Flexible Coaxial Ribbon Cable for High-Density Superconducting Microwave Device Arrays

Jennifer Pearl Smith, Benjamin A. Mazin, Alex B. Walter, Miguel Daal, J. I. Bailey, III, Clinton Bockstiegel, Nicholas Zobrist, Noah Swimmer, Sarah Steiger, Neelay Fruitwala

Abstract—Superconducting electronics often require high-density microwave interconnects capable of transporting signals between temperature stages with minimal loss, cross talk, and heat conduction. We report the design and fabrication of superconducting 53 wt% Nb-47 wt% Ti (Nb47Ti) FLexible coAXial ribbon cables (FLAX). The ten traces each consist of a 0.076 mm NbTi inner conductor insulated with PFA (0.028 mm) and sheathed in a shared 0.025 mm thick Nb47Ti outer conductor. The cable is terminated with G3PO coaxial push-on connectors via stainless steel capillary tubing (1.6 mm, 0.13 mm thick) soldered to a coplanar wave guide transition board. The 30 cm long cable has 1 dB of loss at 8 GHz with -60 dB nearest-neighbor forward cross talk. The loss is 0.5 dB more than commercially available superconducting coax likely due to impedance mismatches caused by manufacturing imperfections in the cable. The reported cross talk is 30 dB lower than previously developed laminated NbTi-on-Kapton microstrip cables. We estimate the heat load from 1 K to 90 mK to be 20 nW per trace, approximately half the computed load from the smallest commercially available superconducting coax from CryoCoax.

Index Terms—Superconducting cables, Superconducting microwave devices, Superconducting filaments and wires, Superconducting resonators, Arrays, Microwave technology, Time domain reflectometry, Microwave power transmission.

I. INTRODUCTION

SUPERCONDUCTING devices are revolutionizing a wide range of research and technological fields including quantum computing [1]–[4], nanowire single-photon detectors [5], X-ray microcalorimeters [6], submillimeter bolometers [7], and Microwave Kinetic Inductance Detectors (MKIDs) [8]–[11]. These applications require increasingly large superconducting arrays, which present the common technical challenge of transporting microwave signals from the cold device stage to room temperature without losing or corrupting the signal or conducting excess heat to the cold stage. Low thermal conductivity is especially important for detector arrays in the field or in space using adiabatic demagnetization refrigerators (ADRs) which have less cooling power than dilution refrigerators but offer smaller form factors and simpler operation.

Commerially available superconducting coaxial cables are often used below 4 K; however, they are either semi-rigid and cumbersome to use in small cryogenic volumes, have large cross-sections yielding excessive heat loads, or both. Another option is flexible superconducting circuits fabricated using lithography techniques. These laminated cable technologies boast low thermal conductivity and high-density interconnects but lack the length, durability, and signal isolation needed for many applications [12]–[16].

An optimal solution should be made from superconducting material with a transition temperature well above 4 K to maximize transmission with an encompassing ground shield to minimize cross talk and pickup. It must have a small cross-section and be made from a low thermal conductivity material. Lastly, it should be flexible, durable, and ideally cheap and easy to manufacture. Such a structure is difficult to realize because few materials have the desired properties and often are difficult to work with and interface with connectors.

In this paper we present a superconducting FLexible coAXial ribbon cable (FLAX) which uniquely satisfies the aforementioned criteria. We developed this solution to carry broadband signals for 10 000+ pixel multiplexed Microwave Kinetic Inductance Detector (MKID) arrays for exoplanet detection operating at 90 mK [17], [18]. We expect this technology to be especially relevant for superconducting technologies requiring high detector isolation and low thermal load.
Fig. 2. Exploded view of cable-end assembly diagram with key dimensions shown in mm. Drawing is not to scale. From top/back to bottom/front: G3PO half-shell connectors are soldered to the transition board. Two ground tabs with via borders and an intervening signal trace create a 50 Ω grounded coplanar waveguide. The FLAX cable center conductors are crimped into stainless steel capillary tubing and soldered to the center traces. The FLAX ground shield is spot welded to the ground tabs. The cable cross-section shows the PFA (blue) insulated NbTi (grey) wire set in semicylindrical crimps made in the shared Nb47Ti foil ground shield. The two sides of the shield are mechanically and electrically bonded with micro spot welds less than \( \lambda/16 \approx 2 \text{ mm} \) (at 8 GHz) apart which run in-between the traces down the length of the cable.

II. FLAX DESIGN AND MANUFACTURE

The FLAX cables are fabricated using 0.076 mm [0.003"] NbTi center conductor insulated with 0.28 mm [0.011"] PFA wire obtained from Supercon\(^1\). The shared outer coaxial conductor is formed with 0.025 mm [0.001"] Nb47Ti foil purchased and rolled by ATC\(^2\) and HPX\(^3\). The wires are held in ten, 0.28 mm semicylindrical crimps made 3.56 mm apart in the foil to achieve a ∼50 Ω characteristic impedance and 3.56 mm standard trace pitch density used by G3PO connectors available from Corning Gilbert\(^4\) (compatible with SMP-S) (see Fig. [1][2]). The two sides of the ground shield are mechanically and electrically bonded by micro spot welds which run the length of the cable between each trace. The welds are approximately every 2 mm which is less than \( \lambda/16 = 2.3 \text{ mm} \) at 8 GHz (see Fig. [1][2]).

At the ends of the cable, the protruding center conductors are threaded into ∅1.6 mm, 0.13 mm thick stainless steel capillary tubing. The tubing is crimped onto the center conductor before the assembly is soldered to the center traces of the transition board using a stainless steel soldering flux (see Fig. [1][2]). The transition board is a 0.25 mm thick RT/Duroid6010LM PCB with 50 Ω grounded coplanar waveguide (GCPW) geometry for increased signal isolation. Between each trace, the Nb47Ti outer conductor foil is micro spot welded to the ground tabs of the transition board while surface mount coaxial G3PO push-on connectors are soldered to the other end of the GCPW (Fig. [4]). The cable end assembly is clamped in a 3 × 7 cm gold-plated copper box which provides strain relief and allows for easy push-on connection of all ten traces with G3PO blind-mate bullet connectors (Fig. [1][2]).

III. PERFORMANCE CHARACTERIZATION

Transmission loss (\( S_{21} \)), cross talk (\( S_{41} \)), and time domain reflectometry measurements were performed in a dilution refrigerator under vacuum at 4 K with a Keysight N9917A network analyzer. The device under test circuit consisted of the assembled FLAX cable with a 3 dB cryo-attenuator obtained from XMA\(^5\) and a 25 cm nonmagnetic SMA-to-G3PO adapter coaxial cable obtained from Koaxis\(^6\) on either end (see Fig. [3]). A Crystek\(^7\) braided, semi-rigid coax through line was used as a calibration reference. Repeated handling through the testing process revealed the cables have a minimum inside bend radius close to 2 mm and are robust to cryogenic cycling.

A. Transmission

Ripples in the FLAX transmission suggest standing wave modes are present on the traces which is indicative of an impedance mismatch between the FLAX cable and the 50 Ω circuit (see Fig. [4]). The transmission ripples are not uniformly harmonic which suggests the impedance is changing with length along each trace. This could be explained by flaws in micro spot welding placements along the cable which determine the distance between the inner and outer coaxial conductors and therefore the characteristic impedance. The characteristic impedance of the traces were probed using a time domain reflectometry measurement adjusted for loss (see [19] for details on loss correction) which confirmed the impedance varies from 55–65±3 Ω along the traces (see Fig. [5]). This mismatch at various points in the cable launches reflected waves which contribute to the observed ripple.

We hypothesize an additional factor contributing to the impedance mismatch originates in the intermediate regions of the cable.

\(^{1}\)Supercon Inc., 830 Boston Turnpike, Shrewsbury, MA.
\(^{2}\)ATI Specialty Alloys & Components, 1600 Old Salem Rd., Albany, OR.
\(^{3}\)Hamilton Precision Metals, 1780 Rohrerstown Rd., Lancaster, PA.
\(^{4}\)Corning Optical Communications, 4200 Comming Place, Charlotte, NC.
\(^{5}\)XMA Corporation-Omni Spectra, 7 Perimeter Road, Manchester, NH. P/N: 2082-6040-03-CRYO
\(^{6}\)Koaxis RF Cable Assemblies, 2081 Lucon Road, Schwenksville, PA. P/N: A010-CC047C-Y018
\(^{7}\)Obtained through Digikey. P/N: CCSMA18-MM-141-12
the cable ends where the center conductor exits the foil sheath and transitions onto the GCPW transition board (see Fig. 1 a.). After exiting the ground shield, the exposed wire can act as an inductor. Previous work done by our group shows inductance on the input and output of a transmission line causes ripples which increase in magnitude at higher frequencies [15]. This is because the impedance of a perfect inductor grows linearly with frequency, i.e., $Z_L = j\omega L$. With each successive cable iteration, manufacturing techniques improved, the length of exposed wire was shortened, and the frequency-dependent ripple amplitude diminished. The use of a capillary tube to pin the hair-like center conductor close to the transition board dramatically reduced the cable end inductance.

Using the peak of the ripple, we report the loss of the 30 cm cable at 8 GHz to be roughly 1 dB which is slightly higher than the 0.5 dB/m loss reported by commercially available superconducting coaxial cables [20], [21]. This difference cannot be explained by a difference in cable materials or geometry [22]. Likely, the source of our additional loss is the impedance mismatch caused by manufacturing imperfections which produce reflections in the cable and off the ends as described above.

### B. Cross Talk

We found the average nearest-neighbor forward cross talk to be -60 dB (see Fig. 4). This is roughly 30 dB lower than what we previously achieved using flexible laminated NbTi-on-Kapton microstrip cables [15]. Since the cable’s installation in the MKID Exoplanet Camera (MEC) at Subaru Observatory, this enhanced isolation has increased our pixel yield ~20% [17]. We suspect this large improvement is because the exposed microstrip geometry allows trace-to-trace coupling whereas the coaxial nature of the FLAX shields the center conductors thereby preventing signal corruption.
early iterations of the cable, we found infrequent or failed micro spot welds in the ground shield lead to much higher levels of cross talk. This leads us to conclude incorporating micro spot welds less than $\lambda/16$ apart between the traces reduces electromagnetic coupling.

### C. Thermal Conductivity

Following previous convention, a cable thermal conductivity $G(T)$, was computed by summing literature values of constituent materials weighted by their cross-sections (see Fig. 6) and dividing by the cable length. The ten-trace FLAX cables are currently installed in the MEC experiment for our application of moving 4-8GHz servicing 10 000+ multiplexed sensors across temperature stages. The FLAX cable represents a 30 dB improvement in cross talk as compared to our group’s previously developed NbTi-on-Kapton microstrip cables. This enhanced isolation facilitated a ~20% increase in MKID pixel yield in the MEC experiment [17]. We expect these results will be especially useful for high-density microwave superconducting detector arrays requiring strong signal isolation.

The cable technology presented in this paper also has very low thermal conductivity. For a given thermal budget, the FLAX cables allow for twice as many detectors as the leading commercial option. The reduced heat load combined with the

### IV. Conclusion

We have manufactured a superconducting flexible coaxial cable capable of delivering microwave signals between temperature stages with minimal loss, cross talk, and heat conduction. Strong signal isolation is especially important for our application of moving 4-8GHz servicing 10 000+ multiplexed sensors across temperature stages. The FLAX cable represents a 30 dB improvement in cross talk as compared to our group’s previously developed NbTi-on-Kapton microstrip cables. This enhanced isolation facilitated a ~20% increase in MKID pixel yield in the MEC experiment [17]. We expect these results will be especially useful for high-density microwave superconducting detector arrays requiring strong signal isolation.

The cable technology presented in this paper also has very low thermal conductivity. For a given thermal budget, the FLAX cables allow for twice as many detectors as the leading commercial option. The reduced heat load combined with the
push-on, small form factor connectors and reduced trace pitch allow for increased detector density in a cryogenic system. We found an attenuation of 1 dB at 8 GHz with ~3 dB ripples which is at worst 2x more loss than commercial options. This magnitude of ripples and loss do not impact our array on the input side as we can drive microwave resonators (MKIDs) located at transmission dips with higher power than their frequency neighbors. However, these features degrade the overall signal to noise ratio on the output. Ripples and loss may become prohibitive for systems operating at frequencies over 8 GHz or systems constrained by amplifier dynamic range. Insertion loss and ripples can be reduced by improving manufacturing precision in the forming of the NbTi foil crimps and location of micro spot welds. Alternative methods to join the push on connectors and traces, e.g., brush plating the NbTi center conductor with an easily solderable material such as nickel may also improve the impedance match.

Lastly, we note these cables are relatively easy to fabricate. Many components, most notably the fine, NbTi center conductor wire, are commercially available. All cable iterations were manufactured in-house at the University of California, Santa Barbara. Ten trace FLAX can be assembled in two days. Overall, we find this cable technology to be superior to the push on connectors and traces, e.g., brush plating the NbTi center conductor with an easily solderable material such as nickel may also improve the impedance match.

ACKNOWLEDGMENT

J. P. Smith is supported by a NASA Space Technology Research Fellowship under grant number 80NSSC19K1126.

REFERENCES

[1] R. Barends, J. Kelly, A. Megrant, A. Veitia, D. Sank, E. Jeffrey, T. C. White, J. Mutus, A. G. Fowler, B. Campbell, Y. Chen, Z. Chen, B. Chiaro, A. Dunswo, C. Neill, P. O’Malley, P. Roushan, A. Vainsencher, J. Wenner, A. N. Korotkov, A. N. Cleland, and J. M. Martinis, “Superconducting quantum circuits at the surface code threshold for fault tolerance,” Nature, vol. 508, no. 7497, pp. 441–445, 2014.

[10] S. R. Meeker, B. A. Mazin, R. Jensen-Clem, A. B. Walter, P. Szpyrty, M. J. Strader, and C. Bockstiegel, “Design and development status of MKID integral field spectrographs for high contrast imaging,” Adaptive Optics for Extremely Large Telescopes 4 - Conference Proceedings, 2015.

[12] C. G. Pappas, J. Austermann, J. A. Beall, S. M. Duff, P. A. Gallardo, E. Grace, S. W. Henderson, S. P. Ho, B. A. Koopman, D. Li, J. McMahon, F. Nati, M. D. Niemann, P. Niraula, M. Salatino, A. Schillauci, B. L. Schmitt, S. M. Simon, S. T. Stagg’s, J. R. Stevens, E. M. Vavagiakis, J. T. Ward, and E. J. Wollack, “High-Density Superconducting Cables for Advanced ACTPol,” Journal of Low Temperature Physics, vol. 184, no. 1-2, pp. 473–479, 2018.

[15] A. B. Walter, C. Bockstiegel, B. A. Mazin, and M. Daal, “Laminated NbTi-on-kapton microstrip cables for flexible sub-kelvin RF electronics,” IEEE Transactions on Applied Superconductivity, vol. 28, no. 1, 2018.

[16] V. Gupta, B. Yelamanchili, S. Zou, T. Isaacs-Smith, J. A. Sellers, D. B. Tuckerman, and M. C. Hamilton, “Thin-film Nb/Polyimide superconducting stripline flexible cables,” IEEE Transactions on Applied Superconductivity, vol. 29, no. 5, 2019.

[17] A. B. Walter, B. A. Mazin, N. Fruitwala, S. Steiger, J. Bailey, N. Zobrist, J. B. Koopman, D. Li, J. McMahon, F. Nati, M. D. Niemann, P. Niraula, M. Salatino, A. Schillauci, B. L. Schmitt, S. M. Simon, S. T. Stagg’s, J. R. Stevens, E. M. Vavagiakis, J. T. Ward, and E. J. Wollack, “High-Density Superconducting Cables for Advanced ACTPol,” Journal of Low Temperature Physics, vol. 184, no. 1-2, pp. 473–479, 2018.

[18] C. G. Pappas, J. Austermann, J. A. Beall, S. M. Duff, P. A. Gallardo, E. Grace, S. W. Henderson, S. P. Ho, B. A. Koopman, D. Li, J. McMahon, F. Nati, M. D. Niemann, P. Niraula, M. Salatino, A. Schillauci, B. L. Schmitt, S. M. Simon, S. T. Stagg’s, J. R. Stevens, E. M. Vavagiakis, J. T. Ward, and E. J. Wollack, “High-Density Superconducting Cables for Advanced ACTPol,” Journal of Low Temperature Physics, vol. 184, no. 1-2, pp. 473–479, 2018.

[19] C. G. Pappas, J. Austermann, J. A. Beall, S. M. Duff, P. A. Gallardo, E. Grace, S. W. Henderson, S. P. Ho, B. A. Koopman, D. Li, J. McMahon, F. Nati, M. D. Niemann, P. Niraula, M. Salatino, A. Schillauci, B. L. Schmitt, S. M. Simon, S. T. Stagg’s, J. R. Stevens, E. M. Vavagiakis, J. T. Ward, and E. J. Wollack, “High-Density Superconducting Cables for Advanced ACTPol,” Journal of Low Temperature Physics, vol. 184, no. 1-2, pp. 473–479, 2018.

[20] C. G. Pappas, J. Austermann, J. A. Beall, S. M. Duff, P. A. Gallardo, E. Grace, S. W. Henderson, S. P. Ho, B. A. Koopman, D. Li, J. McMahon, F. Nati, M. D. Niemann, P. Niraula, M. Salatino, A. Schillauci, B. L. Schmitt, S. M. Simon, S. T. Stagg’s, J. R. Stevens, E. M. Vavagiakis, J. T. Ward, and E. J. Wollack, “High-Density Superconducting Cables for Advanced ACTPol,” Journal of Low Temperature Physics, vol. 184, no. 1-2, pp. 473–479, 2018.

[21] C. G. Pappas, J. Austermann, J. A. Beall, S. M. Duff, P. A. Gallardo, E. Grace, S. W. Henderson, S. P. Ho, B. A. Koopman, D. Li, J. McMahon, F. Nati, M. D. Niemann, P. Niraula, M. Salatino, A. Schillauci, B. L. Schmitt, S. M. Simon, S. T. Stagg’s, J. R. Stevens, E. M. Vavagiakis, J. T. Ward, and E. J. Wollack, “High-Density Superconducting Cables for Advanced ACTPol,” Journal of Low Temperature Physics, vol. 184, no. 1-2, pp. 473–479, 2018.

[22] C. G. Pappas, J. Austermann, J. A. Beall, S. M. Duff, P. A. Gallardo, E. Grace, S. W. Henderson, S. P. Ho, B. A. Koopman, D. Li, J. McMahon, F. Nati, M. D. Niemann, P. Niraula, M. Salatino, A. Schillauci, B. L. Schmitt, S. M. Simon, S. T. Stagg’s, J. R. Stevens, E. M. Vavagiakis, J. T. Ward, and E. J. Wollack, “High-Density Superconducting Cables for Advanced ACTPol,” Journal of Low Temperature Physics, vol. 184, no. 1-2, pp. 473–479, 2018.

[23] C. G. Pappas, J. Austermann, J. A. Beall, S. M. Duff, P. A. Gallardo, E. Grace, S. W. Henderson, S. P. Ho, B. A. Koopman, D. Li, J. McMahon, F. Nati, M. D. Niemann, P. Niraula, M. Salatino, A. Schillauci, B. L. Schmitt, S. M. Simon, S. T. Stagg’s, J. R. Stevens, E. M. Vavagiakis, J. T. Ward, and E. J. Wollack, “High-Density Superconducting Cables for Advanced ACTPol,” Journal of Low Temperature Physics, vol. 184, no. 1-2, pp. 473–479, 2018.
[18] A. B. Walter, “MEC: The MKID Exoplanet Camera for High Speed Focal Plane Control at the Subaru Telescope,” Ph.D. dissertation, University of California, Santa Barbara, 2019.

[19] F. Gisin, “Characterizing Lossy PCB Interconnects Using a TDR Instrument,” Multek, New Territories, Hong Kong, Tech. Rep. March, 2017. [Online]. Available: https://www.multek.com/sites/default/files/2017-09/TDRMeasurementsofPCBInterconnectArtifacts.pdf

[20] CryoCoax, “Cryogenic Cable and Cable Assemblies — CryoCoax.” [Online]. Available: https://cryocoax.com/cryogenic-cable-and-cable-assemblies/

[21] KEYCOM, “Superconducting coaxial cable assemblies(0.085” type NbTi-NbTi superconducting coaxial cables).” [Online]. Available: https://www.keycom.co.jp/products/up/Superconducting coaxial cable assemblies/2/page.htm

[22] Emerson, “PTFE and PFA similarities and differences,” Emerson Automation Solutions, Shakopee, Tech. Rep., 2017. [Online]. Available: https://www.emerson.com/documents/automation/white-paper-ptfe-pfa-similarities-differences-rosemount-en-585104.pdf

[23] A. Kushino, M. Ohkubo, and K. Fujioka, “Thermal conduction measurement of miniature coaxial cables between 0.3 and 4.5 K for the wiring of superconducting detectors,” Cryogenics, vol. 45, no. 9, pp. 637–640, 2005.

[24] M. Daal, N. Zobrist, N. Kellaris, B. Sadoulet, and M. Robertson, “Properties of selected structural and flat flexible cabling materials for low temperature applications,” Cryogenics, vol. 98, pp. 47–59, 3 2019.

[25] J. R. Olson, “Thermal conductivity of some common cryostat materials between 0.05 and 2 K,” Cryogenics, vol. 33, no. 7, pp. 729–731, 1993.

[26] N. Kellaris, M. Daal, M. Epland, M. Pepin, O. Kamaev, P. Cushman, E. Kramer, B. Sadoulet, N. Mirabolfathi, S. Golwala, and M. Runyan, “Sub-kelvin thermal conductivity and radioactivity of some useful materials in low background cryogenic experiments,” in Journal of Low Temperature Physics, vol. 176, no. 3-4. Springer New York LLC, 1 2014, pp. 201–208.