Millimeter-Wave Four-Port Circulator Using Distributed Coupling Effect

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Abstract—**The design and experimental results for a four port circulator based on new concept using a distributed coupling phenomenon are presented. The circulator consists of a *E–H* junction cascaded with the section of two coupled lines containing ferrite magnetized in the propagation direction. The choice of configuration and the design procedure are described. Isolation 15 dB in the 26–30 GHz band is obtained confirming the validity of the theory and design procedure.**

I. Introduction

In recent years, novel nonreciprocal devices, whose construction was based on coupled guides with longitudinally magnetized ferrite slab placed between them, have been presented in literature [1], [2]. Since the operating principle of these devices was not clear and the design procedures were not known, we have proposed [4], [5] the mathematical model of the phenomena occurring in two coupled guides containing longitudinally magnetized ferrite and suggested several new configurations. We also derived the conditions for the nonreciprocity of the structure. In this letter, we use the concepts presented in [4] to design a four port circulator.

II. Operating Principle

Before presenting the design of a four-port circulator, we shall briefly recall the key points of the theory presented in [3], [4]. Using the coupled mode method we have shown [4] that the scattering matrix of section of coupled ferrite lines (CFL) magnetized in the propagation direction is given by

$$S = \begin{bmatrix} 0 & 0 & s_1 & -s_2^* \\ 0 & 0 & s_2 & s_1 \\ s_1 & -s_2^* & 0 & 0 \\ s_2 & s_1 & 0 & 0 \end{bmatrix} e^{j\beta_0 z} \tag{1}$$

with

$$s_1 = \cos(\Gamma z) \qquad s_2 = \frac{\pm|C| - j\Delta\beta}{\Gamma}\sin(\Gamma z)$$

and

$$\beta_0 = \frac{\beta^e + \beta^o}{2}, \quad \Gamma = \sqrt{\Delta\beta^2 + |C|^2}, \quad \Delta\beta = \frac{\beta^e - \beta^o}{2}.$$

In these expressions, the choice of the sign for $|C|$ depends on the magnetization direction, superscripts e and o refer to the even and odd mode supported by the basis guide (i.e., the structure in which ferrite is replaced with an isotropic material having identical permittivity), β stands for the propagation constant and C is the coupling coefficient given by

$$C = \frac{1}{2} k_o \eta_o \mu_a \int_{\Omega_o} \left(H_x^{e*} H_y^o - H_y^{e*} H_x^o\right) d\Omega_o, \tag{2}$$

where Ω_o is the cross-section of the ferrite slab, H is the magnetic field in the basis guide, k_o and η_o is the wavenumber and intrinsic impedance of the free space, respectively, and μ_a stands for the off diagonal element of the permeability tensor.

A section of CFL itself does not exhibit any nonreciprocity other than a nonreciprocal phase shift. It can be shown [4], however, that nonreciprocity is obtained in a cascade consisting of a lossless reciprocal four port and a section of CFL. Maximal nonreciprocity is achieved when the ferrite section is excited either in phase or 180° out of phase. One possible configuration ensuring the proper excitation is a cascade of a hybrid *T*-junction and a section of CFL. The scattering matrix of the cascade is (factor $e^{j\beta_0 z}$ suppressed)

$$S_K = \frac{1}{\sqrt{2}} \begin{bmatrix} 0 & 0 & s_1 + s_2 & s_1 - s_2^* \\ 0 & 0 & s_1 - s_2 & -(s_1 + s_2^*) \\ s_1 - s_2^* & s_1 + s_2^* & 0 & 0 \\ s_1 + s_2 & s_2 - s_1 & 0 & 0 \end{bmatrix}. \tag{3}$$

Ideal nonreciprocal action requires

$$\Delta\beta = 0 \quad \text{and} \quad Cz = \frac{\pi}{4} + \frac{n\pi}{2}, \tag{5}$$

where n is an integer. For $\Delta\beta = 0$ and $Cz = \pi/4$ it yields

$$S_K = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \\ 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{bmatrix}. \tag{6}$$

We have obtained the scattering matrix of an ideal four port circulator with the transmission 1–4–2–3–1. Reversing the magnetization direction we get

$$S_K = \begin{bmatrix} 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \end{bmatrix}. \tag{7}$$

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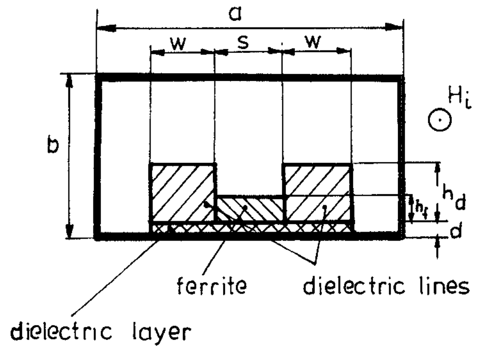

Fig. 1. Cross section of the coupled line section. Dimensions in millimeters are $w = s = 3$, $h_d = 2$, $h_f = 1$, $a = 14.9$, $b = 3.55$, d varies. The permittivities are lateral guides $\epsilon_g = 4$, ferrite slab $\epsilon_f = 13.5$, separating bottom layer $\epsilon_l = 2.4$.

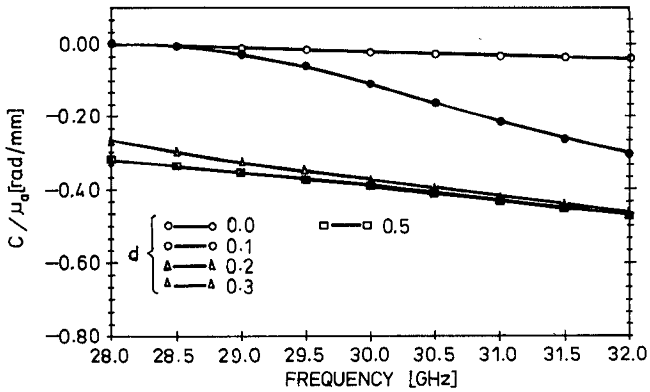

Fig. 3. Normalized coupling coefficient for the structure of coupled ferrite lines shown in Fig. 1.

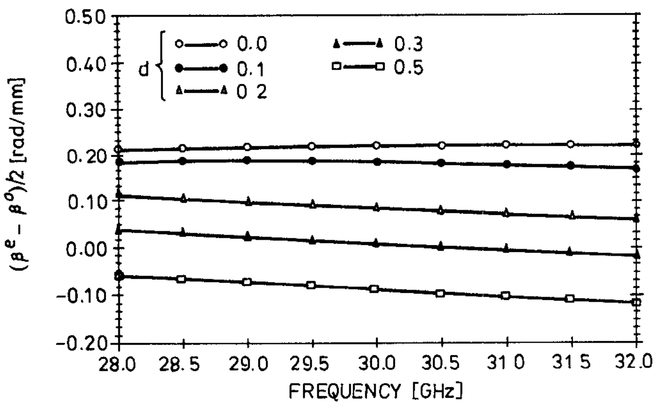

Fig. 2. Propagation constant difference for basis even and odd modes in the basis guide obtained from the structure shown in Fig. 1.

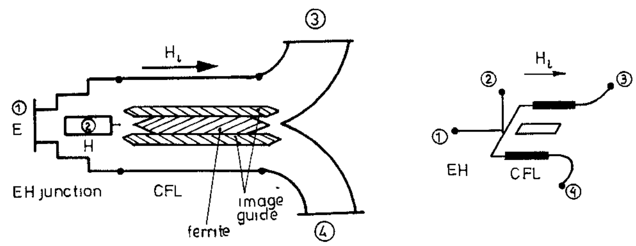

Fig. 4. Plan view of the prototype circulator.

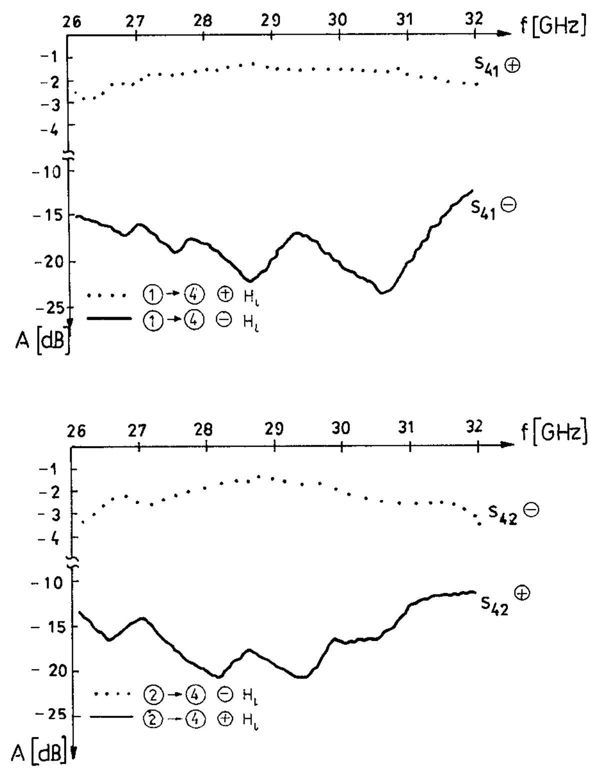

Fig. 5. Transmission characteristics for the prototype four-port circulator consisting of the cascaded hybrid T-junction and a section of CFL shown in Fig. 1. Sign corresponds to the magnetization direction. (a) Excitation in port 1. (b) Excitation in port 2.

III. Design Procedure

For the realization of the four-port circulation, we have chosen the cascade of a hybrid T-junction and a section two parallel dielectric image guides coupled by a ferritė slab. Because the E-H junctions ensures the even and odd mode excitation of the ferrite section, the goal in the design is to compute the parameters of the image guide section that result in the optimal operating conditions (5). Using the rigorous IEEM method [5], [6] we have computed $\Delta\beta$ and C/μ_a for the structure whose cross section is given in Fig. 1. The results are shown in Figs. 2 and 3. We have noticed that by separating the ferrite slab from waveguide broader wall with the thin low-permittivity layer we may control both $\Delta\beta$ and C. The equalization of propagation constants for basis modes occurred for $d = 0.3$ mm at $f \approx 30.25$ GHz. For the saturated ($H_i = 0$), LiZn ferrite with saturation magnetization $M_s = 340$ kA/m, the coupling coefficient C at that frequency is $C = 0.13$–0.15 rad/mm for $d = 0.1$–0.3 mm. Assuming that $n = 2$ we obtain from (5) the length L of the ferrite slab:

$$L = 30.2 \text{ mm}, \qquad \text{for } C = 0.13 \text{ rad/mm},$$
$$L = 26.17 \text{ mm}, \qquad \text{for } C = 0.15 \text{ rad/mm}.$$

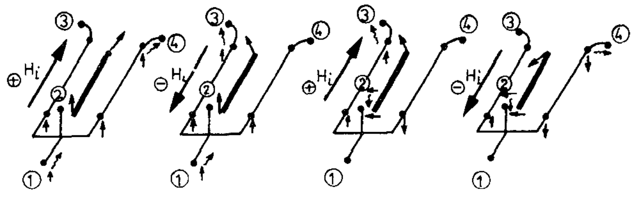

Fig. 6. Operation of an ideal four port circulator consisting of the cascaded hybrid *T*-junction and a section of CFL as predicted in [3], [4] using the Faraday rotation model.

IV. Experiment

Based on the calculations in this letter, we have constructed a prototype circulator shown in Fig. 4. A tapered ferrite slab with length $L = 30$ mm was positioned between tapered dielectric image guides and separated from the waveguide broader wall by a thin $d = 0.2$-mm teflon layer. The longitudinal bias field was obtained with a selenoid.

Fig. 5 shows the transmission characteristics of the prototype. For comparison, Fig. 6 shows the operation of the ideal circulator predicted using the Faraday rotation model explained in [3], [4]. By changing the excitation from port 1 to port 2, we change the excitation of CFL from the even to the odd one. The transmission to the same port is possible only if the bias field is reversed. This property is clearly seen in the measured characteristics where both excitation port and bias direction were changed during the experiment.

The characteristics in Fig. 5 show that the prototype has the isolation better than 15 dB (22 dB maximum) in 16% band the insertion loss better than 3 dB. At this stage of our work, no attempt was made to optimize the design. This is because that the theory behind the operation was derived under a few simplifying assumptions. For instance only two basis modes were considered and the effect of waves travelling in the reverse direction was neglected. The design proves however the validity of the theory presented in [3], [4] and shows that further work is needed to allow one to design optimal structures.

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