Microwave Range Relative Permittivity Measurements using a Rectangular Waveguide for Axion Dark Matter Search

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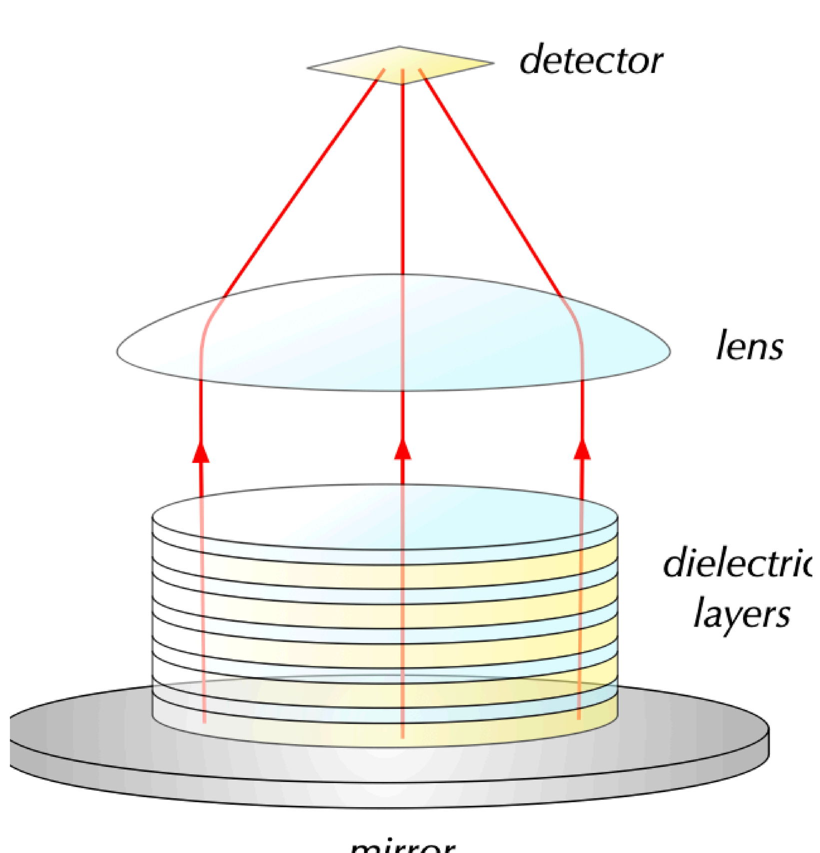
Introduction

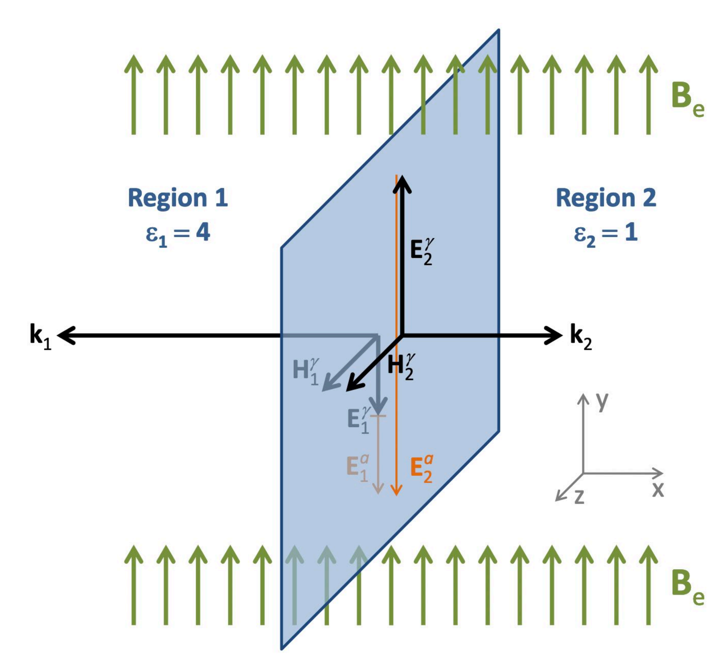
Axions are a hypothetical particle which are a strong candidate for dark matter. These particles arise from the Peccei-Quinn solution to the strong charge-parity problem. The strong-CP problem arises from quantum chromodynamics, which predicts that charge and parity symmetry violation should be possible, but no such violation is found in experiments.

BREAD (Broadband Reflector Experiment for Axion Detection) is an axion search. The main detector has a cylindrical geometry with a parabolic mirror. Our project concerned the dielectric haloscope, an alternative detector, which consists of a stack of dielectrics, a mirror, a focusing lens, and a receiver.

Dielectric haloscopes can detect axions under a strong external magnetic field. When the axion is accounted for, Maxwell's equations require waves to be emitted at the boundary between two dielectrics. In the haloscope, each dielectric boundary emits a wave (caused by axion) and the power builds up through the stack, so that the output wave can be detected by the receiver.

The dielectric haloscope allows greater flexibility and a wider axion mass search range than traditional cavity resonators, since cavity resonators would need to be very small to measure high frequencies (and therefore high masses).





$$E_1^\gamma = -\frac{E_0}{n_1}\left(\frac{1}{n_2}-\frac{1}{n_1}\right) \quad \text{and} \quad E_2^\gamma = +\frac{E_0}{n_2}\left(\frac{1}{n_2}-\frac{1}{n_1}\right)$$

$$H_{1,2}^\gamma = E_0\left(\frac{1}{n_2}-\frac{1}{n_1}\right)$$

Figure 1: Concept design of Dielectric Haloscope from BREAD meeting (Left). A diagram of the boundary between two dielectrics in a magnetic field with formulas for emitted EM waves (Right)

Project Goal

Relative permittivity is a frequency dependent complex quantity whose real part is the dielectric constant and whose imaginary part represents how much like a conductor the material is. The ratio of the imaginary to real parts of the permittivity is the loss tangent, which shows how lossy a medium is. The power of the emitted wave in the haloscope depends on the relative permittivity of the materials used. If the loss tangent is too high, the wave will be absorbed by the dielectrics. Thus, to design an effective dielectric haloscope, we need a way to measure the relative permittivity and loss tangent of dielectric materials.

Relative Permittivity Measurement Setup

We will use a setup consisting of a rectangular waveguide (WR-42), Rogers TMM4, TMM13i, and 3035 Dielectric Sheets, 2 Waveguide to Coaxial Adapters, 2 coaxial cables, a Rohde & Schwarz Vector Network Analyzer, and a Calibration Kit

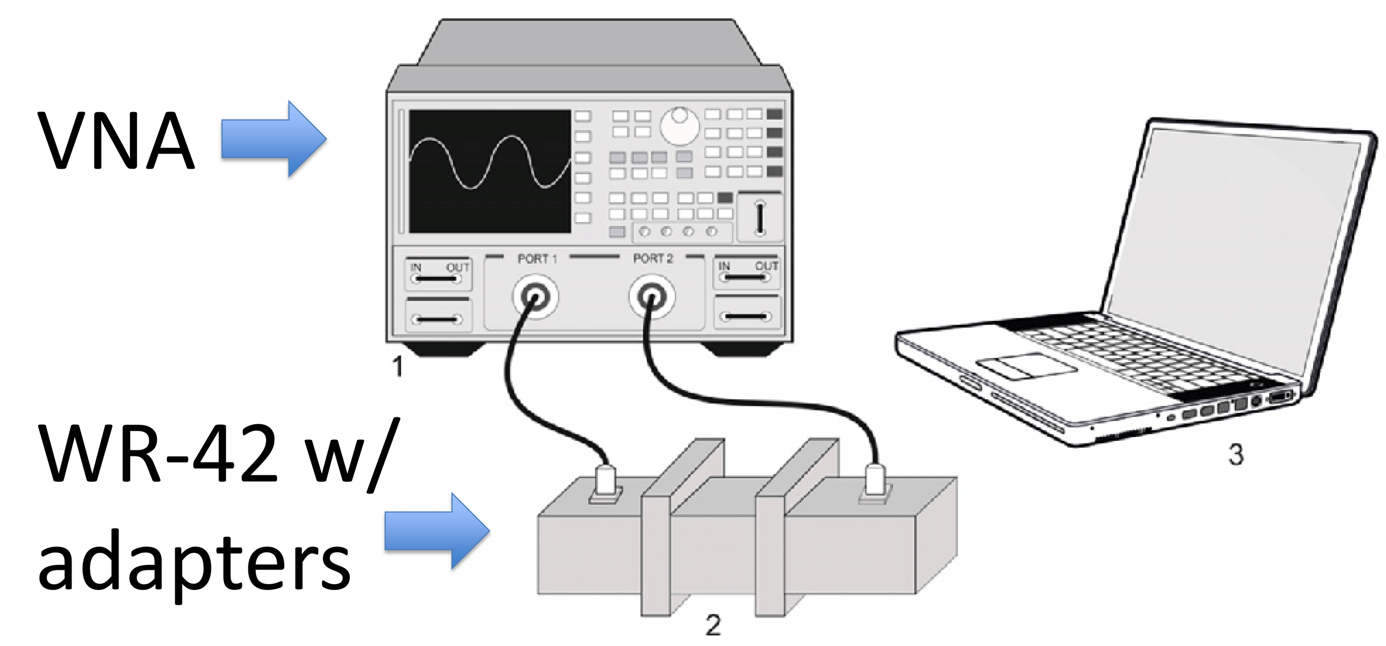


Figure 2: Labelled theoretical schematic of measurement setup

Methods and Results

We used the waveguide method to determine relative permittivity. A piece of the sample is inserted into the waveguide, which is attached to a Vector Network Analyzer (VNA) via 2 coaxial adapters. The VNA measures the S-parameters of the waveguide setup, which can be used to extract the relative permittivity and loss tangent of the materials. Extraction of the material properties from the S-parameters is done via the Nicholson-Ross-Weir (NRW) Algorithm, which was coded in Python. The apparatus was simulated in Ansys HFSS.

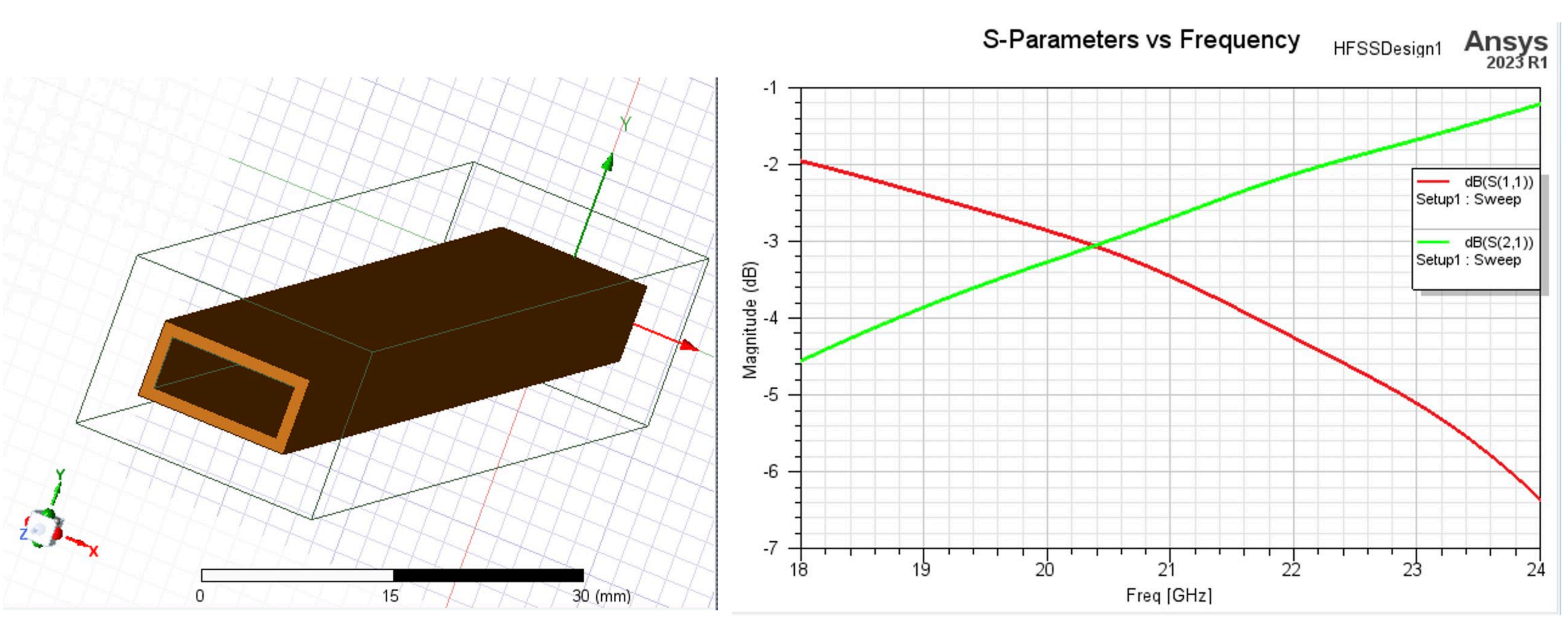


Figure 3: Simulation of waveguide with Rogers TMM4 material inserted (Left). Simulated S-parameters (Right).

Conclusion

We have currently simulated the measurement setup and written code in Python to extract the relative permittivity using the NRW algorithm. The NRW code is still being debugged. We are currently in the process of calibrating the VNA for S-parameter measurements and milling the sample to fit inside the waveguide.

References

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[2] Nowak, Daniel & Gal, B. & Granat, K. & Jaworski, G. & Więcławek, R.. (2017). Determination of Moisture Content in Synthetic Moulding Sand on the Grounds of Relative Permittivity Measurement. Archives of Metallurgy and Materials. 62. 10.1515/amm-2017-0322.

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