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Note: Cryogenic microstripline-on-Kapton microwave interconnects

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Simple broadband microwave interconnects are needed for increasing the size of focal plane heterodyne radiometer arrays. We have measured loss and crosstalk for arrays of microstrip transmission lines in flex circuit technology at 297 and 77 K, finding good performance to at least 20 GHz. The dielectric constant of Kapton substrates changes very little from 297 to 77 K, and the electrical loss drops. The small cross-sectional area of metal in a printed circuit structure yields overall thermal conductivities similar to stainless steel coaxial cable. Operationally, the main performance tradeoffs are between crosstalk and thermal conductivity. We tested a patterned ground plane to reduce heat flux. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4737185]

Simple broadband microwave interconnects are key components for arrays of focal plane heterodyne radiometers. Here we report on an investigation of transmission line arrays printed on flexible circuit board substrates, part of a program to develop and assess components for a scalable millimeter-wave focal plane radiometer.[1] For tens of focal plane elements, microwave intermediate frequency signals can be routed on individual semi-rigid coaxial cables, but this approach becomes cumbersome for large focal plane arrays. Here we report on an alternative interconnect: microstripline on a polyimide (Kapton[2]) flex circuit substrate. A number of papers,[3–5] among others, report microwave characterization of flex substrates, but none that we are aware of report cryogenic properties.

Of the well-developed planar transmission line structures, we chose microstripline because of its mechanical simplicity, its relatively low electrical loss, and because it requires the least metal of common planar transmission lines. The last item is an important consideration for transmission lines between components at different temperatures. In spite of copper's high thermal conductivity, the small metallic cross section of planar lines results in a total heat flow along a flex circuit comparable to that through the much larger cross sections of stainless steel and steel in standard cryogenic coaxial cable. With strength carried by the Kapton substrate, and high-frequency fields confined to a thin layer near the conductor surfaces by the skin effect, very thin conductors are practical for the lines. The thinnest standard copper cladding on Kapton is 0.5 oz/ft^2, or 0.7 mil (0.0007 in., 18 μm) thick. Calculated microstrip/coax heat flow ratios for typical thermal conductivities[6] along an 8-circuit evaluation structure (8 parallel 11 mil strips on an 850 mil wide ground plane) divided by that along 8 stainless-steel 085 coaxial cables are 0.66 for 297 K–77 K end temperatures, and 2.9 for 77 K–20 K. For microstriplines most of the thermal path is in the ground plane, so we investigated a patterned ground plane that reduced the amount of metal.

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We report measurements on two test structures. The first included microwave resonators to evaluate materials properties at 297 and 77 K (room temperature and liquid nitrogen). The second was a set of 8 parallel microstrip lines to evaluate multiple-line performance over two ground plane patterns. Both structures were on DuPont Pyralux AP-8555R stock, which has 0.5 oz/ft^2 rolled[3] copper bonded to both sides of 5 mil thick polyimide substrate material. Although thinner substrates are available, we chose 5 mil mostly because of fabrication tolerances: with this thickness, the microstrip lines are 11 mil wide, and a 10% width fabrication error still produces a line with an impedance close to 50 Ω. As secondary considerations, electrical loss drops with increasing strip width, and an 11 mil width is suitable for solder contact between SMA connector pins and the strip. Most flex circuits have a thin dielectric coverlay to protect the traces, but the adhesive has high electrical loss at microwave frequencies,[3] so the test structures had no coverlays.

A commercial firm fabricated transmission line test structures on a 1.5 in. by 4.1 in. substrate with a full ground plane on one side and three microstrip transmission lines across the short dimension on the other side. Two of the lines had perpendicular shunt open stubs to make tee resonators, with stub lengths 3.000 and 0.550 in. long. Johnson 142-0701-851 edge connectors with 10 mil diameter pins made contact with the lines and ground pads to either side of the line. Gold plating (5 μin. of gold on 100 μin. nickel) kept the traces from oxidizing while allowing wire bond and solder connections.

The substrate shrinks little between room temperature and 77 K, while remaining flexible. There was no apparent bending or other thermally induced stress between the substrate and fully metalized ground plane when the test structure was immersed in liquid nitrogen. We corrected for resonator length change with cooling by measuring the length of the test substrate at room temperature and when immersed with a stainless steel scale in a shallow tray filled with liquid nitrogen; the length change on cooling was only 5 mil on the scale. After correcting for the scale's own length contraction from 293–77 K (Ref. 7) we derived a substrate fractional

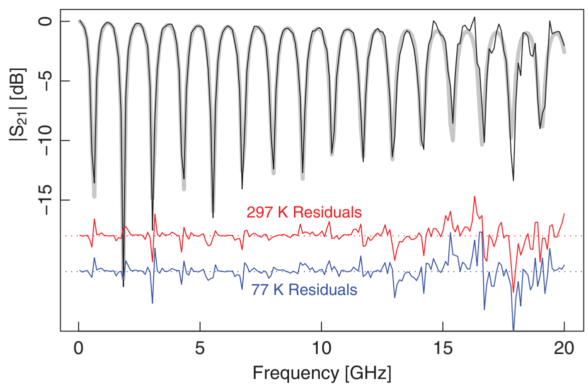

FIG. 1. Comparison of measured data (thin black line) and model fit from 0.05 to 12 GHz (grey line) for the cold resonator. Curves below show residuals from the fit for warm and cold resonators on the same dB scale but with offsets indicated by the dotted lines. This plot shows that the fit is excellent to about 13.5 GHz and is representative to at least 20 GHz.

length contraction of $\Delta L/L = -4.0 \times 10^{-3}$ between 297 and 77 K. At 77 K, the 3 in. resonator was shorter by 13 mil.

All microwave measurements were in vacuum with the substrate attached to the cold plate of a small liquid nitrogen cryostat. A copper radiation shield attached to the cold plate and lined with microwave absorber covered the substrate to block infrared radiation that would otherwise heat the substrate. Comparison of warm transmission with and without the copper cover showed that the cover did not affect microwave transmission. Conformable 085 coaxial cables, 8 in. long, connected the test structure to hermetic SMA feedthroughs passing through the cryostat wall; 3 dB attenuators between the cables and feedthroughs helped reduce residual standing waves. We made measurements of the resonators and the through on the test structure at 297 and 77 K with an Agilent 8722D vector network analyzer, sampling 201 points from 50 MHz to 20 GHz.

Dividing the test structure's resonator transmission ($|S_{21}|$) by that of the through line removed cable, attenuator, and connector losses, giving a clean measurement of the tee resonator alone. We used Microwave Office[8] (MWO) for this division and to fit for substrate dielectric constant and loss tangent by comparing the derived values of $|S_{21}|$ to those from MWO's parametric models (which include finite-element electromagnetic calculations for the discontinuities at the tee) and optimization function. The topmost lines in Figure 1 display the cold measurement and the MWO model fit for the 3 in. resonator. Plots of the residuals between the two, as well as the residual for the warm measurements, show that the models are good representations at both temperatures. Structure at higher frequencies is common to both warm and cold resonators and is probably due to different connector mismatches in the resonator and through lines. The overall agreement between measurement and theory indicates that the material parameters we derive are valid to at least 20 GHz.

Table I summarizes derived electrical properties. The dielectric constant ϵ_r changed by a negligible amount between room temperature and 77 K; a representative value for microwave frequencies is $\epsilon_r = 3.37$. There is a weak dependence on the fit frequency range, 0.05 GHz to f_{upper}, for ϵ_r, which is

TABLE I. Dielectric constants ϵ_r and loss tangents $\tan\delta$ derived from resonator measurements at 297 and 77 K, with fitting from 0.05 GHz to f_{upper}. The change in ϵ_r with frequency shows a small amount of frequency dependence. The change in ϵ_r with temperature is negligible for most purposes. Loss has a clear temperature dependence, however, with $\tan\delta$ dropping by a factor of ∼2 on cooling.

f_{upper}(GHz)	$\epsilon_{r,\,297\,\text{K}}$	$\epsilon_{r,\,77\,\text{K}}$	$\tan\delta_{,297\,\text{K}}$	$\tan\delta_{,77\,\text{K}}$
3	3.378	3.377	0.008	0.000
6	3.372	3.370	0.012	0.006
12	3.348	3.350	0.013	0.007

just visible in plots for different frequencies. Both dielectric and metalization losses contribute to overall loss, but the fits were insensitive to losses in the metal, parametrized by conductivity ρ relative to gold, and we used a value of $\rho = 0.7$. Loss in the dielectric drops by a factor of approximately two on cooling, from $\tan\delta = 0.013$ to 0.007.

We directly assessed the performance of microwave interconnects with a structure with eight parallel microstrip transmission lines with strip widths of 11 mil on 100 mil centers (gaps between lines equal to 8.1 times the strip widths). The minimum line length was 8.5 in., and the maximum was 11.7 in. As shown in Figure 2, four of the lines were over a solid ground plane, and the other four were over a patterned ground plane with reduced thermal conductivity. The patterning was a solid plane 55 mil wide below each 11 mil-wide line, providing termination for most of the field lines, with 10 mil-wide cross-strips on 80 mil centers tying the grounds together across the width of the structure. The cross-strips must have spacing with distance well below a quarter of the shortest wavelength to avoid resonances between the lines, and $\lambda/10$ or closer to reduce structure in S_{21}. With a pattern of relatively narrow ground planes under the lines, joined by thin cross-connects, the calculated heat flow along the structure is a factor of three lower than a solid ground plane. Broader ground strips under the lines would reduce crosstalk at the cost of higher thermal conductivity. Reducing line widths on a thinner substrate is an additional attractive solution at low

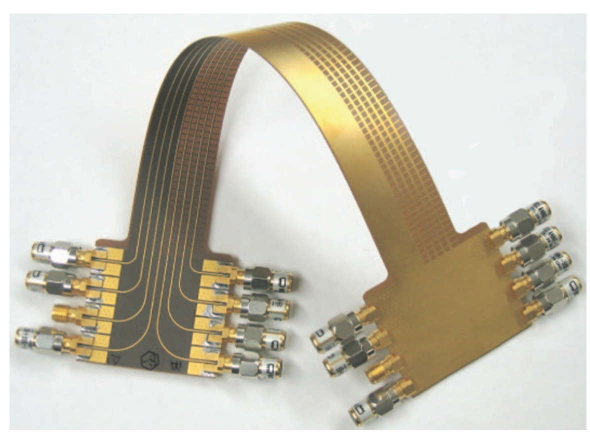

FIG. 2. Photograph of parallel line test structure, with a twist to show both the transmission line layout (left side) and the ground plane patterning (right side).

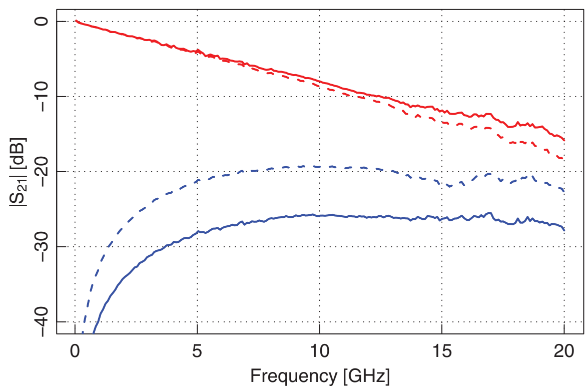

FIG. 3. Transmission and nearest neighbor cross-coupling for solid (solid lines) and patterned (dashed lines) ground planes for a 10.6 in. line with 0.1 in. spacing to its neighbors. Transmission (upper pair of lines) is only slightly affected by the missing metal in the ground plane, but cross-coupling (lower pair of lines) is sensitive to patterning.

temperatures, where the electrical loss is lower, although fabrication tolerances may become critical.

Figure 3 shows the transmission loss and cross-coupling for the 10.6 in. lines over the two ground planes. Cross-coupling in this plot is to a nearest neighbor line with 8.2 in. of parallel run; the nearest neighbor on the other side has 8.8 in. of parallel run. The transmission loss is only slightly higher for the patterned ground plane, but the crosstalk is substantially higher: the far-out field lines carry little power but are responsible for cross-coupling, and are poorly terminated on the strips between the transmission lines.

Transmission loss for this structure with a solid ground plane is closely 0.076 dB/GHz/in. A model fit over 0.05 GHz–12 GHz gives $\tan\delta = 0.018$, slightly higher than the fit to the room-temperature resonator data, $\tan\delta = 0.013$. Loss from cross-coupling between lines is present and is accurately predicted by coupled-line microstrip theory. Modeling for other spacings shows crosstalk decreases with increasing spacing and frequency, but has periodic maxima with line length, as expected for a forward-coupled pair of lines:[9] MWO calculations yield −20 dB maxima for gaps of 6.5 times the strip widths, and −30 dB for 12 times the strip widths. For comparison, standard 085 semi-rigid cryogenic coaxial cable (stainless steel outer jacket, teflon insulation, silver-plated steel wire center conductor) has a loss of about 0.0125 dB/GHz/in. and essentially infinite isolation, but with little possibility for mass connection.

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