Three-strip ferrite circulator design based on Coupled Mode Method

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1. Introduction

Nowadays, microwave integrated systems include nonreciprocal structures such as circulators, isolators, phase shifters, operating over a broad frequency band. Recently, axially magnetized microstrip or slot ferrite coupled line sections have been developed and employed to realize integrated nonreciprocal devices [1–4]. The advantage of this class of the devices is a weak magnetic field required for Faraday’s effect [5] defining their nonreciprocal operation. The potential drawbacks of these structures are high insertion losses associated with a ferrite slab, which is often several wavelengths long.

Recent research of the ferrite coupled line devices is focused on improvement of their parameters such as insertion losses and isolation. These devices are realized in finline [1], slotline [2] or microstrip [3] technology. Also, the investigations aimed at searching for new structures of ferrite coupled lines are conducted [4]. In this paper a new configuration of the ferrite coupled line section consisting of three strips is presented. The coupled mode method was used to determine the propagation coefficients in the ferrite section. To evaluate scattering matrix of the ferrite coupled line junction the mode matching method was utilized. With the use of the S-matrix the performance of the circulator was predicted and verified via experiment. A good agreement between simulation end measurement was achieved.

2. Analysis of ferrite coupled line junction

In this paper the structure consisting of coplanar three strips placed on longitudinally magnetized ferrite substrate is analyzed (see Figure 1). The coupled mode method was used to determine the propagation coefficients of the ferrite structure. In this method [5], we first analyze problem of isotropic guide (named "basis" guide) defined by replacing ferrite with dielectric material described by $\mu_r = 1$ and $\varepsilon_r = \varepsilon_f$ (Figure 1b).

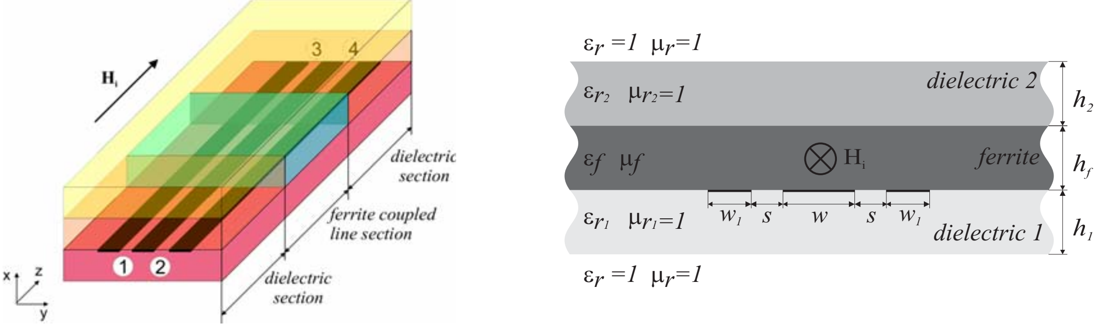

Figure 1: Analyzed structure: a) general view, b) cross section - parameters of the structure: ε_{r1}=2.2, ε_f=13.3, ε_{r2}=9.6, Ms=239kA/m, w_1=w=0.4, s=0.3, h_1=h_2=0.508, h_f=0.5; dimensions in (mm)

In the CMM the transversal fields $\mathbf{E}_t$, $\mathbf{H}_t$ in the investigated guide are expressed in terms of basis guide field eigenfunctions $\mathbf{e}_{ti}$, $\mathbf{h}_{ti}$. Using spectral domain approach we find the phase coefficient β_n and fields distributions for the fundamental modes in the basis structure. The Maxwell's equations for the basis and investigated guides are combined together and after some mathematical manipulations we obtain the following set of coupled mode equations:

$$\frac{\partial U_n}{\partial z} + j\beta_n Z_n I_n = -\sum_m I_m C_{mn}, \qquad \frac{\partial I_n}{\partial z} + j\beta_n \frac{1}{Z_n} U_n = 0, \tag{1}$$

where C_{mn} is defined as follows

$$C_{mn} = k_0 \eta_0 \mu_a \int_{\Omega_f} \left(\vec{h}_{tm} \times \vec{h}_{tn}^{*}\right) \cdot \vec{i}_z \, d\Omega_f \tag{2}$$

and describes the coupling between m-th and n-th isotropic modes and Ω_f is a ferrite area in the cross section, U_n and I_n are z dependent current and voltage functions and Z_n is wave impedance of n-th isotropic mode. Taking into consideration the fields distributions of the basis modes $\mathbf{H}_{tm}$, $\mathbf{H}_{tn}$ instead of their eigenfunctions $\mathbf{h}_{tm}$, $\mathbf{h}_{tn}$ we can formulate:

$$C_{mn} = k_0 \eta_0 \mu_a \frac{\sqrt{Z_m Z_n}}{\sqrt{P_m P_n}} \int_{\Omega_f} \left(\vec{H}_{tm} \times \vec{H}_{tn}^{*}\right) \cdot \vec{i}_z \, d\Omega_f . \tag{3}$$

This formula indicates that the gyromagnetic coupling occurs in the line when the ferrite is located in the area where the magnetic fields vectors of basis isotropic modes are orthogonal. Using (1) and considering two fundamental modes in the basis guide (β_1, β_2) we can derive the propagation constants of two waves guided in the ferrite structure:

$$k_{1,2} = \pm \sqrt{\frac{\beta_1^2 + \beta_2^2}{2} \pm \sqrt{\left(\frac{\beta_1^2 - \beta_2^2}{2}\right)^2 + \frac{C_{12}^2}{Z_1 Z_2} \beta_1 \beta_2}} . \tag{4}$$

Using these propagation coefficients the fields distributions of two fundamental modes of the ferrite structure are obtained.

Next, the scattering matrix of the ferrite coupled line junction is determined using mode matching method [6,7]. To solve the problem the continuity conditions for the tangential field components at the two interfaces between dielectrics and ferrite sections (see Figure 1) are solved using mode matching method. To expand the transverse electromagnetic fields in the dielectric sections the even and odd dominant isotropic modes are used. The transverse electromagnetic fields in the ferrite section are expanded by two forward and backward going dominant ferrite modes obtained from coupled mode method. The scattering matrix, including the response of input even and odd isotropic modes, is formulated. Next, the even-odd S-matrix is rearranged in terms of the port waves using the symmetry of isotropic waves, and in this way the complete scattering matrix of the FCL junction is obtained.

In the design the structure described with parameters reported in Figure 1 is used. The scattering matrix versus length of the ferrite at centre frequency f_0=13GHz is presented in Figure 2a. As one can see the length L=26mm of the ferrite ensures equal output signals at ports (3) and (4) when port (1) is excited. Simulated frequency response of the ferrite coupled line junction with the ferrite of the length L=26mm in Figure 2b is presented. The insertion losses are about -3dB±0.5dB, the reflection losses and isolation are better than -15 dB in the frequency range from 11.5GHz to 15GHz.

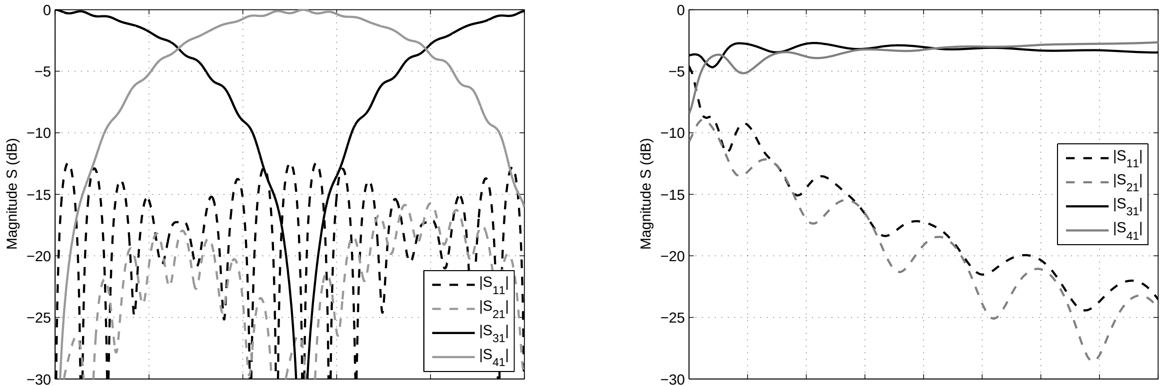

Figure 2: Predicted scattering matrix of the ferrite coupled line junction: a) versus length of the ferrite at f_0=13GHz, b) versus frequency for the length of the ferrite L=26mm

3. Coplanar three-strip circulator

In this section we present a prototype of the FCL circulator using three-strip coupled line junction. The FCL circulator is designed by cascading the ferrite coupled line junction with T-junction. This T-junction ensures even (or odd) excitation of the ferrite section. In Figure 3 the predicted response of the designed FCL junction cascaded with ideal T-junction is shown. As one can see average isolations and reflection losses are about -10dB and insertion losses not exceed -1dB near the designed operation frequency f_0 =13GHz.

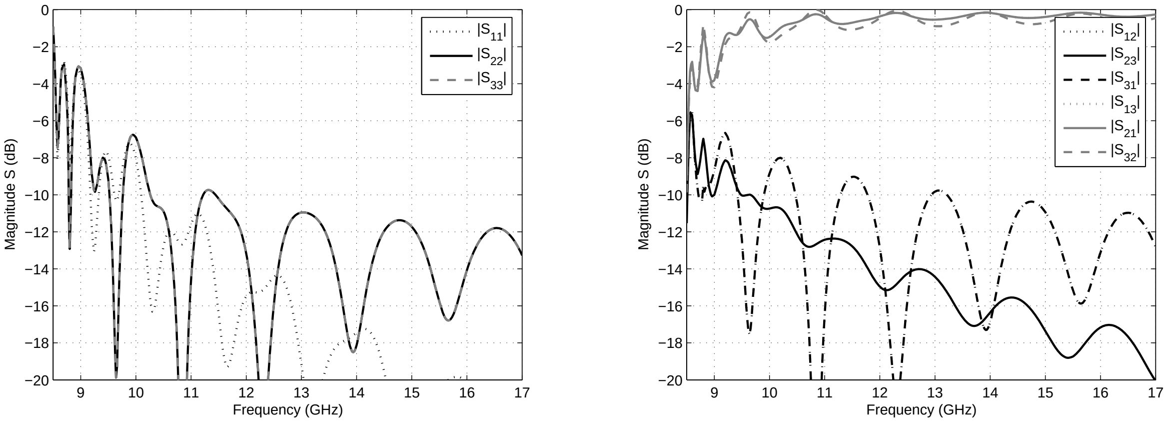

Figure 3: Predicted scattering matrix of the ferrite coupled line circulator: a) reflection losses, b) insertion losses and isolations

A photograph of the fabricated structure is presented in Figure 4. Impedances at all ports are assumed to be matched to 50Ω microwave connector. It is assumed that the middle strip was a signal one, while the side strips were connected to the ground. In the experiment even excitation was realized directly from three-strip line (port (1) in Figure 4). Substantial dimensions of the used connector caused the necessity of increasing the width of the strips and their spacing.

In the output of FCL, the coplanar three-strip structure was divided into two symmetric two-strip lines representing ports (2) and (3).

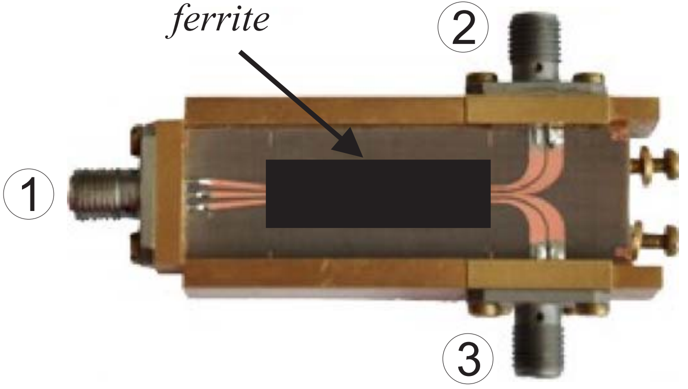

Figure 4: Photograph of the realized structure

The manufactured circuit was magnetized by a set of magnets that produce desired magnetization for ferrite samples. The device was measured using a 37267 Wiltron network analyzer and the results are depicted in Figure 5. As one can see average insertion losses are about -2.5dB and isolation about -12dB in the frequency band 9.8-13.8GHz. In this frequency range reflection losses at port (2) and (3) are better than -12dB, but at port (1) reflection losses are better than -12dB only from 11.3-13.3GHz. This may by the effect of the parasitic capacitances produced during soldering of the connector. The impedance of this kind of lines (edge coupled lines) is strongly dependent on the thickness of the metallization.

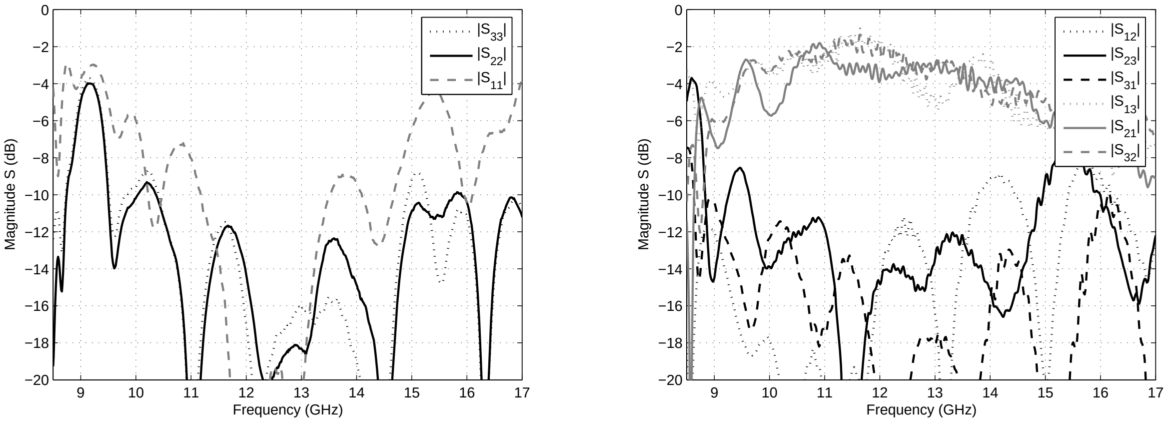

Figure 5: Measured scattering matrix of the ferrite coupled line circulator: a) reflection losses, b) insertion losses and isolations

4. Conclusion

A 3-port circulator realized in three strip coplanar line technology was designed. Coupled mode method and mode matching method are used to determine the propagation coefficients in the ferrite section and scattering matrix of ferrite coupled line junction, respectively. Predicted performance of the circulator was verified via experiment. Measured average insertion losses of the circulator are about -2.5dB and isolations are about -12dB in the frequency band 9.8-13.8GHz. This clearly show nonreciprocal behaviour of the designed device. Further work should be focused on the improvement of the parameters of ferrite coupled line junction and T-junction.

Acknowledgments

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