Characterization of Nonlinear Dielectric Films for the Tuning of Microwave Cavities for Axion Searches

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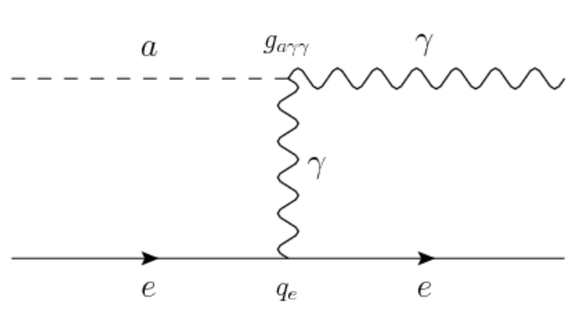
Abstract

The axion is a hypothetical particle that can solve the strong CP problem and that may be the primary component of dark matter in the universe. Experiments such as the Axion Dark Matter eXperiment (ADMX) hope to find the axion through its coupling to photons in the presence of a strong magnetic field. This coupling can be detected using a microwave cavity whose fundamental resonance frequency is matched to that of the photons. By tuning the cavity resonance frequency, the corresponding axion mass range can be scanned. For axion searches above ~1 GHz, future generations of ADMX may use an array of small cavities locked to the same frequency. These cavities will be coarsely tuned using a tuning rod as is done in the current generation of ADMX, but fine-tuning of individual resonators will be necessary for multi-cavity arrays. A candidate fine-tuning method uses nonlinear dielectric films inside the cavities. DC-biasing the films changes their dielectric constant, affecting the frequencies of the cavity modes. This method makes frequency-matched resonator arrays more practical by saving space and minimizing heat load inside the cryostat. This poster presents RF design and simulation and preliminary measurements on the coplanar waveguide resonators used to test the films.

Axions

- Proposed solution to the strong CP problem
- Dark matter candidate
- Mass not well constrained: $m_a = 1\mu\text{eV} - 10\text{meV}$
- Detectable via photons produced in the Primakoff Interaction



$$L_{a\gamma\gamma} = \int_V g_{a\gamma\gamma}\phi_a \mathbf{E}\cdot\mathbf{B}\,dV$$

Figure 1. Coupling of the axion to the magnetic field, resulting in its conversion to a photon (the Primakoff Interaction).[1]

Axion Dark Matter eXperiment

- Resonator cavity axion search in 8 T magnetic field[3]
  - Match the cavity's fundamental resonance frequency to the frequency of the photons from the axion decay.
  - Photons set up a resonance inside the cavity.
- Mass range scanned by tuning the resonance frequency of the cavities with tuning rods
- Current generation has scanned $1.9\mu\text{eV} - 3.6\mu\text{eV}$
- Above ~1 GHz, multiple cavities will be needed:
  - Coarse and fine-tuning necessary
  - Heat load and space constraints

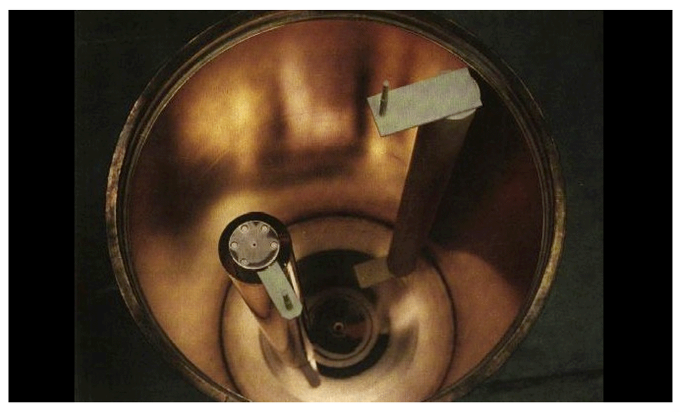


Figure 2. ADMX current-generation cavity with two tuning rods.

Figure 3. Proposed seven-cavity array for next-generation, high-frequency search with example tuning rod assembly for coarse tuning.

Nonlinear Dielectric Materials

- Candidate fine-tuning method
- Dielectric constant changes nonlinearly with applied DC bias voltage
- Individual cavities' resonance frequencies can be shifted using films with different applied voltages.

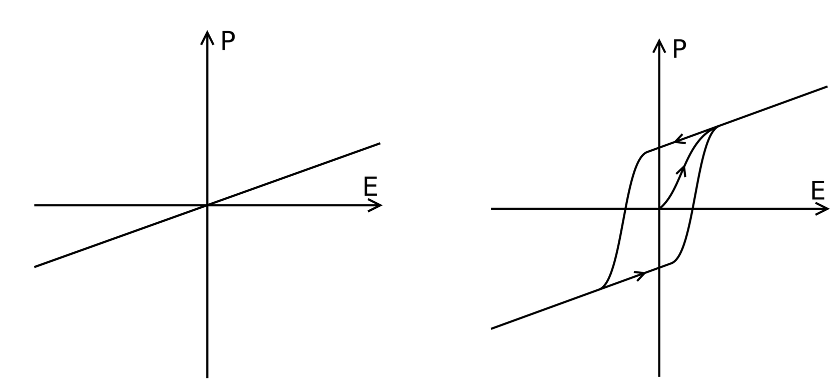


Figure 4. Polarization versus applied electric field for left, a normal dielectric material, and right, a nonlinear dielectric material.[4]

Characterizing the Films

- Coplanar waveguide (CPWG) resonator testing setup with a square film of strontium titanate (STO) nonlinear dielectric film over the resonator
- Adjusting the bias voltage on the dielectric square shifts the resonance of the board, moving the peak in its transmission spectrum

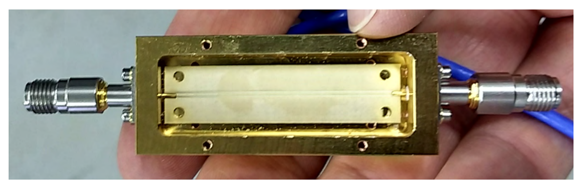


Figure 5. CPWG resonator in box.

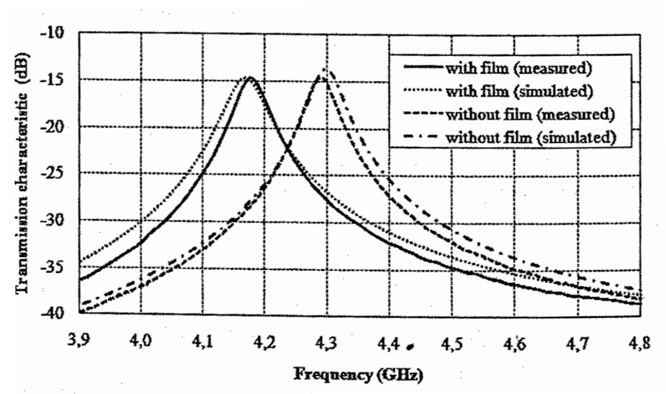


Figure 6. Transmission peak shifting from biased dielectric.[2]

Simulations

- By matching transmission data to simulation, the dielectric constant can be determined.
- Simulations done using Ansys HFSS finite element modeling software

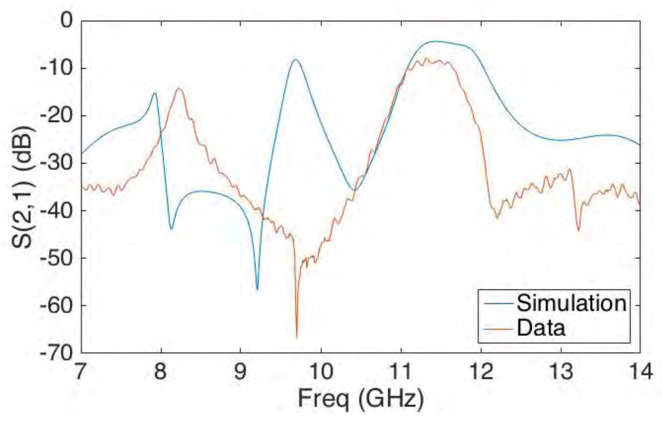


Figure 7. Transmission spectrum of 11.6 GHz resonator without the dielectric square.

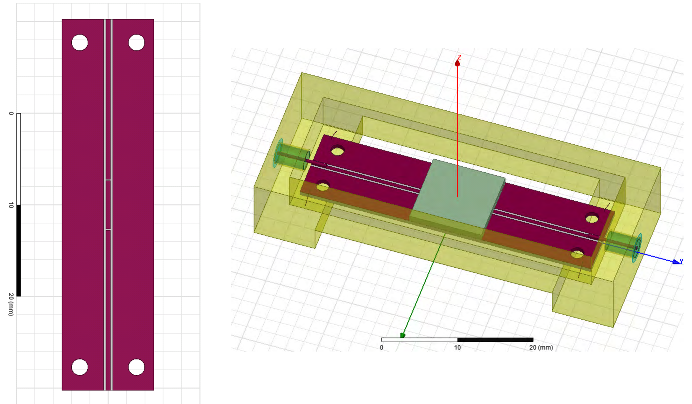


Figure 8. Left, simulated CPWG resonator geometry from HFSS. Right, with dielectric square in its testing box.

Experimental Setup

- Transmission spectra taken as an S21 through-port measurement with a network analyzer
- Future measurements will be taken at cryogenic temperatures in a Physical Property Measurement System (PPMS).

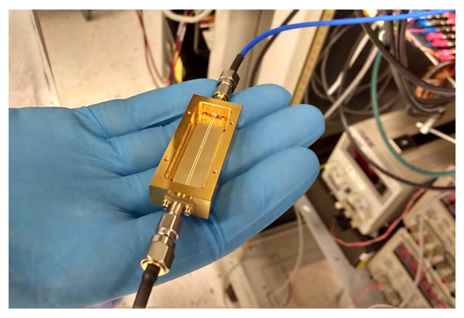


Figure 9. CPWG connected to the network analyzer.

Figure 10. PPMS and insert with CPWG box attachment.

Results

- Matched resonance peak of bare board from simulation and data (See Figure 7.)
- Observed frequency shifting in simulations by changing the dielectric constant of the film square.

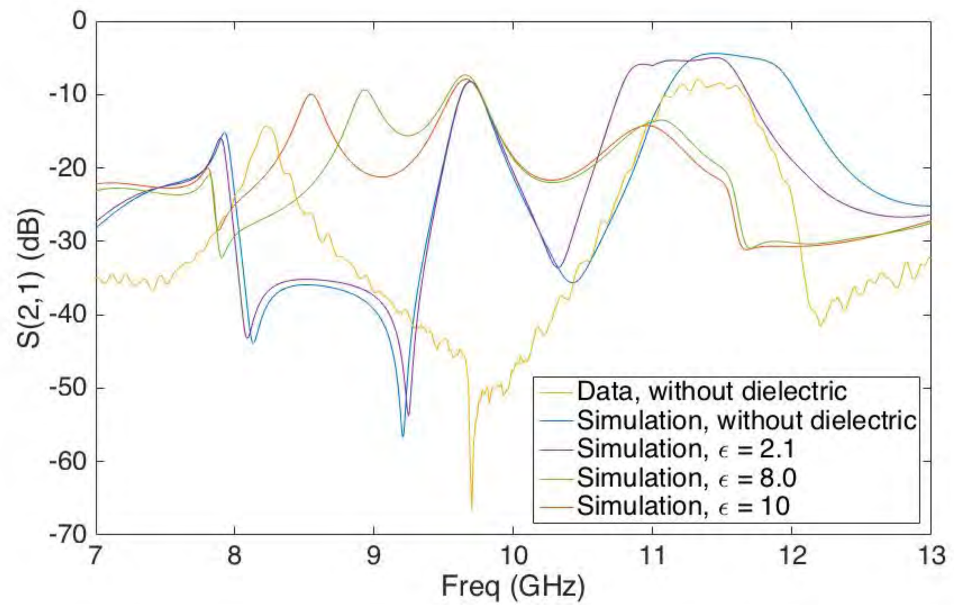


Figure 11. Transmission spectra of simulation and data for CPWG resonator with squares of varying dielectric constant.

- Assessed the field structure of the resonance to confirm the origin of the transmission peak.

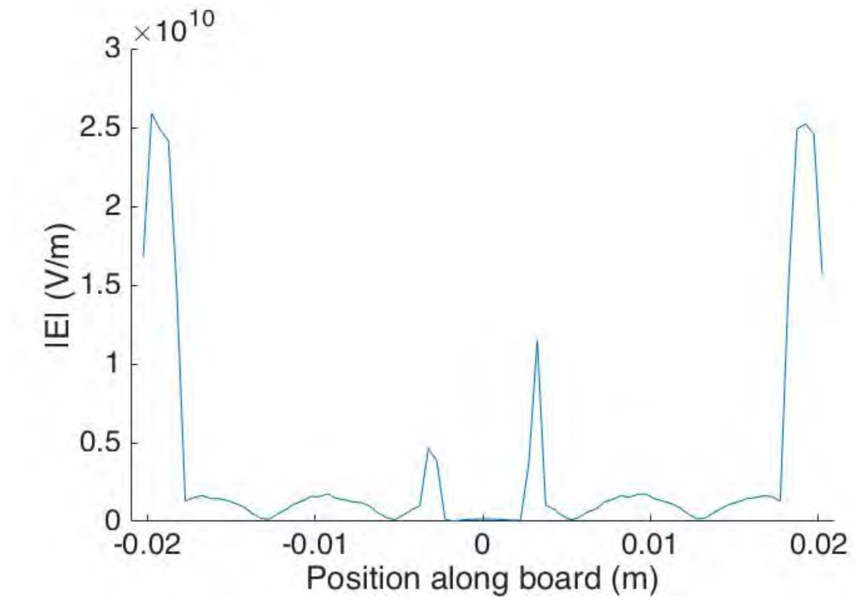


Figure 12. Simulated magnitude of the E field at resonance along the length of the CPWG transmission line with a dielectric square of ε = 8.0 and frequency of 8.9 GHz.

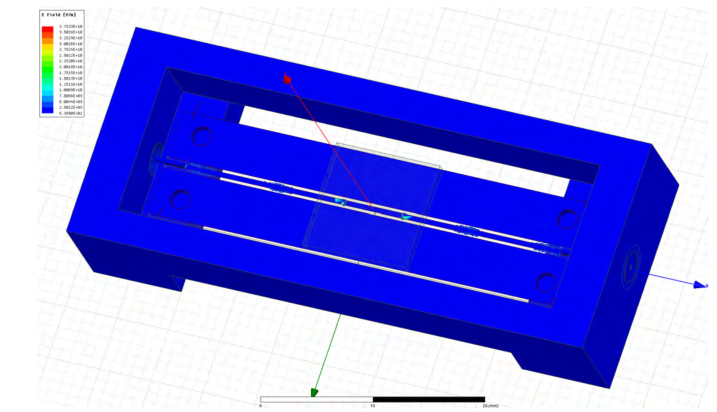


Figure 13. E field plot for the same resonance with an ε = 8.0 dielectric square.

Future Work

- Test the CPWG resonators in the PPMS system.
- Implement and test the films in resonator cavities.

References

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[2] J. I. Marulanda, M. Cremona, R. Santos, M. C. R. Carvalho, and L. S. Demenicis. Characterization of SrTiO3 thin films at microwave frequencies using coplanar waveguide linear resonator method. Microwave and Optical Technology Letters, 53(10):2418–2422, 2011.

[3] L. J. Rosenberg. Dark-matter qcd-axion searches. Proceedings of the National Academy of Sciences, 112(40):12278–12281, 2015.

[4] Wikimedia Commons. Ferroelectricity, 2016.

Acknowledgments

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