Inherently Matched Y-Junction Stripline Circulator

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***Abstract*—An operation principle based on the field-effect displacement phenomenon of the perpendicularly magnetized ferrite striplines constituting the Y-junction circulator is proposed. The experimental results are in agreement with the idea that the striplines of the junction act as half-wavelength transformers ensuring 5%–8% bandwidth of the investigated circulators in the S-band without external matching.**

***Index Terms*—Stripline, Y-junction.**

I. Introduction

THE CLASSICAL stripline circulator consisting of perpendicularly magnetized ferrite disks constituting, together with a circular strip conductor, two TM_{mno} resonators, is known from the remarkable works of Bosma summarized in [1] and additionally described in details in [2]. The input characteristic impedance of this junction is several times smaller than the standard value of 50 Ω and needs matching with quarter-wave transformers, which can ensure narrow-band or wide-band operation in dependence of the design. The other version of the Y-junction circulator—representing the star-coupled striplines, described in the experimental paper [3] is characterizing with higher value of the input impedance, but still needs external matching with a dielectric ring acting as the quarter-wave transformer. For the L- and S-bands, however, both mentioned circulator contractions leading to considerable increasing of the circulator dimensions. Therefore, at lower frequencies, the other circulator junctions, e.g., lumped elements circulators [4], stub-tuned junctions [5], etc., were proposed as an alternative to the classical stripline circulators.

The purpose of this paper is to propose a simple model for operation of a Y-junction constituted by star-coupled perpendicularly magnetized ferrite striplines. Assuming the field-effect displacement of the dominant TEM wave traveling along the striplines of the junction, a supposition for circulator operation is proposed. With a proper choice of the ferrite disks diameter, an inherently matched junction circulator is realized without any external elements. The behavior of the return losses of the investigated junction is then discussed both theoretically and experimentally in details.

II. Theoretical Model

The investigated Y-junction consists of three star-coupled striplines placed between two perpendicularly magnetized ferrite disks with height h and diameter D_f. In the common case

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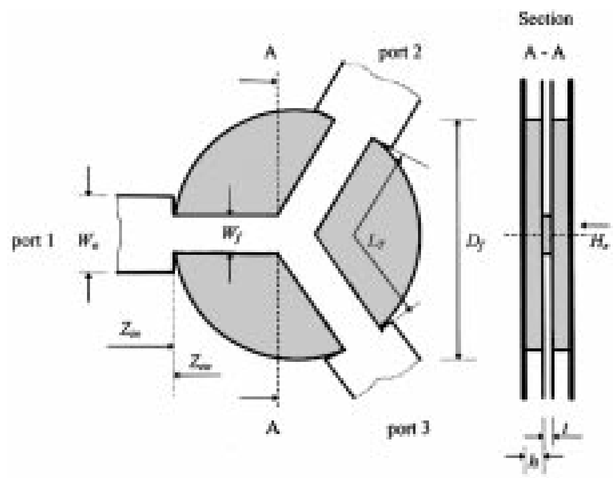


Fig. 1. Y-junction of perpendicularly magnetized ferrite striplines.

shown in Fig. 1, the width of the junction striplines W_f is different from that of the input/output striplines W_o, which are chosen to correspond to 50 Ω.

It is known that in perpendicularly magnetized ferrite striplines a phenomenon of the field-effect displacement can occur for the dominant wave in which distribution in the cross section is similar to a TEM wave [6]. As a result of this, the strength of the electromagnetic field at the edges of the strip conductor can differ considerably. This phenomenon was successfully used for realization of broad-band nonreciprocal phase shifters and isolators, if the edges are terminated with a different medium (e.g., air and lossy material for the case of the isolator).

If the field displacement effect is strong enough, one can suppose that the transverse electromagnetic field of the incident TEM electromagnetic wave traveling from port 1 (for example) to the Y-junction situated in the center of the ferrite disks will be shifted to one of the conductor edges. At that condition, the traveling wave will not be influenced considerably by Y-junction coupling and will follow its way close to the edge of the stripline conductor towards the output port 2. Following the circulation principle, the ferrite stripline between ports 2 and 3 will have the same function, as will that between ports 3 and 1. In this way, one can suppose that the considered Y-junction will act as a junction circulator, with parameters which are determined from the dimensions of the constituted striplines and ferrite parameters.

The phase constant of the dominant TEM-wave traveling along the edge of the stripline [6]

$$\beta_y = \frac{2\pi}{\lambda}\sqrt{\varepsilon_f \mu} \tag{1}$$

depends on the free-space wavelength λ, ferrite permittivity ε_f, and diagonal component μ of the permeability tensor only. Assuming that the ferrite disks are in a partial magnetization state, the approximation proposed in [7] can be used:

$$\mu = \mu_{\text{dem}} + (1 - \mu_{\text{dem}})\left(\frac{M}{M_s}\right)^{3/2} + \frac{H_i M}{H_i^2 - \left(\frac{f}{\gamma}\right)^2}. \quad (2)$$

Here the value of permeability in a demagnetized state [8]

$$\mu_{\text{dem}} = \frac{1}{3}\left\{1 + 2\sqrt{1 - \left(\frac{\gamma M_s}{f}\right)^2}\right\} \quad (3)$$

is determined through the saturation magnetization M_s, operation frequency f, and the gyromagnetic ratio $\gamma = 2.8$ MHz/Oe. The magnetization is calculated from the expression

$$M = M_s\left\{a_1 + (1 - a_1)\left[\frac{1}{th(a_2 H_i)} - \frac{1}{a_2 H_i}\right]\right\} \quad (4)$$

where the internal magnetic field $H_i = H_e - N\,M$ depends on the external field H_e and demagnetizing factor N, while the constants a_1 and a_2 are specified for the case of microwave ferrites as in [7].

If the diameter of the ferrite disk is chosen to be half-wavelength in the ferrite medium $D_f = (\lambda/2)\sqrt{\varepsilon_f \mu}$, the striplines between the two-port will act as a half-wavelength transformer, i.e., no external matching will be necessary when the considered junction is coupled to the standard 50-Ω coaxial or striplines. At these conditions, the choice of the ferrite striplines width W_f is free enough and can be made mainly in dependence of the field-effect displacement requirements. The half-wavelength transformer has a resonance behavior determined from the frequency dependence of the perpendicularly magnetized ferrite-stripline input impedance

$$Z_{\text{in}} = Z_{cf}\,\frac{Z_{co} + jZ_{cf}\tan\left(\frac{2\pi L_T}{\lambda}\sqrt{\varepsilon_f \mu}\right)}{Z_{cf} + jZ_{co}\tan\left(\frac{2\pi L_T}{\lambda}\sqrt{\varepsilon_f \mu}\right)}. \quad (5)$$

Here $Z_{co} = 50\ \Omega$ is the characteristic impedance of the loading coupling striplines of width W_o. The transformer length L_T is shorter than the ferrite disk diameter D_f because the wave is traveling along the strip conductor edge. According to this assumption, the expression

$$L_T = D_f - \frac{W_f}{\sqrt{3}} \quad (6)$$

can be found on the base of the simple geometrical consideration for the Y-junction situated into the disk center. The value Z_{cf} should be considered as the characteristic impedance of the perpendicularly magnetized ferrite striplines. This impedance is determined in [6] for the case of wide stripline width only. To take into consideration the influence of the stray fields, one can reproduce calculations in accordance with the Hines recommendation. As a result of this, the following expression for the characteristic impedance is derived:

$$Z_{cf} = 60\pi^2\frac{h}{\lambda}\,\frac{k}{\mathbf{th}\left(\frac{a_x W_e}{2}\right)} \cdot \frac{1 + \frac{a_x \Delta W\sqrt{\frac{\mu}{\mu_z}}}{th(a_x W_e)}}{\left[1 + \frac{a_x \Delta W\sqrt{\frac{\mu}{\mu_z}}}{2\mathbf{th}\left(\frac{a_x W_e}{2}\right)}\right]^2} \quad (7)$$

where the off-diagonal permeability component [7]

$$\kappa = -\frac{\frac{f}{\gamma}M}{H_i^2 - \left(\frac{f}{\gamma}\right)^2} \quad (8)$$

and the longitudinally permeability component [8]

$$\mu_z = \mu_{\text{dem}}^{[1-(M/M_s)^{5/2}]} \quad (9a)$$

are defined at the above mentioned conditions for the diagonal component μ. The transverse wavenumber characterizing the field displacement of the dominant TEM wave is expressed as in [6]:

$$\alpha_x = \frac{2\pi}{\lambda}\,\frac{\kappa}{\mu}\,\sqrt{\varepsilon_f \mu}. \quad (9b)$$

As can be seen, the expression (7) is similar to that proposed by Hines, but with the addition of the term depending on the edge effect expressed through the effective stripline width

$$W_e = W_f + \Delta W \quad (10)$$

where the edge correction is determined from the Cohn formula [9] for a wide stripline

$$\Delta W = \frac{h}{\pi}\left[2a\ln(1 + a) - (a_1 - 1)\ln(a^2 - 1)\right] \quad (11)$$

depending on the parameters $a = (1 - t/b)^{-1}$, which take into consideration the thickness t of the conductor (note that $2h + t = b$).

When the input characteristic impedance of the ferrite striplines is determined, one can found the frequency dependence of the return loss from the expression

$$RL = 20\ \lg\left|\frac{Z_{in} + Z_{co}}{Z_{in} - Z_{co}}\right|\ \text{dB}. \quad (12a)$$

As is known, the behavior of the return losses can be used to estimate the other circulator parameter—the isolation, which in an ideal case can coincide with that of RL.

TABLE I
JUNCTION PARAMETERS FOR $W_F = 4.7$ MM AND $H_i = 20$ OE

f, GHz	k	μ	$\beta_y L_T$	Z_{cf}, Ω	R_{in}, Ω	X_{in}, Ω	RL, dB
2.320	0.68	0.90	2.993	20.861	45.15	13.07	16.78
2.340	0.68	0.90	3.022	20.884	46.72	10.88	18.67
2.360	0.68	0.91	3.052	20.907	48.02	8.45	21.11
2.380	0.67	0.91	3.081	20.928	49.00	5.82	24.53
2.400	0.66	0.91	3.111	20.948	49.61	3.05	30.25
2.420	0.65	0.91	3.140	20.968	49.84	0.21	53.54
2.440	0.65	0.91	3.169	20.987	49.67	-2.62	31.58
2.460	0.65	0.92	3.198	21.005	49.13	-5.36	25.26
2.480	0.64	0.92	3.227	21.022	48.23	-7.96	21.67
2.500	0.64	0.92	3.256	21.039	47.03	-10.35	19.16
2.520	0.63	0.92	3.285	21.055	45.58	-12.50	17.25
2.540	0.62	0.92	3.314	21.071	43.94	-14.38	15.71

III. NUMERICAL RESULTS

To prove the results obtained, numerical calculations are made for the stripline Y-junction appropriate for S-band. The investigated junction is characterized with dimensions $D_f = 20.5$ mm, $h = 2.5$ mm, $t = 0.15$ mm, and ferrite parameters $\varepsilon_f = 13.3$, $M_s = 700$ G. The frequency behavior of the junction input impedance and return losses are calculated with a FORTRAN program **SLYC** for several values of the ferrite stripline width W_f and internal magnetic field H_i. First, the junction with relatively narrow strips is investigated. For $W_f = 4.7$ mm shown in Table I, the results of the calculations in the frequency range 2.3–2.54 GHz for $H_i. = 20$ Oe are summarized. As can be seen, the maximum value of the return losses corresponds to the input impedance values close to 50 Ω. Note that when the phase angle $\beta_y L_T \rightarrow \pi$, the return losses have its maximum values which are usually much greater than the experimental data. At the level of 20 dB, the bandwidth of 141 MHz is obtained (5.82% of the central frequency 2.421 GHz). The stripline impedance deviates slightly around the value of 21 Ω because the parameters of the ferrite medium are almost constant in the considered frequency band.

The calculation for the other values of the internal magnetic field show similar behavior but with slight deviations of the central frequency and bandwidth. In Table II, both dependencies are shown for an internal magnetic field $H_i. =$ 0–100 Oe. According to the presented data, the magnetic field values $H_i. = 60$ Oe correspond to the lowest central frequency and the widest bandwidth of the investigated circulator.

The influence of the stripline width $W_f.$ is stronger. The calculations for the wider strip show greater shifting of the central frequency and some decreasing of the bandwidth. The corresponding data for $W_f. = 7$ mm are summarized in Table III. Now the central frequency is increased to about 2.6 GHz, because the transformer length (6) becomes shorter. Probably the decreasing of the bandwidth can be explained with the lower value of the stripline characteristic impedance (about 17 Ω). From this point of view, the using of the narrow stripline conductor seams to be more appropriate. For example,

TABLE II
DEPENDENCE OF JUNCTION PARAMETERS FOR $W_f = 4.7$ MM ON THE APPLIED MAGNETIC FIELD H_i

H_i, Oe	0	20	40	60	80	100
f_o, GHz	2489	2421	2404	2411	2426	2445
Δf, MHz	133	141	149	152	151	150
$\Delta f/f_o$, %	5.34	5.82	6.20	6.30	6.22	6.13

TABLE III
JUNCTION PARAMETERS FOR $W_f = 7$ MM AND $H_i = 20$ OE

f, GHz	k	μ	$\beta_y L_T$	Z_{cf}, Ω	R_{in}, Ω	X_{in}, Ω	RL, dB
2.500	0.64	0.92	3.013	16.810	44.15	14.80	15.56
2.520	0.63	0.92	3.040	16.821	46.10	12.29	17.53
2.540	0.62	0.92	3.066	16.831	47.73	9.43	20.12
2.560	0.62	0.92	3.093	16.841	48.93	6.27	23.88
2.580	0.62	0.92	3.119	16.851	49.65	2.91	30.68
2.600	0.61	0.93	3.146	16.860	49.83	-0.55	45.18
2.620	0.61	0.93	3.173	16.869	49.48	-3.97	27.93
2.640	0.60	0.93	3.199	16.878	48.61	-7.25	22.55
2.660	0.60	0.93	3.225	16.886	47.29	-10.29	19.29
2.680	0.59	0.93	3.252	16.894	45.60	-13.00	16.96
2.700	0.58	0.93	3.278	16.902	43.63	-15.34	15.15

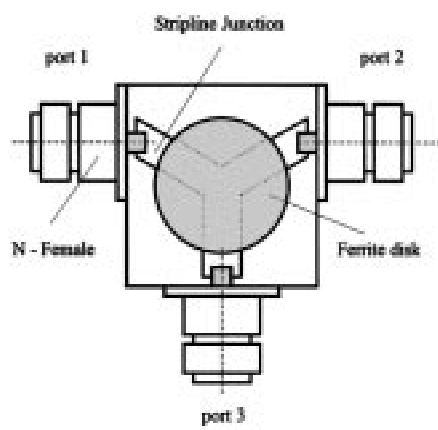
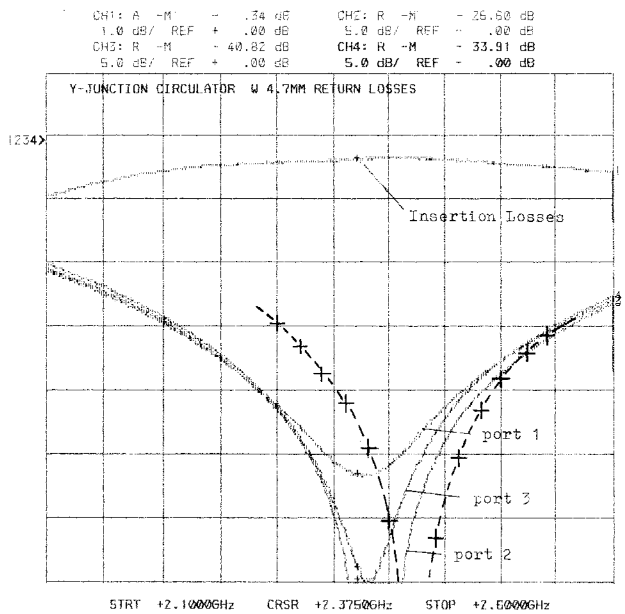


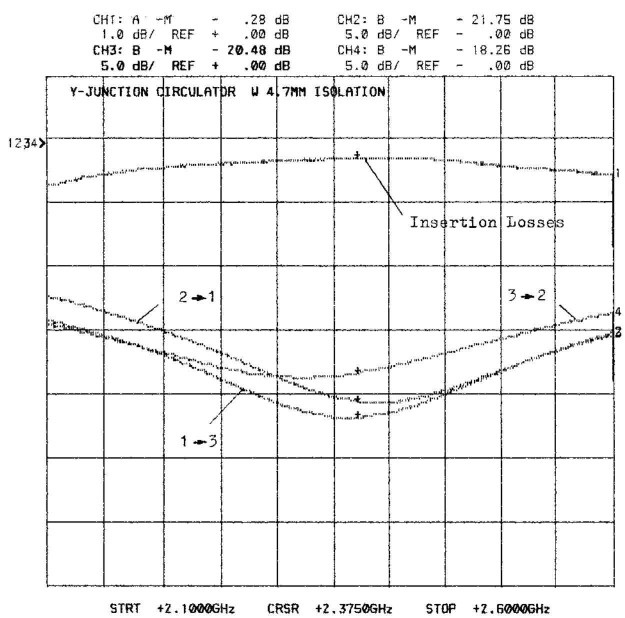
Fig. 2. Experimental model of Y-junction stripline circulator.

calculations show that at the above mentioned conditions, the junction with $W_f = 3$ mm should have the bandwidth of about 180 MHz. This conclusion, however, will be true only for a half-wavelength transformer, not for the investigated junction. Note that at the beginning, the assumption was made for the wide-enough stripline conductors in which a strong enough field-effect displacement takes place. So, the correct choice of the ferrite stripline width W_f should be done as an compromise of both effects during experimental realization.

It is interesting to compare the obtained results for the central frequency of the junction with data suggested by other authors. According to the well-known expression $kR = 1.84$ [1], [2], the diameter of the ferrite disks planar resonators

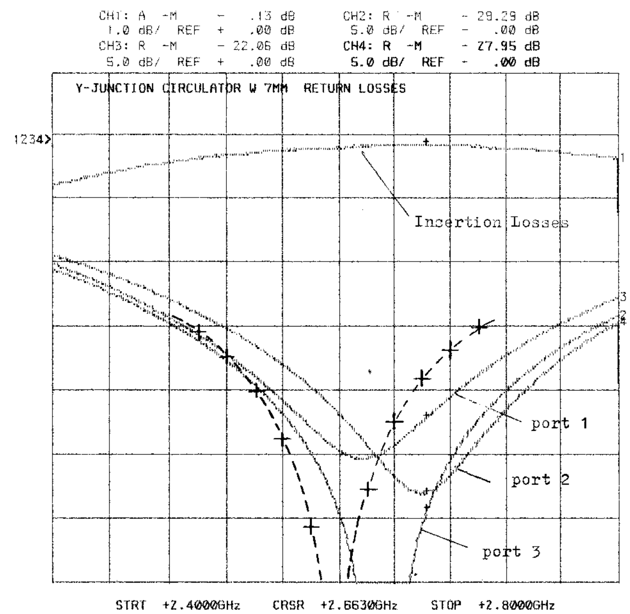


(a)

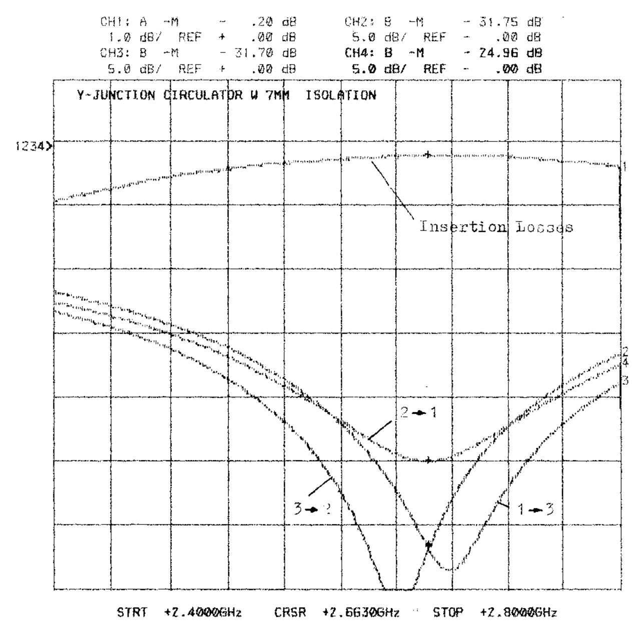


(b)

Fig. 3. (a) Comparison between measured and calculated (+ + +) return losses of the stripline Y-junction with parameters corresponding to Table I. (b) Measured isolation of the junction with $W_f = 4.7$ mm.



(a)



(b)

Fig. 4. (a) Comparison between measured and calculated (+ + +) return losses of stripline Y-junction with parameters corresponding to Table III. (b) Measured isolation of the junction with $W_f = 7$ mm.

supporting the TM_{110} mode of operation can be determined from the formula

$$R = \frac{0.293\lambda}{\sqrt{\varepsilon_f \mu_{\mathrm{eff}}}} = \frac{87.85}{f_o[\mathrm{GHz}]\sqrt{\varepsilon_f \mu_{\mathrm{eff}}}} \text{ mm} \tag{12b}$$

where $\mu_{\mathrm{eff}} = \mu - \kappa^2/\mu$. According to this expression the optimum diameter of the ferrite disks for $f_o = 2.4$ GHz and $\varepsilon_f = 13.3$ should be $D_f \approx 20$ mm if $\mu_{\mathrm{eff}} = 1$. This result is close to that used above. However, $\mu_{\mathrm{eff}} < 1$, as well as the fact that there is no reason to use the result obtained for the circular disk resonator for the case of the Y-junction constituted of striplines. The similar results of $D_f \approx 20.5$ mm can be defined from the curve proposed (probably empirically) in [3]. Obviously, this coincidence can explain why (12b) is widely used for rough determination of the ferrite disk's diameter. However, for the Y-junction considered above, this way seems to be inappropriate because it cannot explain the influence of the stripline width W_f on the central frequency.

IV. Experimental Results

The experimental investigation of the Y-junction stripline circulator is done at the conditions of Tables I and III. For this purpose, an experimental model with a T-shape of the ports shown in Fig. 2 was designed and tested. The input striplines are air filled and of the same height as that of the junction ($W_o = 7$ mm, $h = 2.5$ mm). The circulator is supplied with standard N-Female connectors and measured with the Scalar Network Analyzer System Hp 8757S.

The measured values for return losses of the junction consisting of three perpendicularly magnetized ferrite striplines of width $W_f = 4.7$ mm are presented in Fig. 3(a) together with the theoretical data for RL from Table I. As can be seen, the experimental measured data for RL of the ports has the same behavior as the predicted one. The maximum value is observed around 2.375 GHz, which deviates slightly (2%) from the predicted value 2.425 GHz in Table I. The measured bandwidth at $RL = 20$ dB exceeds 180 MHz and is also in agreement with the theoretical 141 MHz. The measured values for the junction isolation are shown in Fig. 3(b). The isolation behavior coincides with that of the return losses but are smaller and vary in the limits 20± 2 dB for the bandwidth. Probably due to the narrow width of the junction ferrite striplines, the field effect displacement is not strong enough. From this point of view, the junction with wider striplines seems to be more appropriate if a circulator with a higher value of isolation should be realized.

The experimental data for return losses and isolation of the junction constituted by striplines of width $W_f = 7$ mm are shown in Fig. 4(a) and (b). The measured values are in good agreement with that of Table III and this fact can undoubtedly be considered as a confirmation of the proposed model. The central frequency of the junction is now shifted higher—around 2.6 GHz, and the isolation characteristics are better than that in Fig. 3(b). Note that the junction with $W_f = 7$ mm has worse symmetry than the previous one. This can probably be explained by the imperfection of the handmade stripline junction, as well as an inaccuracy during the pasting of the ferrite disk with respect to the Y-junction. The final problem can be solved if the width of the junction W_f is chosen differently from W_o. The other alternative is to use external matching—a procedure widely used during fabrication of the circulators. One can use either small dielectric inserts or tuning screws to symmetrize the junction if definite requirements should be fulfilled.

The behavior of the insertion losses of both investigated junctions correlates well with that of the return losses and isolation. At central frequency, its values are minimum—about 0.2–0.3 dB. For example, Figs. 3 and 4 show the measured curves for insertion losses.

V. Conclusion

The field-effect displacement of the dominant TEM wave traveling between the ports of the Y-junction constituted of perpendicularly magnetized ferrite striplines is suggested as a model for circulator operation. The numerical results for return losses are in good agreement with measured data for the S-band. Through experimental optimization, the width of the junction striplines can be easy defined if the definite value of the isolation (20 dB) should be obtained. The investigated Y-junction circulator may be attractive mainly for a narrow-band microwave system. The dimensions of the proposed devices can be reduced to the ferrite disk diameter and need low magnet fields which simplify its practical realization. Preliminary investigation has shown that by using the matching procedure described in [10], the bandwidth of the considered Y-junction can be improved if the principle of the frequency compensation between the internal half-wavelength and the external quarter-wavelength transformer is properly chosen.

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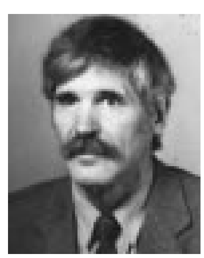

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