upper surface is nominally at the cryogen temperature, serves as a very effective infrared radiation trap.

As a final check, the following experiment was performed. After initial cooling, the load was overfilled repeatedly so that the foam cap remained immersed in liquid nitrogen long enough for thermal equilibrium to be achieved. The radiometric temperature was then monitored with a radiometer having a long-term stability of the order 0.1 K. It was observed that as the cryogen level fell from just above the surface of the cap to somewhat below the tips of the absorber, there was no discernible change in the radiometer reading, and furthermore, the reading corresponded exactly to that obtained without the overfilling procedure. This was taken to be evidence that no gradients of any significance actually existed.

It is worthwhile pointing out that when using this reference with horn antennas, one must be wary of radiative cooling of lossy parts of the antenna such as polarizers and coupling probes, due to the fact that the reference is also quite cold in the infrared. Such effects can cause calibration errors and should be avoided by thin foam plugs or similar radiation traps. Cooling of the antenna skirt is usually not a problem because the skirt normally contributes little to the antenna loss.

Previous microwave thermal noise standards [1], [2] have achieved precisions of order 0.12 K. These are constructed in waveguide and require very careful cryogenic engineering. The present load serves a slightly different purpose, namely the calibration of radiometers directly at the horn output. In part it derives its simplicity from the fact that the problem of waveguide losses is absent. The equivalent problem, losses in the horn skirt, is much less demanding.

ACKNOWLEDGMENT

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A 4-GHz Lumped-Element Circulator

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***Abstract*—The successful application of thin-film lumped-element circulators (LEC) at *L* band has led to the following question: How far can these devices be extended in frequency using our present beam-crossover technology? An exploratory study aimed at building an LEC at approximately 4 GHz was successfully completed. Preliminary tests showed a 20-dB band from 4.2 to 5 GHz with an insertion loss <1 dB (minimum, 0.5 dB). This includes fixture losses, which account for about 0.2 dB. The device has been tuned to operate above 5 GHz, and from the experiments it is concluded that a device of this type could be built at frequencies as high as *X* band. These devices are very small; at 4 GHz, the circulator junction is a 0.075-in diam.**

INTRODUCTION

Recent advances in microwave semiconductors [2]–[6] lead to solid-state microwave amplifiers that, together with other microwave integrated circuits (MIC's), create the need for circulators compatible in size and performance. The thin-film lumped-element circulators (LEC's) to be described are well suited for such applications. They are about an order of magnitude smaller than stripline circulators presently used in MIC's, and thin-film batch processing permits inexpensive manufacture. An exploratory effort was undertaken to extend the *L*-band thin-film LEC previously reported [1] to higher microwave frequencies and to assess the technological limits of such devices. The first attempts were aimed at a device operating in the 4-GHz region.

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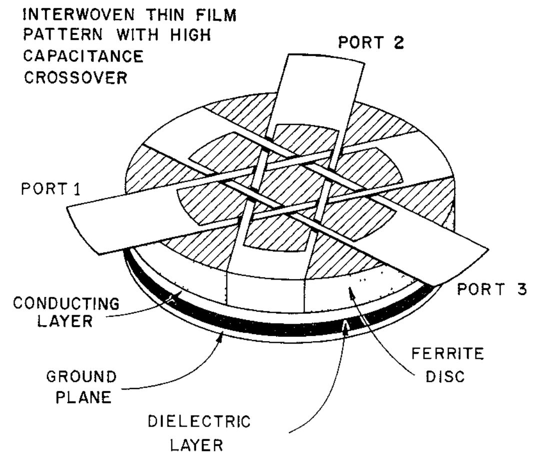

Fig. 1. Thin-film broad-band LEC (schematic).

THEORY AND MEASURED RESULTS

Stripline circulators use a ferrite resonator of approximately half-wavelength diameter and quarter-wavelength transformers for broad-banding. LEC's can be an order of magnitude smaller in diameter. This small size is achieved by using lumped, nonreciprocally coupled, inductive strips that are resonated with the thin-film beam-crossover capacitances. A capacitor common to all three ports broadbands the device. The theory of this LEC, shown schematically in Fig. 1, has been extensively dealt with in previous articles [1], [7], [8] by the author. For the 4-GHz LEC, the same principles and broad-banding mechanism are used. The circulators were batch processed using standard beam-crossover technology as used in the *L*-band LEC's [1]. The diameter of the circulator substrate was 0.175 in; the junction diameter 0.075 in. The garnet used had a saturation magnetization of 1200 G. The circulator was operated in the low field mode (below resonance). This has the advantage of requiring a lower magnetic field and a 0.025-in thick substrate, which can still be handled reasonably well. The same LEC operated in the high field mode (above resonance) scaled from experimental *L*-band units would probably use a much thinner substrate. Deposited garnets or the use of a reinforced garnet substrate may be appropriate in such applications.

The results obtained with the experimental unit in Fig. 2 are shown in Fig. 3. The insertion loss of <1.0 dB over 700-MHz–20-dB bandwidth is very good, considering that no special effort was made yet to optimize the device with respect to bandwidth or loss. Separate measurements using the same fixture, the circulator being replaced by a through-connection on a little microstrip alumina disk of the same diameter as the ferrite, indicate that the fixture loss is about 0.2 dB minimum. Improvements could be expected from optimizing diameter, thickness, crossover capacitance, etc., and by the elimination of the connectors in an integrated-circuit application. Eigenvalue measurements, as described in [8], will help to implement these changes. Since contacts were made by soldering and/or "silver paint," it is probable that a cleaner structure (thermal-compression bonding, etc.) would further reduce the insertion loss.

It was found that this experimental LEC could be tuned to operate at 6 GHz by changing the magnetic biasing field and by adjusting the capacitor common to all three arms. It is expected that a reduction in the linewidth of the low impedance line will further increase the frequency. From experience at *L* band, a frequency increase of 1 GHz could be expected bringing it to about 7 GHz with about a 10-percent bandwidth. This and further scaling of the design should permit LEC's of this type to be fabricated at *X* band. Because of their small size (at *X* band the junction diameter should be about 0.040 in), these devices will need careful handling and extensive fixturing is required to go beyond the exploratory stage. A number of ways by which such a device could be appliqued to an integrated-circuit substrate are evident.

CONCLUSION

It has been shown in preliminary tests that an LEC with good performance can be built at 4–5 GHz. It is compatible in size with microwave semiconductor circuits. It has been demonstrated that the

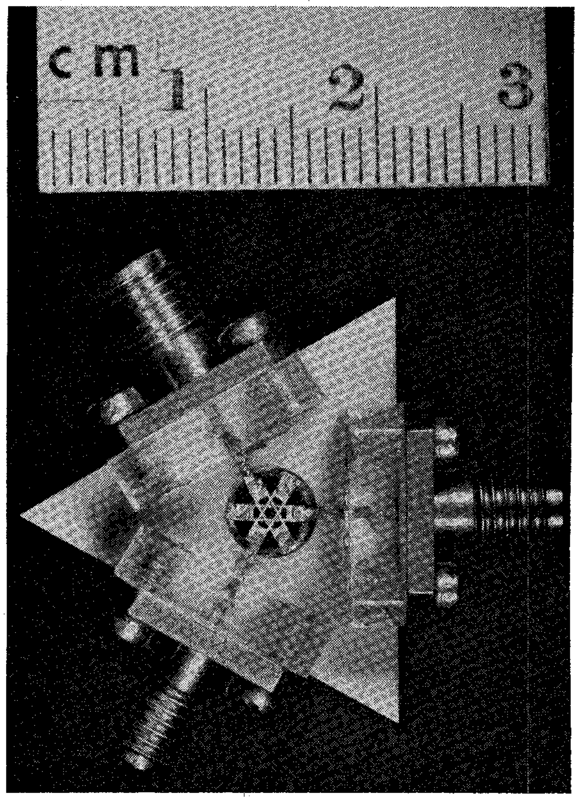

Fig. 2. Four-gigahertz LEC in test fixture.

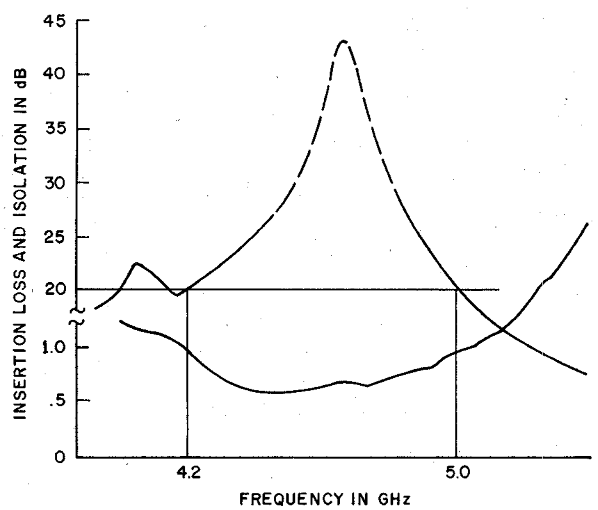

Fig. 3. Measured performance of 4-GHz LEC (fixture losses included).

beam-crossover technology used for the L-band circulators can be extended to at least 6 GHz. Further decrease in dimensions for operation in X band appears possible. A projected substrate thickness of 15–20 mil is still practical for batch processing if the garnet substrates are not so large that breakage would occur in handling.

On the basis of measurements at 4.5 GHz and at L band, a minimum 20-dB bandwidth of 20 percent appears feasible at X band. The insertion loss is expected to be about 0.2 dB higher than for the corresponding suspended stripline circulator.

The major problems with integrating these devices, regardless of the operating frequency, would be the mounting of the LEC assembly on the circuit board, providing a magnetic circuit, and providing RF interconnections. In the author's opinion, discrete LEC units, tuned before being put into the circuit, are the best solution. It is conceivable though that open LEC assemblies, with prior RF testing, could be used with the magnetic circuit contained in the MIC housing. Such utilization of LEC's in MIC's would have compelling advantages in size and wight over conventional circuitry, in addition to the potential cost advantages of using batch-processed circulator elements.

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An Analytical Expression for the Limits of Error in the Measurement of Reflection-Coefficient Phase

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***Abstract*—An exact analytical expression for calculating the limits of phase error that can occur when the reflection coefficient of a load is measured through a lossless two-port network is presented. An empirical expression previously reported by Garver *et al.* agrees well with the exact expression, except when the reflection coefficients of the lossless two-port and the load are nearly the same in magnitude.**

Introduction

A microwave circuit parameter commonly of interest is the input reflection coefficient of a two-port network (or a system) that is terminated in an arbitrary fixed load. For measurement purposes it is convenient to treat the terminated two-port network as an equivalent one-port or an equivalent load. It is general practice to measure load reflection coefficients (magnitude and phase) with slotted lines, reflectometers, or commercially available network analyzers.

In the past, emphasis has been placed on improving accuracies of reflection-coefficient magnitude measurements, but recently there have been increasing needs for improving accuracies of measurements of phase as well. When the magnitude of the load reflection coefficient becomes small, it is known that the absolute accuracy of the measurement of reflection-coefficient phase (and magnitude) becomes increasingly affected by the residual VSWR of the phase measurement system. This effect has recently been analyzed by Garver *et al.* [1]. However, it was stated [1] that many attempts at deriving an exact analytical expression for limits of phase error led to intractable arrays of algebra. Therefore, numerical solutions had to be obtained through the use of a "search"-type computer program. An empirical formula was subsequently derived that fit most of the maximum values found by the computer.

The purpose of this short paper is to show that an exact analytical expression for limits of phase error for the general lossless case can be derived in a straightforward manner. Comparisons will be made between the exact expression derived in this short paper and the empirical expression derived by Garvet *et al.* [1].

Exact Expression

General Lossless Case

Fig. 1 shows a microwave system, similar to that described in [1], for measurement of load reflection-coefficient phase angles. The interconnecting lossless two-port network can represent 1) flange misalignment, 2) junction of slightly different size waveguides, 3) connector discontinuities, or 4) a transition.

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