A Study of Nonreciprocal Coupled Ferrite-Dielectric Image Guide Structure for Ka-band

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Abstract—The nonreciprocal coupled ferrite-dielectric image guide structure with the same geometry as in our previous experimental investigation has been studied numerically by finite element method in the frequency range 26–40 GHz. The ferrite element in the experiment has been inhomogeneously magnetized by using a disk-shaped permanent magnet, whose diameter is comparable with the length of the ferrite bar. Recently, we have modelled the ferrite element as homogeneously magnetized perpendicularly to the ground plane and the direction of propagation. This homogeneous magnetization represents first approximation of the real inhomogeneous one. Here we have extended the numerical examination of the nonreciprocity and as a result we have proposed a procedure for designing isolators with inhomogeneous magnetization. Also, we have investigated the influence of several parameters – permanent magnetic field strength and three ferrite material parameters (saturation magnetization, relative dielectric permittivity and dielectric loss tangent) on the nonreciprocal behavior of the coupled ferrite-dielectric structure.


I. INTRODUCTION

Coupled ferrite-dielectric image guide (CFDIG) structures could represent an alternative of the conventional nonreciprocal devices at millimeter wave frequencies [1-3]. We have investigated experimentally in Ka-band a CFDIG structure with inhomogeneous magnetization and have registered a strong nonreciprocity of the structure with coupling length \( l \) equal to 17.6 mm in a wide frequency range from 33.6 to 34.5 GHz [4].

Numerical investigations offer high potentials to determine the way the different parameters of the structure influence its nonreciprocity [5]. That is a reason we have investigated the same CFDIG structure numerically by the finite element method (FEM) [6]. The ferrite bar has been modelled as homogeneously magnetized perpendicularly to the ground plane and the direction of propagation. The frequency dependences of losses in forward and backward direction of propagation have shown a nonreciprocity that is shifted up to higher frequencies in comparison to experimental results, namely isolation greater than –20 dB has been registered in the frequency range from 36.2 to 38 GHz.

In order to examine the dependence of the nonreciprocity on the coupling length, \( l \) has been successively varied from 12.5 to 19.5 mm [6]. Results have revealed that at longer coupling lengths a better nonreciprocal behavior can be achieved, which means a greater absolute value of isolation and a wider frequency band of operation. Also, the longer the coupling length, the higher the operation frequency (we refer to as operation frequency a frequency of minimal isolation \( f_{\min} \)). The dependence of \( f_{\min} \) on the coupling length explains the difference of operation frequencies obtained experimentally and numerically as the real inhomogeneously magnetized ferrite bar is equivalent to homogeneously ferrite bar of shorter length.

II. DISTRIBUTION OF THE ELECTRIC FIELD MAGNITUDE AND PERIOD OF POWER TRANSFER

The geometry of the model of the CFDIG structure has been discussed in details in [6]. The model volume coincides with the volume of the so-called air box (radiation box) with dimensions 12 mm×6 mm×20 mm. The primary dielectric image guide (IG) represents a parallelepiped (bar) with dimensions 2 mm×0.97 mm×20 mm. It is made by alumina with a relative permittivity \( \varepsilon_r = 9.6 \) and a dielectric loss tangent \( \tan \delta = 10^{-4} \). The dimensions of the primary IG ensure single mode operation in Ka-band with the mode \( E_{11} \) according to the Marcatili’s mode classification [7]. The secondary ferrite IG represents a bar with dimensions 2.2 mm×1.1 mm×17.6 mm and is made by nickel ferrite (1Cr4, Russia). The ferrite has a relative permittivity \( \varepsilon_r = 11.1 \), a dielectric loss tangent \( \tan \delta = 10^{-2} \) and a saturation magnetization \( 4\pi M_s = 0.463 \) T. The coupling length \( l \) coincides with the length of the ferrite IG and is equal to 17.6 mm.

The distributions of the electric field magnitude in forward and backward direction of propagation at a frequency of 37.7 GHz are shown in Fig. 1 and Fig. 2, respectively. These distributions correspond to insertion losses about –2 dB and isolation equal to –36.7 dB. The ferrite bar has been modelled as homogeneously magnetized along \( Oy \) axis with a field strength \( H = 80 \) kA/m. The values of the electric field magnitude in Fig. 1 and Fig. 2 correspond to the transmitted power of 1 W.

The distributions inside of the dielectric and ferrite bars are shown in Fig. 1a and Fig. 2a, and those in the air box outside of the dielectric and ferrite bars – in Fig. 1b and Fig. 2b. These distributions have revealed a nonreciprocal coupling between dielectric and ferrite image IGs. In forward direction of propagation, the period of power transfer \( L_p \) is four times lesser then coupling length \( l \), \( L_p = l/4 \). In backward direction of propagation, the period of power transfer \( L_b \) is three times lesser then coupling length.
$l, L_B = l/3$. We have established a nonreciprocal behaviour with insertion losses about $-2$ dB and isolation better than $-20$ dB in a bandwidth equal to 1.8 GHz, which represents a very good wideband performance for isolators at millimetre waves.

III. CONSIDERATION OF INHOMOGENEOUS MAGNETIZATION

During the examination [6] of the dependence of nonreciprocity on the coupling length $l$ we have found that the structure with $l = 14$ mm has the closest operation frequency to that in the experimental investigation [4], i.e. it is 3.6 mm shorter than the real coupled structure with $l = 17.6$ mm. We can introduce effective coupling length $l_{eff} = l - \Delta l$ to consider the inhomogeneity of the ferrite bar, namely the fact that its middle part is magnetized predominantly transversely but both its ends – longitudinally. Here $l_{eff}$ coincides with length of 14 mm, $\Delta l$ represents the difference between the real coupling length and that obtained numerically and is equal to 3.6 mm.
We could use the following procedure in the design process of isolators on the basis of CFDIG structures with the help of the numerical method. First, with the use of FEM, we can find the effective length $l_{\text{eff}}$ of CFDIG structure that has the desired operation frequency. Second, we can calculate the correction length $\Delta l = Kd$, where $d$ is the diameter of the disk-shaped permanent magnet, and $K$ is an empirical constant. We propose to calculate the empirical constant $K$ as quotient of the registered length difference $\Delta l = 3.6$ mm and the diameter of the permanent magnet used, $d = 20$ mm, giving a value of $K$ equal to 0.18. Finally, we could calculate the length of the real coupled structure $l = l_{\text{eff}} + \Delta l$. The inhomogeneously magnetised structure of length $l$ must have improved parameters of nonreciprocal operation in comparison with the homogeneously magnetised structure of length $l_{\text{eff}}$, namely a better isolation and a wider bandwidth. We suppose that this improvement of the parameters will take place due to the existing longitudinal components of the magnetization of the ferrite bar.

IV. DEPENDENCE OF THE NONRECIPROCITY ON THE PERMANENT MAGNETIC FIELD STRENGTH

The investigation of the influence of permanent magnetic field strength $H$ on the nonreciprocal behaviour of the CFDIG structure with coupling length $l = 17.6$ mm has begun with an identification of the operating frequency $f_{\text{min}}$ at $H$ values between 40 and 130 kA/m. We have found that permanent magnetic field strength does not influence $f_{\text{min}}$ and it is equal to 37.7 GHz for every value of $H$.

The influence of permanent magnetic field strength on the nonreciprocity is shown in Fig. 3, where losses in forward and backward direction of propagation are given. It is evident that insertion losses $S_{21}$ are almost constant and are equal to about $–2$ dB. The losses in backward direction of propagation $S_{12}$ manifest a well-expressed minimum of $–42$ dB.
dB at 90 kA/m, and remain under the level of −20 dB for every value of $H$. We can conclude that permanent magnetic field strength equal to 80 kA/m, as it was in our numerical investigation [6], is quite reasonable.

![Graph](image)

Fig. 3. Dependences of losses in forward and backward direction of propagation on permanent magnetic field strength.

V. DEPENDENCE OF THE NONRECIROCITY ON FERRITE MATERIAL PARAMETERS

We have investigated the dependence of the nonreciprocity on three ferrite material parameters which take part in FEM modelling – saturation magnetization, relative dielectric permittivity and dielectric loss tangent. The losses in forward and backward direction of propagation in the CFDIG structure of length 17.6 mm at a frequency of 37.7 GHz are presented in Fig. 4.

Fig. 4a illustrates the dependence of losses in forward and backward direction on the saturation magnetization $4\pi M_s$. The losses in forward direction $S_{21}$ are approximately equal to −2 dB. The losses in backward direction $S_{12}$ are under the level of −30 dB at values of $4\pi M_s$ in the range 0.45–0.53 T. It is relevant to note that the available microwave ferrites possess saturation magnetization $4\pi M_s$ that is less than 0.52 T. It is assumed that the increase of the saturation magnetization improves the nonreciprocity of ferrite devices. Here we can see the opposite dependence – values greater than 0.55 T correspond to worse isolation. In conclusion, our choice of ferrite with $4\pi M_s = 0.463$ T is excellent from the point of view of nonreciprocity.

Fig. 4b presents the influence of the relative dielectric permittivity $\varepsilon_r$. It has been varied in the range 10.5–11.7 that represents a deviation of about ±5% from the central value of 11.1. The losses in forward direction $S_{21}$ are equal to −2 dB in the middle of the range and reach −3 dB at its ends. The absolute minimum of $S_{12}$, equal to −36.8 dB, has been observed at $\varepsilon_r = 11.1$. It can be seen from Fig. 4b that strong change of losses $S_{12}$ occurs when $\varepsilon_r$ is moving away from its central value, but losses stay under the level of −20 dB for values of $\varepsilon_r$ from 10.9 to 11.3. When a greater deviation from the central value takes place, the change of $S_{12}$ becomes smoother and keeps the level of −15 dB. We can confirm that the choice of the ferrite material with $\varepsilon_r = 11.1$ is optimal at the given CFDIG configuration.

![Graph](image)

Fig. 4. Dependences of losses in forward and backward direction of propagation on ferrite material parameters: (a) saturation magnetization; (b) relative dielectric permittivity; (c) dielectric loss tangent.

Detailed additional investigation of frequency dependence of losses has been completed at several values of $\varepsilon_r$ and the frequency $f_{\text{min}}$ at which isolation has its absolute minimum has been identified. It has been found that at $\varepsilon_r = 10.5$ the frequency $f_{\text{min}}$ is equal to 36.9 GHz, i.e. it has been shifted by 0.8 GHz downwards. At $\varepsilon_r = 11.7$ the frequency $f_{\text{min}}$ equals 39 GHz, i.e. it has been shifted by 1.3 GHz upwards.

When a greater deviation of relative dielectric permittivity $\varepsilon_r$ takes place, we can see more serious changes in the operation of the nonreciprocal structure. For instance, at $\varepsilon_r = 8$ we have observed an interchange of the directions of propagation – $S_{12}$ represents insertion losses and $S_{21}$ represents isolation. The frequency $f_{\text{min}}$ of minimal isolation in this case is equal to 37 GHz. The investigation of the influence of the ferrite relative dielectric permittivity $\varepsilon_r$ has shown that the knowledge of its exact value is of primary
importance to the design process of nonreciprocal devices on the basis of coupled dielectric and ferrite image guides.

Fig. 4c presents the dependence of losses $S_{21}$ and $S_{12}$ on the dielectric loss tangent $\tan \delta_d$. It has been varied from 0.001 to 0.5. As could be expected, the increase of $\tan \delta_d$ leads to greater insertion losses $S_{21}$, but $\tan \delta_d$ also influences the isolation $S_{12}$. The isolation $S_{12}$ varies between $-36.8$ dB and $-7.62$ dB and has its minimum at $\tan \delta_d = 0.01$ that coincides with the dielectric loss tangent of the ferrite used by us. This fact confirms again the appropriateness of our ferrite material choice.

VI. Conclusion

The numerical investigation of coupled ferrite-dielectric image guide structure presented here completes our previous experimental and numerical investigations. It improves understanding of nonreciprocal operation of the structure.

The distributions of the electric field magnitude in forward and backward direction of propagation have been obtained with the use of finite element method. They correlate with the nonreciprocal behaviour of the structure under investigation. The period of power transfer in both directions of propagation has been stated. Procedure for designing isolators with inhomogeneous magnetization on the basis of the coupled ferrite and dielectric image guides has been proposed.

We have investigated the influence of permanent magnetic field strength and three ferrite material parameters on the nonreciprocal behaviour of the coupled ferrite-dielectric image guide structure. The results have confirmed the suitability of our choice of the permanent magnetic field strength and the ferrite material as well.

References


Iliyana Arestova was born in Pernik, Bulgaria. She received her M.Sc. in Radiophysics and Electronics from St. Kliment Ohridski University of Sofia, Sofia, Bulgaria (1987). She has been at the Department of Radiophysics and Electronics, Faculty of Physics, St. Kliment Ohridski University of Sofia, Sofia, Bulgaria since 1996. Until the year 2016 she worked as assistant professor. She is author of tutorials for practical work on Basic Electronics, Oscillations and Waves, Radiation and Propagation of Electromagnetic Waves. She has been working on her Ph.D. Her research interests include ferrite devices for millimetre waves and antennas.