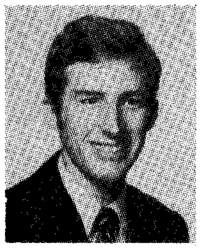
(Philadelphia, PA), Feb. 1975, pp. 136–137.
[7] E. Wilkinson, "An *N*-way hybrid power divider," *IRE Trans. Microwave Theory Tech.*, vol. MTT-8, pp. 116–118, Jan. 1960.
[8] C. T. Rucker, "A multiple-diode, high-average power avalanche-diode oscillator," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-17, pp. 1156–1158, Dec. 1969.
[9] K. Kurokawa, "An analysis of Rucker's multidevice symmetrical oscillator," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-18, pp. 967–969, Nov. 1970.
[10] K. J. Russell and R. S. Harp, "Broadband diode power-combining techniques," Air Force Avionics Laboratory, Wright-Patterson Air Force Base, OH, Interim Tech. Rep. No. 1, Mar. 1978.
[11] J. M. Schellenberg and M. Cohn, "A wideband radial power combiner for FET amplifiers," in *IEEE Int. Solid-State Circuits Conf. Dig.*, (San Francisco, CA), Feb. 1978.
[12] Saleh, A. A. M., "Planar electrically symmetric *N*-way hybrid power dividers/combiners," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-28, pp. 555–563, June 1980.
[13] R. Bellman, *Introduction to Matrix Analysis*. New York: McGraw-Hill, 1970, pp. 242–243.
[14] Peterson, D. F. and Haddad, G. I., "Design, performance and device/circuit limitations of *N*-way symmetrical IMPATT diode power combining arrays," Electron Physics Lab. Univ. Michigan, Ann Arbor, MI, Tech. Report AFWAL-TR-81-1107, Feb. 1981.



**Dean F. Peterson** (S'70–M'71) was born in Melbourne, FL, on March 28, 1945. He received the B.S. degree in electrical engineering from Utah State University, Logan, in 1967, and the M.S. and Ph.D. degrees from the Massachusetts Institute of Technology, Cambridge, in 1969 and 1971, respectively.

From 1971 to 1977 he was a staff member in the Satellite Communications Group at the Massachusetts Institute of Technology, Lincoln Laboratory, and was actively involved in the development of Lincoln Experimental Satellites (LES 8/9). He is currently an Assistant Professor in the Department of Electrical and Computer Engineering, Electron Physics Laboratory, The University of Michigan, Ann Arbor. His present research activities involve microwave solid-state devices and circuits.

Dr. Peterson is a member of Sigma Xi.

# Tunable Low-Loss UHF Circulator for Cryogenic Applications

JARDA KADLEC

*Abstract* —**A 600-MHz above-resonance circulator operating at 4.2 K has been constructed and successfully tested. Its high isolation (>30 dB), extremely low insertion loss (<0.1 dB), low VSWR (<1.1), and acceptable instantaneous bandwidth (~6 percent) make it a promising device for utilization in narrow-band very low-noise systems.**

## I. Introduction

The need for low-loss cryogenic circulators had been recognized many years ago [1], [2]. In conjunction with low-noise reflection amplifiers, their importance follows from the consideration of noise contributions of preamplification losses to the system noise. This paper describes the design, construction, and performance of a $Y$-junction stripline circulator which is being used at the input of a low-noise superconducting unbiased parametric amplifier (SUPARAMP) operating at 4.2 K in a doubly-degenerate mode around 600 MHz [3], [4].

There are a number of publications [5] dealing with theory and design of stripline circulators for room temperature operation, most of them being more concerned with the broadbandness of the device than with minimization of its insertion loss. Only a few papers look into problems of low-temperature design of circulators operating in various frequency bands above 1 GHz [1], [2], [6]–[8]. To the author's knowledge, no work has been published on cryogenic circulators for frequencies below 1 GHz. We have constructed and tested two versions of a circulator designed for a nominal center-band frequency of 600 MHz. With regard to our anticipated application the minimum insertion loss has been emphasized at the expense of the

Manuscript received June 1, 1981; revised September 29, 1981. This work was supported in part by the National Science Foundation under Grant PHY-79-14602.

The author was with the Department of Physics and Astronomy, Louisiana State University, Baton Rouge, LA. He is now with the IBM Thomas J. Watson Research Center, P.O. Box 218, Yorktown Heights, NY 10598.

0018-9480/82/0200-0173$00.75 ©1982 IEEE

broadbandness. We point out some specific design problems and represent data on the successful operation.

## II. Design Theory

The theory [5] for stripline circulator design operating at room temperature is firmly established and may directly be applied to cryogenic circulators as well. We have, however, to keep in mind that the magnetic properties of the ferrite material which is employed as the nonreciprocal medium are temperature dependent. Hence the low-temperature value of the saturation magnetization $4\pi M_s$ and the ferromagnetic resonance linewidth $\Delta H$ of the ferrite must be used in the design equations.

The first decision to be made is whether the circulator is going to work with the magnetic bias below or above the ferromagnetic resonance of the particular material at operating frequency (600 MHz in our case). It becomes clear from the examination of available ferrites that the operating point of the circulator in the below-resonance regime would inevitably land within the high-loss region as a result of the proximity of the resonance absorption peak and/or low-field losses. This situation is especially aggravated in the cryogenic design because of the expected broadening of the resonance linewidth at low temperatures [1], [2]. On the other hand, operation far above the ferromagnetic resonance gives promise of low-loss performance, though at the cost of relatively high magnetic field biasing the ferrite and a limited bandwidth. Because of our primary emphasis on the low losses, we chose this above-resonance regime.

The design parameters for our circulators have been obtained by applying the general equations developed in [9] and [10]. Assuming the material data to be known (see below), our computer model includes a calculation of the complex Polder tensor (not included in [9]) and uses its components in the design equations. The resulting parameters and some construction details are presented in the next section.

## III. Design Praxis and Circulator Performance

### A. Ferrite Material

The proper choice of the ferrite material in a circulator may be crucial for its performance. For the above-resonance operation theoretical considerations require a relatively high value of saturation magnetization [12] and a small resonance linewidth. After an extensive search for suitable materials we decided upon the calcium–vanadium garnet CVG-930 manufactured by Ampex. The value of $4\pi M_s$ changes approximately from 930 G at 300 K to 1530 G at 77 K. The room temperature value of the 3-dB linewidth is $\Delta H \lesssim 15$ Oe. No data on this ferrite was available at 4.2 K. Using the general results on temperature dependence of the above quantities (as measured for other materials [1], [2], [7]) we infer the following values for 4.2 K by way of extrapolation: $(4\pi M_s)_{4.2} \approx 1600$ G, $(\Delta H)_{4.2} \lesssim 100$ Oe.

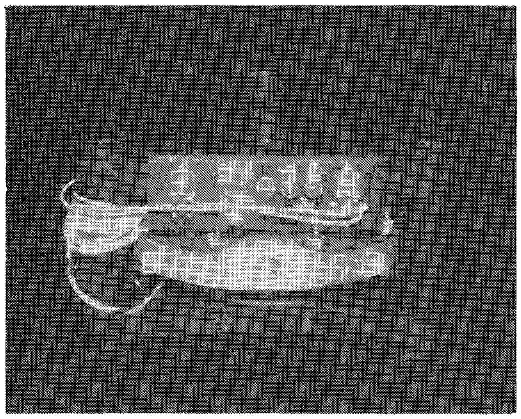


Fig. 1 Photograph of the complete circulator; the case shown schematically in Fig. 2 is mounted between the poles of the superconducting magnet.

These numbers and the known relative dielectric constant of 15 have been used in the calculation.

### B. Superconducting Magnet

The dc magnetic field across the ferrite disks is supplied by a superconducting electromagnet consisting of two coils (2500 turns of Supercon T48B-Type M-wire each) which are mounted on a soft iron yoke having a 120° symmetry (see Fig. 1). A good magnetic return path serves two purposes. First, the cylindrical center posts around which the coils are wound assure a good uniformity of the field within the ferrite disks inside the circulator cavity and, second, the yoke confines the stray magnetic flux. This feature is particularly desirable in our application since the Josephson junctions constituting the active element of the SUPARAMP are extremely sensitive to magnetic fields. The measured intensity of the stray field in the radial distance of 10 cm from the cavity center is less than one percent of the center value. The two series-connected coils of the magnet can be switched into the persistent-current mode; in this mode, no deviation of the tuning point of the circulator from the adjusted value can be observed even after one week of operation.

### C. Circulator—Version 1

Following the theoretical estimate of the minimum insertion loss which can be written [1], [5] as $L(\text{dB}) = 20 \log(1 - Q_L/Q_0)$ where $Q_L$ and $Q_0$ are the loaded and unloaded $Q$'s of the resonator, respectively, the first version of the circulator was designed for a center-band insertion loss below 0.2 dB. Assuming $(\Delta H)_{4.2} \approx 100$ Oe and taking care of some safety margin the calculation gives the height of the ferrite disk equal to 1.5 cm. The matching of the resonator to the outer 50-Ω circuitry must be ensured via quarter-wavelength transformers. Both the height of the disks and the transformers make the physical dimensions of the circulator very large. Nevertheless, the device has been constructed and tested. The measured performance was very good and can be briefly described in the following terms: center-band isolation more than 30 dB within a tuning range 580–600 MHz; instantaneous 20-dB-isolation bandwidth about 3 percent; center-band insertion loss much less than 0.05 dB; center-band input VSWR about 1.07. In particular, we were surprised by the very low insertion loss which is much smaller than the theoretically predicted minimum. To understand this pleasant discrepancy we measured the ferromagnetic resonance absorption of CVG-930 at 4.2 K. The preliminary analysis of the results obtained at 9 GHz (a low-frequency measurement cannot be performed with our present equipment) indicates a rather narrow absorption line whose shape is, however, strikingly different from the simple theoretical assumption [5]. Consequently, the effective linewidth entering the calculation of $Q_0$ is difficult to determine, but it seems to be much less than 100 Oe assumed above. The complete results of the absorption measurement will be published elsewhere. In any case, the measured performance of the circulator suggests that we may be allowed to cut the height of the ferrite disks, thus reducing the height of the circulator and, eventually, being able to directly couple the resonator to 50-Ω circuitry. Elimination of the transformers would substantially reduce the lateral dimensions of the circulator. This modified version is described in some technical detail in the next part.

### *D. Circulator — Version 2*

The starting point of the design is given by the fact that direct coupling to 50-Ω stripline is to be achieved and the center conductor of this stripline has a physical separation from either groundplane equal to 0.65 cm. (This is the length of the chip carrying the array of Josephson junctions in the future amplifier.) Using fused quartz ($\in = 3.78$) as the dielectric of the stripline the width of the center conductor calculates to be 0.69 cm for 50-Ω impedance [11]. This same width is coupled to the rim of the resonator and determines—together with the frequency 600 MHz—the radius of the disk to be 2.48 cm. The required internal magnetic field is 1150 Oe. The instantaneous isolation bandwidth between 20-dB points calculates to 5.2 percent.

The simplified scheme of this circulator is shown in Fig. 2 and its photograph in Fig. 1. The cylindrical aluminum case accommodates two ferrite disks in its center and six identical segments of fused quartz plate which have a radius to fit the disk. Small springs push the plates against the disk thus allowing for different contraction during the cool-down. The center conductor which is machined from a single piece of copper foil (thickness 51 $\mu$m) is sandwiched between the lower and upper disk in its circular part and the lower and upper plate over the transmission lines. The end of the center conductor of the lines is soldered to the sliding contact of the hermetically sealed SMA Microwave Integrated Circuit Launcher, manufactured by Solitron/Microwave. A small air gap between the end of the relatively wide center conductor and the wall of the case compensates for the excessive stray coupling to the wall. The measured VSWR for this transition is less than 1.05 at 600 MHz. The bottom and the cover of the case

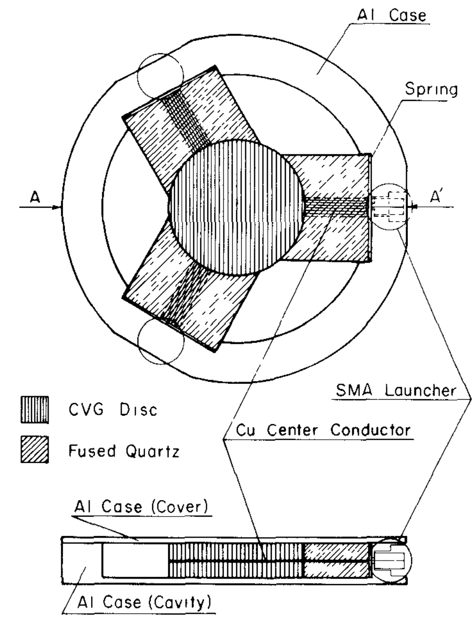



Fig. 2. Scheme of the circulator (version 2); above: top view of the assembled parts without cover, below: cross section $A-A'$ of the closed case.

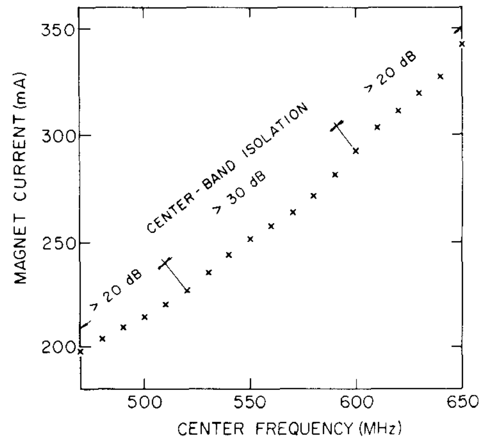



Fig. 3. Tuning curve of the circulator specifying the magnet current necessary for maximum isolation at a given frequency.

provide the groundplanes and excellent shielding. The case with the parts assembled inside is sealed using an indium ring beneath the cover and then centered between the posts of the superconducting magnet (Fig. 1).

The measurements on the circulator immersed in LHe-bath (4.2 K) were performed using low-reflection semirigid coax cables connected to the ports. The isolation and VSWR were measured at the top of the dewar, corrected for the loss of the cables (1.25 dB per cable) and referred to the actual ports of the device. The insertion loss, however, was obtained by direct substitution measurements using a microwave transfer switch connected to the input port of the circulator in LHe-bath. The measurement accuracy and reproducibility obtained in this way is better than 0.05 dB.

Fig. 3 shows the frequency dependence of the magnet current value necessary for maximum isolation. Because of

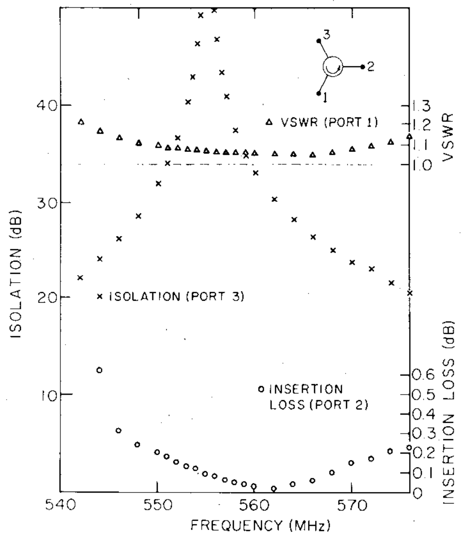



Fig. 4. Frequency dependence of the isolation, VSWR, and insertion loss for a fixed tuning point (center frequency 555 MHz).

the slight magnetic hysteresis of soft iron, the reproducible adjustment requires a well-defined initial condition for the magnetization of the yoke. Therefore, we always started with a current of 1000 mA and then decreased it gradually to the value inducing maximum isolation. If we consider an isolation of 20 dB as the lowest acceptable value, Fig. 3 shows a broad tuning range between 470 and 650 MHz. Assuming a minimum of 30 dB for center-band isolation instead, we still have a tuning option over 80 MHz. The exact frequency for the maximum center-band isolation depends somewhat on the coax cables used for the measurement; this is probably due to reflections between the connectors.

A typical frequency dependence of the isolation, VSWR, and insertion loss for a fixed tuning point—here at 555 MHz—is shown in Fig. 4. The instantaneous 20-dB isolation bandwidth is about 36 MHz or 6.5 percent, which is somewhat more than the theoretical value (5.2 percent). The minimum insertion loss is still below 0.05 dB, though slightly displaced in frequency with respect to the isolation peak. The input VSWR which in theory is directly connected with the isolation seems to be a little too high. We may, however, be measuring the reflections from the connectors of the cable which mask the true value. In any case, the observed VSWR is good enough for most practical purposes.

In other tuning points of Fig. 3, i.e., for other center frequencies, the circulator behaves in a similar way as in Fig. 4, except for the maximum centerband isolation which gradually decreases as the frequency approaches the periphery of the tuning range. The bandwidth, insertion loss, and VSWR are not primarily influenced by shifting the center frequency.

As we mentioned earlier, the design calculations for both versions of the circulator were preformed assuming a nominal operating frequency of 600 MHz. It is interesting to note that in both cases the optimum performance was achieved for frequencies some 3 to 8 percent below the nominal value. This may be due to the fact that the effective magnetic walls of an open resonator lie outside the physical ones.

## Acknowledgment

Fruitful discussions with Prof. W. O. Hamilton and technical assistance provided by D. DeWitt are gratefully acknowledged.

## References

[1] R. L. Comstock and C. E. Fay, "Performance and ferrimagnetic material considerations in cryogenic microwave devices," *J. Appl. Phys.*, vol. 36, pp. 1235–1258, Mar. 1965.

[2] D. H. Roth, W. W. Schedelbeck, and G. H. Schollmeier, "Investigation of ferrimagnetic materials at low temperatures and some applications in low-noise receivers," *IEEE Trans. Mag.*, vol. MAG-2, pp. 256–259, Sept. 1966.

[3] J. Kadlec, "Noise performance and stability of a doubly-degenerate unsaturated SUPARAMP," *J. Appl. Phys.*, vol. 50, pp. 6443–6450, Oct. 1979, and references therein.

[4] J. Kadlec and W. O. Hamilton, "Josephson parametric amplifer as a part of a gravity wave detection scheme," in *SQUID '80-Superconducting Quantum Interference Devices and their Applications*, H. D. Hahlbohm and H. Lübbig, Eds. Berlin–New York: Walter de Gruyter, 1980, pp. 813–829.

[5] J. Helszajn, *Nonreciprocal microwave junctions and circulators*. New York: John Wiley and Sons, 1975, and references therein.

[6] J. A. deGruyl, W. W. Heinz, and S. Okwit, "Helium-cooled *Y*-junction ferrite circulator switch," *Proc. IEEE*, vol. 51, p. 947, June 1963.

[7] S. Yoshida, K. Kurihara, and S. Takahashi, "Strip-line *Y*-circulator at 4.2° K in UHF region," *Proc. IEEE*, vol. 53, pp. 1805–1806, Nov. 1965.

[8] J. Edrich and R. G. West, "Low-loss cryogenic *L*-band circulator," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-18, pp. 743–745, Oct. 1970.

[9] 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.

[10] C. W. Renken, "Speed circulator design with computer modeling," *Microwaves*, pp. 54–64, June 1977.

[11] H. A. Wheeler, "Transmission-line properties of a strip line between parallel planes," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-26, pp. 866–876, Nov. 1978.

[12] G. P. Riblet, "Techniques for broad-banding above-resonance circulator junctions without the use of external matching networks," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-28, pp. 125–129, Feb. 1980.

**Jarda Kadlec** was born in Prague, Czechoslovakia, on August 4, 1945. He received the M.S. degree in solid-state electronics and the Dr. rer.nat. degree in applied physics from the Charles University, Prague, Czechoslovakia, in 1968 and 1970, respectively. His thesis dealt with experimental investigations of secondary-electron emission from thin films.

From 1969 to 1970 he was with the Popov-Research Institute for Telecommunications in Prague, working on *E*-beam lithography and IC design. During 1970–1978 he stayed with the Max Planck Institute for Physics and Astrophysics in Munich, Germany. His research interest in low-temperature tunneling and internal photoemission in thin-film sandwich structures developed into work in the area of Josephson-effect applications. He took active part in development of a Josephson video detector for millimeter waves. From 1978 to 1981 he held the Senior Research Associate and Visiting Assistant Professor positions at the Louisiana State University in Baton Rouge, LA, where he was developing a low-noise Josephson parametric amplifier for utilization in the LSU cryogenic gravity wave experiment. At present he is a Visiting Scientist at the IBM Thomas J. Watson Research Center, Yorktown Heights, NY, where he is concerned with logic applications of Josephson effect.

Dr. Kadlec is a member of the German Physical Society.