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# Precision Temperature Reference for Microwave Radiometry

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The calibration of microwave radiometers is normally achieved by replacing the antenna with a cooled reference termination and then applying corrections for ohmic and reflective losses of the antenna, and for the nonideality of the reference termination. The uncertainty in this correction is the dominating factor in the precision of many high-quality radiometers, and for some applications it is unacceptably large. An alternative is to point the antenna at a target of known temperature. To the extent that this temperature is known and the target is reflectionless and encompasses the full view of the antenna, the calibration is exact and no further corrections are required. A target suitable for high-precision radiometry has been developed that has an accurately known radiometric temperature, a very low reflection coefficient, and whose geometry is well suited to the calibration of horn antennas.

The essence of the temperature reference is as follows. A piece of porous microwave absorber having a convoluted surface for a low reflection coefficient is fitted with a cap of nonporous plastic foam whose mating surface is the inverse of that of the absorber. The microwave-absorbing material is then soaked with the chosen cryogen, liquid nitrogen, or argon, for example, the nonporous cap forcing the liquid to conform to the shape of said absorbing material. This procedure 1) ensures that the temperature at which the microwaves are absorbed (and therefore thermally emitted) is exactly that of the cryogen, and 2) avoids the reflection that would be produced by the dielectric discontinuity of a plane surface of cryogen. The microwave reflection from the external surface of the nonporous foam cap is very small due to the low density of the foam (if necessary, the external surface of the foam could also be convoluted), and the microwave loss in the foam is also very small due to the low density and low intrinsic loss of this plastic material. In addition, most of the foam is at a temperature close to that of the cryogen, and hence contributes negligible error to the overall radiometric temperature.

A reference load used in this laboratory for the calibration of S-band radiometers is shown in Fig. 1. A 2-ft-square piece of microwave absorber with convolutions in the shape of close-packed square pyramids[1] was placed in the bottom of a thermally insulated metal box[2] and a cap of expanded polyeurethane foamed *in situ*. The foam was then milled flat to a level about 1 in above the tips of the absorber and 0.5-in diam vertical vent holes were drilled into the foam at the positions of the peaks of the microwave absorber. The latter operation allowed the escape of the gas produced by the boiling cryogen and ensured that all of the absorber was saturated with cryogen. The foaming had to be done in several steps in order to prevent the occurrence of voids. In addition, the tips of the microwave absorber had to be carefully located before foaming was completed so that accurate drilling of the vent holes could be achieved. Two 1-in diam vertical holes drilled near the corners of the box facilitated filling of the unit with cryogen. An arrangement of brackets (made of metal, plastic foam, or other nonmicrowave-absorbing material) secured to the side of the box may be necessary to prevent the combined assembly of the foam cap and microwave absorber from floating in the cyrogen. For this particular load, strips of expanded polystyrene glued with epoxy to the inner sides of the box were sufficient.

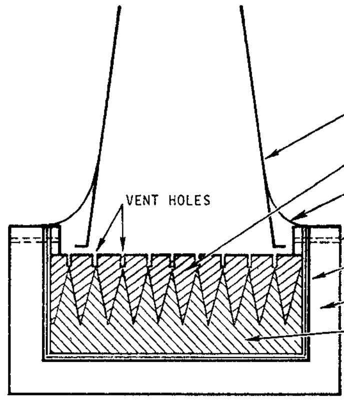

Fig. 1.

The absorber has a specular reflectivity of −40 dB under far-field plane-wave conditions. However, a fraction of 1 percent of incident radiation may be diffusely scattered in random directions. For this reason, a shroud of aluminum foil was used to make electrical contact between the radiometer antenna and the top of the metallic box in such a way that, excluding the small horizontal vent holes, the total assembly could not be penetrated by external microwave sources. This ensured that all energy entering the antenna originated in the cooled absorbing material.

The above described reference has been successfully used with both liquid nitrogen and liquid argon for the calibration of high-precision radiometers operating near 2.7 GHz. Its radiometric temperature was estimated with good confidence to deviate less than 0.1 K from the temperature of the cryogen. The boiling points of nitrogen and argon are, respectively, $T_{N_2}=77.36+0.011$ ($P$-760) K and $T_A=87.28+0.010$ ($P$-760) K, where $P$ is the barometric pressure in millimeters of mercury. This high degree of confidence is based on an accurate knowledge of the emissivity, reasonable estimates of temperature gradients, and, finally, a precision measurement of radiometric temperature versus the cryogen level.

When filled with liquid nitrogen to the tips of the microwave absorber, the average (over the surface) VSWR of the reference was measured[3] at 2.7 GHz to be 1.020, which corresponds to a power reflection coefficient $r$ of $1\times10^{-4}$, and therefore an emissivity of 0.9999. Assuming that all microwave losses are incurred at the temperature of the cryogen $T_c$, the apparent radiometric temperature $T_A$ is given by

$$T_A = T_c + r(T_i - T_c) = T_c + \Delta$$

where $T_i$ is the characteristic temperature of microwave radiation *incident* on the load (nominally that radiated by the antenna). For $T_i = 300$ K (as when an input isolator is used) and $T_c = 77$ K, $\Delta = 0.02$ K, which is very small and in any case can be added as a correction.

The question of temperature gradients is more difficult to deal with in a quantitative manner. Although the microwave absorber is completely immersed in the cryogen, the upper surface of the assembly is exposed to infrared radiation that could possibly cause gradients, especially when bubbles are present. However, such gradients are confined to the surface of the absorbing pyramids, and would therefore have a small effect on the average radiometric temperature, the microwave emission being a volume effect. Furthermore, the nonporous foam cap, which has virtually no microwave loss and whose

Manuscript received July 26, 1972; revised October 16, 1972.
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[1] The microwave absorber used was made by B. F. Goodrich, but is no longer available. It is very similar to −40-dB reflectivity material known as Eccosorb SPY, manufactured by Emerson and Cuming. One would expect its loss tangent to change with temperature, but it still maintains a very low reflection coefficient down to at least 77 K.

[2] Adequate insulation was achieved by epoxying 2-in standard polystyrene foam insulation to the sides and bottom of the box. For this purpose, Emerson and Cuming 2850-FT, a highly filled epoxy, was used because of its good thermal expansion match to many metals.

[3] The VSWR was deduced from the variation in output of a slotted line probe situated between a microwave generator and a horn antenna, as the distance from the horn aperture to the load was varied. The result is clearly not the VSWR for a plane wave incident on the load, although numerically it is probably not very different. In any case, it is this measured quantity that is needed for determining corrections.

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

The author would like to thank A. W. Love for his helpful discussions and M. J. Van Melle for his assistance in the construction of the load and the preparation of this short paper.

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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.

Manuscript received July 31, 1972; revised October 23, 1972.
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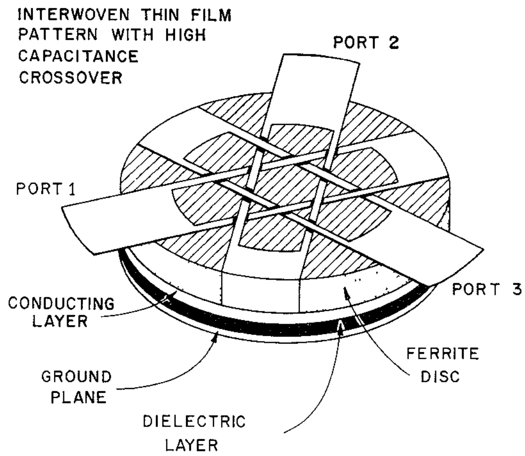


Fig. 1. Thin-film broad-band LEC (schematic).

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