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An Experimental Investigation of Coupled Ferrite and Dielectric Image Guides

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Abstract. This experimental investigation of coupled ferrite (hexaferrite) and dielectric image guides (IG) represents a measurement of the electric field components. The measurement has been performed using electric probes. Two different cases of transverse magnetization of the ferrite IG in respect to the ground plane – parallel (Case 1) and normal (Case 2), have been investigated.

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1 Introduction

The coupled ferrite-dielectric structures are an alternative solution for the design of nonreciprocal devices such as isolators and circulators for millimetre waves where traditional (conventional) approaches are accompanied by difficulties [1–3]. The image guide (IG) is considered as a possible base for their design [1, 2]. The nonreciprocal effects in coupled ferrite-dielectric structures are present at all directions of magnetization of the ferrite element – longitudinal (parallel to the direction of propagation), transverse (parallel and perpendicular to the ground plane), and mixed one.

In practice it is impossible to ensure homogeneous magnetization of the ferrite sample. Usually its magnetization is obtained by using a permanent magnet with a cylindrical geometry. Because of the comparable sizes of the magnet and the ferrite sample, the magnetization of the ferrite sample is inhomogeneous and mixed as it contains both transverse and longitudinal components in respect to the direction of propagation [2].

In order to clarify the process of coupling between dielectric and ferrite IGs and its dependence on the direction of magnetization, the present experimental study is using a hexaferrite with its own field of anisotropy, instead of an ordinary microwave ferrite, which allows to avoid an external system of magnetization. With the aid of an electric probe [4, 5] the distributions of the three components of the electric field have been studied in two cases of magnetization of the ferrite (hexaferrite) sample. In the first case, the magnetization is perpendicular to the direction of propagation and parallel to the ground plane. In the latter case, the magnetization is perpendicular to both the direction of propagation and ground plane.

2 Description of the Coupled Structure

The configuration of the structure under investigation is shown in Figure 1. It comprises a dielectric core *1* stuck on a metal base *5*. The dielectric core *1* at both ends is included in transitions to a standard metal rectangular waveguide (SMRW) *3*, and constitutes the primary waveguide in the coupled structure (Figure 1a). The entire length of the structure is 80 mm together with both transitions, each with a length of 15 mm. Transitions *3* are obtained by symmetrical tapering of the dielectric core *1* in H-plane and by putting each of the ends in the U-shaped metal body containing a channel with the size of the SMRW. Absorber plates *4* are added to reduce reflections. They have a thickness of about 2.5 mm and the same cross-section as the U-shaped metal body. The length of the coupled region is l and the distance between primary and secondary IGs is d.

The cross-section of the coupled IG structure is shown in Figure 1b. The primary IG made from alumina (Al_2O_3) with dielectric parameters $\epsilon_r = 9.6$ and $\tan\delta_\epsilon = 1\times10^{-4}$ has dimensions $a = 2$ mm and $b = 0.97$ mm. The secondary IG is made from barium hexaferrite ($BaO.6Fe_2O_3$) with a partial substitution of ions of trivalent iron with ions of chromium. The

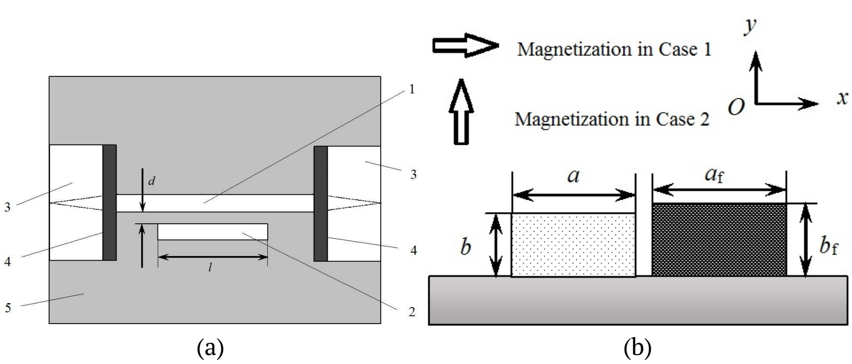


Figure 1: Configuration of the ferrite-dielectric structure: (a) top view; (b) cross section. *1* – primary IG; *2* – secondary IG; *3* – SMRW-IG transition; *4* – absorbing plates; *5* – metal plate.

parameters of the hexaferrite are $\epsilon_r = 14.7$ and $\tan\delta_\epsilon = 9 \times 10^{-4}$. The two different directions of magnetization in both cases are shown in Figure 1b. The effective field of anisotropy in the first case of magnetization is $H_A = 100$ Oe, and in the second case it is $H_A = 350$ Oe. No additional external magnetization has been used.

3 Experimental Setup

The experimental setup is shown in Figure 2. The scalar network analyzer *1* works in the Ka-band (26.5 to 40 GHz) and includes components on the basis of the SMRW with a cross-section of 7.2×3.4 mm^2. The generator *2* can operate both in a swept and in a fixed frequency mode. The directional couplers *4* combined with the built-in detectors *5* allow a separation of the incident wave and the transmitted wave to and out of the structure under investigation *6*. The structure under investigation *6* is arranged between the two directional couplers *4*, as shown in Figure 2. After observation of the losses in the whole frequency range, the frequency can be fixed and the measurements with the electric probe *7* can be performed. The electric probe is connected to waveguide detector *8* and microvoltmeter *9*. Details about the electric probes can be found in Ref. 5. The height of the probe is maintained equal to 0.5 mm at all measurements which is large enough not to disturb the field in the investigated structure, and small enough to allow the use of indicator *9*.

The electrical probe has been mounted on a flexible mechanism that allows positioning with an accuracy of 0.05 mm along the longitudinal axis O_z and accuracy 0.01 mm along the transverse axes O_x and O_y. As outlined in Ref. 5, due to its finite dimensions, each electric probe performs averaging along its length. The electric probe for the E_y component aver-

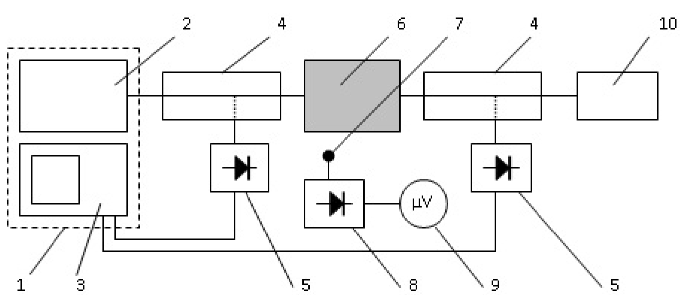


Figure 2: Experimental setup: *1* – scalar network analyzer; *2* – generator; *3* – indicator; *4* – directional couplers; *5* – detectors; *6* – structure under investigation; *7* – electric probe; *8* – detector; *9* – microvoltmeter; *10* – matched load.

ages the electric field along the height above the cores (axis O_y), and the probe for the E_x and E_z components along the axes O_x and O_z, respectively. Since the latter probe contains a bent to $90°$, it is more imperfect than the electric probe for the E_y component and works adequately when the components E_x and E_z are comparable to the E_y component.

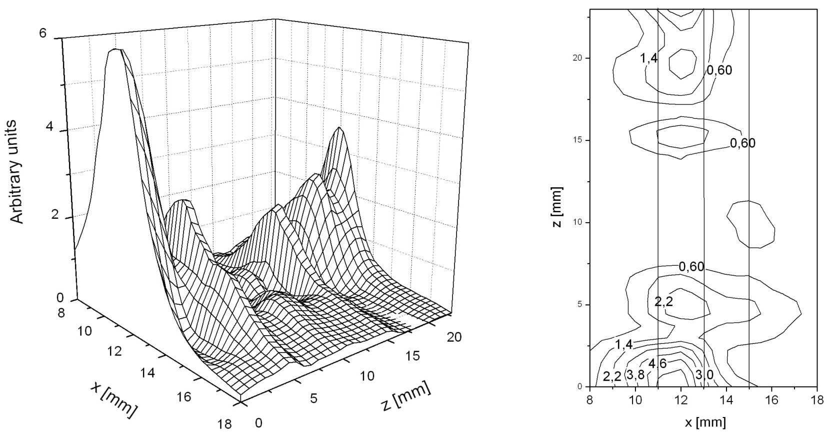
4 Results

In the first case of magnetization in the direction of the axis O_x (Case 1) the dimensions of the cross-section of the secondary IG made of hexaferrite are $a_f = 2$ mm, $b_f = 1.1$ mm, and the parameters of the coupled structure are $d = 0$ mm, $l = 23.1$ mm. The comparison of losses in forward and backward direction in a wide frequency range showed that the structure can be considered reciprocal. The observed differences of 1–2 dB can be attributed both to measurement error and the asymmetry in the structure.

Figures 3–5 present the obtained distributions of the components of the electric field for the first case of the magnetization at a frequency of 31.9 GHz, at which the losses are relatively low, equal to -2.5 dB. The values set in arbitrary units anywhere in Figures 3–5 (and in Figures 6–8) are proportional to the square of the respective components of the electric field, which results from the used square-law detector *8* (Figure 2). The component E_y is shown in Figures 3a and 3b, while the components E_x and E_z in Figures 4a and 4b and Figures 5a and 5b, respectively. The component E_y (Figures 3a and 3b) has the highest values at both the beginning and the end of the coupled structure in the area of the primary IG, which corresponds to a propagation of the mode E^y_{11} in the primary IG. (The mode E^y_{11} has a main component E_y. We use the terminology and designation of the modes according to the classification established by Marcatili [6]).

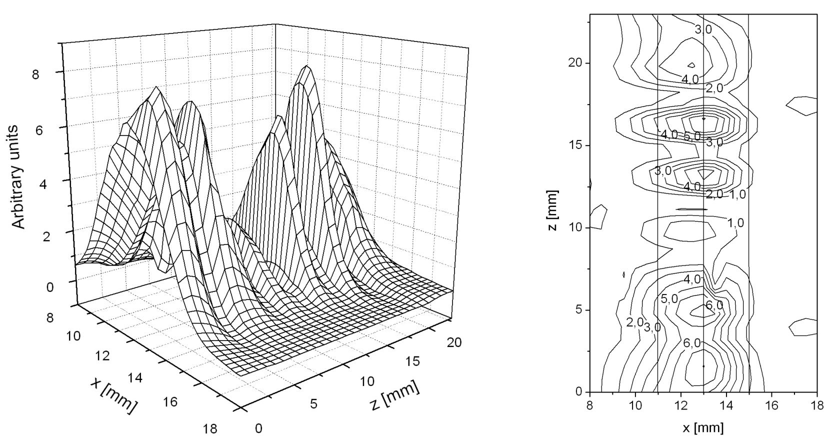
The component E_x (Figures 4a and 4b) has a significant value in the whole coupled region and its maximum is located on the ferrite-dielectric border. In the middle of the coupled structure three increasing maxima of the component E_x are distinctly observed, which means that there is an effective coupling between the modes with main components E_y and E_x. This effectiveness is mainly due to the fact that the secondary IG is tightly connected to the primary IG ($d = 0mm$). The component E_z (Figures 5a and 5b) has significantly lower values compared to the E_x component, with the greatest values being in the end of the coupled structure. This may be due to reflections from the IG-SMRW transition, as well as to the irregularities in which radiation inevitably exists.

In the latter case of magnetization in the direction of the axis O_y (Case 2), the dimensions of the cross section of the secondary IG made of hexa-



(a) (b)

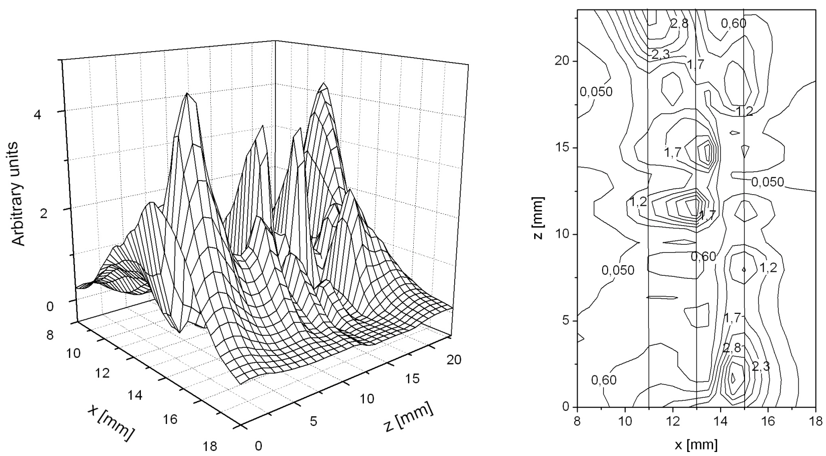
Figure 3: Distribution of the electric field component E_y for Case 1.



(a) (b)

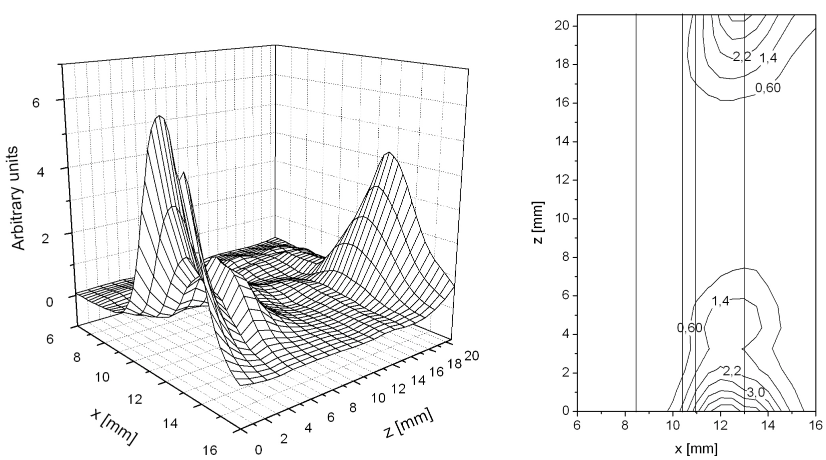
Figure 4: Distribution of the electric field component E_x for Case 1.

ferrite are $a_f = 2mm$, $b_f = 1mm$, and the parameters of the coupled structure are $d = 0.5mm$, $l = 20.8mm$. The study of the losses in forward and backward direction in a wide frequency range showed that this structure can also be considered reciprocal. Figures 6-8 present the obtained distributions of the components of the electric field for the second case of magnetization at a frequency of $33GHz$, at which the losses are equal to $-4dB$. In this case the secondary IG is situated to the left of the primary IG (in Figure 1b it is to the right). The component E_y is shown in



(a) (b)

Figure 5: Distribution of the electric field component E_z for Case 1.

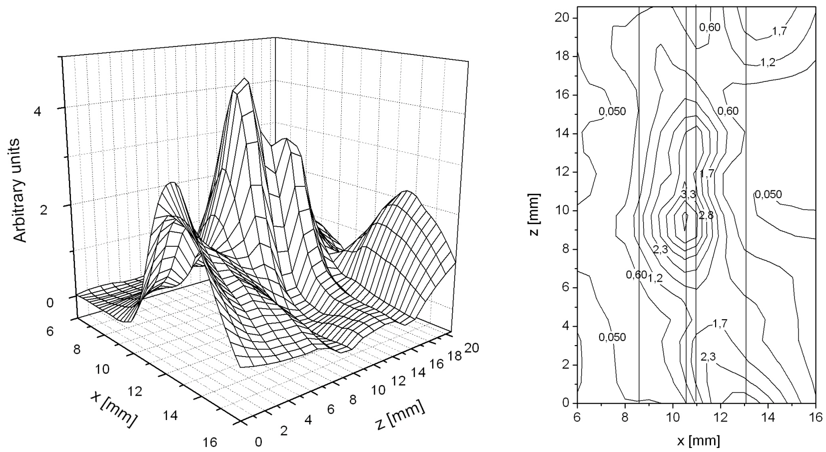


(a) (b)

Figure 6: Distribution of the electric field component E_y for Case 2.

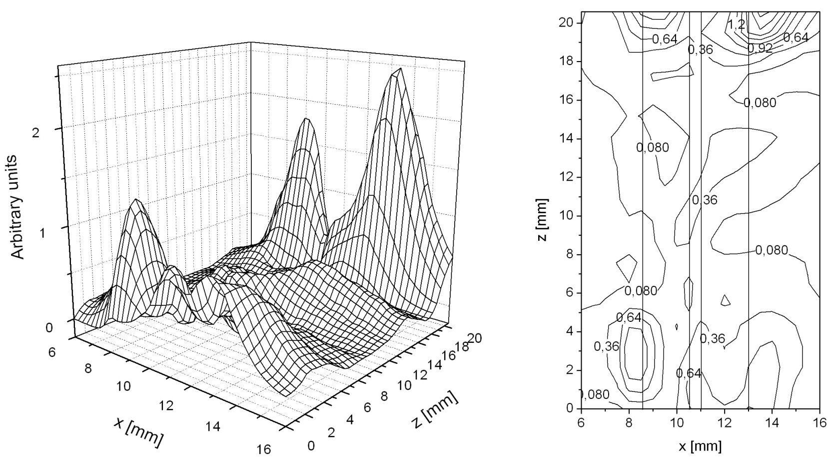
Figures 6a and 6b, and the components E_x and E_z in Figures 7a and 7b and Figures 8a and 8b, respectively. The distribution of component E_y (Figures 6a and 6b) does not substantially differ from the one observed in the first case discussed above.

The larger distance between the primary and secondary IG in the second case ($d = 0.5$ mm) results in a weaker coupling between them. As a result, the measured values of the component E_x (Figures 7a and 7b) are lower



(a) (b)

Figure 7: Distribution of the electric field component E_x for Case 2.



(a) (b)

Figure 8: Distribution of the electric field component E_z for Case 2.

than those in the first case (Figures 4a and 4b). In the middle of the coupled region ($z = 10$ mm) is observed one wide maximum shifted towards the ferrite IG. The component E_z (Figures 8a and 8b) takes smaller values than those in the first case (Figures 5a and 5b), and again it is greatest at the end of the coupled structure. The reason for this should be sought again in the inevitably existing reflections and radiation from irregularities. The comparison between the distributions of the component E_z in both cases indicates that this component has a more significant place in the first case of magnetization.

The accomplishment of a nonreciprocal effect in coupled ferrite-dielectric structures with transverse magnetization obviously requires a reconfiguration of the structure in the direction of its complexity. According to Ref. 7, the introduction of second ferrite-dielectric boundary could lead to a nonreciprocal effect, which could be used for the design of nonreciprocal devices.

5 Conclusions

These results confirm the effectiveness of the method of electric probe for testing of open structures, in particular coupled ferrite and dielectric waveguides. They show that at homogeneous magnetization of the secondary ferrite (hexaferrite) IG in a direction transverse to the direction of propagation, the structure can be considered reciprocal. The results of the electric probe measurements are believed to contribute to the design of nonreciprocal components for millimeter wavelengths due to the information obtained about existing electric field components. The ongoing computer simulation using 3D electromagnetic simulator should complement this research.

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