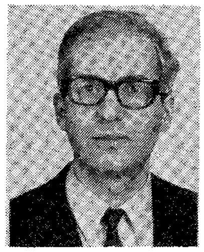
[3] O. P. Ghandhi and C. Dattatreyan, "An *L*-band broad bandwidth circulator," in *Proc. I.E.E.*, vol. 111, no. 7, pp. 1285–1286, July, 1964.
[4] D. Masse, "Broadband microstrip junction circulators," in *Proc. IEEE*, vol. 53, pp. 352–353, Mar. 1968.
[5] J. Edrich and R. G. West, "Very low loss *L*-band circulator with gallium substituted YIG," presented at *IEEE Intermag, Conf.*, (Amsterdam), 1969.
[6] J. Helszajn, "The synthesis of quarter-wave coupled circulators with Chebyshev characteristics," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-20, pp. 764–769, Nov. 1972.
[7] Z. Uzdy, "Computer aided design of stripline ferrite junction circulators," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-28, pp. 1134–1136, Oct. 1980.
[8] G. P. Riblet, "The extent of the similarity between the below and above resonance operation of standard circulator junctions," in *Digest of 1978 MMT-S Int. Symp.*, pp. 323–325.
[9] J. Helszajn, "Scattering matrices of junction circulator with Chebyshev characteristics," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-23, pp. 648–654, July 1975.
[10] J. B. Davies and P. Cohen, "Theoretical design of symmetrical junction stripline circulators," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-11, pp. 506–512, 1963.



Joseph Helszajn (M'64) was born in Brussels, Belgium, in 1934. He received the Full Technological Certificate of the City and Guilds of London Institute from Northern Polytechnic, London, England, in 1955, the M.S.E.E. degree from the University of Santa Clara, Santa Clara, Calif., in 1964, and the Ph.D. degree from the University of Leeds, Leeds, England, in 1969, and the D.Sc. degree from Heriot-Watt University, Edinburgh, Scotland, in 1976.

He has held a number of positions in the microwave industry. From 1964 to 1966 he was Product Line Manager at Microwave Associates, Inc., Burlington, MA. He is a consultant to several microwave companies and is a Reader at Heriot-Watt University. He is the author of the books *Principles of Microwave Ferrite Engineering* (NY: Wiley), *Nonreciprocal Microwave Junctions and Circulators* (NY: Wiley, 1975), and *Passive and Active Microwave Circuits* (New York: Wiley, 1978).

Dr. Helszajn is a Fellow of the Institution of Electronic and Radio Engineers and a Fellow of the Institution of Electrical Engineers. In 1968 he was awarded the Insignia Award of the City and Guilds of London Institute. He is an Honorary Editor of *Microwaves, Optics, and Antennas* (I.E.E. Proceedings).

Equivalent Circuit Representation for the *E*-Plane Circulator

KLAUS SOLBACH, MEMBER, IEEE

***Abstract*—The resonator structure employed in an *E*-plane circulator may be described by a series-resonant circuit as opposed to a parallel circuit in the case of comparable *H*-plane devices. This is shown to result in a change of the direction of circulation at the edges of the circulator passband. Employing the equivalent circuit representation methods to increase the bandwidth of the *E*-plane circulator are discussed.**

I. Introduction

During the last years, millimeter-wave *E*-plane (fin-line) circuits have been developed to a high degree of sophistication. Today, completely integrated RF front ends are available in fin-line technique. Since fin-line is basically an *E*-plane waveguide, where only *E*-plane junctions may be easily realized, circulators compatible with *E*-plane geometry are needed for more complex systems. This leads to new efforts in the investigation of *E*-plane circulators.

Up until now, *E*-plane circulators have been used mainly in high-power applications [1]–[3]. Other workers employ *E*-plane devices in an effort towards miniaturization and compactness [4], [5]. Neither in these papers nor in the only published field theoretical analysis of *E*-plane circulators [6], [7] has there been an analysis of the type of resonant structure employed in the junction circulators. Equally, there is no discussion of the differences in the behavior of the *E*-plane circulator as compared to the *H*-plane circulator.

In this paper the basic behavior of an *E*-plane *Y*-junction circulator with an unsymmetric ferrite insert employing the lowest order resonant mode is contrasted to the behavior of the commonly used *H*-plane devices, and an equivalent circuit representation for the *E*-plane circulator is presented which differs from that of the *H*-plane circulator.

II. The Resonant Structure (Lowest Order Mode)

The basic structure in *Y*-junction circulators is the resonator containing the anisotropic material (ferrite). In the following, the ferrite resonator is assumed to be a purely dielectric structure (zero magnetic bias field).

Manuscript received October 12, 1981; revised December 28, 1981.
The author is with AEG-Telefunken, Geschaeftsbereich Hochfrequenztechnik, A1E32, 7900 Ulm, West Germany.

0018-9480/82/0500-0806$00.75 ©1982 IEEE

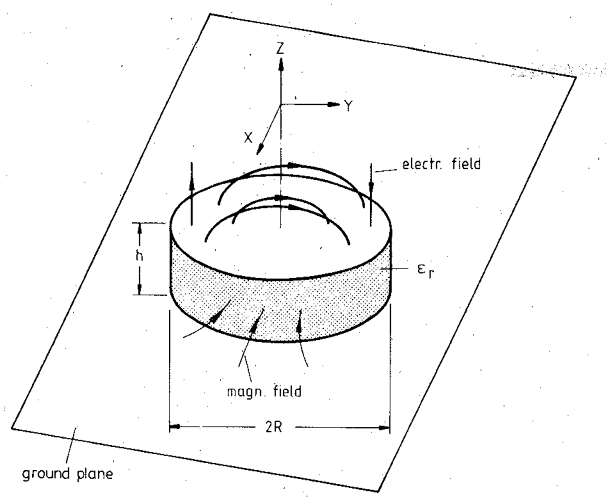


Fig. 1. Sketch of the electric and magnetic field of the lowest order resonant mode of a flat dielectric disk on a conducting ground plane.

The type of dielectric resonator to be discussed here is sketched in Fig. 1. The lowest resonant mode of the flat dielectric disk, as shown in Fig. 1, is a hybrid EH-mode with half-cycle variations of the fields in x- and y-direction and with exponentially decaying fields in the z-direction. This resonant mode is related to the $\lambda/2$-resonance of the fundamental EH_{11}-mode on a rectangular dielectric image line, where the standing wave pattern is in the y-direction between the two open-circuited ends of the dielectric line.

It has been found that this assumption leads to good first order approximations of the resonance frequency if both the width of the equivalent dielectric image line and the length is chosen as $2w = l = \sqrt{\pi}R$. Thus, using published data for the phase constants β of the waves guided by dielectric image lines, e.g., [8], the resonance frequency can be calculated from the condition $l = \lambda/2 = \pi/\beta$.

It is interesting to note here that this resonance mode of the ferrite disk is similar to that employed in many partial-height H-plane junction circulators. Only the ratio of R/h is different: In H-plane structures the ratio will be small ($h > R$), while in E-plane devices, as discussed here, the ratio will be large ($h < R$). The reason for this fact is the different mode of excitation in both cases: In H-plane junctions the waveguide TE_{10}-mode electric field couples mainly through the electric E_z-field of the resonator (tight coupling), while in the E-plane junction the coupling is through the E_y-field of the resonator (loose coupling).

This coupling of the waveguide fields to the resonator fields is indicated in Fig. 2, where the resonator is mounted on the narrow wall of the waveguide. It can be seen here that the transverse electric field and the longitudinal magnetic field of the waveguide mode couple to the resonator fields.

Due to this mode of coupling, the equivalent circuit representation for the resonator-loaded waveguide is a series resonant circuit shunted across the waveguide (Fig. 2). In accordance with this, experimentally it is found that the resonator acts as a stopband filter.

On the other hand, the resonator placed on the broad

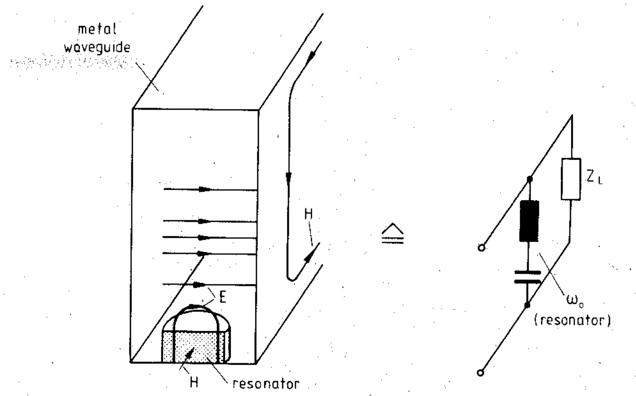


Fig. 2. Sketch of the fields of the disk resonator and the waveguide TE_{01}-mode with the corresponding equivalent circuit.

wall of the waveguide (as in H-plane-junction or stripline circulators) yields a parallel resonant circuit instead [9], [10]. This difference in the equivalent circuits will be shown to be most important for the understanding of the behavior of the E-plane circulator.

III. E-Plane Circulator

The resonator disk placed in the center of an E-plane Y-junction is converted from a stopband filter (series resonant circuit) to a circulator by applying direct magnetic field in the Z-direction of the disk. The physical mechanism employed in the circulator action can be described by a model analog to that used by Bosma [9] and Fay and Comstock [10].

The field distribution as sketched in Fig. 1 can be decomposed into two counter-rotating field patterns of the same configuration. Due to the direct magnetic field applied to the ferrite the two modes split in their resonant frequencies, ω^+ for the positive circulating pattern and ω^- for the negative circulating pattern.

The same considerations as given in [9] and [10] lead to an equivalent circuit representation for the circulator consisting of two resonant circuits for the $+$ and the $-$ mode, Fig. 3. The two circuits must be connected in series to account for the change of the original stopband into a pure passband when direct magnetic field is applied [14].

Perfect circulation is supposed to occur if the resonant circuits have phase angles of $\pm 30°$. The operating frequency is approximately midway between the $+$ and $-$ mode frequencies.

In Fig. 4 the mode impedances are plotted for several frequencies. It can be seen that for frequencies far below Fig. 4(a) and far above the two resonant frequencies Fig. 4(e) the phase of the $+$ mode leads the phase of the $-$ mode, while the $-$ mode leads the $+$ mode between the resonant frequencies (Fig. 4(b)–4(d)).

From this it can be concluded that the direction of circulation for frequencies between the $+$ and $-$ resonances may differ from the direction of circulation for frequencies far below and far above the resonances, even though perfect circulation may only occur at one unique frequency (Fig. 4(c)), where the magnitudes of both imped-

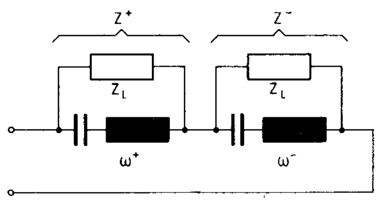


Fig. 3. The equivalent circuit representation of the E-plane Y-junction circulator (lowest order mode).

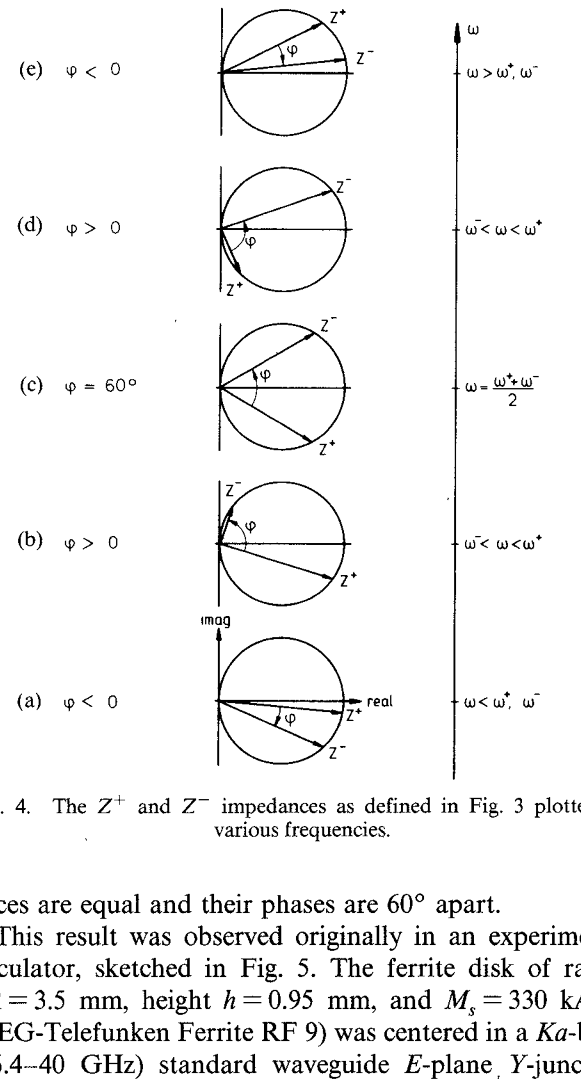


Fig. 4. The Z^+ and Z^- impedances as defined in Fig. 3 plotted for various frequencies.

ances are equal and their phases are 60° apart.

This result was observed originally in an experimental circulator, sketched in Fig. 5. The ferrite disk of radius $2R = 3.5$ mm, height $h = 0.95$ mm, and $M_s = 330$ kA/m (AEG-Telefunken Ferrite RF 9) was centered in a Ka-band (26.4–40 GHz) standard waveguide E-plane Y-junction. With zero direct magnetic field, stopband resonance was found at 31 GHz. With increasing magnetic field, first the stopband transforms into a passband and eventually circulation properties are observed. With a direct magnetic field of 79 kA/m (1000 G) optimum circulation occurred at 30.7 GHz (Fig. 5).

It can be seen from Fig. 5 that above and below the center frequency there is a change in the direction of circulation, although this effect occurs only at the edges of the circulator passband, as may be defined with respect to the input reflection coefficient s_{11}.

Now, from the equivalent circuit representation of the circulator (Fig. 3), it is clear that in order to increase the bandwidth of the circulator, either the line impedances Z_L

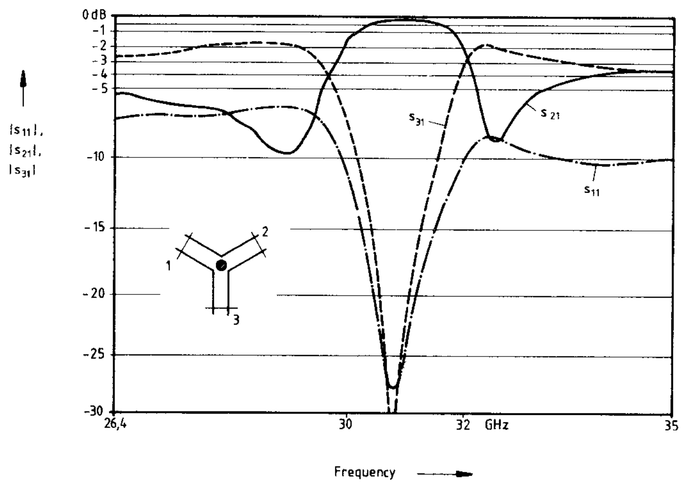


Fig. 5. The measured scattering coefficients of a single ferrite disk E-plane circulator.

of the waveguide arms must be increased or the impedance slope parameters of the resonant circuits must be decreased. This is in contrast to the H-plane case, where the quality factor decreases and the bandwidth increases with decreasing line impedance and increasing resonant circuit impedance.

One way to increase the line impedances is to decrease the width of the waveguides, that means to decrease the height of E-plane junction. This technique is used in several practical circulator designs [5], [11].

The impedance slope parameters of the resonant circuits on the other hand can be decreased by increasing the coupling of waveguide and resonator fields, e.g., by employing a lower height disk (with a larger diameter to keep the resonant frequency constant), by adding dielectric disks on the ferrite [2], [3], or by employing two identical disks on either wall of the junction. This latter alternative has been used in most published designs, but it has been found extremely difficult to achieve the high degree of symmetry that is required for undisturbed circulation characteristics of the device [1], especially in the millimeter-wave frequency range. The basic properties, however, are the same in the single disk and double disk circulator.

Of course, quarter-wave transformation may be utilized for broad-banding E-type circulators in the same way as for other types [12], [13].

IV. Conclusions

It has been shown that the behavior of the described E-plane circulator is different from that of H-plane devices. The employed resonant structure may be described by a series resonant circuit as opposed to a parallel circuit in the case of the H-plane device. This results in a change of the direction of circulation at the edges of the circulator passband. Ways to increase the bandwidth of the E-plane circulator can be derived from the equivalent circuit representation of the circulator and include height-reduction of the junction and the use of a dielectric "transformer" disk on top of the ferrite.

References

[1] A. P. Darwent, "Symmetry in high power circulator for 35 GHz," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-15, p. 120, Feb. 1967.

[2] W. Wright and J. McGowan, "High-power Y-junction E-plane circulator," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-16, pp. 557–559, Aug. 1968.

[3] E. DeCamp and R. True, "1 MW four-port E-plane junction circulator," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-19, pp. 100–103, Jan. 1971.

[4] L. E. Davis and S. R. Longley, "E-plane 3-port x-band waveguide circulators," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-11, pp. 443–445, Sept. 1963.

[5] G. Buchta, "Miniaturized broadband E-Tee circulator at x-band," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-14, pp. 1607–1608 Nov. 1966.

[6] El-Shandwily, A. Kamal, and E. Abdallah, "General field theory treatment of E-plane waveguide junction circulators–part I: Full-height ferrite configuration," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-25, pp. 784–793, Sept. 1977.

[7] El-Shandwily, A. Kamal, and E. Abdallah, "General field theory treatment of E-plane waveguide junction circulators–part II: Two-disk ferrite configuration," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-25, pp. 794–803, Sept. 1977.

[8] K. Solbach and I. Wolff, "The electromagnetic fields and the phase constants of dielectric image lines," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-26, pp. 266–274, Apr. 1978.

[9] H. Bosma, "On strip line Y-circulation on UHF," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-12, pp. 61–72, Jan. 1964.

[10] C. E. Fay and R. L. Comstock, "Operation of the ferrite junction circulator," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-13, pp. 15–27, Jan. 1965.

[11] J. Helszajn and M. McDermott, "Mode chart for E-plane circulators," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-20, pp. 187–188, Feb. 1972.

[12] I. M. Alexander and K. L. Flett, "Design and development of high power Ku-band junction circulators," *IEEE Trans. Magn.*, vol. MAG-13, 1255–1257, Sept. 1977.

[13] M. Braas and C. Schieblich, "E-type circulator for fin-lines," *Electron. Lett.*, vol. 17, no. 19, 701–702.

[14] M. Omori, "An improved E-plane waveguide circulator," presented at *IEEE G-MTT Int. Microwave Symp.* 1968, May 20–22 1968.

Klaus Solbach (M'80) was born in Witten, West Germany in 1951. He received the Dipl.-Ing. degree from the Technical University of Aachen, West Germany in 1974 and the Dr.-Ing. degree from the University of Duisburg, West Germany in 1979.

From 1975 to 1980 he had been employed at the University of Duisburg as a research assistant. He has been engaged in investigations of the properties and circuit applications of dielectric image lines in the millimeter-wave frequency range.

In 1981 he joined AEG-Telefunken in Ulm, West Germany, where he is engaged in the development of integrated millimeter-wave circuits.

Higher Order Mode Interaction in Nonreciprocal Periodic Structures

T. A. ENEGREN AND M. M. Z. KHARADLY

Abstract—**This paper is an extension of previous work on nonreciprocal periodic structures where only dominant mode interaction was considered. Higher order mode interaction is taken into account by using multimode wave matrix analysis. Numerical results for the propagation coefficient characteristics are given for a specific example of a twin-slab ferrite-loaded rectangular waveguide, periodically loaded with thin metallic diaphragms. These characteristics show similar trends to those observed in a previous experimental investigation.**

I. Introduction

IN A RECENT paper, wave matrix analysis has been used to study nonreciprocal periodic structures [1]. The analysis presented in [1] enabled determination of the propagation constants of the forward and backward traveling Bloch waves, based on single dominant mode interaction between the discontinuities. Comparison between theoretical prediction and measurement for a ferrite loaded waveguide periodically loaded by thin inductive diaphragms showed that the single dominant-mode theory gave good results only when higher order mode interaction between the diaphragms could be neglected [1]. When the spacing between the loading elements became small, there were significant discrepancies between measurement and prediction. This paper shows that these discrepancies can be attributed to the effects of higher order mode interaction between the discontinuities.

The numerical analysis presented in [2] for the scattering problem of the infinitely thin metallic diaphragm in a magnetized ferrite-loaded waveguide can be extended to

Manuscript received April 22, 1981; revised November 24, 1981.

The authors are with the Department of Electrical Engineering, University of British Columbia, 2075 Wesbrook Mall, Vancouver, British Columbia, Canada.

0018-9480/82/0500-0809$00.75 ©1982 IEEE