Pacific Northwest
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ADMX 2-4GHz Electronic Tuning Update

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U.S. DEPARTMENT OF ENERGY   BATTELLE

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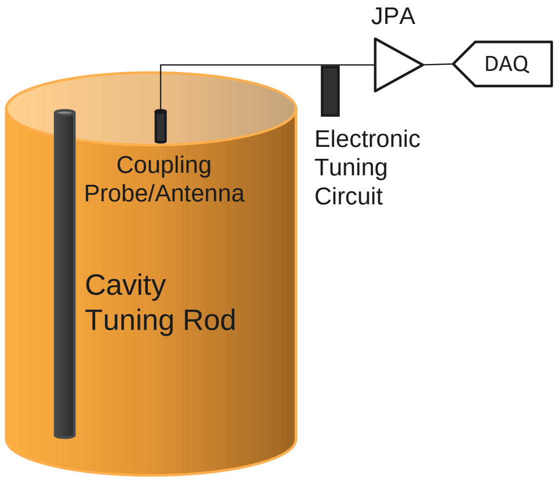
Outline

- Background and motivation
- Summary of research to date
- Simulation and measurement details
- Next steps

Background and Motivation

- As the cavity resonant frequency changes due to tuning rod location, the coupling antenna needs to be tuned to couple into the right frequency
- Current methods use mechanical tuning of coupling antenna
  - Critically coupling of probe into microwave cavity resonant frequency
  - Providing good energy transfer
- Electronic tuning could provide advantages to the current matching technique
  - Removing potential mechanical failure point
  - Heat load
  - Physical size
  - Scalable design for many cavity systems
- Industry applications
  - Reconfigurable antennas
  - Tunable filter / switched filter banks



Microwave Cavity

Example of Electronic Tuning Impedance Match

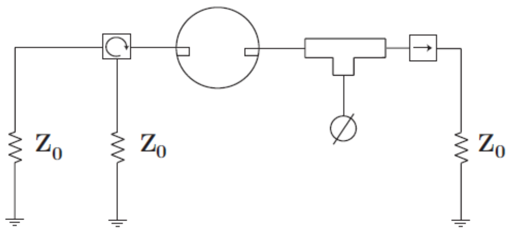
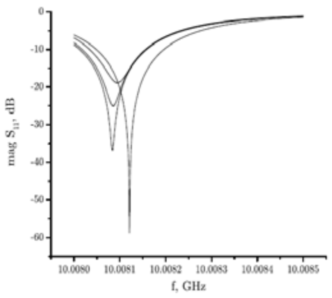


Fig. 8. Simplified diagram of cavity circuit with output matching. Z_0 is the system's characteristic impedance.

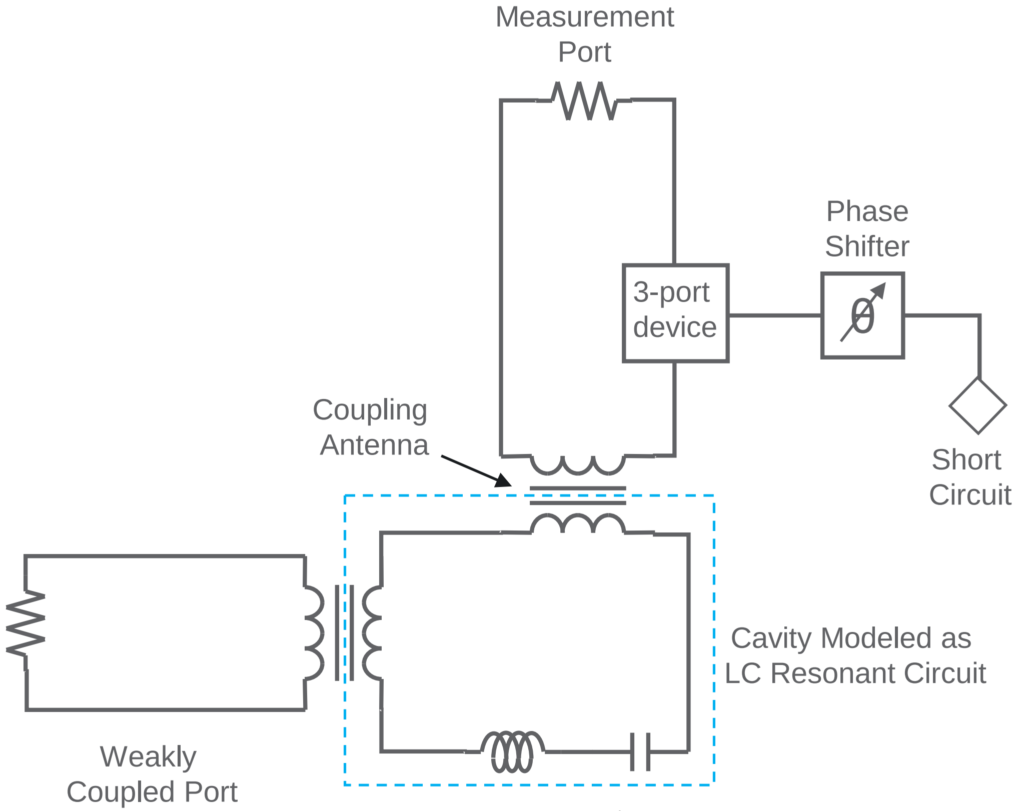


Impedance Control for Critically Coupled Cavities

Bill Riddle and Craig Nelson
National Institute of Standards and Technology
325 Broadway
Boulder, CO 80305-3328
Email: Bill.Riddle@nist.gov

Background: Electronic Tuning Model

- Adopted high level design from LLNL previous work and NRAO
- Cavity simple representation by using ideal LC resonant circuit
- Coupling efficiency set by transformer ratios into cavity
- Phase shifter used to adjust reactance for best coupling from measurement port into cavity
- 3-port network used to connect electronic tuning element with cavity and measurement port



$$f_{res} = \frac{1}{2\pi\sqrt{LC}}$$

Research Summary to Date

- Cavity simulations cascaded with impedance transformers →
- Tunable cavity, adjustable Q, full system s-parameters

- Circulator vs. unmatched tee →
- Unmatched tee providing best result with no isolation between ports

- Tuning stub vs. digital phase shifter →
- Ideal tuning stub (microstrip line) produces good impedance matching, but requires many lengths to match over a broad bandwidth
  - Digital phase shifter proved too lossy

- Tuning JPA inductance via magnetic flux bias →
- New concept proposed by Aaron Cho, research underway

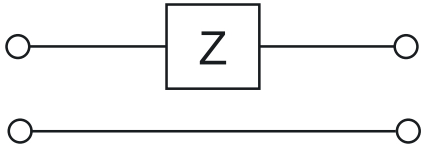
Cavity Simulation

- Cavity simulation created from simple LCR resonant circuit
  - Tunable vs. frequency
  - LC values computed based upon desired Q, resonant frequency and resistance
- Cavity impedance then translated to ABCD matrix
- ABCD matrix then translated to scattering parameter matrix (s-parameters)
- S-parameters used in microwave cascaded analysis simulations

Cavity Modeled as
LCR Resonant Circuit

$$C_{cavity} = \frac{1}{Q * R * 2\pi f_{res}}$$

$$L_{cavity} = \frac{Q * R}{2\pi f_{res}}$$



$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} 1 & Z \\ 0 & 1 \end{bmatrix}$$

$$S_{11} = \frac{A + \frac{B}{Z_0} - CZ_0 - D}{A + \frac{B}{Z_0} + CZ_0 + D}$$

$$S_{12} = \frac{2(AD - BC)}{A + \frac{B}{Z_0} + CZ_0 + D}$$

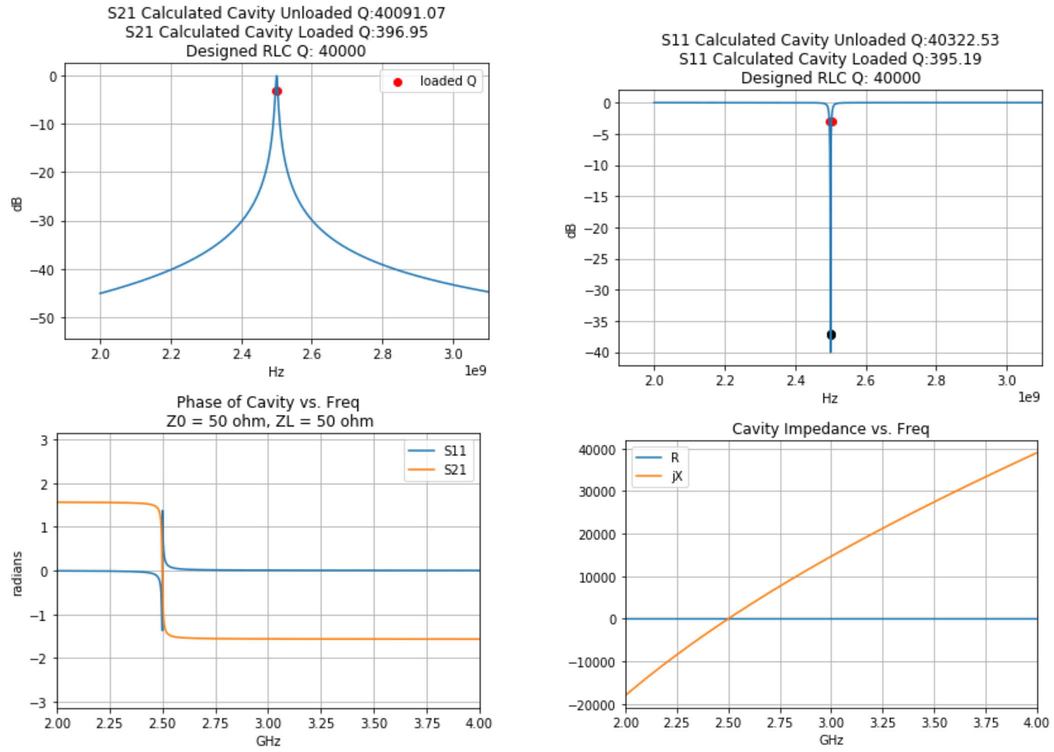
$$S_{21} = \frac{2}{A + \frac{B}{Z_0} + CZ_0 + D}$$

$$S_{22} = \frac{-A + \frac{B}{Z_0} - CZ_0 + D}{A + \frac{B}{Z_0} + CZ_0 + D}$$

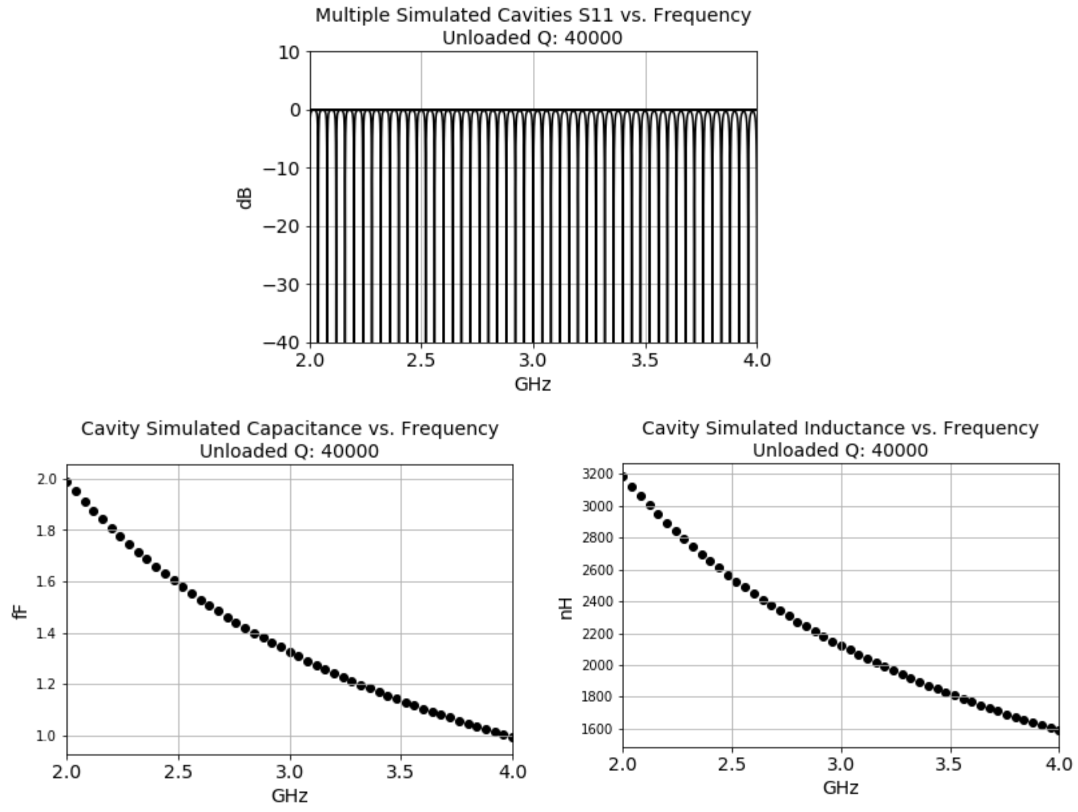
Cavity Simulation Results

- Simplistic LCR cavity model produces desired results
  - Cavity unloaded Q values
  - Resonance frequency
  - Complex impedance

Isolated 2.5GHz Cavity LCR Performance

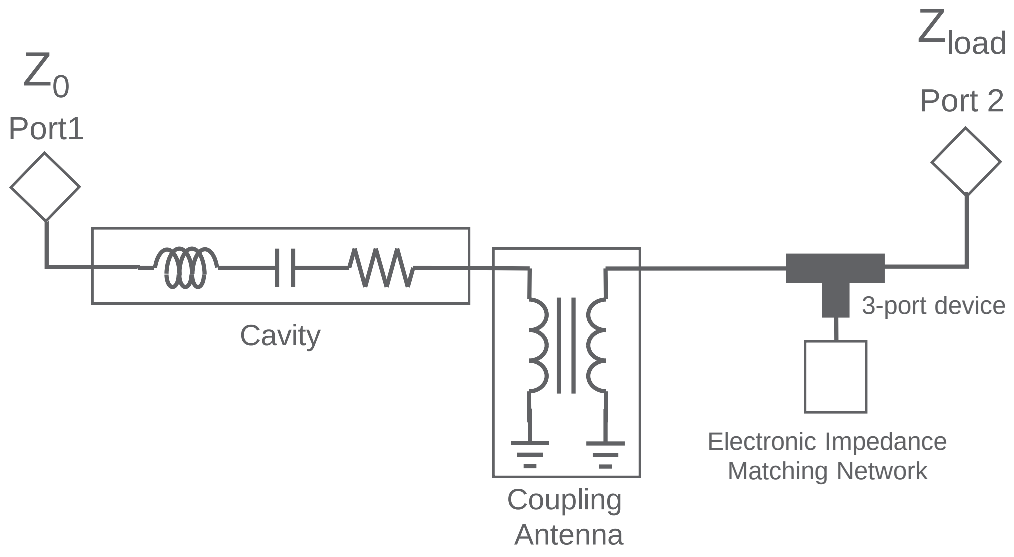


Multiple Cavity Simulations Tuned for Different Frequencies



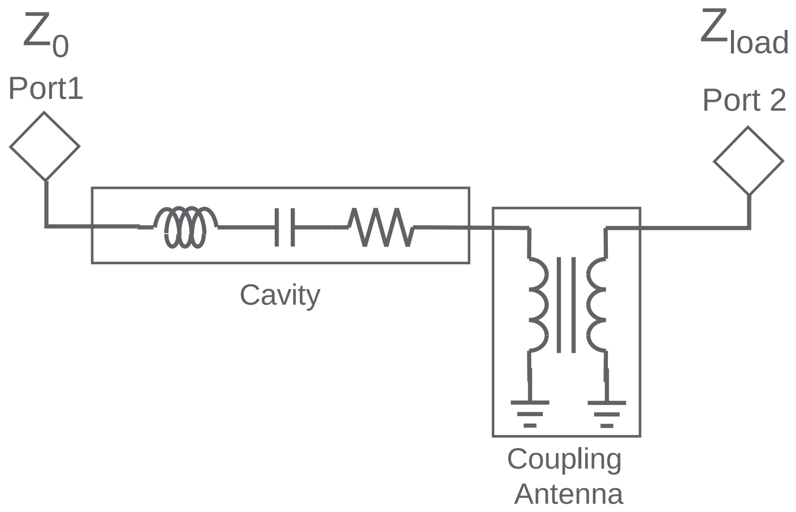
Microwave Cascade Analysis

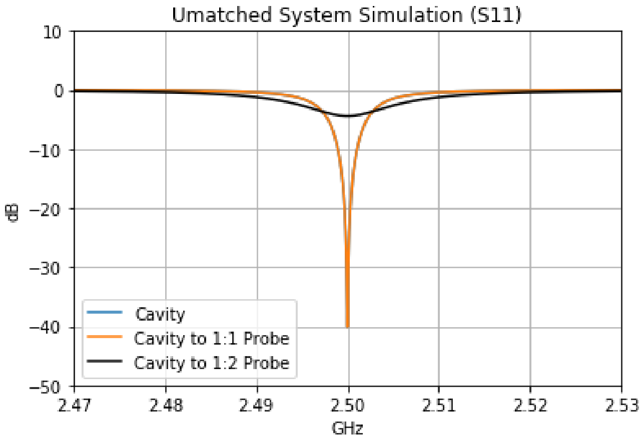
- Cascading s-parameter matrices preserving magnitude and phase relationships vs. frequency
- Allows for transmission and reflection measurements through the cavity system
- Optimization of a tuning circuit for matching Port 2 to the impedance of the cavity
- Initial building blocks established but parameter refinement necessary post proof of concept

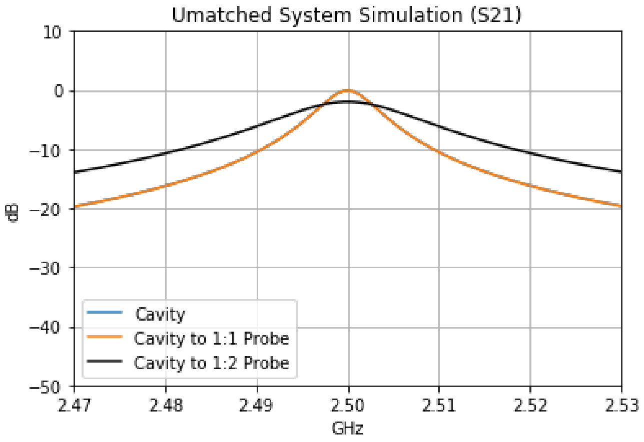


Unmatched System Simulation

- System simulations shown for a 2.5GHz cavity with a 1:2 transformer for the coupling antenna
- S11 goes from -40dB to -4.4dB
  - Appropriate for N^2 impedance change
- S21 incurs loss of 1.9dB due to mismatch
- Transformer coupling used as placeholder to evaluate tuning techniques

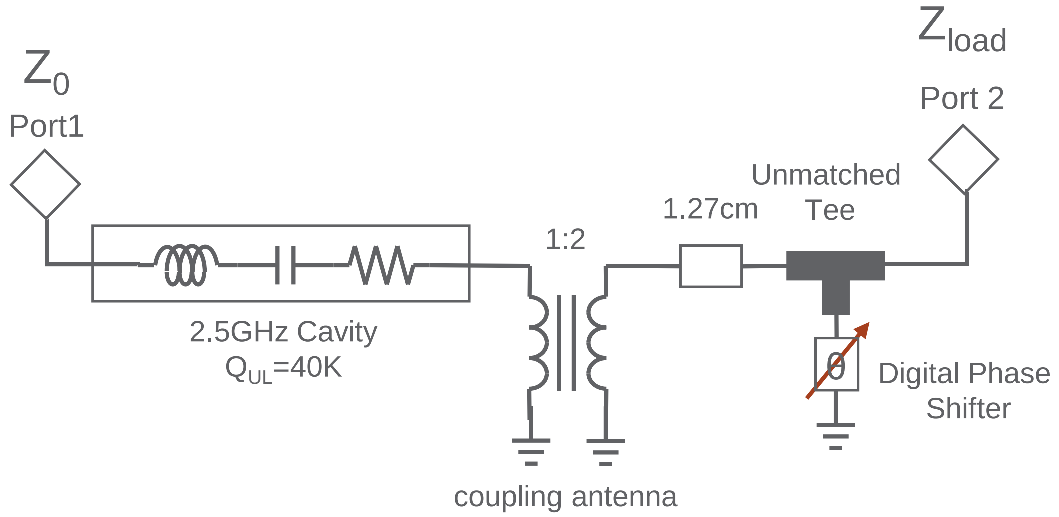




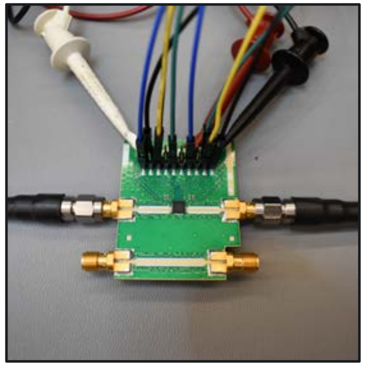


Electronic Tuning via Digital Phase Shifter

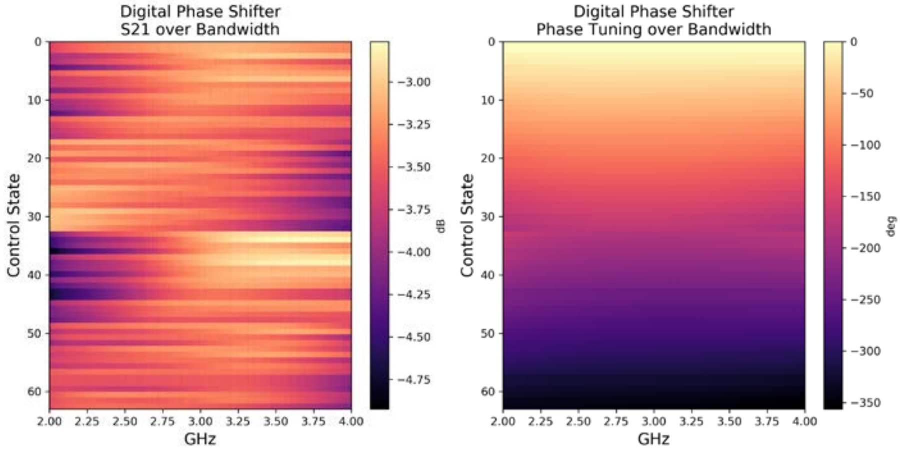
- Measured s-parameters from 2-4GHz vs. control state
- Digital phase shifter s-parameters applied to impedance tuning circuit and system cascade
- Phase shifter showed minimal ability to impact impedance match

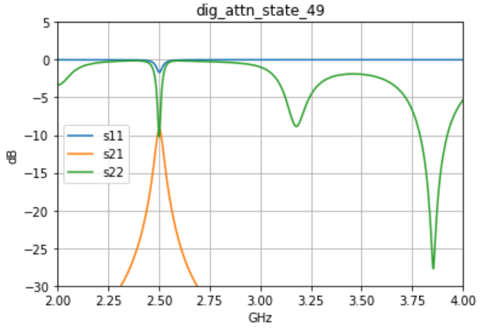


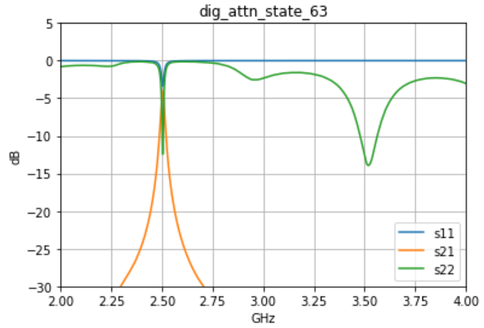
Digital Phase Shifter Under Test



Digital Phase Shifter Performance vs. Control State (calibration line magnitude and phase removed)

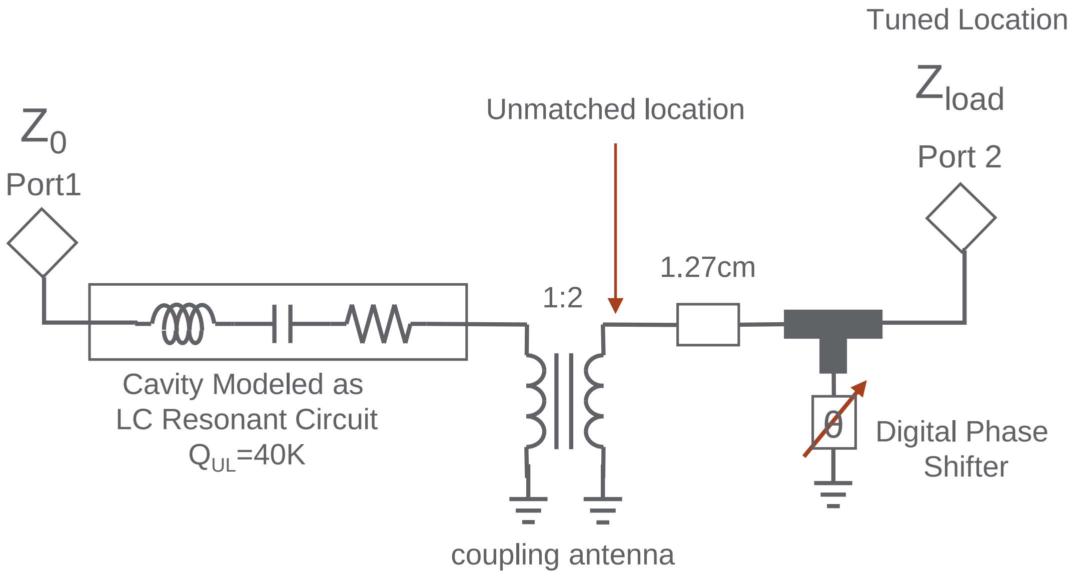


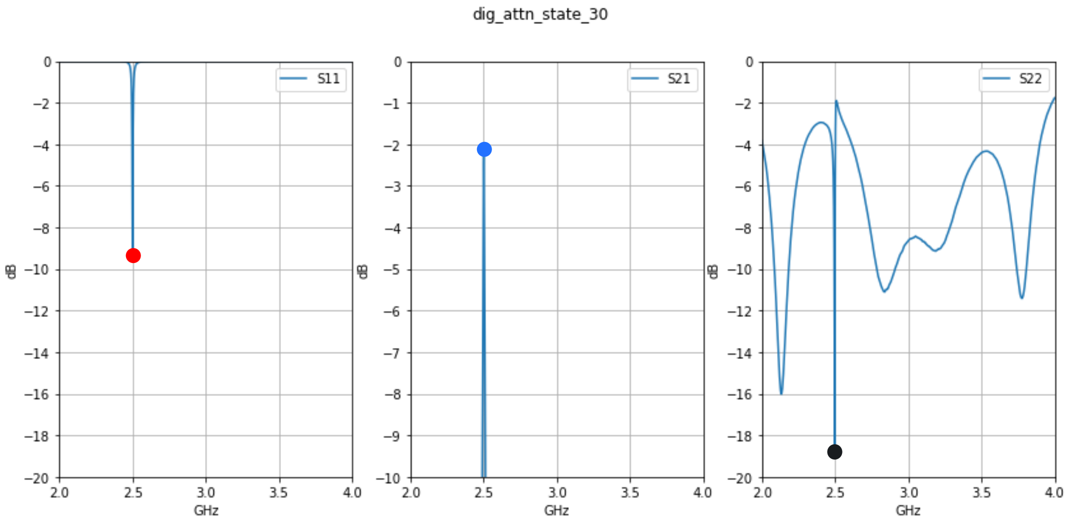


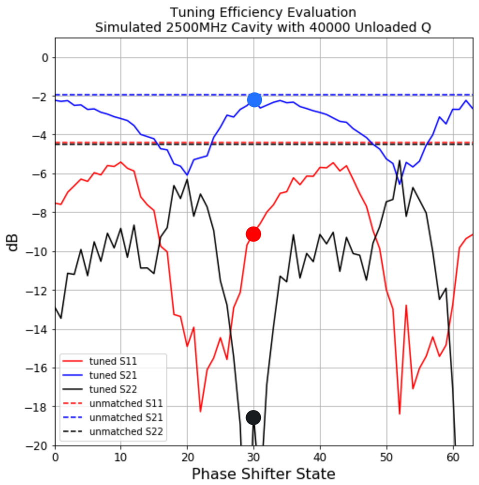


Electronic Tuning with Digital Phase Shifter

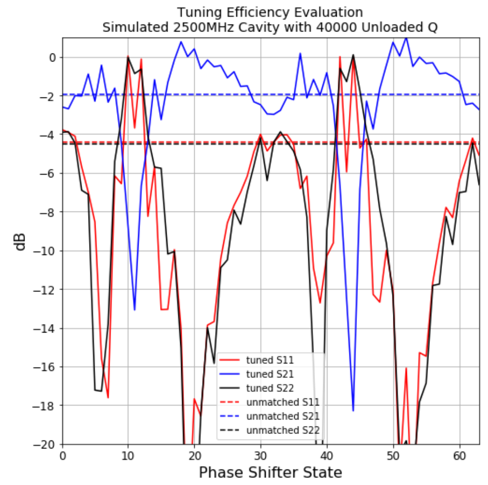
- Digital phase shifter state 30 (best case scenario)
  - S11 (cavity perspective): -9dB
  - S22 (JPA side): -18.5dB
  - S21: -2.2dB
- Summary plots shown for s-parameter performance at 2.5GHz vs. control state
- De-embedding DPS state 0 (for example only)
  - Loss removed but phase adjustment preserved
  - Phase shifter loss requirements ~0.5dB max





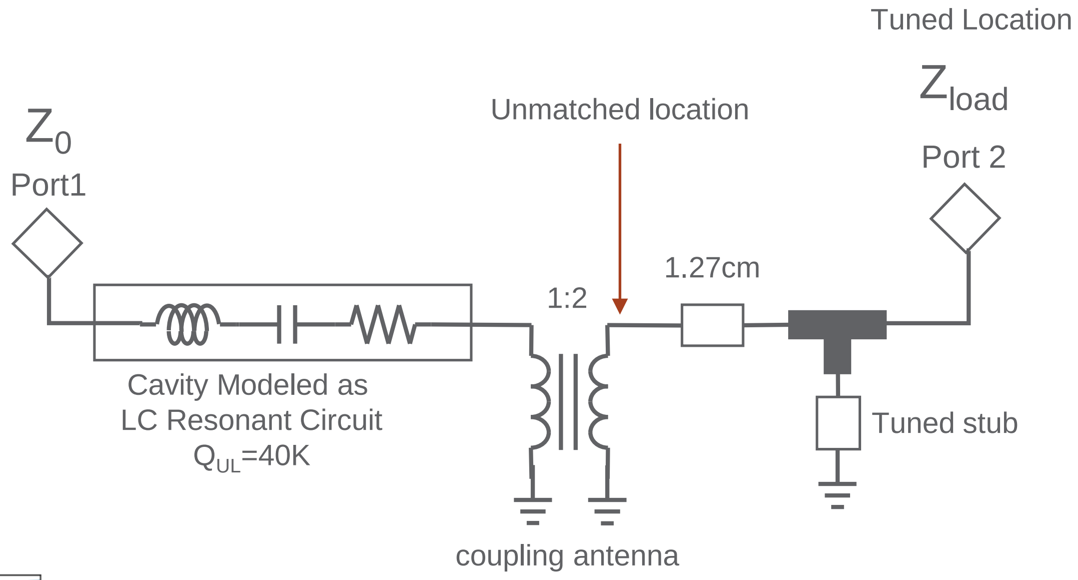


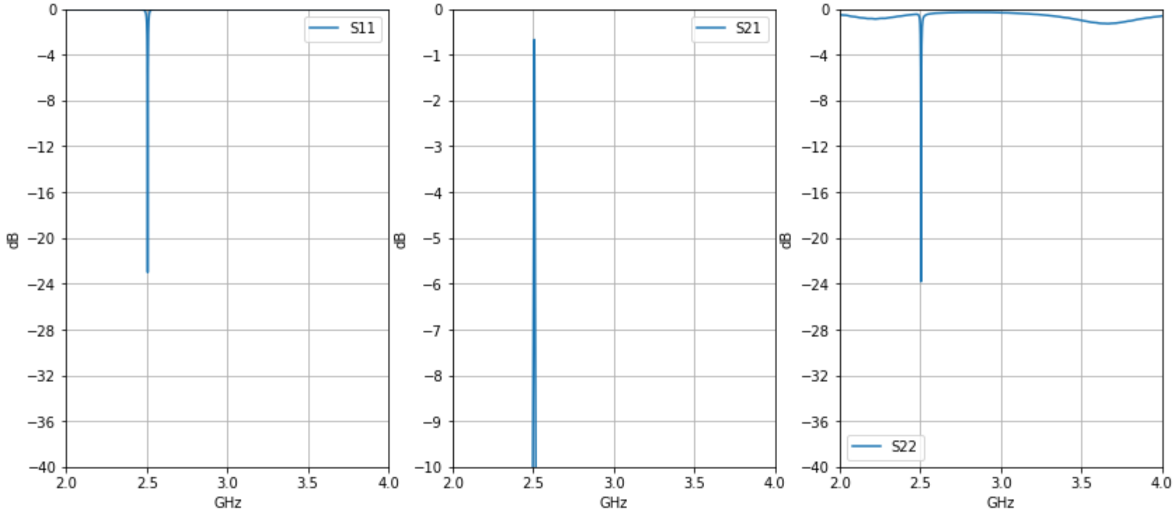
De-Embedded Loss Example

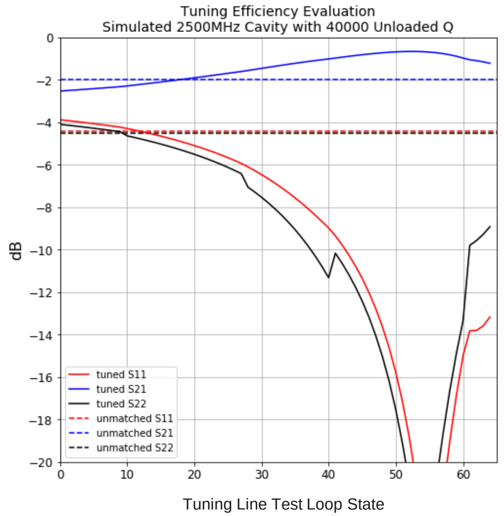


Electronic Tuning with Shorted Transmission Lines

- Tuning is sensitive to preceding transmission line length
- Best case shown with tuning stub
  - S11 (cavity perspective): -23dB
  - S22 (JPA side): -24dB
  - S21: -0.6dB



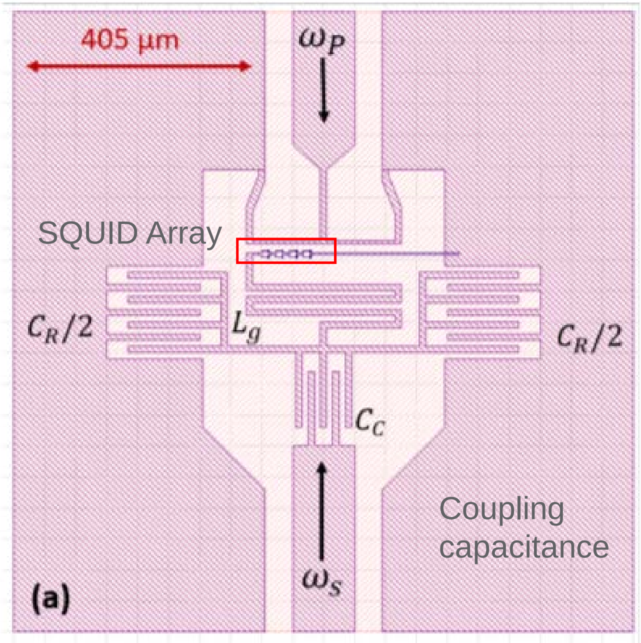




Tuning via JPA Magnetic Flux Bias

- If the ideal tuning stub provides a good impedance match, but the loss associated with a switched – tuning stub network would render it ineffective, a JPA may be able to work as a tunable inductor
- JPA is a resonant amplifier circuit with a coupling capacitance, a capacitance to ground and a tunable inductance
- The magnetic flux bias provided to the SQUID array within the JPA may be used to tune the circuit's inductance
  - This inductance occurs on the non-linear transmission line where the center conductor is an array of squids, and the inductance per unit length is comes mostly from the nonlinear Josephson inductance of the SQUIDS
- Literature shows tuning bandwidth of JPA at ~ 1 octave
  - Lends to determining inductance range

Pump Tone



Signal

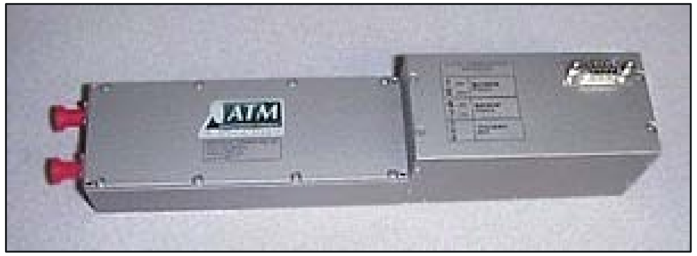
Development and Characterization of a Flux-Pumped Lumped Element Josephson Parametric Amplifier
Esposito M., Rahamim J.

Summary

- Simulations have been developed to:
  - Create LCR cavity s-parameter matrix
    - Tunable vs. frequency, selectable Q
  - Impedance transformers for synthesizing impedance mismatch
- Simulations comparing impedance matching results
  - Circulators vs. unmatched tee
  - Digital phase shifter vs. tuning stub
- Current work
  - Studying JPA tunable inductance
  - Market research on servo-controlled phase shifters for cryogenic applications

	Unmatched Tee w/ DPS	Unmatched Tee w/ Tuning Stub	Unmatched Tee w/ Servo Controlled PS	Unmatched Tee w/ JPA
Tuning Sensitivity	Low	High	High	TBD
Transmission loss	High	Low	Low	TBD
Frequency tunable	Yes	Requires switched tuning stub network	Yes	TBD
Size	Small	Med	Large	TBD
Cryogenic Operation	Yes	Yes	TBD	Yes

Low Loss Motor Driven Phase Shifter



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Thank you

Backup Slides

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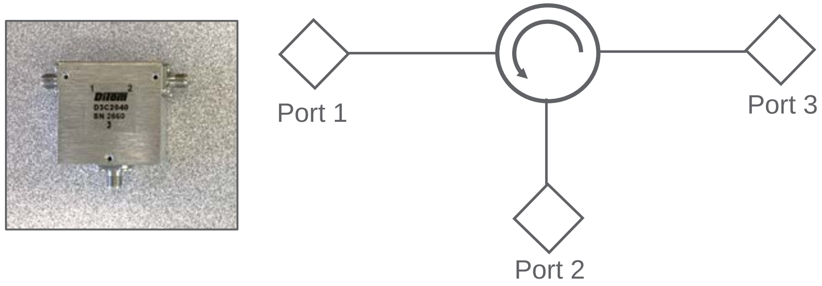
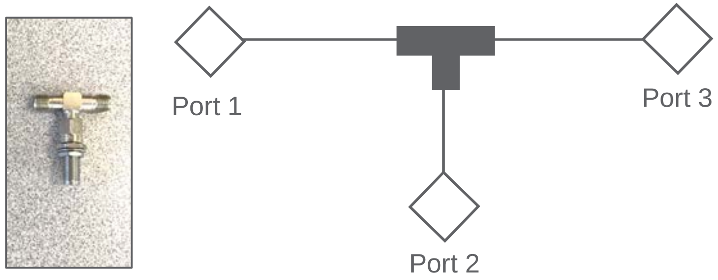
3-Port Network: Circulator vs. Unmatched Tee

- Initial testing of two variations of the three-port network
- Circulator – directional device, S21 != S12, provides isolation between paths
  - Low loss in standard operating direction (~0.6dB)
- Unmatched tee – no impedance matching or isolation.
  - Most sensitive to 3 port impedance matching network

Circulator

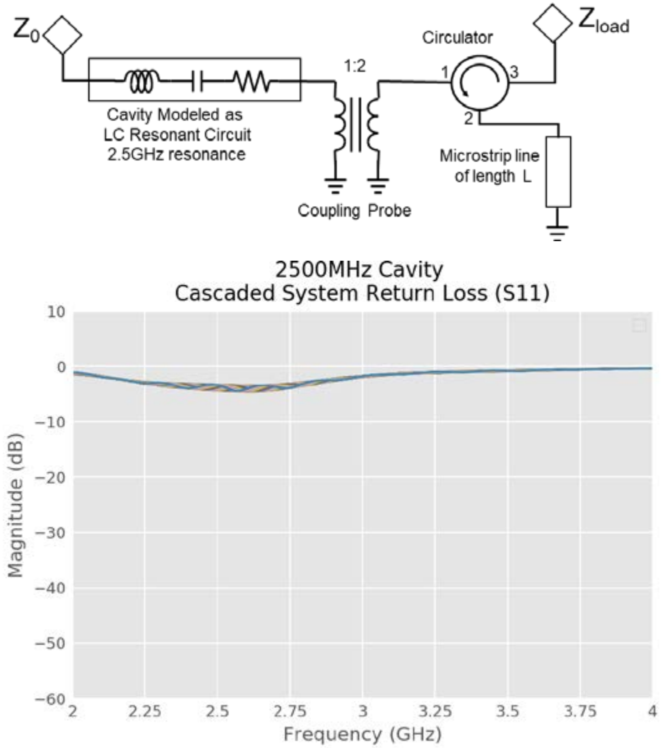


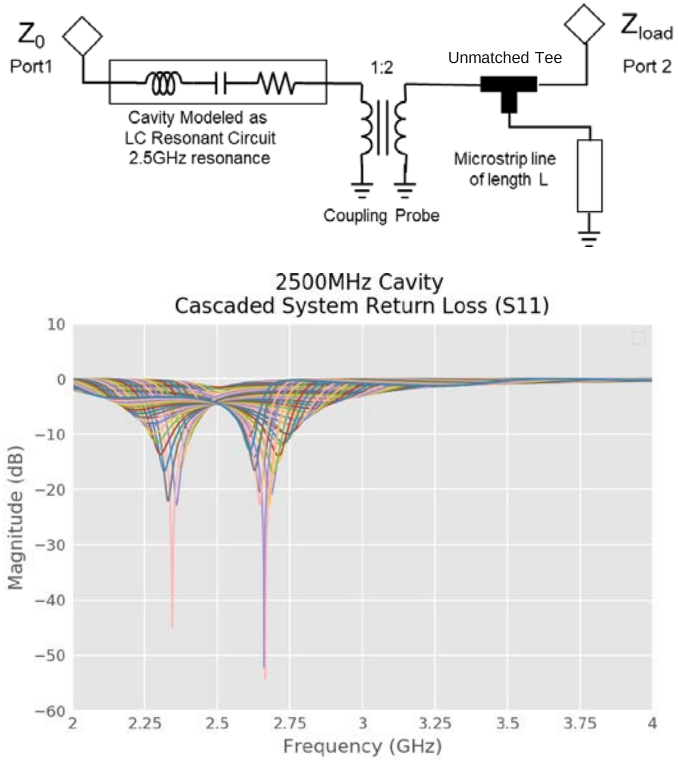
Unmatched Tee



3-Port Network: Circulator vs. Unmatched Tee Simulation Results

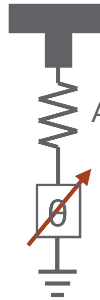
- 3-port network using either a circulator or an unmatched tee
- Shorted microstrip line used as a tuning stub, length varied producing multiple S11 curves
- Isolation from circulator reduces effectiveness of tuning stub
- Unmatched tee connection behaves well and allows for impedance matching





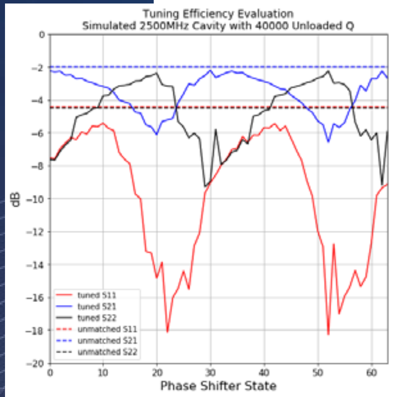
Electronic Tuning with Digital Phase Shifter

- Attenuator placed before de-embedded phase shifter to determine how much loss renders the phase shifter ineffective
  - Leads to phase shifter requirements
- Phase shifter IL needs ~0.5dB IL or less to be effective
  - Possible with large mechanical tuned phase shifters or servo-controlled phase shifters

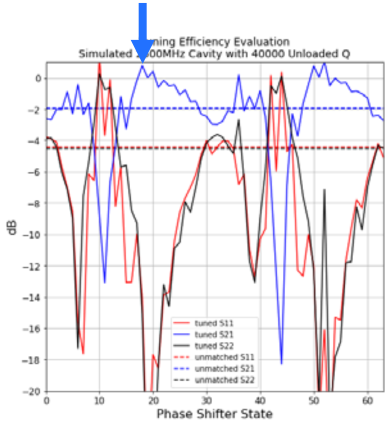


Low Loss Motor Driven Phase Shifter

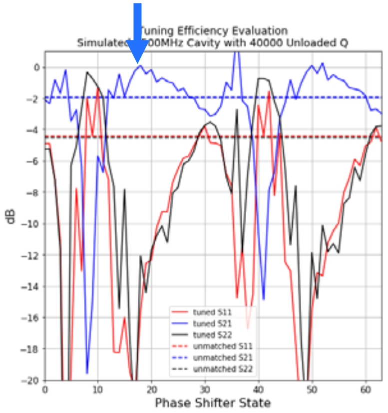
Original phase shifter simulation



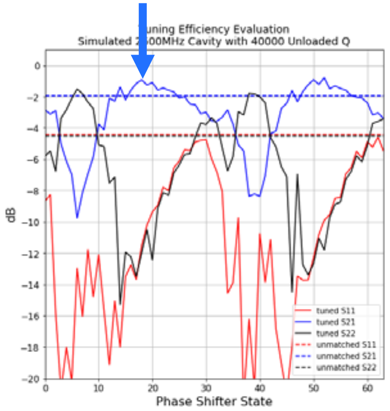
De-embedded Phase Shifter



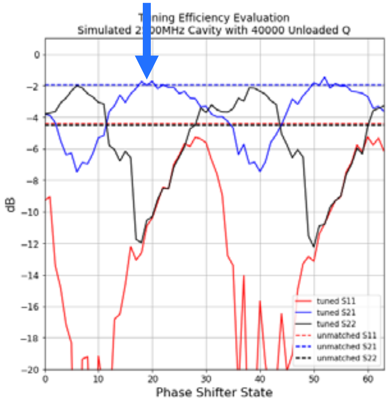
De-embedded Phase Shifter & 0.2dB Attn



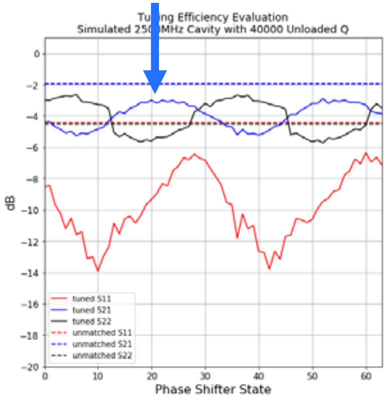
De-embedded Phase Shifter & 1dB Attn



De-embedded Phase Shifter & 2dB Attn



De-embedded Phase Shifter & 5dB Attn



Tuning via JPA Magnetic Flux Bias

- Strategy
  - Determine typical LC parameters values for JPA
    - Values from literature search
  - Determine tunable range for Lg term
  - Apply simplified JPA C-L||C model to cavity simulation to determine tuning effectiveness
- Literature shows tuning bandwidth of JPA at ~ 1 octave
  - Lends to determining inductance range