Mentor

DMTS: Billy C. Brock

Manager

Kurt W. Sorensen

Passive & Active Electromagnetic Frequency Selective Surfaces for High-Power Beam Applications

Org: 05345 SAR Sensors & Technologies

Jacques H. Loui

TRUMAN FELLOWSHIP
2006-2009

LDRD Investment Area: Strategic Partnerships

LDRD Day, 2008

Sandia National Laboratories

Goal, Approach and Content

Goal:
Produce novel, reconfigurable, metal/dielectric surfaces/volumes for adaptive control over EM scattering.

Approach:
Embed tunable materials as periodic unit-cells in a thick metal plate to affect electromagnetic wave propagation based on electrical configuration.

Variation of unit-cell geometry

Controls Frequency & Angle Dependence

Variation of unit-cell filling

Addresses Tunability

- tapered unit-cells
- compound unit-cells
- sub-wavelength unit-cells
- anomalous transmission

EM Applications

Radome/Filters

Flat Lens

Tunable Absorbers

Meta-Surfaces

- changing permittivity
- permeability tensors
- ferrite-based FSSs
- dispersion engineering

Content:
Progress made in areas →

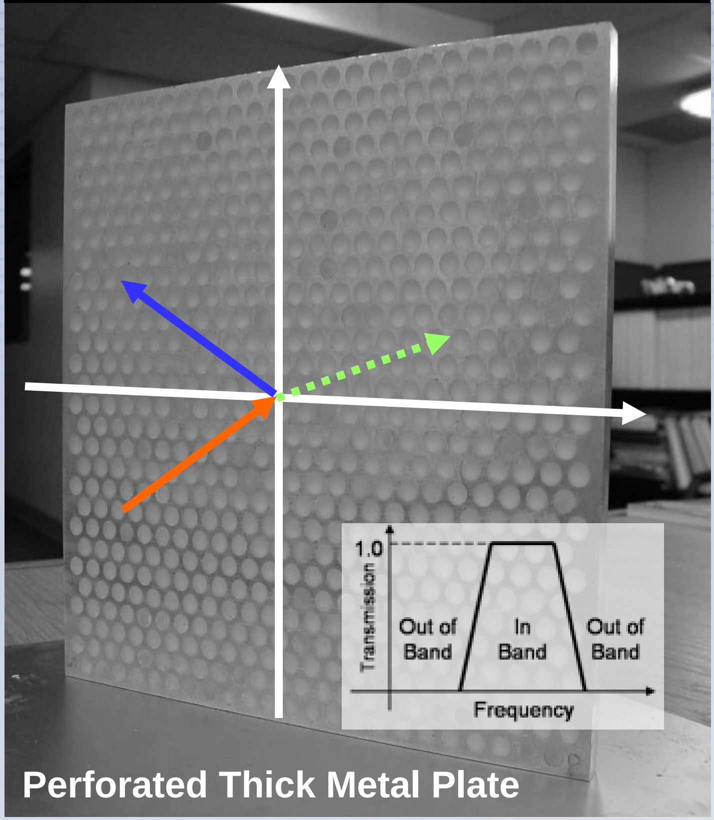
Theoretical | Numerical | Experimental | Application

Approach for tunable FSSs

- switches
- attenuator
- feed
- diode
- amplifiers
- delay

→

Natural Heat Sink, Compact and Rigid

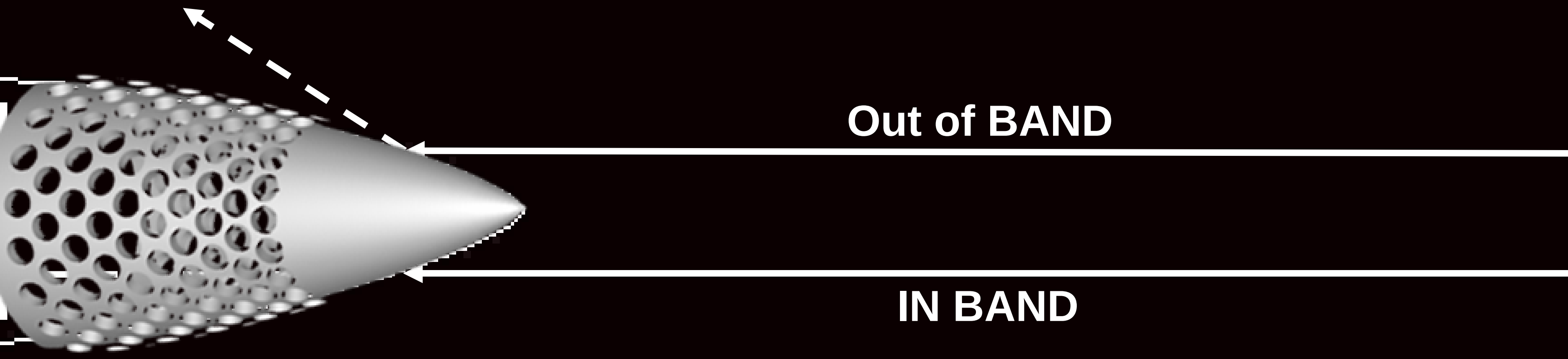


Perforated Thick Metal Plate

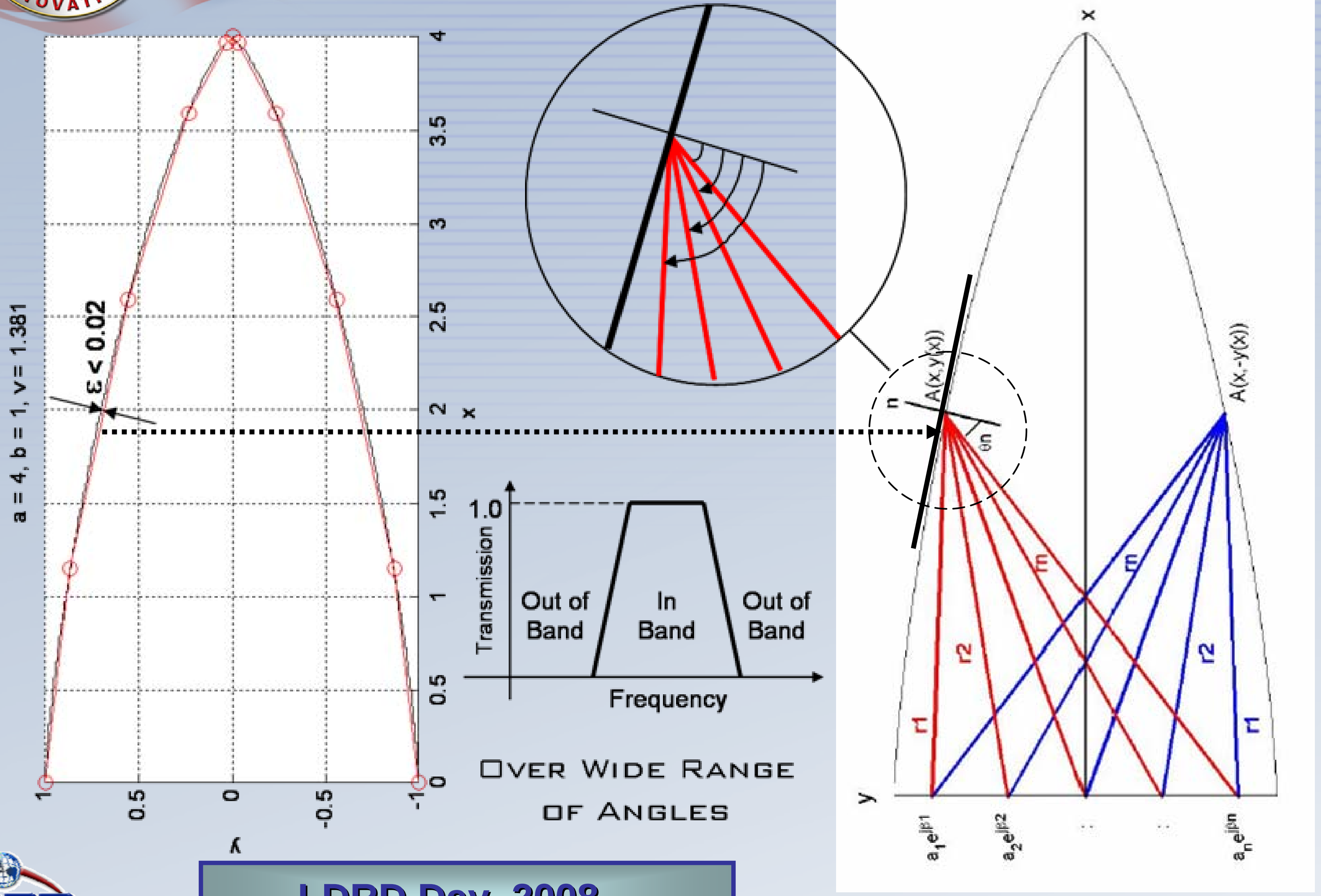
→

- Shutters
- Absorbers
- Antenna Arrays
- Mixers/Sensors
- Power Combiner
- Flat Lens

Bi-static scattering of out-of-band signals

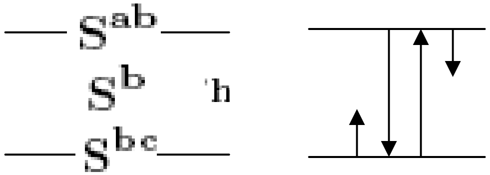


Angle response requires unit-cell modification



OVER WIDE RANGE OF ANGLES

Angle response can be improved via hole taper



$$S^{ac} = S^{ab} \star S^{b} \star S^{bc}$$

$$S^{b}_{11} = S^{b}_{22} = 0$$

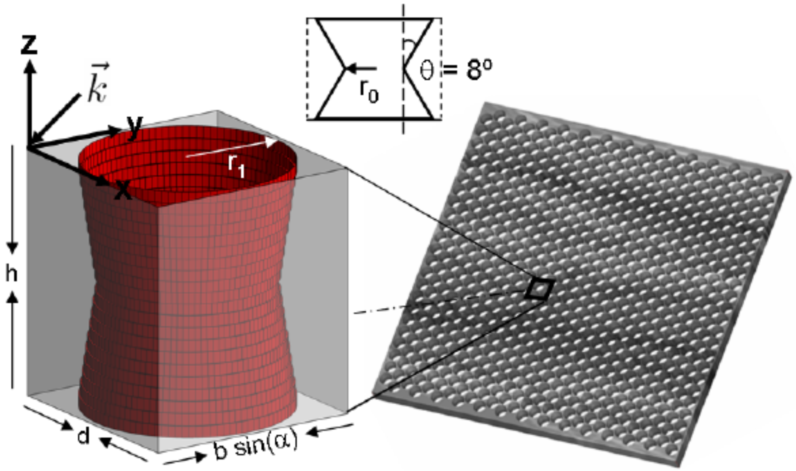
$$S^{b}_{12} = S^{b}_{21} = \mathrm{diag}\{e^{-\gamma^{b}_{1} h}, \ldots e^{-\gamma^{b}_{n} h}\}$$

$$\begin{aligned}
S^{ac}_{11} &= S^{ab}_{11} + S^{ab}_{12} S^{b}_{12} \left[I - \Delta_R\right]^{-1} S^{bc}_{11} S^{b}_{21} S^{ab}_{21}, \\
S^{ac}_{12} &= S^{ab}_{12} S^{b}_{12} \left[I - \Delta_R\right]^{-1} S^{bc}_{12}, \\
\boxed{S^{ac}_{21}} &\boxed{= S^{bc}_{21} \left[I - \Delta_F\right]^{-1} S^{b}_{21} S^{ab}_{21},} \\
S^{ac}_{22} &= S^{bc}_{22} + S^{bc}_{21} \left[I - \Delta_F\right]^{-1} S^{b}_{21} S^{ab}_{22} S^{b}_{12} S^{bc}_{12},
\end{aligned}$$

$$\left.\begin{aligned}
\Delta_R &= S^{bc}_{11} S^{b}_{21} S^{ab}_{22} S^{b}_{12}, \\
\Delta_F &= S^{b}_{21} S^{ab}_{22} S^{b}_{12} S^{bc}_{11},
\end{aligned}\right\}$$

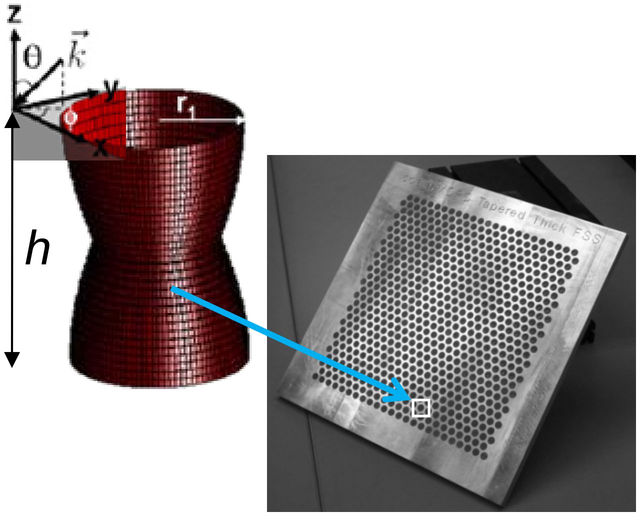
$$\boxed{\angle \Delta_{F,R} = 2\pi \, \mathrm{diag}\{n_1, \ldots, n_m\}}$$

- Phase criterion determines resonance location
- $|\Delta_{F,R}|$ determines Q of the resonance and is dependent on the diameter/period ratio, larger d/p leads to broadband response



Parabolic taper allows more rays to pass

Microwave Active Antenna Group
University of Colorado Graduate Studies



Dual-polarization large scan angle broadband thick-metal FSS

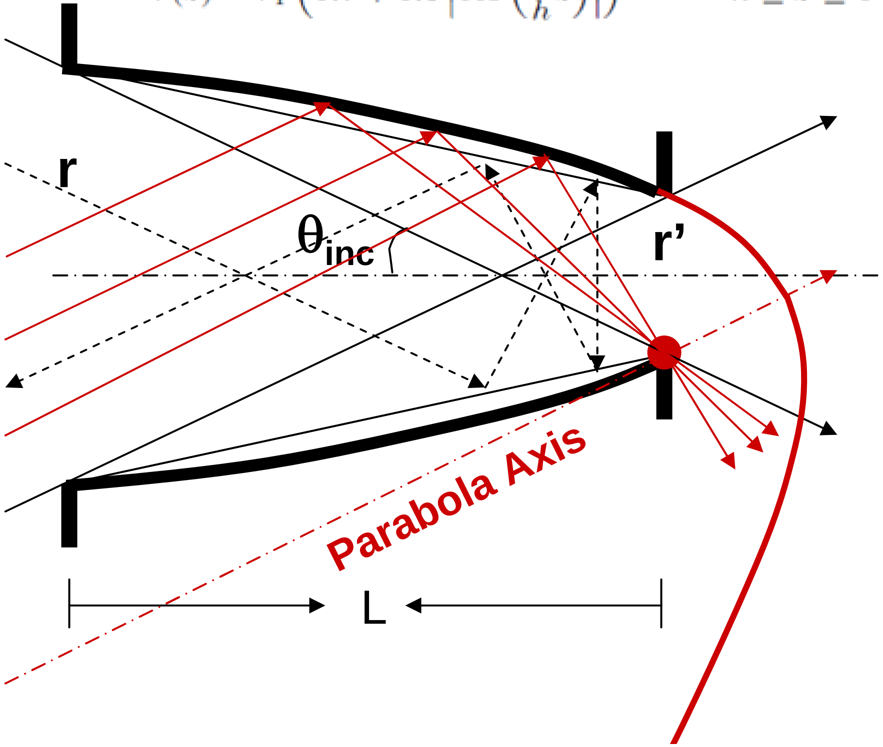
Negar Ehsan[1], Hung Loui*[2], Edward F. Kuester[1], and Zoya Popović[1]

[1] Department of Electrical and Computer Engineering, University of Colorado, Boulder, CO, 80309

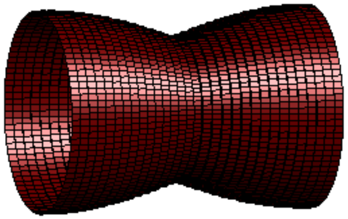
[2] Org. 05345, Sandia National Laboratories, Albuquerque, NM 87185-1330

IEEE AP-S International Symposium 2007
Honolulu, Hawaii USA :: June 10 - 15
01-16-2007

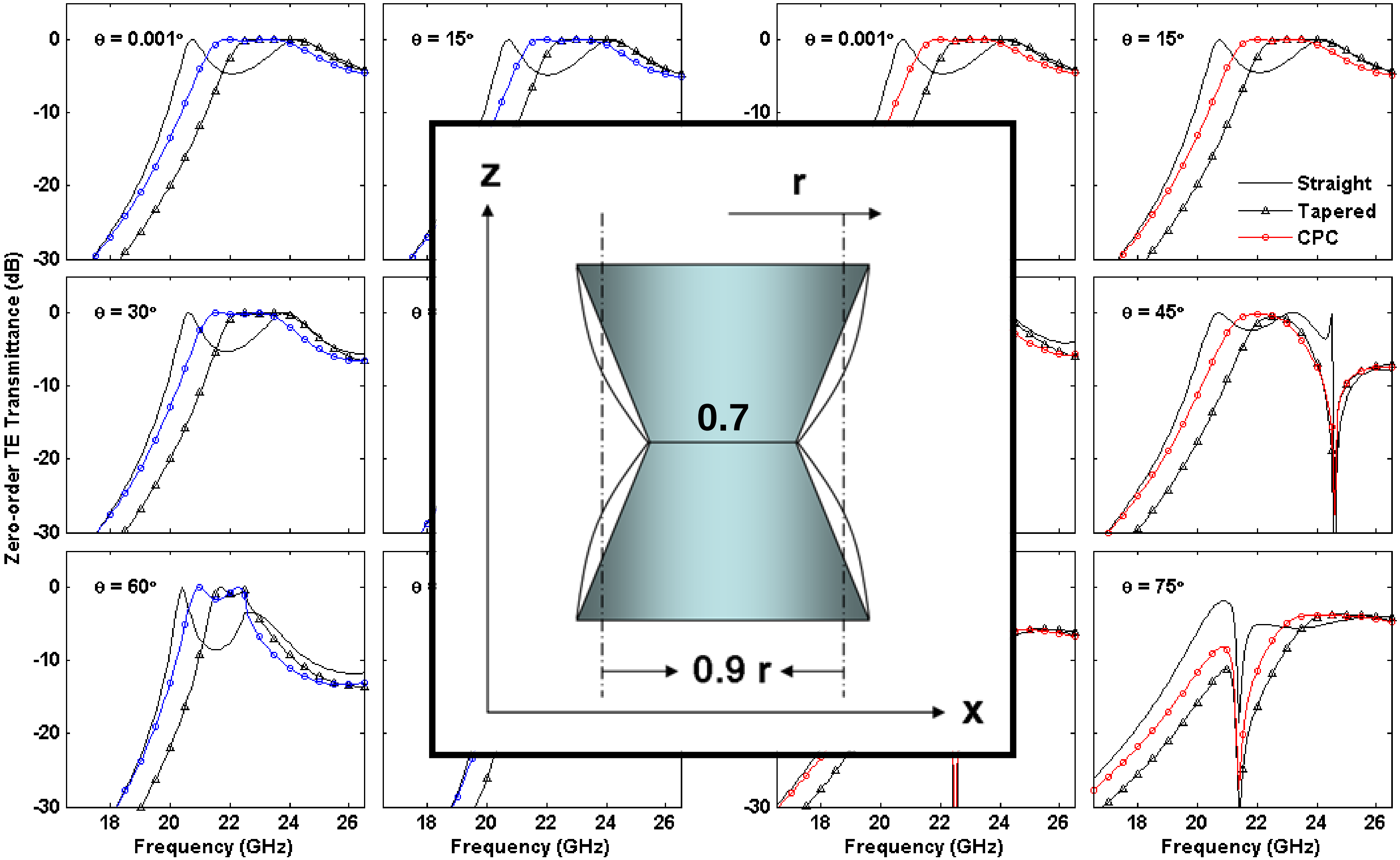
$$r(z) = r_1 \left(0.7 + 0.3 \left|\cos\left(\frac{\pi}{h} z\right)\right|\right) \qquad -h \le z \le 0$$



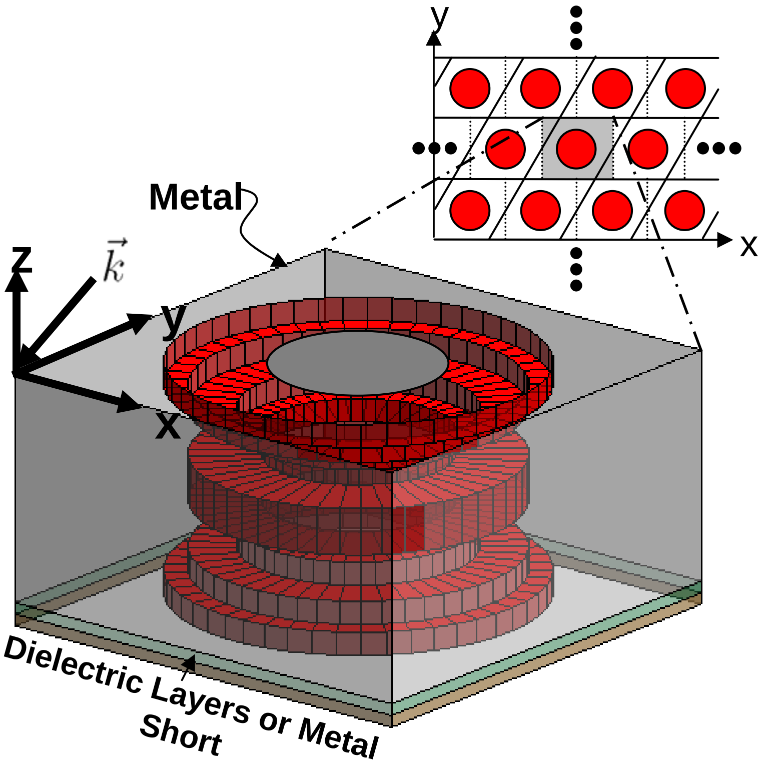
New Parabolic Taper



TE/TM transmittance through tapered-hole array

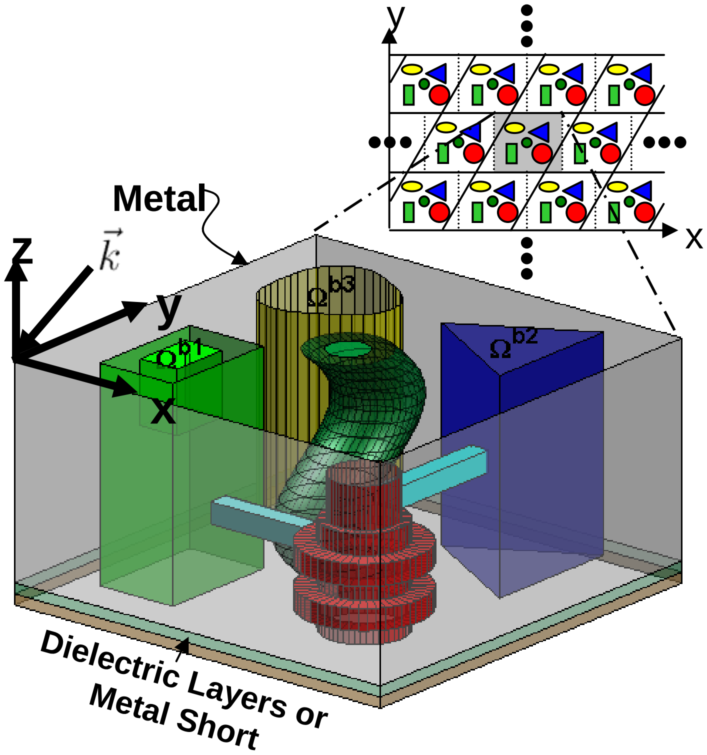


Introduction to compound unit cell

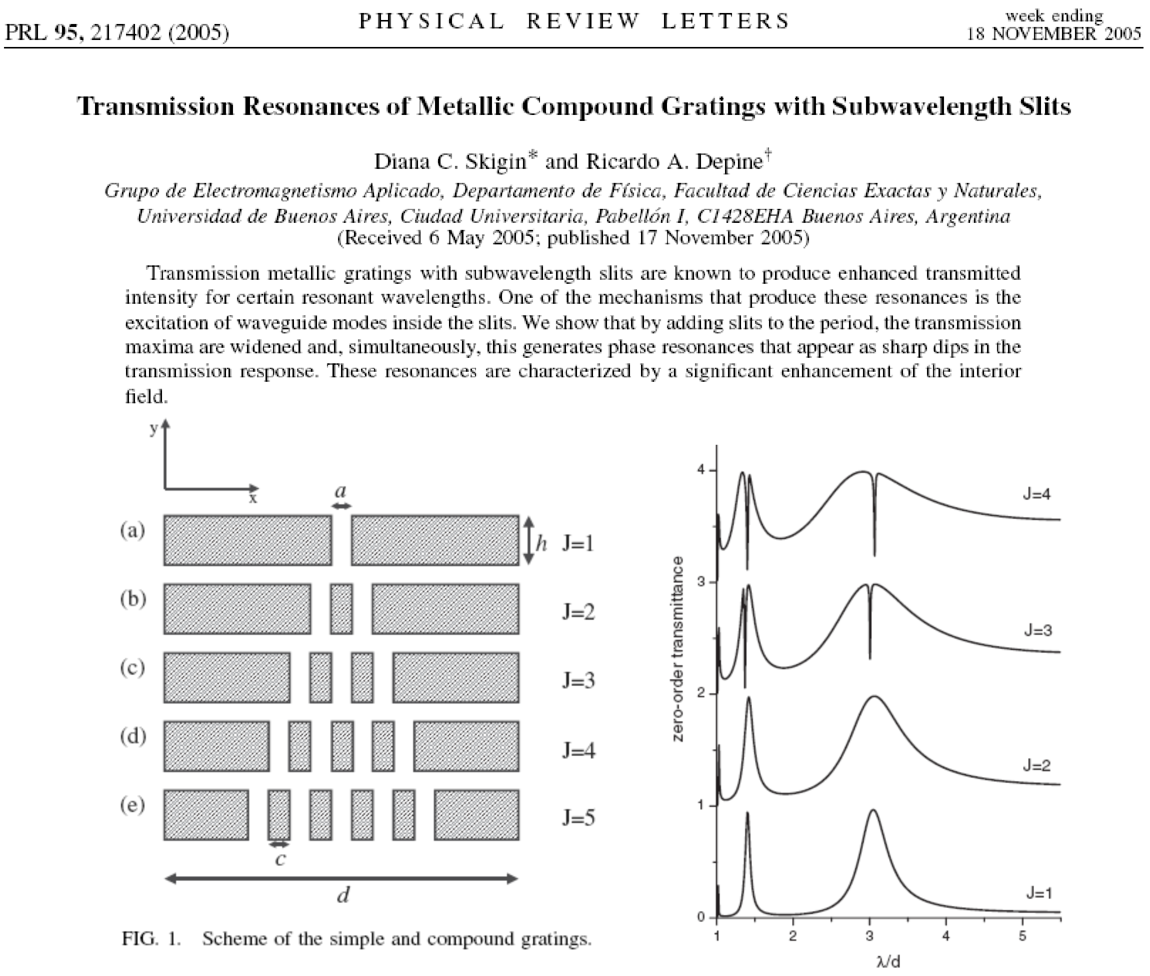


Current State of the Art (Simple Unit Cell)

New Contribution (Compound Unit Cell)



Numerical discovery of anomalous transmission



PRL **95,** 217402 (2005) PHYSICAL REVIEW LETTERS week ending 18 NOVEMBER 2005

Transmission Resonances of Metallic Compound Gratings with Subwavelength Slits

Diana C. Skigin* and Ricardo A. Depine†

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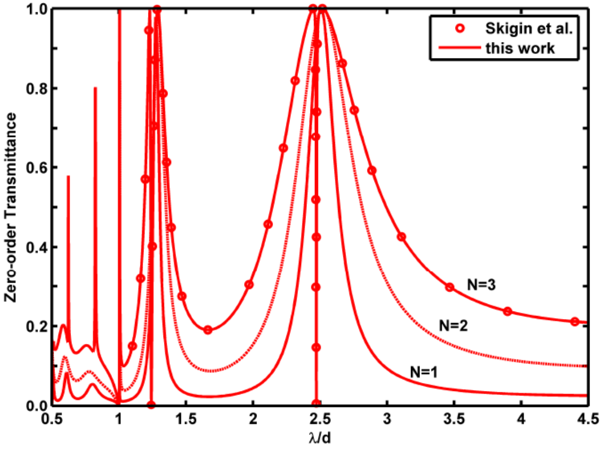
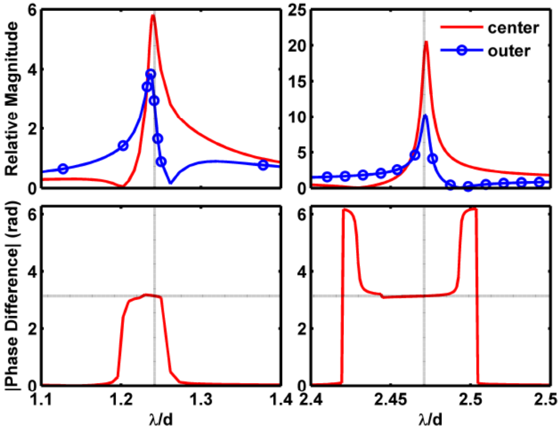
(Received 6 May 2005; published 17 November 2005)

Transmission metallic gratings with subwavelength slits are known to produce enhanced transmitted intensity for certain resonant wavelengths. One of the mechanisms that produce these resonances is the excitation of waveguide modes inside the slits. We show that by adding slits to the period, the transmission maxima are widened and, simultaneously, this generates phase resonances that appear as sharp dips in the transmission response. These resonances are characterized by a significant enhancement of the interior field.

FIG. 1. Scheme of the simple and compound gratings.

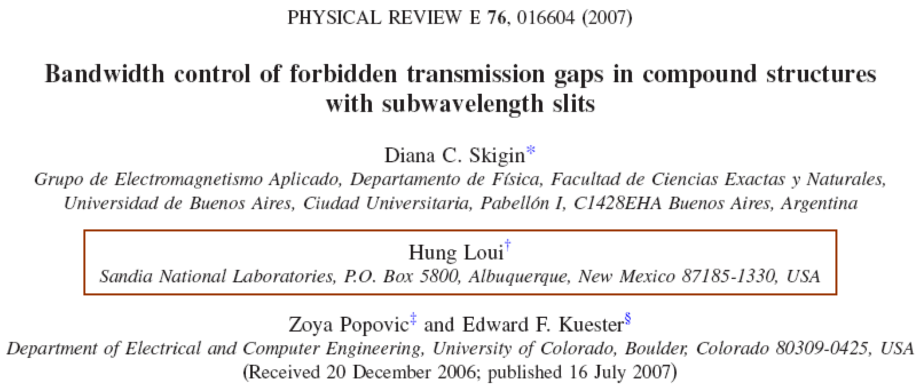


(a) Zero-order TM Transmittance



(b) Relative magnitude and phase differences between slits

Changing the length and permittivity in one slot



PHYSICAL REVIEW E **76**, 016604 (2007)

Bandwidth control of forbidden transmission gaps in compound structures with subwavelength slits

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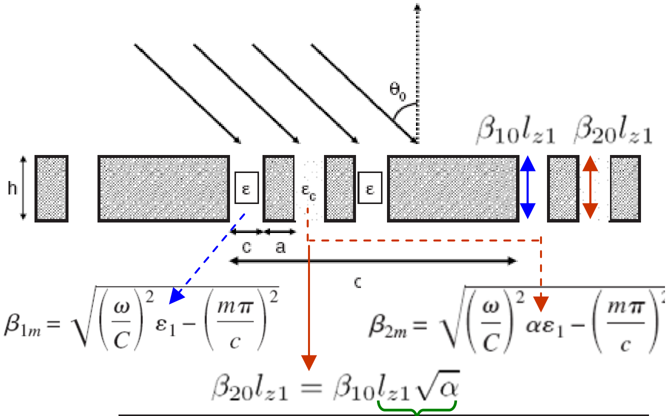
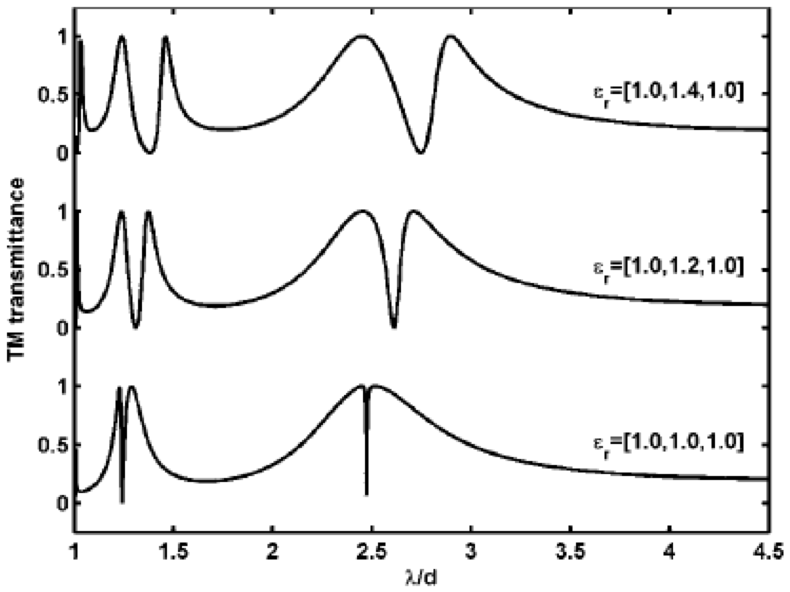
(Received 20 December 2006; published 16 July 2007)

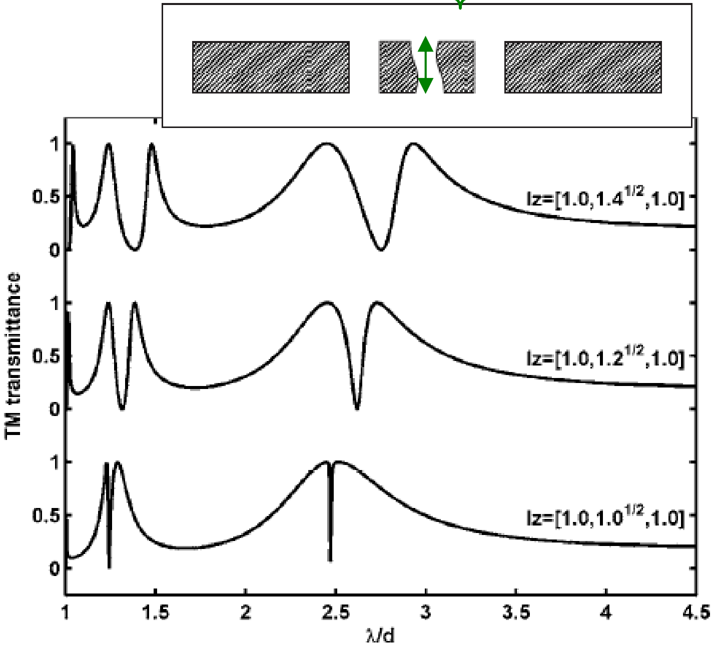


$$\beta_{1m} = \sqrt{\left(\frac{\omega}{C}\right)^2 \varepsilon_1 - \left(\frac{m\pi}{c}\right)^2}$$

$$\beta_{2m} = \sqrt{\left(\frac{\omega}{C}\right)^2 \alpha\varepsilon_1 - \left(\frac{m\pi}{c}\right)^2}$$

$$\beta_{20} l_{z1} = \beta_{10} \underbrace{l_{z1}\sqrt{\alpha}}$$





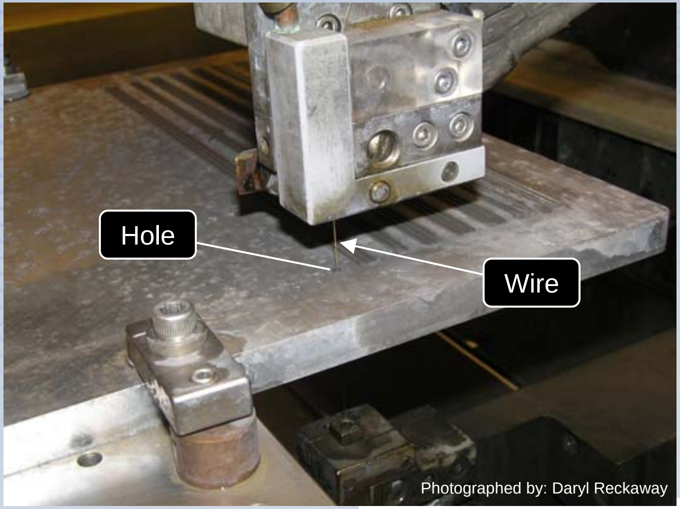
Experimental work on compound FSS

CNC Wire Electrical Discharge Machining

Photographed by: Daryl Reckaway

Clarence D. Esquibel

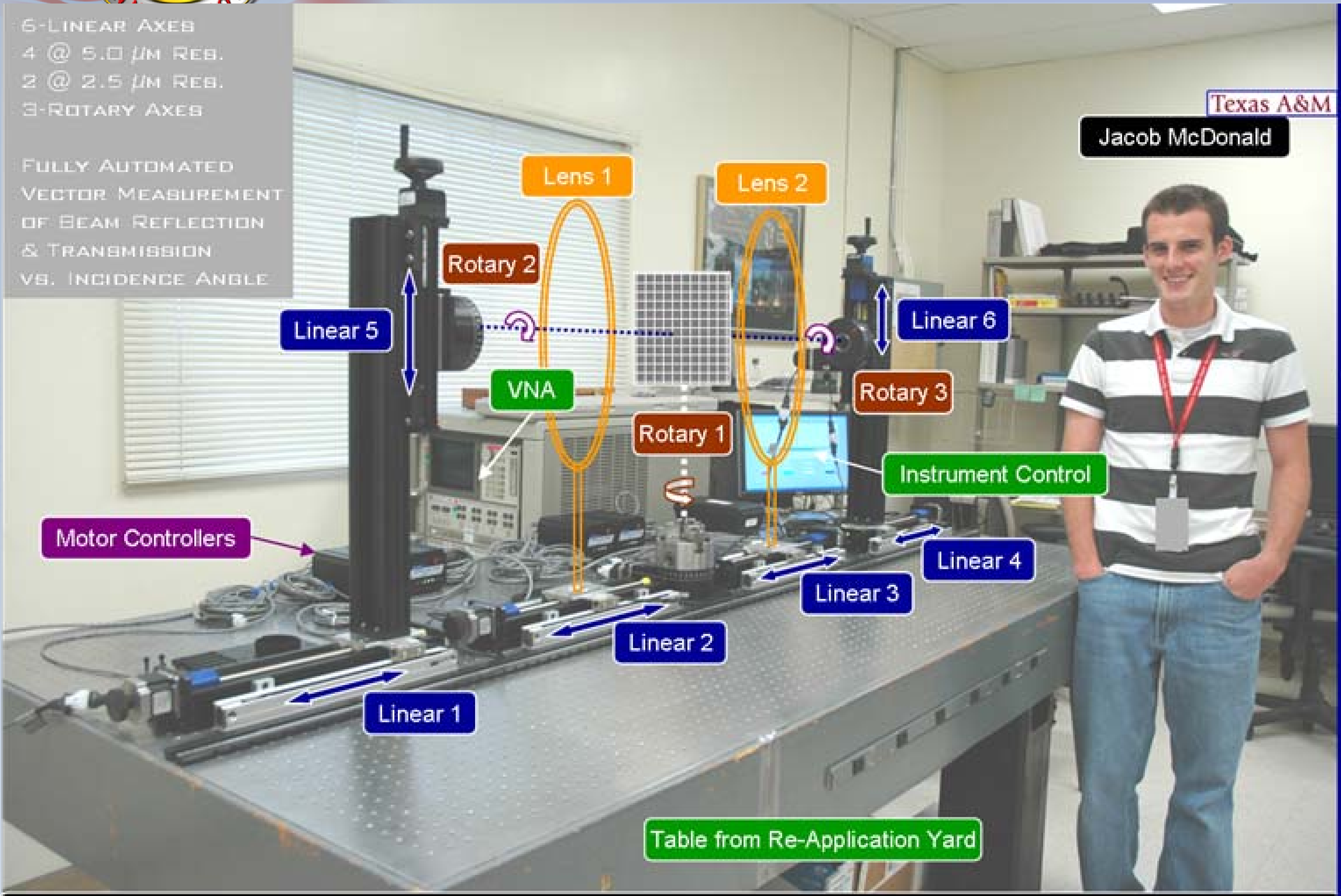
Org. 024312 Project Machining & Rapid Turn



Photographed by: Daryl Reckaway

- Stress relief by oven curing is necessary before Wire EDM
- Oxidation in small holes prevents electrical discharge
- 3-hrs of machine time per slit

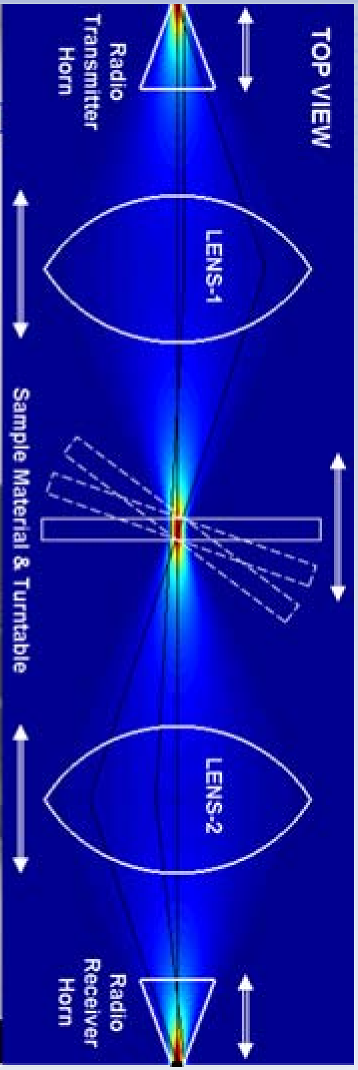
Construction of a FSS measurement apparatus



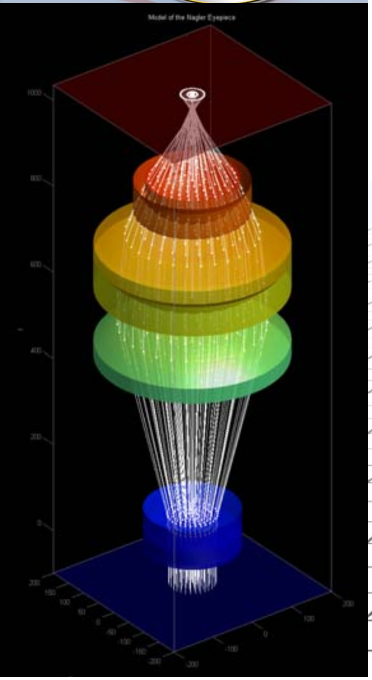
6-Linear Axes
4 @ 5.0 μm Res.
2 @ 2.5 μm Res.
3-Rotary Axes

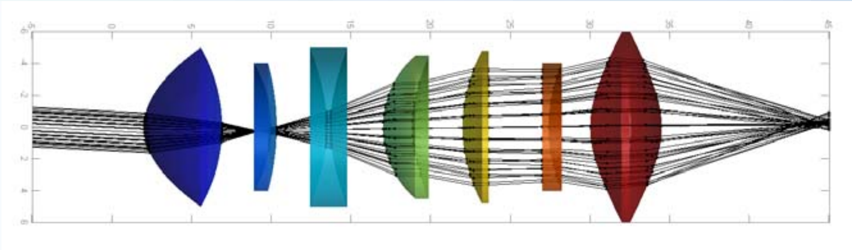
Fully Automated
Vector Measurement
of Beam Reflection
& Transmission
vs. Incidence Angle

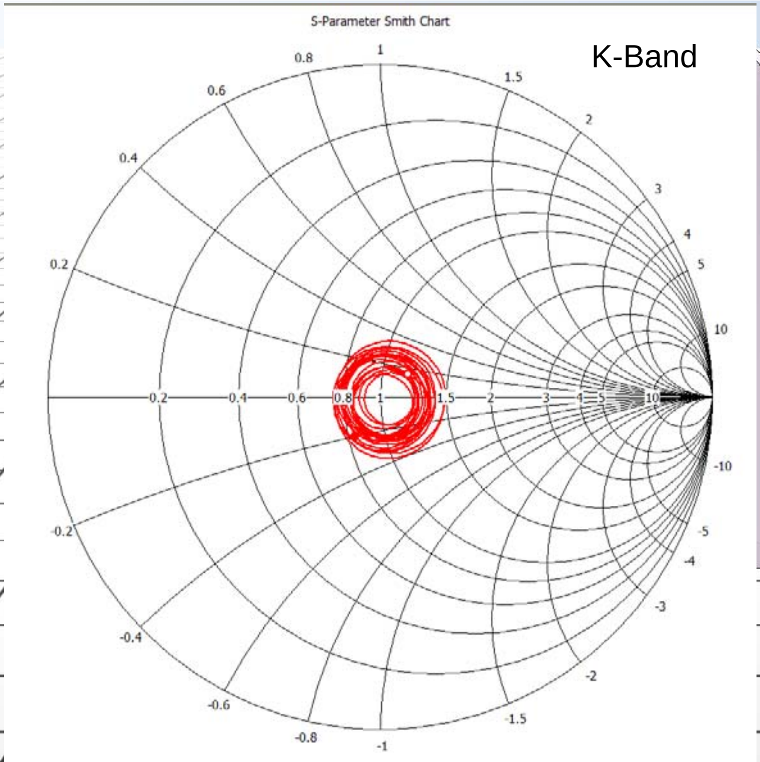
Located @ 9972 - Facility for Antenna and Radar Cross-Section Measurement, Sandia National Laboratories

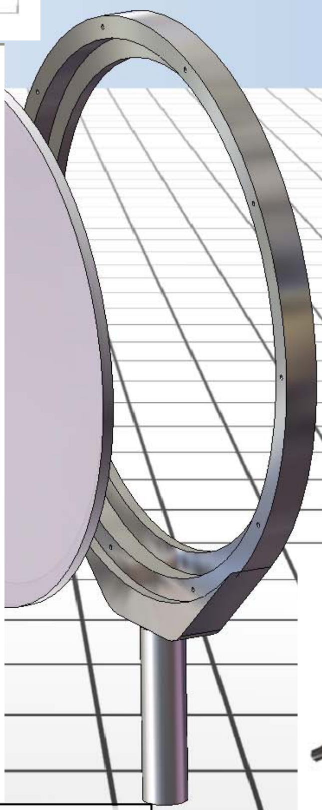


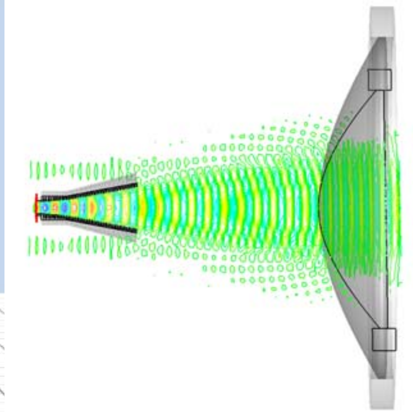
In-house microwave aspheric lens design code











MATLAB code

3D skew ray

Aspheric lenses

Dynamic movement

Spot diagrams

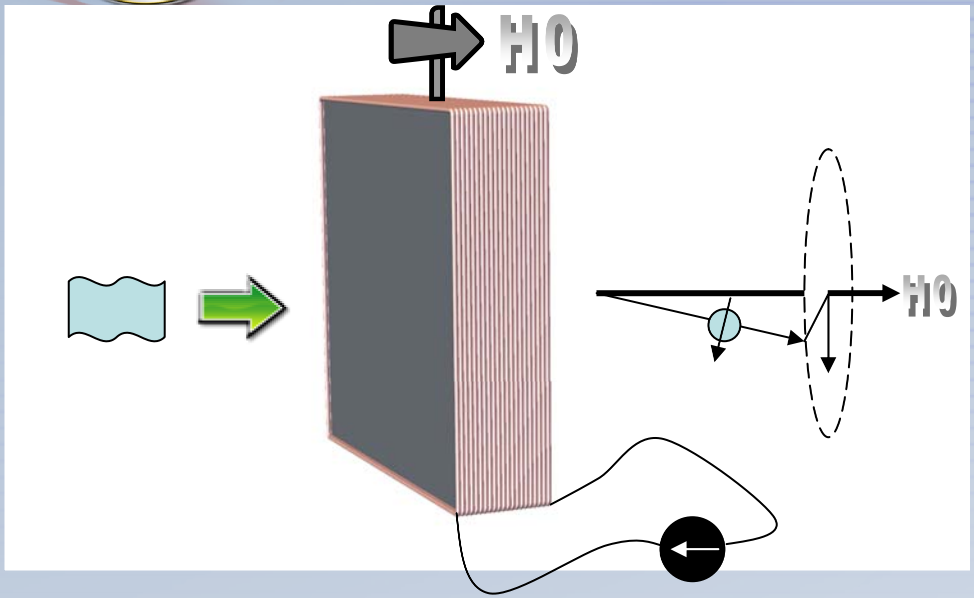
Beam tracing*

280mm f-1 Hyperbolic Lens and its holder

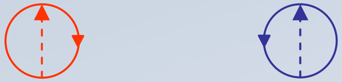
LDRD Day, 2008

* Work in progress

Magnetically biased ferrite can provide tunability



Enables active amplitude, phase and polarization control

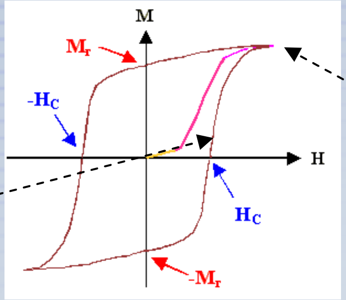


$$E_x\hat{x} = \left(\frac{E_x}{2}\hat{x} + j\frac{E_y}{2}\hat{y}\right) + \left(\frac{E_x}{2}\hat{x} - j\frac{E_y}{2}\hat{y}\right)$$

Current controls magnetic bias H0

H0 changes permeability tensor

which affects propagation constant



Partially saturated case

Fully saturated case

There are two models for

the permeability tensor:

1. <u>Fully saturated</u> based on physical arguments.
2. <u>Partially saturated</u> based on empirical data.
3. Problem: they don’t agree

Tunability in infinite ferrite medium (Saturated)

Saturated Ferrite under $\hat{z}$ bias

$$\vec{B} = \mu_0(\vec{M} + \vec{H}) = [\mu]\vec{H}$$

$$\uparrow$$

$$\vec{M} = [\chi]\vec{H}$$

$$[\mu] = \mu_0([I] + [\chi]) = \mu_0 \begin{bmatrix} \mu_r & j\kappa_r & 0 \\ -j\kappa_r & \mu_r & 0 \\ 0 & 0 & \mu_z \end{bmatrix}$$

gyrotropic

$$\kappa_r = \frac{w w_m}{w_0^2 - w^2}$$

$$\mu_r = 1 + \frac{w_0 w_m}{w_0^2 - w^2}$$

$w_0 = \mu_0 \gamma_g H_0$ bias (precession frequency)

$w_m = \mu_0 \gamma_g M_s$ saturation magnetization

gyro-magnetic ratio

$$\gamma_g = \frac{q_e}{m_e} = \frac{1.602 \times 10^{-19}\text{C}}{9.107 \times 10^{-31}\text{Kg}} = 1.759 \times 10^{11}\text{C/Kg}$$

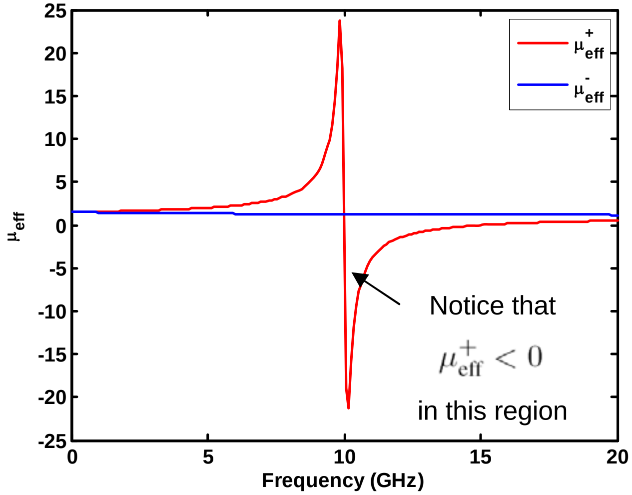
3µm	3.57 KT
30µm	357 T
1 THz	35.7 T
100 GHz	3.57 T
10 GHz	3570 G

Frequency range limited by available magnet

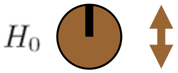
Circular polarized wave propagation

$$\gamma_\pm = \alpha_\pm + j\beta_\pm = jw\sqrt{\epsilon_r \epsilon_0 \underbrace{(\mu_r \pm \kappa_r)}_{\mu^{\pm}_{\text{eff}}} \mu_0}$$

(Infinite Ferrite medium)



Notice that $\mu^+_{\text{eff}} < 0$ in this region

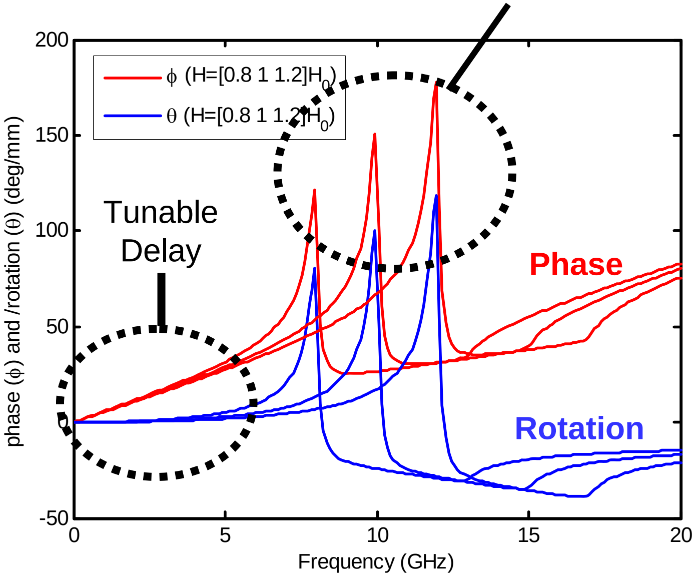


It would be really nice if we had

$$\epsilon_r < 0$$

in the same region… for now we have attenuation

Tunable Absorption



Tunable Delay

Infinite ferrite medium (Partially Saturated)

Saturated Ferrite under $\hat{z}$ bias

$$\vec{B} = \mu_0(\vec{M} + \vec{H}) = [\mu]\vec{H}$$

$$\uparrow$$

$$\vec{M} = [\chi]\vec{H}$$

gyrotropic

$$\kappa_r = \frac{w w_m}{w_0^2 - w^2}$$

$$[\mu] = \mu_0([I] + [\chi]) = \mu_0 \begin{bmatrix} \mu_r & j\kappa_r & 0 \\ -j\kappa_r & \mu_r & 0 \\ 0 & 0 & \mu_z \end{bmatrix}$$

$w_0 = \mu_0 \gamma_g H_0$ bias (precession frequency)

$w_m = \mu_0 \gamma_g M_s$ saturation magnetization

Circular polarized wave propagation

$$\mu_r = 1 + \frac{w_0 w_m}{w_0^2 - w^2}$$

$$\gamma_\pm = \alpha_\pm + j\beta_\pm = jw\sqrt{\epsilon_r \epsilon_0 \underbrace{(\mu_r \pm \kappa_r)}_{\mu_{\text{eff}}^{\pm}} \mu_0}$$

Partially Saturated Ferrite under $\hat{z}$ bias

$$\kappa_r = \frac{\mu_0 \gamma_g M}{w}$$

10% Error [Rado, 1953]

$$\mu_{\text{dem}} = \frac{2}{3}\sqrt{1 - \left(\frac{w_m}{w}\right)^2} + \frac{1}{3}$$

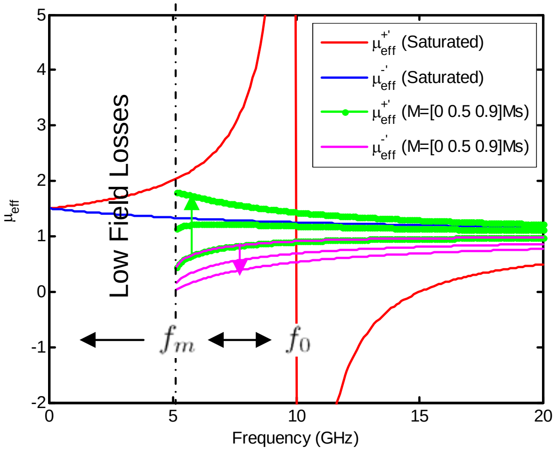
$$\mu_z = \mu_{\text{dem}}\left(1 - \frac{M(H_0)}{M_s}\right)^{5/2}$$

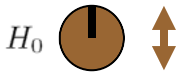
$$\mu_r = \mu_{\text{dem}} + (1 - \mu_{\text{dem}})\left(\frac{M(H_0)}{M_s}\right)^{3/2}$$

[Green & Sandy, 1974]

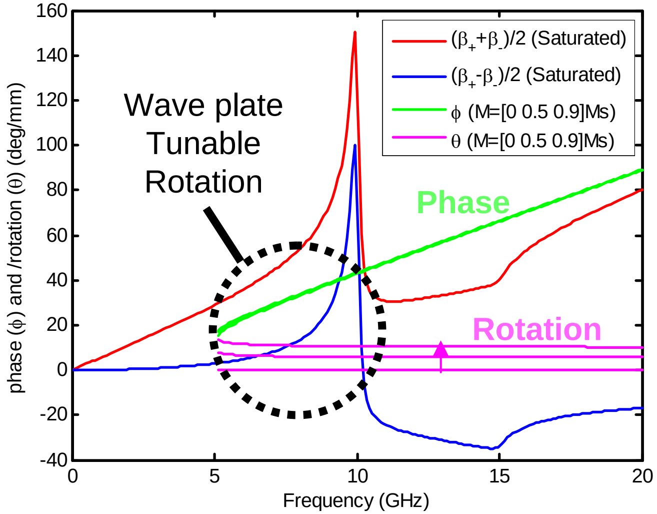
Curved fitted with no physical bases

(Infinite Ferrite medium)





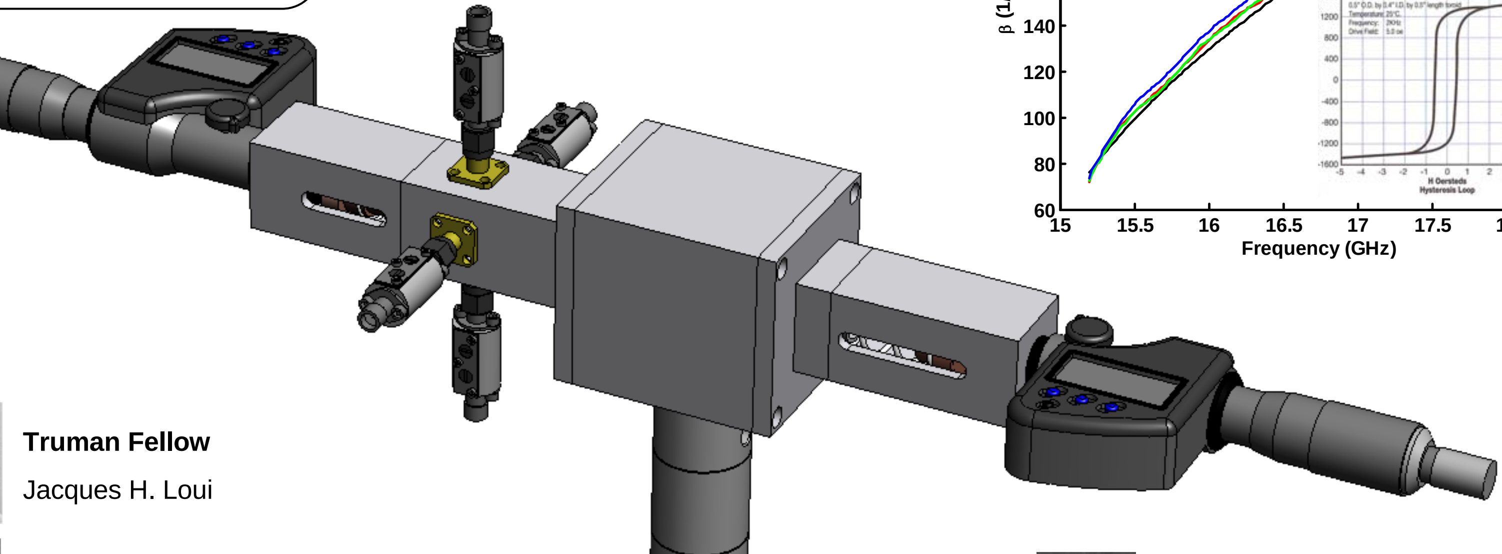
As M from 0 → Ms, the partially saturated tensor model (green & pink) and the fully saturated tensor model (red and blue) do not connect!

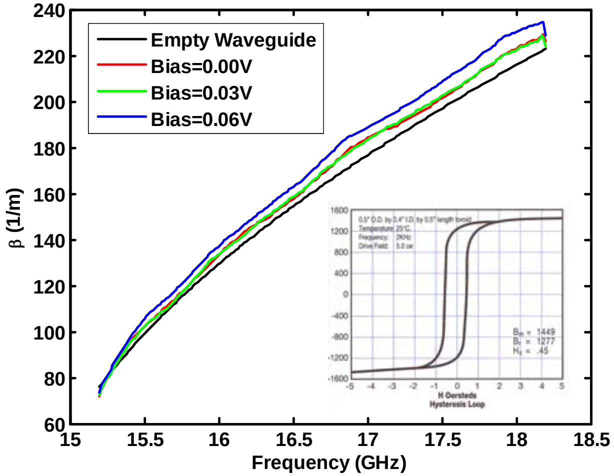


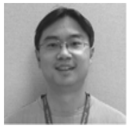
Measuring the tensor permeability of ferrites

Freq: Ku-Band

Measures permeability tensor of partial & saturated cylindrical ferrite samples







Truman Fellow

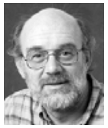
Jacques H. Loui

Mentor – DMTS

Billy C. Brock

Graduate Student
Texas A&M

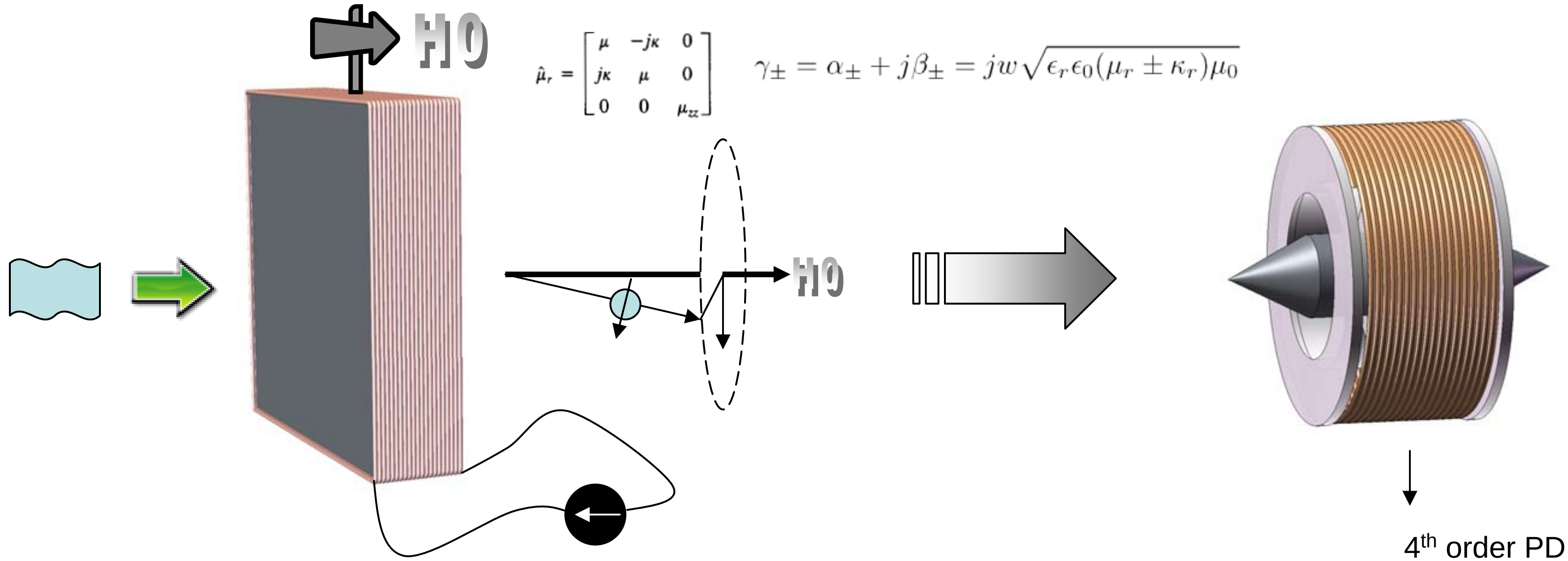
Jacob J. McDonald



EE Professor
CU Boulder

Edward F. Kuester

How do we put ferrite inside the unit-cells?



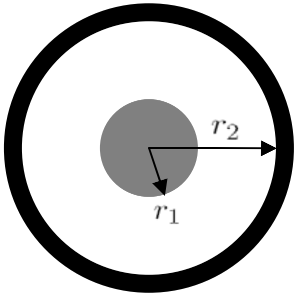
$$\hat{\mu}_r = \begin{bmatrix} \mu & -j\kappa & 0 \\ j\kappa & \mu & 0 \\ 0 & 0 & \mu_{zz} \end{bmatrix}$$

$$\gamma_\pm = \alpha_\pm + j\beta_\pm = jw\sqrt{\epsilon_r\epsilon_0(\mu_r \pm \kappa_r)\mu_0}$$

4th order PDE

$$[(\mu\nabla_t^2)^2 + [(w^2\epsilon\mu - \beta^2)(\mu+\mu_0) - w^2\epsilon\kappa^2](\mu\nabla_t^2) + \mu\mu_0[(w^2\epsilon\mu - \beta^2)^2 - (w^2\epsilon\kappa)^2]]\,\psi_z = 0$$

Parameter of Interest



Specific solutions only possible for simple structures

General Solution

$$\psi_z = [K_1J_n(\gamma_+r) + L_1Y_n(\gamma_+r) + K_2J_n(\gamma_-r) + L_2Y_n(\gamma_-r)]\,e^{jn\theta}$$

$$\gamma_\pm = \sqrt{\frac{2\pi^2\epsilon_r}{\mu_r}\left(\mu_r(\mu_r+1)(1-\beta') - \kappa_r^2 \pm \sqrt{[(1-\beta')(\mu_r-1)\mu_r - \kappa_r^2]^2 + 4\kappa_r^2\mu_r\beta'}\right)}$$

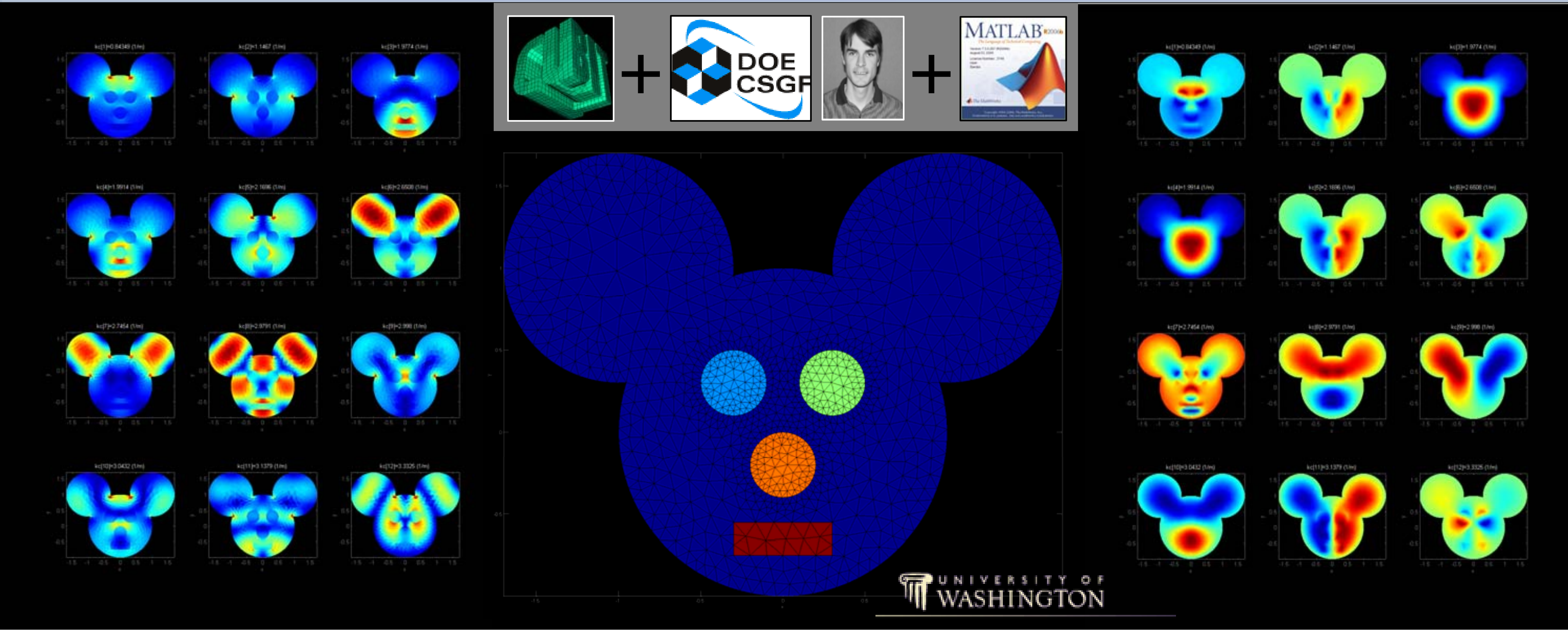
$$\beta' = \frac{\beta_n^2}{\epsilon_r\mu_r} \leftarrow \beta_n = \frac{\boxed{\beta}}{k_0^2}$$

parameter of interest

← waveguide filling

Development of a high-order 2D Eigen-solver

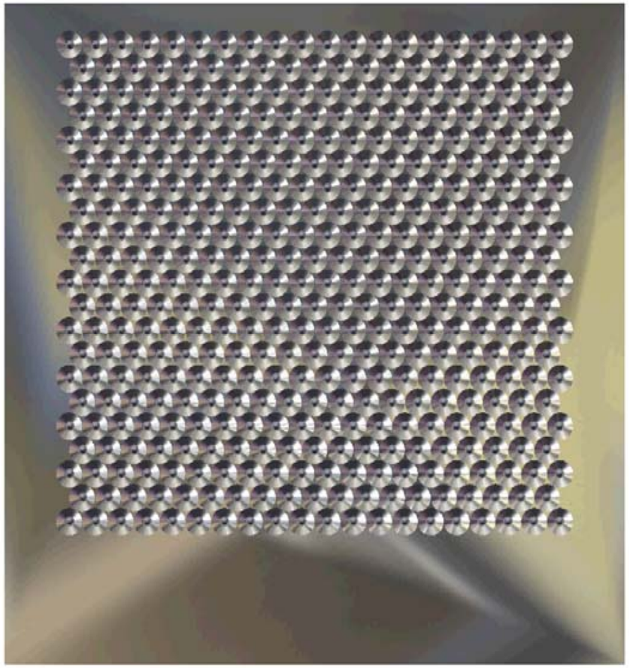
Department of Applied Mathematics



Edge-Based Eigen Mode Solver – Inhomogeneous [Tensor]

LDRD Day, 2008

Active Ferrite-based FSS Concept



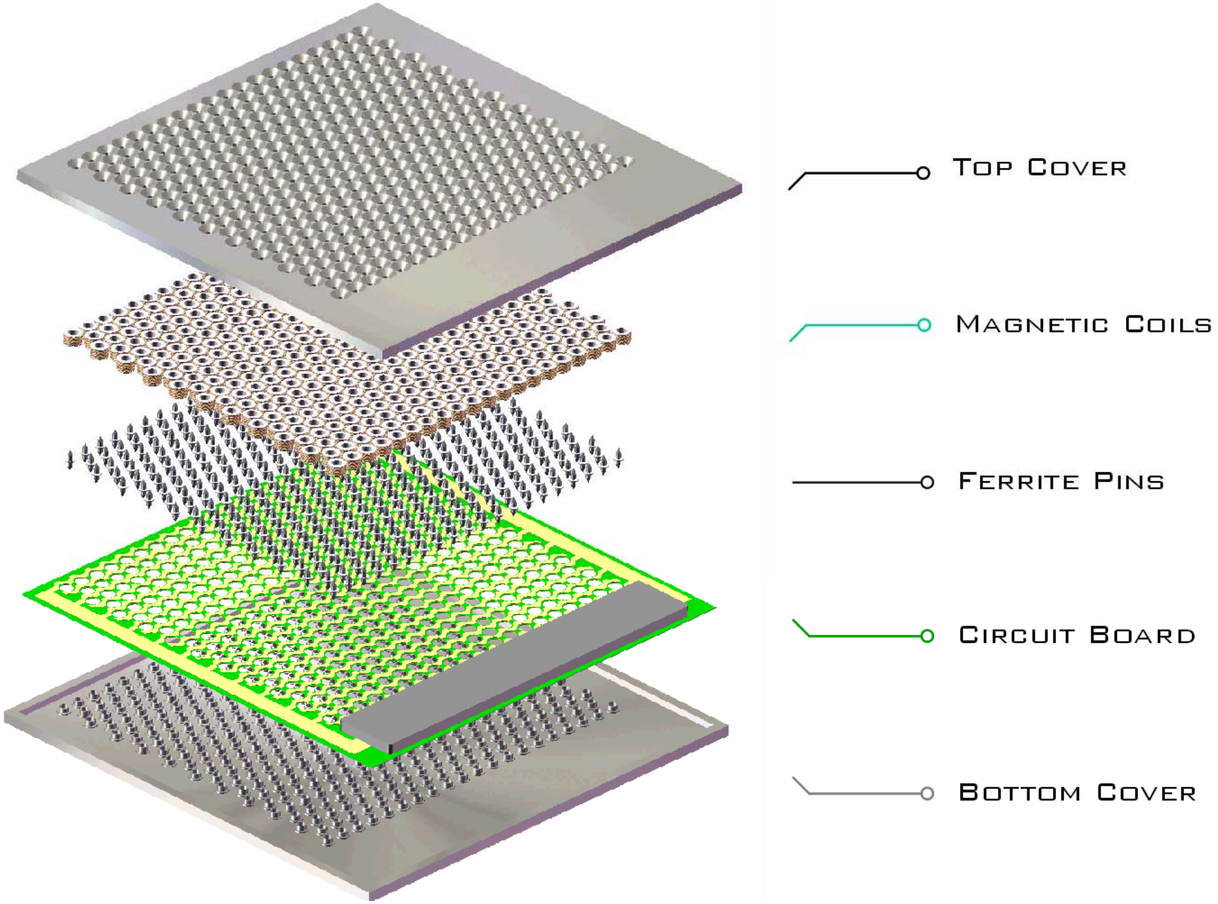
Fields of research involved:

- Tunable materials [dispersive tensor]
- Electromagnetic scattering
    - Periodic structures
- In homogeneously filled waveguides
    - Dispersion engineering
- Material measurement capabilities
- Quasi-optic measurement techniques

TRUMAN FELLOWSHIP
2006-2009

Active ferrite-based FSS concept

- COMPACT
- LIGHTWEIGHT
- HEAT SINK
- ACTIVE ABSORBER
- ACTIVE SHUTTER
- ACTIVE FSS FILTER
- ACTIVE POLARIZER
- PHASE CHANGER
- MICROWAVE LENS



Summary & Conclusions

Goal:
Produce novel, reconfigurable, metal/dielectric surfaces/volumes for adaptive control over EM scattering.

Approach:
Embed tunable materials into the periodic unit-cells of a thick metal plate to affect electromagnetic wave propagation based on electrical configuration.

Significance:

1. This work satisfies the strategic intent of the Truman fellowship.
    - [multiple orgs., 3 universities, 2 graduate students, 6+ publications (one in physical review, 3 journal, 3 conference), 3 TAs, 4+ Sand Reports, 1 additional LDRD for SAR, and supported the efforts of GC-LDRD in meta-materials]
2. Provided Sandia a firm footing (tools & infrastructure) in the area of sub-wavelength EM scattering and RF ferrite based innovations.
3. Multi-morphic surfaces open new venues for low-observables and benefits both Strategic Partnership and Defense Assessment Investment Areas.

Accomplishments:

Theoretical:

- Explained the origin of anomalous transmission
- Showed via net-work theory the mechanism that governs scattering from thick FSSs

Numerical:

- MM-EGSM method for analyzing anomalous and extraordinary transmission problems
- High-Order 2D FEM Eigen mode solver
- 3D – skew ray tracing lens design software
- CST script for design corrugate horns

Experimental:

- Gaussian beam measurement system
- Ferrite tensor characterization system

Application:

- Ferrite based thick-metal FSSs for radome applications
- Ferrite based devices for beam steering (SAR related)

Utilization of laboratory resources & thank you!

Mentor

DMTS: Billy C. Brock

- Mentor -

Billy Brock

- Manager -

Kurt W. Sorensen

- Org. 5345 SAR Sensors -

- Org. 1652 Plasma Physics -

- Org. 1727 Applied Photonics -

Truman Committee!

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LDRD Day, 2008

Sandia National Laboratories