Electromagnetic Modeling of a Millimeter-Wavelength Resonant Cavity

COMSOL CONFERENCE
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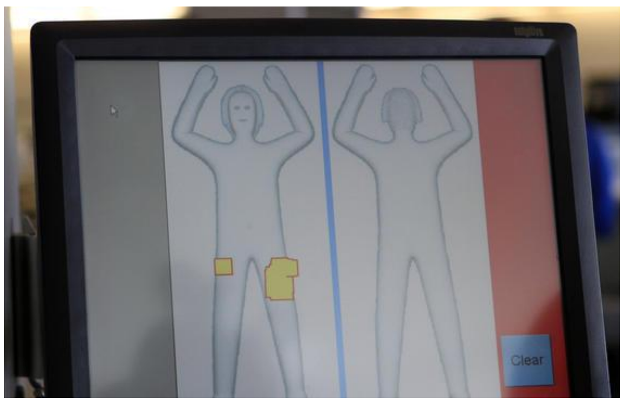
Dielectric Measurement

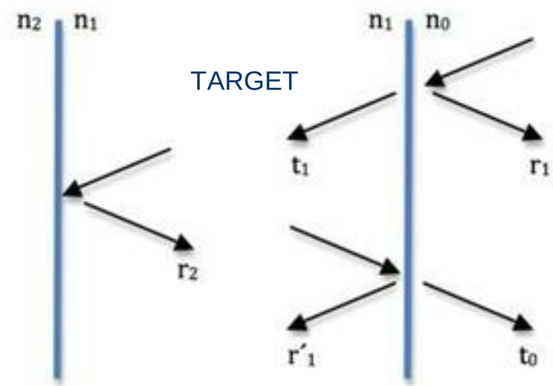
Motivation

- Advanced Imaging Technology (AIT) passenger screening systems identify potential threats in millimeter-wave images



A TSA officer demonstrates the use of full-body scanners at Ontario International Airport.
(Irfan Khan / Los Angeles Times December 28, 2015)

- Governing physics:
  Fresnel equations
- Phenomenology:
  Refractive index $n = \sqrt{\varepsilon}$



$$r = r_1 + t_0 r_2 t_1 \left(e^{i\theta} + (r_1' r_2) e^{i2\theta} + \cdots\right)$$

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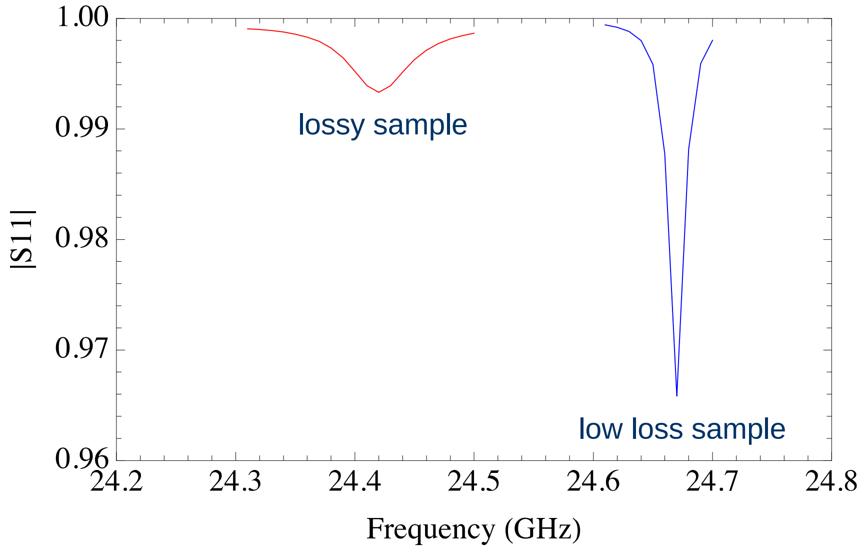
Resonant Cavity Method



- Frequency shift: Re ε
- Frequency width : Im ε
- Vary ε in *EM* simulation to match experiment

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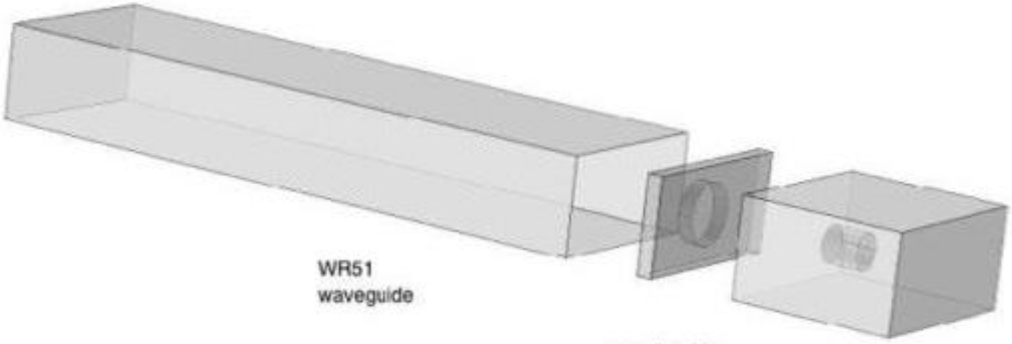
Experimental Design

- Cavity constructed from WR51 waveguide 12.95 x 6.48 mm, height 11.09 mm
- Sample embedded in plastic HDPE fixture
- Waveguide transmission line
- Coupling iris in wall of waveguide and cavity



Ref: Weatherall, J.C., Barber, J. Smith, B.T., Resonant System and Method of Determining a Dielectric Constant of a Sample, U.S. Patent Application 14/943,362 , Nov. 17, 2015.

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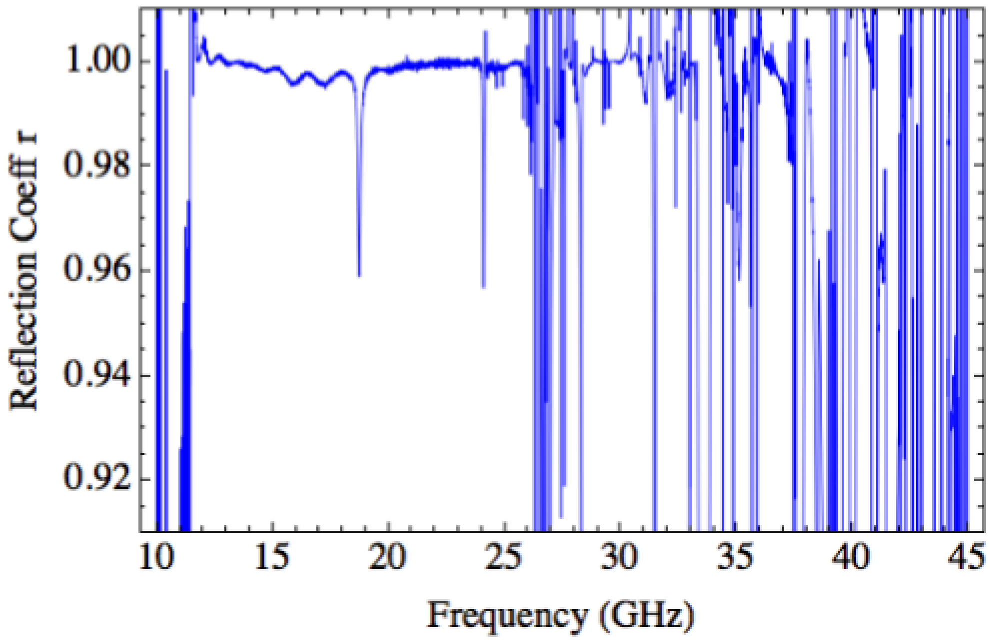
WR51 Cavity Spectrum

- Modes TE102 and TE301



Simulation Fidelity

- Simulation must include effect of the external components (network analyzer, waveguide, and coupling iris/antenna)

- Lumped circuit theory? OR

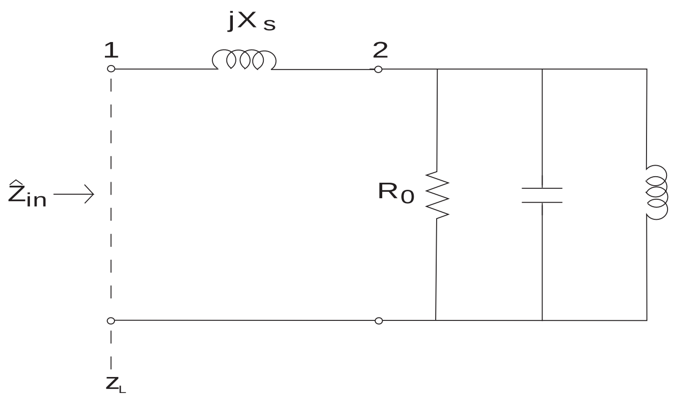


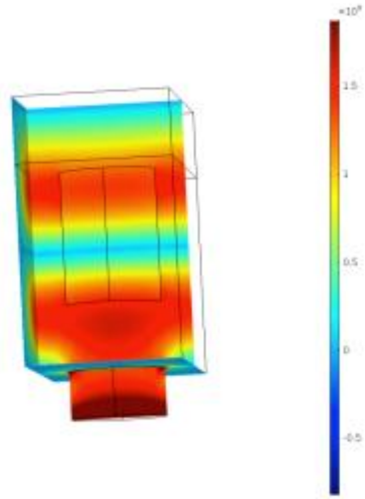
Fig. 2. Circuit diagram used to analyze the cavity mode with a parallel resonant circuit. X_s represents the coupling loop inductance. The input reference plane is located at $z = z_L$, which represents the input connector to the cavity.

Riddle, B., and Nelson, C., Proc of the 2005 IEEE Intl Frequency Control Symp, p 488-493, 2005.

- Field solution

  COMSOL RF module

  Frequency domain study



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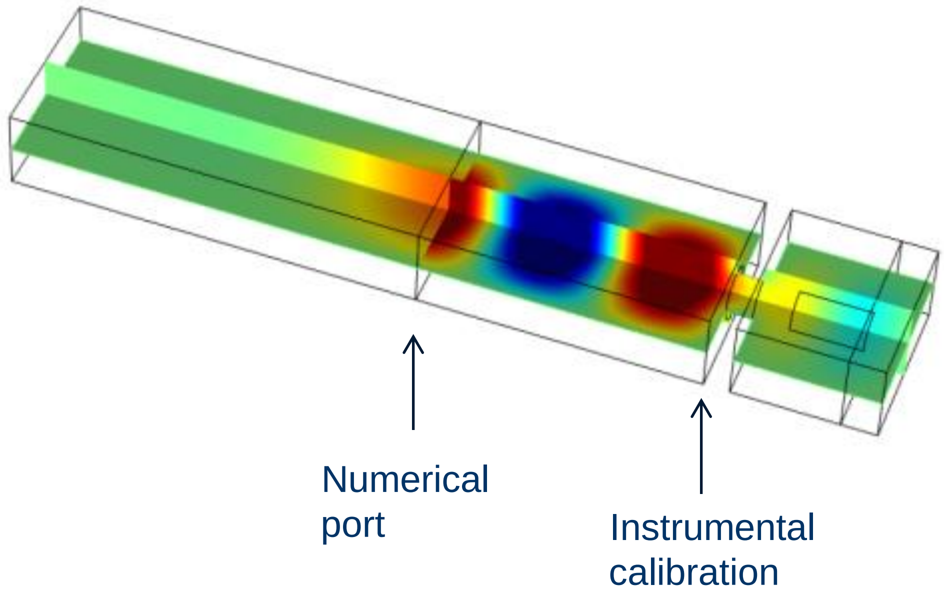
COMSOL Simulation

- Experiment:
  - Measurement of S11 reflection coefficient
- Simulation:
  - S11 at internal simulation port, calibrated to correct loading due to measurement system

OR

  - Compute input impedance *at iris* from Poynting's theorem to compute S11



Electric field E_y at 19.51 GHz

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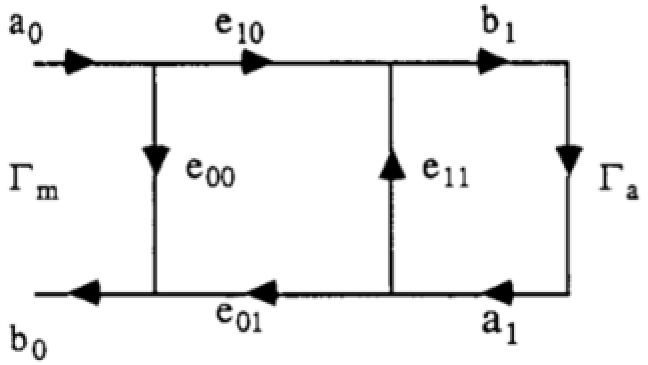
Method 1: S11 Calibration

- One-port calibration, compute corrections: e_{00}, e_{01}, e_{11}
- Three simulations:
  1. Metal-backed waveguide, $r = 1$
  2. Metal backed waveguide, displaced ΔL, $r = exp(i2k_z \Delta L)$
  3. Absorber/PML at reference plane, $r = 0$



$$r = \frac{S_{11} - e_{00}}{e_{01}e_{10} - e_{11}e_{00} + e_{11}S_{11}} \rightarrow \frac{S_{11} - e_{00}}{e_{01}e_{10}}$$

(no multi-path)

REF: Umari, et al., IEEE Trans. Instrum. and Meas., 40, 19-24 (1991).

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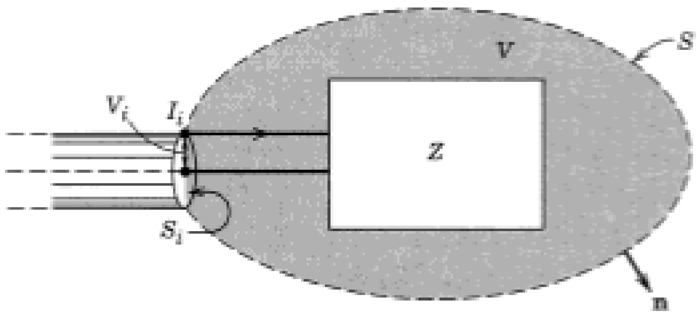
Method 2: Poynting's Theorem

- Input impedance of two-terminal linear network computed from fields

$Z = R - i\,X$

$$R = \frac{1}{|I_i|^2}\left\{Re \int_V \mathbf{J}^* \cdot \mathbf{E}\, d^3x + \oint_{S-S_i} \mathbf{S} \cdot \mathbf{n}\, da + 4\,\omega\, Im \int_V (w_m - w_e)\, d^3x \right\}$$

$$X = \frac{1}{|I_i|^2}\left\{4\omega\, Re \int_V (w_m - w_e) d^3x - Im \int_V \mathbf{J}^* \cdot \mathbf{E}\, d^3x \right\}$$



REF: Jackson, Electrodynamics, Sec. 6.9, 3rd ed (1999).

- Expressions computed by COMSOL: *Wmav, Weav, Qrh*
- Input current, I_i, computed by integrating displacement current over iris aperture
- S11 calculated $S_{11} = \frac{Z - Z_0}{Z + Z_0}$

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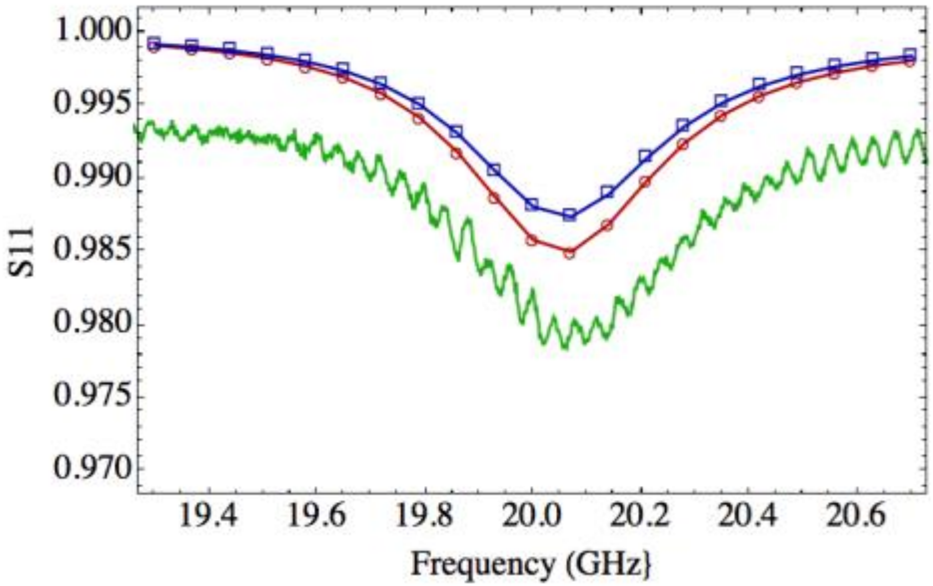
Results



Method 2 (Poynting)

Method 1(Calibration)

Experiment

Solution:

$\varepsilon = 2.57 + 0.28i$

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Conclusion

- Frequency-domain computer modeling accomplishes the identification of dielectric constant of material-under-test by matching reflection coefficient to experimental measurement.
- Physics-based calculation of the reflection coefficient allows calculation at reference planes that are not conveniently connected to a simulation port.
- Reference measurement inside resonant system removes effects of loading by measurement system.

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