A Superconducting Phase Shifter and On-Chip Fourier Transform Spectrometer for W-Band Astronomy

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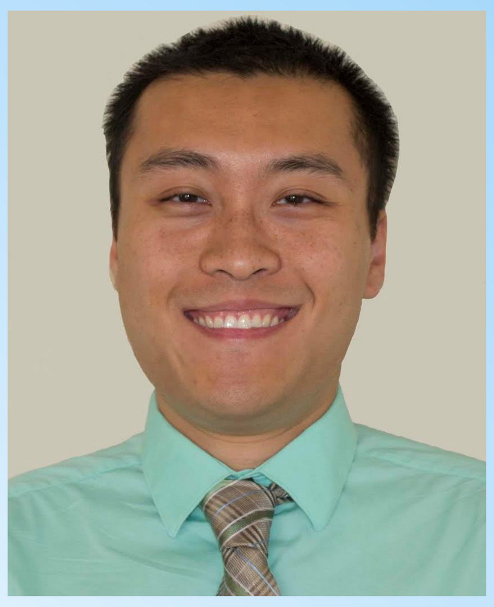

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Overview

W-Band (75-110 GHz) contains a plethora of information about star formation, galaxy evolution, and the cosmic microwave background. We designed and fabricated a dual-purpose superconducting circuit to facilitate the next generation of observations in this regime. In phase shifter mode, our device provides circuit parameters to design and optimize kinetic inductance parametric amplifiers (KIPs) that offer substantial bandwidth, dynamic range, and noise performance improvements over state-of-the-art transistor-based amplifiers. Our device can also operate as an on-chip Fourier transform spectrometer (FTS) which is much smaller than a mechanical FTS and has no moving parts. In order to characterize this circuit and other W-Band devices, we have developed a cryogenic waveguide feedthrough to deliver W-Band signals to our DUTs.

Predicted Results

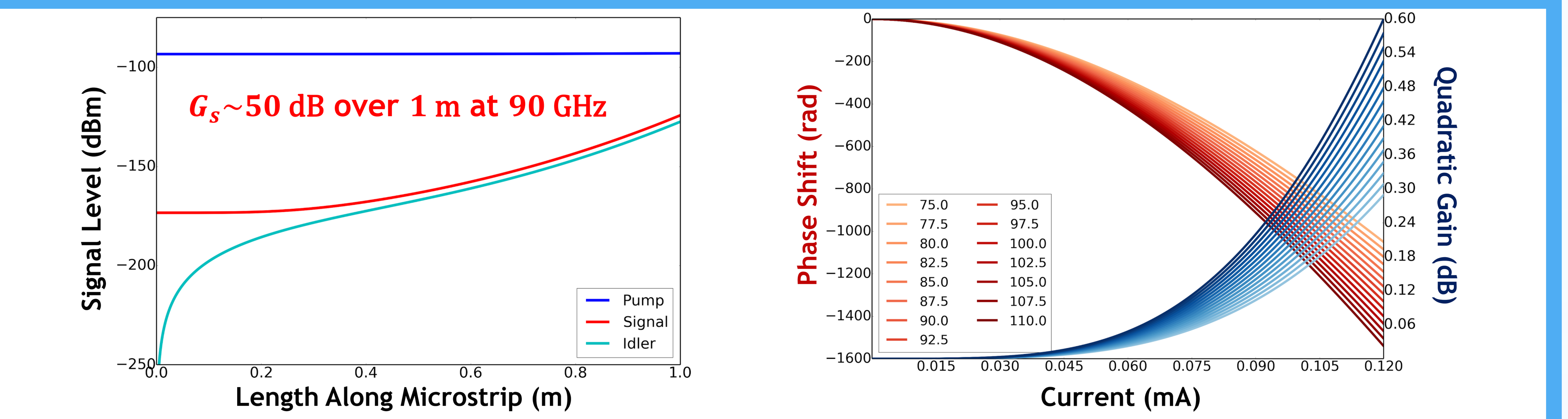

Figure 3: FWM over 1 m of $w = 3$ μm NbTiN line at 90 GHz under $I_* = 0.12$ mA DC bias (Gordon et al. 2015) (left). Predicted phase shift and quadratic gain for same parameters (right). True KIP gain is exponential function of $\Delta\phi_m(I)$, but simulation excludes dispersion features, which also explains relatively small gain.

Device Design

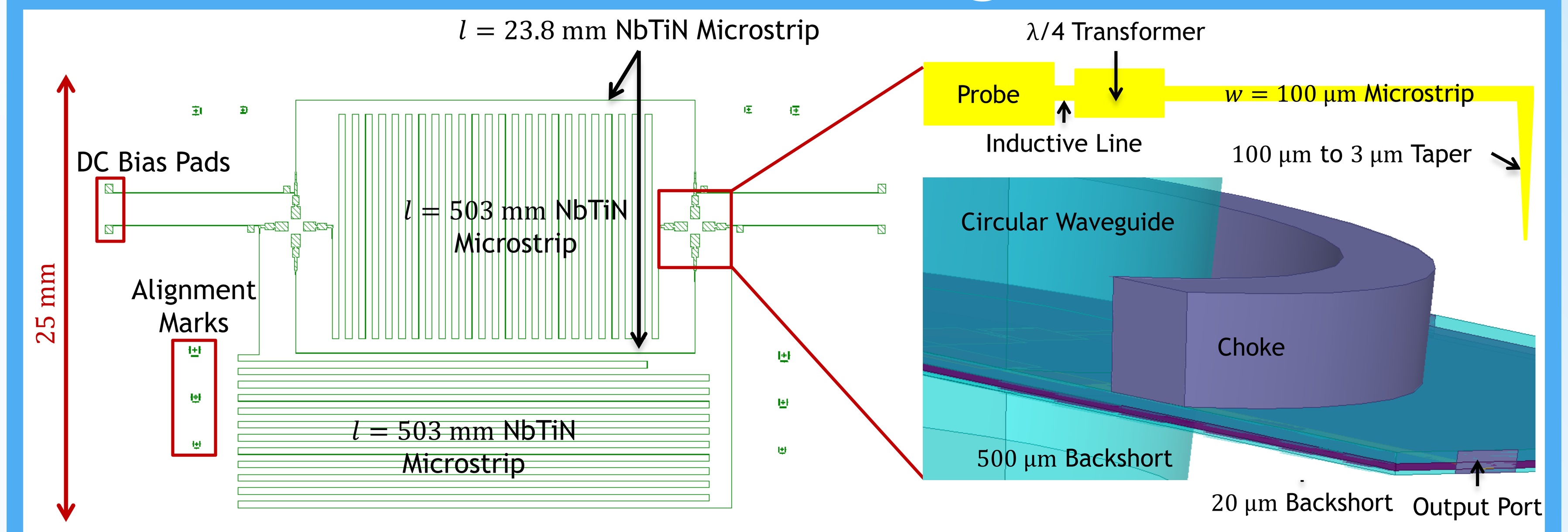

Figure 1: Phase shifter/On-Chip FTS circuit layout (left) with detailed planar (top right) and cross-sectional (bottom right) views of broadband circular waveguide-to-microstrip transition based on designs from Datta et al. 2014 and Schulz et al. 2011.

- KIPs (e.g. Eom et al. 2012 & Adamyan et al. 2016) exploit non-linear kinetic inductance to produce gain via degenerate four-wave mixing (FWM)
- Quantum noise-limited, multi-octave gain, & high dynamic range
- Maximum gain is function of superconductor's non-linear current parameter I_* & maximum non-linear phase shift $\Delta\phi_m(I)$
- Circuit designed to measure $\Delta\phi_m(I)$ for NbTiN and be on-chip FTS

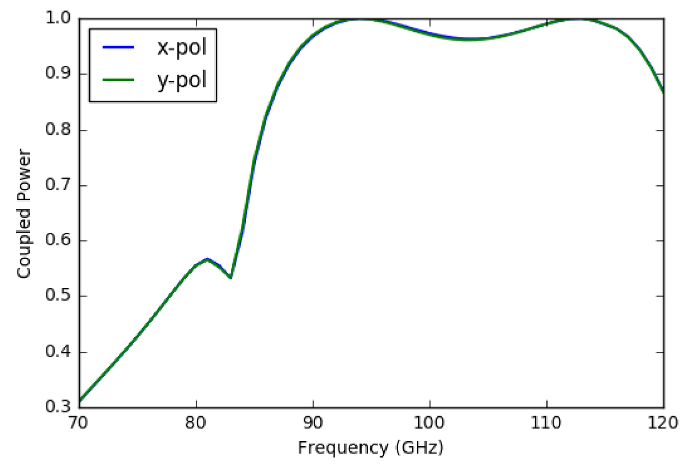

Figure 2: Power coupled to microstrip probe for optimized circuit geometry indicating broadband match between circular waveguide and NbTiN microstrip with $Z = j\omega L_k$, where $L_k = 5.7$ pH/square.

Device Fabrication & Packaging

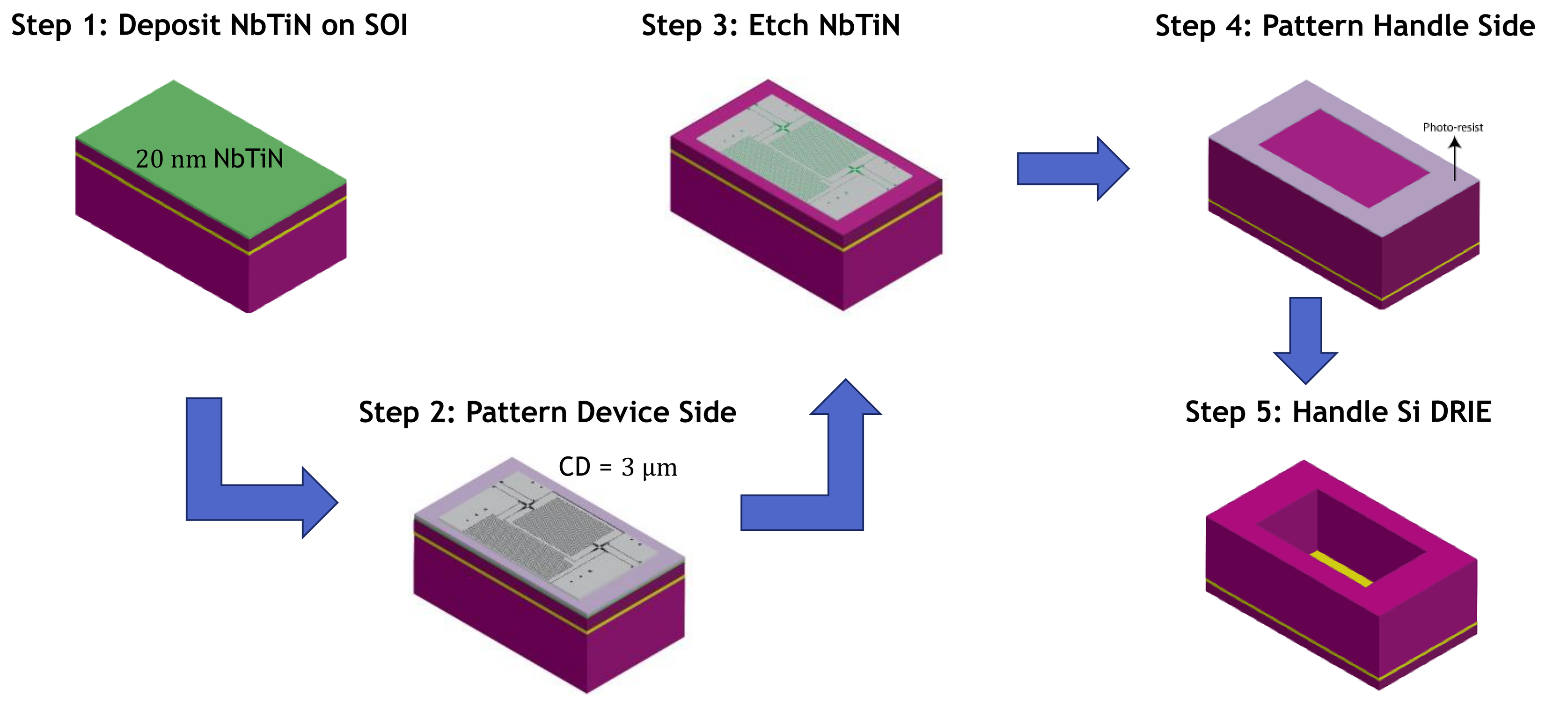

Figure 4: Phase shifter/On-Chip FTS fabrication process. NbTiN is deposited via reactive sputtering. Central hole shown in Step 5 is etched completely through handle Si and mates with raised section of package backplate (shown in Figure 6). DRIE also separates die from wafer along scribe lines.

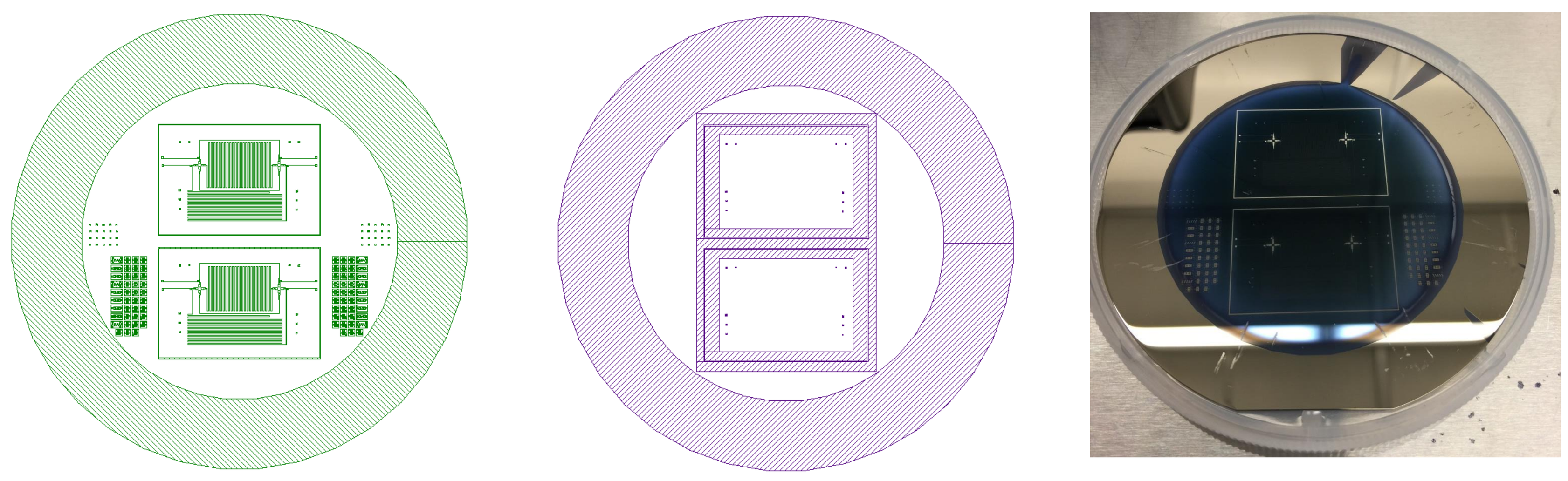

Figure 5: Device (left) and handle (middle) side pattern mask layouts. Photo of pure Nb prototype fabricated at ASU NanoFab (right) for continuity test. Nb device is unlikely to produce measurable phase shift due to lower kinetic inductance.

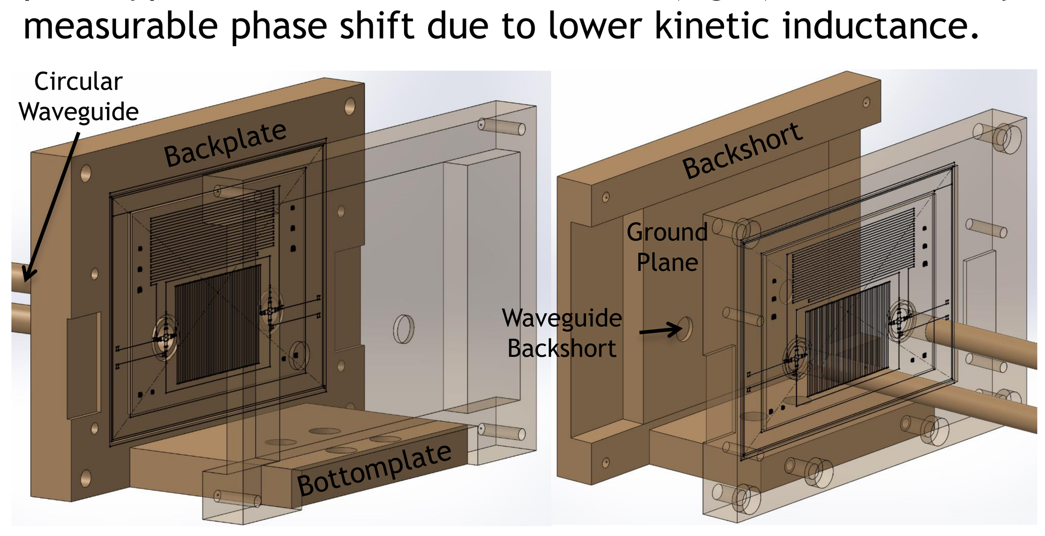

Figure 6: 3-Piece copper package for phase shifter/on-chip FTS. Device is mounted to backplate (left), which contains waveguide chokes and indents to mount bias Ts. Backshort (right) contains ground plane and waveguide backshorts. When in contact with backplate, backshort maintains 20 μm gap between device and ground plane. Bottomplate mounts to 4 K stage of testbed.

Waveguide Feedthrough

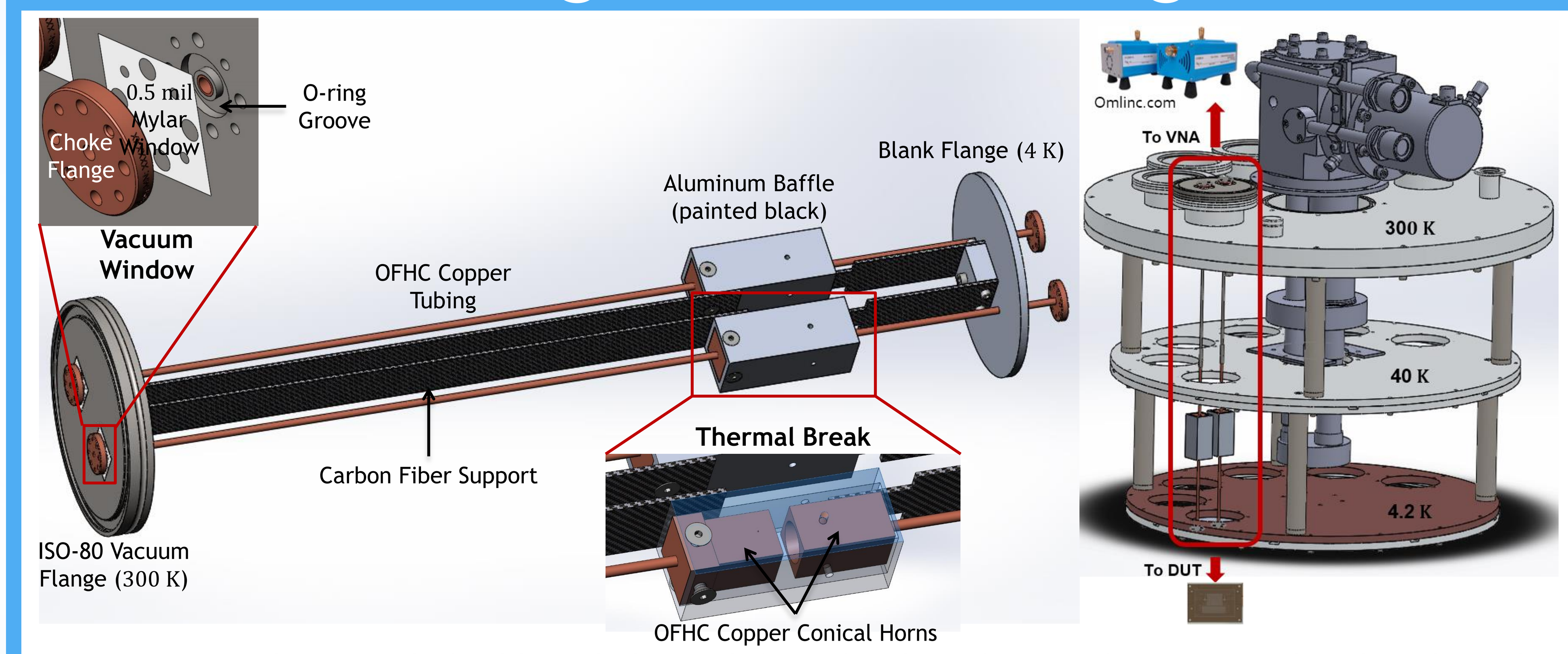

Figure 7: W-Band waveguide feedthrough design (left) with enlarged views of vacuum window (based on Ediss et al. 2005 design) and thermal break (modified Melhuish et al. 2016 design). Gap between warm and cold horn is 0.250 in. Model of our pulse tube cryostat with feedthrough installed (right).

- Delivers W-Band signals to DUT mounted on 4 K stage while minimizing heat load on cooling system
- Avoids stray light issues that complicate solutions employing mirrors and lenses
- Within 30 dB electromagnetic loss budget for phase shifter testing
- Provides in-house capability to test future W-Band devices
- Potentially scalable to higher frequencies

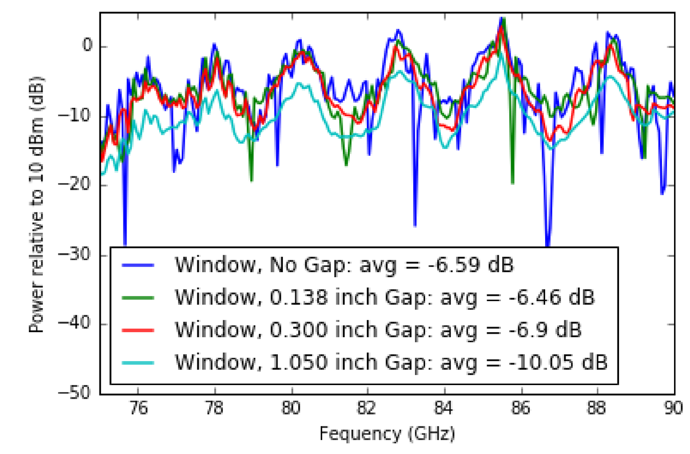

Figure 8: Room temperature loss measurements at different thermal break gap distances with original 0.063 in thick HDPE window and two 4.5 in sections of waveguide.

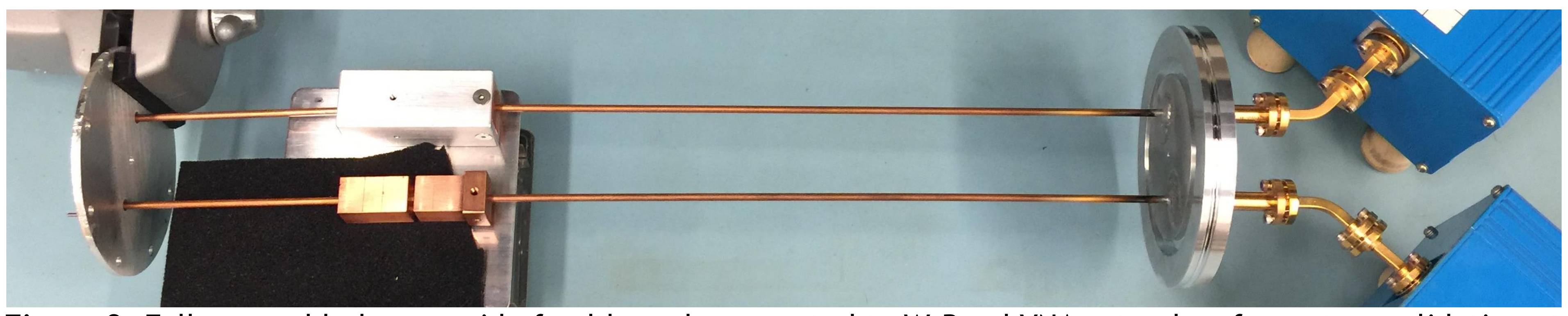

Figure 9: Fully assembled waveguide feedthrough connected to W-Band VNA extenders for system validation at room temperature. One thermal break is unbaffled to show horns. ISO-80 flange connects to WR-10 VNA extender via circular-to-rectangular waveguide transition followed by 45° H-plane bend.

Summary & Future Work

- Designed NbTiN phase shifter/on-chip FTS for applications in W-Band astronomy
- Fabricated Nb prototype and designed package
- Developed feedthrough for W-Band testing

Next Steps

- Integrate feedthrough into cryogenic testbed
- Nb prototype continuity test
- Fabricate NbTiN device and measure $\Delta\phi_m(I)$

Acknowledgements

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