# Nonreciprocal Operation of Structures Comprising a Section of Coupled Ferrite Lines with Longitudinal Magnetization

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*Abstract* —Nonreciprocal devices based on a section of two coupled lines containing ferrite magnetized in the propagation direction are investigated. The necessary conditions for nonreciprocal operation are derived. Several new configurations are proposed and their scattering matrices are given. An explanation of the action of experimental devices constructed by other researchers is proposed and substantiated by a numerical investigation of their simplified models under nonideal operating conditions.

## I. Introduction

THE DEVELOPMENT of nonreciprocal devices for millimeter-wave frequencies is inhibited by the fact that traditional structures operating with transverse magnetization require a strong biasing magnetic field and the application of hexagonal ferrites. These problems can be avoided if ferrites with longitudinal magnetization are used. In this configuration, due to the small demagnetization factor, a gyromagnetic material can be easily saturated with a weak biasing field, and conventional lithium or YIG ferrites can be used. Recently, several papers have been published [1], [2] reporting the promising results of the experimental study of novel nonreciprocal devices whose construction is based on coupled guides with a longitudinally magnetized ferrite slab placed between them. The results of measurements proved the feasibility of isolators and four-port circulators in finline and image guide technology. Since the operating principle of these devices is not clear [3], we proposed [4] a mathematical model of the phenomena occurring in two coupled guides containing longitudinally magnetized ferrite.

In this paper we developed the theory presented in [4], giving an explanation of the operation of all nonreciprocal structures investigated experimentally by other researchers [1], [2] and proposing several new configurations. We also derive the conditions for the nonreciprocity of the structure and investigate the behavior of various configurations under nonideal operating conditions.

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## II. Scattering Matrix of a Section of Coupled Ferrite Lines

The nonreciprocal properties of microwave devices can best be studied in terms of a scattering matrix. According to the established nomenclature [10], [11] a device is called nonreciprocal if the elements of its scattering matrix satisfy the condition

$$s_{ik} \neq s_{ki}. \tag{1}$$

This definition, however, does not allow one to distinguish between such structures as circulators or isolators in which the nonreciprocity leads to the difference in power transmitted from port $k$ to $i$ and $i$ to $k$ and structures in which the only nonreciprocal effect is the nonreciprocal phase shift, e.g. a gyrator. Since in this paper we are mainly interested in structures of the first type, we shall modify the established definition and reserve the term *nonreciprocal* for devices which satisfy the relation

$$|s_{ik}| \neq |s_{ki}|. \tag{2}$$

The structures which do not satisfy the above condition and yet are nonreciprocal in the sense of definition (1) may be referred to as phase-nonreciprocal structures.

All experimental devices investigated in [1] and [2] comprised a section of coupled ferrite lines (CFL's) magnetized in the propagation direction. In order to derive the scattering matrix of CFL's we have to find expressions for the electromagnetic field in each guide. Since the problem of electromagnetic wave propagation in the $z$ direction in a structure of two coupled symmetrical guides filled with longitudinally magnetized gyromagnetic medium (Fig. 1) was investigated in detail in [4], we will summarize only the results of the analysis.

The solution to the problem can be found using the coupled mode method [5], [6]. According to this procedure the fields in the analyzed guide are expressed in terms of the fields of a second, basis guide whose modal solutions are known. In our case the basis guide is filled with isotropic gyromagnetic material and is otherwise identical to the investigated structure. Assuming that only two fundamental modes of the basis structure, namely the even

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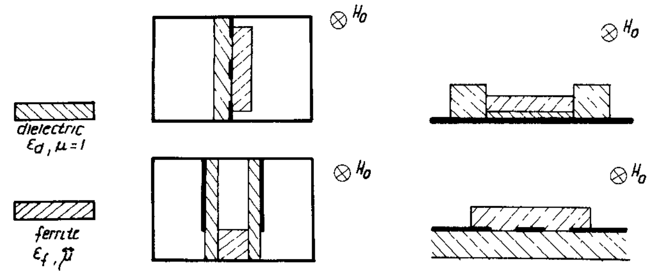


Fig. 1. Examples of coupled guides containing ferrite slabs magnetized in the propagation direction.

and the odd, are taken into account in the field expansion, we obtain, for the weakly magnetized ferrite, the following expressions for the fields in each line constituting the guide:

$$e^{(1)} = E\cos(\Gamma z)e^{-j\beta_0 z}$$

$$e^{(2)} = E\frac{\mp|C| - j\Delta\beta}{\Gamma}\sin(\Gamma z)e^{-j\beta_0 z} \tag{3}$$

with

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

In the above expressions the choice of sign in the double sign depends on the magnetization direction, the superscripts $e$ and $o$ refer to the even and the odd mode supported by the basis guide, and $\beta$ stands for the propagation constant. $C$ is the coupling coefficient:

$$C = \frac{1}{2}k_0\eta_0\mu_a\int_{\Omega_0}\left(H_x^{e*}H_y^o - H_y^{e*}H_x^o\right)d\Omega_0 \tag{4}$$

where $\Omega_0$ is the cross section of the ferrite slab, $k_0$ and $\eta_0$ are, respectively, the wavenumber and intrinsic impedance of free space, and $\mu_a$ stands for the off-diagonal element of the permeability tensor.

A thorough examination of the above expressions revealed [4] that anisotropy of the ferrite perturbs the fields in the basis guide, which results in the coupling of normal modes. As the wave propagates, the energy of one basis mode goes to the other. The strongest effect occurs for equal phase velocities of the even and odd modes in the basis guide ($\Delta\beta = 0$). If the modes are degenerate, the total exchange of energy between the modes occurs over the distance $Cz = \pi/2$. The coupling between modes is tantamount to the exchange of energy between the lines (Fig. 2).

Using (3) we can define the scattering matrix of a section of coupled ferrite lines (factor $e^{j\beta_0 z}$ suppressed):

$$\underline{\underline{S}} = \begin{bmatrix} 0 & \underline{\underline{S}}_F \\ \underline{\underline{S}}_F & 0 \end{bmatrix} = \begin{bmatrix} 0 & 0 & s_1 & -s_2^* \\ 0 & 0 & s_2 & s_1 \\ s_1 & -s_2^* & 0 & 0 \\ s_2 & s_1 & 0 & 0 \end{bmatrix} \tag{5}$$

with

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

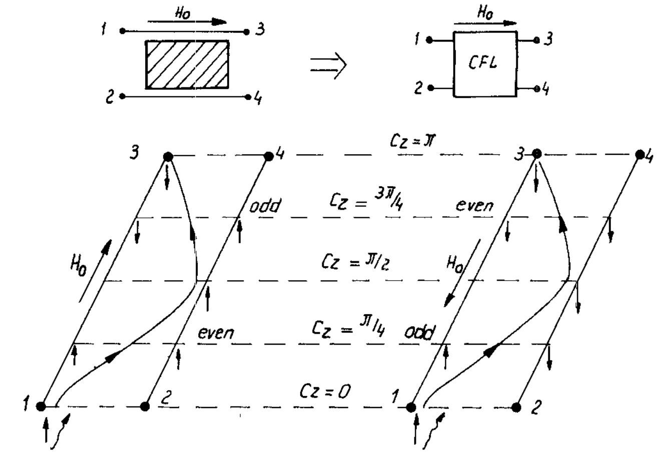


Fig. 2. Exchange of energy and nonreciprocal mode coupling along coupled ferrite lines (CFL's).

In (5) the off-diagonal submatrices are identical. Hence, CFL is a symmetric directional four-port. It can be readily shown that the only nonreciprocal effect which may occur in a symmetric four-port is a nonreciprocal phase shift. This implies that a section of CFL is not nonreciprocal in the sense of definition (2).

## III. Nonreciprocity Condition

In order to establish the necessary conditions for the construction of nonreciprocal devices we shall now investigate a cascade of a reciprocal four-port A and a section of CFL. Assuming that the scattering matrix of the four-port A is given by

$$\underline{\underline{S}} = \begin{bmatrix} 0 & \underline{\underline{S}}_A \\ \underline{\underline{S}}_A^T & 0 \end{bmatrix} \tag{6}$$

where

$$\underline{\underline{S}}_A = \begin{bmatrix} |p|e^{j\varphi_{13}} & |q|e^{j\varphi_{14}} \\ |q|e^{j\varphi_{23}} & |p|e^{j\varphi_{24}} \end{bmatrix} \tag{7}$$

with $|p|^2 + |q|^2 = 1$, we obtain the following expressions for the scattering matrix of the cascade:

$$\underline{\underline{S}}_K = \begin{bmatrix} 0 & \underline{\underline{S}}_A\underline{\underline{S}}_F \\ \underline{\underline{S}}_F\underline{\underline{S}}_A^T & 0 \end{bmatrix} = \begin{bmatrix} 0 & \underline{\underline{S}}_K^{ab} \\ \underline{\underline{S}}_K^{ba} & 0 \end{bmatrix} \tag{8}$$

with

$$\underline{\underline{S}}_K^{ab} = \begin{bmatrix} s_1|p|e^{j\varphi_{13}} + s_2|q|e^{j\varphi_{14}} & s_1|q|e^{j\varphi_{14}} - s_2^*|p|e^{j\varphi_{13}} \\ s_1|q|e^{j\varphi_{23}} + s_2|p|e^{j\varphi_{24}} & s_1|p|e^{j\varphi_{24}} - s_2^*|q|e^{j\varphi_{23}} \end{bmatrix}$$

$$\underline{\underline{S}}_K^{ba} = \begin{bmatrix} s_1|p|e^{j\varphi_{13}} - s_2^*|q|e^{j\varphi_{14}} & s_1|q|e^{j\varphi_{23}} - s_2^*|p|e^{j\varphi_{24}} \\ s_1|q|e^{j\varphi_{14}} + s_2|p|e^{j\varphi_{13}} & s_2|q|e^{j\varphi_{23}} + s_1|p|e^{j\varphi_{24}} \end{bmatrix} \tag{9}$$

where $T$ in (6) and (8) stands for the transposition sign.

From the above expressions it is seen that in general $\underline{\underline{S}}_K^{ab} \neq \underline{\underline{S}}_K^{ba^T}$ and $\underline{\underline{S}}_K^{ab} \neq \underline{\underline{S}}_K^{ba}$. Hence, a cascade consisting of a

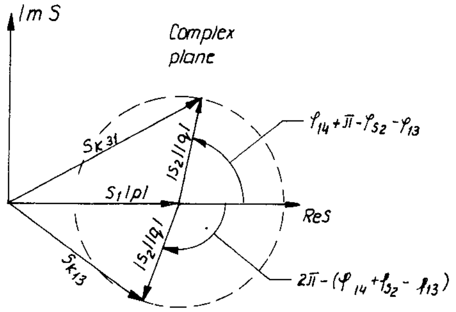


Fig. 3. Graphical representation of $S$ matrix elements $s_{K_{13}}$ and $s_{K_{31}}$ on the complex plane.

reciprocal four-port and CFL is potentially nonreciprocal. Let us consider elements $s_{K_{13}}$ and $s_{K_{31}}$. From (9) we have

$$s_{K_{13}} = \left[ s_1|p| + |s_2||q| e^{j(\varphi_{14}+\varphi_{S_2}-\varphi_{13})} \right] e^{j\varphi_{13}}$$

$$s_{K_{31}} = \left[ s_1|p| + |s_2||q| e^{j(\varphi_{14}+\pi-\varphi_{S_2}-\varphi_{13})} \right] e^{j\varphi_{13}} \qquad (10)$$

where $\varphi_{S_2}$ is the argument of the complex element $s_2$. Let us assume that neither $s_1|p|$ nor $|q||s_2|$ vanishes. Fig. 3 shows $s_{K_{13}}$ and $s_{K_{31}}$ rotated by $-\varphi_{13}$ on the complex plane. From the figure it can readily be inferred that the magnitudes of both elements will be different if

$$\varphi_{14} + \pi - \varphi_{S_2} - \varphi_{13} + 2n\pi \neq 2\pi - (\varphi_{14} + \varphi_{S_2} - \varphi_{13}). \qquad (11)$$

The above condition can also be written as

$$\varphi_{14} - \varphi_{13} \neq \frac{\pi}{2} + n\pi \qquad (12)$$

with $n$ being an integer.

Comparing elements $s_{K_{24}}$ and $s_{K_{42}}$ under the condition that both $s_1|q| \neq 0$ and $|p||s_2| \neq 0$, we get

$$\varphi_{24} - \varphi_{23} \neq \frac{\pi}{2} + n\pi. \qquad (13)$$

Since the arguments of the scattering matrix of a lossless reciprocal four-port satisfy the relation [11]

$$\varphi_{14} + \varphi_{23} = \varphi_{13} + \varphi_{24} + (2n+1)\pi \qquad (14)$$

(12) and (13) form a pair of equivalent necessary nonreciprocity conditions. However, neither (12) nor (13) constitutes the sufficient condition. Additionally, for the cascade to be nonreciprocal, none of the elements $s_1, s_2, |p|, |q|$ can vanish. This can formally be written as

$$s_1 s_2 |p||q| \neq 0. \qquad (15)$$

In practical terms conditions (12) and (13) mean that the four-port in cascade with CFL has to be asymmetric with respect to the plane parallel to the propagation direction while condition (15) states that both CFL and the four-port driving the ferrite section have to be designed in such a way that the excitation of port 1 results in signals emerging from ports 3 and 4. If both (12) and (15) are met, the device obtained by cascading a lossless reciprocal four-port A and a section of CFL is nonreciprocal. The maximal nonreciprocity is achieved when

$$\varphi_{14} - \varphi_{13} = n\pi. \qquad (16)$$

The above relation means that the optimal excitation is obtained if the signals arriving at the input of CFL are either in phase or 180° out of phase. An additional condition has to be met if a second reciprocal four-port, B, is cascaded with the four-port A and CFL. The scattering matrix of the cascade is then

$$\underline{S}_K = \begin{bmatrix} 0 & \underline{S}_A \underline{S}_F \underline{S}_B \\ \underline{S}_B^T \underline{S}_F \underline{S}_A^T & 0 \end{bmatrix}. \qquad (17)$$

If $\underline{S}_B = \underline{S}_A^T$, i.e., when four ports A and B are identical and the cascade is symmetric with respect to the plane perpendicular to the propagation direction, then $\underline{S}_K^{ab} = \underline{S}_K^{ba}$. This means that the cascade has the properties of a symmetric directional four-port which, according to the previous section, cannot satisfy condition (2). Thus the asymmetry of the structure with respect to the plane perpendicular to the propagation direction is the prerequisite for the construction of the nonreciprocal devices discussed in this paper.

## IV. Nonreciprocal Devices Using CFL

Condition (12) can be readily satisfied in a number of reciprocal four-ports. One example is a hybrid T junction. The scattering matrix of the hybrid T junction has the following form:

$$\underline{S}_{EH} = \frac{1}{\sqrt{2}} \begin{bmatrix} 0 & 0 & 1 & 1 \\ 0 & 0 & 1 & -1 \\ 1 & 1 & 0 & 0 \\ 1 & -1 & 0 & 0 \end{bmatrix}. \qquad (18)$$

From (8) we get the scattering matrix of the cascade:

$$\underline{S}_K = \frac{1}{\sqrt{2}} \begin{bmatrix} 0 & 0 & s_1 + s_2 & s_1 - s_2^* \\ 0 & 0 & s_1 - s_2 & -(s_1 + s_2^*) \\ s_1 - s_2^* & s_1 + s_2^* & 0 & 0 \\ s_1 + s_2 & s_2 - s_1 & 0 & 0 \end{bmatrix}. \qquad (19)$$

For $\Delta\beta = 0$ and $Cz = \pi/4$, matrix $\underline{S}_K$ becomes

$$\underline{S}_K = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \\ 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{bmatrix}. \qquad (20)$$

We have obtained the scattering matrix of an ideal four-port circulator with the transmission from port 1 into 4, from 4 into 2, from 2 into 3 and from 3 into 1.

The configuration described above leads to an entire family of nonreciprocal four-, three-, and two-ports. Fig. 4 shows several examples. Terminating port 1 or 2 of the hybrid T junction with a magnetic or electric wall, we get a device consisting of either an $E$ or an $H$ junction and

CFL (fig. 4(b) and (d)). Its scattering matrix is given by

$$\underline{\underline{S}}_E = \frac{1}{\sqrt{2}} \begin{bmatrix} 0 & s_1 - s_2 & -(s_1 + s_2^*) \\ s_1 + s_2^* & \frac{1}{\sqrt{2}}(s_1 - s_2^*)(s_1 + s_2) & \frac{1}{\sqrt{2}}(s_1 - s_2^*)^2 \\ s_2 - s_1 & \frac{1}{\sqrt{2}}(s_1 + s_2)^2 & \frac{1}{\sqrt{2}}(s_1 - s_2^*)(s_1 + s_2) \end{bmatrix} \tag{21}$$

or

$$\underline{\underline{S}}_H = \frac{1}{\sqrt{2}} \begin{bmatrix} 0 & s_1 + s_2 & s_1 - s_2^* \\ s_1 - s_2^* & \frac{1}{\sqrt{2}}(s_1 + s_2^*)(s_2 - s_1) & \frac{1}{\sqrt{2}}(s_1 + s_2^*)^2 \\ s_2 + s_1 & \frac{1}{\sqrt{2}}(s_1 - s_2)^2 & \frac{1}{\sqrt{2}}(s_1 + s_2^*)(s_2 + s_1) \end{bmatrix}. \tag{22}$$

The device has the properties of a three-port circulator so we will henceforth refer to this structure as a circulator junction (CJ). Note that the circulation direction depends on whether the phase difference between signals at the input of CFL is 0° or 180°. This observation is very important since it opens up an opportunity for constructing novel electronically switched circulators.

Cascading two CJ's, we obtain a four-port circulator (Fig. 4(c)) whose scattering matrix is

$$\underline{\underline{S}}_K = \begin{bmatrix} s_{22}^{CJ} & s_{23}^{CJ} & s_{21}^{CJ}s_{31}^{CJ} & s_{21}^{CJ}s_{13}^{CJ} \\ s_{32}^{CJ} & s_{22}^{CJ} & s_{31}^{CJ}s_{31}^{CJ} & s_{13}^{CJ}s_{31}^{CJ} \\ s_{21}^{CJ}s_{31}^{CJ} & s_{21}^{CJ}s_{13}^{CJ} & s_{22}^{CJ} & s_{23}^{CJ} \\ s_{31}^{CJ}s_{31}^{CJ} & s_{13}^{CJ}s_{31}^{CJ} & s_{32}^{CJ} & s_{22}^{CJ} \end{bmatrix} \tag{23}$$

where $s_{ik}^{CJ}$, $i, k = 1,2,3$, are the elements of the $S$ matrix of the CJ defined by (21) or (22). Loading one port, say port 3, of CJ with an absorber characterized by the reflection coefficient $\Gamma_l$ we get an isolator (Fig. 4(e)). The elements of its scattering matrix are given by

$$s_{ij}^{I1} = s_{ij}^{CJ} + \frac{s_{i3}^{CJ}s_{3j}^{CJ}\Gamma_l}{1 - \Gamma_l s_{33}^{CJ}}, \qquad i, j = 1,2. \tag{24}$$

An isolator can be also obtained if the absorber is placed in one common arm between two CJ's magnetized with antiparallel fields (Fig. 4(f)). The elements of the scattering matrix then become

$$s_{11}^{I2} = s_{22}^{I2} = s_{11}^{I1} + \frac{s_{12}^{I1}s_{21}^{I1}s_{22}^{I1}}{1 - s_{22}^{I1}s_{22}^{I1}}$$

$$s_{12}^{I2} = \frac{s_{12}^{I1}}{1 - s_{22}^{I1}s_{22}^{I1}} \qquad s_{21}^{I2} = \frac{s_{21}^{I1}}{1 - s_{22}^{I1}s_{22}^{I1}}. \tag{25}$$

Obviously in all the above structures the T junction can be replaced by a Y junction.

In all the devices described above the optimal excitation is ensured by the properties of the reciprocal junction. It can readily be verified that, as in the case of the four-port circulator, ideal isolation or ideal circulation is obtained if $\Delta\beta = 0$ and $Cz = \pi/4$. Hence, we may conclude that, for even- or odd-mode excitation, $\Delta\beta = 0$ and $Cz = \pi/4$ constitute the optimal operating conditions of CFL. $Cz$ depends on the magnetic parameters of the ferrite material and the physical length $z$ and in practice can easily be controlled, whereas $\Delta\beta = 0$ can be achieved by a suitable choice of line dimensions and media permittivity.

An alternative to the hybrid T junction is a 3 dB 0°/180° hybrid/coupler. If a coupler is symmetrical, the phase difference at its output is always $\pi/2$. Therefore, if a symmetrical structure is used, an extra line of electrical length $\pi/2$ or $3\pi/2$ should be included in one arm feeding CFL (Fig. 4(g)). An interesting structure is obtained if the fixed length of line is replaced by a switched 90°/270° phase shifter. In this structure, by changing the inserted phase from 90° to 270° the circulation direction can be reversed.

Another possibility of obtaining the desirable 0°/180° phase difference at the input of CFL is an asymmetrical proximity coupler. Let us assume that the four-port A consists of a section of two arbitrary parallel guides. The scattering matrix of such a coupler has the following form:

$$\underline{\underline{S}}_C = \begin{bmatrix} 0 & 0 & A_1(z) & A_2(z) \\ 0 & 0 & A_2(z) & A_1^*(z) \\ A_1(z) & A_2(z) & 0 & 0 \\ A_2(z) & A_1^*(z) & 0 & 0 \end{bmatrix} \tag{26}$$

with

$$A_1(z) = \cos(\Gamma_c z) - j\frac{\Delta\beta_c}{\Gamma_c}\sin(\Gamma_c z)$$

$$A_2(z) = j\frac{C_c}{\Gamma_e}\sin(\Gamma_c z) \tag{27}$$

and

$$\Gamma_c = \sqrt{\Delta\beta_c^2 + C_c^2} \qquad \Delta\beta_c = (\beta_a - \beta_b)/2 \tag{28}$$

where $\beta_a$ and $\beta_b$ are the propagation constants of each guide constituting a coupler in the absence of coupling, whereas $C_c$ stands for the coupling coefficient [8]. If $\beta_a = \beta_b$

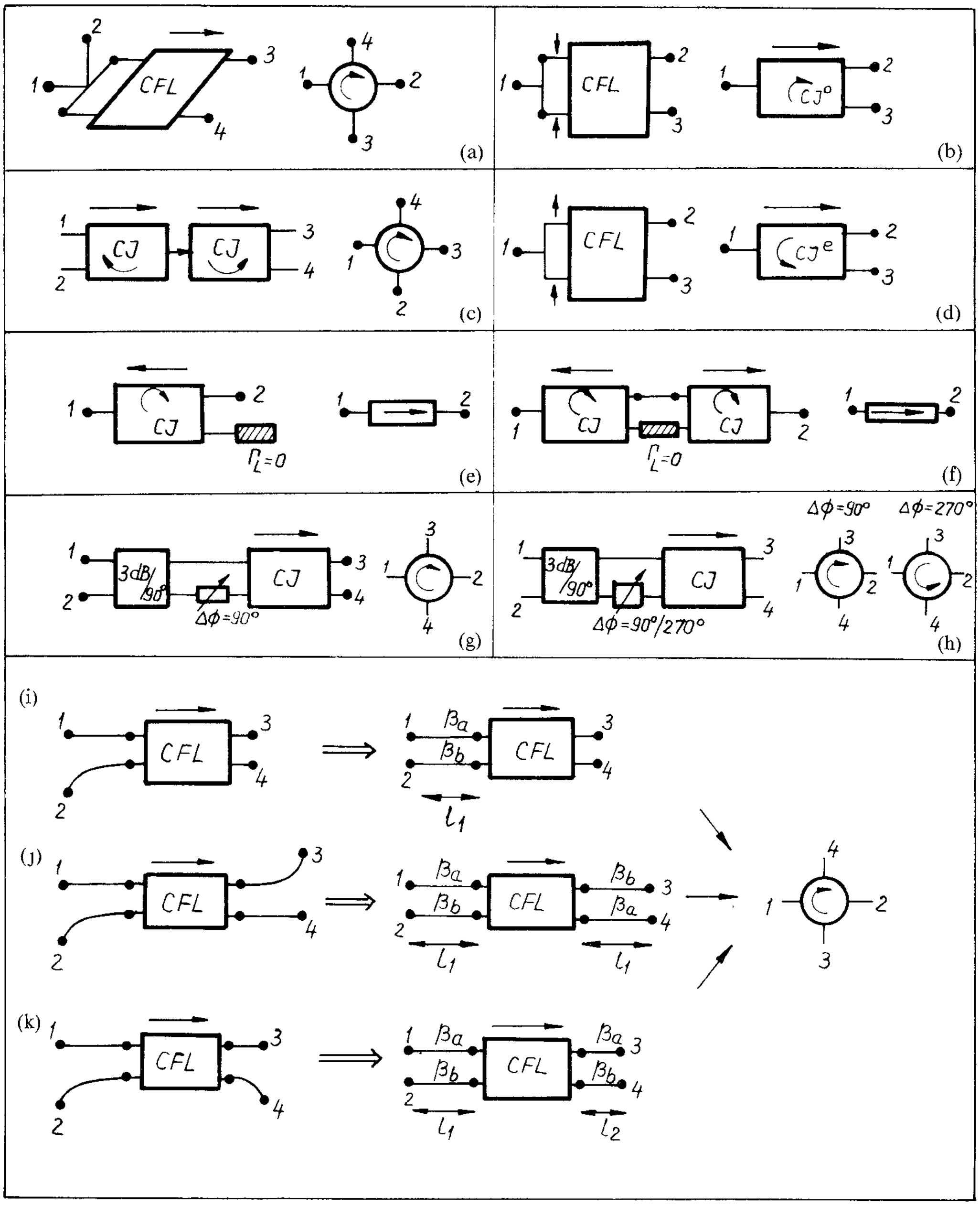


Fig. 4. Examples of nonreciprocal devices comprising a section of CFL. (a), (c), (g), (h), (i)–(k)—four-port circulators, (b), (d)—three-port circulators, (e)–(f)—isolators.

the coupler becomes symmetrical and the phase difference between the output ports of a coupler is $\pi/2$. However, $\beta_a \neq \beta_b$ results in $\arg A_1 - \arg A_2 \neq \pi/2$ and the whole device becoming nonreciprocal.

Finally, nonreciprocity can be obtained if a straight section of a symmetrical coupler, which by itself cannot produce any phase difference other than $\pi/2$, is fed from identical curved guides with different radii of curvature (Fig. 5). In the first approximation, the asymmetric curved section can be modeled by two straight guides with $\beta_a \neq \beta_b$, and consequently the necessary nonreciprocity condition (12) can be satisfied. In addition to the slight change of propagation constants resulting from the curvature [7], there are two other phenomena which provide a basis for such a model. First, as the radii of curvature are not equal, the electric lengths along each guide are different. Second, there is radiation due to curvature. The radiated field interferes with the guided modes, changing their propagation constants. If the radiation from each curved arm is different, the propagation constants of each guide in the straight section are not identical [9].

Fig. 4(i)–(k) shows examples of nonreciprocal devices comprising couplers with curved sections. The scattering matrix for these structures is given by formula (17) with

$$\underline{\underline{S}}_A = \begin{bmatrix} A_1(l_1) & A_2(l_1) \\ A_2(l_1) & A_1^*(l_1) \end{bmatrix} \qquad \underline{\underline{S}}_B = \begin{bmatrix} A_1(l_2) & A_2(l_2) \\ A_2(l_2) & A_1^*(l_2) \end{bmatrix} \tag{29}$$

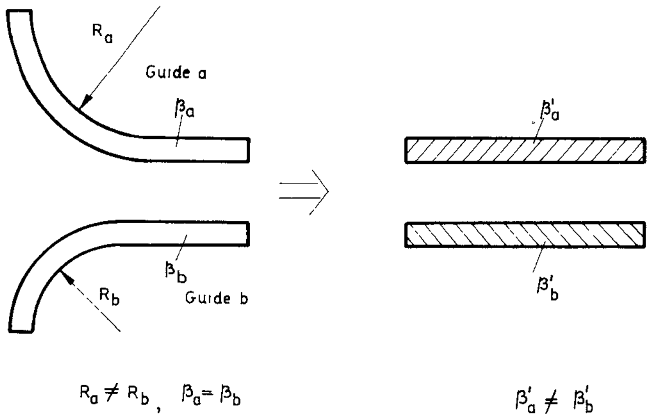


Fig. 5. Simplified model of a nonuniform coupler with different radii of curvature.

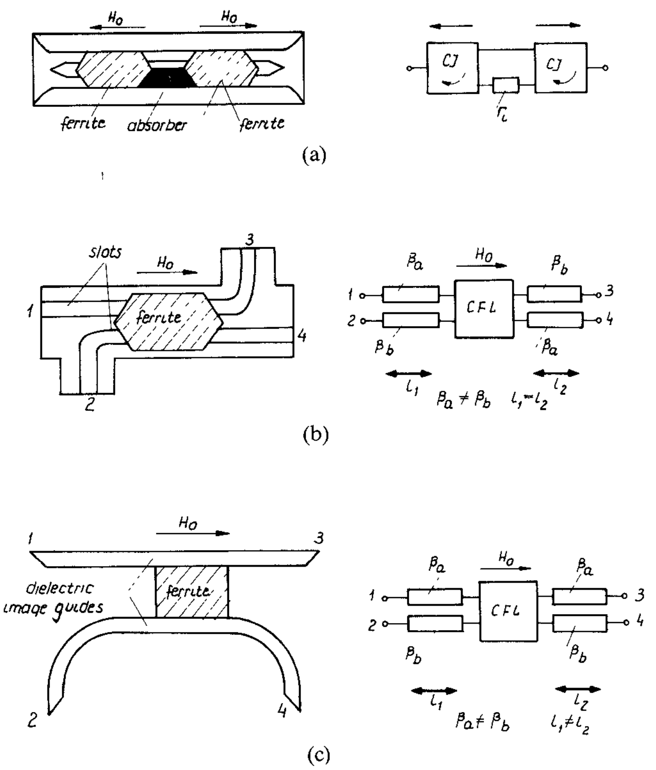


Fig. 6. Experimental devices investigated in [1] and [2] and their models resulting from our theory. (a) A finline isolator. (b) A finline four-port circulator. (c) Dielectric image line four-port circulator.

for the devices shown in Fig 4(i) and (k) and

$$\underline{S}_A = \begin{bmatrix} A_1(l_1) & A_2(l_1) \\ A_2(l_1) & A_1^*(l_1) \end{bmatrix} \qquad \underline{S}_B = \begin{bmatrix} A_1^*(l_1) & A_2(l_1) \\ A_2(l_1) & A_1(l_1) \end{bmatrix} \tag{30}$$

for the device depicted in Fig. 4(j).

Structures shown in Fig. 4, in addition to new configurations, also include devices proposed by other researchers. Note that in finline technology a tapered transition from a single slot to two coupled slots forms a T junction. Thus the isolator shown in Fig. 4(f) is identical to the experimental isolator investigated by Davis and Sillars [1], whose operating principle was qualitatively explained in our earlier paper [4]. Likewise, the four-port circulators proposed in [1] and [2] can be modeled by structures consisting of two couplers and a section of CFL. Fig. 6 shows three experimental configurations and their equivalents resulting from our theory. We shall use these models in the subsequent section, where the results of numerical investigations are presented.

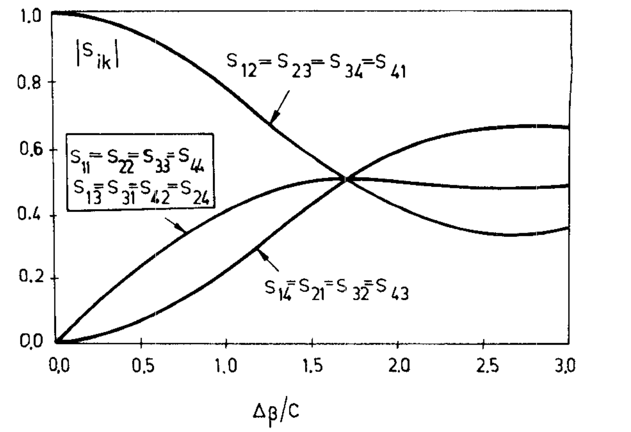


Fig. 7. Characteristics of a four-port circulator obtained by cascading two CJ's (cf. Fig. 4(c)): $Cz = \pi/4$.

## V. Numerical Results

Having defined the scattering matrices of nonreciprocal structures using CFL, we shall now investigate the behavior of a few exemplary devices. The action of some of these devices was qualitatively explained in our earlier paper [4]. However, the expressions derived in the previous section allow an investigation of the behavior of various configurations when the conditions for optimal operation are not fulfilled. Since in practice it is possible to control $Cz$ by suitable choice of magnetic parameters of the gyromagnetic medium or the section dimensions, we assumed in our computations that the ferrite section has the optimal length $Cz = \pi/4$.

Fig. 7 shows the influence of the normalized difference between propagation constants of the even and odd modes supported by the basis structure, $\Delta\beta/C$, on the $S$ matrix elements of a four-port circulator obtained by cascading two CJ's (cf. (23) and Fig. 4(c)). Note that $\Delta\beta/C$ changes with frequency. Thus, Fig. 7 also shows the frequency characteristics of the circulator. In a circulator junction the CFL's are fed from the T junction, and consequently the signals at the input of the CFL are always either in phase or 180° out of phase; i.e., the necessary nonreciprocity condition (12) is always satisfied. However, according to (15) the device becomes reciprocal if either $s_1$ or $s_2$ vanishes. This effect is seen in the figure. At the point where all three curves cross one another $\Gamma_z = \pi/2$, which entails the vanishing of $s_1$ and brings about the reciprocity of the structure. Note that if both modes in the basis structure have equal phase velocities ($\Delta\beta = 0$) there is no isotropic coupling between the guides in the basis structure and the exchange of energy is due only to the anisotropy of the ferrite. When $\Delta\beta$ increases, the isotropic coupling on the

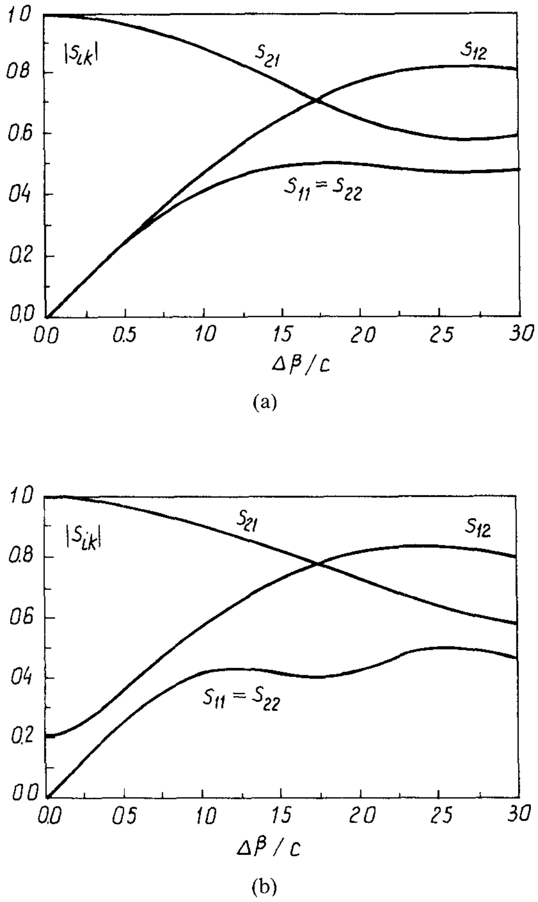


Fig. 8. Characteristics of an isolator consisting of two CJ's magnetized with antiparallel magnetic fields (cf. Fig. 4(f)): $Cz = \pi/4$ (a) Absorber matched. (b) Absorber not matched, $\Gamma_l = 0.2$.

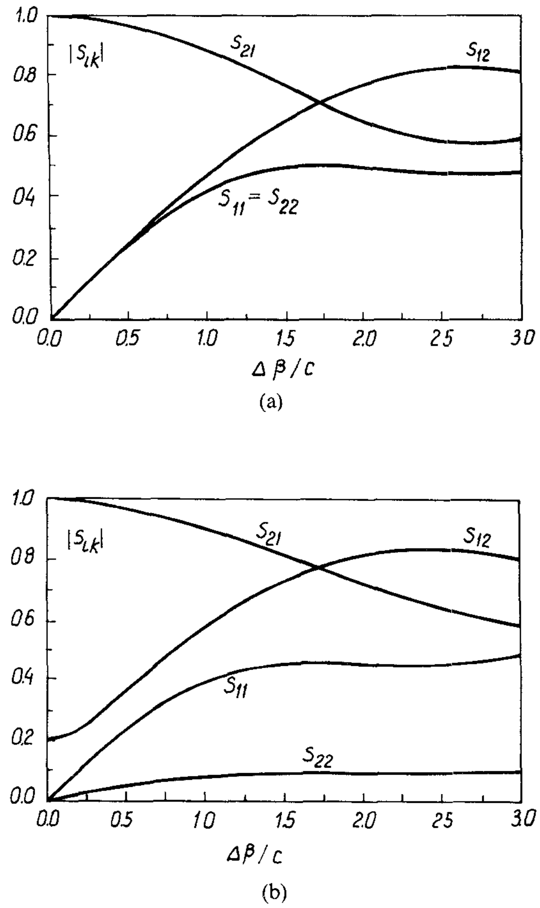


Fig 9. Characteristics of an isolator obtained by loading one port of CJ with the absorber (cf. Fig. 4(e)): $Cz = \pi/4$. (a) Absorber matched. (b) Absorber not matched, $\Gamma_l = 0.2$

fixed length of guides becomes stronger and starts to balance the nonreciprocal effects resulting from the anisotropy of the gyromagnetic medium.

Figs. 8 and 9 show the characteristics of two isolators obtained from CJ's. As was stated in the previous section, the structure in which the absorber is placed in one arm between two CJ's magnetized with antiparallel magnetic fields is identical to the one investigated experimentally by Davis and Sillars [1]. The nonreciprocal behavior of the device observed experimentally is confirmed in our computations. If the absorber is matched ($\Gamma_l = 0$) both structures give identical responses. For $\Gamma_l = 0.2$ the transmission is not affected but the isolation decreases. Figs. 8(b) and 9(b) show also that the isolator obtained by loading one port of the CJ with an imperfect load has a lower output reflection coefficient than the structure using two CJ's.

We shall now concentrate on the devices in which the desired phase relation between signals at the input of CFL is achieved by using asymmetrical couplers. Numerical computations were carried out for the nonreciprocal structures proposed in [1] and [2], whose models are given in Fig. 6(b) and (c). The ratio $l_2/l_1$ assumed in the computations corresponds to the lengths of isotropic coupled line sections used in the experiments reported in [1] and [2]. Since we do not know of any reliable method which would enable us to compute the coupling coefficients in the asymmetrical couplers used in the experiments and we had no measurement data, we have made an arbitrary choice of $C_c$. For the sake of clarity we show only the characteristics of the parameters which were discussed in [1] and [2].

Fig. 10 shows the characteristics of a four-port finline circulator plotted against $\Delta\beta_c/C_c$. Circulation occurs, as expected, for $\Delta\beta_c/C_c \neq 0$ and is reversed if the direction of the biasing field is reversed. Furthermore, the computed diagrams show an effect identical to the one observed in experimental devices, namely that the isolation bandwidths change considerably if the magnetization is reversed.

Finally, Fig. 11 illustrates the nonreciprocal coupling in the dielectric image line four-port circulator [2] whose model is shown in Fig. 6(c). The computed characteristics are again similar to the measured ones. In particular it may be seen that as $\Delta\beta_c/C_c$ increases the circulation direction is reversed. The same effect for the frequency characteristics was reported in [2].

## VI. Conclusions

The operation of novel nonreciprocal ferrite devices with longitudinal magnetization is investigated. Since in this configuration saturation can be obtained with a weak

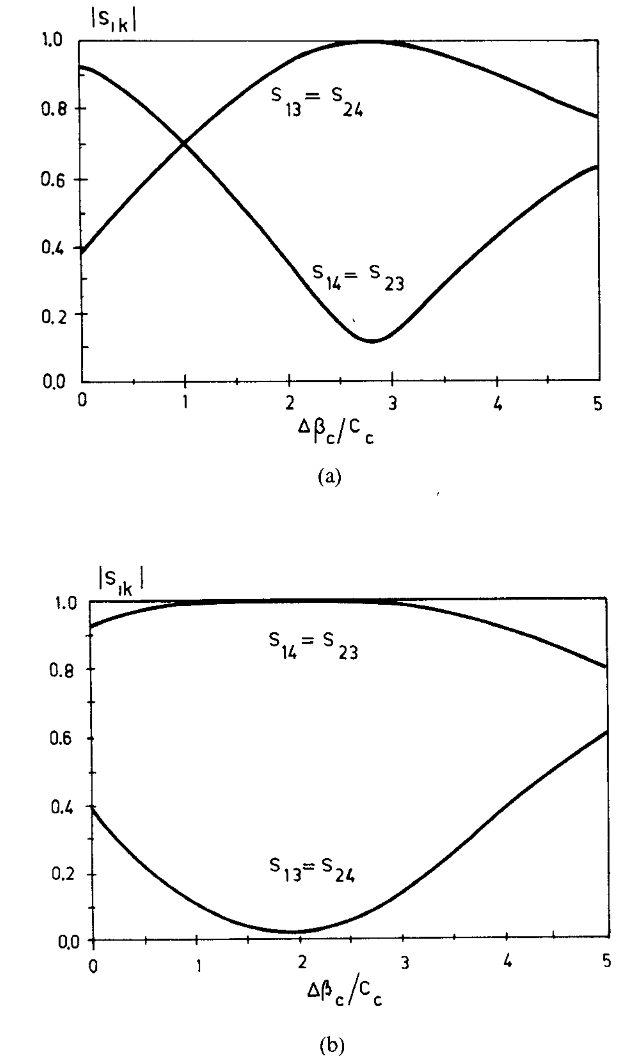


Fig. 10. Characteristics of a four-port circulator using identical inverted couplers at the input and output of CFL (cf. Fig. 4(j)): $Cz = \pi/4$, $\Delta\beta/C = 0$, $C_c z = 0.5$, $l_2/l_1 = 1$. (a) Forward magnetization. (b) Reverse magnetization.

magnetic field and conventional ferrites can be used, these new structures are particularly attractive from the point of view of application in the millimeter-wave range. The theory is based on the mathematical model presented in [4]. It was found that nonreciprocity can be obtained in the structures comprising a section of coupled ferrite lines cascaded with a reciprocal four- or three-port which produces phase difference between the output ports other than $\pi/2 + n\pi$. The maximum nonreciprocity is achieved if the signals at the input of CFL are either in phase or 180° out of phase. The reciprocal structures which may be used in the construction of nonreciprocal devices include hybrid junctions, T and Y junctions, 3 dB 0°/180° hybrids/couplers, and asymmetrical uniform and nonuniform couplers. Various novel configurations as well as the models of the experimental devices investigated by other researchers are proposed. The theoretical predictions were confirmed by numerical investigations. The results of this study may be used for designing nonreciprocal components operating at millimeter-wave frequencies.

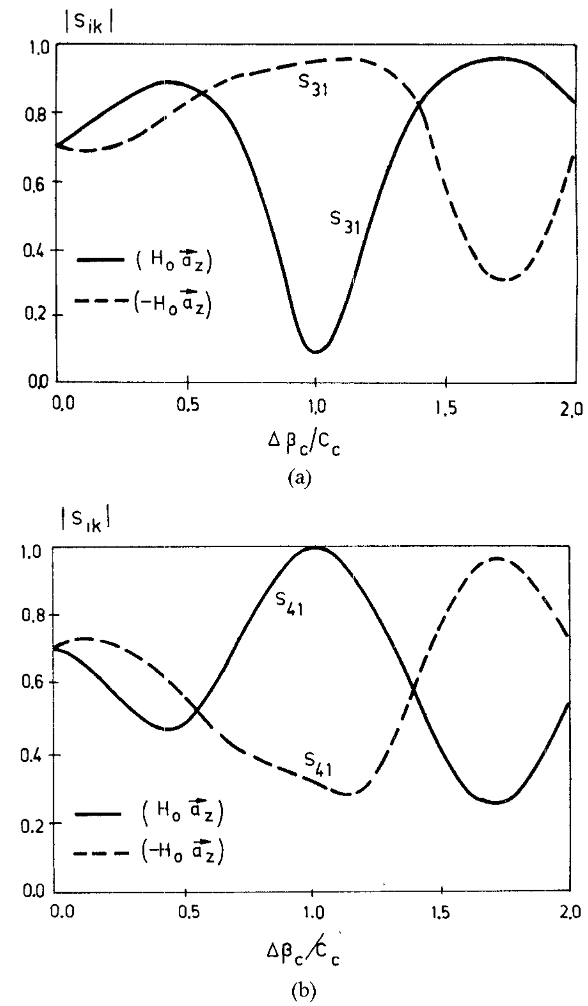


Fig. 11. Characteristics of a four-port circulator using couplers of different length at the input and output of CFL (cf. Fig. 4(k)): $Cz = \pi/4$, $\Delta\beta/C = 0$, $C_c z = \pi$, $l_1/l_2 = 3/4$. (a) $|s_{31}|$; (b) $|s_{41}|$.

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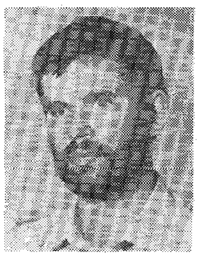

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