However, if a straight line is fitted to the experimental points in Fig. 7 (curve 1) using a least square fitting procedure the intercept at $4\pi M = 0$ yields an $H_0$ of 1265 Oe, in good agreement with the external field of 1240 Oe used for these ferrites. The slope yields an $\langle N_z(x_0,z)\rangle$ of 0.607 which lies between the value of $N_z(a,0)$ and $N_z(0,0)$ (see Fig. 6). If this latter value is used for $\langle N_z(x_0,z)\rangle$ in (19), the agreement with the experimental curve is improved as shown by curve 4 in Fig. 7. This curve now predicts frequencies within three percent of the observed ones.

For the lithium ferrites, curves of the type displayed in Fig. 7 could not be set up because $g_{eff}$ was not constant from sample to sample. Table I compares the measured frequencies of the reverse loss peaks of these lithium ferrites with those predicted from (10). The agreement is better than 8 percent; however, it is important to note that separate $g_{eff}$ measurements had to be made at $S$ band in order to arrive at accurate values of $H_i$.

Insertion-loss measurements have also been made on ferrite slabs of various thicknesses in the $x$ direction (0.020 in $\leq 2a \leq$ 0.060 in), the ferrite-to-helix distance being held constant. The measurements showed that the insertion loss increases moderately with the ferrite thickness. This is in qualitative agreement with our interpretation of the resonant frequencies in that it confirms that the excitation is not tightly confined to the sample surface.

## IV. CONCLUSION

Two simple equations [(8) and (10)] have been derived and compared with the observed resonance-loss frequencies of ferrites near $S$ band delay lines. The comparison has shown that (10), which corresponds to $k_z = 0$, agrees with the measured frequencies to within 3 percent, if a value of $N_z$ somewhere between surface and bulk (but closer to bulk) values is chosen.

If the effective $g$-value of the polycrystalline material differs substantially from the single-crystal value ($\simeq 2$), as was the case for the lithium ferrites used in the present experiments, a separate determination of $g_{eff}$ in the frequency band of interest is necessary in order to derive reliable estimates of the frequency at which the delay line has maximum absorption.

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[4] E. Schlömann and R. I. Joseph, "Spin waves and magnetostatic waves," Raytheon Tech. Rep. R-68, Mar. 1968, pp. 30–39, unpublished.

[5] R. I. Joseph and E. Schlömann, "Demagnetizing field in nonellipsoidal bodies," *J. Appl. Phys.*, vol. 36, pp. 1576–1593, May 1965.


# An Annotated Bibliography of Microwave Circulators and Isolators: 1968-1975

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***Abstract*—A bibliography of microwave circulators and isolators from 1968 to 1975 is presented. Some observations on selected topics are made.**

## INTRODUCTION

THIS PAPER presents a bibliography building on the one published in an earlier review paper.[1] As such, it precludes the reexamination of most of the more fundamental papers which were published before 1968. The literature is not critically surveyed; rather, some observations on selected topics are made. The emphasis on different contributions is somewhat influenced by the author's own background and experience.

In the years after 1968, microwave circulator and isolator[2] design techniques have matured and have been furthered by systematic, scientific studies. Waveguide circulators have become better understood and the computer has been successfully applied to solve the awkward boundary value problems for some of the simpler structures. In the next section, the renewed effort to use $S$-parameter eigenvalues for circulator design will be reviewed in more detail.

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[1] R. F. Soohoo, "Microwave ferrite materials and devices," *IEEE Trans. Magn.*, vol. MAG-4, pp. 118–133, June 1968.

[2] Since circulators are frequently used as isolators by terminating one port, all comments concerning circulators apply to those as well.

Stripline circulators have found wide application in microwave integrated circuits, and well-established design procedures have been refined.

In frequency ranges where stripline devices become too bulky, mainly at $L$ band or below, lumped-element circulators have become well established and have started to compete for higher $S$-band frequencies.

Novel devices such as the edge-guided mode isolator, which shows good multioctave performance, have emerged. Lumped-element multioctave isolators have been developed by cascading nonsymmetrically terminated circulators. In spite of their high insertion loss, the latter are well suited for applications at television frequencies.

Other devices, such as transistor (electronic) circulators, manifest themselves. In the coming years there will be more advances and strong emphasis on making the existing designs more economical to ensure that the design engineer can use them as a convenience rather than only as a necessity.

## SELECTED TOPICS

### *Eigenvalue Approach to 3-Port Y-Junction Circulator Design*

The author considers the "revival" of the eigenvalue analysis and especially its experimental application to circulator design as one of the main achievements in the review period. This analysis of the $Y$-junction circulator in terms of its scattering parameter eigenvalues and eigenvectors was introduced in 1959 [1] and used successfully by several authors [2]–[4] to analyze circulators.

It was realized very early that the fields resulting from the eigenexcitations could be influenced individually [1], and it is well known [5] that in the lossless case[3] a symmetrical 3-port is an ideal circulator if its $S$-parameter eigenvalue phases are 120° apart. However, it was only very recently that they were measured [1.5] and, together with the analysis, were proven to be an excellent tool for designing a new generation of broad-band circulators [1.5], [3.6]–[3.8]. The experimental setup is shown in Fig. 1. This circuit permits the excitation of the $Y$ junction by the different eigenvectors and the $S$-parameter eigenvalue phases or amplitude to be displayed on a network analyzer. This setup has the advantage of giving an instantaneous analog display. An indirect measurement of magnitude and phase has been obtained by appropriately programming a computerized network analyzer [3.7].

## PERIPHERAL MODE ISOLATOR

The problem of obtaining a stable amplification with negative resistance diodes distributed along a transmission line has been partially solved by the edge-guided wave isolator or peripheral-mode TM isolator [6] first analyzed by Hines [4.12]. The structure is shown in Fig. 2 and a typical performance is shown in Fig. 3. An isolator of this type is about 2–2.5 in long, and, as the mechanical construction implies, lends itself readily to integration. The principle of operation of the device is quite simple. In a microstrip line of significant width on a ferrite slab magnetized perpendicular to the ground plane, the dominant mode exhibits an exponential field

[3] For the lossy case see [3.8] and [7].

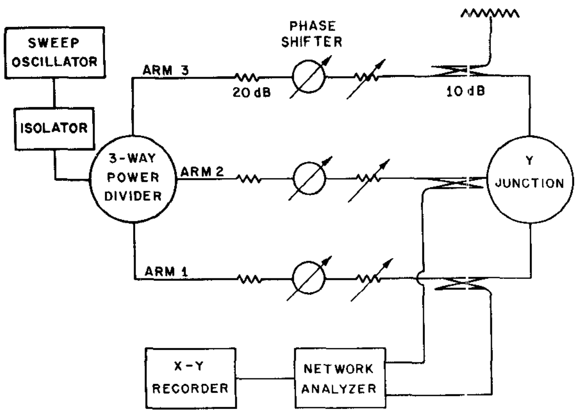


Fig. 1. Eigenvalue measuring set courtesy of B. Owen [1.5], Bell Labs., Allentown, Pa. 18103.

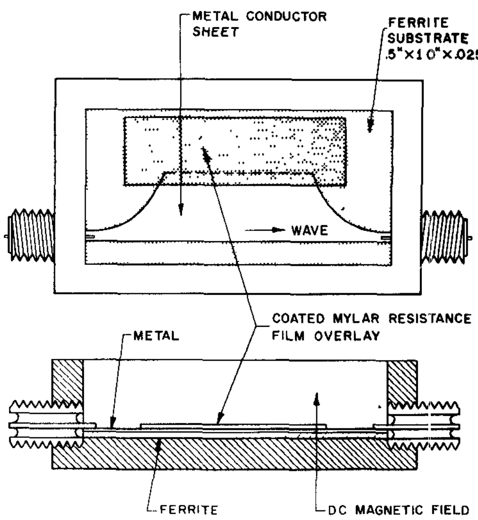


Fig. 2. Experimental microstrip isolator, courtesy of M. E. Hines [4.12], Microwave Associates, Inc., Burlington, Mass. 01803.

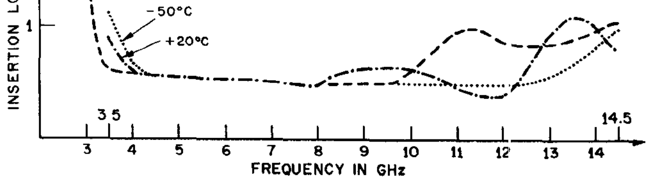


Fig. 3. Measured performance of edge-guided mode isolator, courtesy of L. Courtois, B. Chiron, and G. Forterre [4.7], Lignes Telegraphiques et Telephoniques, 78-Conflans-ste-Honorine, France.

variation in the direction perpendicular to the edge, i.e., the energy is concentrated near one edge of the conductor. In the opposite direction of propagation, the wave will propagate along the other edge and can eventually be dissipated in an absorbing film, leading to isolator action. The simple mechanical structure and extreme bandwidth (Fig. 3) make this device attractive for many applications. A good, approximate analysis of the device is given in [4.12] where it was assumed that the center conductor (Fig. 4) is wide compared with the substrate thickness thus locating most of the TE-mode energy in zone 1 between the conductors. The fringing field admittances are then approximately determined and matched to the edge admittance of zone 1.

## ELECTRONIC CIRCULATOR

Passive circulators using the gyromagnetic properties of garnets become bulky and are low-performance devices below 50 MHz. Part of their function is being taken over by electronic circulators or, as they are sometimes referred to, transistor circulators or active circulators. These devices are known to circuit designers as gyrators which usually are nonreciprocal 2-ports. So-called 3-port gyrators are pushing for higher frequencies and are now referred to as circulators as mentioned previously. Several devices of this kind are listed in [4.1]–[4.3]. A very complete treatment in terms of $S$ parameters is given in [4.2]. The device contains 6 transistors, 3 Zener diodes, and 15 resistors. Its frequency of operation is 0–30 MHz; minimum isolation, 20 dB; maximum insertion loss, 0.5 dB.

Now there are also commercial units available covering the range up to 150 MHz. At this time these devices are input power limited to about 17–20 dBm. For higher power levels a passive device would still be desirable.

## WIDE-BAND UHF CIRCULATORS

The extensive list of literature in Section III indicates substantial work. At $L$ band, 20-dB isolation bandwidths of 40 percent or more have been reported [3.4]–[3.8] with low insertion loss (<0.4 dB). There are applications at UHF, however, which require multioctave isolators. At these frequencies (used for television broadcasting), gain is relatively easy to get and therefore isolators with high insertion loss are still useful. Konishi [3.1], [3.2] has found a way to increase the isolation bandwidth by reactively terminating one port of a lumped-element circulator [Fig. 5(a)]. This makes the device nonsymmetrical, and the isolation bandwidth is obtained at the expense of return and insertion loss [Fig. 5(b)]. By cascading six of these isolators, each one tuned to a different frequency, Konishi has obtained an isolation bandwidth of 20 dB from 70 to 800 MHz. Insertion loss over the band was <3 dB (Fig. 6).


[1] B. A. Auld, "The synthesis of symmetrical waveguide circulators," *IRE Trans. Microwave Theory Tech.*, vol. MTT-7, pp. 238–246, Apr. 1959.
[2] U. Milano, J. H. Saunders, and L. Davis, Jr., "A $Y$-junction strip-line circulator," *IRE Trans. Microwave Theory Tech.*, vol. MTT-8, pp. 346–351, May 1960.
[3] J. B. Davies and P. Cohen, "Theoretical design of symmetrical junction stripline circulators," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-11, pp. 506–512, Nov. 1963.
[4] Y. Konishi, "Lumped element Y circulator," *IEEE Trans. Microwave Theory Tech. (1965 Symp. Issue)*, vol. MTT-13, pp. 852–864, Nov. 1965.
[5] H. J. Carlin, "Principles of gyrator networks," in *Proc. Symp. Modern Advances in Microwave Techniques*, Polytech. Inst. Brooklyn (New York, N. Y., Nov. 1954).


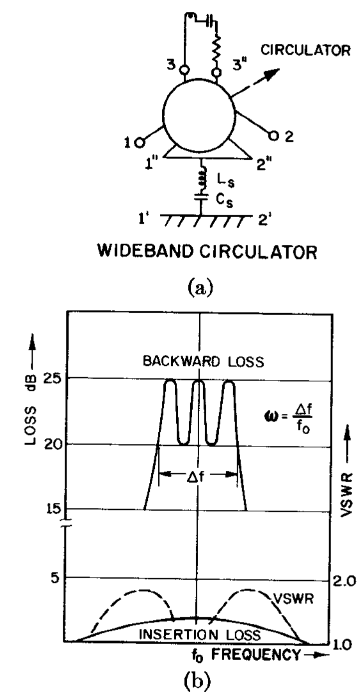


Fig. 5. Performance of wide-band circulator, courtesy of Dr. Y. Konishi, N.H.K., Japan [3.1], [3.2].

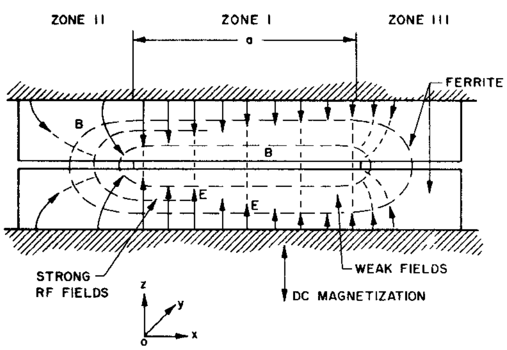


Fig. 4. Cross section of stripline showing RF fields of dominant mode, courtesy of M. E. Hines [4.12], Microwave Associates, Inc., Burlington, Mass. 01803.

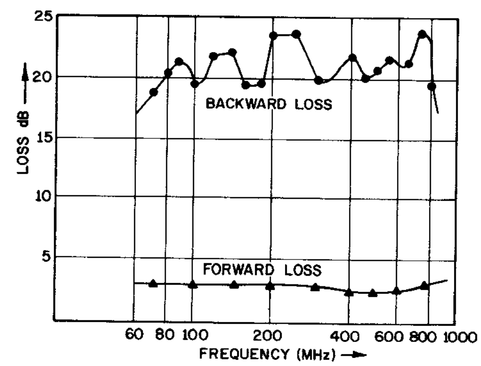


Fig. 6. Performance of trial ultrawide-band isolator, courtesy of Dr. Y. Konishi, N.H.K., Japan [3.1], [3.2].

[6] R. Anderson, U. S. Patent 3 555 459.
[7] H. Bosma, "Performance of lossy $H$-plane $Y$ circulators," *IEEE Trans. Magn.* (*1966 INTERMAG Issue*), vol. MAG-2, pp. 273–277, Sept. 1966.

## LITERATURE

The bibliography is subdivided into different topics. Each topic contains several papers with more extensive comments. The author considered these to be the most significant contributions. The remaining papers are listed under Further References.

Under each heading an approximately chronological order is followed starting with the most recent publication.

## I. WAVEGUIDE CIRCULATORS

[1.1] M. E. El-Shandwily, A. A. Kamal, and E. A. F. Abdallah, "General field theory treatment of $H$-plane waveguide junction circulators," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-21, pp. 392–403, June 1973.

[1.2] J. B. Costillo and L. E. Davis, "A higher order approximation for waveguide circulators," *IEEE Trans. Microwave Theory Tech.* (Short Papers), vol. MTT-20, pp. 410–412, June 1972.

[1.3] ——, "Identification of spurious modes in circulators," *IEEE Trans. Microwave Theory Tech.* (Corresp.), vol. MTT-19, pp. 112–113, Jan. 1971.

[1.4] ——, "Computer-aided design of three-port waveguide junction circulators," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-18, pp. 25–34, Jan. 1970.

*Comment:* Waveguide circulator design has been hampered by the complexity of the field theory problem imposed by the involved junction geometry. For some simpler structures such as latching circulators, simple ferrite-rod Y and T junctions, and various inhomogeneous ferrite cylinders (ferrite post; ferrite tube–dielectric rod–dielectric sleeve; ferrite post–metal pin–dielectric sleeve) this problem has been overcome by numerical techniques. The previous papers predict the performance correctly, but they are still restricted in the junction geometry and do not yet lend themselves economically to computer optimization routines.

[1.5] B. Owen, "The identification of modal resonances in ferrite loaded Y-junctions and their adjustment for circulation," *Bell Syst. Tech. J.*, vol. 51, pp. 595–627, 1972.

*Comment:* In 1959 Auld[4] characterized the circulator in terms of its $S$ parameter and eigenvalues. This principle has now been put to use by Owen in a laudable paper. He measures the frequency-dependent eigenvalues and utilizes them to identify the principal junction modes involved, examines their sensitivities to various junction parameters, and arranges their correct displacement for circulation. The knowledge gained from these measurements is used to explain the mode of operation of the partial height ferrite Y-junction circulator, and to introduce other novel configurations.

### *High-Power Waveguide Circulators*

[1.6] R. A. Stern, "High power $S$-band junction circulator," in the *1973 IEEE G-MTT Int. Microwave Symp. Dig.* (Boulder, Colo.), Paper IV-3, pp. 89–91 (IEEE cat. no. 73 CHO 736-9 MTT).

[1.7] A. Lagrange, H. Lahmi, and B. Vallantin, "$X$-band high-peak-power junction circulator: Influence of the static magnetic field," *IEEE Trans. Magn.*, vol. MAG-9, pp. 531–534, Sept. 1973.

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

[1.9] F. E. Gardiol, "On high-power circulators with mismatched terminations," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-19, pp. 561–562, June 1971.

[1.10] W. W. Siekanowicz, R. W. Paglione, and T. E. Walsh, "A latching ring-and-post ferrite waveguide circulator," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-18, pp. 212–216, Apr. 1970.

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[1.16] W. Glogier, Z. Krzycki, and R. Zuberek, "An influence of a saturation magnetization on a bandwidth of the $Y$-type ferrite junction circulator," in *Proc. 5th Colloq. Microwave Communication* (Budapest, Hungary, June 1974), vol. 4, MT-197-206.

[1.17] E. J. Denlinger, "Design of partial height ferrite waveguide circulators," *IEEE Trans. Microwave Theory Tech.* (Short Papers), vol. MTT-22, pp. 810–813, Aug. 1974.

[1.18] Y. Akaiwa, "Operation modes of a waveguide $Y$ circulator," *IEEE Trans. Microwave Theory Tech.* (Short Papers), vol. MTT-22, pp. 954–960, Nov. 1974.

[1.19] B. Owen, "A narrow-band millimeter wave $Y$-junction circulator with wide-band tuning capability," in *Proc. 1974 IEEE S-MTT Int. Microwave Symp.* (Atlanta, Ga.), Paper 16-4 (IEEE catalog no. 74 CHO 838-3 MTT).

[1.20] Y. Akaiwa, "Bandwidth enlargement of a millimeter-wave $Y$-circulator with half-wavelength line resonator," in *Proc. 1974 IEEE S-MTT Int. Microwave Symp.* (Atlanta, Ga.), Paper 16-6 (IEEE catalog no. 74 CHO 838-3 MTT); also *IEEE Trans. Microwave Theory Tech.* (Short Papers), vol. MTT-22, pp. 1283–1286, Dec. 1974.

[1.21] H. C. Okean and L. J. Steffek, "Low loss, 3 mm junction circulator," *Microwave J.*, pp. 58–61, Apr. 1974.

[1.22] J. Helszajn, "Waveguide and stripline 4-port single-junction circulators," *IEEE Trans. Microwave Theory Tech.* (Short Papers), vol. MTT-21, pp. 630–633, Oct. 1973.

*Comment:* Eigenvalue approach is used to describe theory and construction of 4-port circulators.

[1.23] H. C. Okean and L. J. Steffek, "Low loss, 3 mm junction circulator," in the *1973 IEEE G-MTT Int. Microwave Symp. Dig.* (Boulder, Colo.), Paper III-8, pp. 80–81 (IEEE catalog no. 73 CHO 736-9 MTT).

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

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[1.27] N. D. Kozyrev and A. V. Khramov, "Filter circulator for radio relay communication link," *Telecommun. Radio Eng.* (USSR), vol. 25/26, pp. 127–128, Oct. 1971.

*Comment:* 5-port waveguide circulator.

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[4] B. A. Auld, "The synthesis of symmetrical waveguide circulators," *IRE Trans. Microwave Theory Tech.*, vol. MTT-7, pp. 238–246, Apr. 1959.

vol. MTT-16, pp. 256–258, Apr. 1968.
[1.31] M. V. Vamberskiy and V. I. Kazantsev, "Design of *H*-plane waveguide Y-circulators," *Telecommun. Radio Eng.* (USSR), vol. 23, pp. 76–81, 1968.

## II. STRIPLINE CIRCULATORS

Since the thorough analysis by Bosma[5] and Fay and Comstock's design procedures,[6] no fundamentally new approach has emerged. An attempt is made in [2.1] and [2.10], but there is not yet conclusive experimental evidence confirming the validity of the approach. Most papers deal with applications in microwave integrated circuits or relatively small improvements in performance.

[2.1] Y. S. Wu and F. J. Rosenbaum, "Wide-band operation of microstrip circulators," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-22, pp. 849–856, Oct. 1974.

*Comment:* Very good analytical paper predicting octave-bandwidth stripline circulators.

[2.2] G. R. Harrison, G. H. Robinson, B. R. Savage, and D. R. Taft, "Ferrimagnetic parts for microwave integrated circuits," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-19, pp. 577–588, July 1971.

*Comment:* Gives up-to-date information on microstrip circulators and their application in microwave integrated circuits and includes an extensive list of references.

[2.3] N. R. Dietrich, "TH-3 microwave radio system: Microwave integrated circuits," *Bell Syst. Tech. J.*, vol. 50, pp. 2175–2194, 1971.

*Comment:* Shows some interesting applications of 6-GHz high-performance suspended stripline circulators in microwave integrated circuits.

[2.4] R. Trambarulo, "A 30-GHz inverted-microstrip circulator," *IEEE Trans. Microwave Theory Tech.* (Corresp.), vol. MTT-19, pp. 662–664, July 1971.

*Comment:* Attempt to use stripline circulators with fused quartz substrate at millimeter wavelength.

[2.5] S. Nakahara and N. Orime, "Broadband stripline miniature circulators," *Mitsubishi Denki Lab. Rep.* (Japan), vol. 11, pp. 66–88, Apr. 1970.

*Comment:* Analysis of stripline circulators and experimental results showing different dielectric loading schemes for weight and size reduction.

[2.6] M. V. Vamberskiy and V. I. Kazantsev, "Optimization of stripline transmission–resonance Y-circulators," *Radio Eng.* (USSR), vol. 25, pp. 105–109, 1970.

*Comment:* Rather theoretical paper with only sketchy experimental results.

[2.7] M. Lemke, "Microwave integrated devices and substrates on ferrite," in the *1969 European Microwave Conf. Dig.* (London, England), pp. 53–56.

*Comment:* Shows nonmagnetic ferrite substrate with magnetized zones (circulator junctions) for microwave integrated circuits.

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[2.11] J. Helszajn, "Frequency response of quarter-wave coupled reciprocal stripline junctions," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-21, pp. 533-537, Aug. 1973.
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[2.17] E. J. Denlinger, D. H. Temme, and J. A. Weiss, "Stepped ground plane circulator," in the *1971 IEEE G-MTT Int. Microwave Symp. Dig.*, pp. 78–79 (IEEE catalog no. 71 C25-M).
[2.18] C. P. Hartwig *et al.*, "Microstrip circulator design," in *NEREM Conf. Rec.*, pp. 381–384, 1971.
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[2.20] S. Rossner, "Microstrip-Zirkulator," *Nachrichtentech. Z.*, vol. 21, pp. 380–381, 1971.
[2.21] A. L. Poirier, "An integrated microstrip circulator," *IEEE Trans. Microwave Theory Tech.* (Corresp.), vol. MTT-19, pp. 661–662, July 1971.
[2.22] C. P. Hartwig and D. W. Readey, "Ferrite film circulator," *J. Appl. Phys.*, vol. 41, pp. 1351–1352, 1970.
[2.23] J. Helszajn, "Ferrite parameters of the junction circulator," *Electron. Components*, pp. 785–793, July 1970.
[2.24] J. Edrich and R. G. West, "Low loss cryogenic *L*-band circulator," *IEEE Trans. Microwave Theory Tech.* (Corresp.), vol. MTT-18, pp. 743–745, Oct. 1970.
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[2.29] W. W. Siekanowicz and W. A. Schilling, "A new type of latching switchable ferrite junction circulator," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-16, pp. 177–183, Mar. 1968.
[2.30] M. V. Vamberskiy and V. I. Kazantsev, "Design of decimeter wavelength stripline Y-circulators," *Radio Eng.* (USSR), vol. 23, pp. 77–81, 1968.
[2.31] J. L. Allen and D. R. Taft, "Ferrite elements for hybrid microwave integrated systems," *IEEE Trans. Microwave Theory Tech.* (*Special Issue on Microwave Integrated Circuits*), vol. MTT-16, pp. 405–411, July 1968.

*Comment:* Review article.

[2.32] D. Masse, "Broadband microstrip junction circulators," *Proc. IEEE*, vol. 56, pp. 352–353, Mar. 1968.
[2.33] L. K. Anderson, "An analysis of broadband circulators with external tuning elements," *IEEE Trans. Microwave Theory Tech.*, vol. 15, pp. 42–47, Jan. 1967.

## III. LUMPED-ELEMENT CIRCULATORS

Lumped-element circulators have moved up in frequency. Their main application used to be in the UHF range while now they have been built at frequencies as

[5] H. Bosma, "On the principle of stripline circulators," *Proc. Inst. Elec. Eng.* (Part B Suppl.), vol. 109, pp. 137–146, Jan. 1962.
[6] C. E. Fay and R. L. Comstock, "Operation of the ferrite junction circulator," *IEEE Trans. Microwave Theory Tech.* (*1964 Symp. Issue*), vol. MTT-13, pp. 15–27, Jan. 1965.

high as 5 GHz. In the upper $L$ and lower $S$ band they match the performance of microstrip devices.

[3.1] Y. Konishi, "New theoretical concept for wide band gyromagnetic devices," *IEEE Trans. Magn.* (*1972 INTERMAG Conf.*), vol. MAG-8, pp. 505–508, Sept. 1972.
[3.2] Y. Konishi and N. Hoshino, "Design of a new broad-band isolator," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-19, pp. 260–269, Mar. 1971.

*Comment:* These two papers describe a multioctave isolator obtained by cascading circulators whose third port is intentionally mismatched. Broad bandwidth is obtained at the expense of insertion loss. A 20-dB isolation is obtained from 70 to 800 MHz; insertion loss <3 dB.

[3.3] D. E. Biglin, "The NRJ—A new circuit element," *Marconi Rev.*, vol. 33, pp. 55–78, 1970.

*Comment:* This paper gives a review of the "classical" lumped-element circulator theory.

[3.4] R. H. Knerr, "A 4-GHz lumped-element circulator," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-21, pp. 150–151, Mar. 1973.
[3.5] ——, "A microwave circulator that's smaller than a quarter," *Bell Lab. Rec.*, vol. 51, pp. 78–84, Mar. 1973.
[3.6] ——, "A proposed lumped-element switching circulator principle," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-20, pp. 396–401, June 1972.
[3.7] ——, "An improved equivalent circuit for the thin-film lumped-element circulator," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-20, pp. 446–452, July 1972.
[3.8] R. H. Knerr, C. E. Barnes, and F. Bosch, "A compact broadband thin-film lumped-element *L*-band circulator," *IEEE Trans. Microwave Theory Tech.* (*1970 Symp. Issue*), vol. MTT-18, pp. 1100–1108, Dec. 1970.

*Comment:* The foregoing papers by Knerr give a complete analysis of the lumped-element circulator in terms of input impedance and $S$-parameter eigenvalues. The insight gained therefrom is applied to a simple broadbanding and switching scheme. Experimental results at 1.4 and 5 GHz are given. Thin-film batch processing is used; [3.8] shows the simple realization of the broadbanding scheme.

[3.9] T. Hashimoto, T. Iwata, and M. Sasaki, "Junction circulator wherein each center conductor leg appears on both sides of the insulation board," U. S. Patent 3 522 555.

*Comment:* This patent describes a very simple dielectric flexboard pattern with plated through holes and patterns on both sides. This technique achieves the interlaced lumped-element conductor pattern of Konishi [3.1] while permitting complete threefold symmetry as is achieved in the thin-film beam-crossover approach of Knerr [3.4]–[3.8].

[3.10] Y. Naito and N. Tanaka, "Broad-banding and changing operation frequency of circulator," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-19, pp. 367–372, Apr. 1971.
[3.11] J. Helszajn, D. Walker, and F. M. Aitken, "Varactor-tuned lumped-element circulators," *IEEE Trans. Microwave Theory Tech.* (Corresp.), vol. MTT-19, pp. 825–826, Oct. 1971.

*Comment:* Both papers use a variable-capacitance diode in the resonator circuit of the lumped-element circulator. Thus by changing the diode voltage, the operating frequency of the circulator is changed.

[3.12] J. Helszajn and M. McDermott, "The junction inductance of a lumped-constant circulator," *IEEE Trans. Microwave Theory Tech.* (Corresp.), vol. MTT-18, pp. 50–52, Jan. 1970.

*Comment:* This paper contains graphs which give good starting values for the mesh dimensions of a lumped-element circulator.

[3.13] S. Okamura and T. Nagai, "VHF- and UHF-band stacked-junction circulators," *IEEE Trans. Microwave Theory Tech.* (Corresp.), vol. MTT-17, pp. 1151–1152, Dec. 1969.

*Comment:* High-power scheme (3-kW CW).

*Other References*

[3.14] P. Barsony, "Investigation on lumped element ferrite junction at high frequencies," in *1974 Proc. 5th Colloq. Microwave Commun.*, vol. 4 (Budapest, Hungary, June 1974), pp. MT-53–62; also, New York: Academic, 1974.
[3.15] R. H. Knerr, "A lumped-element circulator without crossovers," *IEEE Trans. Microwave Theory Tech.* (Short Papers), vol. MTT-22, pp. 544–548, May 1974.
[3.16] I. Ikushima and M. Maeda, "A 1.7 GHz lumped-element circulator, highly stabilized with temperature," in *Proc. 1974 IEEE S-MTT Int. Microwave Symp.* (Atlanta, Ga.), Paper 16-6 (IEEE catalog no. 74 CHO 838-3 MTT); also ——, "A temperature-stabilized broad-band lumped-element circulator," *IEEE Trans. Microwave Theory Tech.* (*Part II of Two Parts—1974 Symp. Issue*), vol. MTT-22, pp. 1220–1225, Dec. 1974.
[3.17] M. Kitlinski, "Bidirectional thin-film lumped-element circulator," *Electron. Lett.*, vol. 10, pp. 66–68, Mar. 21, 1975.
[3.18] J. Helszajn and F. M. Aitken, "U.H.F. techniques for lumped constant circulators," *Electron. Eng.*, pp. 53–59, Nov. 1973.
[3.19] C. M. Pascual, "Optimización de un circulador de tipo 'malla'" (Optimization of a lumped-element circulator), *Electron. Fisc. Apl.* (Spain), vol. 16, pp. 11–16, 1973.
[3.20] A. Y. Panov, "A ten centimeter Y-circulator with lumped element," *Radio Eng. Electron. Phys.* (USSR), vol. 18, pp. 1908–1909, 1973.
[3.21] S. Okamura and T. Nagai, "A lumped-element circulator on ceramic substrates," in *Proc. 1972 IEEE G-MTT Int. Microwave Symp.* (Arlington Heights, Ill.), Paper 12-4, pp. 243–245.
[3.22] S. J. Saley and H. J. Peppiatt, "Input impedance behavior of stripline circulator," *IEEE Trans. Microwave Theory Tech.* (Corresp.), vol. MTT-19, pp. 109–110, Jan. 1971.
[3.23] H. Bex, "Über Konzentrierte Zirkulatoren" (About lumped element circulators), *Nachrichtentech. Z.* (Germany), no. 5, pp. 249–254, 1971.
[3.24] H. Bex and E. Schwarz, "Wirkungsweise Konzentrierter Zirkulatoren" (Mode of operation of lumped-element circulators), *Frequenz* (Germany), vol. 24, pp. 288–293, 1970.
[3.25] F. M. Magalhaes, "Circulator having conductive post capacitively coupled between first and second transmission line conductors for broadbanding purposes," U. S. Patent 3 517 340, June 1970.
[3.26] A. Y. Panov, "Analysis of a lumped element ferrite Y-circulator," *Radio Eng. Electron. Phys.* (USSR), vol. 15, pp. 258–266, 1970.
[3.27] E. Fliegler, "A 350-MHz broad-band lumped element circulator as a protective isolator," *IEEE Trans. Microwave Theory Tech.* (Corresp.), vol. MTT-17, pp. 275–277, May 1969.
[3.28] R. H. Knerr, "A thin-film lumped-element circulator," *IEEE Trans. Microwave Theory Tech.* (Corresp.), vol. MTT-17, pp. 1152–1154, Dec. 1969.
[3.29] J. O. Bergman and C. Christensen, "Equivalent circuit for a lumped-element Y circulator," *IEEE Trans. Microwave Theory Tech.* (Corresp.), vol. MTT-16, pp. 308–310, May 1968.
[3.30] Y. Konishi, "VHF power circulator with slow-wave circuits," *Inst. Electron. Commun. Eng. Japan*, vol. 51, pp. 118–120, Aug. 1968.

## IV. OTHER TYPES OF CIRCULATORS

*Electronic Circulators*

Electronic circulators have now become commercially available in the 1–150-MHz band. They are small and have relatively low power consumption. Their main drawback is the low power handling capability and nonlinear behavior with power.

[4.1] R. S. Andrews, "Scattering-matrix measurements on 3-port electronic circulators," *Electron. Lett.*, vol. 7, pp. 351–353, June 17, 1971.
[4.2] B. Rembold, "Ein 3-Tor-Zirkulator mit Aktiven Bauelementen" (A 3-port circulator made of active elements), *Nachrichtentech. Z.*, vol. 24, pp. 121–125, Mar. 1971.
[4.3] W. H. Holmes and C. Sripaipan, "A minimal sensitivity circulator using differential transconductances," *Proc. IEEE* (Lett.), vol. 58, pp. 1143–1145, July 1970.

*Peripheral or Edge-Guided Mode Devices*

[4.4] T. J. Gerson and J. S. Nadan, "Surface electromagnetic modes of a ferrite slab," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-22, pp. 757–763, Aug. 1974.
[4.5] P. De Santis, "Edge-guided modes in ferrite microstrips with curved edges," *Appl. Phys.* (Germany), vol. 4, pp. 167–174, July 1974.
[4.6] L. Courtois, B. Chiron, and G. Forterre, "A new edge mode isolator in the VHF-range," in *Proc. 1974 IEEE S-MTT Int. Microwave Symp.* (Atlanta, Ga.), Paper 16-3 (IEEE catalog no. 74 CHO 838-3 MTT).
[4.7] ——, "Propagation dans une lame de ferrite aimantée. Application à de nouveaux dispositifs non réciproques à large bande" (Propagation in a magnetized ferrite substrate. Application to a novel broad-band nonreciprocal device), *Cables Transmission* (France), no. 4, pp. 416–435, Oct. 1973.
[4.8] J. Puyhaubert, "Visualisation des ondes électromagnétiques hyperfréquence à l'aide des cristaux liquides" (Visualization of microwaves with liquid crystals), *Onde Elec.* (France), vol. 52, pp. 213–217, May 1972.
[4.9] M. E. Hines, "Ferrite transmission devices using the edge guided mode of propagation," in the *1972 IEEE G-MTT Int. Microwave Symp. Dig.* (Arlington Heights, Ill.), Paper 12-1, pp. 236–237.
[4.10] P. De Santis and F. Pucci, "Novel type of M.I.C. symmetrical 3-port circulator," *Electron. Lett.*, vol. 8, pp. 12–13, Jan. 13, 1972.
[4.11] ——, "Experiments on the optimization of a novel M.I.C. symmetrical three-port circulator," in the *1972 IEEE G-MTT Int. Microwave Symp. Dig.* (Arlington Heights, Ill.), Paper 12-2, pp. 238–239.
[4.12] M. E. Hines, "Reciprocal and nonreciprocal modes of propagation in ferrite stripline and microstrip devices," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-19, pp. 443–451, May 1971.
[4.13] ——, "A new microstrip isolator and its application to distributed diode amplification," in the *1970 IEEE G-MTT Int. Microwave Symp. Dig.*, pp. 304–307 (IEEE catalog no. 70 C10-MTT).

*Comment:* These devices have been demonstrated as multioctave isolators, and some promising results on circulators have been obtained. The isolator structure is very simple and is carefully analyzed in Hines' paper as pointed out in the introductory section of this paper.

*Other References*

[4.14] M. Igarashi and Y. Naito, "Theoretical analysis of magnetic resonance nonreciprocal circuit — Limitations of 3-dB bandwidth and available range," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-22, pp. 821–829, Sept. 1974.
[4.15] ——, "Theory of 4-port nonreciprocal circuit-filter and circulator," presented at the 1974 IEEE S-MTT Int. Microwave Symp., Atlanta, Ga., Paper 16-7.
[4.16] M. DeVecchis, L. Raczy, and P. Gelin, "A new stripline broadband isolator," presented at the European Microwave Conf., Brussels, Belgium, Sept. 1973, Paper B.9.6.
[4.17] M. Igarashi and Y. Naito, "Properties of a four-port nonreciprocal circuit utilizing YIG on stripline—Filter and circulator," *IEEE Trans. Microwave Theory Tech.* (*1972 Symp. Issue*), vol. MTT-20, pp. 828–833, Dec. 1972.
[4.18] N. Ogasawara and M. Kaji, "Coplanar-guide and slot-guide junction circulators," *Electron. Lett.*, vol. 7, pp. 220–221, May 6, 1971.
[4.19] S. R. Longley, "Multioctave tunable 3-port circulator using a Y.I.G. sphere," *Electron. Lett.*, vol. 6, pp. 406–408, June 25, 1970.
[4.20] Y. P. Ilyasov and S. N. Ivanov, "Meter band applications of ferrites," *Telecommun.* (USSR), vol. 23, pp. 46–49, 1967.
[4.21] G. T. Roome and H. A. Hair, "Thin ferrite devices for microwave integrated circuits," *IEEE Trans. Microwave Theory Tech.* (*Special Issue on Microwave Integrated Circuits*), vol. MTT-16, pp. 411–420, July 1968.

*Comment:* Describes pioneering work on planar reciprocal and nonreciprocal phase shifters and their combination to multiport circulators.

## V. GENERAL PAPERS APPLICABLE TO ALL CIRCULATORS

[5.1] R. Roveda, C. Borghese, and G. Cattarin, "Dissipative parameters in ferrites and insertion losses in waveguide Y circulators below resonance," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-20, pp. 89–96, Feb. 1972.

*Comment:* Relates device losses to material parameters. Useful for choosing ferrite. Applies in principle to any linear ferrite device, examples are given for waveguide circulators.

[5.2] H. Bex and E. Schwartz, "Performance limitations of lossy circulators," *IEEE Trans. Microwave Theory Tech.* (Corresp.), vol. MTT-19, pp. 493–494, May 1971.
[5.3] S. Hagelin, "Analysis of lossy symmetrical three-port networks with circulator properties," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-17, pp. 328–333, June 1969.

*Comment:* Both papers give a good analysis of the performance limitations of circulators due to insertion loss.

[5.4] R. C. Kumar, "Ferrite-junction circulator bibliography," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-18, pp. 524–530, Sept. 1970.

*Comment:* Listing of literature from 1956 through 1969.

*Other References*

[5.5] F. E. Gardiol, "Propriétés gyromagnétiques des ferrites en hyperfréquences" (Gyromagnetic properties of microwave ferrites), *Mitt. Arbeitsgemeinschaft Elek. Nachrichtentech. Stiftung Hasler-Werke* (Bern, Switzerland), pp. 47–55, Dec. 1973.
[5.6] N. Ogasawara, "Device-oriented review of recent Japanese developments in magnetic materials for gyromagnetic applications," *IEEE Trans. Magn.*, vol. MAG-9, pp. 538–545, Sept. 1973.
[5.7] Y. Akaiwa, "Input impedance of a circulator with an in phase eigen-excitation resonator," *Electron. Lett.*, vol. 9, pp. 274–275, June 1973.
[5.8] S. J. Salay and H. J. Peppiatt, "An accurate junction circulator design procedure," *IEEE Trans. Microwave Theory Tech.* (Short Papers), vol. MTT-20, pp. 192–193, Feb. 1972.
[5.9] J. Helszajn, "The adjustment of a *m*-port single-junction circulator," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-18, pp. 705–711, Oct. 1970.
[5.10] B. Chiron, "Etude et réalisation en microélectronique hyperfréquence des dispositifs à ferrite du type remanent" (Study and realization of miniature microwave devices using remanent ferrites), *Onde Elec.* (France), vol. 50, pp. 779–785, Oct. 1970.
[5.11] N. Eberhardt, V. V. Horvath, and R. H. Knerr, "On plane and quasi-optical wave propagation in gyromagnetic media," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-18, pp. 554–565, Sept. 1970.
[5.12] R. Janke, "Abschluss eines Zirkulators mit Fehlangepasstem Absorber" (Termination of a circulator with a mismatched absorber), *Nachrichtentech. Z.*, vol. 20, pp. 414–421, 1970.
[5.13] E. Schanda, "Ausbreitung Elektromagnetischer Wellen in Anisotropen Medien" (Propagation of electromagnetic waves in anisotropic media), *Bull. Tech. PTT* (Switzerland), vol. 26, pp. 173–186, Apr. 1968.
[5.14] E. Schwarz, "Broadband matching of resonant circuits and circulators," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-16, pp. 158–165, Mar. 1968; also correction: ——, *IEEE Trans. Microwave Theory Tech.* (Corresp.), vol. MTT-16, p. 894, Oct. 1968.
[5.15] H. Bosma, "A general model for junction circulators; Choice of magnetization and bias field," *IEEE Trans. Magn.*, vol. MAG-4, pp. 587–596, Sept. 1968.
[5.16] J. Helszajn and C. R. Buffler, "Adjustment of the 4-port single-junction circulator," *Radio Electron. Eng.*, pp. 357–360, June 1968.

## VI. ISOLATORS

The term isolator has a dual meaning, it can stand for a device which is used in an isolator function such as a circulator with one port terminated, or for an isolator per se. The first one is covered in the section on circulators (see for example [3.1], [3.2], [3.15]). The latter one comprises some very recent devices as covered in [4.6]–[4.9] or the resonance waveguide isolator. The literature on resonant waveguide isolators has become scarce. This is mainly because they are frequently replaced by circulators with one port terminated. This solution is generally preferred because the main dissipation occurs in the termination rather than in the RF-carrying ferrite.

Two companion papers on *E*-plane resonance isolators give the background information to understand a general computer program description. This program permits the study of possible higher order modes and ways to avoid them. It is used to demonstrate the sensitivity of the device performance for different parameter changes. In the other paper, an optimization program is described which determines the optimum geometry and dielectric material for a specified performance and ferrite.

The papers give no direct design information and no listing of the probably very involved computer program.

[6.1] M. C. Decréton, E. F. Loute, A. S. Vander Vorst, and F. E. Gardiol, "Computer optimization of *E*-plane resonance isolators," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-19, pp. 322–331, Mar. 1971.

[6.2] F. E. Gardiol and A. S. Vander Vorst, "Computer analysis of *E*-plane resonance isolators," *IEEE Trans. Microwave Theory Tech.*, vol. 19, pp. 315–322, Mar. 1971.

*Further References*

[6.3] M. Kanda and W. G. May, "Hollow-cylinder waveguide isolators for use at millimeter wavelengths," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-22, pp. 913–917, Nov. 1974.

[6.4] F. E. Gardiol and O. Parriaux, "Cutoff frequencies in ferrite-loaded waveguides," in *Proc. 5th Colloq. Microwave Communication* (Budapest, Hungary, June 1974), vol. 4, pp. MT-167–176.

[6.5] A. D. Muravtsov, "Design and experimental investigation of a miniature stripline isolator," *Telecommun. Radio Eng.* (USSR), vol. 27/28, pp. 94–97, Oct. 1973.

[6.6] V. I. Volman and A. D. Muravtsov, "Miniature stripline isolator," *Radio Eng.* (USSR), vol. 25, no. 7, pp. 152–154, 1970.

## VII. BOOKS

As mentioned in the Introduction, microwave engineering science has matured considerably, and as a consequence, several books on the subject have been published during the review period.

Bosma's book [7.3] on junction circulators gives a very elegant, self-consistent theoretical treatment of all types of junction circulators. It is recommended for the reader who wants to look into the more general theoretical aspects of junction circulators. This will hopefully enrich his knowledge and lead to new innovations and to a higher level of design practices.

The books by von Aulock and Fay [7.5] and Helszajn [7.4] are more design oriented; each one covers the whole spectrum of microwave ferrite devices. Von Aulock and Fay's work puts slightly more emphasis on physical concepts, consistent with their earlier publications. Helszajn gives a comprehensive introduction to the subject of wave propagation in gyromagnetic media. His treatment of the devices is well balanced; it gives theoretical derivations leading to useful design rules for numerous devices.

In Rosenbaum's book [7.1] the microwave properties of ferrimagnetic materials are reviewed and their interaction with electromagnetic waves propagating in bounded waveguiding structures is developed. An analysis based on the parallel-plane waveguide is used to derive the characteristic of propagation in ferrite loaded structures, then extended, phenomenologically, to microstrip, slot-line and coplanar waveguides. The operation and design of phase shifters and circulators are presented. Finally, field displacement devices based on the edge-guided mode are considered.

[7.1] F. J. Rosenbaum, "Integrated ferrimagnetic devices," in *Advances in Microwaves*, vol. 8, H. Sobol, Ed. New York: Academic, 1974.

[7.2] L. R. Whicker, "Ferrite control components," in *Junction Circulators, YIG Filters and Limiters*, vol. 1. Dedham, Mass.: Artech Hse., 1974.

*Comment:* Reprint volume, i.e., collection of important papers on the subjects mentioned in the title.

[7.3] H. Bosma, "Junction circulators," in *Advances In Microwaves*, vol. 6, Leo Young, Ed. New York: Academic, 1971.

[7.4] J. Helszajn, *Principles of Microwave Ferrite Engineering.* New York: Wiley-Interscience, 1969.

[7.5] Wilhelm H. von Aulock and Clifford E. Fay, "Linear ferrite devices for microwave applications," in *Advances In Electronics And Electron Physics—Supplement 5.* New York: Academic, 1968.

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