Simulating noisy superconducting qubits

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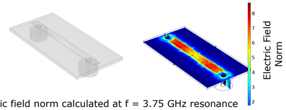
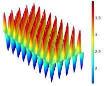
Microstripline and Coplanar Waveguide Resonator Permittivity and Conductivity Studies

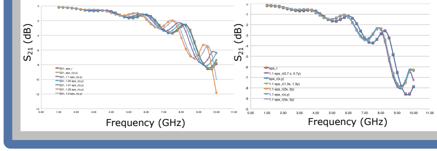
- Microstripline resonator offers a simple geometry to probe surface states



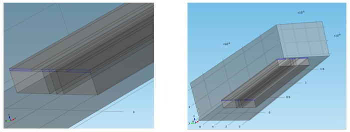
- Electric field norm calculated at f = 3.75 GHz resonance
- Baseline model with spatially independent permittivity, ε_r
- Electric permittivity a uniform function of x, y: $\varepsilon_r(x,y) = \sin(w_x x)\sin(w_y y)$
- Troughs represent through-holes/vias or macroscopic defects



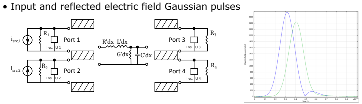
- Transmission measurements reflect changes in $\varepsilon_r(x,y)$ and correspond to resonant shifts due to noise in more detailed models



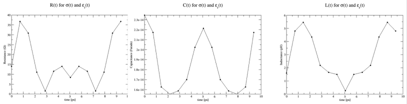
- Coplanar waveguide modeled with air box scattering boundary condition



- Current source excitation lumped circuit model with lumped circuit element representation of the coplanar waveguide as a transmission line
- Input and reflected electric field Gaussian pulses

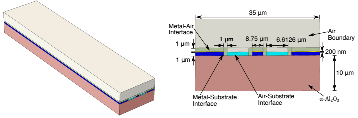


- Extracted lumped circuit parameters as functions of time for $\varepsilon_r(t)$ and $\sigma(t)$



Interface Models of Coplanar Waveguide as Participation Ratio Study Candidates

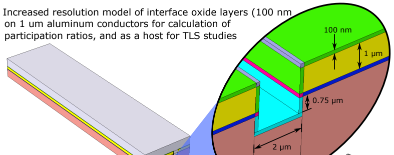
- Model of intentionally oxidized coplanar waveguide with extrinsic concentration of two level systems (TLS's) supplied by 1 μm thick SiN layer [J. Gao, PhD Thesis, Caltech, 2008]

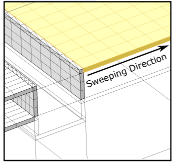


- Participation ratios calculated for SiN and modeled instrinsic oxides [J. Wenner *et al.* APL **99**, 113513 (2011)]

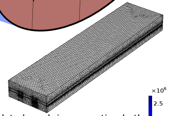
Model	Dimensions (θm)	Substrate-Air (Vertical, ppm)	Substrate-Air (Horizontal, ppm)	Substrate-Air (Corner, ppm)	Metal-Air (Vertical, ppm)	Metal-Air (Horizontal, ppm)	Metal-Air (Corner, ppm)	Metal-Substrate (ppm)
SiN$_x$ Coated	w, s, t_{cpw}, t_{ox}							
	3, 8, 0.2, 1							
Interface Layers	w, s, t_{cpw}, t_{ox}							
	5, 2, 1, 0.100	0.58	8.89	1.29	1.25	0.33	0.32	17
	5, 2, 1, 0.15	0.89	11	2.67	2.26	0.49	0.60	25

- Increased resolution model of interface oxide layers (100 nm on 1 um aluminum conductors for calculation of participation ratios, and as a host for TLS studies

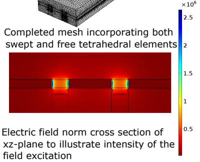




- Swept mesh features used to resolve oxide layers and neighboring domains



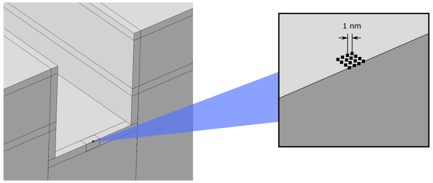
- Completed mesh incorporating both swept and free tetrahedral elements



- Electric field norm cross section of xz-plane to illustrate intensity of the field excitation

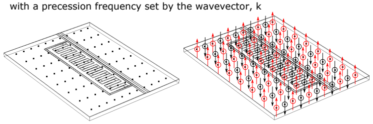
Coplanar Waveguide and Interdigitated Capacitor as Magnetic Dipole Hosts

- Extension of high resolutioin coplanar waveguide model to include a small, dense population of magnetic dipoles as artifical TLS's

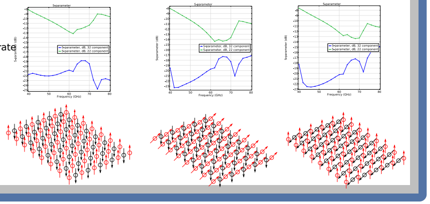


S21, and other figures for measuring the loss due to precessing magnetic diples on a small surface of the cpw.

- Interdigitated capacitor (IDC) as a large area, lumped element capacitor similar to those used in transmon qubits [J. Koch *et al*, PRL A. **76**, 042319 (2007)]
- Magnetic dipoles are dispersed over the surface of the conducting fingers and substrate with a precession frequency set by the wavevector, k

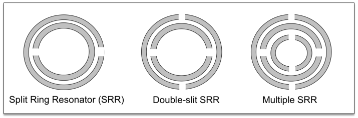


- Antialigned array of dipoles with the orientations shown below the transmission coefficient figures (S_{21}) for the IDC driven by an incident plane wave

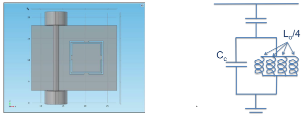


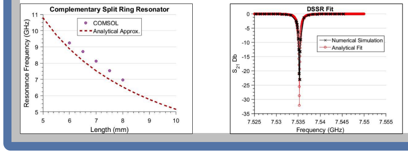
All Metal Dielectric-free Superconducting Resonator

- Systematic investigation of noise sources in superconducting devices

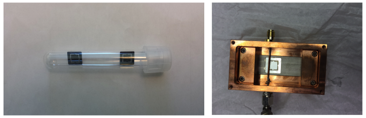


- To the greatest extent possible, eliminate material interfaces from resonator
  - Dielectric-metal, dielectric-vacuum, oxide-metal, oxide-dielectric, etc.
  - Dielectric materals can be incorporated into the resonator design in a controlled fashion to facilitate system study of TLS noise

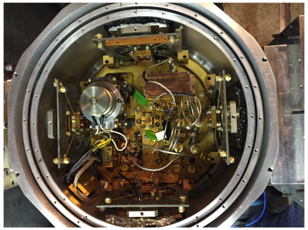




- Two superconducting dual split ring resonators and sample holder



- Sample box inserted into adiabatic demanetization refridgerator (ADR) for first cool down



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