Design and Prototyping of New Flexible Stripline based Transmission Lines as Alternatives to Semi-Rigid Coaxial Cables

Marko Neric, Hamdi Mani, Thomas Mozdzen, and Chris Groppi

***Abstract*—We present the design, assembly, and prototyping of new multi-channel flexible printed circuit board stripline based transmission lines for transmitting RF signals. Stirpline transmission lines have been used for decades and consist of a narrow center conductor that is surrounded by a dielectric substrate and then sandwitched between two grounding planes. Incorporating several striplines in the same substrate using flexible materials may be used as alternatives to industry standard stainless steel semi-rigid coaxial cables which are frequently used as RF transmission lines in a variety of devices. This is often the case for astronomy instruments that have multiple pixels working together to form a focal plane array. Larger arrays require many coax transmission line cables which can increase the footprint of a device, as well as add to the total heat load of an instrument. We have developed a single flexible circuit ribbon that can replace up to 8 individual coaxial cables. The flex circuits were designed in CST Studio Suite where transmission characteristics were simulated and subsequently optimized by adjusting the circuit dimensions. The flexible circuits make use of a novel design wherein the top and bottom stripline grounding layers are reduced to 0.015" wide strips rather than a full grounding plane. This minimization of copper grounding material increases flexibility, while decreasing heat load, all without introducing significant loss of signal. The circuits will be used in an upcoming NASA Class-D Balloon mission: GUSTO[1]. Specifically for GUSTO the circuits will need to transmit over an IF bandwidth from 0.3 - 5 GHz while one end of the ribbon is held at 20 K, and the other end is at 300 K. In this temperature configuration, a 20" length of flex circuit has a loss of 5.77 dB at 5.00 GHz which is roughly the equivalent of a stainless steel coaxial cable with an outer diameter of 0.085". In this same configuration the flex circuit loss is 9.67 dB at 10 GHz. Due to its reduced grounding layer the flex ribbon generates 75% less heat than 0.085" diameter coax. The flexible ribbon is also made of durable Kapton material which makes the circuit considerably more malleable than semi rigid coax. The full bandwidth of the flex ribbon is 0 - 10 GHz. The flex circuits have been tested at cryogenic temperatures for multiple cool-down and warm-up cycles without any signs of degradation. They are capable of delivering the comparable transmission characteristics as coaxial cables while offering improvements on versatility, and thermal conductivity.**

***Index Terms*—RF, Cryogenics, Transmission Lines.**

I. Introduction

DISCRETE sets of semi rigid coaxial cables are widely used in THz astronomy instrumentation. They can transmit IF signals from individual pixels in a larger focal plane array to the read out electronics. As the pixel count of future arrays increases so too does the amount of individual cables. This will make for more difficulty in routing coax cables through instruments. A new scheme for IF transmission will be needed. The motivation of this work is to replace bulky semi rigid coax cables in larger arrays.

One potential option for replacing coaxial cables is a flexible cryogenic printed circuit board. Multi channel flexible ribbons have been developed in the past[2]. Using closely packed striplines within a single substrate the flex ribbons could transmit up to 16 different channels in the same ribbon in a much smaller form factor than an equivalent bundle of coax[2]. Optimizing this initial design for use with the upcoming NASA Class-D Balloon Mission, GUSTO, is the focus of this work.

The design goals for this flex circuit are the same as the mission requirements for the GUSTO IF system. The IF bandwidth is 0.3 - 5.0 GHz. The circuits must operate at temperatures as low as 20 K. The circuits must be comparable in performance to UT 85 SS-SS coax while at cryogenic temperatures.

II. Design and Simulation

Using the original design for the ASU flex circuit[2] as a starting point, we modeled the channels as stripline transmission lines. The substrate used was Dupont 8545 Kapton and it was 0.004" (0.1 mm) in thickness. The substrate was plated with 1/2 oz copper cladding. The central conductor of a stripline is buried in the substrate so a radial transition was needed to reach the top layer. Surface mount connectors would be used on both ends. Plated through hole (PTH) signal and ground vias extended from the center conductor to an anti-pad at the top and bottom of the flex circuit. The anti-pad size was determined by the size and type of surface mounted connectors. For this design we use SMP press on connector types.

A three channel flex circuit was designed using CST Studio Suite. The channels were 50 Ω stripline transmission lines. Spacing between channels directly impacts the form factor of the flex circuit. A CST simulated parameter sweep of channel spacing ranging from 0.24" (6.1 mm) to 0.05" (1.3 mm) was executed. The effects on signal transmission were only fractionally changed. Since it is preferential to use surface mount connectors, the channel spacing was set at 0.120" (3 mm) instead of a much tighter spacing. This makes it easy to hand solder connectors. At this spacing an 8 channel circuit would be 1.1" (2.8 cm) wide.

M. Neric, H. Mani, T. Mozdzen, and C. Groppi are with the School of Earth and Space Exploration, Arizona State University, Tempe, AZ, 85287 USA e-mail: mneric@asu.edu.

The GUSTO mission requires that the flex circuit S_{21} be above -6 dB at 5 GHz over a 20 inch flex circuit. This must be achieved at cryogenic temperatures. The IF bandwidth of the circuit must be 0.3 - 5.0 GHz. The adjacent channels need to have 30 dB of isolation or better. CST simulations of a three channel circuit were done over a 5 GHz bandwidth. Figure 1 shows the simulation results.

Because GUSTO is a balloon mission it will have a limited supply of coolant for its cryogenic components. Reducing the heat load of the IF chain is a critical design goal. The heat load directly impacts the mission life expectancy. To reduce the heat load of the circuit the stripline ground planes that are traditionally solid copper layers are reduced into thin strips. CST simulations predict that a reduction in copper content of the top and bottom planes will have negligible impact on performance. As seen in Table I the heat load of a single channel of the striped flex ribbon can be reduced to 25 % of the heat load of industry standard coaxial cables.

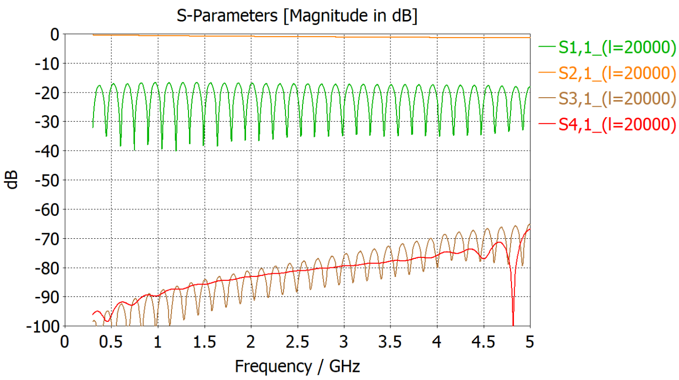

Fig. 1. CST Studio Suite Simulated transmission characteristics of a three channel flex ribbon. Input signal was from port 1 to port 2. Ports 3 and 4 were the nearest neighbors and used to simulate isolation. Design goals for insertion loss (< 6 dB), and isolation (> 30 dB) are met according to software.

UT 85 is the most commonly used coax. UT 20 is not typically used in missions since it is very fragile, but has its place when extreme space saving is necessary. Even though stainless steel has much less thermal conductivity, the striped version of the flex circuits have significantly less cross sectional conductor area. This allows them to produce a quarter of the heat per channel.

The ground strips were designed in 0.015" (0.38 mm) strips, and 0.025" (0.635 mm). These widths are chosen to protect the circuit from a misalignment between ground strips and the center conductor. A copper tab was added to the striped flex circuit for heat sinking. Fiber glass composite material FR-4 was added to strengthen the connection sites.

III. Results

Two sets of the flex circuit were fabricated by Coast to Coast Circuits Inc. Each set of three flex circuits, much like Table I, had a circuit with 15 mil ground strips, 25 mil strips, and one that was full plane copper. One set of three ribbons was a straight flex circuit with 8-channels, and the other had a 1 inch minimum radius of curvature built in to one end.

TABLE I
Thermal Calculations and Comparison of Flexible Circuit to SS-SS Coax

Circuit Type	Cross Sectional Area (m^2)	Thermal Load (WmK^{-1})	Ratio to UT 85
Flex(15 mil)	1.70×10^{-8}	6.83×10^{-6}	0.25
Flex(25 mil)	2.74×10^{-8}	1.10×10^{-5}	0.41
Flex(260 mil)	2.70×10^{-7}	1.08×10^{-4}	4.01
Coax(UT 85)	1.66×10^{-6}	2.70×10^{-5}	1.00
Coax(UT 47)	5.98×10^{-7}	9.75×10^{-6}	0.36
Coax(UT 20)	9.89×10^{-8}	1.61×10^{-6}	0.06

Thermal conductivity of stainless steal is 16.3 $WK^{-1}m^{-1}$, and for Cu: 403 $WK^{-1}m^{-1}$. Thermal analysis shows the narrowest ground stripes far surpass industry standard UT 85 coax in heat performace.

All testing was done with a Rhode & and Schwarz ZVA 24 Vector Network Analyzer (VNA) that was calibrated with a ZV-52 electronic cal-kit. The VNA was calibrated at 0 dBm test power, and averaged 16 times. Data was taken from 0.3 to 5.0 GHz at room Temperature first.

The insertion loss for a flex circuit with 15 mil ground strips is 0.3 dB higher than an equivalent length flex with full ground planes. This is a 6 % difference in power. When heat load is put into consideration such a low change in raw performance is more than acceptable. Low noise amplifiers in the GUSTO IF chain will more than make up for the difference in power regardless. Moving forward only the 15 mil ground strip flex circuits were considered.

Cryogenic testing was done in a closed cycle system capable of reaching 10 K temperatures under vacuum. The flex circuit was tested at 20 K at one end, and 300 K at the other. This operating condition will be commonplace in most cryogenic instruments. The flex circuit was bonded directly to vacuum flanges using epoxy. This is another major benefit of flex circuits over coax - the flex circuits do not need expensive and complex hermetic connectors to make vacuum tight transitions outside of a cryostat. Kapton substrate out-gassing is extremely low making it very easy to use in vacuum chambers, cryogenic systems, and space hardware.

Figure 2 is the plot of the first cryogenic test. The insertion loss of the flex circuit at 5 GHz is 5.77 dB. This is within the spec of not exceeding 6 dB. The Isolation is approximately 60 dB over the entire bandwidth. This is again better than the required spec. Another way to look at insertion loss is in terms of dB/ft in which case the flex circuit with 0.015" ground strips has 3.5 dB/ft of loss at 5 GHz. This is more than the UT 85 coaxial cable which is only 2.8 dB/ft, but again with the benefit from 75 % less heat transmission, and the fact that IF LNAs will be providing additional gain the trade off is more than worth it. Additionally the flex circuit has smaller form factor, is light-weight, and more convenient for routing makes it the more applicable choice for DC - 10 GHz transmission.

IV. Conclusion

We have developed the prototype for a next generation of microwave flexible circuit that can be used in cryogenic instruments to replace coaxial cables over a wide IF bandwidth. The new flex circuits are ideal wherever complex routing of

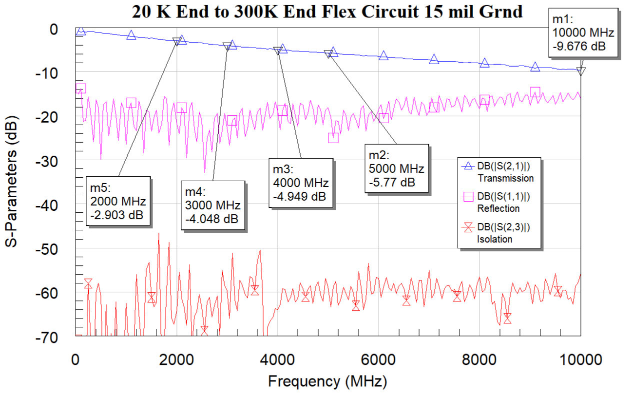

Fig. 2. S-parameters of an 8 channel flex circuit at cryogenic temperatures. The flex circuit has 3.5 dB/ft of loss at 5 GHz. The return loss is 20 dB so only 1 % of the incident power is reflected back though the port. Isolation is approximately 60 dB for nearly the entire bandwidth meaning that cross-talk between adjacent signal traces is negligible.

IF components is needed and or wherever the focal plane array has a high pixel count requiring a direct connection to their output. The improvement of heat load using a striped flex circuit is vital to increasing mission duration by reducing coolant loss.

With a 3.5 dB/ft loss at 5 GHz, stable return loss over a 5 GHz bandwidth, and outstanding isolation between channels, the prototype flex circuits meet all requirements for their role in GUSTO. The advantages of the customizable flex circuit makes it an appropriate choice for use in future missions.

ACKNOWLEDGMENT

The authors would like to thank Bob Giambrone, and Hector Ramirez of Coast to Coast circuits for their help and support during the fabrication of the flexible test circuits.

REFERENCES

[1] C. Walker, C. Kulesa, P. Goldsmith, C. Groppi, F. Helmich, D. Hollenbach, J. Kawamura, W. Langer, G. Melnick, D. Neufeld, J. Pineda, G. Stacey, A. Stark, A. Tielens, M. Wolre, H. Yorke, and E. Young, "GUSTO: Gal/Xgal U/LDB Spectroscopic-Stratospheric TeraHertz Observatory," Amer. ASTRO. Soc., AAS, 231, 2018

[2] P. McGarey, H. Mani, C. Wheeler, C. Groppi, "A 16-channel flex circuit for cryogenic microwave signal transmissions," SPIE, 9153, 2014

Marko Neric graduated from Arizona State University (ASU) in 2014 earning a B.S. in Physics. He is currently a Ph.D. candidate in the School of Earth and Space Exploration (SESE) at ASU. He is pursuing his Ph.D. in astrophysics, and an M.S. in electrical engineering. His focus is on THz astronomy, and instrument building.

Hamdi Mani has been an engineer at the ASU radio astronomy lab for the past 7 years. His main areas of research: design of wideband cryogenic low noise RF/ Microwave amplifiers and receivers, development of microwave and millimeter wave instrumentation, electronics packaging and cryogenic systems design . Prior to joining ASU, he worked at Caltech/JPL on developing SiGe cryogenic low noise amplifiers and wideband radio astronomy receivers.

Thomas J. Mozdzen received the B.S. in Physics in 1978 and the M.S. in Electrical Engineering in 1980 from the University of Illinois Urbana-Champaign, the M.S. in Physics from the University of Texas at Dallas in 1985, and the PhD in Astrophysics from Arizona State University in 2017. He has worked in the semiconductor industry for several years beginning as a reliability engineer at Mostek Corp, Dallas, Tx., and then mainly as a circuit design engineer at Siemens, Munich Germany, and at Intel, Chandler, Arizona. His PhD. Thesis focused on reducing systematic error in experiments to detect the sky-averaged redshifted 21 cm epoch of reionization signature. He holds several engineering related US patents and has authored several papers in both electrical engineering and astrophysics. He is currently employed at Arizona State University as a Postdoctoral researcher.

Christopher E. Groppi received the B.A. degree in astronomy (with honors) from Cornell University in Ithaca, NY, in 1997 and the Ph.D. degree in astronomy with a minor in electrical and computer engineering from the University of Arizona in Tucson, AZ, in 2003. In 2003, he joined the National Radio Astronomy Observatory as a Directors Post-doctoral Fellow. He then moved to the University of Arizona as an assistant staff astronomer in 2005. In 2006, he received an Astronomy and Astrophysics Postdoctoral Fellowship from the National Science Foundation. In 2009, he joined the Arizona State University School of Earth and Space Exploration in Tempe, AZ as an assistant professor. He became an associate professor in 2015. He is an experimental astrophysicist interested in the process of star and planet formation and the evolution and structure of the interstellar medium. His current research focuses on the design and construction of state of the art terahertz receiver systems optimized to detect the light emitted by molecules and atoms in molecular clouds, the birthplace of stars. He also applies terahertz technology developed for astrophysics to a wide range of other applications including Earth and planetary science remote sensing, hazardous materials detection and applied physics.