Frontier Applications of Metamaterials to Magnetic Confinement Fusion

F.A. Volpe

Columbia University, New York, NY

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Plasmas and metamaterials have a long history of flirting with each other

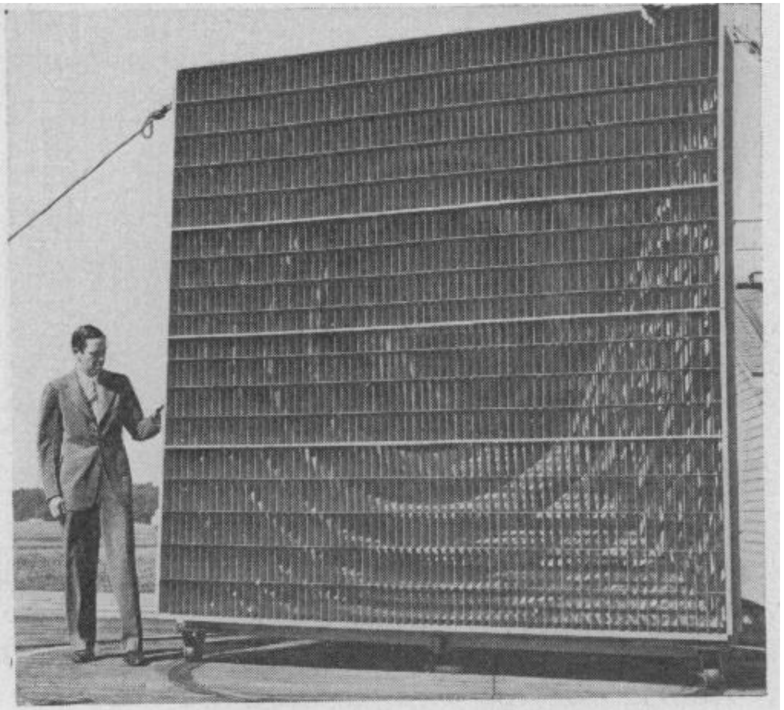


Fig. 20—4000-megacycle repeater antenna.

- Artificial dielectrics [Kock 1946] applied to plasma diagnostics in 1980-90's (e.g. [Volpe-Laqua 2003] and refs. therein).

- In plasmas $\epsilon < 1$ and, at $\omega < \omega_{\mathrm{p}}$, $\epsilon < 0$, as later realized in metamaterials.
- Similar to metamaterials, optical properties of plasma can be "engineered" by proper choice of n_{e}, n_{i}, T_{e}, T_{i}, B and their gradients.
- Pendry's 1996 seminal work on metamaterials mentions 'plasma' and 'plasmons' 42 times.
- Plasmons and magnetoplasmons reminiscent of plasma waves and Electron Bernstein Waves in plasmas

Outline

- Motivation
- Reverse chromatic aberration
- Metamaterial lens
- Numerical opimization
- Ink-jet manufacturing
- Rapid frequency-controlled steering

Example of special needs of plasma diagnostics that can be addressed by metamaterials

- Electron Cyclotron Emission is microwave emission from gyrating electrons in magnetized plasmas
- Important for temperature measurement
- Emission at different frequencies f originates at different locations → Challenge for focusing:

  focal length should vary dramatically (*increase)* with f

- This “reverse” chromatic aberration cannot be obtained with convergent lenses of *conventional* materials.
- It can be obtained with a *metamaterial* lens.

High sensitivity of focus to *f* might find application in survey, satellite observations, directed energy.

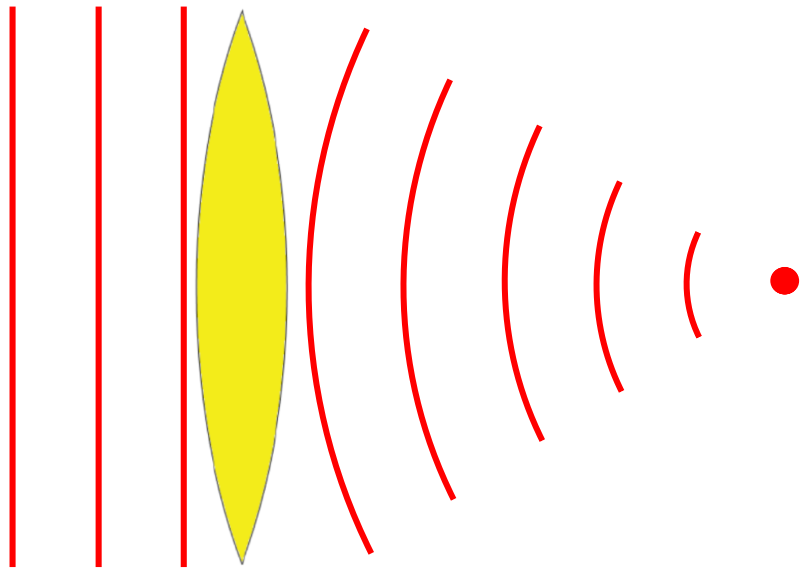
- If object to be detected/irradiated is
  - Moving
  - Non-monochromatic
- And sensor/receiver is rapidly (electrically) tunable
- Then rapid change of *f* → rapid change of focus
- No moving parts in the optics

Control of chromatic aberration at design stage and rapid inexpensive ink-jet manufacturing also have numerous applications

- Reverse chromatic aberration lens can compensate for regular chromatic aberration of other lenses in optical system
- Flat lens of *zero* chromatic aberration can be designed and manufactured by same methods

- Ink-jet printing can be applied to RF IC circuits, antennas, magnetic sensors, etc.
- It can allow rapid prototyping, manufacturing and customization to specific frequency, polarization, focus etc.

What is "reverse" Chromatic Aberration?



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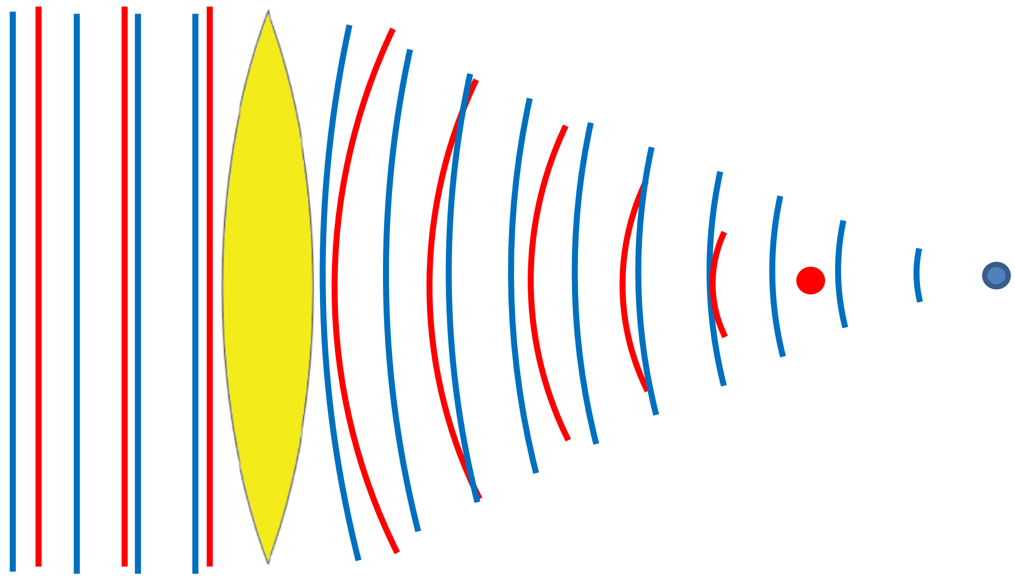
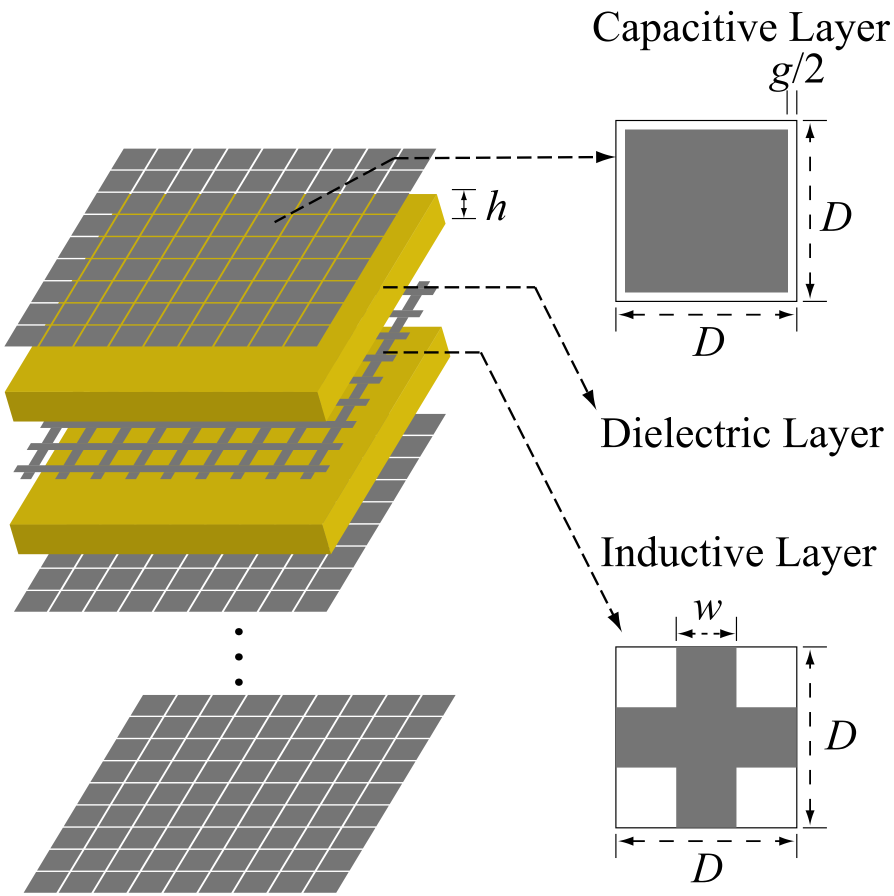
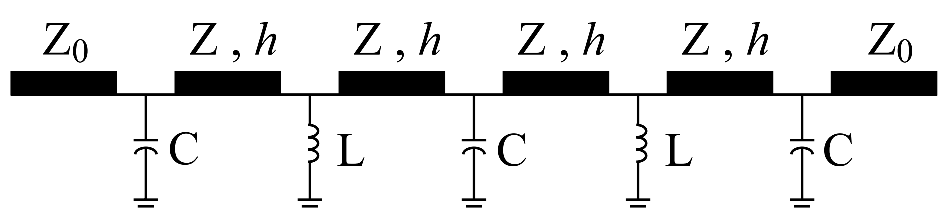


Sandwiches of inductive and capacitive layers behave like LC transmission lines

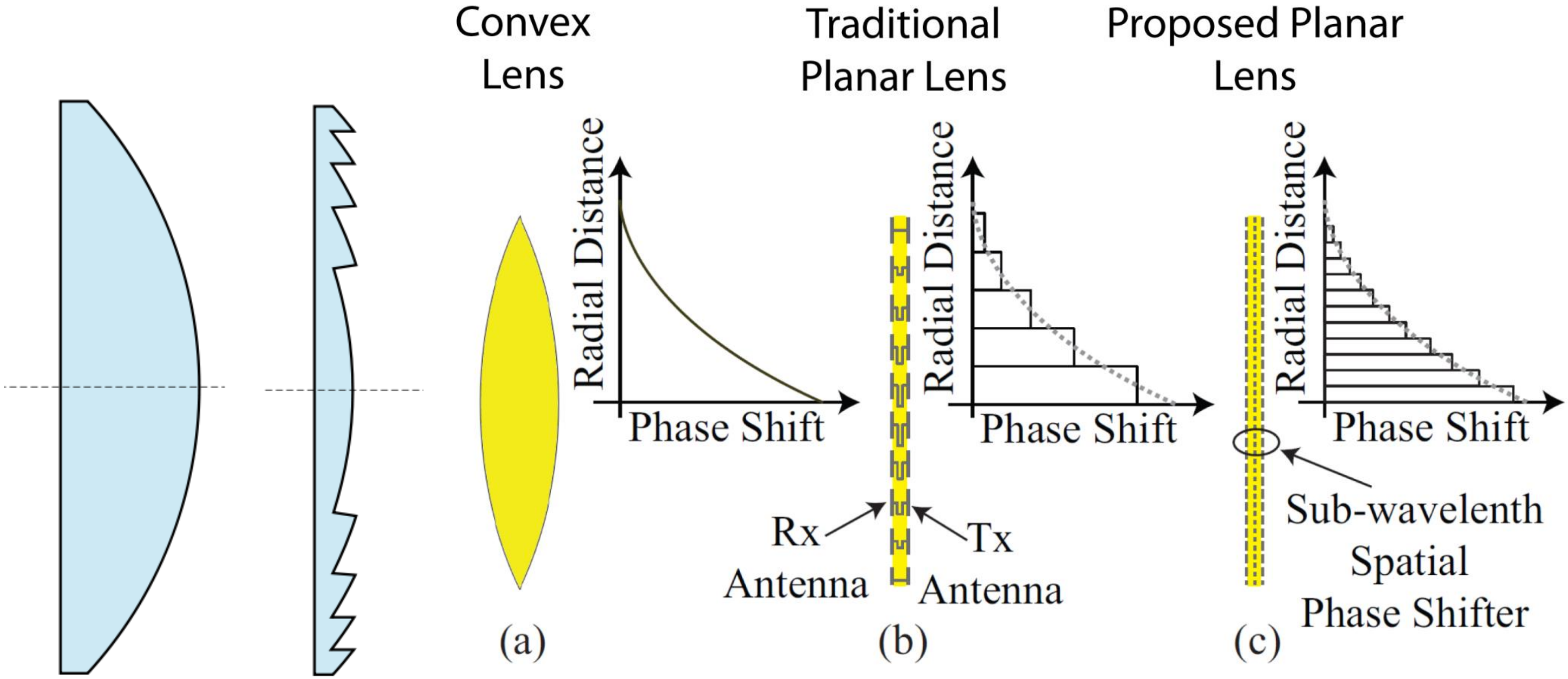


$$C_1 = \epsilon_0 \epsilon_{eff} \frac{2D}{\pi} \ln\left[\frac{1}{\sin\left(\frac{\pi g_1}{2D}\right)}\right]$$

$$L = \mu_0 \mu_{eff} \frac{D}{2\pi} \ln\left[\frac{1}{\sin\left(\frac{\pi w}{2D}\right)}\right]$$



2D array of LC filters imparting different $\Delta\phi$ behaves like a Fresnel lens



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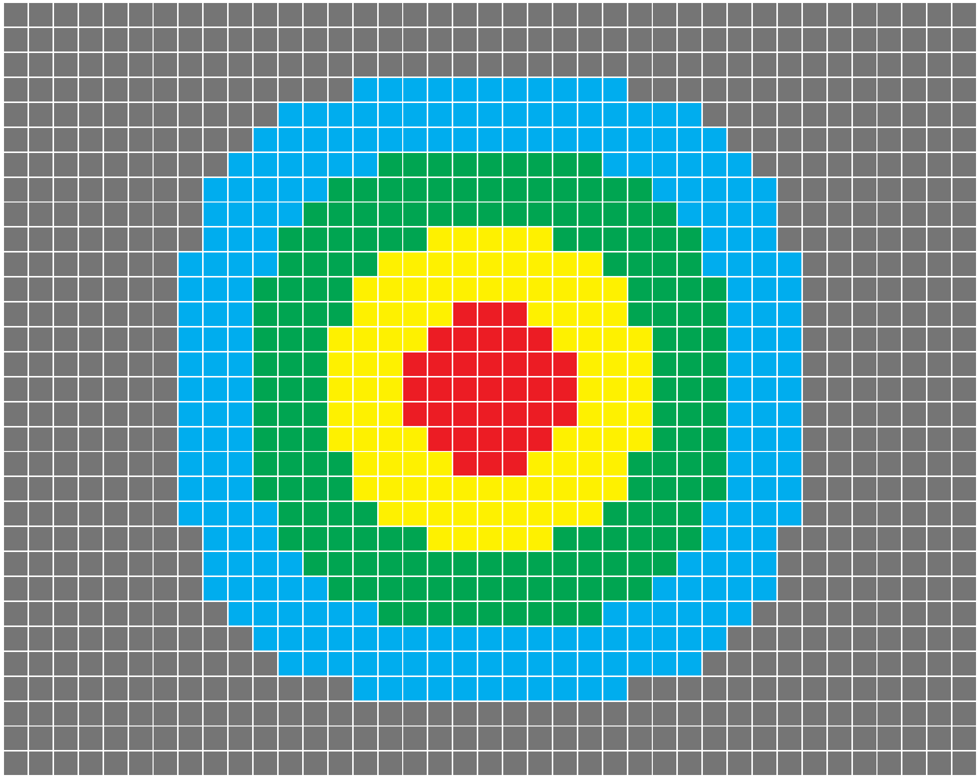
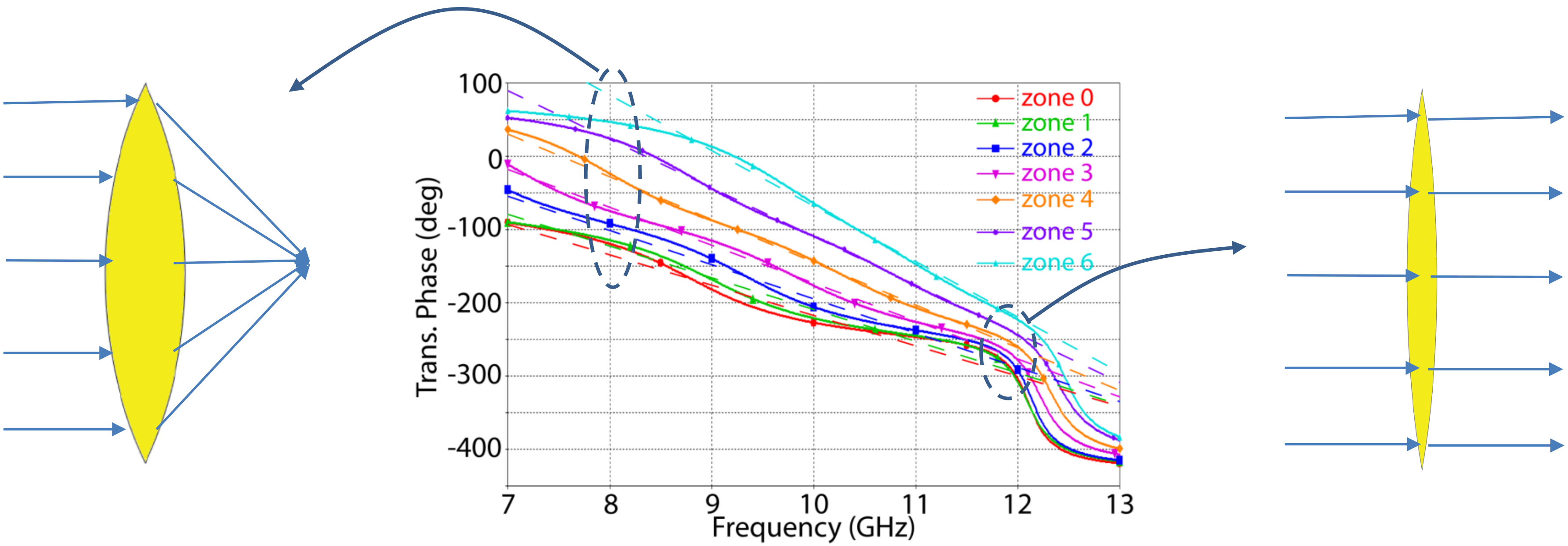


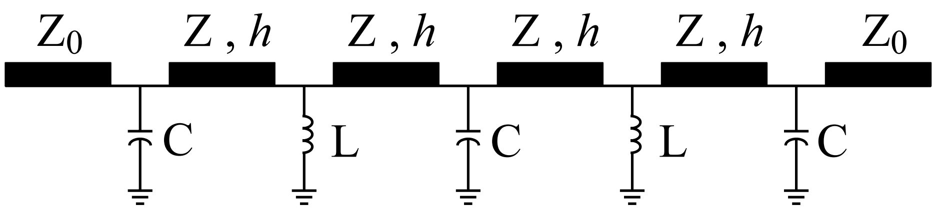
Designed, built and testing a 7 zone RCA lens for 8-12 GHz.
Designed an 83 zone RCA lens for 80-130 GHz.

Reverse Chromatic Aberration is obtained by imposing vast zone-to-zone variation of $\Delta\phi$ at low *f* and more uniform response at high *f*



Geometrical dimensions can be analytically optimized to obtain desired Δϕ(*f*) in each zone

$$L = \mu_0 \mu_{eff} \frac{D}{2\pi} \ln\left[\frac{1}{\sin\left(\frac{\pi w}{2D}\right)}\right] \qquad C_1 = \epsilon_0 \epsilon_{eff} \frac{2D}{\pi} \ln\left[\frac{1}{\sin\left(\frac{\pi g_1}{2D}\right)}\right]$$



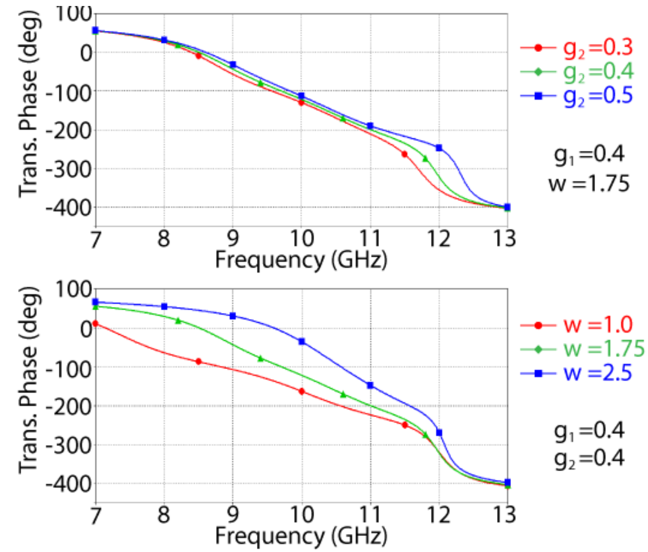
$$\boxed{T = \frac{2}{A + \frac{B}{Z_0} + CZ_0 + D}}$$

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ j\omega C_1 & 1 \end{bmatrix} \begin{bmatrix} \cos\beta h & jZ\sin\beta h \\ \frac{j}{Z}\sin\beta h & \cos\beta h \end{bmatrix} \begin{bmatrix} 1 & 0 \\ \frac{1}{j\omega L} & 1 \end{bmatrix} \begin{bmatrix} \cos\beta h & jZ\sin\beta h \\ \frac{j}{Z}\sin\beta h & \cos\beta h \end{bmatrix} \begin{bmatrix} 1 & 0 \\ j\omega C_2 & 1 \end{bmatrix} \times$$

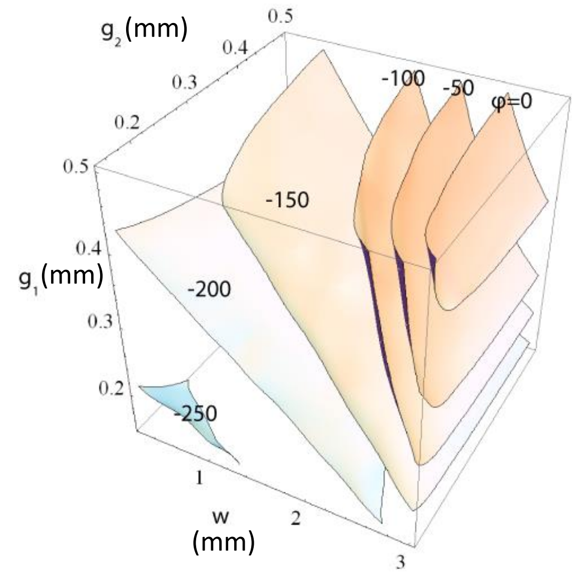
$$\begin{bmatrix} \cos\beta h & jZ\sin\beta h \\ \frac{j}{Z}\sin\beta h & \cos\beta h \end{bmatrix} \begin{bmatrix} 1 & 0 \\ \frac{1}{j\omega L} & 1 \end{bmatrix} \begin{bmatrix} \cos\beta h & jZ\sin\beta h \\ \frac{j}{Z}\sin\beta h & \cos\beta h \end{bmatrix} \begin{bmatrix} 1 & 0 \\ j\omega C_1 & 1 \end{bmatrix}$$

…or problem can be solved numerically

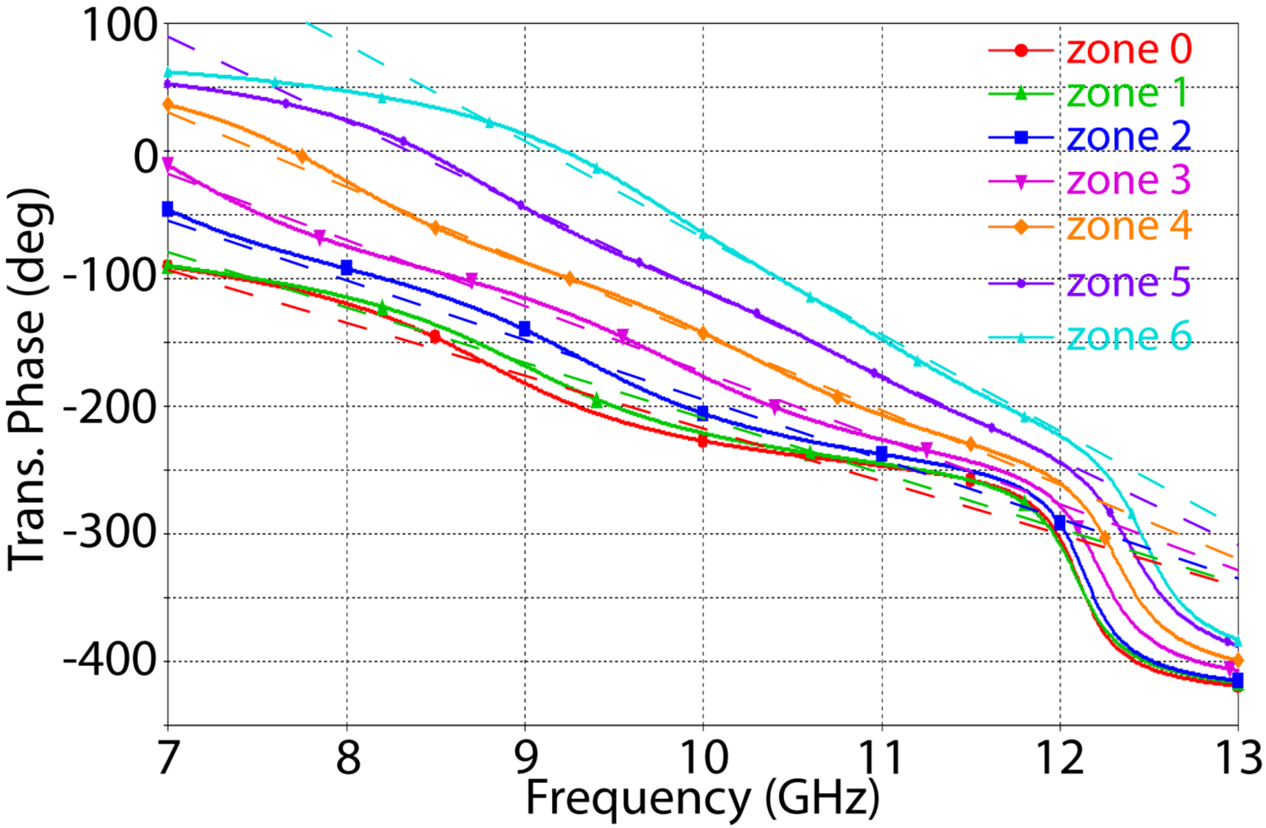
- Single cell of dimensions D, w, g_1, g_2, etc. is modeled with finite element code (CST).
- Transmittance T and phase-shift $\Delta\phi$ at various frequencies f_1, f_2, etc. are stored.
- Calculation is repeated for various D, w, g_1, g_2, etc. Database is built.
- For each zone, we pick D, w, g_1, g_2, etc. yielding best match between calculated T and $\Delta\phi$ and desired T and $\Delta\phi$



Contours of $\Delta\phi$(deg) at f=10GHz

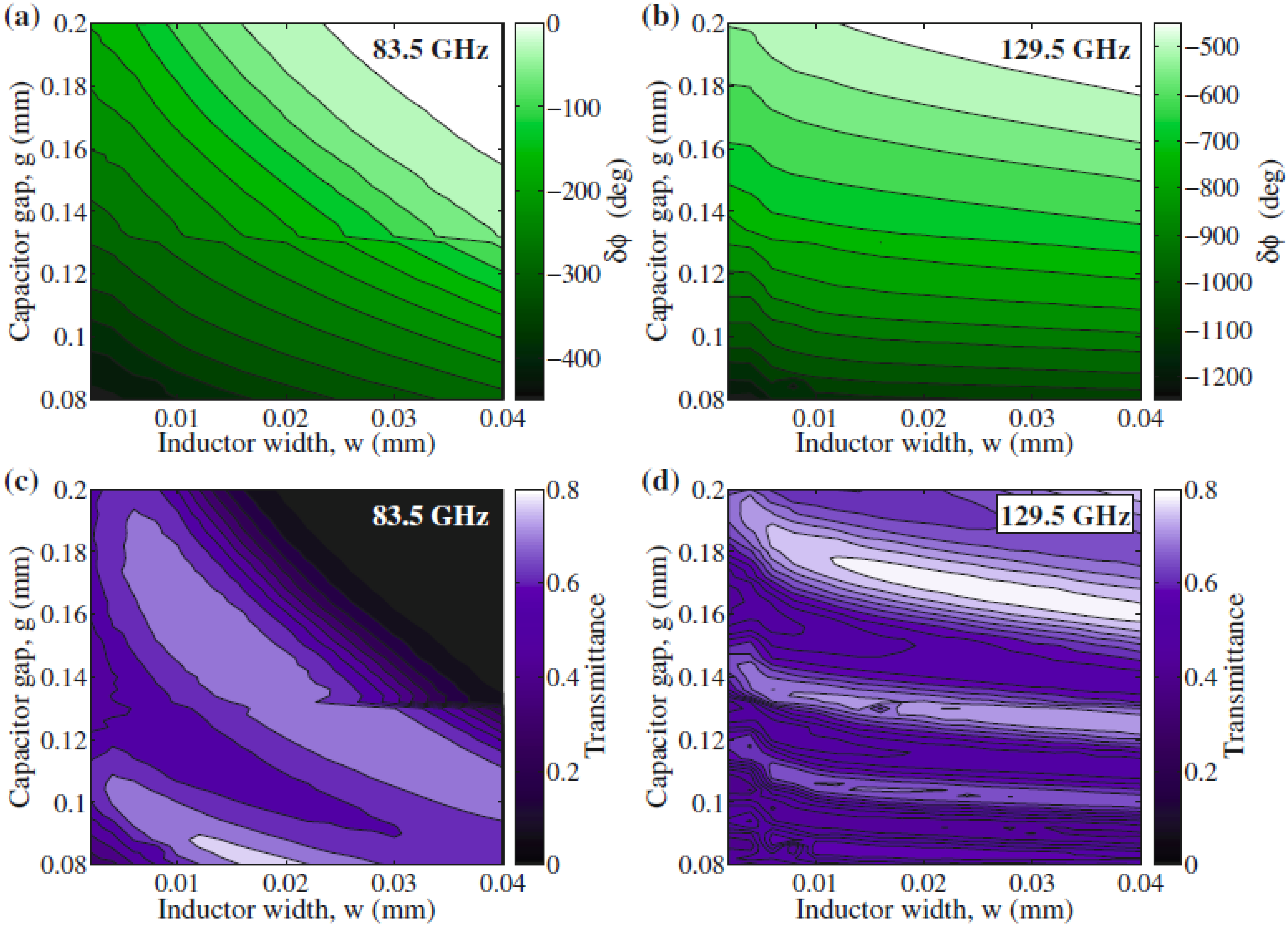


Numerically optimized $\Delta\phi(f)$ matches desired $\Delta\phi(f)$ for RCA at f=8-12GHz



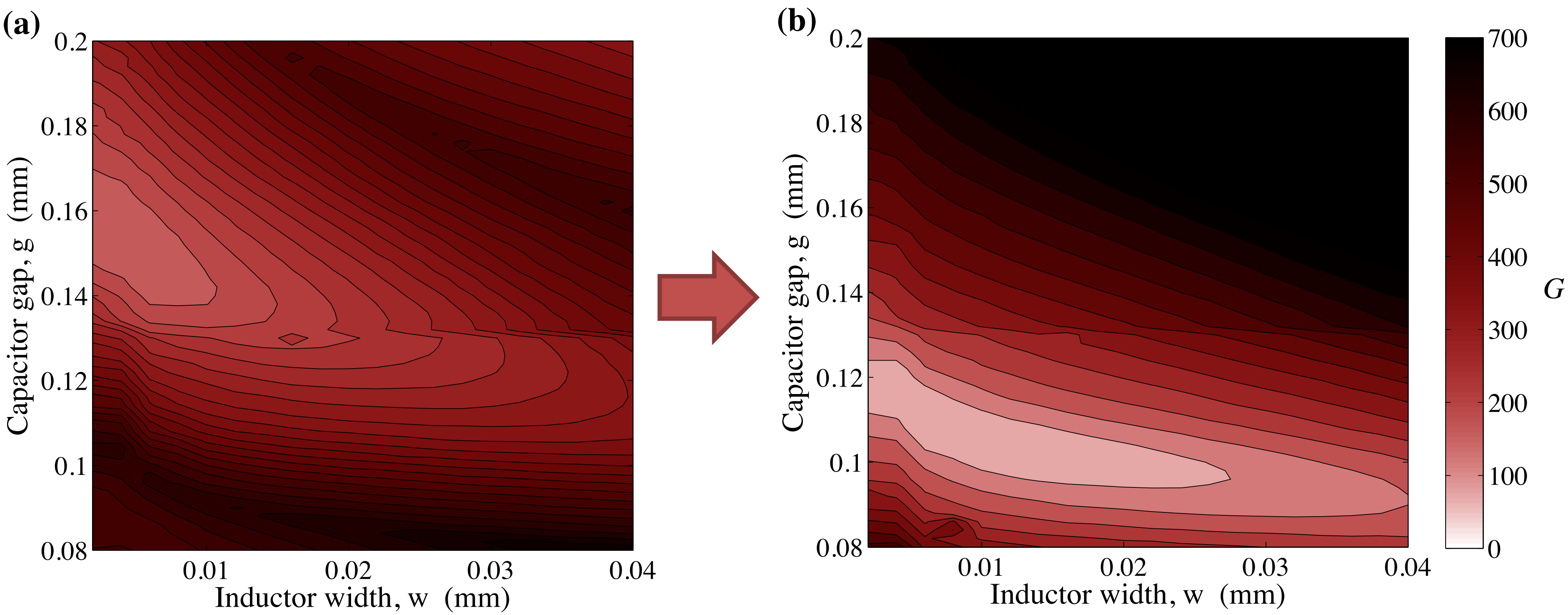
W.J. Capecchi *et al., Optics Express* **20**, 8761 (2012)

Database was also built for *f*=80-130 GHz (ECE at DIII-D)



Relaxing constraints on *absolute* phase improves agreement with desired $\Delta\phi(f)$

Only *relative* phase (zone-to-zone) matters



G="Goal function" (the smaller the better)

K.C. Hammond *et al., J Infrared Milli Terahz Waves* **34**, 437 (2013)

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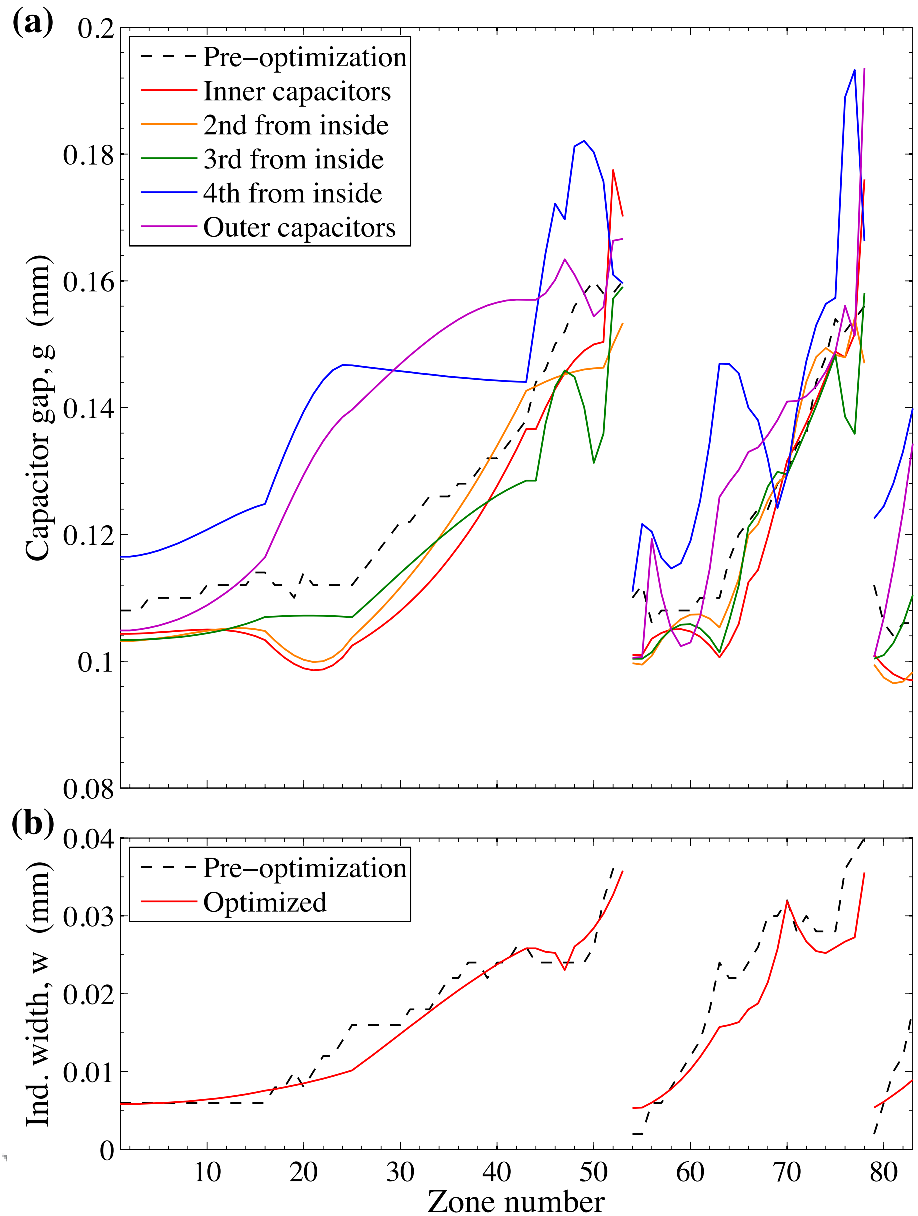
Individual fine-tuning of geometrical parameters in each layer further improves the agreement



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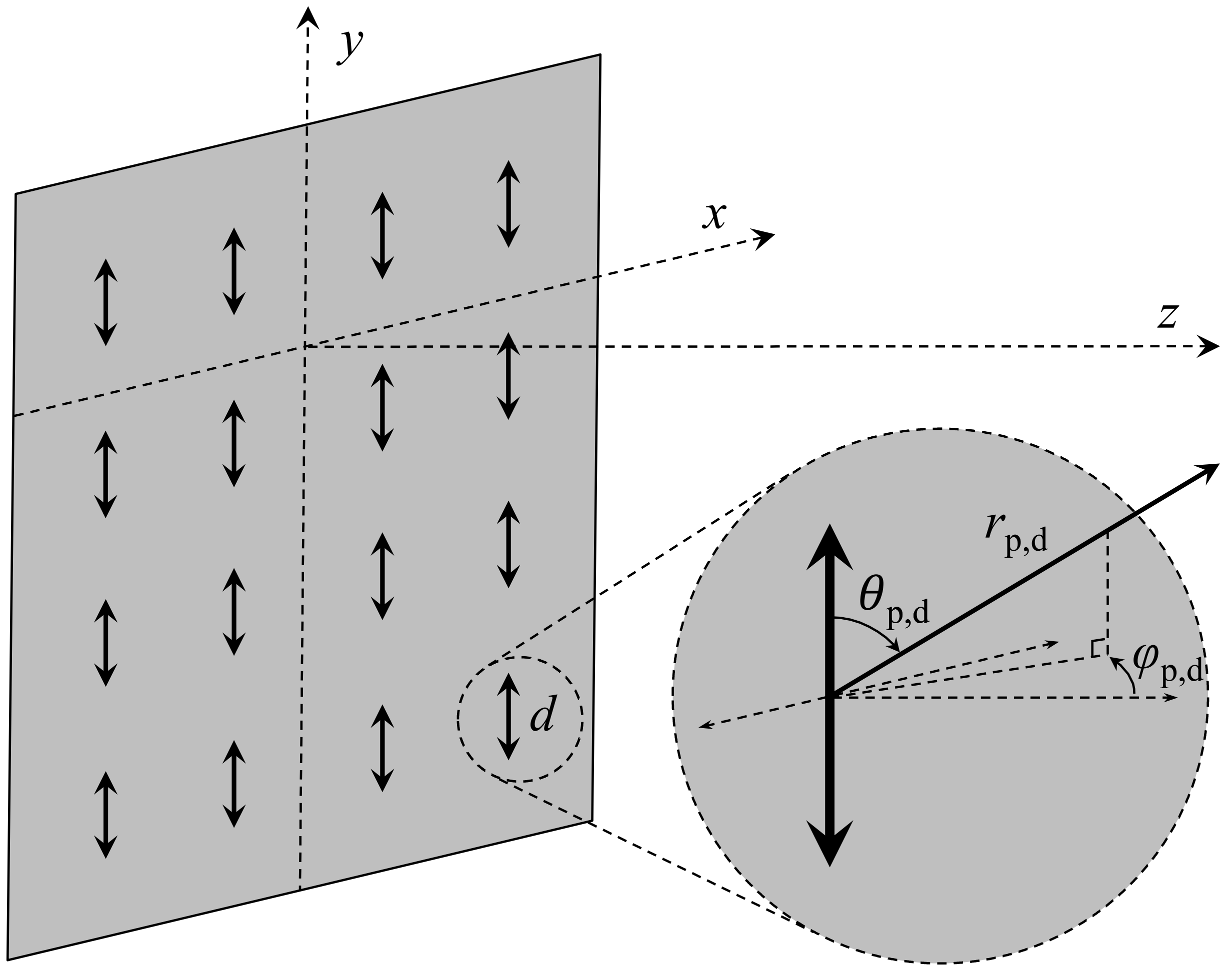
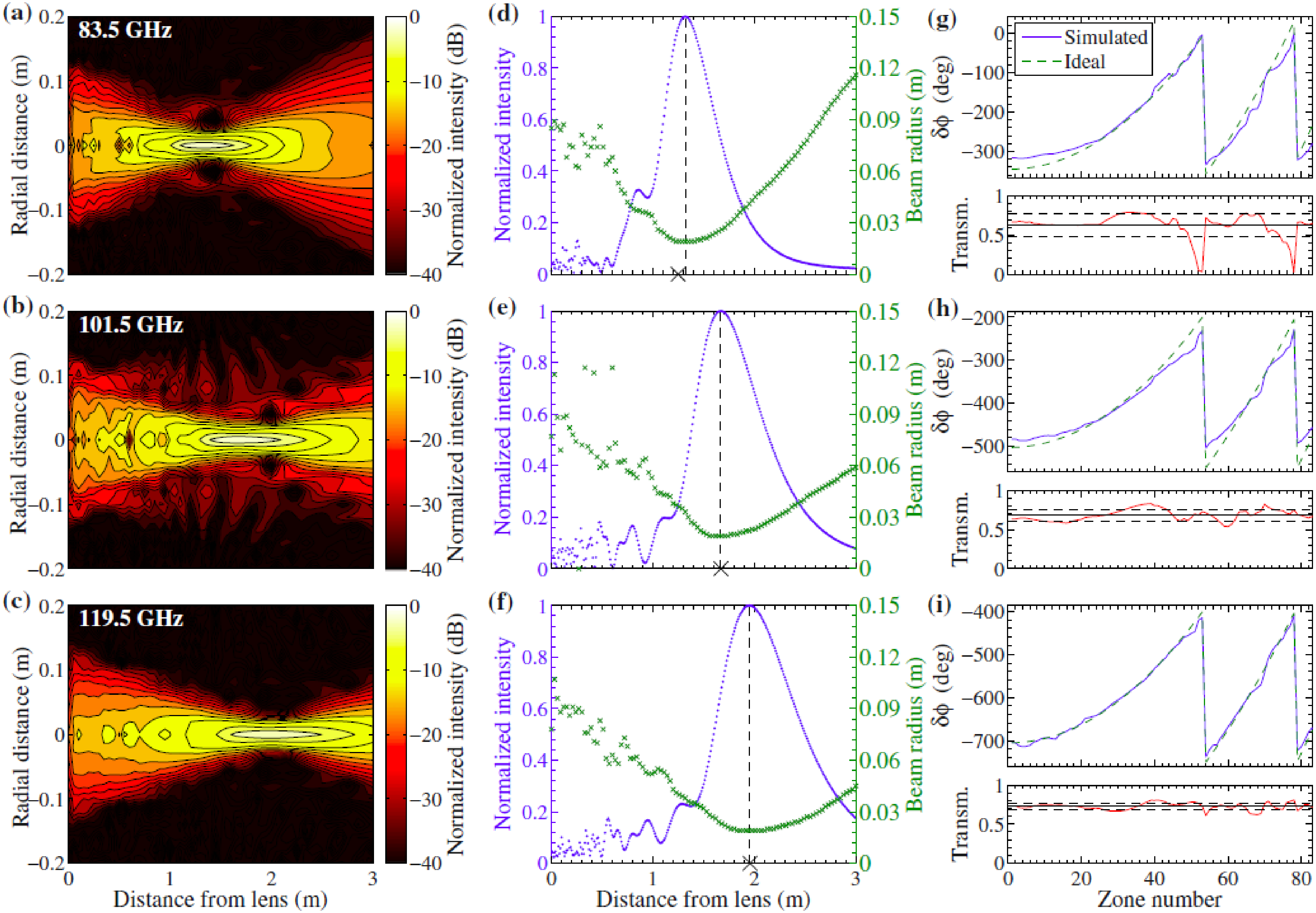
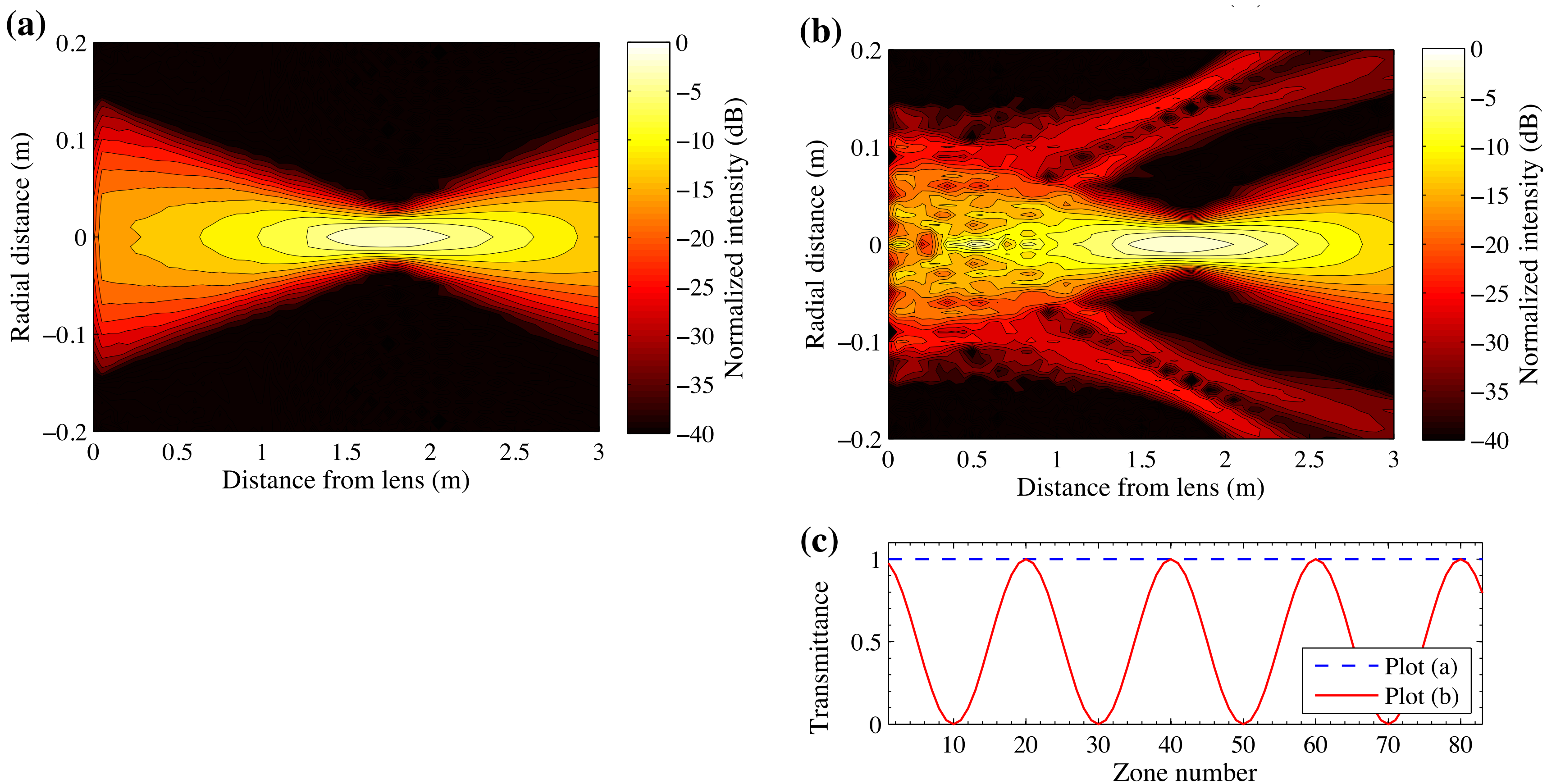
Optimized cells put together and treated as attenuated and delayed dipole-emitters → Interference pattern → Global lens response



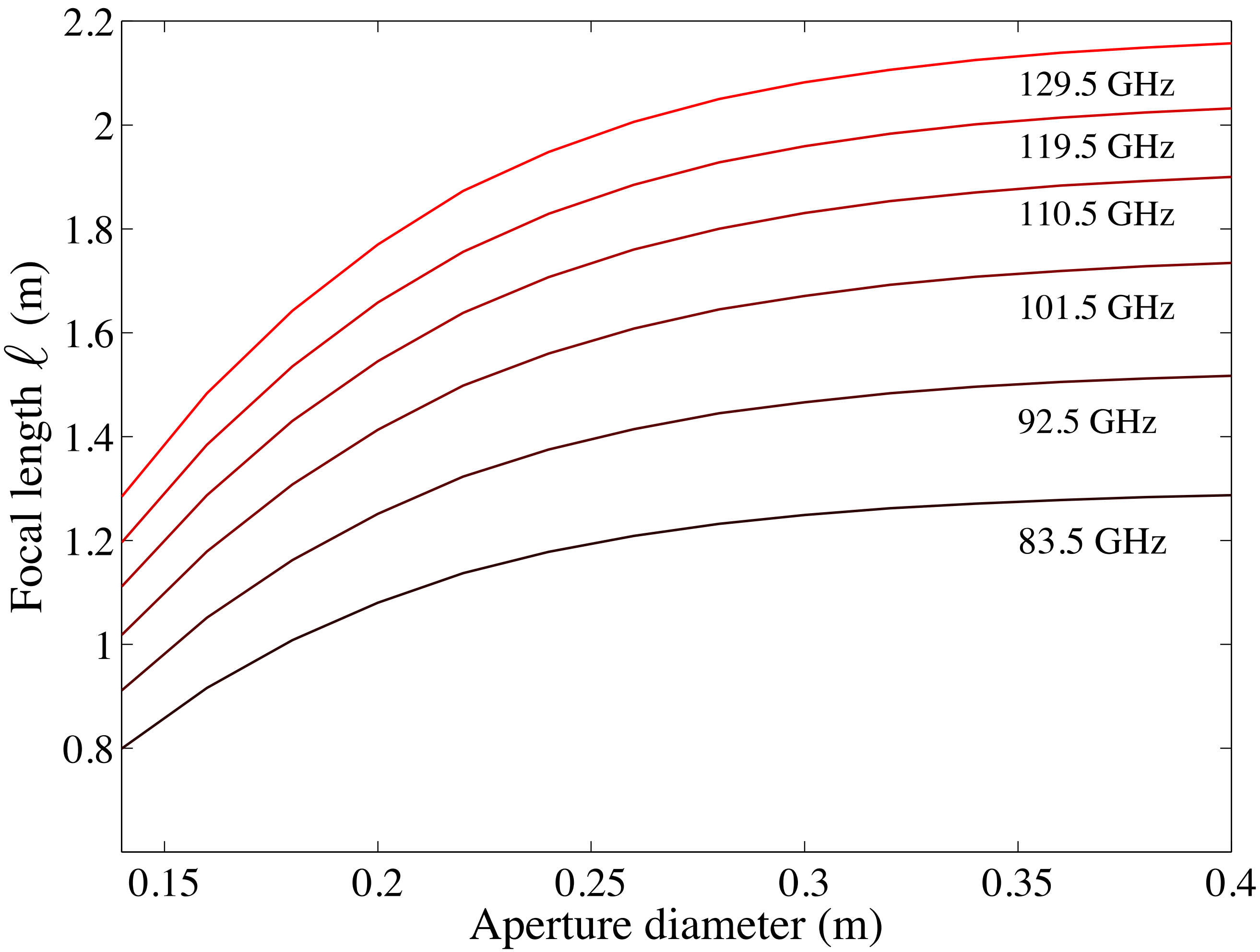
Obtained desired RCA for maximum transverse resolution in ECE at at DIII-D.
A single lens focuses different *f* at different locations where that *f* is EC-emitted.



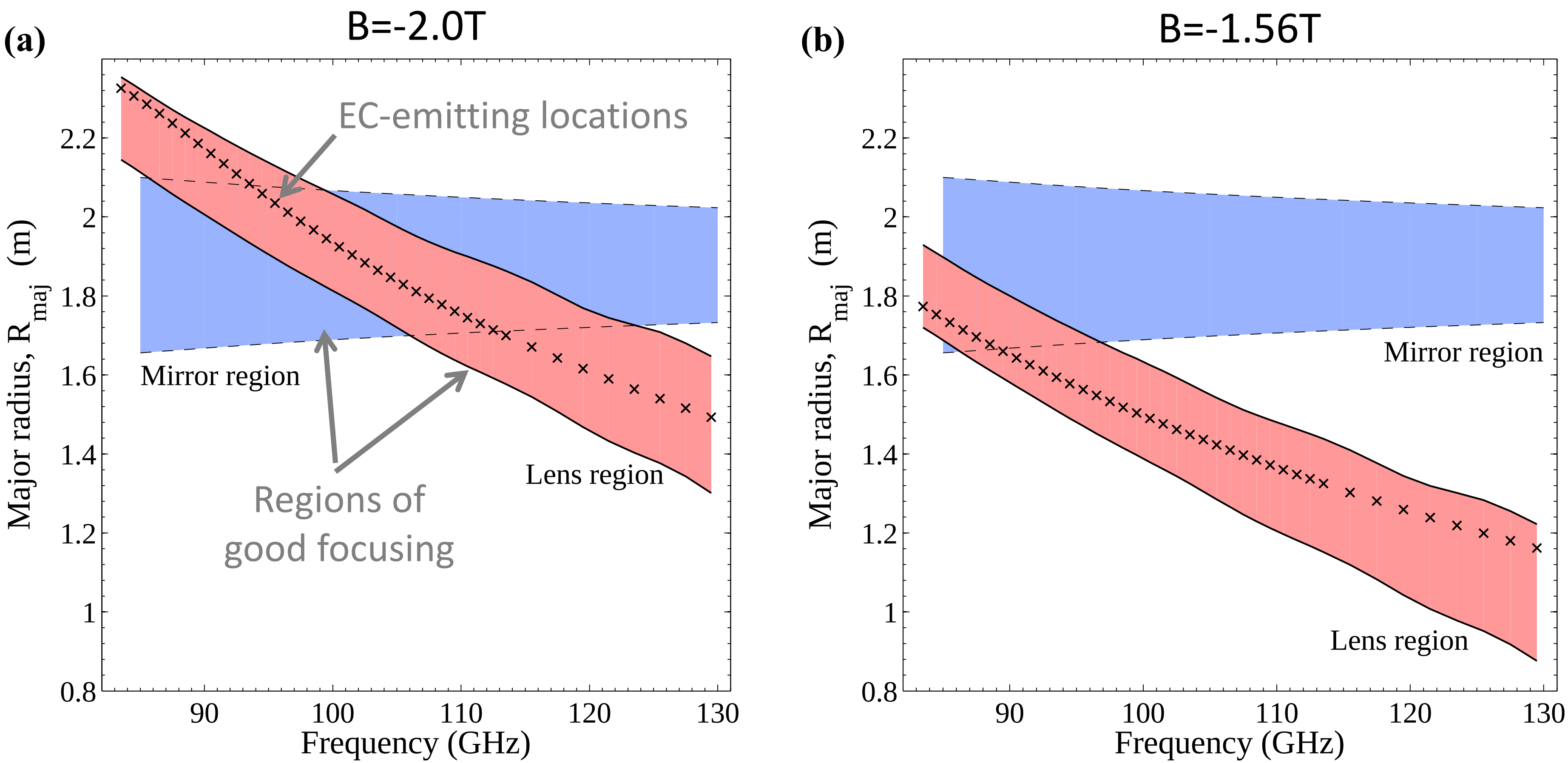
Sidelobes were explained with non-uniform transmissivity across zones → grating → diffraction maxima



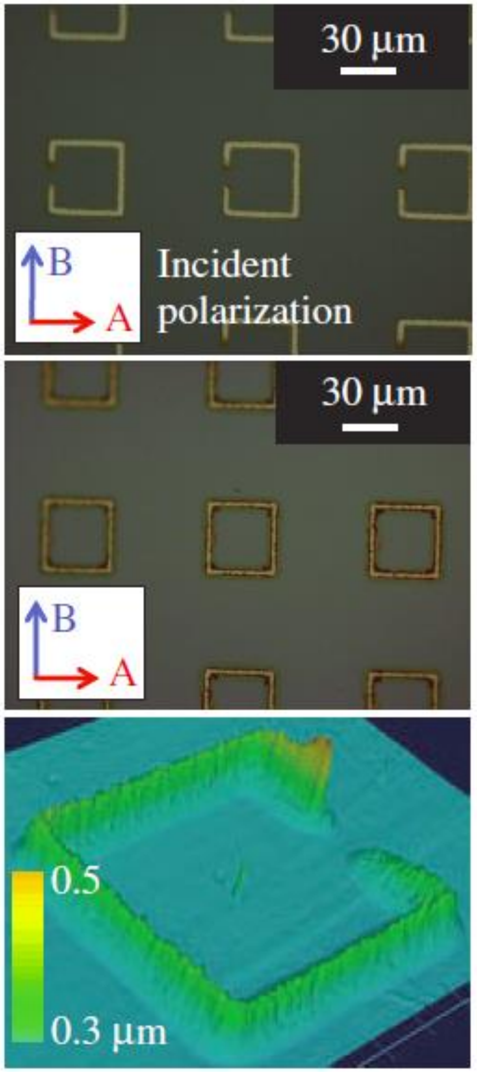
Simulations show that varying the lens aperture changes its focal length → a diaphragm acting as a zoom!

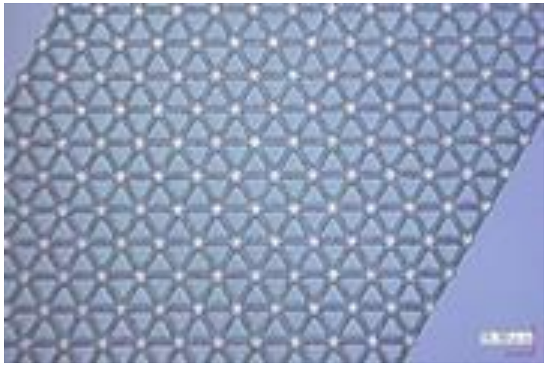


EC-emitting locations are always in focus, with metamaterial lens. They are not in focus with present mirror.

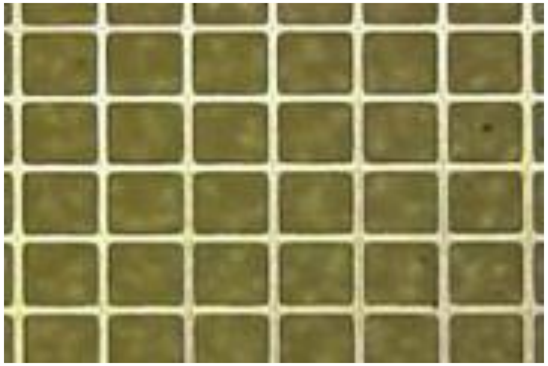


Ink-jet printing is capable of 1-5μm details

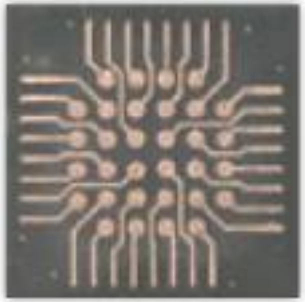




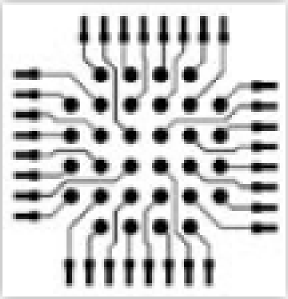
Silver, lines: 3μm, spacing: 15μm



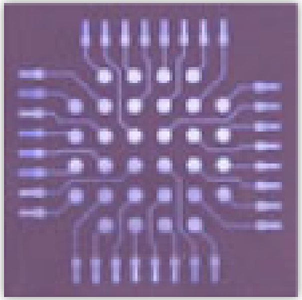
Gold, lines: 5μm, spacing: 50μm



Conventional printer



CAD



Super-fine Printer

K. Takano *et al*., Applied Phys. Expr. 2010
Sjctechnology.com

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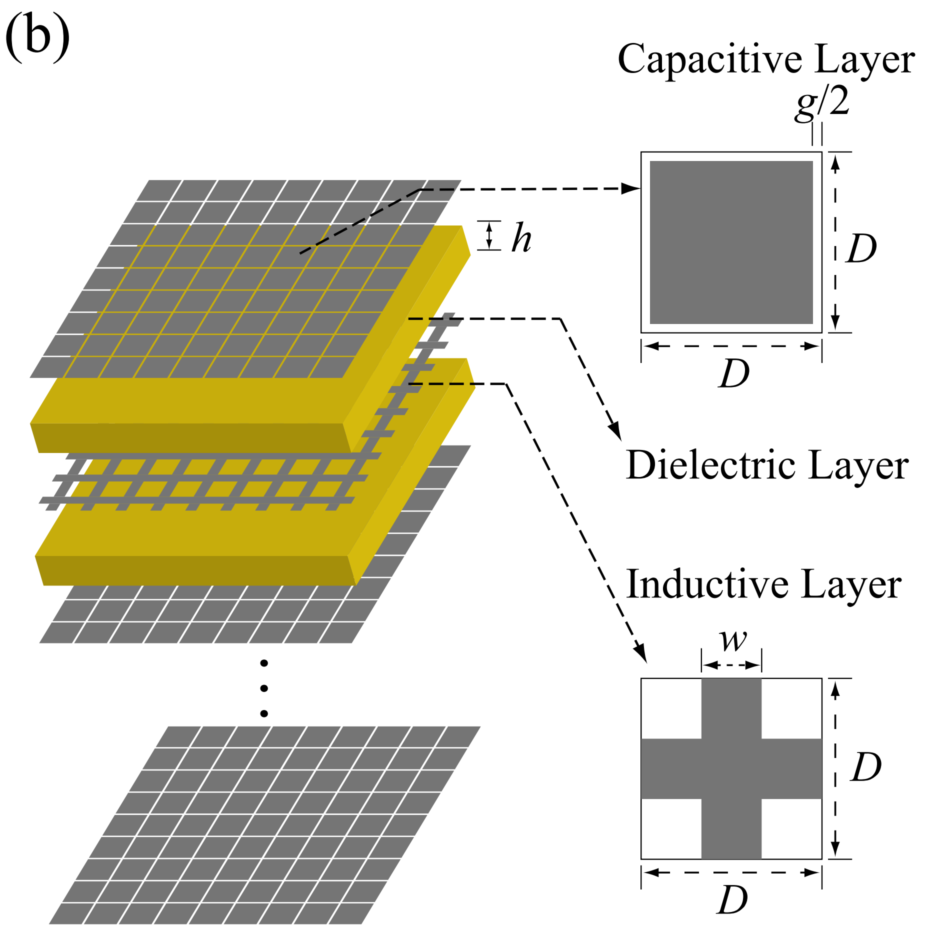
Low-power 8-12 GHz lens manufactured using an ink-jet printer and silver-nanoparticle ink

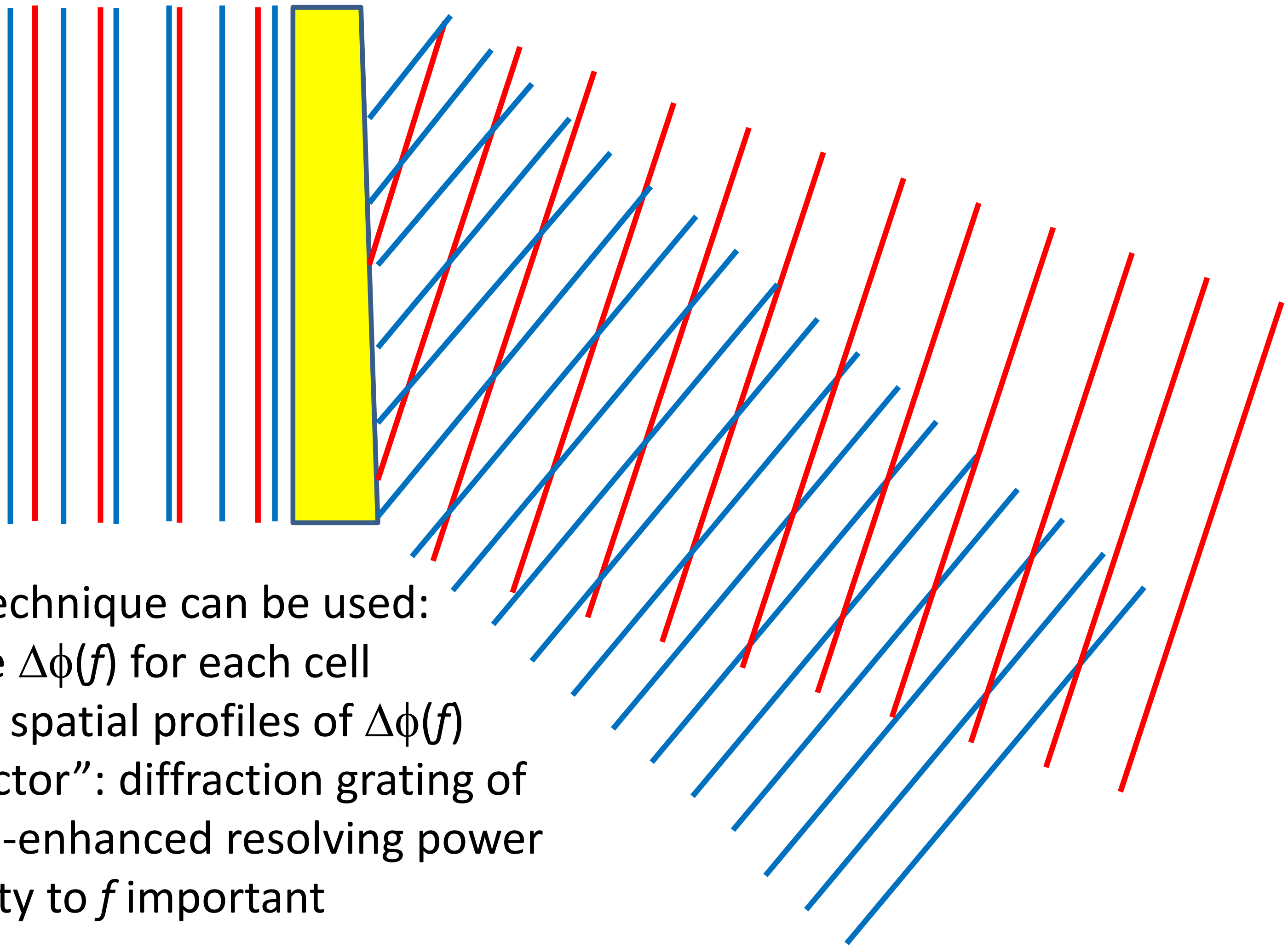
- (show samples)
- Ink = liquid suspension of ~5nm Ag nanoparticles
- Resistivity 3$\mu\Omega$cm after 1h sintering at 150-200^{o}C (bulk Ag 1.6$\mu\Omega$cm).
- Printed circuit board (PCB) techniques (e.g., laser) also under consideration
- 80-130 GHz might require lithography, laser raster or integrated circuit (IC) nano/microfabrication techniques
- Tests of 8-12 GHz lens starting soon

Extension to high power requires modified design and materials

- Some motivations:
  - Tunable gyrotrons
  - Rapid steering of ECCD for NTM stabilization w/o moving mirrors in vessel
  - Collective Thomson Scattering
- Simple! Replace:
  - plastic dielectric → recirculating cooling fluid (freon FC-75)
  - Square patches → stripes (2 sets, orthogonal)



Frequency-controlled Steering



- Same num. technique can be used:
  - Prescribe $\Delta\phi(f)$ for each cell
  - Different spatial profiles of $\Delta\phi(f)$
- “Super-diffractor”: diffraction grating of metamaterial-enhanced resolving power
- High sensitivity to f important

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Conclusions

- Proper array of microfabricated phase-shifters acts as a lens.
- Optimizing its dimensions allows to match a desired dependence of focal length on frequency, including extreme and reverse chromatic aberration.
- Numerical example for 8-12 and 80-130 GHz.
- Lens for 8-12 GHz was manufactured by ink-jet printing (with silver nanoparticle ink) on dielectric substrate.
  - Inexpensive, fast, suited for low-power, low-frequency.
  - Alternatives at high-power and/or high-frequency were discussed.
- Numerical technique can be extended to:
  - aberration-free lens
  - rapid frequency-controlled steering
- With different designs and materials, manufacturing can be extended to high-power heating, current drive & active diagnostics.