The optimization algorithm determined the saturated electron velocity in the two-dimensional electron gas to be $(1.77 \pm 0.07) \times 10^5 \mathrm{m} \cdot \mathrm{s}^{-1}$. This value is in good agreement with the value of $1.8 \times 10^5 \mathrm{m} \cdot \mathrm{s}^{-1}$ reported by de la Houssaye *et al.* [3] for a pseudomorphic AlGaAs/InGaAs HEMT with a 0.3-μm-long gate and a 15% indium fraction. The error in the 2DEG velocity is estimated by repeating the optimization with the critical parameters of doping density and doped layer thickness set to their worst case values, $(8.0 \times 10^{23}\mathrm{m}^{-3}, 54.5$ nm) and $(7.6 \times 10^{23}\mathrm{m}^{-3}, 52.5$ nm), and the other parameters held constant at the values listed in Section II and Tables I–III.

The optimization algorithm also determined the saturated electron velocity in the parasitic MESFET to be $8.6 \times 10^4 \mathrm{m} \cdot \mathrm{s}^{-1}$. This value is in good agreement with the value of $8.9 \times 10^4 \mathrm{m} \cdot \mathrm{s}^{-1}$ reported in [2] for a standard AlGaAs/GaAs HEMT with a 25% aluminum fraction and a 0.25-μ m-long gate.

IV. Conclusion

In this paper we have established the usefulness over an extended range of a previously reported model [1]. Good agreement has been obtained between measured and simulated dc drain current and s-parameters from 1 to 50 GHz, both as a function of the applied gate voltage. We have also confirmed a published value of $\approx 1.8 \times 10^5 \mathrm{m} \cdot \mathrm{s}^{-1}$ for the saturated electron velocity in the pseudomorphic $\mathrm{In_{0.15}Ga_{0.85}As}$ channel layer of a HEMT with a gate length of ≈ 0.3 μm, and obtained again from unrelated measurements a saturated electron velocity of $\approx 8.9 \times 10^4 \mathrm{m} \cdot \mathrm{s}^{-1}$ in the doped $\mathrm{Al_{0.25}Ga_{0.75}As}$ layer of a HEMT with a gate length ≈ 0.25 μm.

Acknowledgment

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Millimeter-Wave Three-Port Finline Circulator Using Distributed Coupling Effect

Jerzy Mazur

Abstract—**The design and experimental results for a novel three-port finline circulator are presented for the frequency range 26–40GHz. The circulator consists of a T^E-junction cascaded with the section of ferrite coupled slot finlines magnetized in the propagation direction. The T^E-junction structure refers to a transition from unilateral single slot finline taper into coplanar line region via a tapered center conductor. The design procedure of the structure confirmed by experimental results is described. The proposed structure adjoins to the family of the distributed coupled ferrite line nonreciprocal devices suitable for application in the millimeter-wave range.**

I. Introduction

Recently, a number of novel nonreciprocal components applicable at millimeter-wave frequencies has been presented [1], [2]. The principle of operation of some of these devices was based on the nonreciprocal Faraday rotation phenomenon appearing in distributed coupled ferrite line structures magnetized longitudinally in the propagation direction [3], [4]. The mathematical model of the phenomena proposed in [3] and [4] makes it possible to predict the nonreciprocal behavior of the section of coupled ferrite lines, and provides conditions indispensable to design the structure. In this paper, a new three-port finline circulator based on the concept proposed in [4] is presented. The circuit employs a combination of unilateral finline T^E-junction and a section of coupled ferrite slot finline. The nonreciprocity conditions formulated in [4] were used to design the structure of the device. Nonreciprocal operation of the proposed circuit, confirmed by experimental results, indicates the validity of the theory and of the design procedure.

II. Nonreciprocity Condition

Before presentation of the design of a three-port circulator, it will be useful to recall some points of the theory presented in [3] and [4]. Using the coupled mode method, the scattering matrix of coupled ferrite lines (CFL) magnetized in the propagation direction has been reported in [4]. Under the assumption that reflected waves are neglected in the structure, the scattering matrix of CFL is given by

$$\underline{\underline{S}}^f = \begin{bmatrix} 0 & 0 & s_1 & -s_2^* \\ 0 & 0 & s_2 & s_1 \\ s_1 & -s_2^* & 0 & 0 \\ s_2 & s_1 & 0 & 0 \end{bmatrix} e^{j\beta_0 z} \quad (1)$$

with

$$s_1 = \cos(\Gamma z) \qquad s_2 = \frac{\pm|C| - j\Delta\beta}{\Gamma} \sin(\Gamma z) \quad (2)$$

and

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

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The author is with the Department of Electronics, Technical University of Gda\'nsk, 80-952 Gda\'nsk, Poland.

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In the above expressions, the choice of sign in the double sign depends on the magnetization or propagation direction; the superscripts e and o refer to the even and odd mode supported by the basis guide. The basis guide is the structure in which ferrite is replaced with an isotropic material having the same value of the permittivity, and is otherwise identical to investigated structure. The β stands for the propagation constant, and C is the coupling coefficient resulting from the anisotropy of the ferrite and is defined as follows:

$$C = \frac{1}{2} k_0 \eta_0 \mu_a \int_{\Omega_0} (H_x^{e*} H_y^o - H_y^{e*} H_x^o)\, d\Omega_0 \tag{3}$$

where Ω_0 is the cross section of the ferrite slab, $H^{e(o)}$ are eigenfunctions of the magnetic field in the basis guide; k_0 and η_0 are the wavenumber and intristic impedance of the free space, respectively; and μ_a stands for the off-diagonal element of the permeability tensor.

It may be concluded from (1) that the considered CFL is a symmetric directional four-port junction, and the only nonreciprocal effect which may occur in the structure is a nonreciprocal phase shift. However, it was shown in [4] that nonreciprocity is obtained in a cascade consisting of a reciprocal three-port and a section of CFL. Optimal nonreciprocity effect is achieved when the CFL section is excited via three-port by the even or odd mode. One possible configuration of the three-port structure which ensures the proper excitation of CFL is a T^E-junction which may be realized in finline technology as a transition between unilateral single slot finline and a coupled slot finline (coplanar line). In this structure, only the odd-mode becomes excited in the coplanar line. Another useful configuration is a T^H-junction which may be designed as a transition from a suspended microstrip to a coupled slot finline. In this case, the even mode only appears in the coplanar line.

Assuming that the scattering matrix of the T^E-junction is given by

$$\underline{\underline{S}}^T = \begin{bmatrix} s_{11}^o & s_1^o & -s_1^o \\ s_1^o & s_2^{o'} & s_2^{o''} \\ -s_1^o & s_2^{o''} & s_2^{o'} \end{bmatrix}, \tag{4}$$

then the following expressions for the scattering matrix of the cascade of CFL and T^E junctions is obtained and shown in (5) at the bottom of the page. Having defined the scattering matrix $\underline{\underline{S}}^c$, we could not investigate the nonreciprocal behavior of the device. It is seen from the above matrix that optimal nonreciprocal action of the structure will occur if the following conditions are satisfied:

- the ideal T^E junction is required, i.e., in (4) is assumed that

$$s_{11}^o = 0, \qquad s_1^o = 1/\sqrt{2}, \qquad s_2{}' = 1/2$$

- the terms constituting the optimal structure of CFL section are given by

$$\Delta\beta = 0 \quad \text{and} \quad Cz = \pi/4 + n\pi/2, \tag{6}$$

where (n) is integer.

It can be noticed that $\Delta\beta = 0$ can be achieved by a suitable choice of line dimensions and media permittivities, whereas Cz depends on the magnetic parameters and the physical length of the ferrite sample. It indicates that these conditions provide the design formulas of CFL.

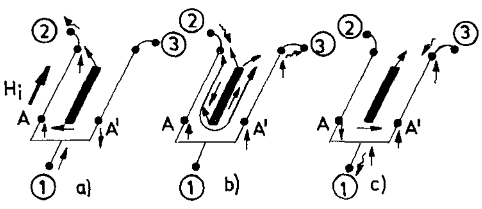

Fig. 1. Operation of an ideal three-port circulator consisting of the cascaded T^E-junction and a section of CFL. (a) Excitation in port 1, (b) excitation in port 2, (c) excitation in port 3.

For these conditions (under $n = 0$), the scattering matrix (5) takes the form

$$\underline{\underline{S}}^c = \begin{bmatrix} 0 & 0 & -1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix}. \tag{7}$$

We have obtained the scattering matrix of an ideal three-port circulator with the transmission $1 \to 2 \to 3 \to 1$. By reversing the magnetization direction, (5) is converted into

$$\underline{\underline{S}}^c = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ -1 & 0 & 0 \end{bmatrix} \tag{8}$$

and one can notice that circulation direction is reversed.

Let us now introduce an alternative Faraday model of the phenomena to explain the operation of the circulator as shown in Fig. 1. It was presented in [3] that when the isotropic coupling in the *CFL* vanishes, i.e., $\Delta\beta = 0$, the rotation Faraday angle $\theta = Cz$. From Fig. 1(a), we may conclude that the odd excitation at the input of *CFL* will result in the transmission of the wave to port 2, via rotation of the excitation vector by 45° in clockwise direction. A wave incident at port 2 will excite the even mode at the inputs (plane AA′) of the T^E-junction where it is reflected and, according to the Fig. 1(b), the wave is transmitted to port 3. For excitation in port 3, the wave appears at the plane AA′ of the T^E-junction as odd mode and, consequently, emerges from port 1, [cf. Fig. 1c)]. The change of magnetization direction induces the reverse direction of the Faraday rotation and changes the circulation direction.

III. Design Procedure and Experimental Result

The cascade of a T^E-junction and coupled slot finlines loaded with a ferrite slab as shown in Fig. 2 was chosen for the realization of the three-port circulator. Because the junction represents the tapered transition from a unilateral slot finline to a coplanar line, it therefore ensures the odd mode excitation of the ferrite section. The transition consists of a cascade of three regions—1,2 and 3—marked respectively in Fig. 2. Region 1 employs the triangular protrusion of 5 mm in length cut in the finline substrate to match the hollow waveguide and the finline taper. The following region 2 refers to the exponential finline taper of 7 mm in length which was designed using the procedure reported in [6]. The method is based on solution of the telegraphist equation for waveguides of a varying cross section. Region 3 presents the transition from single slot to coplanar finline via triangular tapered center conductor of 3 mm in length. The shapes

$$\underline{\underline{S}}^c = \begin{bmatrix} s_{11}^o & s_1^o(s_1 - s_2) & -s_1^o(s_1 + s_2^*) \\ s_1^o(s_1 + s_2^*) & s_2^{o''} s_1(s_2 - s_2^*) + s_2^{o'}(s_1^2 - |s_2|^2) & s_2^{o''}(s_1^2 + s_2^{*2}) - 2 s_1 s_2^{o'} s_2^* \\ -s_1^o(s_1 - s_2) & s_2^{o''}(s_1^2 + s_2^2) + 2 s_1 s_2^{o'} s_2 & s_2^{o''} s_1(s_2 - s_2^*) + s_2^{o'}(s_1^2 - |s_2|^2) \end{bmatrix}. \tag{5}$$

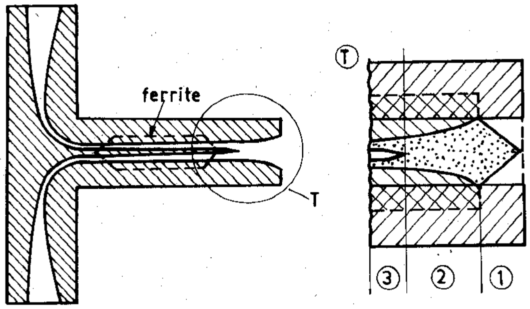

Fig. 2. Plan view of the prototype of three-port circulator.

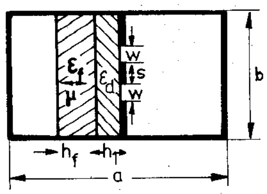

Fig. 3. Cross section of coupled ferrite line section. Dimensions in millimeters are: $a = 7.2$, $b = 3.4$, $w = s = 0.5$, $h_1 = 0.127$, $h_f = 0.5$. The permittivities are: finline substrate $\epsilon_d = 2.22$, ferrite slab $\epsilon_f = 13.5$, and saturation magnetization $M_s = 340$ kA/m.

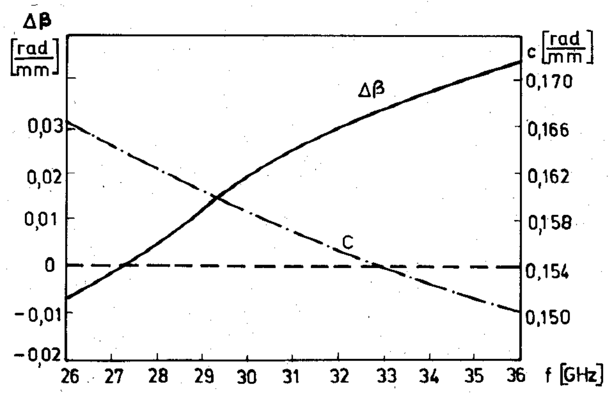

Fig. 4. Propagation constant difference $\Delta\beta$ for fundamental even and odd modes in the basis guide and coupling coefficient C obtained from the structure shown in Fig. 3.

of the regions 1 and 3 were designed similarly to the procedure described in [5].

The goal in the design of the ferrite section of the structure is to compute the parameters of the CFL finline which result in the optimal operating condition (6). In this case, the values of the $\Delta\beta$ and C were computed for the coplanar finline structure (cross section is given in Fig. 3) using the rigorous spectral domain method. The results are shown in Fig. 4. It may be noticed that the equalization of propagation constants for basis modes occurred for thickness of the ferrite plate h_f = 0.5 mm at $f \approx 27.5$ GHz. For saturated ($H_i = 0$) LiZn ferrite with saturation magnetization $M_s = 340$ kA/m, the coupling coefficient is $C \approx 0.166$–0.152 rad/mm for the frequency range $f = 26$–34 GHz. Assuming that $n = 1$, we obtain from (6) that for the above values of C, the length of the ferrite slab is $L \approx 14.2$–15.1 mm.

Expression (5) can now be used to evaluate the scattering $\underline{\underline{S}}$-matrix parameters of the CFL circulator within the frequency range 26–32 GHz. Figs. 5 and 6 show the characteristics of the circulator derived under the assumption that the value of the reflection coefficient s_{11}^{o}

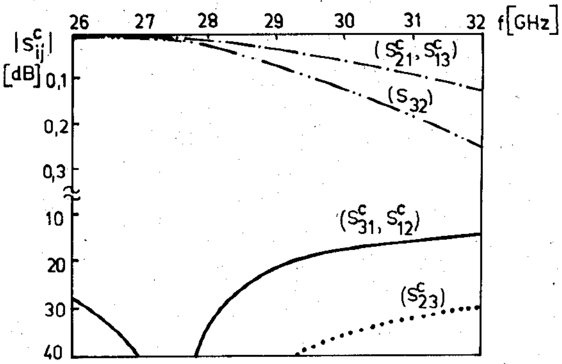

Fig. 5. Theoretical characteristics of circulator consisting of T_E ideal junction ($s_{11}^{o} = 0$) and CFL finline section. Cross section of CFL is shown in Fig. 3, the length of the ferrite $L = 14.3$ mm.

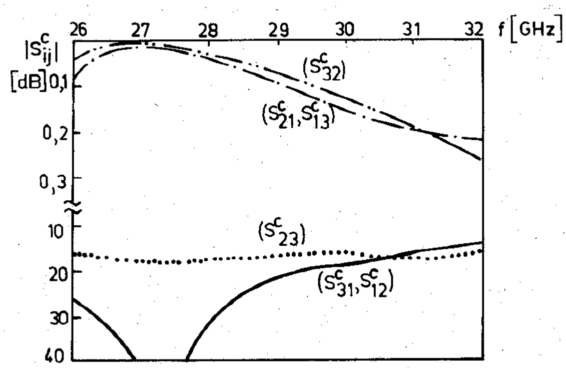

Fig. 6. Theoretical characteristics of circulator containing nonideal T_E-junction ($s_{11}^{0} = 0.1$). Cross section of CFL is shown in Fig. 3, the length of the ferrite $L = 14.3$ mm.

at the input of the device increases from 0 to 0.1, respectively. It may be seen that in this case the parameters of the circulator are not considerably deteriorated except from decreasing the isolation between isolated ports (S_{23}^c).

Based on the above calculations, a ferrite slab with length $L = 14.3$ mm, which is positioned on the bottom of the substrate of coupled slot finline, was used in the prototype of the circulator. In order to reduce the discontinuity of the ferrite slab, the triangular taper with length 3 mm was made at both ends of the sample. The longitudinal bias field produced by a solenoid was sufficient to saturate the ferrite slab. The scattering $\underline{\underline{S}}$-matrix parameter characteristics of the prototype of the circulator are shown in Fig. 7 where nonreciprocal behavior of the device is clearly evident. The characteristics show that isolation better than 18 dB was produced in the bandwith of 3 GHz at the isolated ports (S_{31}^c, S_{12}^c) together with 1.5–3 dB insertion losses appearing between transmission ports (S_{13}^c, S_{21}^c). The operation bandwidth between ports 2 and 3 increases to 4.5 GHz, although the level of the isolation S_{23}^c is approximately 15 dB and losses S_{32}^c are greater than 2.5 dB. The asymmetrical operation of the device observed in the experiment was expected from the theory presented above. The measured return losses S_{11}^c were better than 15 dB. It was observed that the direction of circulation is reversed by reversing the magnetization direction.

IV. Conclusion

A novel three-port finline circulator based on the nonreciprocal Faraday rotation phenomenon appearing in distributed coupled ferrite

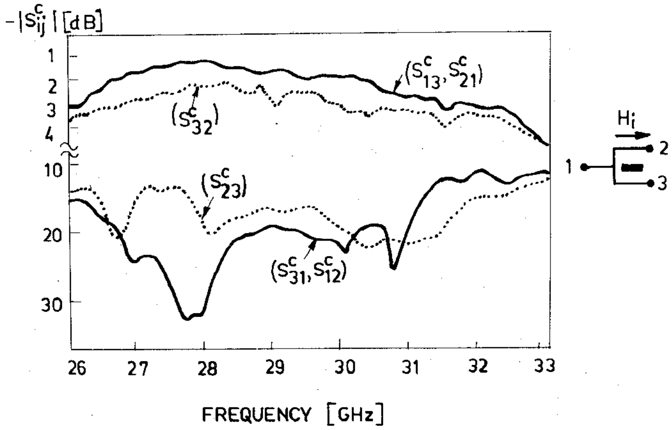

Fig. 7. Experimental transmission characteristics for the three-port circulator prototype shown in Fig. 2 (cf. Figs. 5 and 6).

line structure magnetized longitudinally has been presented. As expected, the proposed method allows us to design only approximately the circulater structure. This is because the operational principle of the device was derived under a few simplifying assumptions. For instance, only two basis modes were considered, and the interaction between the traveling and reflected waves in the structure of CFL has been neglected. Nevertheless, the comparison of the theoretical and experimental characteristics proves that the procedure can be applicable for approximate design of the nonreciprocal CFL components. The finline circulator proposed in this paper, as well as nonreciprocal CFL devices presented earlier [2], can be competitive with the traditional nonreciprocal structures operating at millimeter-wave band. Therefore, further theoretical and experimental investigations are needed to allow us to design optimal structures.

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The Magnetostatic Waves in Ferrite Film with Losses

S. A. Vyzulin, A. E. Rosenson, and S. A. Shekh

***Abstract*—The influence of relaxation processes on dispersion equation solutions for surface and volume magnetostatic waves (MSW) propagating in ferrite film has been theoretically investigated. It has been shown that dissipation is the reason for the appearance of complementary MSW branches in frequency intervals which adjoin to "standard" branches in spectra. The existence of the threshold MSW wave numbers which are restricted above the spectra of possible wave numbers is established. Asymptotic frequencies and frequencies corresponding to the threshold values of wave numbers have been calculated. The features of dissipation effects on boundary locations of MSW existence ranges were calculated. The frequental dispersion of the losses spectra was also calculated.**

I. THEORY

One of the main problems with using ferrite films for designing a magnetostatic wave (MSW) device [1]–[3] is the necessity of carrying out the additional analysis of MSW spectrum, taking into account the MSW attenuation. These analyses are being carried out actively, both theoretically and experimentally, by several authors [4]–[10]. The new results of a theoretical analysis of a feature MSW spectrum in ferrite film with losses are presented in this paper.

Let the thin ferrite film with thickness d and magnetized at saturation be in the constant internal magnetic bias field $\vec{H}$ ($\vec{H}_e$ is the corresponding external field). There are three pure kinds of modes of MSW which can propagate in the ferrite film:

- magnetostatic surface waves (MSSW) (at $\vec{H} \perp \vec{n}, [\vec{H}, \vec{n}] \parallel \vec{k}$),
- magnetostatic forward volume waves (MSFVW) (at $\vec{H} \parallel \vec{k} \perp \vec{n}$), and
- magnetostatic backward volume waves (MSBVW) ($\vec{H} \parallel \vec{n}$).

$\vec{n}$ is a unit vector normal to the film plane.

The dispersion equations for these modes, without taking into account finite film width depending on mutual orientation of the vector $\vec{H}$, the wave propagation direction, and surface of film, are as follows:

$$k = -\frac{1}{2d}\ln\frac{\omega_0^2 - \omega^2}{(\omega_M/2)^2}, \tag{1}$$

for MSSW;

$$k = \frac{\sqrt{-\mu}}{d}\left[\text{arctg}\left(\frac{2\sqrt{-\mu}}{1+\mu}\right) + \pi l\right], \quad l = 0, 1, 2, \cdots, \tag{2}$$

for MSBVW;

$$k = \frac{1}{\sqrt{-\mu}d}\left[\text{arctg}\left(\frac{-2\sqrt{-\mu}}{1+\mu}\right) + \pi l\right], \quad l = 0, 1, 2, \cdots, \tag{3}$$

for MSFVW; where

$$\mu' = 1 + \frac{\omega_M[\omega_H(\omega_H^2 - \omega^2(1+\alpha^2)) + 2\cdot\alpha^2\omega\cdot\omega_H]}{[\omega_H^2 - \omega^2(1+\alpha^2)]^2 + 4\alpha^2\omega_H^2\cdot\omega^2},$$

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The authors are with the Microwave Laboratory, Kuban State University, 149, K. Liebknecht Str., Krasnodar, 350640, Russia.
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