A Low-Loss Thermal Isolator for Waveguides and Coaxial Transmission Lines

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Abstract—**A low-loss element insertable into microwave coaxial transmission lines and waveguides is designed to provide a thermal isolation barrier at the point of insertion.**

I. Introduction

CRYOGENICALLY cooled devices placed in dewars require electrical connections to external power supplies. The standard microwave transmission media, i.e. waveguides or cables, cannot be used for this purpose as they are excellent heat conductors and as such would typically provide a very low thermal-resistance path. When placed in a high-temperature gradient the transmission lines will conduct heat from the external environment to the cooled devices, necessitating use of large pumps to maintain required device temperatures.

The purpose of this communication is to describe a thermal isolator designed to alleviate the heat-loading associated with transmission lines in cryogenic systems. The above-named device is to act as a very high thermal resistance element in the heat flow path, with minimal disturbance to the transmission characteristics of the electrical connection.

The currently acceptable method of isolating devices in a dewar from the external environment entails the use of extremely small cross-section coaxial cables [1]. Cross-section reduction affords higher thermal resistance. However, such cables are inherently fragile and thus inconvenient to handle and unreliable. Their primary disadvantage, moreover, is their extremely high ohmic loss. Since the loss is a distributed effect, long (with respect to the guide wavelength at the frequency of operation) cable runs in the dewar result in prohibitive electrical system losses. It is, therefore, desirable to retain the standard low-loss lines, while providing thermal isolation by means of a "lumped" isolator element. The proposed isolator can be spliced into a line run at a dewar entry point, effectively "choking off" heat flow.

II. Device Description

A circumferential gap in a hollow-tube waveguide has a relatively minimal effect on the microwave transmission characteristics, provided it is electrically very small. On the other hand, if the radiative and convective exchange across the gap can be made negligible, its thermal resistance is practically infinite. To maintain axial alignment of the waveguide after a gap is introduced, high-strength foam, or comparable

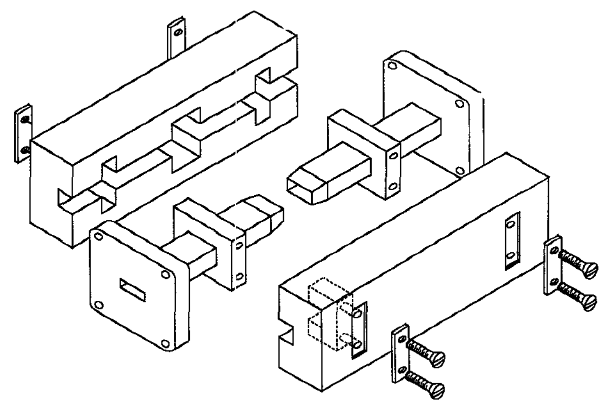

Fig. 1. Structure of the thermal isolator.

low-thermal-conductivity material, can used to encase the waveguide. The foam's inherent low thermal conductivity lends itself to a package that presents a very high thermal resistance in parallel with the gap in the waveguide.

It is clear that the design of such a thermal isolator requires a balanced trade-off among electrical, thermal, and mechanical constraints. Since the theoretical tools required to carry out the necessary analyses were not available, a combination of empirically derived data and rudimentary equations was used to design a prototype. Presently, a brief description of this device and its performance characteristics will be given.

The prototype was constructed utilizing the standard Ka-band (WR-42) rectangular waveguide. The mechanical drawing presented in Fig. 1 demonstrates the structure of the device tested. The photograph in Fig. 2 depicts the assembled thermal isolator.

The key geometrical and material parameters for the design are

1) *The gap-width* w_g: The microwave characteristics of the device are almost exclusively determined by this parameter. The results of an experimental electrical characterization of the gap in the WR-42 rectangular waveguide are summarized in the insertion and return-loss plots (Fig. 3(a) and (b), respectively). A 12-in. section of the WR-42 guide, bisected and aligned in a rigid foam support, was utilized in the experiment. It should be noted that the results presented in Fig. 3 include the intrinsic waveguide propagation losses; the 12-in. section of WR-42 guide used in the experiment had a 0.2-dB insertion loss prior to the introduction of the gap. Based on the results of the aforementioned

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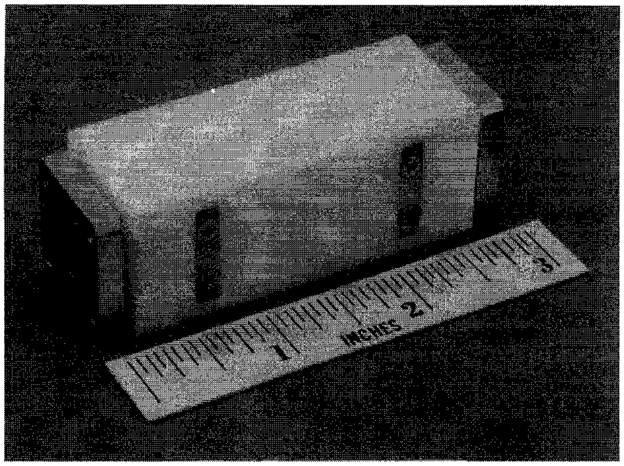


Fig. 2. Thermal isolator prototype.

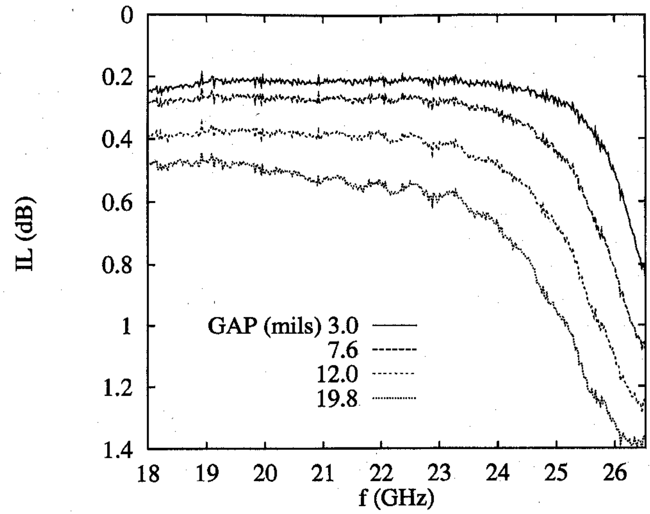
experiment, the prototype gap width was chosen to be 10 mils; after fabrication it was found to be 13 mils (at room temperature and atmospheric pressure).

2) *The thermal conductivity of the foam (k):* The foam chosen for the construction of the prototype was the Cummings RH-10 polyimid, closed-cell type, with a manufacturer-specified $k = 0.3 \frac{BTU\ in}{ft^2\ hr\ ^\circ F}$ at room temperature. The accuracy of this thermal conductivity value could not be ascertained.

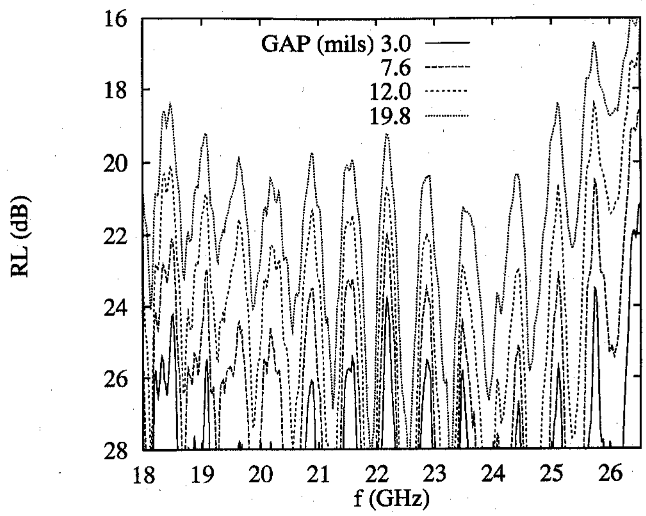
3) *The cross-section of the rectangular foam cylinder* formed by the recessions in the foam encasement used to link and align the two halves of the isolator; the cross-section and length of the this cylinder determine its thermal resistance, which is the dominant contribution to the overall thermal resistance of the device. This is also the weakest link in the structure, largely controlling its mechanical characteristics. The aforementioned cylinder cross-section for the prototype was 0.776 in^2, over a length of 0.250 in. Using the vendor-supplied thermal conductivity value, the thermal resistance of the cylindrical foam link was estimated at $\mathcal{R}_{cyl} = 293 \frac{^\circ K}{W}$. It should be noted that this figure is a rough estimate. Determination of the actual value would require consideration of the spatially dependent geometrical and material distributions.

III. Electrical and Thermal Performance Characteristics

Two-port network properties of the device under room-temperature conditions are presented in Fig. 4(a) and (b). The insertion loss remains less than 0.5 dB over a wide frequency band. The return loss is greater than 20 dB throughout almost the entire waveguide band. The effects of the experimental embedding circuit, up to the flanges of the isolator, were removed through a TRL calibration. A calibrated electrical measurement could not be performed under the actual operating conditions. However, it has been shown (Fig. 3) that the return and insertion loss degrade gracefully as the gap width is perturbed. Since the device contains materials with relatively small coefficients of thermal expansion the gap-



(a)



(b)

Fig. 3. The (a) insertion loss (IL) and (b) return loss (RL) as a function of frequency and gap size in WR-42 waveguide.

width, and therefore the electrical performance, should not change drastically.

The thermal conductivity of the foam used in isolator fabrication is a nonconstant function of temperature. Therefore, measurements were conducted over a range of thermal conditions. The parameter used as the indicator of the performance is the thermal resistance. In essence, this parameter was obtained by placing the device in an *evacuated* dewar between two metal supports maintained at constant temperatures. One of the supports was attached to a liquid-nitrogen or liquid-helium cooled "cold-finger," while thermal power was supplied to the other support by a calibrated heater. Temperature sensors were embedded in the supporting structures close to the ends of the device. To ensure maximum thermal power flow into the isolator, care was taken to decouple the end attached to the heater from other heat sinks and sources. Radiative exchange between the isolator and other surfaces was neglected in both the experiment and theoretical predictions.

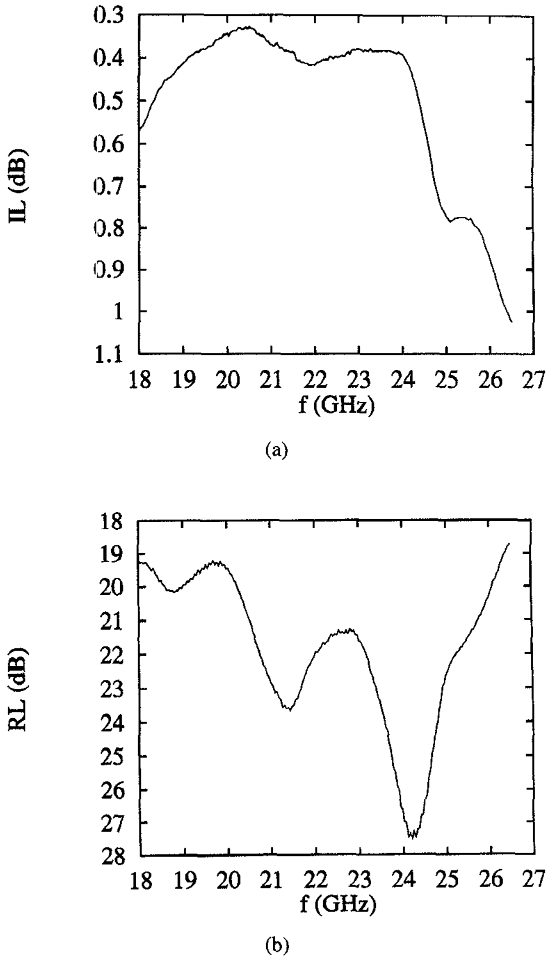


Fig. 4. Frequency dependence of the (a) insertion loss (IL) and (b) return loss (RL) for the thermal isolator prototype.

Laboratory measurements of thermal resistance $\mathcal{R}$ values were taken for three different operating points, distinguished by the temperature difference $\triangle T = T_1 - T_2$ maintained at the two ends of the element:

1) Power input of $168.8mW$ was required to sustain $T_1 = 324°K$, $T_2 = 299.25°K$, yielding $\mathcal{R} = 146.6\ \frac{°K}{W}$.
2) For $T_1 = 320°K$, $T_2 = 78.36°K$ the required power was $414.5mW$, yielding $\mathcal{R} = 583\ \frac{°K}{W}$.
3) For $T_1 = 320°K$, $T_2 = 7.28°K$ the required power was $433.4mW$, yielding $\mathcal{R} = 722\ \frac{°K}{W}$.

A comparison of the theoretically estimated thermal resistance with the measured value stated in the first entry of the preceding summary reveals a factor of two discrepancy. This is not unexpected in light of the approximate nature of the estimate. The thermal performance of the isolator exceeds expectations as the operating temperature drops, perhaps reflecting a decrease in the thermal conductivity of the foam at lower temperatures.

IV. Conclusion

A waveguide component designed to present a high thermal impedance and low electrical losses in the transmission path was designed and characterized. The thermal performance was on the order of magnitude predicted using basic theoretical constructs. Good insertion and return losses were observed over a wide band of frequencies.

Alternative versions of the same device type may contain other waveguide and transmission line types, possessing different (broader) bandwidth characteristics. Gap loss can also be reduced by flaring the guide open ends into horns to smooth the transition. When intended for insertion into coaxial cable runs, the waveguide-to-coaxial cable launchers may be incorporated directly into the isolator, resulting in a more compact element. Further optimization, including structural modification and use of lower thermal-conductivity foams, is expected to enhance the thermal isolation performance significantly.

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[1] J. Madden, "Microwave applications of high-temperature superconducting thin films," Application Notes, Superconducting Technologies Inc., Santa Barbara, CA, May 1993.
[2] S. Weinreb, H. Dill, and R. Harris, "Low-noise, 8.4 GHz, cryogenic GASFET front-end," VLBA Tech. Rep. no. 1, NRAO, Charlottesville, VA, Aug. 1984.

[1] In the review process the author was made aware of related work on a circular waveguide flange design incorporating a high-thermal resistance path, performed at the National Radio Astronomy Observatory and described in an internal report [2].