THz Sommerfeld Wave Propagation on Superconducting Niobium Wire for Millimeter-Wave Interconnects

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Introduction

- Scalability and transmission of quantum information remain important issues in the development of superconducting microwave circuits.
- One viable approach is its transduction from μ-waves to mm-waves.
- To transmit mm-waves, we have proposed to propagate a low-loss Sommerfeld mode on the surface of a superconducting Nb wire (at 4.2K).

Background

Conductivity of Nb from London's theory[1]:

$$\sigma = \sigma_1 - i\sigma_2 \qquad \sigma_1 = \frac{n_n e^2 \tau}{m(1+\omega^2\tau^2)},$$

$$\sigma_2 = \frac{n_s e^2}{m\omega} + \frac{n_n e^2 \omega^2 \tau^2}{m\omega(1+\omega^2\tau^2)}$$

σ_1 = 4.6 x 10^7 S/m and σ_2 = 2.3 x 10^9 S/m at T = 4.2K and f = 105GHz

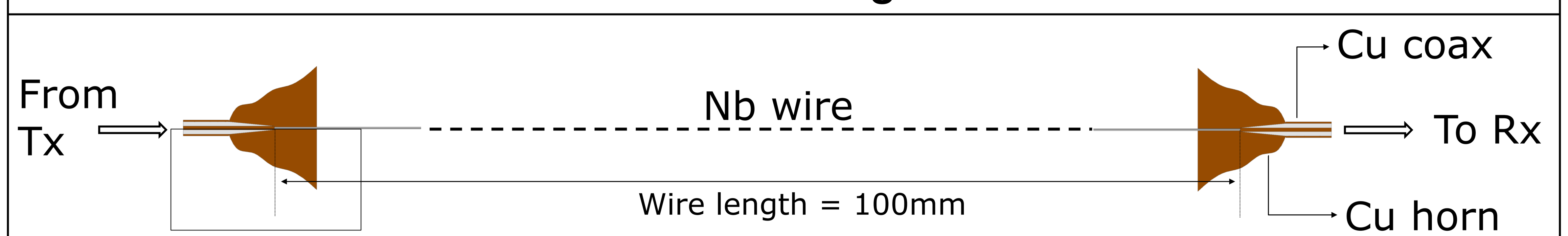
Sommerfeld surface TM mode[2]:
For a wave propagating along z

$$E_\rho = iA\frac{k_z}{\gamma}H_1^{(1)}(\gamma\rho), \quad H_\phi = iA\frac{k^2}{\omega\mu\gamma}H_1^{(1)}(\gamma\rho)$$

$$E_z = AH_0^{(1)}(\gamma\rho)$$

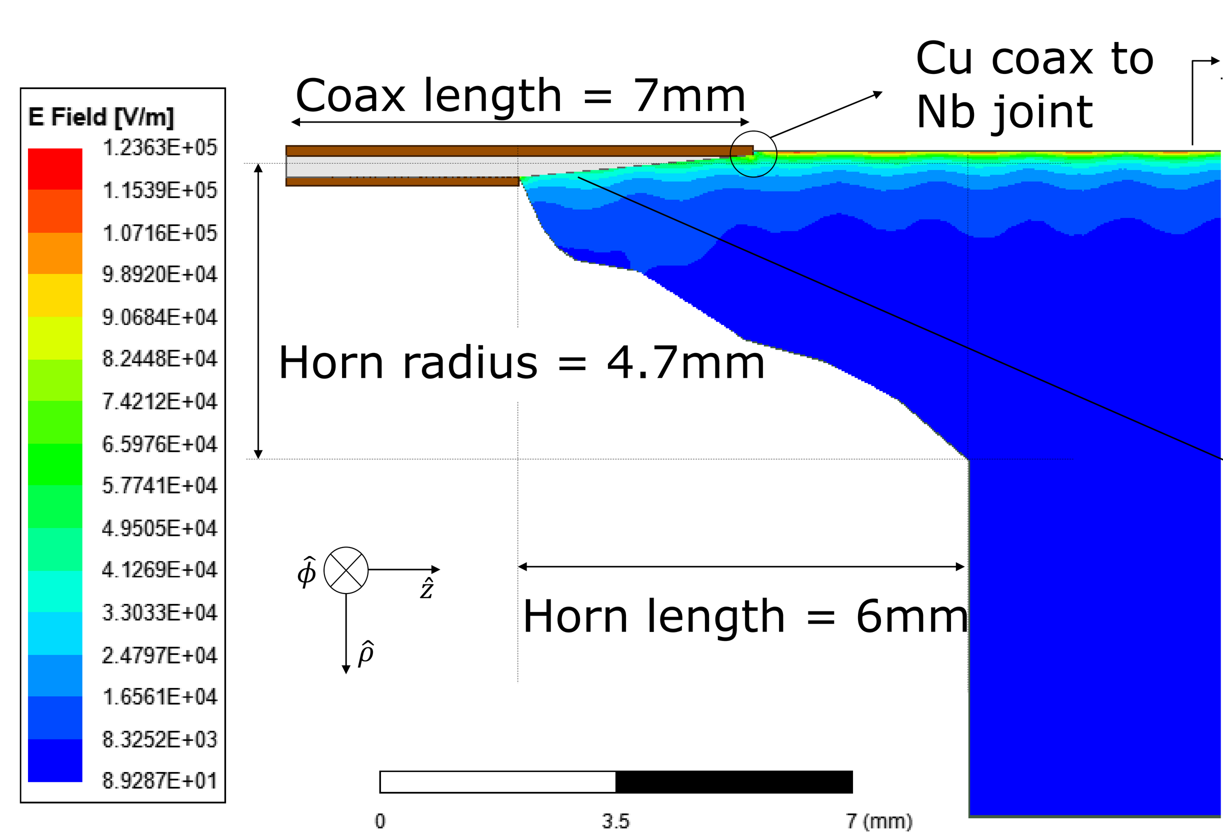
Here $H_0^{(1)}(x)$ and $H_1^{(1)}(x)$ are the Hankel functions

Basic Design



Top: Figurative description of a Nb wire held between coaxial cables and horn mode converters. The insulator is tapered and the shields of the coaxes have been stripped off inside the horns to ensure propagation of Sommerfeld mode.

Right: Design of the Cu coax + horn + Nb wire in the inset above with electric field distribution.



Nb wire:
- Dia = 0.17mm
- σ_{Nb} = (4.6 – 230i) x 10^7 S/m

Cu coax:
- Outer dia = 1.2mm
- Core dia = 0.29mm
- Z = 50Ω
- Dielectric = Teflon
- Teflon dia = 0.94mm
- σ_{Cu} = 5.8 x 10^7 S/m

Simulation Results

Electric Field plots and Loss calculations

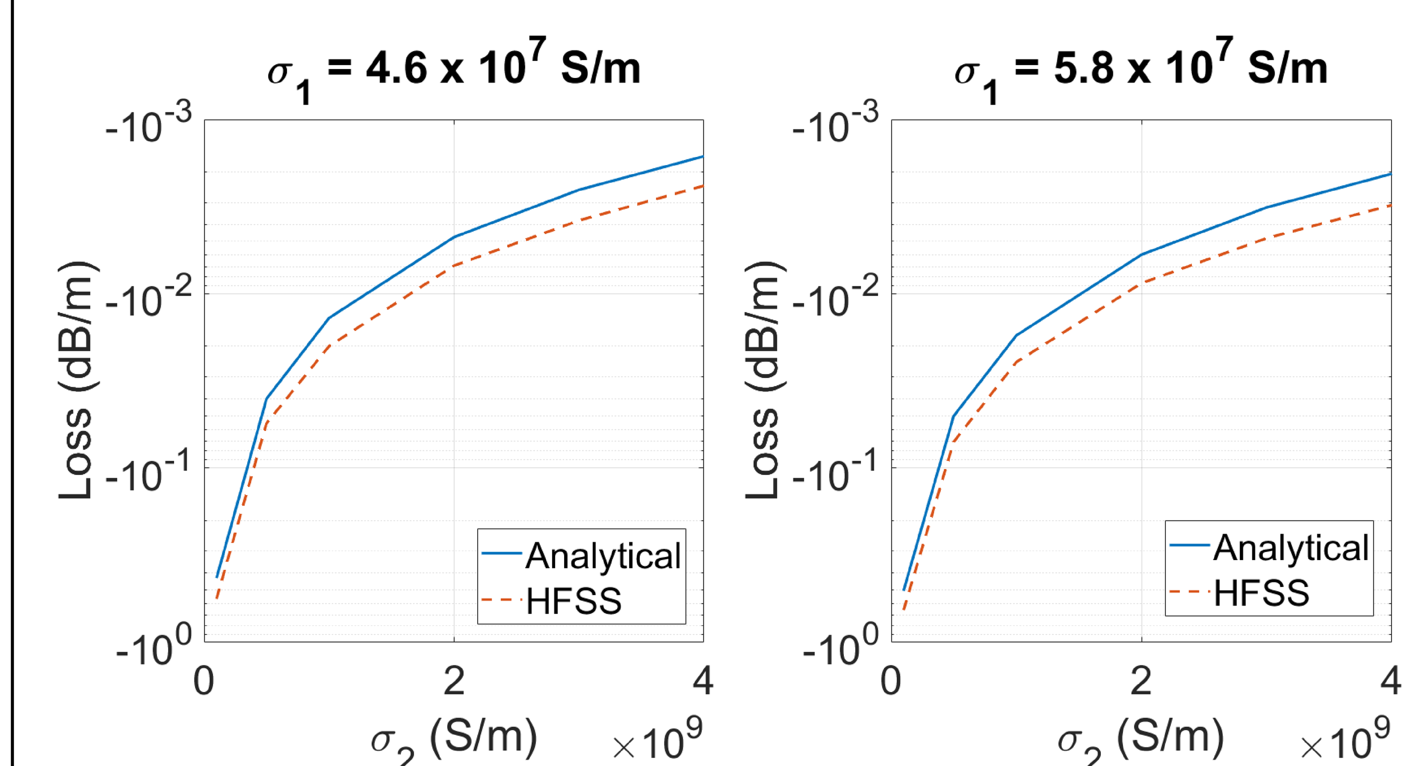


Fig. 1: A study indicating good agreement between theory and HFSS simulations for loss variation with complex bulk conductivity.

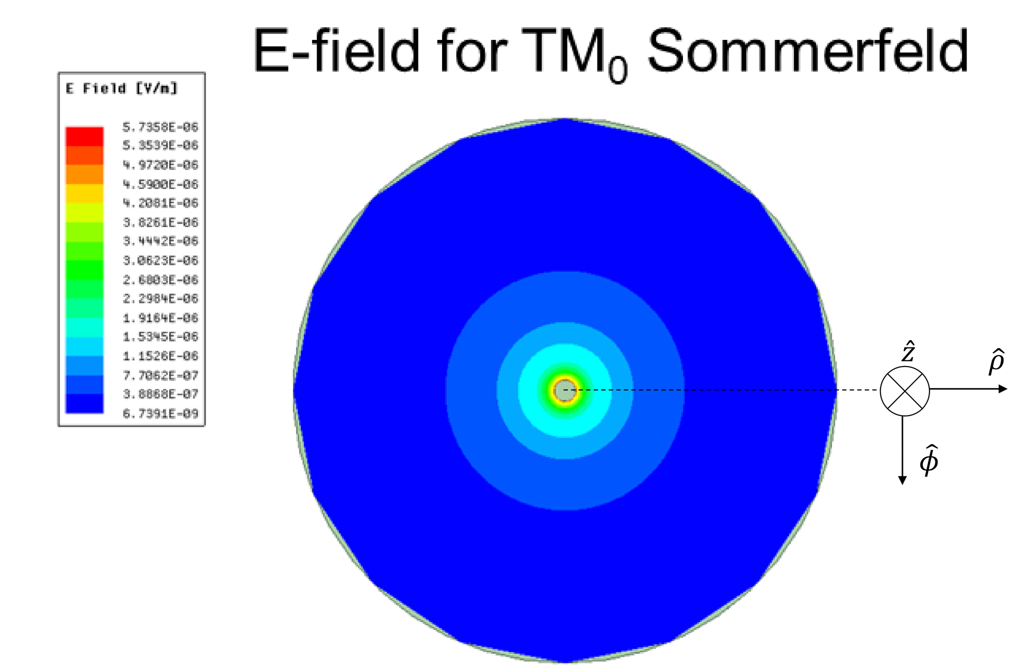
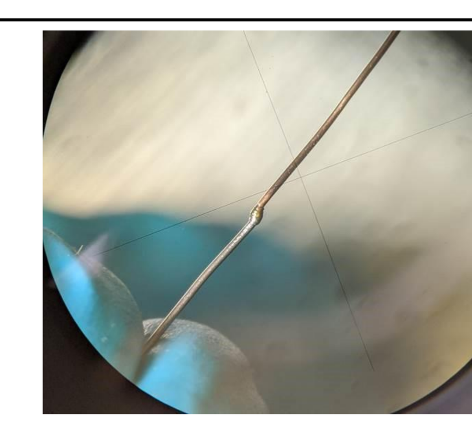


Fig. 2: Radial electric field profile for a TM_0 Sommerfeld mode

As pointed out earlier, superconductors have complex conductivities. But such materials are hard to simulate in HFSS. So we decided to simulate structures with surface impedance boundary conditions corresponding to various σ's, and thus calculated our losses (Fig. 1). For our purposes, i.e., for σ_{Nb} = (4.6 – 230i) x 10^7 S/m, Z_s = (1.9 + 189i) x 10^{-4} Ω/□, resulting in a loss ≈ -0.0047 dB/m. These low values suggest that most of the electric field dissipation should be radially outward as can be seen in Fig. 2. Thus, for the mode converter design with a 100 mm wire, we get S_{11} = -13.6 dB and S_{21} = -1.46 dB.

Preliminary Tests




An experimental challenge in the design is the transverse connection of the coaxial cable and the Nb wire. As a preliminary test, a Cu and a Nb wire have been joined by laser welding.

Conclusions

- Our calculations and simulations show that a surface mode with a theoretical loss of -0.0038dB/m can propagate along the surface of a superconducting Niobium wire
- To join 2 wires of different radii transversely, laser welding proved practicable with minor protrusions due to the melting and solidification of the metals.

Acknowledgments

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