Lightweight, space efficient low-pass radio-frequency interference filter modules for bolometric detectors

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Extremely lightweight and space efficient low-pass radio-frequency interference (RFI) filter modules have been developed and tested for use with bolometric detectors. These filters are based on the compactness of a surface mount electro-magnetic interference chip filter. We have produced densely packed modules containing 21 filtered lines, which weigh 60 g, with dimensions of $38\times36\times11$ mm. These modules provide greater than 20 dB attenuation over the entire frequency range tested (50 MHz–10 GHz) while providing over 60 dB attenuation for frequencies greater than 4.5 GHz. The filters suppress rf voltage noise and prevent radiation from RFI on the lines from entering the detector environment and heating up the bolometers. Modules have been used on bolometric detector systems containing as many as 16 RFI filtered bolometers. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1502019]

I. INTRODUCTION

Bolometric detectors are extremely sensitive to thermal variations caused by power fluctuations. One source of these fluctuations is radio-frequency interference (RFI) from sources that couple through the wires into the cryostat, which normally forms a Faraday cage. Thorough filtering of these lines at the outer wall of the cryostat can provide adequate suppression to reduce the RFI to below the noise level of the detectors. Since the signals carried on the readout lines are near dc (usually less than 1 kHz), a simple low-pass filter suffices for this purpose. A previous device developed by Freund *et al.*, for the Infrared Telescope in Space, addressed constraints on compactness and suppressed noise by 80 dB from 5–20 MHz.[1] This filter module used single element surface mount LC filters packed densely on printed circuit boards, which were then stacked for maximum density in a rf-tight box. Radiative coupling between the input and output ends of the filters caused a loss of attenuation at higher frequencies. This did not pose a problem since these devices were to be used in an environment with low levels of transmitted power above 20 MHz.

Recently, increased use of higher frequency communication systems has imposed a requirement of added high frequency rejection for RFI filters. Due to weaker constraints on the size and weight of instruments that operate from suborbital platforms, the filters used for the SUZIE[2] and BOOMERanG[3] bolometric instruments were simply long lengths of stripline cables potted in cast Eccosorb[4]—a material that dissipates rf energy by resistive losses in tiny grains of suspended magnetically permeable conductors. These filters were bulky and heavy, but were reported to provide significant attenuation above a few GHz.[3]

In future satellite missions such as the Planck-high frequency instrument (HFI)[5] and the spectral and photometric imaging receiver (SPIRE),[6] there will be a need for combining the two constraints of compactness and higher frequency attenuation in RFI filters. Our anticipation of this need has prompted the development of prototype filter modules for use on ground based bolometric receivers [Polatron[7] and the arcminute cosmology bolometer array receiver (ACBAR)[8]]. In this article we report the results of our work.

II. RFI FILTER MODULE DESIGN

Compactness can be achieved with the use of surface mount devices.[1] A Murata surface mount electro-magnetic inductance (EMI) chip filter[9] provides a space efficient RFI filter. In contrast to the single element LC filters used in the Freund *et al.* design,[1] the Murata filters are lumped elements that house an entire filter within a single device of dimensions $4.5\times1.6\times1.25$ mm. The equivalent circuit (Fig. 1) is similar to a simple pi filter. However, a varistor is used as the capacitive element of the filter for the added function of surge suppression. Structurally similar to capacitors, varistors contain grains of ZnO (a ceramic) between their conductors instead of a dielectric. Figure 2 shows the manufacturer's specifications for the insertion loss of these Murata filters.

To prevent degradation of high frequency attenuation in our modules by radiative coupling between input and output lines, it was decided that the Murata filters should be mounted in a firewall that split a rf-tight box into two Faraday cavities. For added high frequency attenuation, we filled the cavities with Eccosorb.

Preliminary testing was necessary to confirm that the loss characteristics of the Murata filters did not change appreciably at cryogenic temperatures. These were carried out using a rf-tight box with bayonet naval connector (BNC) breakouts. A single filter was inserted in a firewall placed across the middle of the box and silver epoxy was used to

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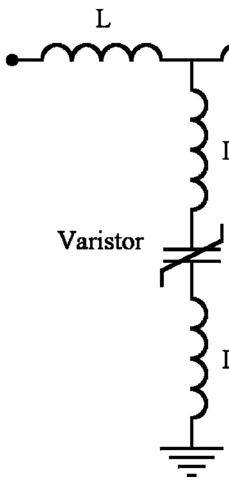

FIG. 1. Equivalent circuit for the varistor filter used in the low-pass RFI filter modules.

create rf seals while providing electrical connection between the box, firewall, and ground plane of the filter. Connection between the BNC connectors and the filter terminals were made with insulated copper wire. Before closing up the box, the two cavities were stuffed with foam Eccosorb.[10] The measurements were made using a sweep oscillator[11] with a rf plug-in[12] in conjunction with a spectrum analyzer.[13] Filter performance was tested at 77 K by submersing the entire box in liquid nitrogen. We determined that this configuration achieved the specified insertion loss of the Murata filters (Fig. 2) and that there was negligible degradation of performance at 77 K.

Following these tests, we designed our RFI filter modules to be multichannel versions of this preliminary device. Cannon micro-*D* metal shell connectors[14] were used as breakouts because of their compact size and ability to withstand extremely low temperatures. These were mounted on either ends of an aluminum casing designed to hold an aluminum firewall such that maximum rf insulation between the input and output cavities could be achieved once silver epoxy was applied. The filters were arranged in two rows through the firewall. This allowed connections to be made between the connectors and the filter terminals by using a

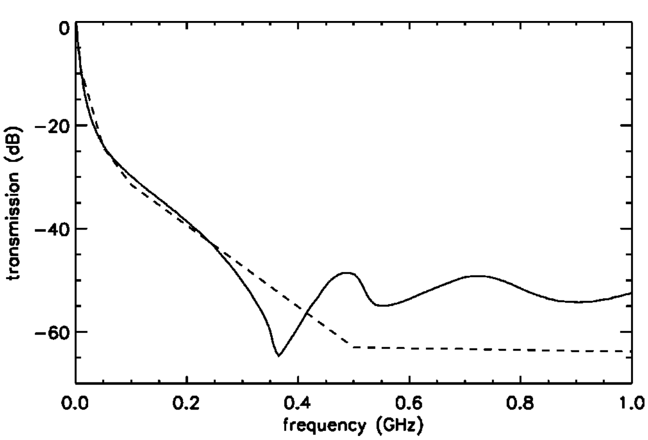

FIG. 2. Murata's specifications for the insertion loss of their surface mount EMI chip filters (solid line) and the transmission spectrum obtained from our preliminary testing (dashed line).

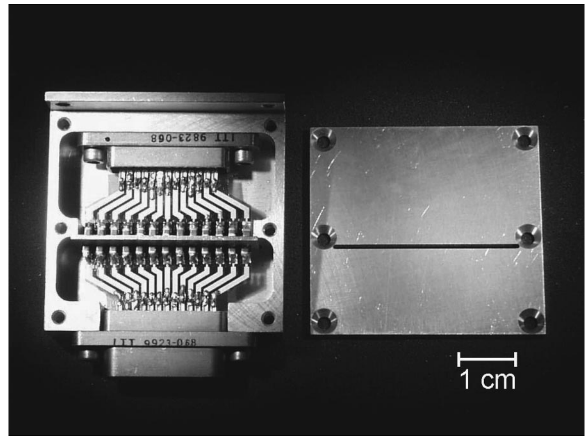

FIG. 3. A 25-channel RFI filter module before the cavities are potted with cast Eccosorb and sealed with silver epoxy.

Kapton ribbon deposited with gold traces rather than point-to-point wiring. Figure 3 shows a picture of a 25-channel module at this stage of the assembly.

After sealing the insides up with silver epoxy, both cavities were potted in cast Eccosorb and the module was sealed up. Table I summarizes the dimensions and performance characteristics of our modules in comparison to the Freund *et al.* modules.

III. TEST SETUP

Before measuring the transmission spectra of the RFI filter modules, each module was thermally shocked once by submersing them in liquid nitrogen then warming to room temperature. Checks for dc continuity and shorts between neighboring lines, as well as to ground, were carried out using a Fluke multimeter. Continuity failures were extremely rare (1 in 120 times).

All the measurements of transmission spectra that we will discuss in the remainder of this article were carried out on the 21-channel modules, or modified versions using the same housing geometry and connectors, with a network analyzer.[15] Three channels were chosen for testing (two neighboring channels in the middle and one off to the side, all in the same row within a filter module). To couple high frequency power through the RFI filter modules, between the input and output arms of the network analyzer, sub-miniature A (SMA) connectors were used for the three breakouts from each micro-*D* connector because of their low reflection coefficient (or voltage standing wave ratio) at these frequen-

TABLE I. The physical and performance characteristics of the low-pass RFI filter modules described in this article in comparison to the Freund *et al.* filters.

Characteristic	21-channel RFI filter module	35-channel Freund *et al.* filter module
Dimensions length×width×height (mm)	38×36×11	76×26×20[a]
Mass (g)	60	Not reported
Stop band (MHz)	4500–10 000	5–15
Maximum attenuation (dB)	>75	>80

[a]See Ref. 20.

cies. For the same reason, the arms of the network analyzer each terminated in an SMA connector. Due to the difficulty of providing adequate shielding for these breakout cables by conventional methods, radiative coupling between the input and output cables was prevented by housing them within an aluminum testing module with a firewall where the filter module was mounted, which isolated the cables from each other by enclosing them within separate Faraday cavities.

Care was taken during the design and construction of the test module to ensure that we allowed for the ability to reasonably subtract the effects of this test module as a baseline from our observed data. This was accomplished by requiring that the two micro-*D* connectors on the breakout cables could be mated at the firewall. The use of foam Eccosorb to fill the space within the cavities of the testing module was required for the purpose of suppressing resonances that existed in this ''baseline'' setup, but not when the RFI filter module was inserted. Because these resonances were not eliminated entirely, we were careful when interpreting the transmission spectrum of the filter modules over frequencies in which small resonances in the baseline occurred—an illusion of lower attenuation over these frequencies is created.

Measurements of the filter performance at cryogenic temperatures were carried out by submersing the entire test setup in liquid nitrogen.

IV. RESULTS AND PERFORMANCE

Figure 4(a) shows the observed transmission spectrum, using the above setup after subtraction of the baseline spectrum, of a single channel on one of the 21-channel RFI filter modules at the two temperatures, 300 and 77 K. We see that this channel provides at least 20 dB of attenuation over the entire frequency range. Attenuation of less than 20 dB is only observed over frequencies where the baseline contained a resonance. Above about 4.5 GHz, the filter response has dropped to below -70 dB where it appears to be dominated by the noise floor of the network analyzer. Except for the understandable difference of increased resonances, usually occurring when resonant cavities are cooled, the filter performance at cryogenic temperatures (77 K) appears to be very similar.

The crosstalk at low frequencies (up to 800 Hz) was measured using a network signal analyzer.[16] As a check, the transmission spectrum of each channel was measured and found to produce negligible attenuation. The crosstalk between nearest channels in a single row was found to be a negligible, -50 dB, over most of this frequency band.

Although this module provides sufficient suppression for preventing bolometer heating on the Polatron and ACBAR, a close inspection of the transmission spectrum below 2 GHz, in comparison to the results from our preliminary testing [Fig. 4(b)] reveals that it may be possible to make improvements to our RFI filter modules. We observed considerable degradation in attenuation between 10 and 40 dB in this frequency band. This inconsistency prompted a more thorough investigation to isolate the effects caused by various elements within the modules, in hopes of identifying the origin of this discrepancy.

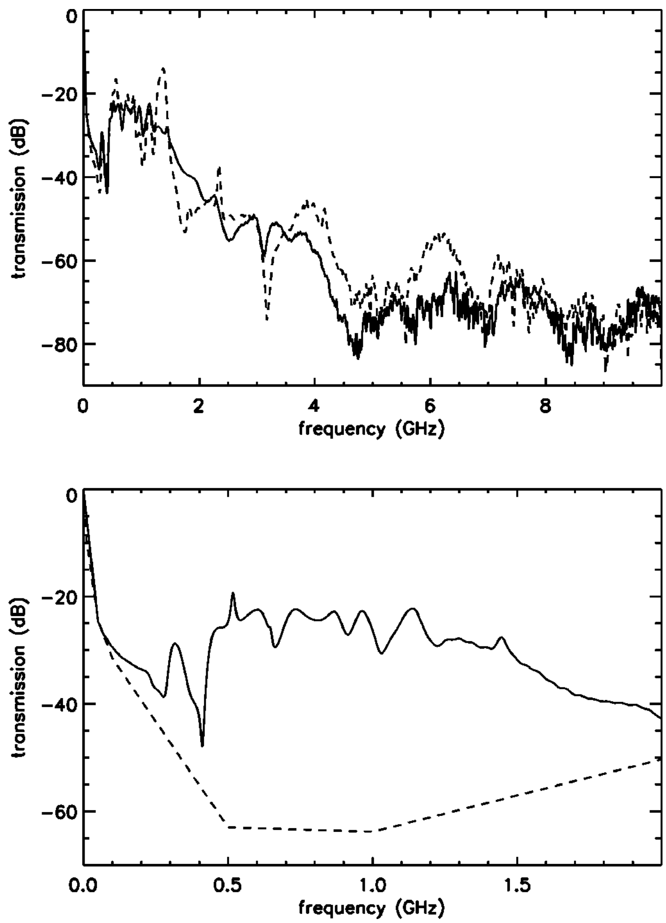

FIG. 4. (a) Normalized transmission spectra of a single channel on a 21-channel RFI filter module at 300 (solid line) and 77 K (dashed line); (b) 300 K spectrum from (a) over the lower frequencies (solid line) in comparison with the spectrum obtained from our preliminary testing (dashed line).

The effects on filter response caused by potting the cavities of the modules in cast Eccosorb were isolated by measuring the transmission spectrum both before and after the potting. For this purpose a module was constructed which only contained three filters all in the same row. We see from Fig. 5(a) that upon potting with Eccosorb, the attenuation suffered very slightly at lower frequencies while providing increased high frequency suppression. It is clear from these tests that the Eccosorb is not the cause of the discrepancy mentioned above. We also conducted the same tests on a module containing two filters, which did not use the Kapton ribbon for connections [Fig. 5(b)]. Rather, insulated copper wire provided the connections needed using Stycast[17] to insulate any other exposed conductors (filter terminals and connector solder cups). These tests reveal that using wires instead of the Kapton ribbon (which allows the Eccosorb to completely surround the conductors) eliminates the degradation at lower frequencies by extending the added high frequency suppression to these frequencies.

Crosstalk between channels occurs when multiple filters are placed into the same module. From a comparison of the performance of the module used to test the effects of the Eccosorb with our original module, we see some improvement by reducing the number of filters, eliminating the second row. We have reason to believe that it is the crosstalk

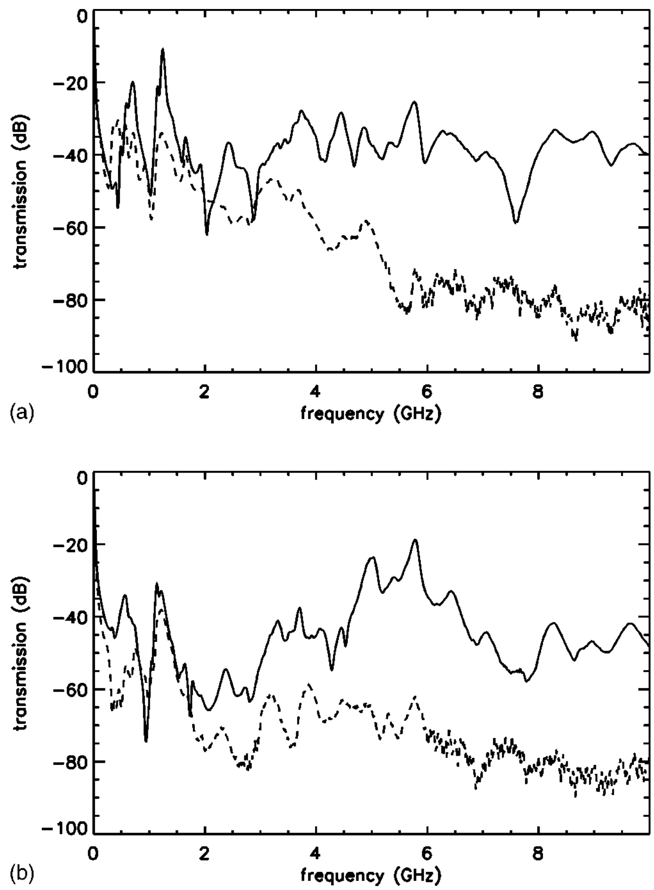

FIG. 5. (a) Normalized transmission spectra of a single channel in a module constructed to illuminate the effects of the Eccosorb before (solid line) and after (dashed line) potting; (b) same as in (a) but for a module in which connections were made with insulated copper wire rather than the Kapton ribbon.

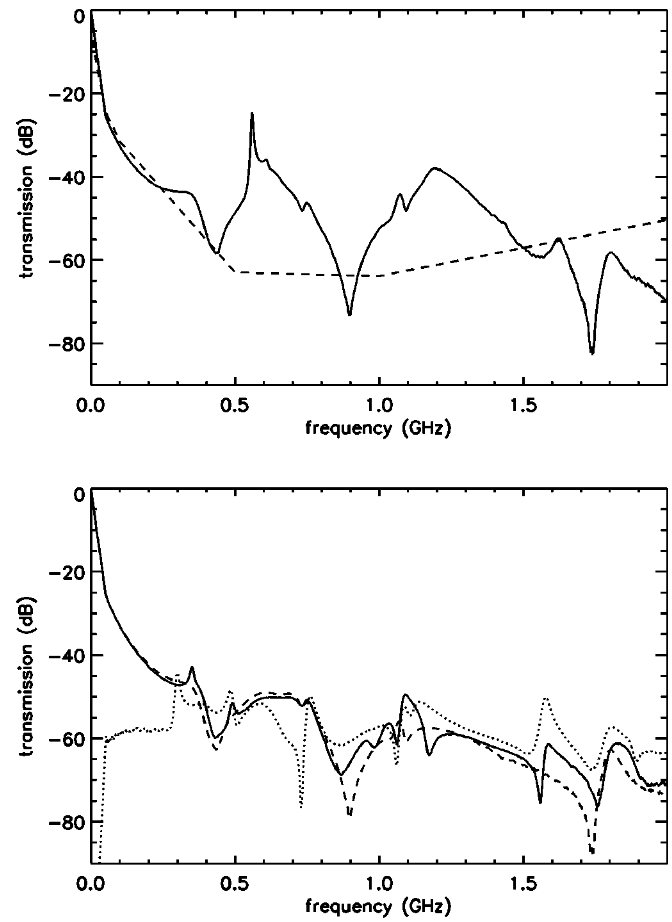

FIG. 6. (a) Normalized transmission spectrum of the channel in a module containing only a single filter constructed to eliminate the crosstalk (solid line), in comparison with the spectrum obtained from our preliminary testing (dashed line); (b) unnormalized transmission spectra of the same channel in (a) before (dashed line) and after (solid line) adding a second filter to the module in order to illuminate the crosstalk problem, along with the cross transmission between the two channels (dotted line).

that is the cause of the discrepancy. To test this hypothesis, we constructed a module containing a single filter, which eliminated the crosstalk (between channels), with connections made from insulated copper wire rather than the Kapton. From the transmission spectrum of the single channel in this module compared to our preliminary test results [Fig. 6(a)], we see that aside from resonances, these two spectra agree reasonably. We conclude that the discrepancy is due to crosstalk.

To test this further we constructed a simple module with two filters using point to point soldering rather than the Kapton ribbon. Transmission spectra were recorded as well as spectra of the crosstalk for these two channels. Figure 6(b) shows unnormalized spectra of a single channel in this module compared to the corresponding channel before adding the second filter as well as the crosstalk between the two channels. We find that the crosstalk increases dramatically around the lowest frequency in which the two unnormalized transmission spectra diverge and contains many of the same characteristics that appear in the spectrum taken with the double-filter module, especially the ones that are not present in the spectrum from the single-filter module. This information provides added support to our conclusions about the crosstalk as it causes the attenuation to degrade (due to radiative coupling).

We have simulated the equivalent circuit incorporating a simple model for crosstalk via capacitive coupling. For our circuit simulation, we use a program called RFSIM99.[18] The equivalent circuit used for our chip filters was the same one shown in Fig. 1 where we obtained the capacitance value from the Murata specification sheet and varied the inductances so that the transmission spectra would match the specified insertion loss (Fig. 2). Figure 7 is the simulated version of Fig. 6(b) where we have assumed that capacitive coupling between two filter circuits is responsible for the crosstalk. We notice that this idealized simulation reproduces the low frequency characteristic of the crosstalk where a sharp increase in cross transmission forces the attenuation of the filter to degrade, forming a spike near the cutoff frequency.

Although these tests have revealed only a slight degradation in attenuation for this case of minimal crosstalk (two non-neighboring filters), it is plausible that the crosstalk is greatly increased by the 21 filters and the conductor geometry existing in our original modules. Rather than two widely separated wires, our original modules used the Kapton ribbon, which contained parallel traces that were very closely spaced, especially for those on opposite sides of the Kapton

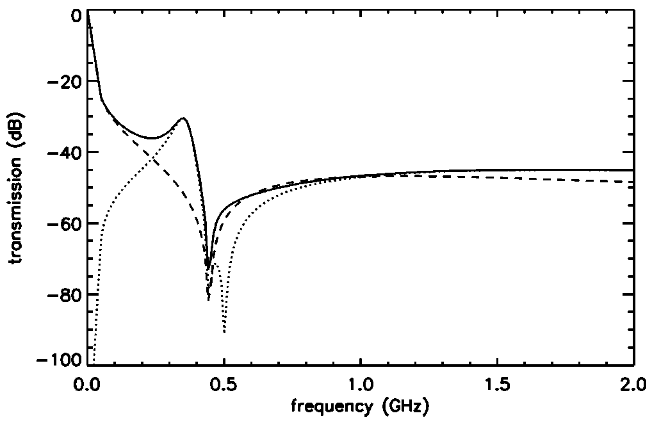

FIG. 7. Simulated transmission spectra of a filter with (solid line) and without (dashed) capacitive coupling to another filter, along with the simulated cross transmission between the two filters (dotted line). Circuit simulations were carried out with RFSIM99 using the equivalent circuit shown in Fig. 1 as the filter.

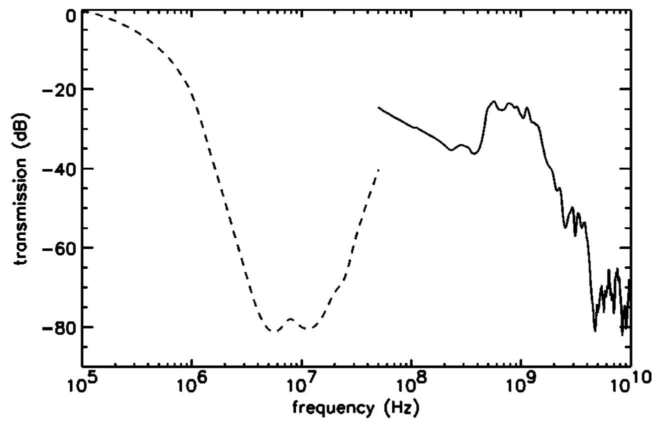

FIG. 9. Normalized transmission spectrum of a single channel in a 21-channel RFI filter module (solid line) in comparison to the results on filter performance obtained by Freund *et al.* (dashed line).

thickness (0.127 mm). As a check, we measured the crosstalk of neighboring channels for our original module (Fig. 8) and found that over the lower-half of the measured frequency band, the cross transmission was comparable to, or greater than, the unnormalized transmission of a single channel (excluding the lowest frequencies). In the upper-half of the band, the cross transmission is on average about 10 dB lower than the single channel unnormalized transmission. These data can account for all of the observed discrepancy over the lower-half of the band while only partially accounting for it in the upper-half of the band. However, noting that the trace separation for neighboring channels is an order of magnitude larger than that of adjacent channels on opposite sides of the Kapton, the capacitive crosstalk between the latter pair should account for the rest of the discrepancy at the higher frequencies. We, therefore, conclude that capacitive crosstalk is the major source of the discrepancy observed between the cryostat RFI module with 21 lines and the modules constructed with only a single filter.

V. DISCUSSION

Our work has culminated in the implementation of a new generation of RFI filters suited for use with bolometric detectors. In addition to the 21-channel modules, we have also developed modules containing 15 and 25 filters. The 25-channel modules have been used on the 4 K stage of the ACBAR instrument at the South Pole and were reported to supply sufficient attenuation to prevent bolometer heating by RFI in the field environment. As a comparison to the filters developed by Freund *et al.*, we plot the results observed by Freund *et al.*[1] along with our results on filter performance on the same graph (Fig. 9). This illuminates our added concern for providing a module with a rf-tight seal between the separate cavities.

From these investigations, we are able to design near optimal modules in future iterations. We have found that the capacitive crosstalk between lines is a major source of degradation in the attenuation provided by our modules. One solution to reduce crosstalk is to print a ground strip alongside each of the lines. This configuration (stripline transmission line) reduces crosstalk by effectively containing fields propagating along a line to within the boundary formed by the ground strips. We have already conducted a preliminary test to verify the effectiveness of this procedure. A module was constructed with two neighboring channels with connections made with bare copper wire. After measuring the transmission spectrum, two parallel ground wires were added on either side of the pair (one was not added between the two because of size constraints). The unnormalized results are given in Fig. 10 where we see that the side effect is the elimination of the spike near the cutoff frequency described above. Since this is the primary difference between the single filter and the coupled filter in our simulation, we conclude that the stripline transmission line configuration is a promising modification to pursue.

Potting the cavities of the module in cast Eccosorb provides excellent high frequency suppression, pushing the attenuation below −80 dB (the noise floor of the network analyzer). There is only a small loss of attenuation at low frequencies in exchange for this large improvement. We can improve the attenuation by using insulated wires for our connections rather than the Kapton ribbon so that the Eccosorb is allowed to surround the full circumference of the conductors. This substitution also has consequences for the crosstalk

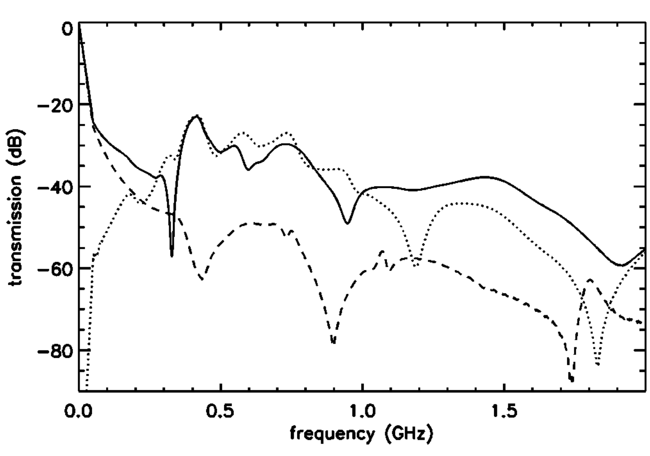

FIG. 8. Unnormalized transmission spectra of both a single channel in a 21-channel RFI filter module (solid line) and the channel in the single-filter module (dashed line), along with the cross transmission between neighboring channels in the 21-channel module (dotted line).

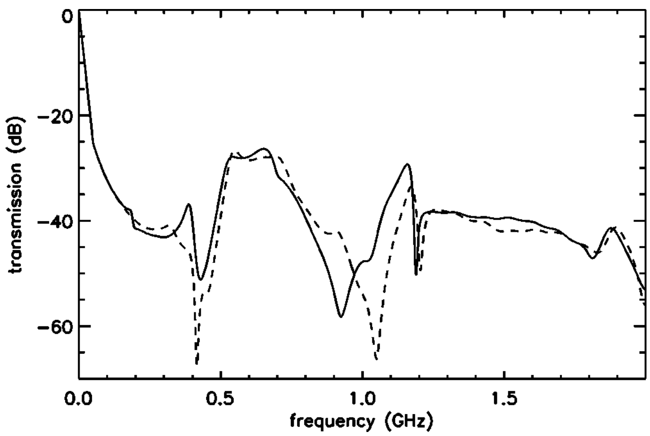

FIG. 10. Unnormalized transmission spectra of a single channel in a module containing two neighboring filters before (solid line) and after (dashed line) the addition of two ground wires parallel to the two channels.

since it lowers the low-pass cutoff frequency of the Eccosorb. This frequency gets lowered to near the frequency at which the cross transmission dramatically increases, thus eliminating the crosstalk problem entirely.

Although the use of insulated wires improves the attenuation of our RFI filter modules, their use results in significant complication in fabrication. Rather than the single step needed to provide the connections for each end of a trace on the Kapton ribbon, use of insulated wires requires multiple steps to make a single connection. It is possible that bare wires can be used to obtain the same results as insulated wires. This would reduce the fabrication difficulty making the individual wire option more feasible but still more labor-intensive than the Kapton ribbon method.

As a final note, we explore the possibility of using a different lumped filter component into our RFI filter modules. Syfer[19] manufactures lumped EMI pi filters that use a capacitor rather than a varistor as the capacitive element. These could lead to improvements in the transmission spectra of filter modules. Also, surface mount device manufacturers generally produce pi filters of many different capacitances. Increasing the capacitance lowers the cutoff frequency. In future work, we will use a variety of filters with different capacitance values to optimize the design for a given frequency regime.

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[16] Stanford Research Systems, Model SR780.
[17] Part Number 2850 F, manufactured by Emerson and Cumming, http://www.emersoncuming.com/
[18] HyDesign Ltd., http://www.hydesign.co.uk/
[19] Syfer Technology Limited, a part of the Dover Technologies Group of Companies, http://www.syfer.com/
[20] Dimensions are of the circuit board stack (five filter boards) before inserting into the module casing.