Symmetry in a High Power Circulator for 35 GHz

A ferrite loaded junction circulates at many values of frequency and applied magnetic field, sometimes giving circulation over a useful bandwidth. In the empirical design of a circulator, the various combinations of field and frequency must be found and modified to give circulation at the required frequency. An E-plane junction[1,2] with a ferrite disk on each narrow wall was selected for high power operation. (Figure 1 shows the final circulator with a permanent magnet.) The best conditions for circulation were found, but results from the three-ports differed substantially with the circulation bands for the three-ports in some cases not overlapping. This asymmetry was independent of mechanical tolerances in waveguide manufacture and cleanliness of ferrite. It was presumably due to differential scatter caused by inhomogeneity of the ferrite material of the linear effects of surface grinding. As it was easier to investigate surface finish effects, three forms of improved finish were devised and tested.

In the first experiment ferrite disks were polished with 6_μ grit and showed no improvement over normal samples. It was later concluded that this grit was too fine to have appreciable effect. The next disks were lapped with 26_μ grit. The resulting circulator had a bandwidth for 20 dB isolation of 3.2 GHz and an asymmetry spread between ports of 0.1 GHz (see Table I). The third pair of experimental disks were finished by grinding, at a constant level setting, in three directions 120° apart. The symmetrical bandwidth is 3.1 GHz (32.7–35.8 GHz), and one-port gave 3.6 GHz (32.3–35.9 GHz); the difference of 0.4 GHz at the low-frequency end is a measure of the asymmetry.

Of these three methods, the latter two gave improved symmetry. The last process was the best mechanically and was selected for further work. Some more samples were made from the next batch of ferrite materials, but, on inspection, the surfaces appeared coarsely ground and the effects of grinding in three directions were not visible. The results are given in Table I (line 4). The circulator bandwidth is reduced because of a change in the ferrite batch, but the symmetry is reasonable. The next samples were made by reducing the disk height in 0.0001 inch steps and then grinding in three directions 120° apart. Two pairs of disks were also made by this method for an application at 33 GHz.

The results showed improved symmetry, but the grinding method was tedious and attempts were made to simplify it. To verify the need for small cuts during the grinding operation, this procedure was omitted. The final cut was 0.0005 inch and then the disks were ground in the usual three directions. In the next sample, the disk height was finally reduced by five cuts of 0.0001 inch and the grinding in three directions was omitted. In the last experiment all attempts at a good surface finish were omitted and the grinding finished with a cut of 0.0005 inch.

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[1] S. Yoshida, "An E-type T circulator," *Proc. IRE (Correspondence)*, vol. 47, p. 2018, November 1959.

[2] L. E. Davies and S. R. Longley, "E-plane 3-port X-band waveguide circulators." *IEEE Trans. on Microwave Theory and Techniques*, vol. MTT-11, pp. 443–445, September 1963.

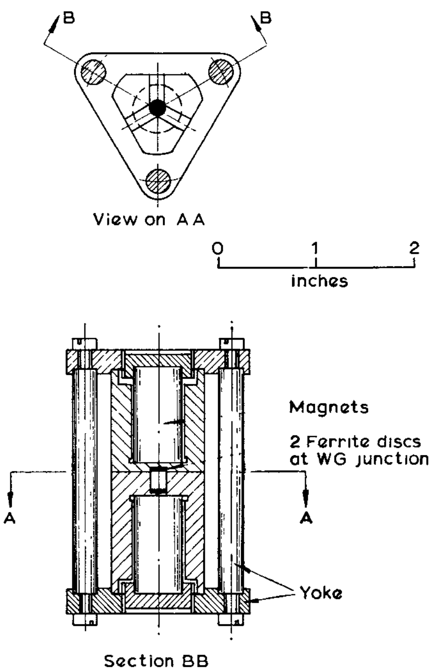

Fig. 1. Circulator with permanent magnet.

TABLE I

	20 dB Band-width GHz	Asym-metry GHz
26^μ grit	3.2	0.1
*	3.1	0.4
(Rotate disk	2.6	0.8)
New samples* seemed coarse 1)	1.7	0.2
2)	1.8	0.3
New sample fine cut*	1.5	0.3
fine cut* 33 GHz 1)	1.6	0.2
2)	1.4	0.1
New sample coarse cut*	0.8	0.6
New sample fine cut 1)	1.4	0.1
2)	1.5	0.1
New sample coarse cut	0.8	0.6

* Ground in three directions, 120° apart.

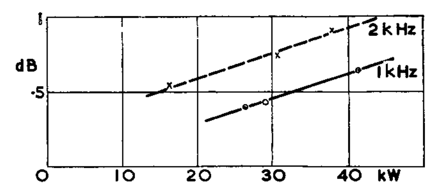

Fig. 2. Insertion loss against peak power for pulse repitition rate, 1 kHz and 2 kHz.

The above experiments demonstrated the effect of ferrite surface finish on circulation. As the asymmetry could be reduced to a negligible value, the possible material inhomogeneity was considered unimportant.

The size of the ferrite disks was optimized for circulation at the required frequency and gave 20-dB isolation over a 1.5-GHz band. The effect of a reduction in waveguide width and also the addition of dielectric loading were investigated but gave no improvement in bandwidth. The simple circulator of Fig. 1 was therefore selected.

To improve the high power operation of the circulator, the ferrite disks were reduced in diameter and surrounded by polytetrafluoroethylene rings 0.005 inch thick. This modification prevented breakdown at powers up to the maximum available (41 kW peak). The insertion loss of the circulator was measured at several power levels up to 40 kW peak (8 or 16 watts mean) using a pulse length 0.2 μs, and repetition rate 1 or 2 kHz. The results are presented in Fig. 2. There was no measurable change in isolation. The circulator was also assessed for another application and operated satisfactorily at 2.5 watts mean, 25 kW peak between −10 and +40°C.

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The Directional Coupler—1966

I Introduction

The directional coupler is a well-known device used as an attenuator, power splitter, hybrid junction, local oscillator injection device, and, most commonly, a sampling device for measuring separately the forward and backward waves on a transmission line. Over a period of twenty-five years many papers have appeared dealing with analysis, design, and application of the device.

In 1954, R. F. Schwartz prepared a bibliography of 91 papers which had appeared up to that time relating to the directional coupler field and, in 1955, Schwartz and Medhurst prepared a supplement of 41 additional papers. The present correspondence focuses attention on those problems which were treated up to 1954–55, highlights the significant advances to date, and points out some of the fruitful areas for further work.

While a considerable number of bibliographical entries are presented here, it is almost impossible to be exhaustive. Some restricted circulation reports and theses have been noted, for they help to indicate certain areas of interest as well as organizations and people involved. It is recognized, however, that there are probably many more entries that could be added.

II. Pre-1955 Directional Couplers

The directional coupler became a common transmission line and microwave device during World War II. It was early appreciated that two distinct mechanisms could be exploited: 1) the constructive and destructive interference of waves coupled by two superimposed, but different type, couplings as in the Bethe-hole and loop-type directional couplers, and 2) the constructive and destructive interference produced by waves arriving

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at a given point by different paths as in the multihole directional coupler. During the 1940's many different configurations of couplers utilizing these principles were developed and couplings in the range of 15 to 60 dB with directivities of 20 dB or greater were common. Bandwidths in most types of couplers were rather narrow, even though the principles which could lead to broader band performance were known. Many of the early couplers were severely limited by other defects in the transmission systems, e.g., connectors.

In the early 1950's refinements were beginning to be made. Lower dB values of coupling were sought with greater directivity over wide bands, 40 dB in waveguide and 30 dB in coaxial line being typical. The trend in radars was toward higher and higher powers and therefore power handling capability became an area of concern. During this period the awareness of the coupled-mode viewpoint and the concept of odd and even mode distributions grew and with it developed techniques for design. The application of Fourier transforms in the approximate analysis and the carry over of information from modern circuit theory was also accomplished. The loop-type and coupled transmission line coupler were reinvestigated to develop quantitative criteria for design. These techniques and principles were subsequently applied to coaxial, open wire, and strip transmission lines, as well as to waveguide. New applications were also constantly being developed in operational and measurement systems.

III. 1955–1965 Directional Couplers

In the most recent decade the problem emphasis has broadened. Further improvement of conventional directional couplers has continued. The 3 dB broadband coupler has become a reality, and octave or more bandwidths in some types of directional couplers have been attained.

Directional couplers for other transmission systems such as, for example, ridged waveguide and strip line, have been developed. The latter in particular has led to new techniques of design which were impossible to utilize with other TEM transmission lines. The improvement of other components such as loads and connectors, and the design of broad-banded transitions between systems have made it possible in many cases to realize the full benefit of coupler design improvements. The availability of good miniature connectors has allowed some types of directional couplers to be shrunk in size.

Modern network theory has continued to influence directional coupler design and a general body of knowledge on coupling structures has evolved. At the same time the digital computer has been put to work calculating parameter tables so that for certain types of directional couplers the design task has become almost routine.

The marriage of directional couplers with filters has been consummated both in design and application. Directional coupling in multimode systems for the purpose of measurement, filtering, and multiplexing has been accomplished.

Directional coupling structures utilizing ferrite and YIG materials have also received some attention. Quasi-optical couplers in the mm range and also at optical wavelengths have been realized.

IV. The Future

Undoubtedly, the influence of modern network theory and the trend toward computer-generated design tables will continue in the directional coupler field. Probably formalized synthesis procedures will also be developed. Continued gains from these techniques as well as from improved connectors will make possible tight couplings over extremely wide bands. Perhaps the log periodic principle will be applied in some of these designs. While conventional waveguide will continue to be limited by dominant-mode bandwidth, there will be applications where ridged waveguide will be further exploited for multiband operation. One could also expect continued efforts in over moded systems, and as mm and sub-mm waves find more applications, quasi-optical directional coupler design will receive more attention. Constructions using prisms will probably become quite familiar.

Finally, it would be expected that a great deal more will be done in applying anisotropic and gyrotropic materials to directional couplers. What will evolve from this is a matter for speculation.

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Bibliography

Reference Articles

[1] R. F. Schwartz, "Bibliography on directional couplers," *IRE Trans. on Microwave Theory and Techniques*, vol. MTT-2, pp. 58–63, July 1954.

[2] R. F. Schwartz and R. G. Medhurst, "Addenda to bibliography on directional couplers," *IRE Trans. on Microwave Theory and Techniques*, vol. MTT-3, pp. 42–43, April 1955.

Additional Pre-1955 Publications

1951

[3] F. Bolinder, "Approximate theory of the directional coupler," *Proc. IRE*, vol. 39, p. 291, March 1951.

[4] Tsuchey and Takahashi, "CM type directional coupler," *The 1951 Three Electricity Societies (Japan)*, pp. 10–12, 1951.

1952

[5] F. Assadourian and E. Rimai, "Simplified theory of microstrip transmission systems," *Proc. IRE*, vol. 40, pp. 1651–1657, December 1952.

[6] D. Grieg and H. Englemann, "Microstrip—a new transmission technique for the kilomegacycle range," *Proc, IRE*, vol. 40, pp. 1644–1650, December 1952.

[7] J. Kostriza, "Microstrip components," *Proc. IRE*, vol. 40, pp. 1658–1663, December 1952.

[8] H. Riblet, "Super directivity with directional coupler arrays," *Proc. IRE*, vol. 40, pp. 994–995, August 1952.

1953

[9] "Unidirectional coupler research and development program," Sperry Gyroscope Co., Great Neck, N. Y., Final Rept. 5224–1240-8, 1953.

[10] S. Kobayashi, "Directional couplers of the bridged-T type," *J. Inst. Elect. Commun. Engrs. (Japan)*, vol. 36, pp. 475–480, September 1953.

[11] S. Kumagai and K. Itakura, "Theoretical and experimental researches on new type directional couplers," Osaka Univ., Japan, Tech. Rept., p. 257, 1953.

[12] S. Tanaka and T. Okakura, "Characteristics and improvement of Bethe-hole directional couplers for waveguides," *J. Inst. Elect. Commun. Engrs. (Japan)*, vol. 36, pp. 489–493, September 1953.

1954

[13] F. Barnett, P. Lacy, and B. Oliver, "Principles of directional coupling in reciprocal systems," *Proc. on Mod. Advances in Microwave Techniques*, pp. 251–269, November 1954; also, New York: Interscience, 1955.

[14] L. I. Kent, "The optimum design of multi-element directional couplers," M.S. thesis, Polytechnic Inst. of Brooklyn, N. Y., 1954.

[15] B. Oliver, "Directional electromagnetic couplers," *Proc. IRE*, vol. 42, pp. 1686–1692, November 1954.

[16] Weissfloch, "Use of short circuiting pistons in the study of junctions and directional couplers," *Ann. Telecomm. (France)*, vol. 9, pp. 81–92, March 1954.

[17] E. M. Wells, "A short-slot hybrid for 9 mm," *Marconi Rev.*, vol. 17, pp. 86–87, 3rd Quarter 1954.

Post-1954 Publications

1955

[18] P. Andrew, "A simple waveguide directional coupler," *J. Instn. Radio Engrs. (Britain)*, vol. 15, pp. 112–116, February 1955.

[19] E. Belohonbek, "Investigations on a broad-band coupling between a coaxial line and a waveguide; I. theoretical part," *Arch. elekt. Ubertragung (Germany)*, vol. 9, pp. 432–440, September 1955 (in German).

[20] ——, "Investigations on a broad-band coupling between a coaxial line and a waveguide; II, mechanical part," *Arch. elekt. Übertragung (Germany)*, vol. 9., pp. 469–474, October 1955 (in German).

[21] S. Cohn, "Shielded coupled-strip transmission line," *IRE Trans. on Microwave Theory and Techniques*, vol. MTT-3, pp. 29–38, October 1955.

[22] J. Cook, "Tapered velocity couplers," *B.S.T.J.*, vol. 34, pp. 807–822, July 1955.

[23] R. Damon, "Magnetically controlled microwave directional coupler," *J. Appl. Phys.*, vol. 26, pp. 1281–1282, October 1955.

[24] A. Fox, "Wave coupling by warped normal modes," *Bell Sys. Tech. J.*, vol 34, pp. 823–852, July 1955.

[25] J. K. Hunton, H. C. Poulter, and C. S. Reis, "High directivity coaxial directional couplers and reflectometers," *Hewlett-Packard J.*, vol. 7, October 1955.

[26] R. Knechtli, "Further analysis of transmission-line directional couplers," *Proc. IRE*, vol. 43, pp. 867–869, July 1955.

[27] R. L. Kyle, "A new broad band coax directional coupler," *Proc. NEC*, pp. 402–414, October 1955.

[28] W. Louisell, "Analysis of the single tapered mode coupler," *Bell Sys. Tech. J.*, vol. 34, pp. 853–870, July 1955.

[29] G. Monteath, "Coupled transmission lines as symmetrical directional couplers," *Proc. IEE (London)*, vol. 102B, pp. 383–392, May 1955.

[30] H. Wolf, "Anwendung theorie des reflectometers," *Arch. elekt. Übertragung*, vol. 9, pp. 221–227, May 1955.

1956

[31] A. Berk and E. Strumwasser, "Ferrite directional couplers," *Proc. IRE*, vol. 44, pp. 1439–1445, October 1956.

[32] F. S. Coale, "A traveling wave directional filter," *IRE Trans. on Microwave Theory and Techniques*, vol. MTT-4, pp. 256–260, October 1956.

[33] E. Jones and J. Bolljahn, "Coupled-strip-transmission-line filters and directional couplers," *IRE Trans. on Microwave Theory and Techniques*, vol. MTT-4, pp. 75–81, April 1956.

[34] P. P. Lombardini, R. F. Schwartz, and P. J. Kelly, "Criteria for the design of loop-type directional couplers for the *L* band," *IRE Trans. on Microwave Theory and Techniques*, vol. MTT-4, pp. 234–239, October 1956.

[35] ——, "Multi-output directional couplers," Moore School of Elec. Engrg., University of Pennsylvania, Philadelphia, Final Rept., Contract AF 30(635)-2801, January 31, 1956.

[36] J. Reed and G. Wheeler, "A method of analysis of symmetrical four-port networks," *IRE Trans. on Microwave Theory and Techniques*, vol. MTT-4, pp. 246–252, October 1956.

[37] H. Wolf, "Coupled high frequency transmission lines for use as directional couplers," *Nachrichtentech. Z. (Germany)*, vol. 9, pp. 375–382, August 1956 (in German).

[38] L. Young, "Branch guide couplers," *Proc. NEC*, vol. 12, pp. 723–732, 1956.

1957

[39] S. B. Cohn, P. M. Sherk, J. K. Shimizu, and E. M. T. Jones, "Strip transmission line and components," Stanford Research Inst., Menlo Park, Calif., Final Rept., Contract DA 36-039-SC-63232, March 1957.

[40] J. Crompton, "A contribution to the design of multi-element directional couplers," *Proc. IEE (London)*, vol. 104C, pp. 398–402, September 1957.

[41] R. Koike, T. Asano, and A. Morishima, "Coaxial directional couplers," *J. Inst. Elect. Commun. Engrs. (Japan)*, vol. 41, pp. 626–631, June 1958 (in Japanese).

[42] P. P. Lombardini, and R. F. Schwartz, "A new type of directional coupler for coupling coaxial line to TE_{10} waveguide," *IRE WESCON Conv. Rec.*, vol. 1, pt. 1, pp. 22–29, 1957.

[43] P. D. Lomer and J. W. Crompton, "A new form of hybrid junction for microwave frequencies," *Proc. IEE (London)*, vol. 104B, pp. 261–263, May 1957.

[44] H. Perini and P. Sferrazza, "Rectangular waveguide to strip-transmission-line directional couplers," *IRE WESCON Conv. Rec.*, vol. 1, pt. 1, pp. 16–21, 1957.

[45] J. K. Shimizu, "A strip line 3 db directional coupler," Stanford Research Inst., Menlo Park, Calif., Sci. Rept. 1, Contract AF 19(604)-1571; also, *IRE WESCON Conv. Rec.*, vol. 1, pt. 1, pp. 4–15, 1957.

1958

[46] G. Broussaud, "Waveguide coupling—theory of thin slot directional couplers," *Ann. Radioelect. (France)*, vol. 13, pp. 187–199, July 1958 (in French).

[47] S. B. Cohn et al., "Design criteria for microwave filters and coupling structures," Stanford Research Inst., Menlo Park, Calif., Tech. Rept. 3, Contract DA36-039-SC-74862, August 1958.

[48] J. M. C. Dukes, "Broad-band slot coupled microstrip directional couplers," *Proc. IEE (London)*, vol. 105B, pp. 147–154, March 1958.

[49] J. Figanier and E. A. Ash, "Intrinsic directional coupler using elliptical coupling apertures," *Proc. IEE (London)*, vol. 105C, pp. 432–437, March 1958.

[50] A. Jaumann, "Directional couplers for the production of the H_{01} wave in circular waveguide," *Arch. elekt. Übertragung (Germany)*, vol. 12, pp. 440–446, October 1958 (in German).

[51] S. Kurokawa, T. Takahashi, and M. Arai, "Mutually coupled CR type directional coupler," *J. Rad. Res. Lab. (Japan)*, vol. 5, pp. 127–133, April 1958.

[52] I. Lucas, "Matching elements for the coupling of periodic structure waveguide directional couplers," *Arch. elekt. Übertragung (Germany)*, vol. 12, pp. 91–96, February 1958 (in German).

[53] L. Milosevic, "Frequency selective directional couplers for hyperfrequencies," *Revue-Tech. de la Compagnie Francaise Thomson-Houston*, no. 29, pp. 49–54, September 1958.

[54] J. Reed, "The multiple branch waveguide coupler," *IRE Trans. on Microwave Theory and Techniques*, vol. MTT-6, pp. 398–403, October 1958.

[55] E. Schuon, "Properties and design of long slot directional couplers," *Arch. elekt. Übertragung (Germany)*, vol. 12, p. 237, 1958.

[56] J. Shimizu and E. Jones, "Coupled-transmission-line directional couplers," *IRE Trans. on Microwave Theory and Techniques*, vol. MTT-6, pp. 403–410, October 1958.

[57] D. C. Stinson, "Ferrite directional couplers with off-center apertures," *IRE Trans. on Microwave Theory and Techniques*, vol. MTT-6, pp. 332–333, July 1958.

1959

[58] G. L. Allerton, "Microwave directional couplers," *Electronics*, vol. 32, p. 40, September 18, 1959.

[59] T. Anderson, "Directional coupler design nomograms," *Microwave J.*, vol. 2, pp. 34–38, May 1959.

[60] D. J. Angelakos, "An image line coupler," *IRE Trans. on Microwave Theory and Techniques*, vol. MTT-7, pp. 391–392, July 1959.

[61] E. S. Hensperger, "The design of multi-hole coupling arrays," *Microwave J.*, vol. 2, pp. 38–42, August 1959.

[62] D. J. Lewis, "Mode couplers and multimode measurement techniques," *IRE Trans. on Microwave Theory and Techniques*, vol. MTT-7, pp. 110–116, January 1959.

[63] V. V. Meriakri, "Closely coupled directional couplers in multimode circular waveguides," *Radiotekhnika i Elektronika (U.S.S.R.)*, vol. 4, pp. 1929–1931, November 1959 (in Russian).

[64] D. J. Nigg, "Shrinking the directional couplers," *Electronic Industries*, vol. 18, pp. 92–96, September 1959.

[65] H. Pascher, "Long-slot directional coupler for H-mode waves," *Arch. elekt. Übertragung (Germany)*, vol. 13, pp. 76–82, February 1959 (in German).

[66] K. G. Patterson, "A method for accurate design of a broad-band multibranch waveguide coupler," *IRE Trans. on Microwave Theory and Techniques*, vol. MTT-7, pp. 466–473, October 1959.

[67] V. V. Tyazhelov, "An experimental investigation of the interaction of single wire transmission lines," *Radiotekhnika i Elektronika (U.S.S.R.)*, vol. 4, pp. 592–598, 1959 (in Russian).

[68] T. A. Vereschnakova and V. V. Tyazhelov, "Experimental investigation of space-beats in a two-wire decimetric waves," *Bulletin of Higher Education Institutions, Radio Engineering (U.S.S.R.)*, vol. 2, p. 217, 1959 (in Russian).

[69] W. G. Voss, "Modified two-hole directional coupler," *Electronic Rad. Eng.*, vol. 36, p. 28, June 1959.

1960

[70] F. Andeceza, "Coupling of coaxial transmission lines and waveguide," *Rev. Telecom. (Madrid)*, vol. 15, pp. 20–25, March 1960 (in Spanish).

[71] A. N. Akhiezer, "Coupling of rectangular waveguides by means of a hole in the wide wall," *Zh. tekh. phys. (U.S.S.R.)*, vol. 30, pp. 851–854, July 1960 (in Russian).

[72] R. Mashkovtsev, L. Bensman, and A. A. Khokhrev, "A wide band waveguide directional coupler," *Radiotekhnika (U.S.S.R.)*, vol. 15, pp. 8–17, April 1960 (in Russian).

[73] D. I. Mirovitsky and G. G. Valieev, "Surface wave directional couplers," *Radiotekhnika i Electronika (U.S.S.R.)*, vol. 5, pp. 1078–1084, 1960 (in Russian).

[74] W. Nonak, "Application of unsymmetrical coupling for waveguide directional couplers with frequency independent coupling factor," *Hochfrequenztech. u. Elektakust. (Germany)*, vol. 69, pp. 179–188, October 1960 (in German).

[75] B. Oguchi, "Circular electric mode coupler," *IRE Trans. on Microwave Theory and Techniques*, vol. MTT-8, pp. 660–666, November 1960.

[76] L. Solymar, "Some properties of three coupled waves," *IRE Trans. on Microwave Theory and Techniques*, vol. MTT-8, pp. 284–291, May 1960.

[77] W. Stosser, "The 3-db coupler," *Frequenz (Germany)*, vol. 14, pp. 117–121, April 1960 (in German).

1961

[78] V. J. Albanese and H. Kagan, "The cross-over directional coupler," *Microwave J.*, vol. 4, pp. 88–91, September 1961.

[79] K. Araki, "Study of the design for directional couplers," Rept. of the Elec. Commun. Lab. (Japan), no. 1311, 1961.

[80] S. B. Cohn and S. L. Wehn, "Microwave hybrid coupler study program," Rantee Corp., Calabasas, Calif., 2nd Quart. Rept., Contract DA 36-2395c-87435, November 1961.

[81] A. L. Feldshtein, "Synthesis of stepped directional couplers," *Radiotekhnika i Electronika (U.S.S.R.)*, vol. 6, pp. 234–240, February 1961 (in Russian); also, New York: Pergamon Press, pp. 74–85 (in English).

[82] R. Z. Gerlack, "10-dB X_L cross-guide coupler," *IRE Trans. on Microwave Theory and Techniques*, vol. MTT-9, p. 571, November 1961.

[83] W. J. Getsinger, "Ridge waveguide directional couplers," Stanford Research Inst., Menlo Park, Calif., Contract AF 19(604)3502 AD 260, 246, May 1961.

[84] W. J. Getsinger, "A coupled strip line configuration using printed circuit construction that allows very close coupling," *IRE Trans. on Microwave Theory and Techniques*, vol. MTT-9, pp. 535–544, November 1961.

[85] R. Koike, "Recent advances in the use of coupled transmission lines as directional couplers," *Proc. IEE (London)*, vol. 108B, pp. 120–124, January 1961.

[86] Z. Krzycki, "Cross-guide coupler with a ferrite filled coupling hole," *Rozprawy elektrotech. (Poland)*, vol. 7, pp. 355–364, 1961 (in Polish).

[87] B. Maher, "An L-band loop type coupler," *IRE Trans. on Microwave Theory and Techniques*, vol. MTT-9, pp. 362–363, July 1961.

[88] Z. Novotny, "Directional coupler of optimum directivity," *Slaboproudy Obzor (Czechoslavakia)*, vol. 22, pp. 653–659, 1961 (in Czechoslovakian).

[89] W. Nowak, "Two new waveguide directional couplers with particularly frequency independent coupling," *Wiss. Z. Tech. Hochsch. Dresden (Germany)*, vol. 10, pp. 743 and 747, 1961 (in German).

[90] L. L. Oh and C. D. Lunden, "Zig zag-line couplers transfer microwave power," *Electronics*, vol. 34, pp. 58–59, July 14, 1961.

[91] C. Y. Pon, "Hybrid-ring directional coupler for arbitrary power division," *IRE Trans. on Microwave Theory and Techniques*, vol. MTT-9, pp. 529–535, November 1961.

[92] B. Richard, "High performance directional couplers," *Ann. Rad oelect. (France)*, vol. 16, pp. 293–301, October 1961 (in French).

[93] W. Shelton, "Compact multihole directional couplers," *Microwave J.*, vol. 4, pp. 89–92, July 1961.

[94] S. Tschiya, "On the action of dipoles in waveguide circuits," *J. Inst. Elect. Commun. Engrg. (Japan)*, vol. 44, pp. 963–973, June 1961 (in Japanese).

[95] C. W. van Es, M. Gevers, and F. C. deRonde, "Waveguide equipment for 2mm microwaves," *Philips Tech. Rev.*, vol. 22, p. 122, January 16, 1961.

[96] A. I. Zykov and I. N. Dudkina, "Coupling of matching elements in diaphragm-type waveguides," *Pribory i Tekh. Eksper. (U.S.S.R.)*, no. 2, p. 191, March–April 1961 (in Russian); also, *Instrum. Exper. Tech. (U.S.A.)*, no. 2, p. 390, December 1961 (in English).

1962

[97] K. Araki, "The characteristic impedance of the pair cable type directional coupler," *Rev. of the Elect. Commun. Lab. (Japan)*, vol. 10, pp. 607–625, November–December 1962.

[98] C. R. Boyd, "On a class of multiple line directional couplers," *IRE Trans. on Microwave Theory and Techniques*, vol. MTT-10, pp. 287–294, July 1962.

[99] S. B. Cohn and R. H. Koontz, "Microwave hybrid coupler study program," Rantee Corp., Calabasas, Calif., 3rd Quart. Rept., Contract DA36-239-SC-87435, February 1962.

[100] A. L. Feldshtein and E. S. Zhavoronka, "The design of loosely coupled Chebyshev directional couplers," *Radiotekhnika (U.S.S.R.)*, vol. 17, pp. 40–50, January 1962 (in Russian); also, New York: Pergamon Press, pp. 39–50 (in English).

[101] W. J. Getsinger, "Coupled rectangular bars between parallel plates," *IRE Trans. on Microwave Theory and Techniques*, vol. MTT-10, pp. 479–491, November 1962.

[102] H. Huang, "Generalized theory of coupled local normal modes in multiwave guides," *Acta Phys. Sinica (China)*, vol. 18, pp. 325–333, July 1962 (in Chinese).

[103] H. J. Hinden and J. J. Taub, "Oversize waveguide directional coupler," *IRE Trans. on Microwave Theory and Techniques*, vol. MTT-10, pp. 394–395, September 1962.

[104] E. A. Marcatili and D. H. Ring, "Broad-band directional couplers," *IRE Trans. on Microwave Theory and Techniques*, vol. MTT-10, pp. 251–257, July 1962.

[105] B. M. Mashkovstev, "A method of analyzing multicircuit directional couplers with rotating field polarization," *Radiotekhnika (U.S.S.R.)*, vol. 17, pp. 3–10, 1962 (in Russian).

[106] L. O. Sweet, "Analysis of a two-section coupler," *IRE Trans. on Microwave Theory and Techniques*, vol. MTT-10, p. 295, July 1962.

[107] J. Willis, "A plasma controlled directional coupler," *IRE Trans. on Microwave Theory and Techniques*, vol. MTT-10, pp. 383–389, September 1962.

[108] L. Young, "Synchronous branch guide directional couplers for low and high power applications," *IRE Trans. on Microwave Theory and Techniques*, vol. MTT-10, pp. 459–475, November 1962.

1963

[109] M. E. Brodwin and V. Ramaswamy, "Continuously variable directional couplers in rectangular waveguide," *IEEE Trans. on Microwave Theory and Techniques*, vol. MTT-11, pp. 137–142, March 1963.

[110] S. B. Cohn, "The re-entrant cross section and wide-band 3 dB hybrid coupler," *IEEE Trans. on Microwave Theory and Techniques*, vol. MTT-11, pp. 254–258, July 1963.

[111] A. F. Harvey, *Microwave Engineering*. New York: Academic Press, 1963, ch. 3., sec. 3.3.

[112] H. Huang, "Theory of coupled waveguides," *Acta Phys. Sinica (China)*, vol. 18, pp. 27–55, January 1963 (in Chinese).
[113] H. Huang, "Notes on discontinuity problems in coupled wave theory," *Acta Phys. Sinica (China)*, vol. 18, pp. 56–62, January 1963 (in Chinese).
[114] J. G. Humphreys, "Microwave coaxial line components," *Brit. Commun. and Electron.*, vol. 10, pp. 362–367, May 1963.
[115] R. Levy, "General synthesis of asymmetric multi-element coupled-transmission-line directional couplers." *IEEE Trans. on Microwave Theory and Techniques*, vol. MTT-11, pp. 226–237, July 1963.
[116] R. J. Mohr and J. E. McFarland, "Exact analysis of asymmetric couplers," *Microwaves*, vol. 2, pp. 90–93, March 1963.
[117] L. L. Oh, "Serpentine line directional couplers," *Microwaves*, vol. 2, p. 32, December 1963.
[118] J. Reed, "Branch waveguide coupler design charts," *Microwave J.*, vol. 6, p. 103, January 1963.
[119] H. Smith, "Tables for the design of aperture type waveguide couplers," *Microwave J.*, vol. 6, pp. 91–94, June 1963.
[120] L. Sweet, "A method of improving the response of waveguidedirectional couplers," *IEEE Trans. on Microwave Theory and Techniques*, vol. MTT-11, p. 554, November 1963.
[121] W. A. G. Voss, "Optimized cross slot directional coupler," *Microwave J.*, vol. 6, pp. 83–87, May 1963.
[122] L. Young, "The analytical equivalence of TEM-mode directional couplers and transmission-line stepped impedance filters," *Proc. IEE (London)*, vol. 110, pp. 275–281, February 1963.

1964

[123] E. G. Cristal, "Coupled circular cylindrical rods between parallel ground planes." *IEEE Trans. on Microwave Theory and Techniques*, vol. MTT-12, pp. 428–439, July 1964.
[124] R. G. Fellers and J. Taylor, "Internal reflections in dielectric prisms," *IEEE Trans. on Microwave Theory and Techniques*, vol. MTT-12, pp. 584–587, November 1964.
[125] V. D. Kuznetsov and V. K. Paramonov, "Stepped directional couplers," *Telecom. and Radio Engrg. (U.S.S.R.)*, vol. 19, January 1964 (in Russian); also, New York: Pergamon Press, pp. 100–113 (in English).
[126] R. Levy, "Tables for asymmetric multi-element coupled tranmission-line directional couplers," *IEEE Trans. on Microwave Theory and Techniques*, vol. MTT-12, pp. 275–279, May 1964.
[127] W. R. Lind, "A TE mode selective coaxial directional coupler," M.S. thesis, Moore School of Elect. Engrg., University of Pennsylvania, 1964.
[128] G. L. Matthaei, L. Young, and E. M. T. Jones, *Microwave Filters, Impedance Matching Networks and Coupling Structures*. New York: McGraw-Hill, 1964.
[129] L. Young, "Waveguide 0-db and 3-db directional couplers as harmonic pads," *Microwave J.*, vol. 7, p. 79, March 1964.

1965

[130] E. G. Cristal and L. Young, "Theory and tables of optimum symmetrical TEM-mode coupled-transmission-line directional couplers," *IEEE Trans. on Microwave Theory and Techniques*, vol. MTT-13, pp. 544–558, September 1965.
[131] H. Berger, "Nonreciprocal directional couplers," *IEEE Trans. on Microwave Theory and Techniques*, vol. MTT-13, p. 474, July 1965.
[132] J. Daglian, "A contradirectional waveguide coupler with high directivity and tight coupling," M.S. thesis, Moore School of Elect. Engrg., University of Pennsylvania, Philadelphia, 1965.
[133] L. C. Gunderson and A. Guida, "Stripline coupler design," *Microwave J.*, vol. 8, pp. 97–101, June 1965.
[134] H. Jones and R. Norris, "Plated dielectric waveguide components," *Microwaves*, vol. 4, pp. 14–18, July 1965.
[135] R. J. Kalagher, "A TEM mode-selective coaxial directional coupler," M.S. thesis, Moore School of Elect. Engrg., University of Pennsylvania, Philadelphia, 1965.
[136] L. Lavendol and J. J. Taub, "Re-entrant directional coupler using strip transmission line," *IEEE Trans. on Microwave Theory and Techniques*, vol. MTT-13, pp. 700–701, September 1965.
[137] R. Levy, "Transmission line directional coupler for very broadband operation," *Proc. IEE (London)*, vol. 112, pp. 469–476, April 1965.
[138] E. Martin, "Calibrating directional couplers en masse," *Microwaves*, vol. 4, pp. 40–43, June 1965.
[139] J Shelton, J. Wolfe, and R. Van Wagoner, "Tandem couplers and phase shifter for multi-octave bandwidth," *Microwaves*, vol. 4, pp. 14–19, April 1965.
[140] P. P. Toulios and A. C. Todd, "Synthesis of symmetrical TEM-mode directional couplers," *IEEE Trans. on Microwave Theory and Techniques*, vol. MTT-13, pp. 536–544, September 1965.

Reflections from Rotary-Vane Precision Attenuators

Due to finite thickness of the absorbing vanes, the scattering coefficients [1] S_{11} and S_{22} of a rotary-vane attenuator [2] are not zero (as would be true of an "ideal" device) but are, in fact, functions of attenuator setting. Thus, terminal reflections cannot be eliminated by simply fixed-tuning the ports. In this correspondence we derive an equation relating S_{11} (S_{22}) to the attenuator setting by considering the effects of small reflections from vanes of an otherwise perfect attenuator. The result is found to contain three complex constants that can be determined experimentally, with this expression one can, when necessary, take reflections into account analytically by determining the constants appropriate to the attenuator under consideration. This procedure is useful, e.g., when using a combination of an attenuator and a movable short-circuit as a variable impedance standard [3]; or, when determining "mismatch error" in a transmission system in which the generator or load are not matched to the line [4], [5].

Consider the cascade of three networks shown in Fig. 1. Since each circular waveguide supports two mutually-orthogonal dominant modes, the transitions and circular section are three- and four-ports, respectively. The (symmetrical) scattering matrices of these networks are thus of the form

$$S_a = \begin{bmatrix} S'_{55} & S'_{56} & S'_{57} \\ & S'_{66} & S'_{67} \\ & & S'_{77} \end{bmatrix} \qquad (1)$$

$$S_b = \begin{bmatrix} S'_{11} & S'_{12} & S'_{13} & S'_{14} \\ & S'_{22} & S'_{23} & S'_{24} \\ & & S'_{33} & S'_{34} \\ & & & S'_{44} \end{bmatrix} \qquad (2)$$

$$S'_c = \begin{bmatrix} S'_{88} & S'_{89} & S'_{8,10} \\ & S'_{99} & S'_{9,10} \\ & & S'_{10,10} \end{bmatrix} \qquad (3)$$

where coefficients subscripts are defined by the polarization directions shown in Fig. 1. Absorbing vanes are assumed to lie in the horizontal plane of each transition and in the 2–4 plane of the rotating section.

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By applying the appropriate coordinate transformation, one can solve for the overall scattering matrix

$$S = \begin{bmatrix} S_{11} & S_{12} \\ S_{12} & S_{22} \end{bmatrix} \qquad (4)$$

of the cascade. To simplify this calculation, we assume that S_{56}', S_{13}', and S_{89}' are of the form

$$S_{ij}' = 1 - \delta_{ij} \qquad (5)$$

while all other terms are of the form

$$S_{ij}' = \delta_{ij} \qquad (6)$$

with δ_{ij} small. Retaining only terms to first order in δ_{ij} yields an equation of the form

$$S_{11} = A_{11} + B_{11} \sin^2 \theta + C_{11} \sin^2 (2\theta) + D_{11} \sin (2\theta) + E_{11} \sin (4\theta) \qquad (7)$$

with a similar result for S_{22}. The constants in (7) are complicated functions of the various δ_{ij}'s; and the vane angle θ is related to the attenuator setting in dB by

$$\cos^2 \theta = 10^{-\mathrm{dB}/20}. \qquad (8)$$

Equation (7) can be simplified by assuming further that vanes absorb all transmitted waves polarized parallel to them and that no cross-coupling occurs between spatially orthogonal modes. That is

$$\left.\begin{array}{l} S'_{57} = S'_{67} = S'_{8,10} = S'_{9,10} = 0 \\ S'_{12} = S'_{14} = S'_{23} = S_{34}' = 0 \\ S'_{24} = 0 \end{array}\right\}. \qquad (9)$$

The overall reflection coefficient S_{11} is then of the form

$$S_{11} = A_{11} + B_{11} \sin^2 \theta + C_{11} \sin^2 (2\theta) \qquad (10)$$

with a similar result for S_{22}. Under the same approximations which lead to (10), the transmission coefficient is found to be

$$S_{12} = A_{12} \cos^2 \theta \qquad (11)$$

where A_{12} is a complex constant with magnitude less than unity. Thus, besides causing variable terminal reflections, slightly reflecting vanes will also introduce a fixed insertion loss and a fixed phase shift. To first order they do not, however, cause variable errors in attenuation, nor do they cause phase shift that varies with attenuator setting. Equation (11) has been found to be well satisfied in measurements of attenuation [5] and phase shift [6] of actual rotary-vane attenuators.

In order to check the validity of (10), the magnitude $|S_{11}|$ and $|S_{22}|$ of several commercially-made X- and K-band attenuators were measured with reflectometers that had been tuned by the procedure of Engen and Beatty [7]. In each measurement, the opposite port of the attenuator was terminated in a matched load that had been tuned to eliminate reflections. Figures 2 and 3 show typical results. Points represent experimental values while curves were calculated from (10) using the constants given in Table I. These constants were determined by fitting the results to (10) at five experimental points. Since the magnitude of S_{ii} depends on A_{ii}, B_{ii}, and C_{ii} only to within a common arbitrary phase angle, A_{ii} was assumed real. One notes excellent agreement between theory and experiment over the entire attenuation range. Although