Superconducting NbTi and Pb(Cu) Bandpass Filters

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Superconducting $Nb_{0.45}Ti_{0.55}$ and Pb electroplated on Cu bandpass microwave filters have been constructed to investigate their low-loss properties at 4.7 K. An interdigital stripline filter configuration was selected as the optimum structure for future applications. The filter was designed to operate at 8.45 GHz with an equal ripple bandwidth of 0.15 GHz. The insertion loss and the noise temperature contribution were measured at 4.7 K. In addition, the insertion loss was studied as a function of out-of-band power (up to 1 watt) and temperature (4.7 K up to T_c). Results of an oxygen-free high conductivity Cu filter are included for comparison.

I. Introduction

Communication with deep-space probes requires an extremely sensitive system that has an extraordinarily low system noise temperature, 13 to 25 K. The increased bandwidth and sensitivity of the Deep Space Network (DSN) maser-based receiver systems along with the increase in worldwide microwave spectrum usage have dictated the need for employing measures to protect these systems from radio frequency interference (RFI). The effect of RFI on the maser performance is primarily determined by the level of the RFI, its frequency, and how it relates to the frequency of the maser pump source(s). Both in-band and out-of-band RFI can result in gain loss and/or spurious output signals in the maser signal bandpass (Ref. 1).

The objective of this work is to develop filters that will protect the cryogenically-cooled front-end receiver components (e.g., masers, mixers, and upconverters) from the effects of out-of-band RFI. This has to be accomplished without significantly degrading the system noise temperature as well as other microwave performance specifications (e.g., VSWR and group delay variation). Clearly, the very low-loss RF properties of superconducting materials make them attractive choices for use as microwave circuit elements in very-low-noise receivers operating at liquid-helium temperatures.

II. Filter Structure

An interdigital balanced-stripline structure with an air or vacuum dielectric was selected as the optimal design because of its favorable performance characteristics and ease of fabrication from commercially available materials. This structure is compact and has the highest unloaded resonator Q of the commonly used structures (with the exception of the waveguide filter structure) (Ref. 2).

The prototype NbTi filter shown in Fig. 1 consists of five TEM-mode stripline resonators between parallel ground planes.

Each foreshortened resonator is approximately a quarter-wavelength long at the midband frequency and is short-circuited at one end and open-circuited at the other. Final bandpass tuning is accomplished by varying the end capacitance of the resonators with the adjustable screws opposite the open-circuited end. The ground plane contacts are lapped planar and are attached to the filter body with as many screws as possible to reduce the losses at the joints (Ref. 3).

This particular structure was designed with the aid of the low-pass prototype synthesis methods outlined by Matthei, Young, and Jones (Ref. 4). It is an 0.05-dB equal-ripple filter with an equal-ripple bandwidth of 0.15 GHz centered at 8.45 GHz.

Four identical filter structures were machined for the purposes of this work: two from OFHC copper and two from niobium titanium (Ref. 5). All the dimensional tolerances were kept to ±0.051 mm (±0.002 in.) and the cavity surfaces received a 32 machine finish. The center conductor pins were then welded to the input and output launchers while in an inert environment.

Before testing, each filter was given a different final surface preparation. The copper filters were successively rinsed in acetone, dilute nitric acid, and Bright Dip (BD-295). One of the copper filters was next electroplated with a thin layer of lead approximately 10 μm in thickness, chemically polished, and then stored in a dry nitrogen environment (Refs. 6 and 7). Of the two NbTi filters, one (NbTi-II) was mechanically polished with 5-μm alumina powder suspended in water, cleaned, and then given a final rinsing in acetone. The other filter (NbTi-IIA) was left as machined but provided with a machined "knife edge" 0.13 mm (5 mils) wide to further improve the contact at the ground plane joints and then rinsed in acetone.

III. Insertion Loss Measurements

A conventional microwave network analyzer test set was utilized for the return and insertion loss measurements. To measure the losses at 4.7 K, the filters and associated microwave circuit were cooled with a three-stage closed-cycle refrigerator (CCR).

Two copper-plated stainless-steel waveguides (WR-90) with end-on SMA transitions served to carry the input and output signals from 300 K to 4.5 K. These assemblies were tuned to better than 20 dB of return loss across the frequency band of interest.

The reference signal (repeatable to within ±0.05 dB) was obtained by switching the filter out of the microwave circuit with two (commercially available) toggle latching switches modified to operate at 4.5 K. Figure 2 contains a schematic representation of the cryogenic microwave circuit and the measurement setup.

IV. Noise Temperature Measurements

An X-band traveling-wave maser amplifier with an input flange temperature of approximately 4.5 K was used to determine the noise temperature contribution of the filter. The noise temperature of the maser with filter installed and the maser alone was measured using a standard DSN radiometric substitution method (Refs. 8 and 9). In this Y-factor technique, a calibrated horn antenna is used at the receiver input (in this case a Block-IIA prototype DSN maser) to utilize the sky (antenna, atmosphere, and cosmic background) as the cold noise source and an ambient load (Rantec Microwave Absorber positioned over the horn antenna) as the hot noise source.

The respective noise sources are amplified by the maser and the followup field-effect transistor (FET) amplifier, filtered by an adjustable bandpass filter, and the output monitored by a power meter. (Figure 3 contains a schematic representation of the Y-factor method used.) The measured noise powers are then ratioed and substituted in the following expression to obtain the receiver noise temperature (T_r):

$$T_r = T_m + T_f = (T_{am} - YT_{sky})/(Y - 1) \tag{1}$$

where T_m = noise temperature of the maser, T_f = noise temperature contribution at the maser input due to the followup FET, T_{sky} = noise temperature contribution of horn + atmosphere + cosmic background, T_{am} = noise temperature of ambient load, and Y = ratio of system noise power with hot load to noise power with cold load (Refs. 8 and 9).

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

At midband for a Tchebyscheff equal-ripple filter, the insertion loss is given by the expression:

$$L_0 \text{ (dB)} = 8.686\,(C_n/WQ_u) \tag{2}$$

where W = fractional bandwidth, Q_u = unloaded resonator Q, and C_n = a coefficient determined by the filter order and its inband ripple value (Ref. 10).

At X-band frequencies, the classical-to-anomalous skin-effect transition occurs at approximately 50 K (Ref. 11). Since the insertion loss is proportional to the surface resistance, the loss is thus expected to remain constant below 50 K. For the prototype filter investigated, the minimum insertion loss for Cu is limited by the anomalous skin effect and is one-quarter to one-fifth of its room temperature value (Refs. 12 and 13). Thus, the evaluation of Eq. (2) yields a lower limit of 0.1 dB.

It is well established that at X-band frequencies and at 4.5 K, suitably prepared Pb (T_c = 7.2 K) and NbTi (T_c = 9.8 K) can have surface resistance values three orders of magnitude less than Cu (Refs. 6, 7, 14 and 15). The expected insertion loss for a similar filter made of these superconductors is thus approximately 10^{-4} dB at 4.7 K.

As expected, at room temperature the NbTi and Pb(Cu) filters exhibited higher losses (4.5 and 2.0 dB, respectively) than did the Cu filter (1.0 dB). It was further noticed that the loss of the NbTi was independent of the temperature from 300 to 9.8 K, while the Pb(Cu) displayed a continuous improvement in insertion loss as it cooled from 300 to 4.7 K. Although the predicted superconductor losses at 4.7 K are well below the measurable limits of the test equipment used, measurable losses were present. The lowest value measured for Cu was 0.5 ± 0.06 dB, while NbTi and Pb(Cu) both yielded 0.1 ± 0.06 dB at 4.7 K. (Figure 4 shows the measured insertion loss of the Pb(Cu) filter.)

At the start of this investigation, it was discovered that inadequate ground-plane contacts for the NbTi could result in insertion loss values no better than 0.5 dB at 4.7 K. This was improved by reducing the number of filter assembly parts, maximizing the number of assembly screws, and carefully lapping the contact surfaces before final assembly. The fabrication of a 0.13-mm (5-mil) "knife edge" (NbTi-IIA) at the ground-plane contacts and mechanical polishing (NbTi-II) of the inner filter surfaces did not produce any further measurable improvements.

In addition, it was also found that from 6.0 to 4.7 K the measured insertion loss for the Pb(Cu) and NbTi remained constant. (Figure 5 shows several insertion loss plots at different tempetatures for the NbTi-II filter.)

It is suspected that the measured losses are probably associated with the SMA connections at 4.7 K, which were determined to contribute approximately 0.06 ± 0.06 dB.

B. Power Level Effects

Inband and out-of-band CW power tests showed that the inband loss of the Pb(Cu) filter was independent of frequency and power up to 1 watt. The NbTi filter loss, on the other hand, was seriously degraded depending on the CW power level and its frequency relative to the filter's center frequency.

For out-of-band CW signal levels up to 1 watt and frequencies greater than 1.5 GHz on either side of the center frequency, the NbTi inband insertion loss remained unaffected. However, as the center frequency was approached, the affect became more pronounced. For example, at 1.0 GHz on either side of 8.45 GHz for 1 watt of power, the loss increased to 2.0; at 0.5 GHz it increased to 3.0 dB. Inband CW power slightly above 100 mwatts was sufficient to degrade the loss by 2.0 dB. At approximately 50 mwatts, the increase was 0.1 dB. Below 50 mwatts, no inband loss affects were detected.

In addition, inband signal power of approximately 150 mwatts gradually increased the loss 4.0 dB in a manner similar to "thermal runaway." This is caused by the poor thermal conductivity of NbTi (which is 1/1000 times the value for Cu at 4.5 K) and the nearly exponential temperature dependence of the surface resistance below 9.8 K. This difficulty is not present in Pb(Cu) (at least for the power levels of interest) and can be partially alleviated in NbTi by improving the thermal contact.

C. Noise Temperature Contribution

For a low loss and reasonably matched filter, the effective input noise temperature (T_e) of the filter plus maser amplifier can be approximated by the following expression:

$$T_e = (((L - 1) + r^2)\, T_L + LT_m)/(1 - r^2) \tag{3}$$

where T_L = physical temperature of the filter, T_m = noise temperature of the maser amplifier, L = 1/(transmission coefficient)^2, and r = reflection coefficient (Ref. 16). In the case of a superconducting filter, L is approximately 1, so that Eq. (3) reduces to:

$$T_e = (r^2 T_L + T_m)/(1 - r^2) \tag{4}$$

Thus, for a filter having r = 0.1 (return loss = 20 dB) and T_L = 4.7 K, the noise temperature contribution ($T_e - T_m$) will be less than 0.05 K. This would represent an increase of approximately 1% in the input noise temperature of a typical X-band maser (T_m = 4.0 - 4.5 K).

In Fig. 6 are shown the maser and the maser plus filter (NbTi-IIA) input noise temperatures along with their associated return losses. One can see from the figure that the noise temperature of the maser is increased only in the regions where the input return loss is poor. For these measurements the maser input return loss was laboriously and carefully adjusted to a value of 18 dB or better across the band of interest (0.12 GHz).

For these noise temperature measurements it was found that the largest source of error was associated with the repeatability of the SMA connections and subsequent thermal cycling. This was determined by repeating the input noise temperature measurements of the maser alone and maser plus filter after reconnecting the appropriate low temperature SMA connectors. After several tests of both maser configurations, the repeatability was found to be ±0.5 K between cool-down cycles, while during the particular run the repeatability was ±0.3 K. The worst-case error for these measurements is then ±0.8 K.

To better illustrate the affects of a poor match and to show that the noise temperature measurements are in agreement with the insertion loss measurements, the results in Fig. 6 are replotted in Fig. 7 as the noise temperature contribution. Also shown are the results predicted by Eq. (4) using measured return loss data (continuous curve) assuming a lossless filter. Included for comparison are the results for the Cu filter and the values predicted by Eq. (3) assuming $L(\mathrm{dB}) = 0.5$ dB (dashed curve). Figure 8 contains the same information for the NbTi-II and Pb(Cu) filters, again assuming a lossless filter. It is thus evident from Figs. 7 and 8 that the loss and noise temperature measurements are in agreement. Finally, it is noted that the superconducting filter with the best match (NbTi-II) also yielded the lowest noise temperature contribution.

VI. Conclusion

It has been demonstrated that bandpass, interdigital filters constructed from low-loss superconducting NbTi and Pb(Cu) can be utilized to protect maser amplifiers from out-of-band RFI. In circumstances where power level dependence of the NbTi filter is undesirable, it was shown that Pb(Cu) is the more suitable material.

It is also evident that the noise temperature contribution of superconducting filters to ultra-low-noise maser amplifier systems is more a function of input return loss than dissipation loss. Hence, for the noise temperature contribution of a Block-IIA maser to remain below 0.2 K, the maser-plus-filter-input return loss must be 17 dB or better.

VII. Acknowledgements

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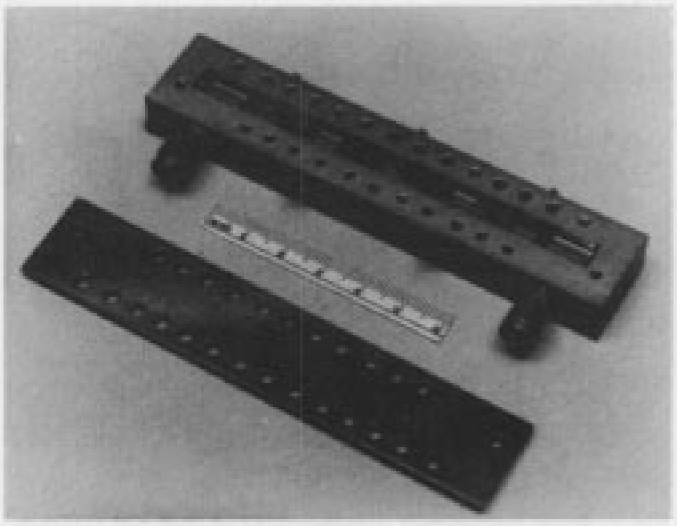

Fig. 1. Photograph of NbTi-II filter

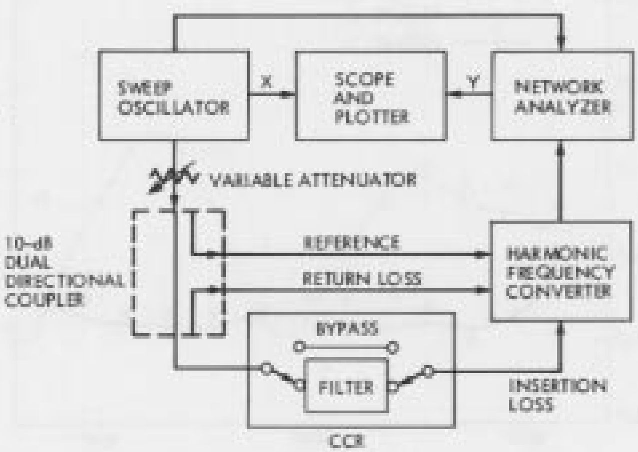

Fig. 2. Insertion loss measurement setup

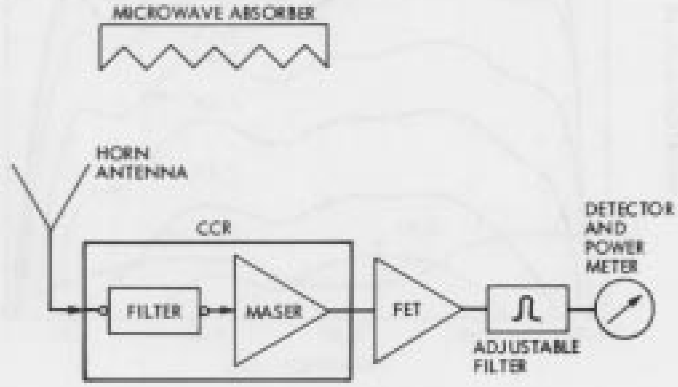

Fig. 3. Noise temperature measurement setup

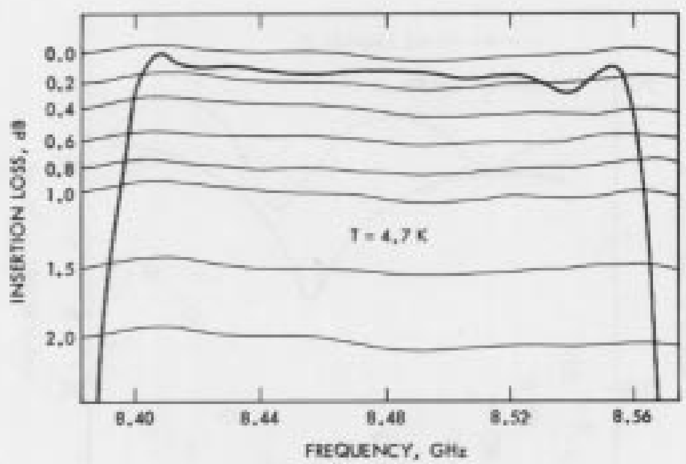

Fig. 4. Insertion loss of the Pb(Cu) filter at 4.7 K

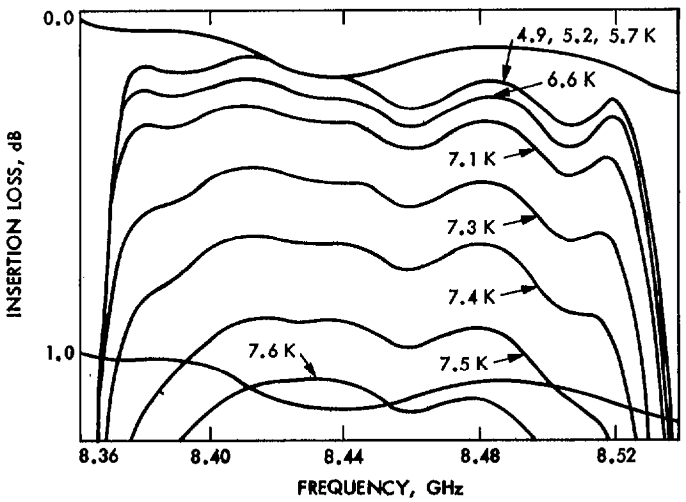

Fig. 5. Insertion loss of the NbTi-II filter for various temperatures

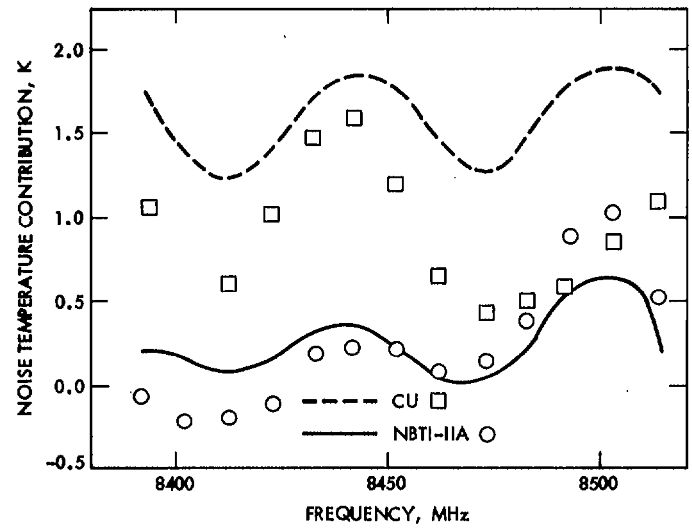

Fig. 7. Noise temperature contribution of NbTi-IIA and Cu filters

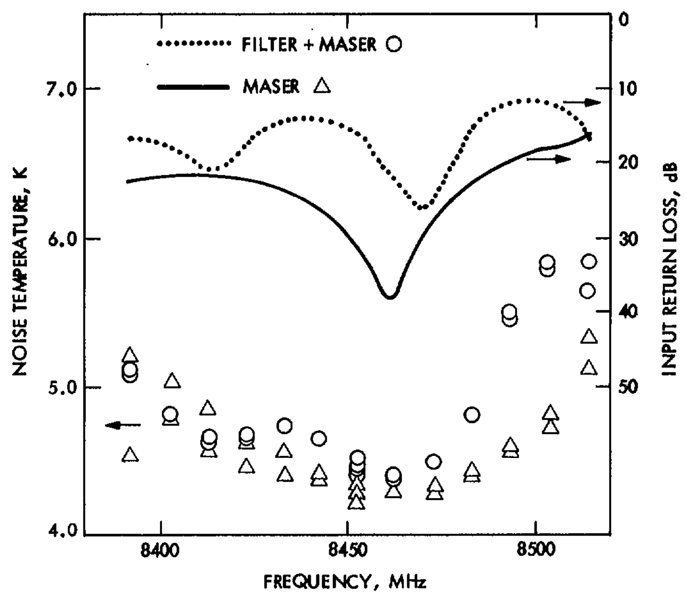

Fig. 6. Measured noise temperature and return loss of filter plus maser and maser alone

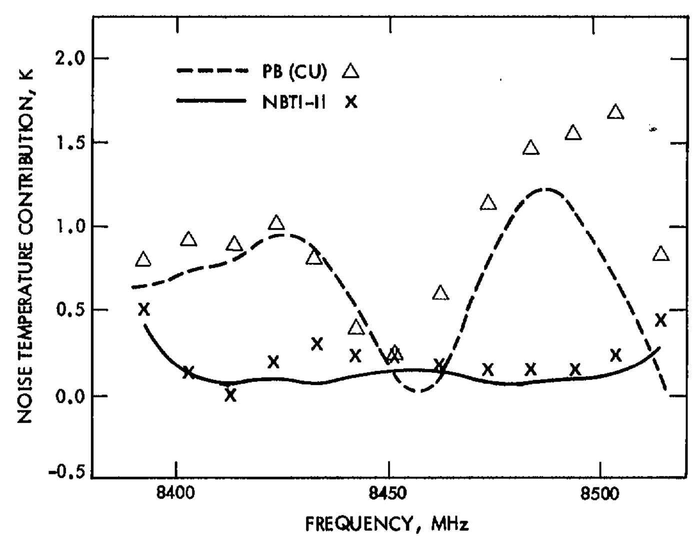

Fig. 8. Noise temperature contributions of Pb(Cu) and NbTi-II filter