Insertion Loss and Noise-Temperature Contribution of High-Temperature Superconducting Bandpass Filters Centered at 2.3 and 8.45 GHz

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Two superconducting Tl-Ca-Cu-Ba-O bandpass filters have been fabricated for JPL by Superconductor Technologies Incorporated, Santa Barbara, California. The filters were designed to operate at 2.3 GHz (S-band) with a 0.5-dB bandwidth of 60 MHz and at 8.45 GHz (X-band) with a 0.5-dB bandwidth of 150 MHz. The structure selected for both filters incorporates half-wavelength thin-film resonators in a stripline configuration. The S-band filter uses an edge-coupled interdigital design and the X-band filter uses an end-coupled design. The insertion loss and the noise-temperature contribution were measured at 12 K for both filters.

I. Introduction

The DSN uses extremely sensitive receiver systems to communicate with deep-space probes and to perform radio science experiments. They incorporate ultralow noise amplifiers, such as masers and high-electron mobility transistor (HEMT) amplifiers, at the front end of these systems. Radio frequency interference (RFI) can significantly degrade the performance of these receiver systems. Out-of-band RFI can result in gain compression, noise-temperature increases, and spurious output signals. This in turn can lead to the loss of received data.

Historically, masers have been the primary low-noise front end for deep-space communication, but HEMT amplifiers are now providing similar low-noise results. Both masers and HEMT amplifiers are susceptible to RFI, but HEMT amplifiers can be manufactured and maintained at a fraction of the cost. HEMT amplifiers have another advantage in that they inherently have a much broader bandwidth, but this makes them more susceptible to RFI. Therefore, work on RFI reduction is being conducted to improve the reliability of HEMT amplifiers.

Low-loss bandpass filters fabricated from high-temperature superconducting (HTS) materials can provide out-of-band RFI protection for HEMT low-noise receivers while providing minimum degradation to noise and microwave performance (e.g., return loss and group delay variation). The objective of this article is to demonstrate HTS RFI filters for cryogenic HEMT low-noise amplifiers (LNA's) at 2.3 and 8.45 GHz. The ultimate goal is to provide greater RFI protection without significantly degrading DSN receiver performance.

II. Filter Structure

Both thallium- and yttrium-based superconductors were considered as the superconducting material. The thallium-based superconductor was chosen over the more widely used yttrium-based one for its higher critical temperature (T_c) of 123 K. Yttrium has a T_c of only 90 K. The possible configurations considered were stripline, microstrip, and coplanar. Calculations determined that the presence of two superconducting ground planes would significantly reduce radiative losses, so the stripline configuration was chosen.

Superconductor Technologies Incorporated (STI) in Santa Barbara, California, designed and fabricated the 2.3-GHz (S-band) and 8.45-GHz (X-band) bandpass filters for JPL. They were designed to have bandwidths of 60 MHz and 150 MHz, respectively, with an insertion loss goal of less than 0.5 dB.

Both filters utilize five, half-wavelength resonators in a stripline configuration with Tl-Ca-Ba-Cu-O thin-film superconductors on a lanthanum aluminate ($LaAlO_3$) substrate [1,2]. At S-band, the filter structure uses a parallel array of broadside-coupled, half-wavelength resonators. Each resonator is offset with respect to its neighbor to create the desired narrow-band response (Fig. 1). The X-band filter uses end-coupled resonators with quarter-wavelength transformers at the input and output to match to 50 ohms (Fig. 2). The dimensions of the finished packages, excluding normal metal connectors, are 3.1 × 2.63 × 1.02 cm for S-band and 3.87 × 1.70 × 3.87 cm for X-band.

III. Insertion Loss Measurements

An automatic microwave network analyzer test set was used to measure the insertion and return losses of the filters. The filters and the necessary microwave circuits were cooled in a two-stage closed-cycle refrigerator (CCR) (Fig. 3).

Two low-loss 7-mm coaxial transmission lines with APC7 connectors and end-on subminiature adapters (SMA's) served to carry the input and output signals from 300 K to 12 K. The end-to-end setup with a bypass coaxial line substituted in place of the filter showed a return loss of better than 16 dB across the frequency bands of interest. Figure 4 is a schematic of the CCR input lines.

IV. Noise Temperature Measurements

S-band and X-band Berkshire (Berkshire Technologies, Berkeley, California) cryogenic HEMT LNA's were used to determine the noise-temperature contribution of the filters. The noise temperatures of the amplifiers were measured using a conventional Y-factor method. A commercial nitrogen cold load at 77 K was used as the cold noise source and an ambient 50-Ω termination was used as the hot noise source. A Hewlett Packard coaxial switch allowed alternation of the noise sources.

The noise sources are amplified by the HEMT amplifier, down-converted, and detected by a power meter (Fig. 5). These three components form the receiver. The ratio of measured noise powers is then substituted into the following expression to obtain the receiver noise temperature (T_r):

$$T_r = \frac{T_{am} - YT_c}{Y - 1} \qquad (1)$$

where T_r = noise temperature of the receiver, T_c = noise temperature of the cryogenic load, T_{am} = temperature of the ambient load, and Y = ratio of the system noise power with the hot load to the noise power with the cold load.

The difference between the receiver plus filter noise temperature and the noise temperature of the receiver is taken to be the filter noise-temperature contribution.

V. Results and Discussion

A. Insertion Loss

The filters were designed to have a 0.5-dB bandwidth of 60 MHz at S-band and 150 MHz at X-band with an inband ripple of less than 0.05 dB. The insertion loss at midband for a Tchebyscheff equal-ripple filter is given by the expression [3].

$$L_o(dB) = 8.686 \left(\frac{C_n}{WQ_u}\right) \qquad (2)$$

where W = fractional bandwidth, Q_u = unloaded resonator Q, and C_n is a coefficient determined by the filter order and its inband ripple value. Based on an optimistic estimate of the unloaded Q (~10,000), the midband insertion loss at 2.3 GHz is expected to be 0.17 dB and 0.24 dB at 8.45 GHz. However, the measured insertion loss is expected to be higher because the filters use normal metal SMA connectors that can contribute up to 0.2 dB of additional loss.

At 12 K, the S-band filter exhibited a bandwidth of 75 MHz with a passband peak-to-peak ripple of 0.874 dB. The maximum insertion loss of 1.07 dB corresponded exactly with the poorest return loss value of 7.8 dB. However, at frequencies where the filter was well matched, the insertion loss was approximately 0.30 dB. Figure 6 is a plot of the insertion and return loss results.

Thermal-mechanical problems were encountered during the manufacturing of the first S-band filter prototypes. The major source of problems is the very hard substrate material ($LaAlO_3$). The stripline configuration used required that the circuit pattern be etched on the upper and lower substrates. The substrates have to be precisely aligned and properly grounded for optimum performance. The prototype filter that was tested was loaned to JPL and had poor performance near the center frequency. This was probably due to substrate misalignment and poor ground contact.

The X-band filter exhibited a passband peak-to-peak ripple of 0.31 dB with a maximum insertion loss of 0.66 dB and a bandwidth of 160 MHz. Figure 7 is a plot of the insertion and return loss results for this filter.

Taking into account the losses contributed by the connectors, the filter losses agree reasonably well with the measured results. The out-of-band rejection for both filters was greater than 40 dB.

B. Noise-Temperature Contribution

For a low-loss and reasonably matched filter (return loss $\geq$ 15 dB), the effective input noise temperature (T_e) of the filter plus HEMT amplifier can be approximated by the following expression:

$$T_e = \frac{((L-1) + r^2)T_L + T_H}{1 - r^2} \tag{3}$$

where T_L = physical temperature of the filter, T_H = noise temperature of the HEMT amplifier, $L = 1/$(transmission coefficient)^2, and r = reflection coefficient [4].

Figures 8 and 9 show the measured and predicted added noise contributions of the 2.3- and 8.45-GHz bandpass filters to the S-band and X-band HEMT LNA's, respectively. At the frequencies where the return loss is better than 20 dB, the noise temperature contributions of the filters are the lowest. The measured and predicted results show good correlation except in regions where the return loss is poor.

VI. Concluding Remarks

Currently, the normal metal evanescent mode and interdigital filters used are larger in bandwidth than the HTS filters tested. Yet the insertion loss of the HTS filters is of the same order of magnitude. The normal metal filters have an insertion loss of about 0.1 dB at cryogenic temperatures at S-band. These HTS prototypes are expected to meet or exceed the low-loss performance of their normal metal counterparts with smaller bandwidths to provide greater RFI protection. This can be achieved through further circuit design iterations and the reduction of connector losses by incorporating the HTS filter and HEMT LNA into a single hybrid package.

References

[1] G. L. Matthaei and G. L. Hey-Shipton, "High Temperature Superconductor 8.45 GHz Bandpass Filter for the Deep Space Network," paper presented at the MTT-S International Microwave Symposium, Atlanta, Georgia, June 14–18, 1993.

[2] G. L. Matthaei and G. L. Hey-Shipton, "Novel Staggered Resonator Array Superconducting 2.3 GHz Bandpass Filter," paper presented at the MTT-S International Microwave Symposium, Atlanta, Georgia, June 14–18, 1993.

[3] G. L. Matthaei, L. Young, and E. M. T. Jones, *Microwave Filters, Impedance-Matching Networks, and Coupling Structures*, Dedham, Massachusetts: Artech House, Inc., pp. 144-145, 1980.

[4] T. Y. Otoshi, "The Effect of Mismatched Components on Microwave Noise-Temperature Calibrations," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-16, no. 9, September 1968, pp. 675–686.

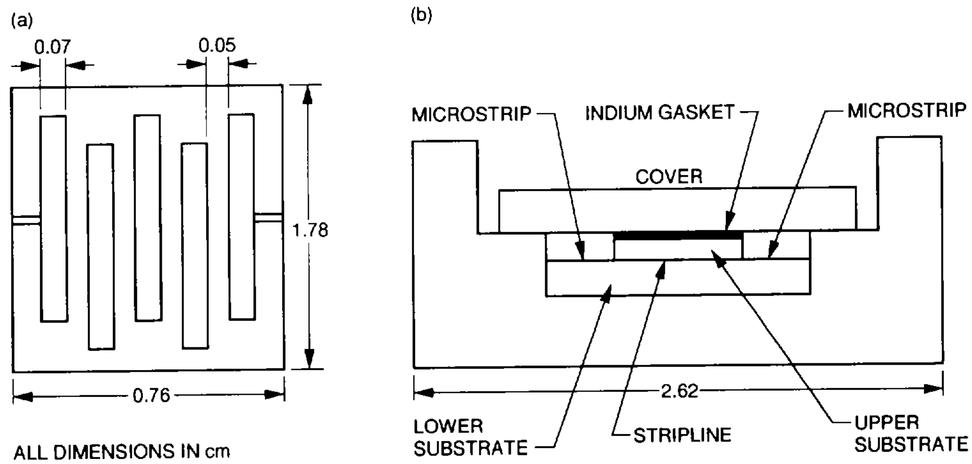

Fig. 1. S-band filter structure: (a) five-resonator parallel-array stripline and (b) cross-sectional view of the filter.

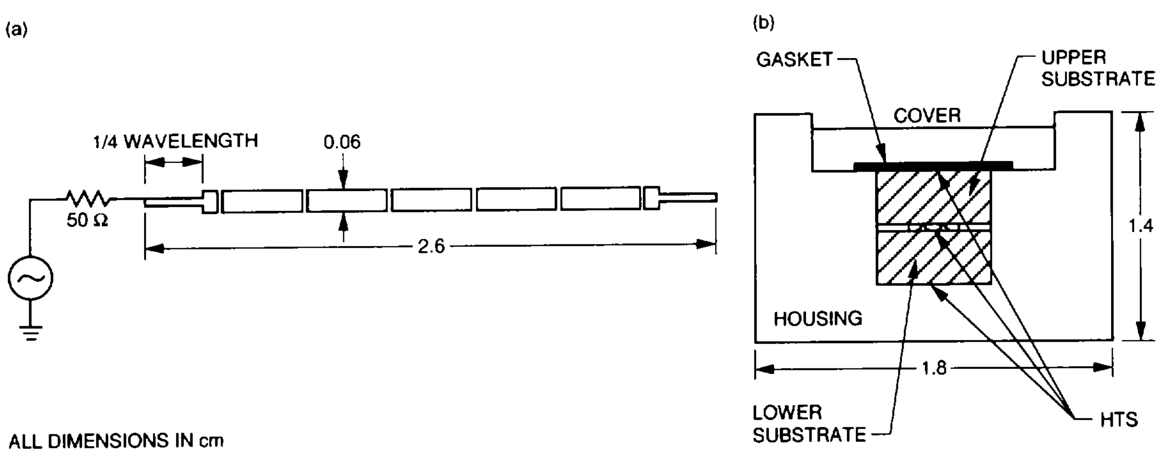

Fig. 2. STI's 8.45-GHz filter structure: (a) five-resonator end-coupled stripline and (b) cross-sectional view of the filter.

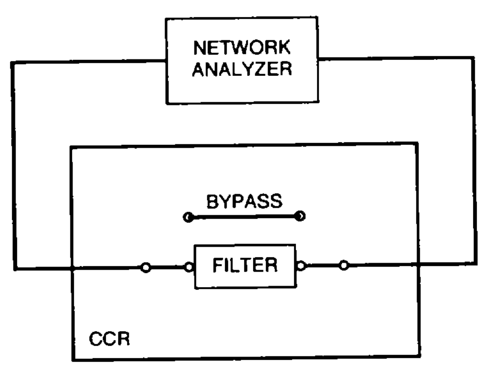

Fig. 3. Insertion-loss measurement setup.

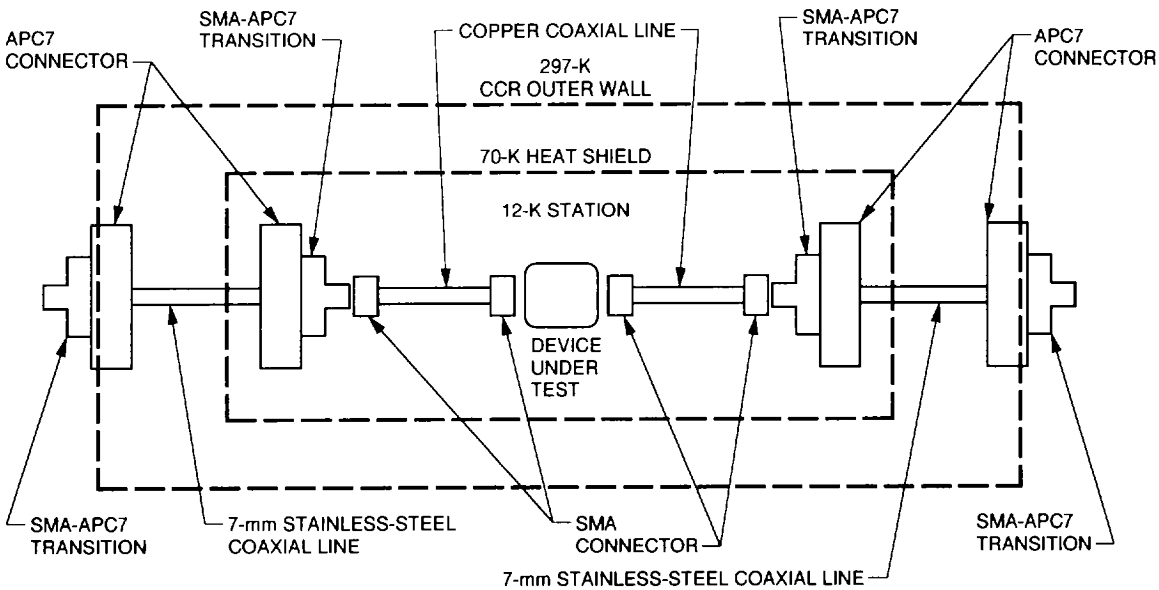

Fig. 4. Coaxial lines for the CCR.

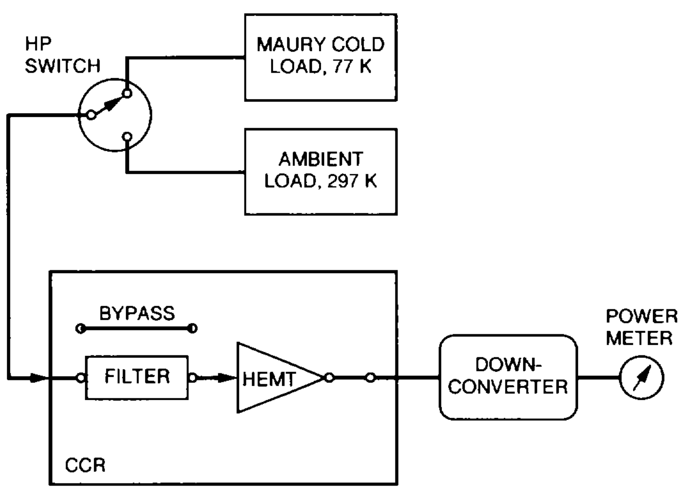

Fig. 5. Noise-temperature measurement setup.

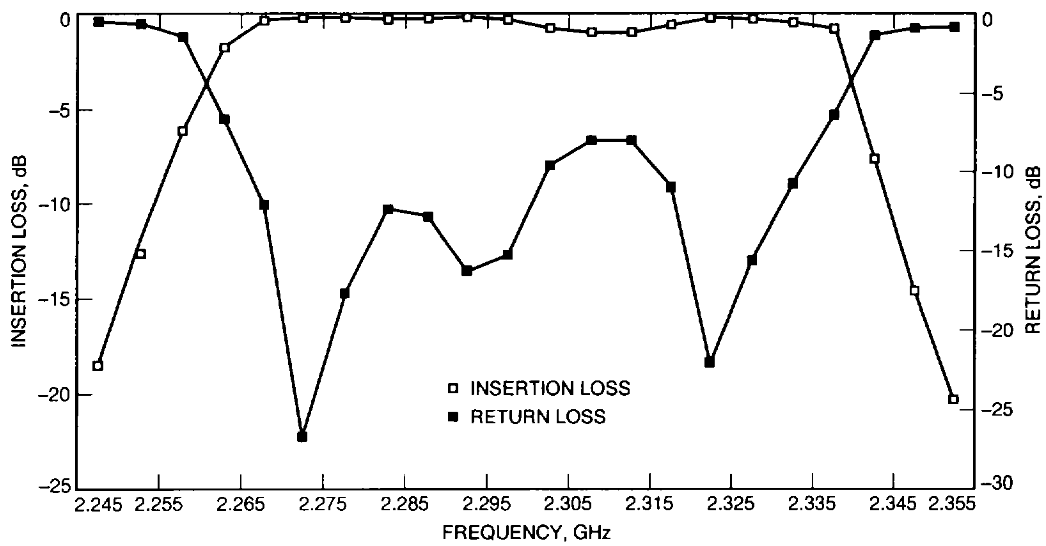

Fig. 6. Insertion loss and return loss of S-band filter.

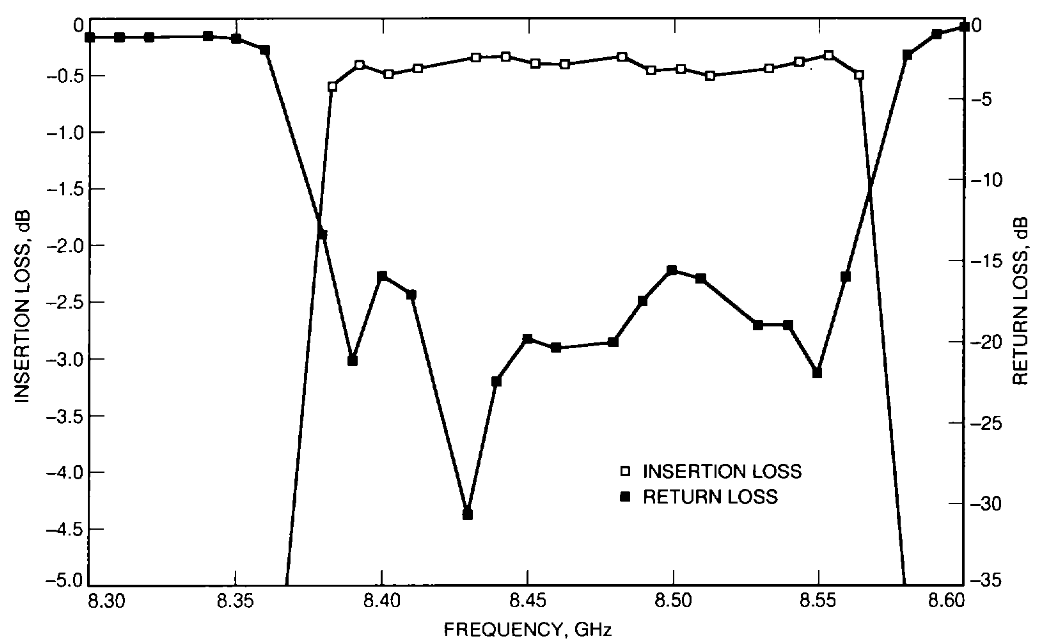

Fig. 7. Insertion loss and return loss of X-band filter.

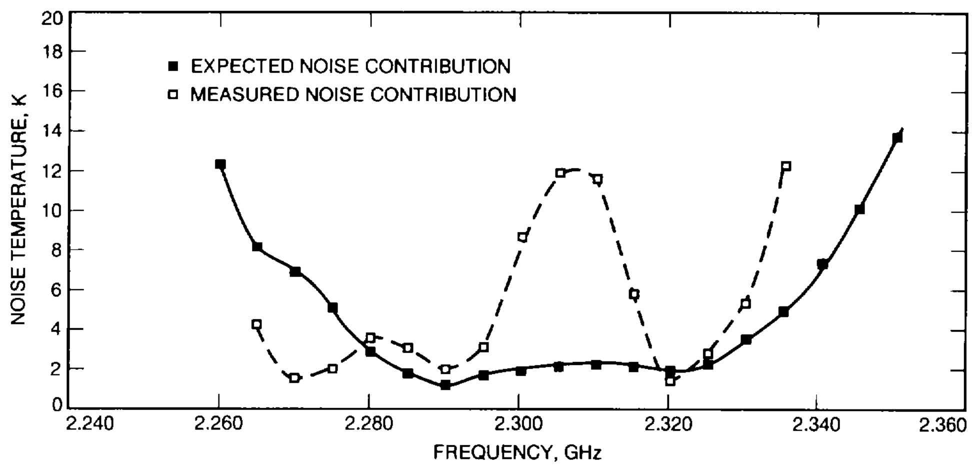

Fig. 8. Measured and expected noise contributions of the S-band filter.

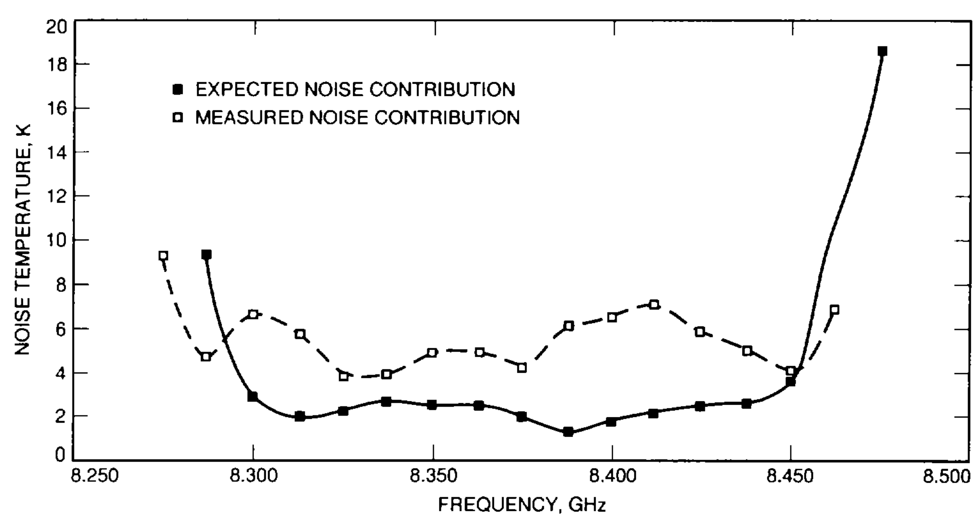

Fig. 9. Measured and expected noise contributions of the X-band filter.