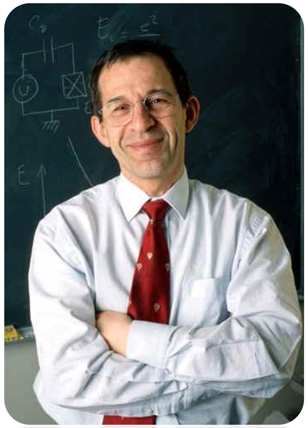
QUANTRONICS LABORATORY
Department of Applied Physics
Yale University

Superconducting Whispering Gallery Mode Resonators

Zlatko Minev



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Luigi
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QuLab
RSL Lab

Motivation

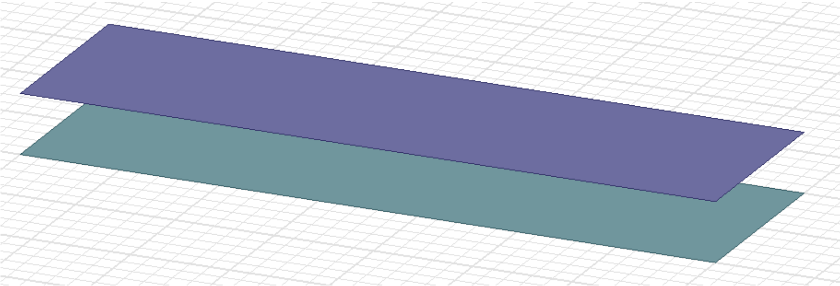
I. \`Wafer-Scalable\` Circuit-QED architecture
   A. Multiple resonators & qubits
   B. Allow flux bias for a qubit coupled to a high-Q superconducting microwave cavity

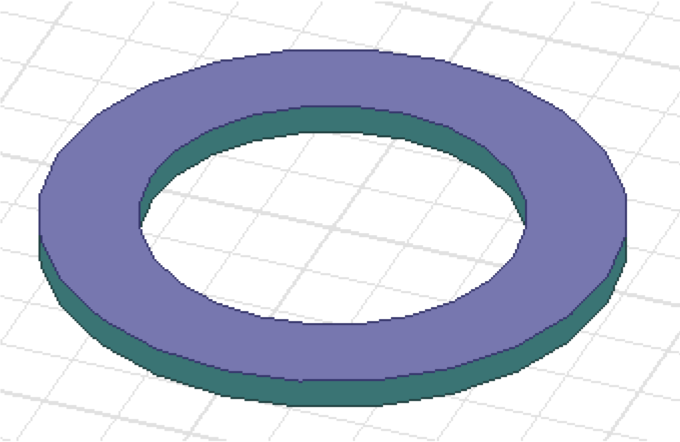
II. What is the intrinsic limit to superconducting devices?
   I. Use a simple and robust platform to characterize cryogenic material properties of metals and dielectrics at the single photon level

Part I: `Wafer-Scalable` Circuit-QED architecture

1. Concept: Photon on a Ring & Modular Setup
2. Experimental Setup
3. Characterization:
    1. Modes & Quality factors
    2. Lifetimes & Coherence Times

Concept I: Photon Particle on a Ring

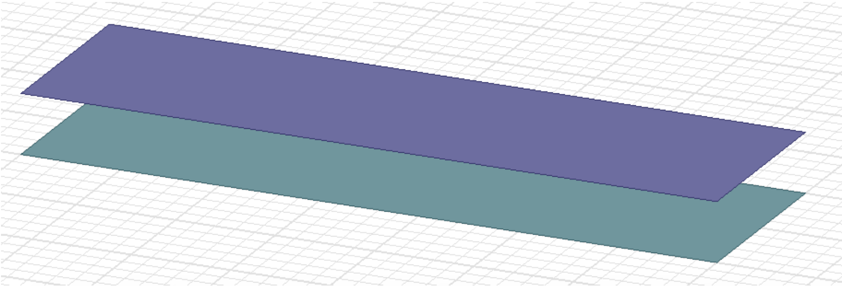


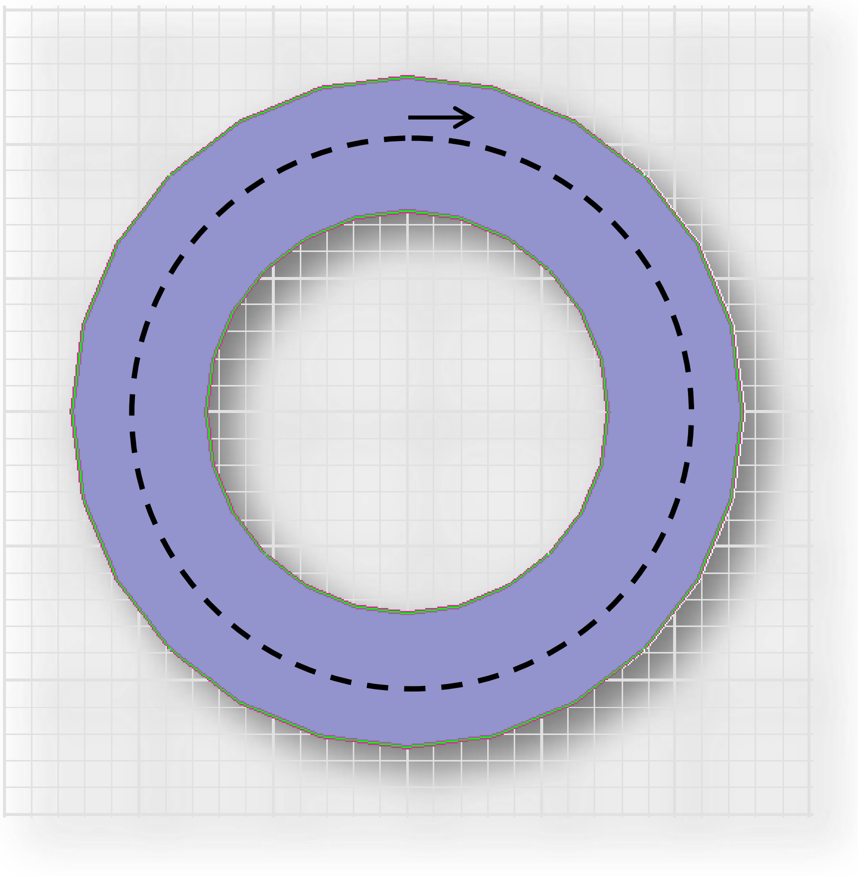


Design Strategy:

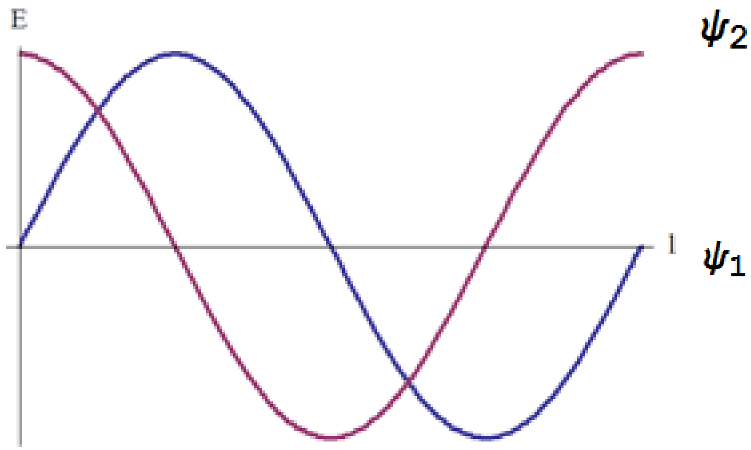
- **Confine energy in lossless vacuum**
- **Keep geometry & design parameters simple**

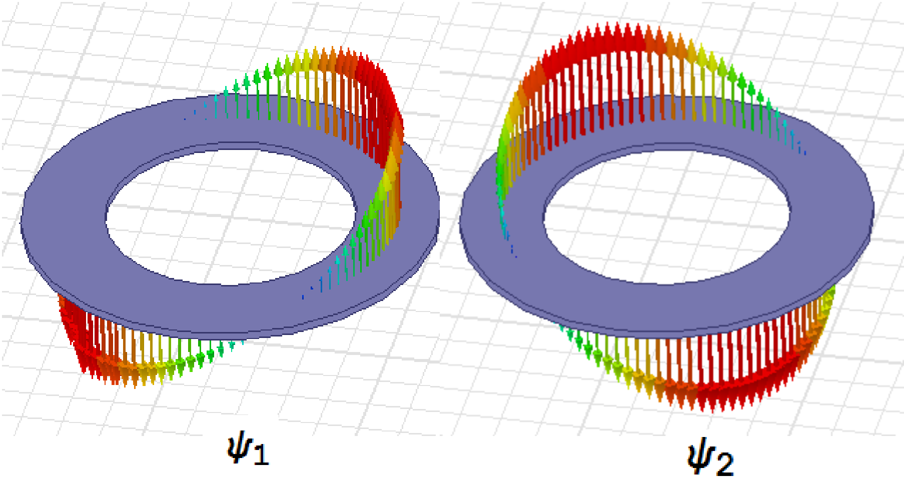
1D Description – 2 Degenerate Ground Modes



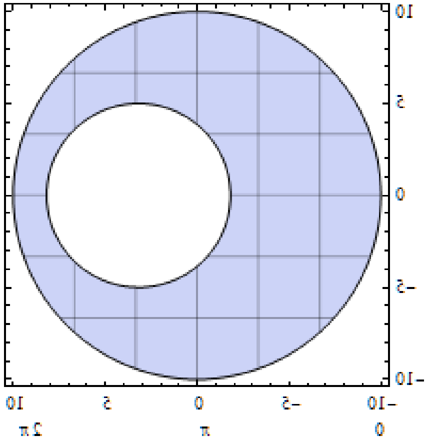


$$\nabla^2\psi + \frac{w^2}{c^2}(1+\Delta n(x)^2)\psi = 0$$



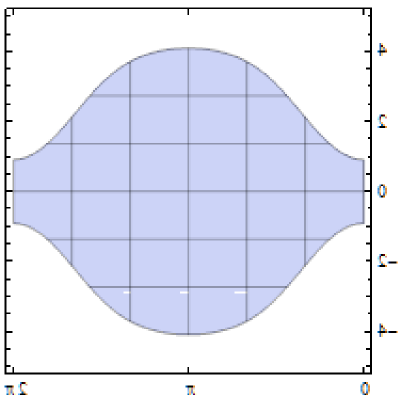


Lift Degeneracy

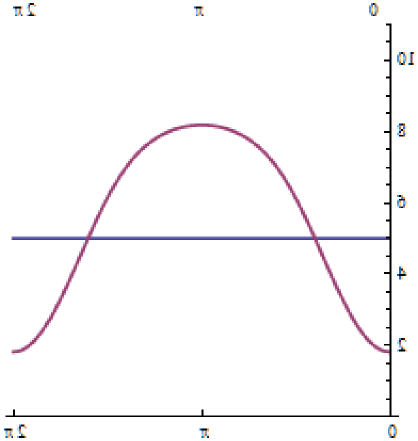


Simplified impedance view from top

$$Z \propto \sqrt{\frac{L}{C}}$$

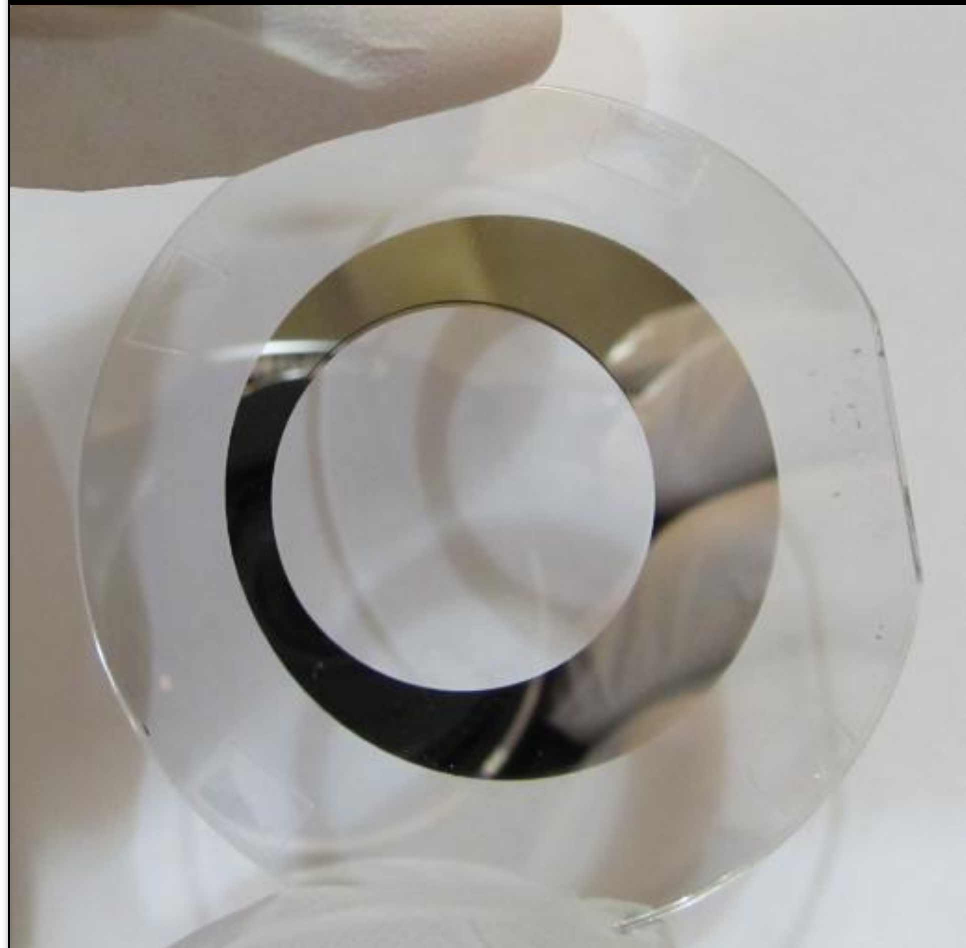


What the Photon sees along its path of travel

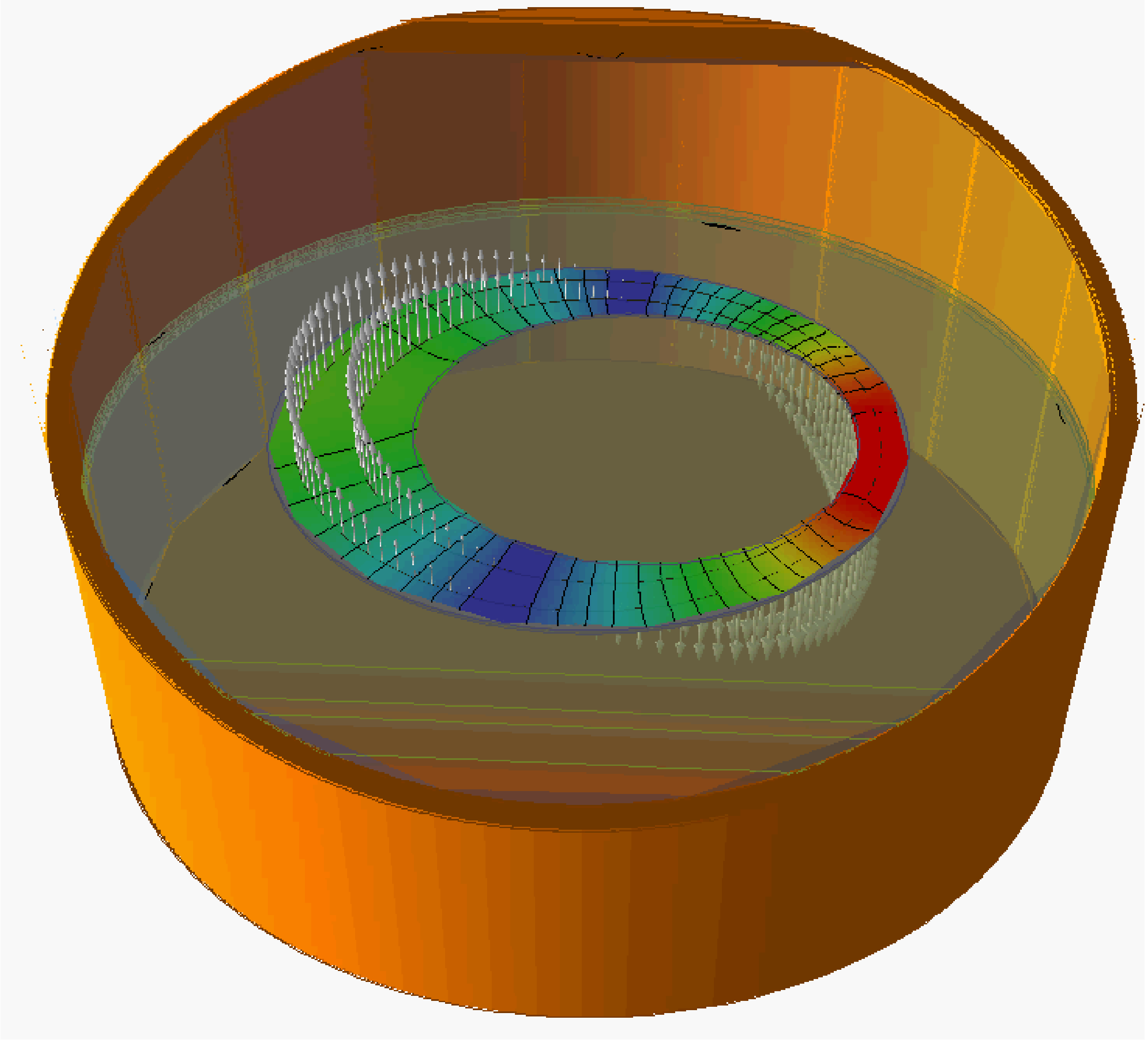


An effective 1D *admittance* for the photon along its path

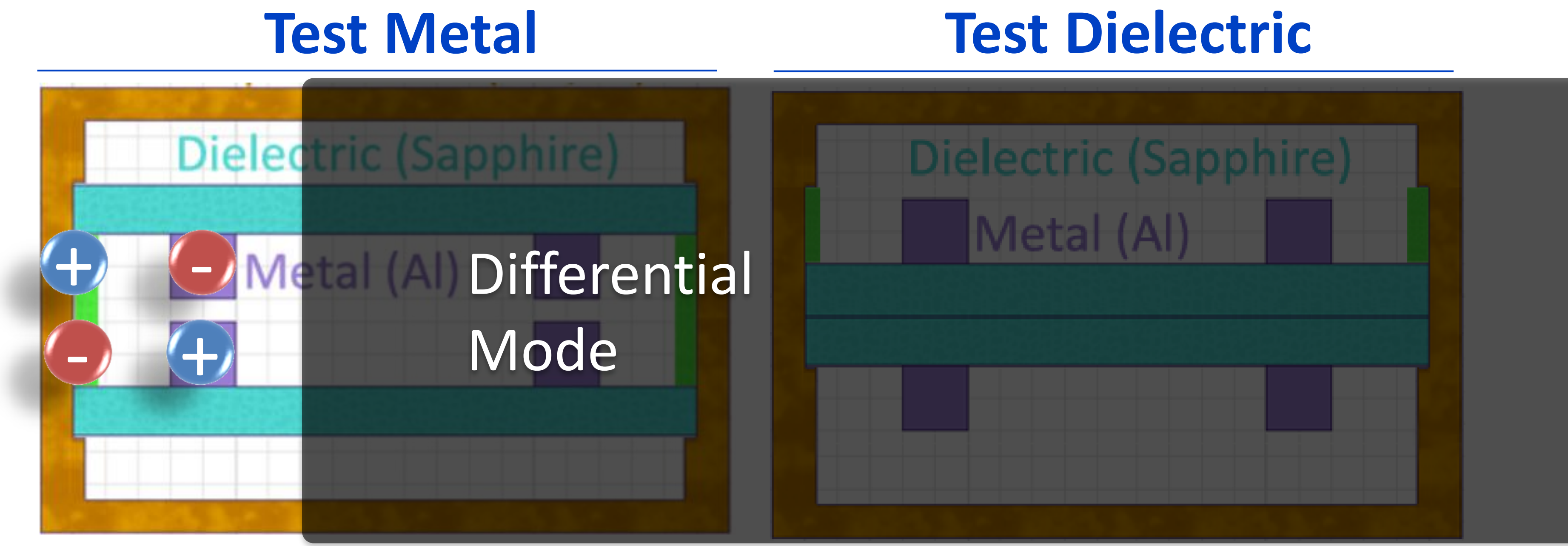
$$Y_{\infty\,\mathrm{TL}} = \frac{1}{377\,\Omega}\,\frac{w}{d}$$



Differential Parallel Mode: Electric Fields



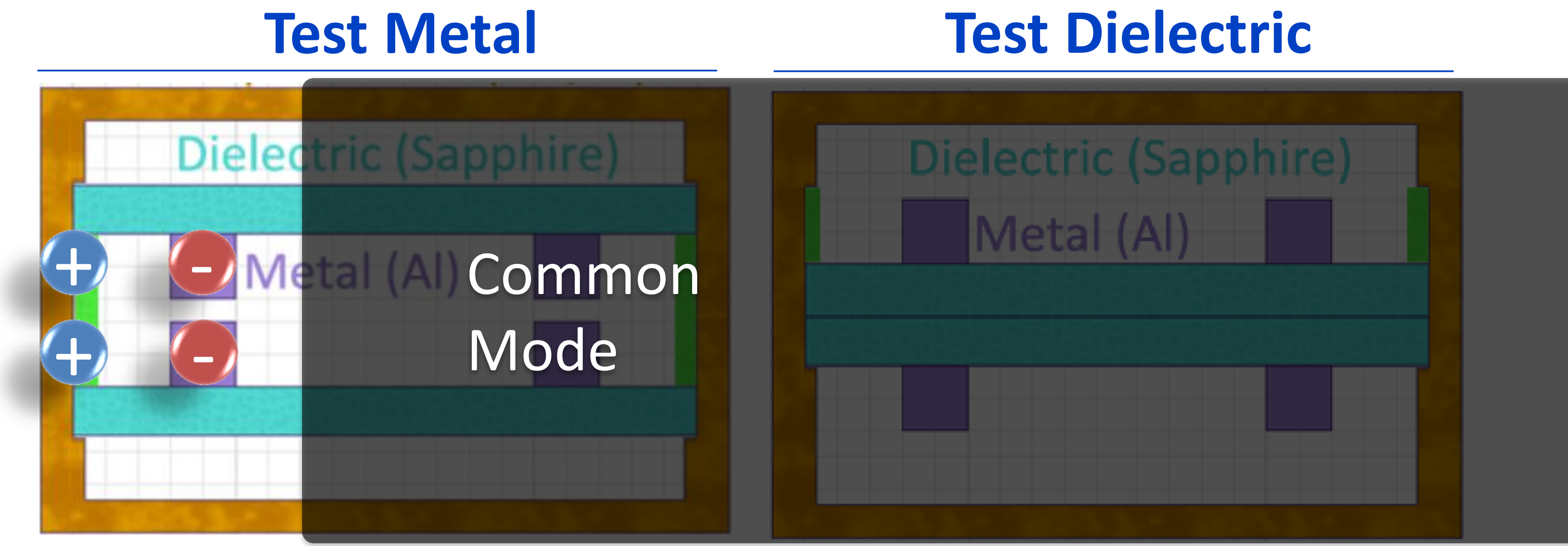
Concept II: Modular Setup



Not To Scale!

- Experimental setup is modular
- In the `test metal` setup, the thin-film rings confine the fields in lossless vacuum
- In the `test dielectric` setup, the fields are confined in the substrate dielectric

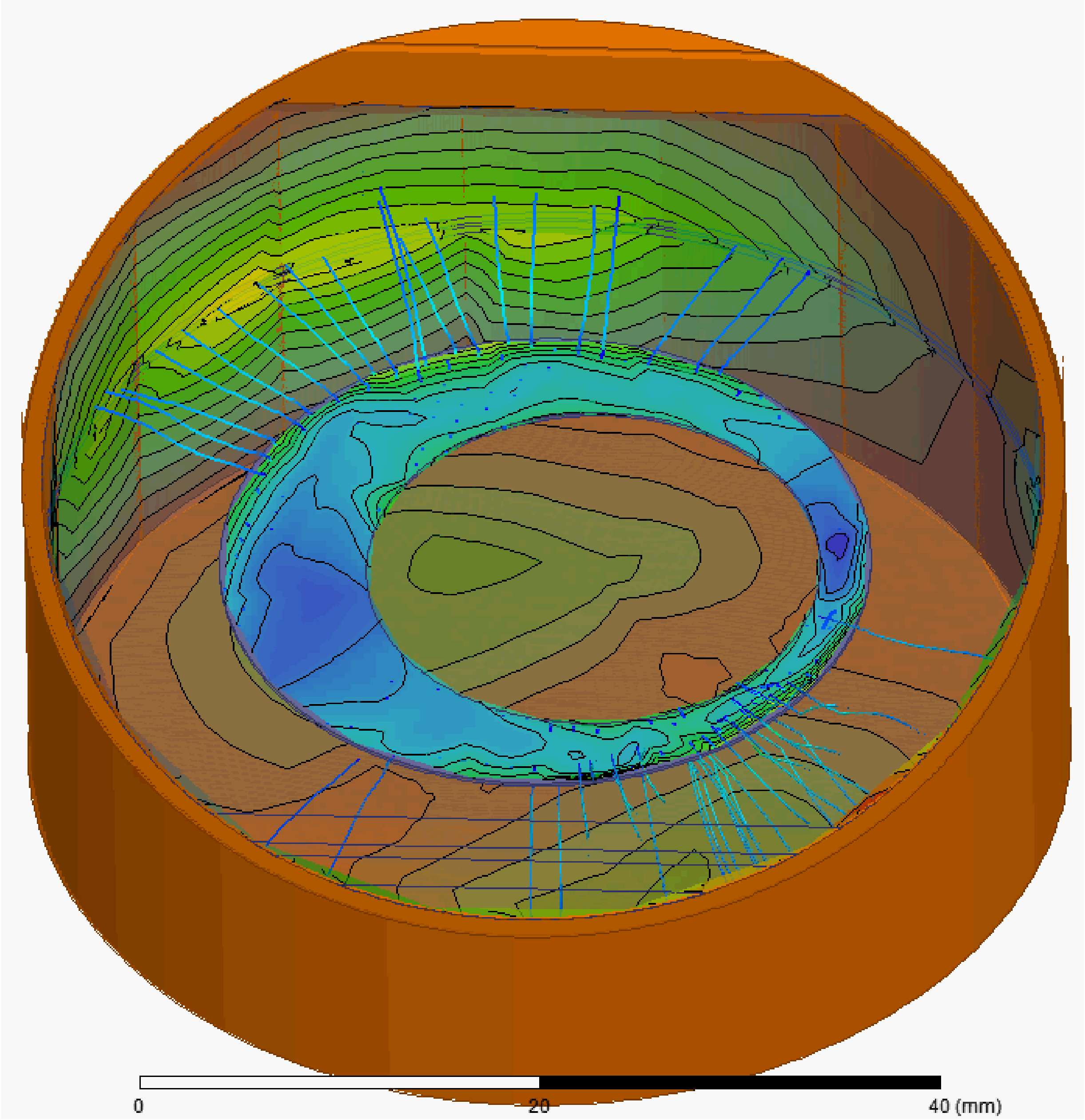
Concept II: Modular Setup



Not To Scale!

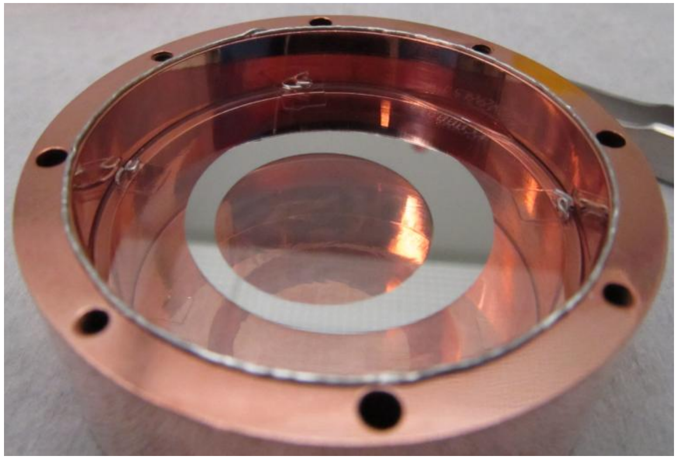
- **Experimental setup is modular**
- **In the `test metal` setup, the thin-film rings confine the fields in lossless vacuum**
- **In the `test dielectric` setup, the fields are confined in the substrate dielectric**

Common Perpendicular Mode: Electric Fields

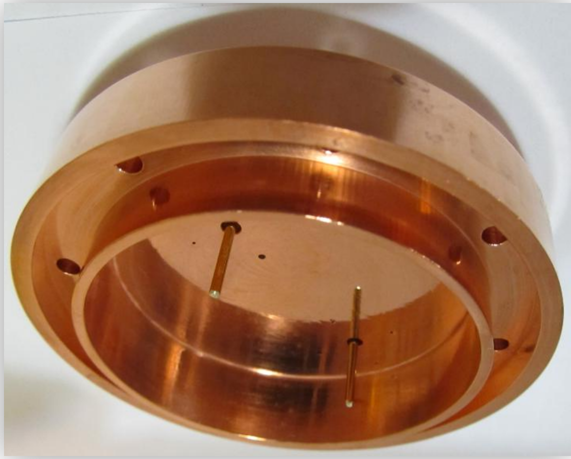


Modular Cavity & Sample Holder

Sample Holder Bottom



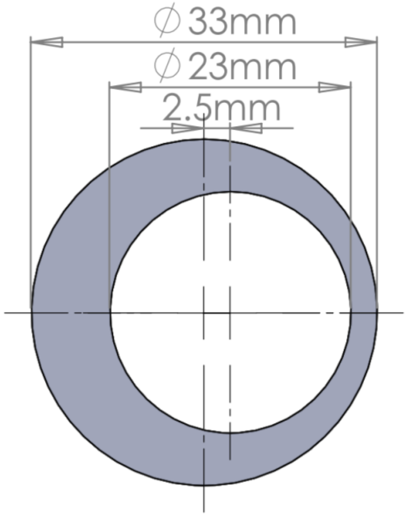
Sample Holder Top



SMA Pin Coupler (Non Magnetic)

- Sample holder can be copper or aluminum
- Use custom *non-magnetic* SMA pin coupler

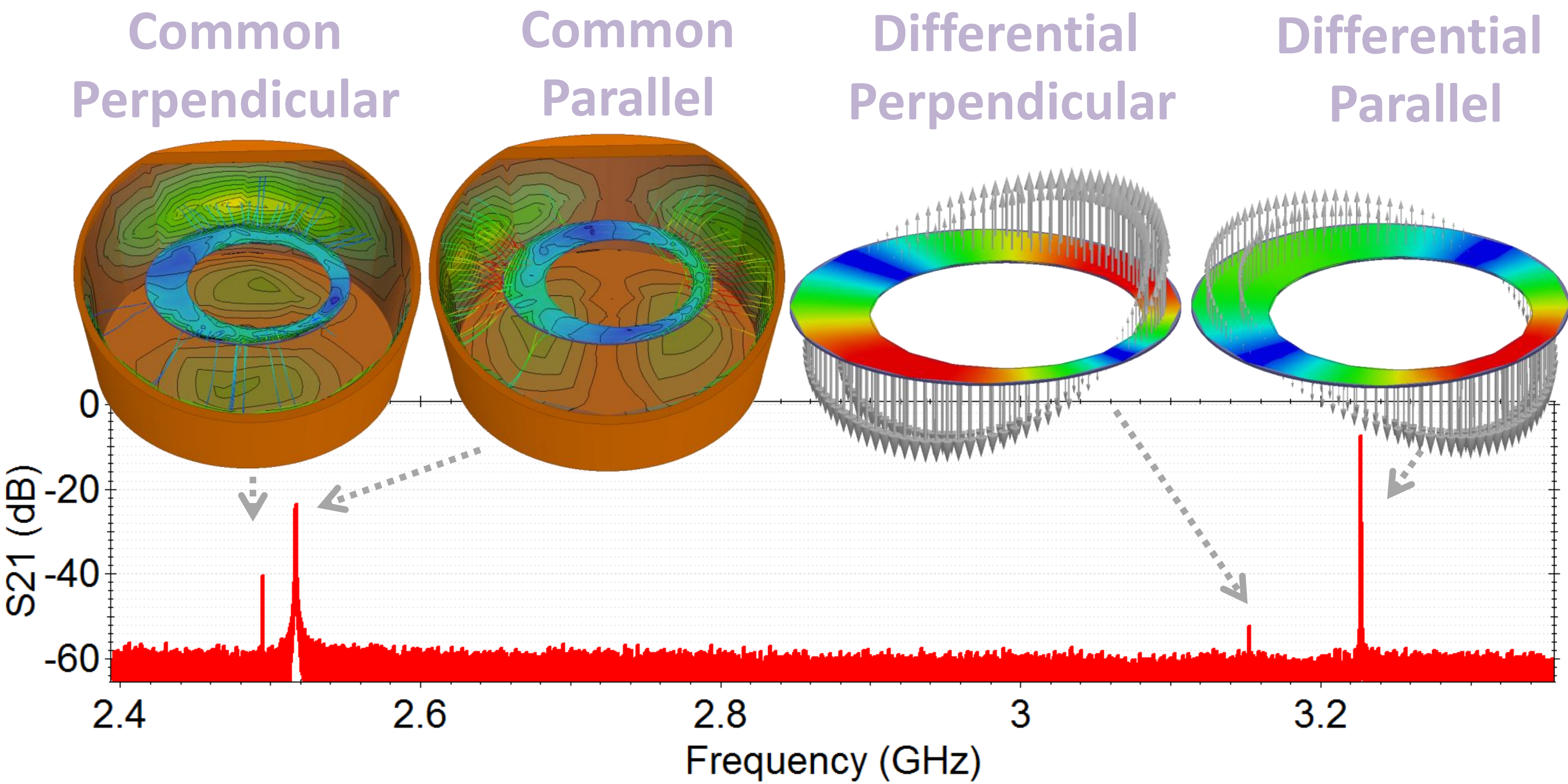
Ring Dimensions



Technical Parameters:

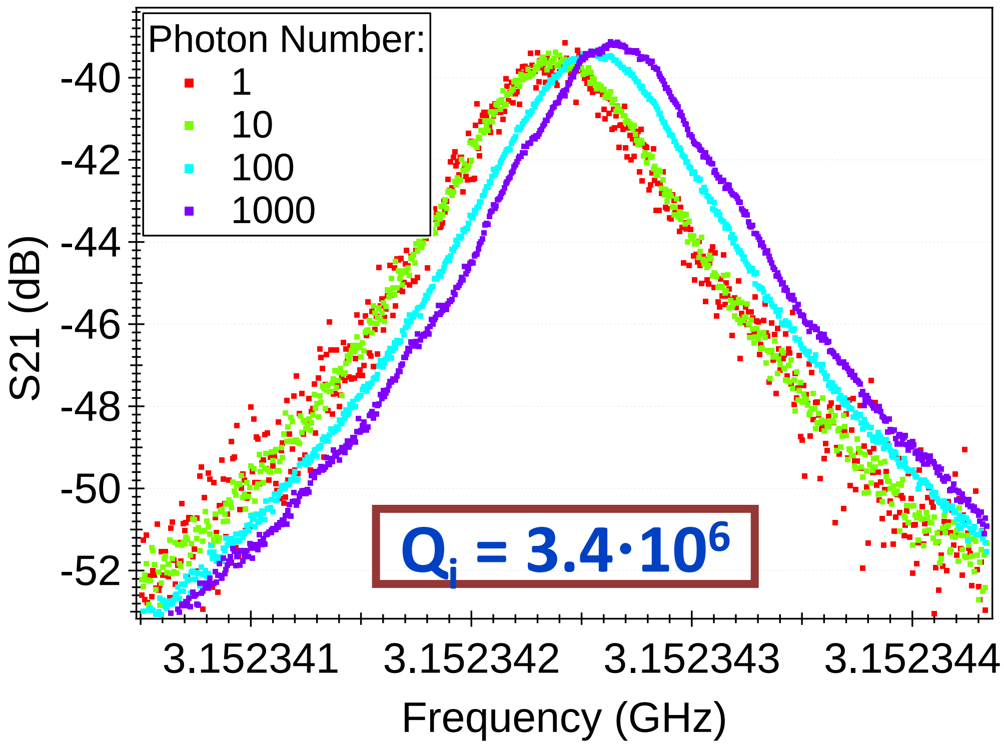
- Al film thickness 300 nm
- O_2 plasma cleaning prior to deposition
- Sapphire wafer thickness 450 µm
- Wafer spacing 200 µm

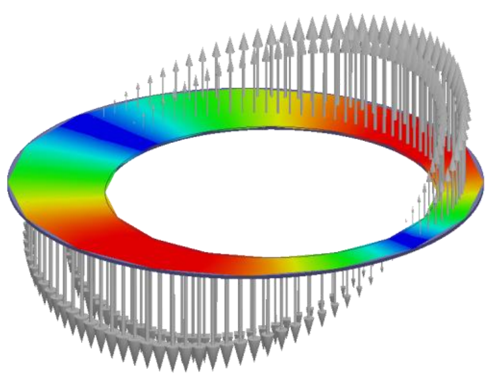
Identifying Modes (S_{21})



- The modes are easily identified and understood with the help of HFSS numerical simulations (Top Picture)
- Differential modes contain > 98% of mode energy in between the rings

Total Q vs Power (S_{21})

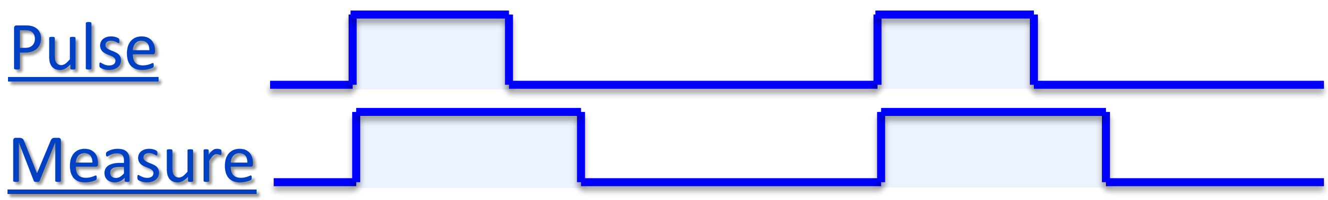


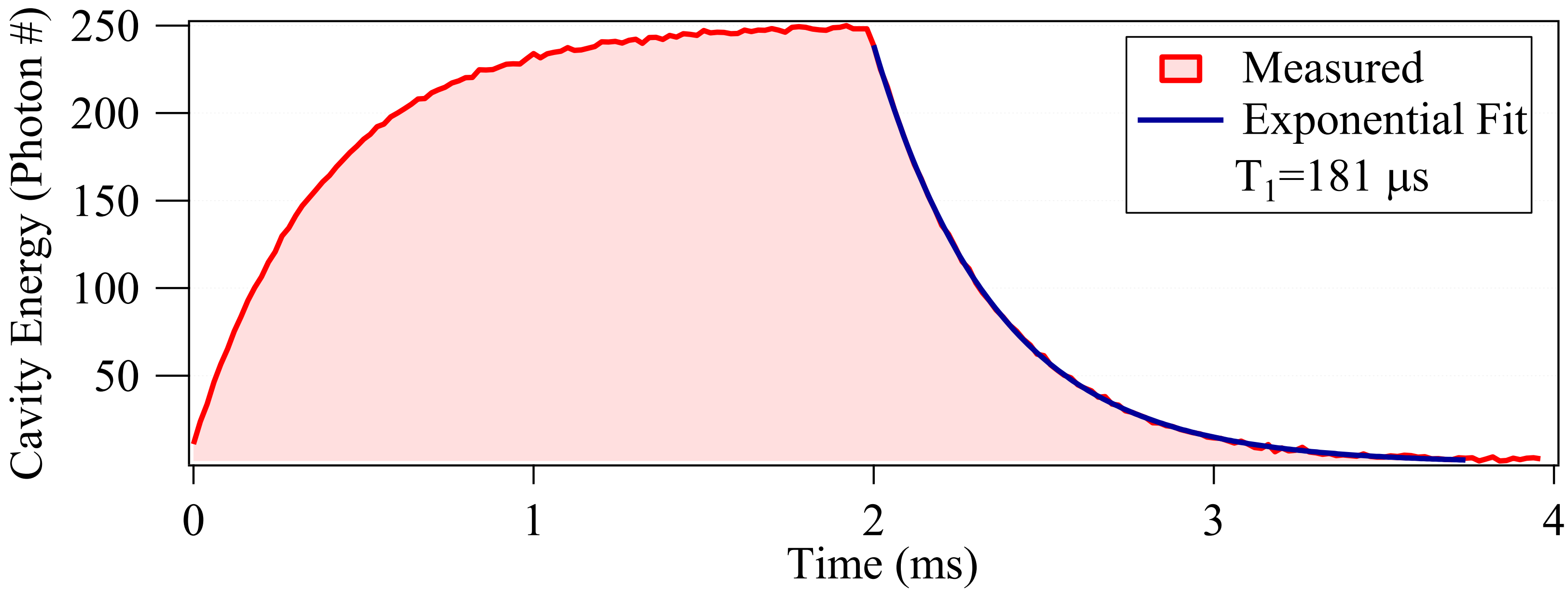


- **Differential perpendicular mode in `test metal` configuration**
- **BW = 940 Hz**
- **Q_i is power independent**
- **Undercoupled**
- **Single Photon Current = 80 nA**
- **Aluminum sample holder**
- **Copper sample holder measured Q = $2 \cdot 10^5$**

Energy Relaxation (T_1)

Pulse Sequence

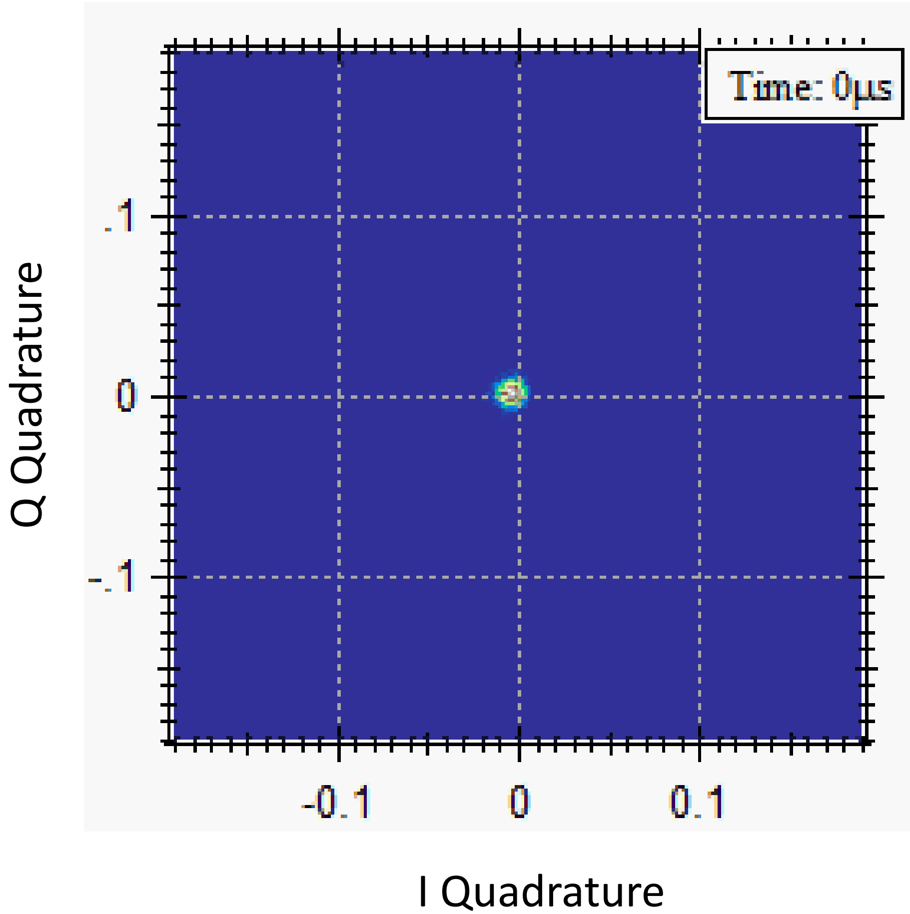




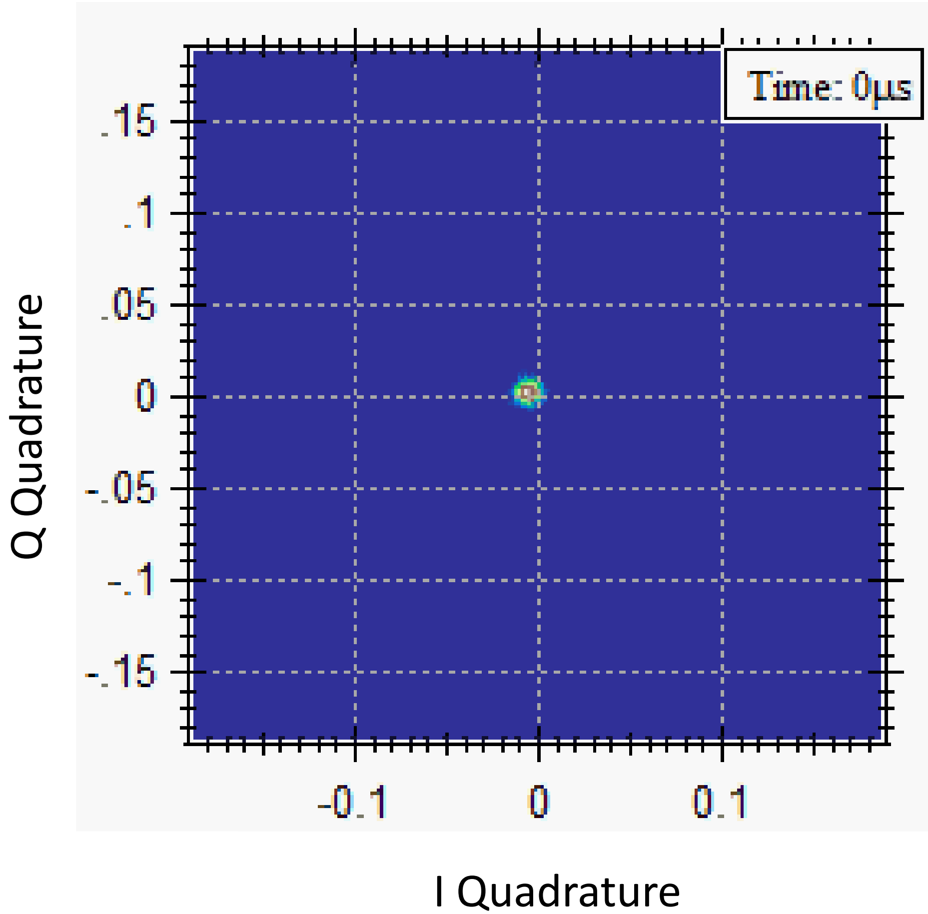
Heterodyne measurement of ring-up and ring-down of differential perpendicular mode in `test metal` set-up

In IQ Space: Overcoupled Mode & Mechanical noise

Roots on & Dephasing



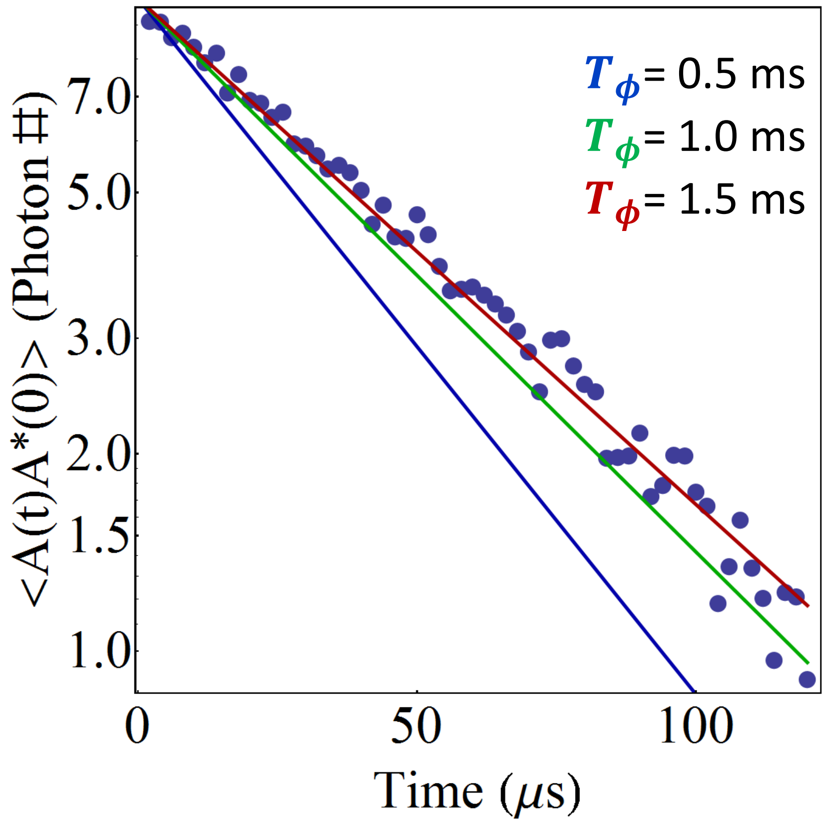
Roots off



Phase Coherence (T_ϕ)

- **Free relaxation autocorrelation function measures T_2**
- $\frac{1}{T_2} = \frac{1}{2T_1} + \frac{1}{T_\phi}$

- **Use circular statistics ad wrapped normal distribution**
- **Assume uncorrelated phase and magnitude noise**



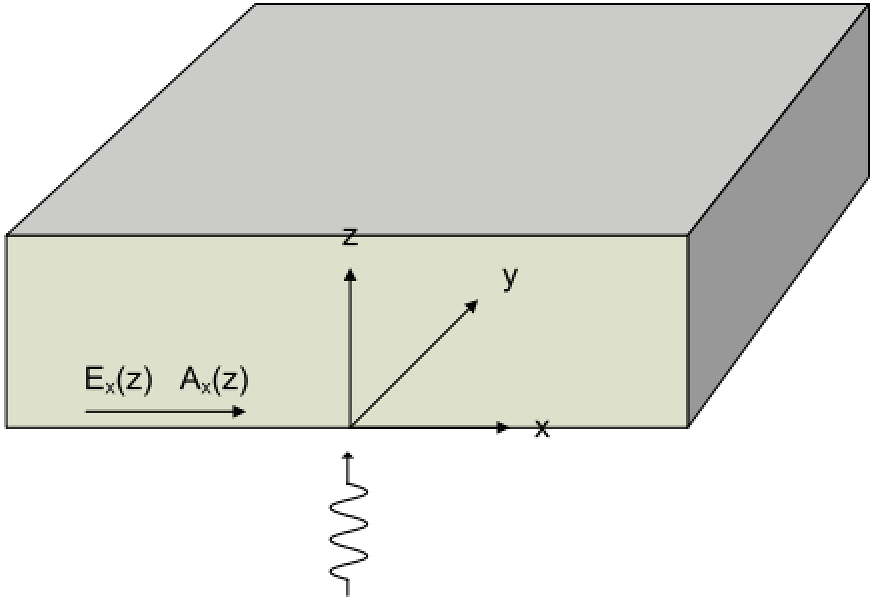
$$
\begin{aligned}
& < A(t+\tau)A^*(t) > \\
= & < V(t+\tau)V(t) >< e^{i(\phi(t+\tau)-\phi(t))} > \\
= & V_0^2 e^{-\frac{1}{2T_1}} < e^{i\phi(\tau)} > \\
= & V_0^2 e^{-\frac{1}{2T_1}} e^{-\frac{1}{T_\phi}\tau} \\
= & V_0^2 e^{-\frac{1}{T_2}}
\end{aligned}
$$

$$A = I + iQ$$

Part II: On the `Dissipation Budget`

1. Surface impedance & surface Q
2. Aluminum thin film measurements
3. Sapphire loss tangent measurements

Surface Impedance



$$Z_S = \frac{E_{\text{tangential}}(x)}{H_{\text{tangential}}(y)}\Big|_{\text{at surface}\,(z=0)}$$

$$= R_s + i\, X_s$$

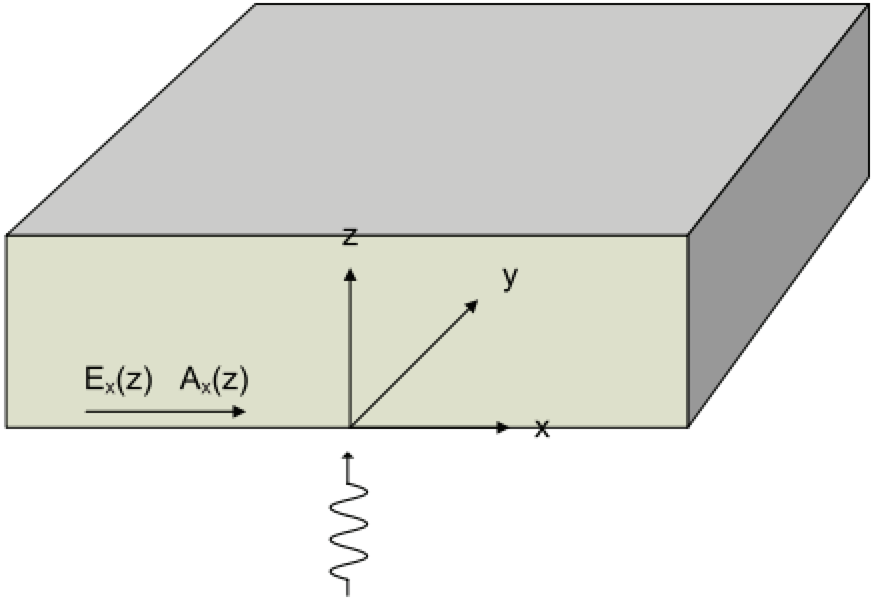
Rate of energy dissipation in δ

Quasiparticles

~ EM energy stored in δ

<u>Kinetic</u> Inductance

Surface Impedance & Surface Q



$$Z_S = \frac{E_{\text{tangential}}(x)}{H_{\text{tangential}}(y)}\Big|_{\text{at surface }(z=0)}$$

$$= R_s + i\,X_s$$

Rate of energy dissipation in δ

~ EM energy stored in δ

Quasiparticles

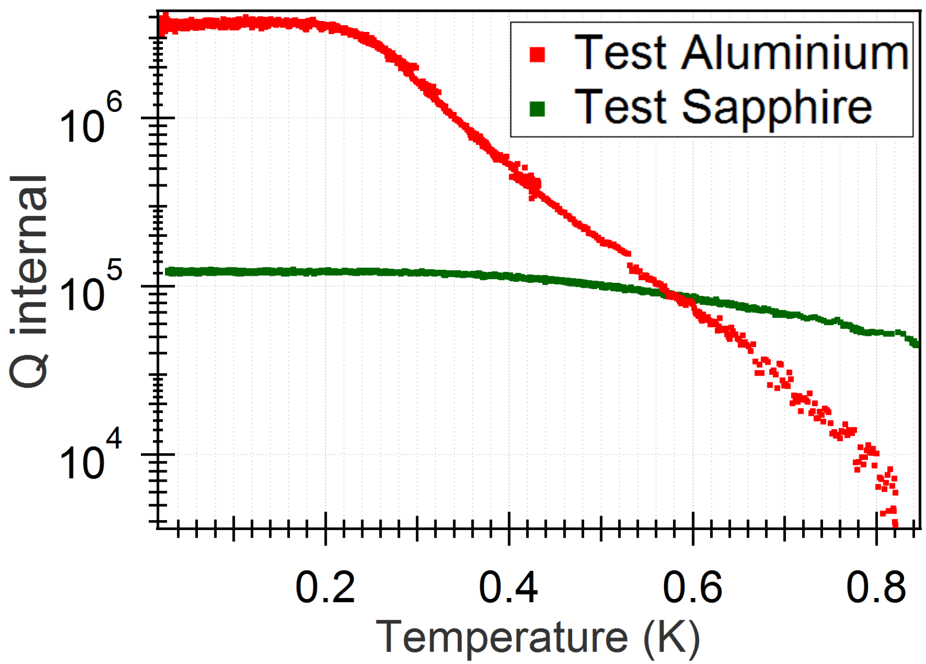
Kinetic Inductance

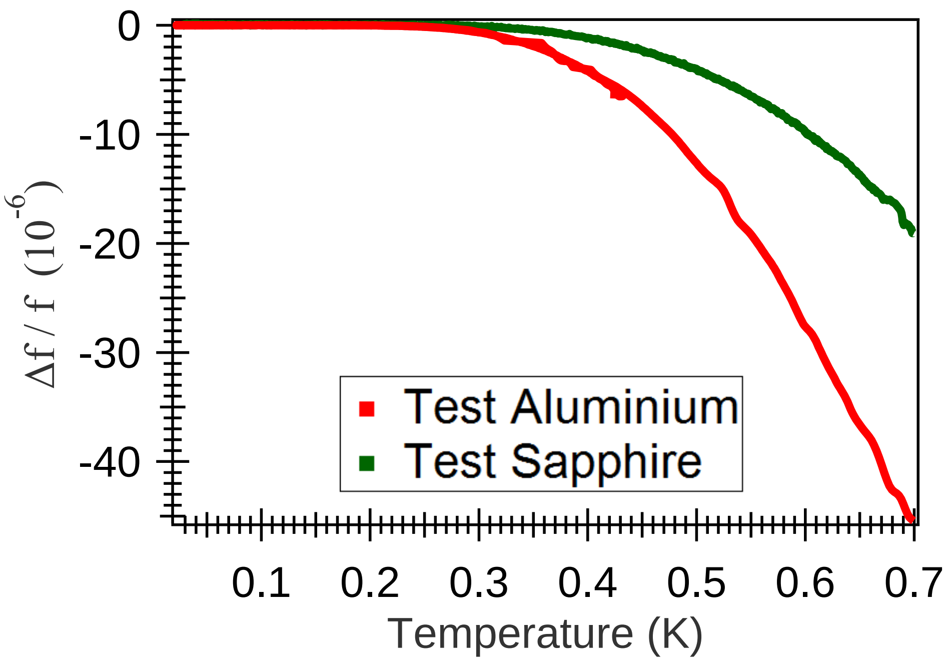
Qs = X_s / R_s

Normal Metal: Qs ~ 1

Superconductor: Qs ~ 1/n_q

Loss Properties of Aluminum





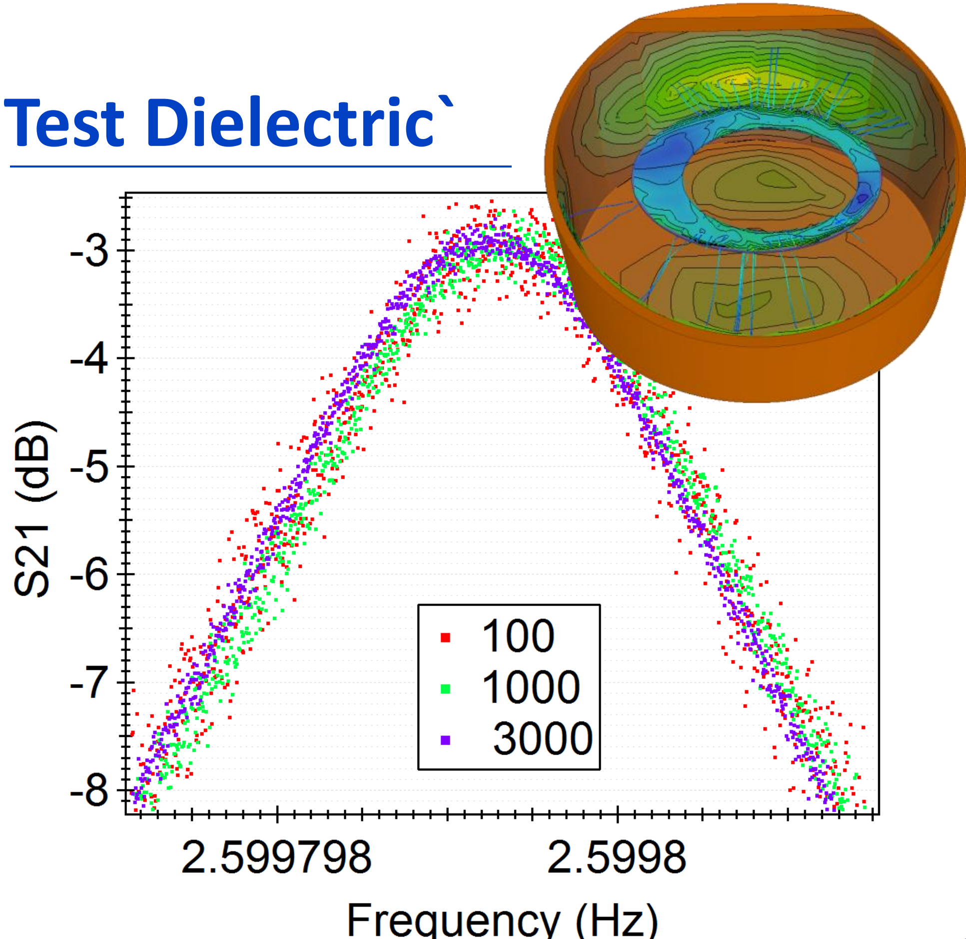
- **Extracted upper bound of the surface square resistance of thin film aluminum:**

$$\boxed{\begin{array}{c} R_{\square} \leq 250\ n\Omega \\ Q_s > 5000 \end{array}}$$

See Matt Reagor's MLS for more details

Loss Properties of Sapphire

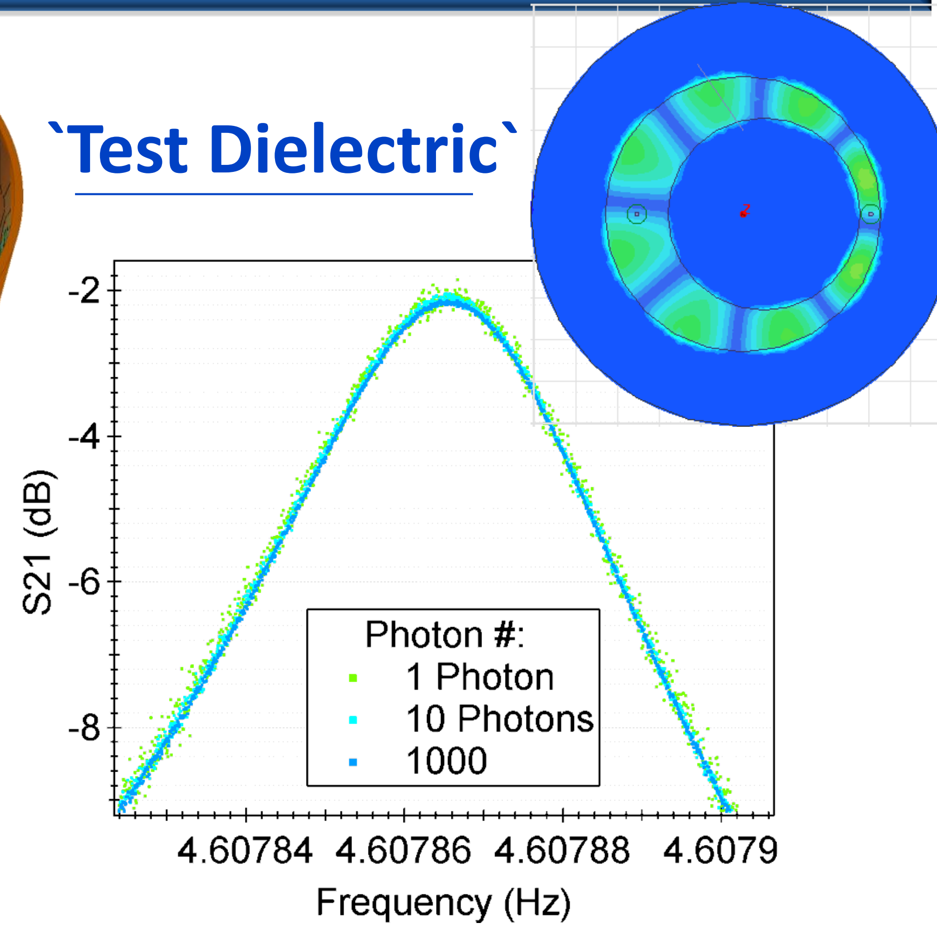
\`Test Dielectric\`



- HFSS participation ratio: 44%
- Common Perpendicular

$Q_i = 1.6 \cdot 10^6$
$\tan \delta < 1.4 \cdot 10^{-6}$

\`Test Dielectric\`

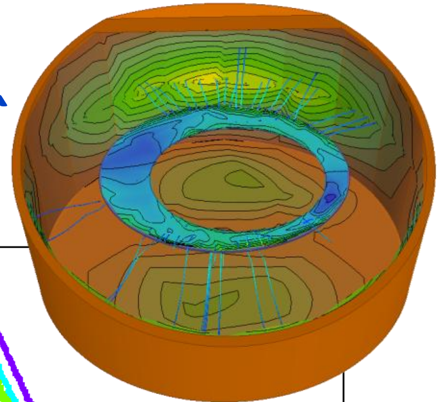


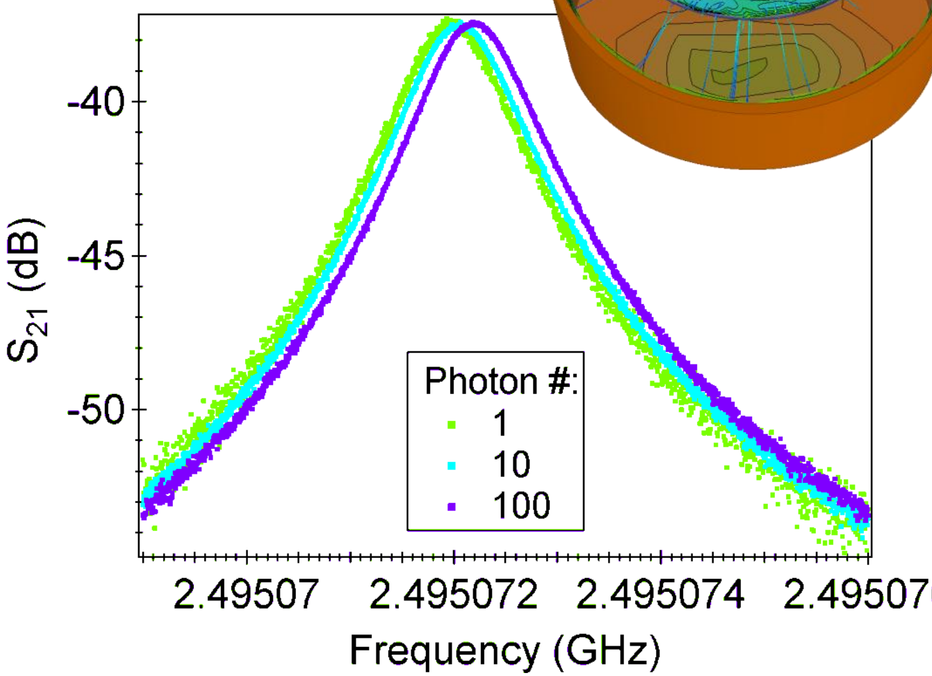
- HFSS participation ratio: 98%
- Differential 4th Harmonic

$Q = 2.0 \cdot 10^5$
$\tan \delta < 5 \cdot 10^{-6}$

Loss Properties of Sapphire

`Test Metal Setup`

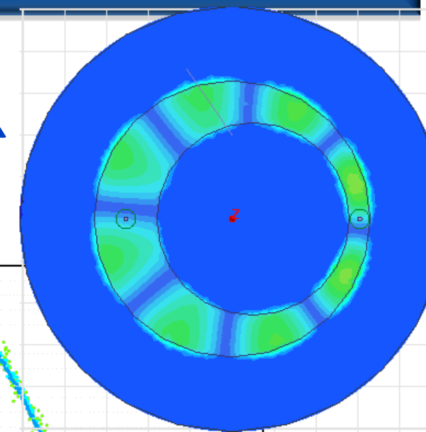


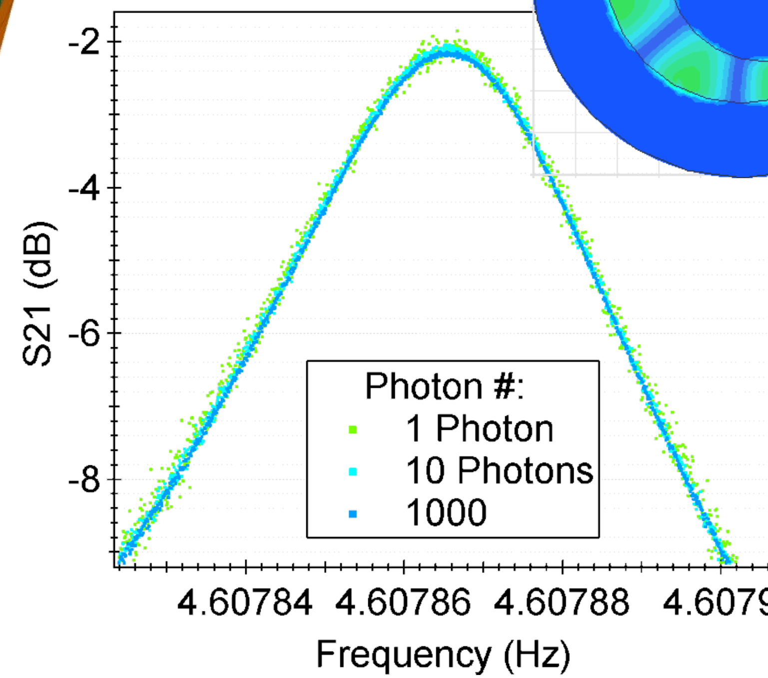


- HFSS participation ratio: 44%
- Common Perpendicular

$Q = 2.1 \cdot 10^6$
$\tan \delta < 1 \cdot 10^{-6}$

`Test Dielectric`



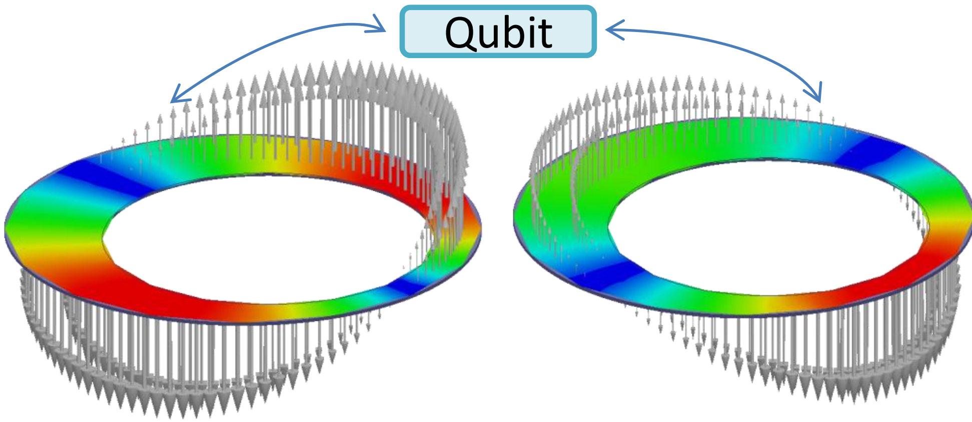


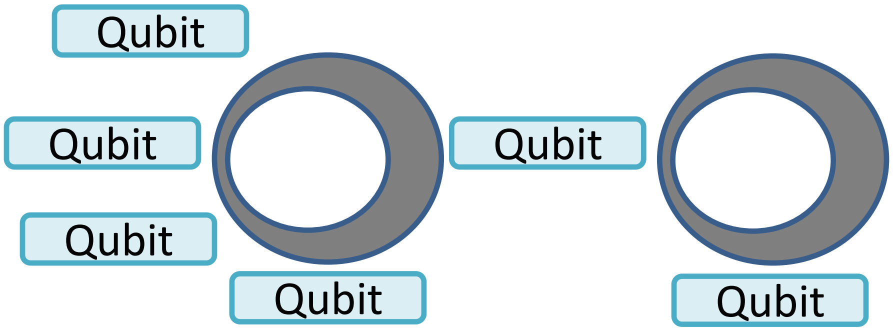
- HFSS participation ratio: 98%
- Differential 4th Harmonic

$Q = 2.0 \cdot 10^5$
$\tan \delta < 5 \cdot 10^{-6}$

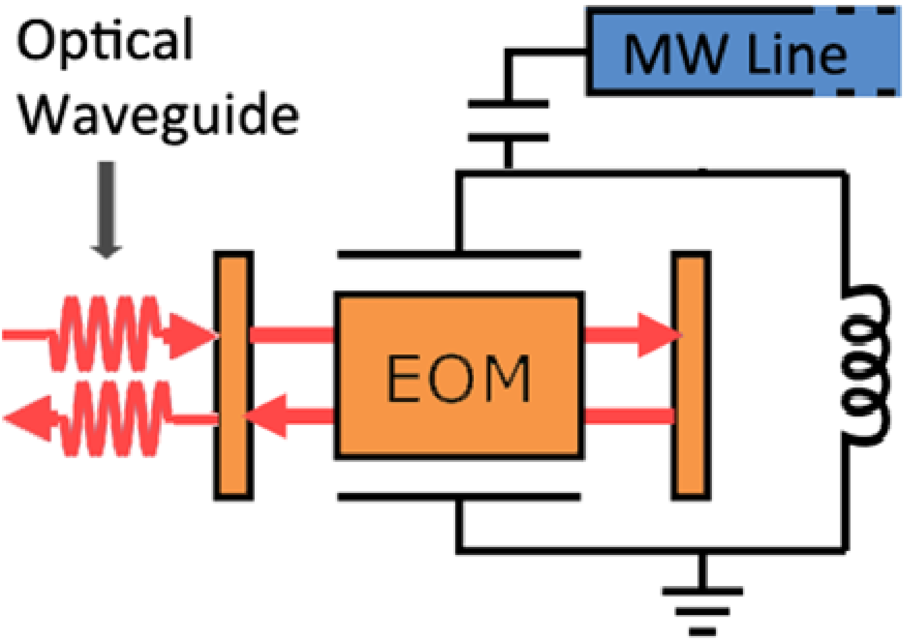
Future Direction

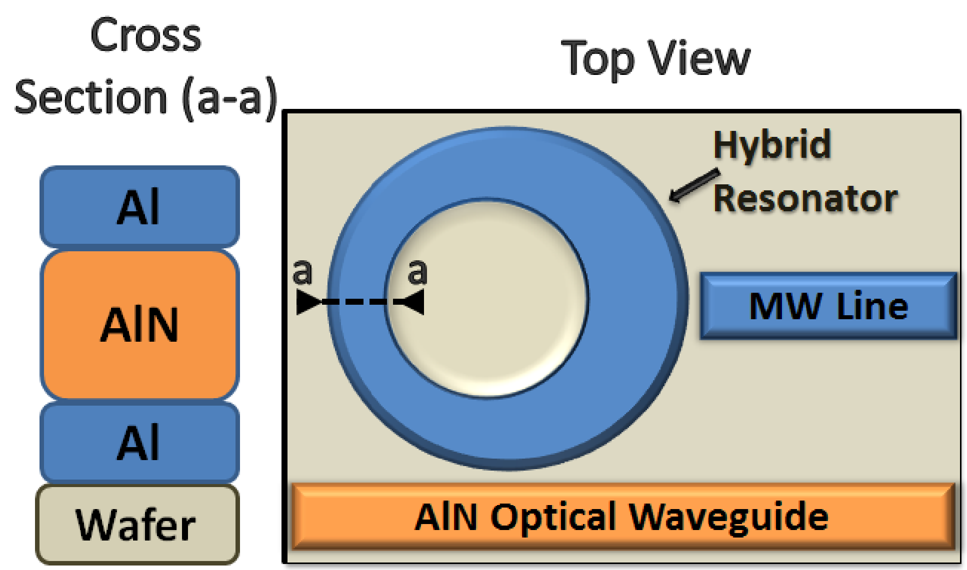
- *Cryogenic material properties*
- *Inductive/Capacitive/ Galvanic coupling to Fluxonium*
- **Integration with multiple qubits and resonators in a '*Wafer-Scalable*' Circuit-QED architecture.**
- **Quantum Bus**





An Idea: EOM





- $\mathcal{H}_C = -\hbar g\left(b + b^\dagger\right)a^\dagger a$
- g ~ 1kHz
- Entanglement
- Laser cooling
- Back-action evading optical measurements of mesoscopic devices

- $\chi^{(2)}$ ~ 4.7 pm/V (among the largest in integrated photonic)
- AlN WGMR Q ~6E5 at 1550 nm

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