Low-Loss THz Sommerfeld Mode on a Superconducting Niobium Wire for Millimeter-Wave Interconnects

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***Abstract*— Ongoing progress in the development of superconducting microwave circuits has highlighted the additional vital challenge of transmitting quantum information robustly. As a practical solution to this problem, we propose to propagate a low loss (~ -0.004 dB/m) TM Sommerfeld mode on the surface of a superconducting niobium wire held between transmitters and receivers or between different quantum systems. Here we present simulations performed in ANSYS-HFSS pertaining to this mode along with the theoretical results obtained for a niobium wire at THz frequencies and temperatures of a few Kelvin.**

I. INTRODUCTION

Microwave circuits have played an important role in the pursuit of developing practical quantum computers. However, progress in superconducting microwave circuit development must also be accompanied by new technology to address the challenges of scalability and transmission of quantum information over long distances. Given the widespread use of optical fibers due to their incredibly low losses, it seems practical to first convert microwave signals to optical wavelengths prior to transmission. But this method is highly restricted by the heat load generated at dilution fridge base temperatures. Another approach proposed by Pechal et. al. [3] is to instead convert these microwave signals to mm-waves in order to reduce the heat load and transmit the information via superconducting mm-wave interconnects. In this article, we propose to propagate a low loss Sommerfeld mode on the surface of a superconducting niobium wire. We investigate utilizing niobium, because, in addition to its excellent electrical conductivity, it has low thermal conductivity in the superconducting state. This will ensure there is very low thermal leakage to the circuit kept at 100 mK.

The microwave to mm-wave converters are outlined by Stokowski et. al. [2] and will utilize two 50 GHz pump photons and the 5 GHz signal photon from a microwave circuit incident on a nonlinear circuit maintained at 100 mK. The circuit, through a four-wave mixing process, will then combine the three photons to produce a 105 GHz photon. This mm-wave signal, now able to propagate at 4 K, will instead travel through a transmitter – mm-wave interconnect – receiver system. We aim to integrate the interconnect with these converters for applications in quantum sensing and quantum computing.

We expect this interconnect to have incredibly low loss due in part to the Sommerfeld mode [1] and in part to the fact that superconducting niobium wires have a largely reactive impedance because of the high kinetic inductance. Since this setup will be in a cryogenic system, we are also developing vacuum windows to allow input and output of 50 GHz and 105 GHz signals.

II. PROPOSED SETUP

This article presents the theoretical and simulated performance of these mm-wave interconnects in addition to the mode converters which will be required to transition from standard coaxial waveguides to the Sommerfeld mode. The proposed setup consists of a niobium wire held between two coaxial cables and two horn mode converters, as shown in Fig. 1. The mm-wave signal will be fed from a transmitter to a standard W-band coaxial cable with 1 mm SMA connectors. The cable is held within a copper horn mode converter, the shape of which was optimized to do a TEM↔TM_0 Sommerfeld mode conversion efficiently at 105 GHz. The cable transmits a TEM signal and then transitions into a niobium wire, 0.09 mm in radius. The insulator encasing the inner conductor of the coax extends into the horn mode converter and is tapered to ensure a smoother transmission of the signal without any abrupt discontinuities. The inner copper conductor stripped off the insulator will be laser welded to the wire. The signal then propagates as a guided TM_0 Sommerfeld mode [1] on the surface of the wire as it acts like a transmission line with its own surface impedance. The TM_0 signal is then converted to a TEM mode by the horn, picked up by the other coaxial cable, and finally picked up by the receiver.

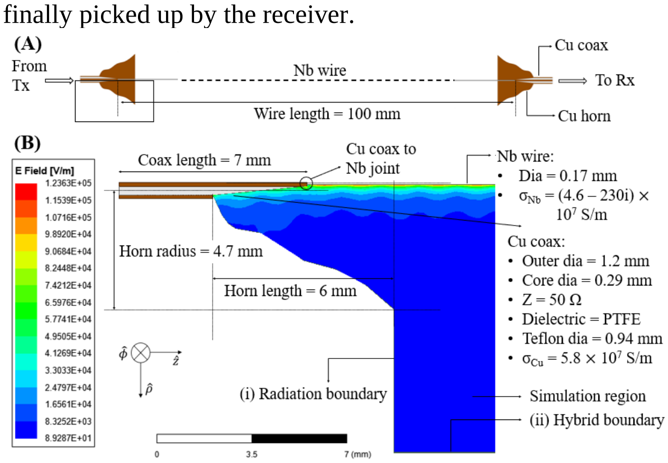

Fig. 1. (A) Design of the mm-wave interconnect consisting of copper horn mode converters, copper coaxial cables, and a 100 mm long niobium wire. **(B)** Description of each component in the inset in (A) with field profile from ANSYS-HFSS.

III. RESULTS

To investigate the Sommerfeld mode, we simulated it in ANSYS-HFSS and compared it to theory [1] with a complex conductivity calculated from the two-fluid model of superconductivity [4] at 4.2 K and 105 GHz. Eigenmode simulations were performed with a wire of radius 0.09 mm in a Perfect H symmetrized region, with a phase advance set by

Lattice Pair boundaries and a PML boundary set at a large radial distance to get a field profile for the TM mode, i.e., (E_ρ, H_ϕ, E_z). Fig. 2 shows an excellent agreement between theory and simulations for E_ρ and H_ϕ. A power flow calculation revealed that the power decays to its 1/e value within 5 mm from the surface of the wire, verifying that our simulation range fully covers our region of interest.

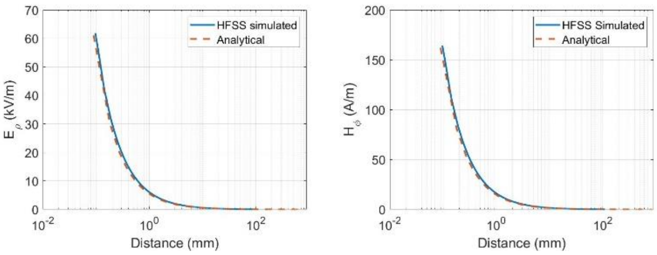

Fig. 2 Semilog plots of E_ρ and H_ϕ of the TM_0 Sommerfeld surface mode with radial distance at 105 GHz.

To analyze the losses after confirming the TM mode, we varied both the real and imaginary parts of the bulk conductivity while comparing it to the analytical theory. As can be seen in Fig. 3, we used two real values and swept the imaginary part. Our focus was aimed at understanding the agreement with and without a large contribution from the imaginary component.

For a wire operating at 4.2 K and 105 GHz, we anticipate a conductivity of $\sigma = (4.6 - 230i) \times 10^7$ S/m or a corresponding surface impedance $Z_s = (1.9 + 189i) \times 10^{-4}$ Ω/sq. The figure shows excellent agreement between theory and simulations. Further, we can expect a loss of approximately -0.0047 dB/m, indicating that the surface of a superconducting niobium wire can act as a low loss single conductor waveguide.

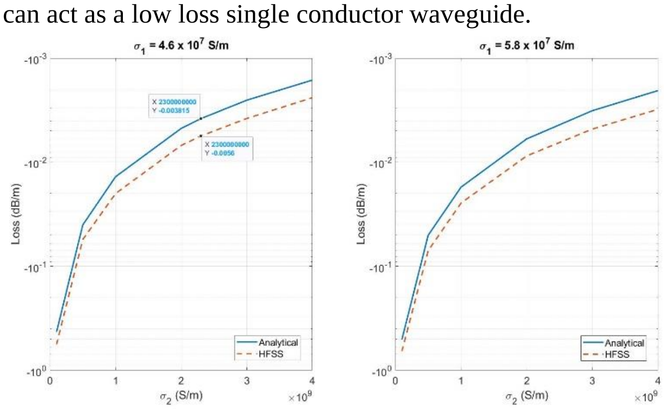

Fig. 3 Log-log plots of Losses vs imaginary parts for two different real parts of bulk conductivities. As indicated in the left figure, we expect an analytical loss of -0.0038 dB/m and a simulated loss of -0.0056 dB/m for $\sigma = (4.6 - 230i) \times 10^7$ S/m.

We then simulated our desired structure with the wire attached to coaxial cables and horn mode converters. As can be understood from Fig. 1(A), we have an azimuthally symmetric structure. This allowed us to work with a Perfect H symmetrized 5˚ wedge (Fig. 1(B)) with Radiation and Hybrid boundaries set on faces (i) and (ii), respectively. Then Driven Modal simulations were performed with ends of the coaxial cables acting as wave-ports with signals entering from the transmitter and exiting to the receiver. To optimize transmission, we experimented with the length of the coaxial cables, the taper of their insulators, and the shape of the horns. The coaxial cables need to be approximately 7 mm in length with the outer shells stripped off from the part inside the horns. In addition, the insulators inside the horns need to be tapered from the part where they enter the horn to their end. The horns were designed to work well with ~100 GHz. For our specific case of 105 GHz, six points on the horn fit with a spline were varied horizontally and vertically. The chosen wire length of 100 mm was big enough to not see any diffraction effects due to the horns and small enough to not make our computations time consuming. With these measures, we were able to reach a S_{21} of -1.46 dB with a S_{11} of -13.6 dB. Our current value of S_{21}, in comparison to our loss of -0.0047 dB/m, can mostly be attributed to mode conversion losses between the coaxial cables and the wire surfaces due to the horn converters.

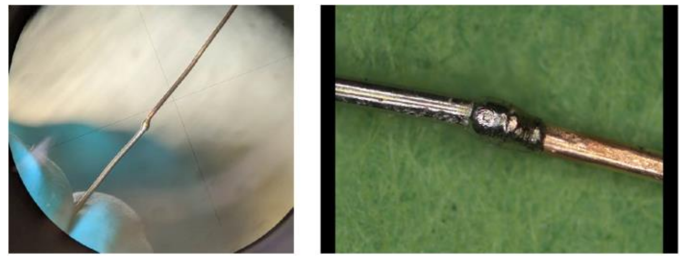

Fig. 4 Laser welding tests for wire bonding copper to niobium.

To produce the copper coax to niobium wire joint, as a first attempt, we laser welded a bare copper wire with a niobium wire, both 0.1mm in diameter (Fig. 4). But, as can be seen, a bulge is formed by the melting and solidification of the metals which could hinder the transmission. While concerning, our simulations indicate that the effect will be negligible if the bulge is within ~1 mm in diameter.

IV. Conclusion

In summary, we have designed a mm-wave interconnect based on the propagation of a 105 GHz low loss TM_0 mode on the surface of a superconducting niobium wire held at 4.2 K. Our simulations indicate excellent agreement with theory. The wire will be held between copper horns and tapered copper coaxial cables to create the interconnect. In the future, we will be testing the setup at room and cryogenic temperatures, and finally integrate it with the 5 GHz → 105 GHz nonlinear circuit.

V. Acknowledgements

The work has been supported by the U.S. Department of Energy under contract number DE-AC02-76SF00515 and the LDRD program, SLAC National Accelerator Laboratory.

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