1=1.05 mm; guide 2: epsilam-10, W_2=0.938 mm; frequency: 50 GHz.

Coupling spacing, s (mm)	Exact solution			Conventional CMT (this work)			Relative error (%)
	β_{even} (mm^{-1})	β_{odd} (mm^{-1})	L_π^e (mm)	k_1 (mm^{-1})	k_2 (mm^{-1})	L_π^{CMT} (mm)	$\left\lvert\frac{L_\pi^{CMT} - L_\pi^e}{L_\pi^e}\right\rvert$
0.2	1.4053	2.0372	4.9715	1.3281	1.8689	5.8088	16.84
0.5	1.4627	1.7960	9.3832	1.4350	1.7620	9.6070	2.39
0.9	1.5208	1.6878	18.8151	1.5149	1.6821	18.7898	0.13
1.0	1.5317	1.6728	22.2650	1.6692	1.5278	22.2450	0.09
2.0	1.5856	1.6120	118.8794	1.6117	1.5853	118.8770	0.002

CONCLUSIONS

In this work, the combined effect of uniaxial dielectric and magnetic anisotropies on the performance of nonidentical and asymmetric NRD-guides using the conventional CMT approach was investigated. Numerical results show that in some investigated cases the uniaxial anisotropy cannot be neglected, especially at millimeter-waves.

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