V-7. Integrated Circulator Design for Parametric Amplifier Application

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A paper[1] accepted for presentation at the 1964 International Solid State Circuits Conference describes a two-stage, L-band parametric amplifier with a gain of 19 $\pm$0.25 db over a 20% band, and a 1.5 db noise figure in the 15% band of interest. The achievement of maximum performance in a parametric amplifier of this type depends critically upon the characteristics of the associated circulators. It is felt that a discussion of the techniques used in the design of the circulator package for this amplifier might prove helpful to other designers in the field.

The circulator package, which was approximately 8 $\times$ 22 $\times$ 1 inches in over-all dimensions, consisted of five completely integrated circulators built in stripline using photoetched circuitry on 1/8" tellite board. The circulators were of the Y-junction, field-below-resonance type using aluminum substituted YIG (YAIG). Each of three of the circulators had one port terminated and were used as input, output and interstage isolators. The two remaining circulators were used to separate the input and output of the two parametric amplifier stages and to tune the amplifiers for best gain characteristics.

The loss characteristics in a 15% band for the package with the amplifiers removed were:

Insertion loss, input to output	$\leq$ 1 db
Insertion loss per circulator pass	$<$.15 db
Isolation, output to input	$>$ 90 db
Isolation per isolator	$>$ 30 db
Return loss, input and output	$>$ 30 db
Return loss, intercirculator	$>$ 30 db

While the basic circulators were nearly identical stripline Y-junctions identically loaded with high-density aluminum oxide and YAIG discs, there were distinctly different requirements for the admittances of various circulator ports, and none of the circulators had identical requirements on all three ports. These requirements were matches to 50 ohm coaxial cable, to 50 ohm stripline terminations, and to other circulators, and finally, a very specific admittance complementary to that of the amplifier.

It was not possible to maintain complete electrical symmetry in the circulators and meet the design objectives. Fortunately, such symmetry was was not required outside of the immediate bounds of the junction. It was found that each of the ports of a three-port circulator could be independently tuned by measuring its admittance and applying coupling networks designed to transform that admittance into the desired form. In order to insure independent tuning, the remaining ports had only to be reasonably well matched, and their combined return loss had to be appreciably greater than that of the port being operated upon. It has been observed experimentally that a *Y*-junction circulator behaves in many ways like a cavity resonator,[2] and indeed, subject to the above provisions on the match, it was found that the admittance of the circulator referred to a point near the edge of the junction could be represented, as in Fig. 1, by a simple parallel resonant circuit shunted by a field-dependent conductance, G. The resonant frequency was determined by the diameters of the junction elements and, to first order, was independent of the field.

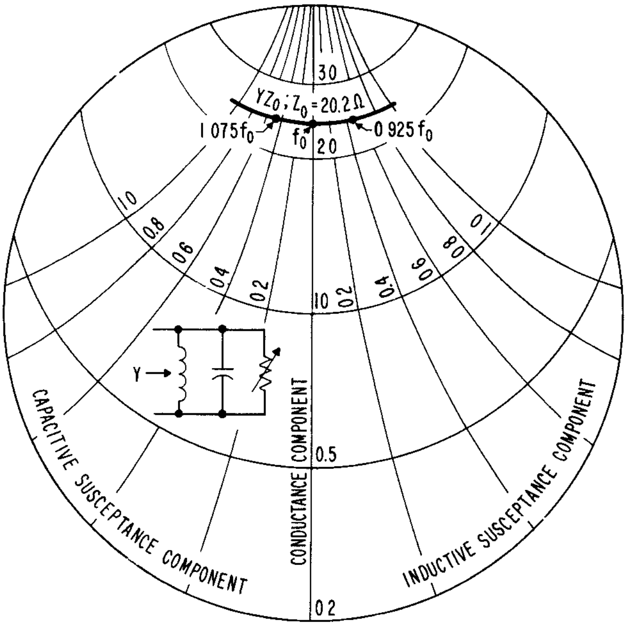

Fig. 1 Basic circulator admittance.

At resonance, the circulator admittance may be transformed to a pure conductance of .02 mhos (50 ohms) by means of a simple quarter-wave transformer. The frequency dependence inherent in the quarter-wave transformer can be made to compensate that of the resonant junction when a proper choice of G and transformer impedance is made, as illustrated in Fig. 2. This was the technique used in matching to the 50 ohm coaxial cables at the input and output of the package and to the stripline terminations.

A match between identical circulator junctions can be obtained at midband, i.e., at their resonant frequency, with a half-wavelength of line of any impedance. By proper choice of line impedance, the admittances of the junctions referred to the center of the half-wave line (Fig. 3) may be made pure real at two other frequencies in the band. Thus, a perfect match is obtained at each of the three points of real admittance, and the intercirculator return loss has the character shown in Fig. 3. In practice, since the circulators being joined may not have the same functions, there may be reason to set their conductances at different values. An intercirculator return loss

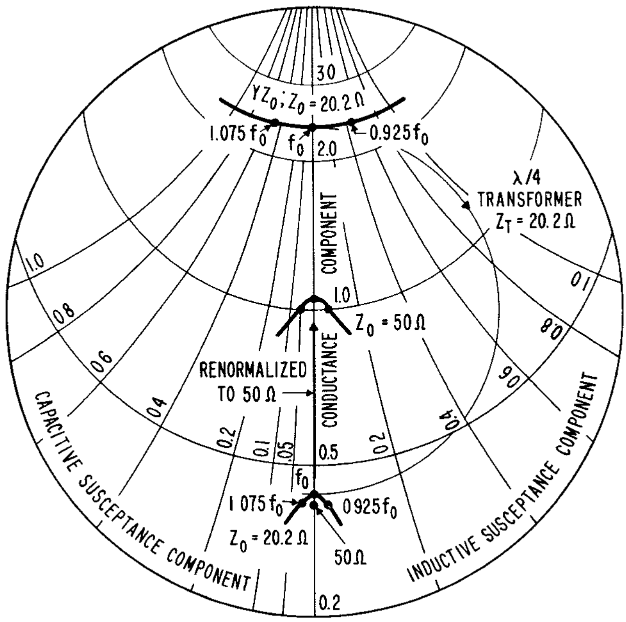

Fig. 2 Matching to 50 ohms.

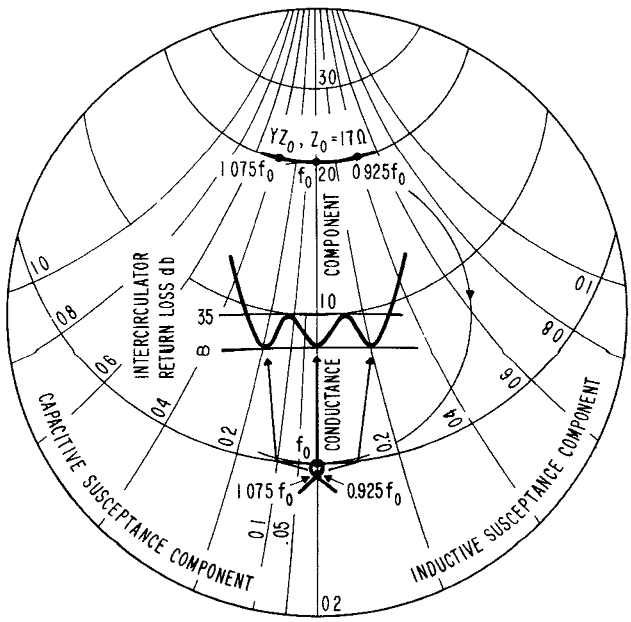

Fig. 3 Intercirculator match.

essentially like that of Fig. 3 may still be obtained by correcting the admittance of one of the circulators with an appropriately placed, open-circuited, capacitive stub on the center strip.

One of the amplifier port admittance characteristics acceptable to this amplifier design was that of a parallel resonant circuit with a conductance at resonance of .02 mhos and a specified Q. An idealized characteristic is shown in Fig. 4. This was accomplished with a modified "quarter-wave" transformer used to bring the midband impedance to 50 ohm followed by a half-wavelength section of 50 ohm line. The modified transformer was of higher impedance and shorter length than the quarter-wave transformer and was compensated at the 50 ohm end by a high-impedance, open-circuited, capacitive stub. By proper selection of the impedance and length of the transformer and stub, it was possible to obtain an admittance characteristic (Fig. 5) which, when transformed through the half-wave section, was exactly that of the parallel resonant circuit required, but with too low a Q (Fig. 6). The Q, however, may be increased to the required value with the addition of an open-circuited half-wavelength stub, the change in Q obtained in this way being dependent upon the impedance of the stub.

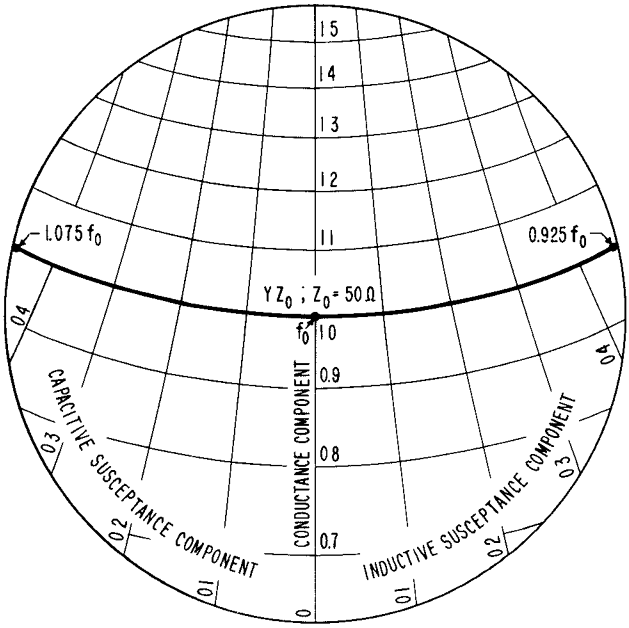

Fig. 4 Idealized amplifier port admittance.

The design philosophy regarding the tuning of the circulator package was that adjustable tuning should be held to a minimum, both to simplify production line adjustment and to insure unique tuning solutions. Uniqueness in the tuning was required to maintain acceptable interfaces between circulators and to avoid the necessity of reiterative tuning. To this end, the design was first done with fixed tuning as described above. Then, in order to

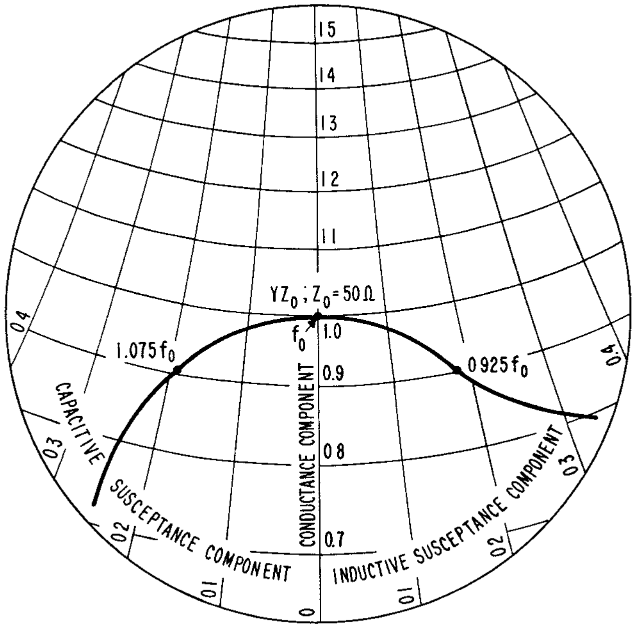

Fig. 5 Admittance at 50 ohm end of modified λ/4 transformer.

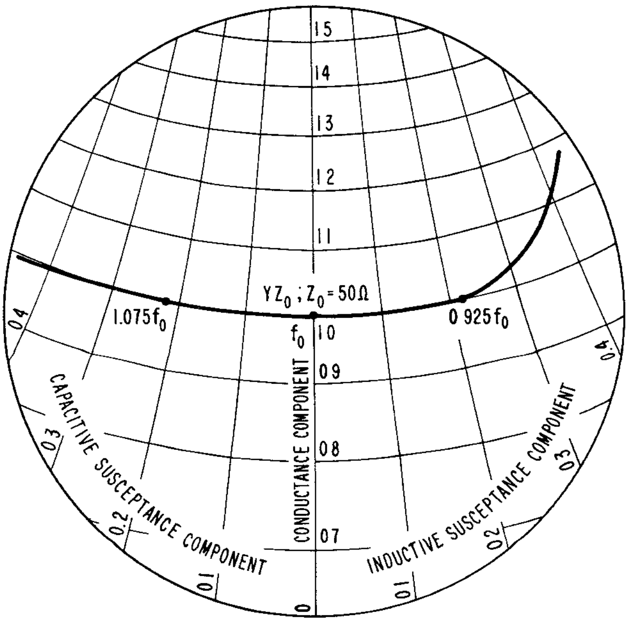

Fig. 6 Amplifier port admittance.

tolerate expected variations in materials, capacitive *trimming* screws were introduced at the ends of transformers and stubs and at the centers of intercirculator half-wave sections, where they effectively varied the lengths of the respective elements without affecting the conductance level requirement at the circulator junction. The conductance level of the circulator junction was independently adjusted by means of the magnetic field. Using this tuning and a relatively tight control on the YAIG and ceramic materials, it was possible to obtain consistently the loss performance presented above while controlling the normalized admittance of the amplifier port to better than $\pm.01$ in conductance and approximately $\pm.02$ in susceptance in the 15% band.

REFERENCES

1. Barnes, Bertram, and Cowan, "A Low-Noise, Wideband, L-Band Parametric Amplifier." Paper presented at International Solid State Circuits Conference, Philadelphia, Pa., February 19-21, 1964.
2. C. E. Fay and R. L. Comstock, "On The Theory of the Ferrite Junction Circulator," Paper II-2, this *Digest*.