High-Throughput Bulk Materials Loss Characterization

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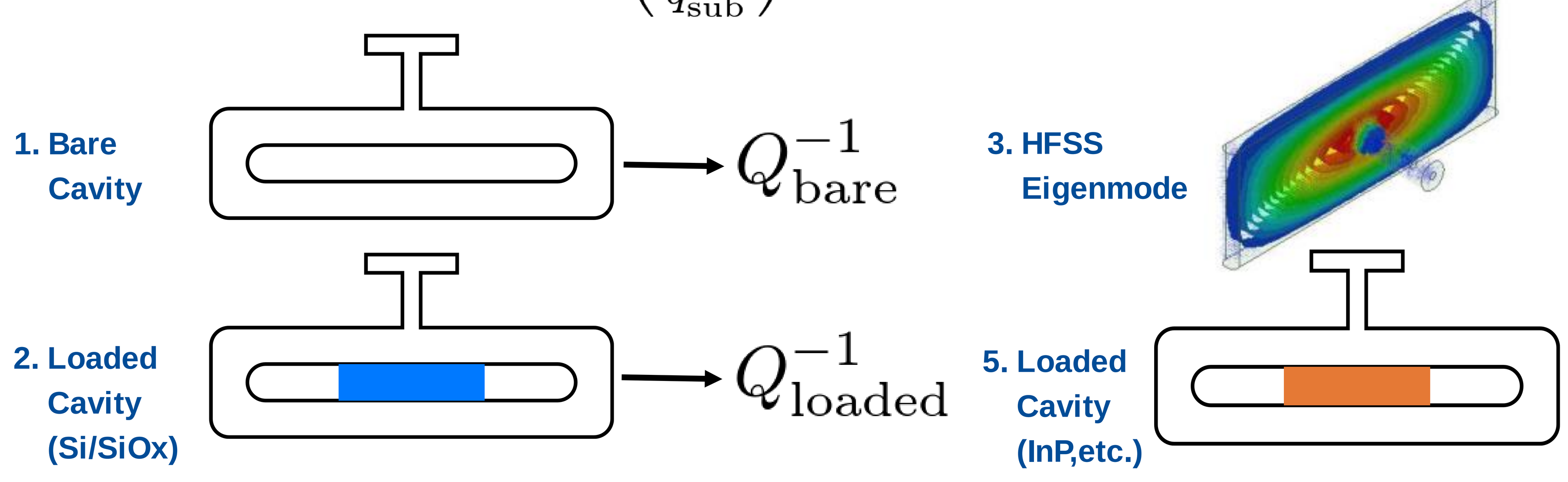
Introduction

Conventional superconducting loss measurements using coplanar waveguide (CPW) resonators and related fabrication processes present a high barrier to entry to study novel materials. Isolating loss mechanisms can require multiple devices and cooldowns, further increasing the time and cost to screen for low loss materials [1]. Superconducting cavities are low barrier-to-entry, complementary loss measurement systems, providing sensitivity to bulk losses in dielectrics greater than their low intrinsic losses.

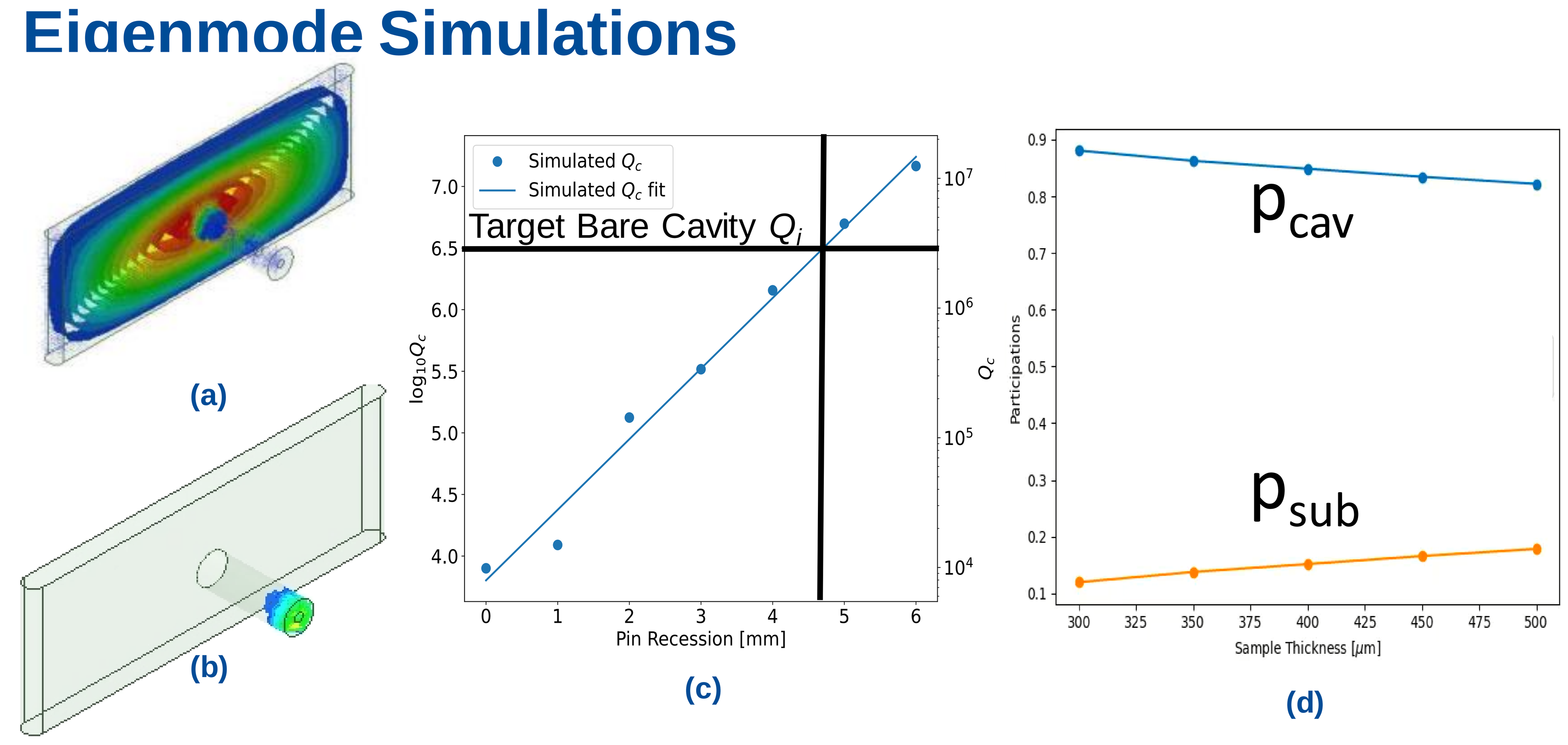
Methods

1. Measure bare cavity
2. Measure loaded cavity
3. Compute participations in HFSS
4. Solve for conductive, metal-air, substrate losses, Eq. (1) [2]
5. Repeat 2 – 4 with novel materials

$$\begin{pmatrix} \widetilde{p}_{\text{cond}}^{\text{bare}} & p_{\text{MA}}^{\text{bare}} & p_{\text{bulk}}^{\text{bare}} \\ \widetilde{p}_{\text{cond}}^{\text{loaded}} & p_{\text{MA}}^{\text{loaded}} & p_{\text{bulk}}^{\text{loaded}} \end{pmatrix} \begin{pmatrix} \widetilde{q}_{\text{cond}}^{-1} \\ q_{\text{MA}}^{-1} \\ q_{\text{sub}}^{-1} \end{pmatrix} = \begin{pmatrix} Q_{\text{bare}}^{-1} \\ Q_{\text{loaded}}^{-1} \end{pmatrix} \qquad (1)$$



Eigenmode Simulations



HFSS Eigenmode Simulations. (a) Fundamental mode electric field intensity, (b) coupling pin mode electric field intensity (c) coupling quality factor as a function of pin recession distance, (d) participations as a function sample thickness.

References

[1] W. Woods, G. Calusine, A. Melville, A. Sevi, E. Golden, D. K. Kim, D. Rosenberg, J. L. Yoder, and W. D. Oliver, "Determining interface dielectric losses in superconducting coplanar-waveguide resonators," Phys. Rev. Applied 12, 014012 (2019).

[2] A. P. Read, B. J. Chapman, C. U. Lei, J. C. Curtis, S. Ganjam, L. Krayzman, L. Frunzio, and R. J. Schoelkopf, "Precision measurement of the microwave dielectric loss of sapphire in the quantum regime with parts-per-billion sensitivity," arXiv:2206.14334 [quant-ph] (2022),10.48550/ARXIV.2206.14334.

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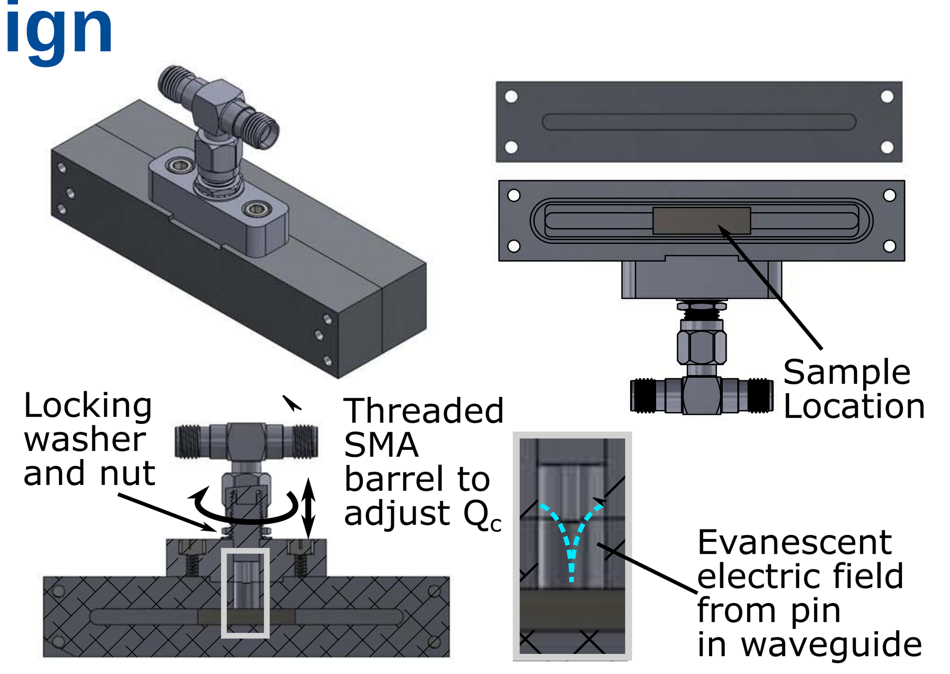
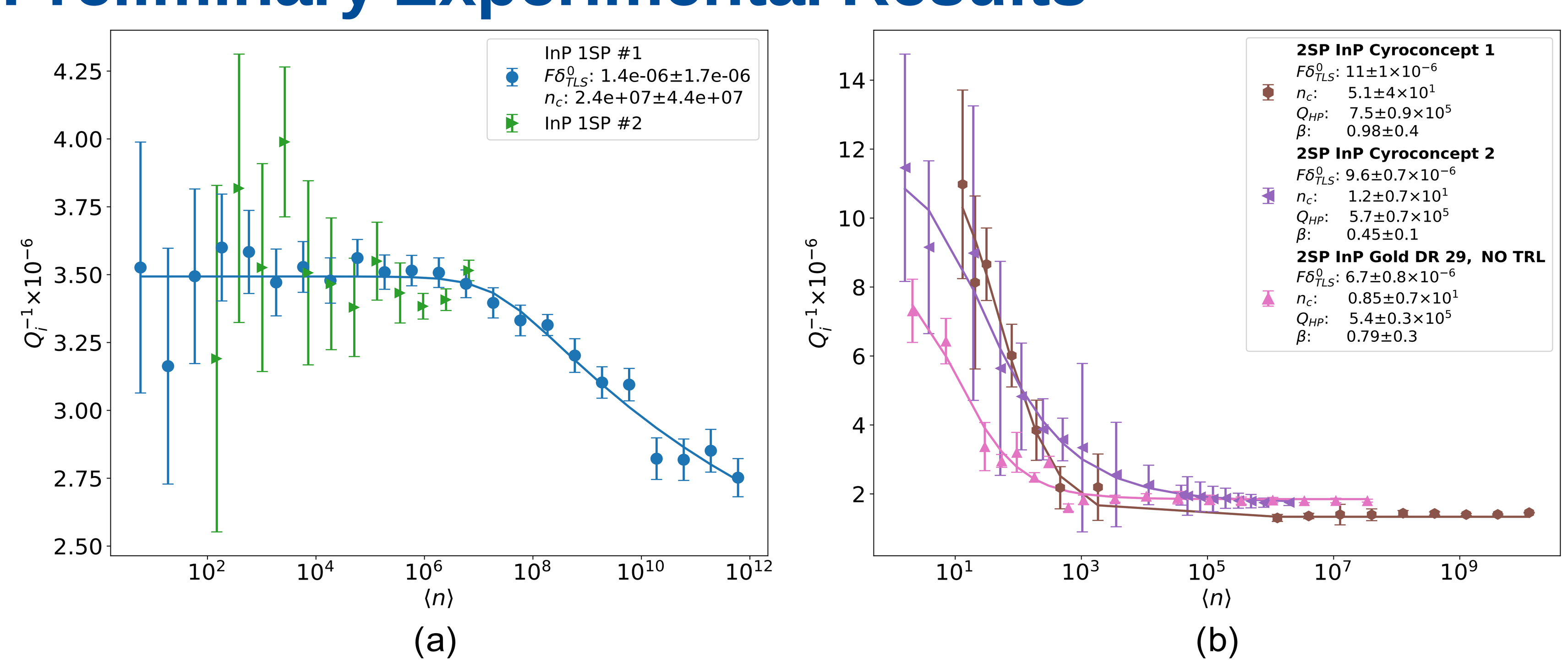
Cavity Design

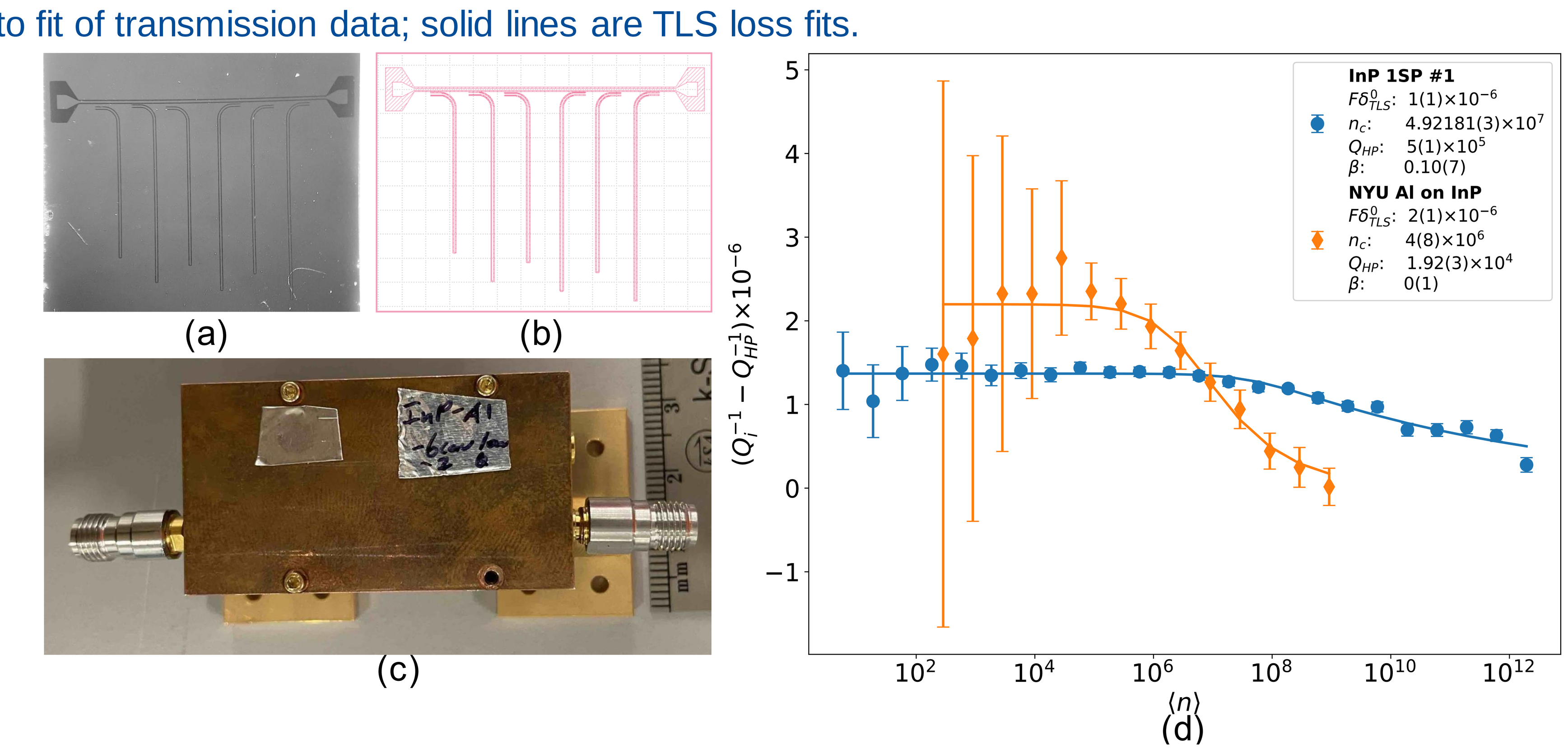


Superconducting rectangular cavity design for reproducible, high-throughput substrate measurements. Top left: Isometric view of cavity with SMA Tee. Bottom left: cavity cross section and motion of tunable input/output pin. Top right: cavity halves with sample loaded in the bottom half. Bottom right: inset of bottom left illustrating TM_{01} mode electric field profile of circular waveguide between the SMA pin and cavity volume.

Preliminary Experimental Results



Reproducibility studies. Repeated loss measurements as a function of photon power of a superconducting aluminum cavity loaded with (a) a single side polished InP substrate and (b) a double side polished InP substrate sourced from AXT. Error bars are 95 % confidence intervals to fit of transmission data; solid lines are TLS loss fits.



Comparison with planar measurements. (a) Optical microscope image and (b) mask file of CPW resonator chip loaded in (c) NYU package. (d) Comparison of single side polished InP losses loaded in the cavity and the CPW resonator losses with high-power losses subtracted to illustrate the TLS loss behavior. Error bars are 95 % confidence intervals to loss fit of transmission data; solid lines are TLS loss fits.

TABLE I. TLS Loss Model Fit Parameters

Sample	$F\delta_{\text{TLS}}{}^0 \times 10^{-6}$	n_c	β	$Q_{\text{HP}} \times 10^5$
Cavity #1 + Si/SiO_x	-	-	0.27(7)	12.50(8)[a]
Cavity #1 + 1SP InP	1(2)	$2(4)\times10^{7}$	0.10(7)	4.92181(3)
Al CPW on 1SP InP	2(1)	$4(8)\times10^{6}$	0(1)	0.192(3)
Cavity #1 + 2SP InP, Cryoconcept 1	11(1)	$2(1)\times10^{-1}$	1.0(4)	7.3(8)
Cavity #1 + 2SP InP, Cryoconcept 2	9.7(7)	$4(2)\times10^{-2}$	0.44(1)	5.8(7)
Cavity #1 + 2SP InP, Gold DR 29	6.7(8)	$3(2)\times10^{-2}$	0.7(2)	5.5(3)
Cavity #1 + 2SP InP, Gold DR 32	3.8(5)	$3(4)\times10^{-1}$	0.9(8)	8(1)
Bare Cavity #2	-	-	-	-
Cavity #2 + Si/SiO_x	-	-	-	-
Cavity #2 + 1SP InP	-	-	-	-
Cavity #2 + 2SP InP	-	-	-	-

[a] Overcoupled cavity measurements, $Q_c \ll Q_i$

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