Gradient-index metamaterials and spoof surface plasmonic waveguide

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City University of Hong Kong, 11 October 2016

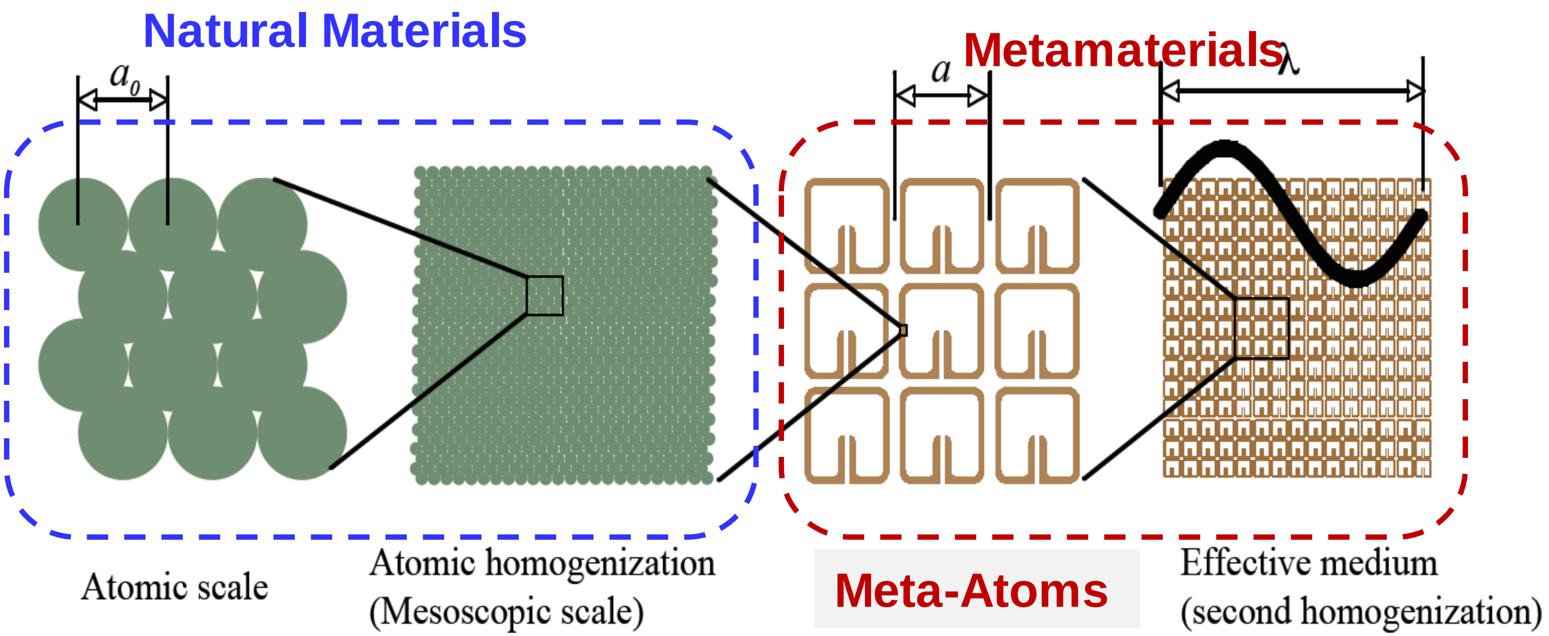
Contents

◆Background and motivation

◆ Inhomogeneous gradient-index (GRIN) metamaterials

◆ Spoof surface plasmonic waveguide

Metamaterials



1) The number of atom kinds is limited (119)
2) It is difficult to arrange atoms as desired

1) The types of meta-atoms can be countless
2) The meta-atoms can be arranged as desired

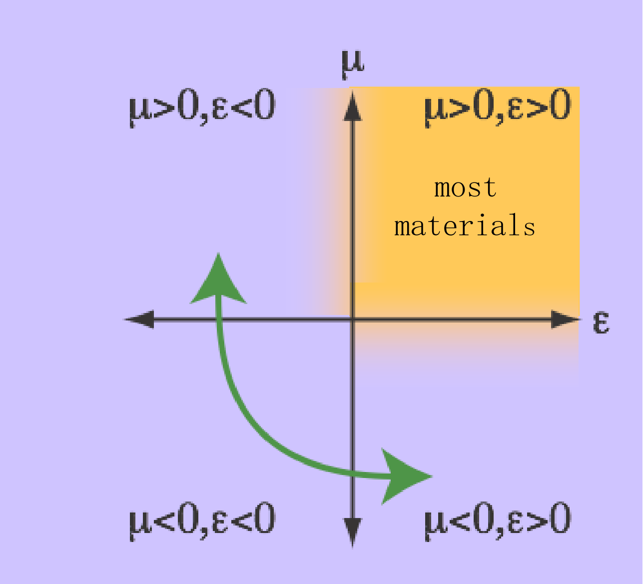
Effective Metamaterial Properties

Design of Meta-Atoms

- Resonant meta-atoms: provide extreme parameters (Narrow band and high loss)

- Nonresonant meta-atoms: provide wideband parameters with low loss

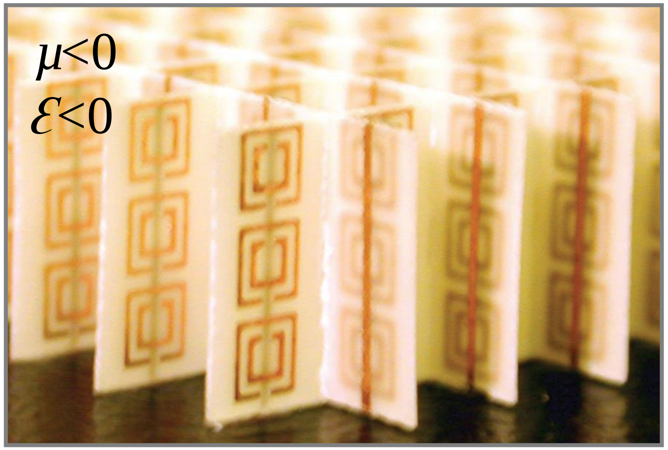
- Provide fully electromagnetic characteristics
- Provide highly anisotropic characteristics



Design of Arrangement of Meta-Atoms

◆ Metamaterials can be homogeneous or highly inhomogeneous

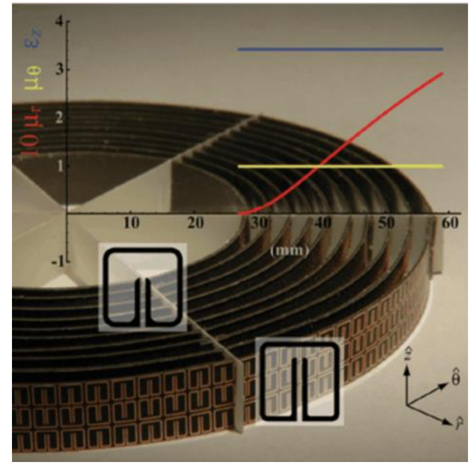
Some examples of metamaterial experiments



Verification of a Negative Index of Refraction

Resonant & homogeneous

Science **292**, 77 (2001)

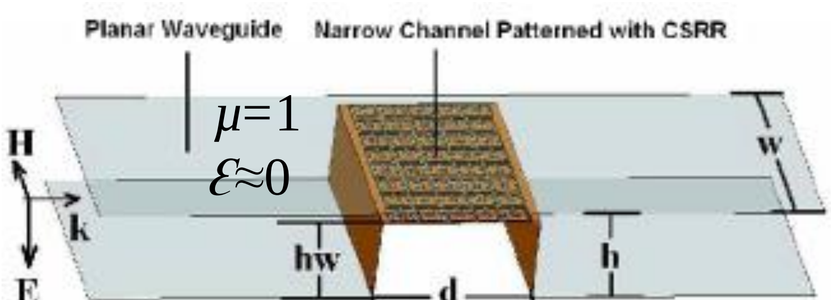


$\mu_r>0$
μ_θ=const.
$\mathcal{E}_r$=const.

Invisible cloak

Resonant & inhomogeneous

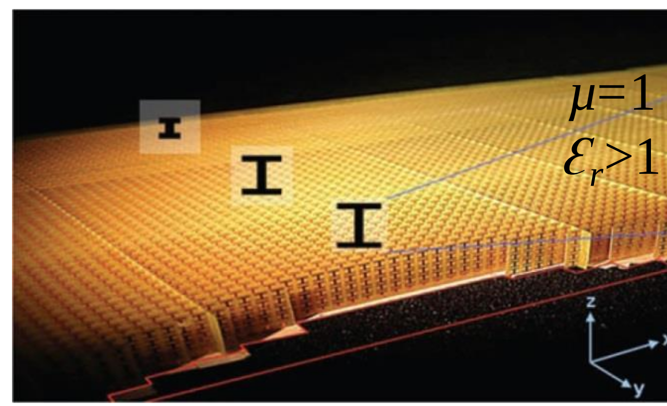
Science **314** 977 (2006)



Electromagnetic tunneling

Resonant & homogeneous

PRL **100**, 023903 (2008)



Ground-plane cloak

Nonresonant & inhomogeneous

Science **323**, 366 (2009)

Problem and Motivation

Advantage

- Metamaterials – Exciting topics
- A lot of new concepts, new findings

Problem

- Large amount of theoretical work and/or numerical simulations, and lack of experimental realization
- The realizable metamaterial devices are mostly narrow band with big loss
- The most experiments are limited in 2D space

Motivation

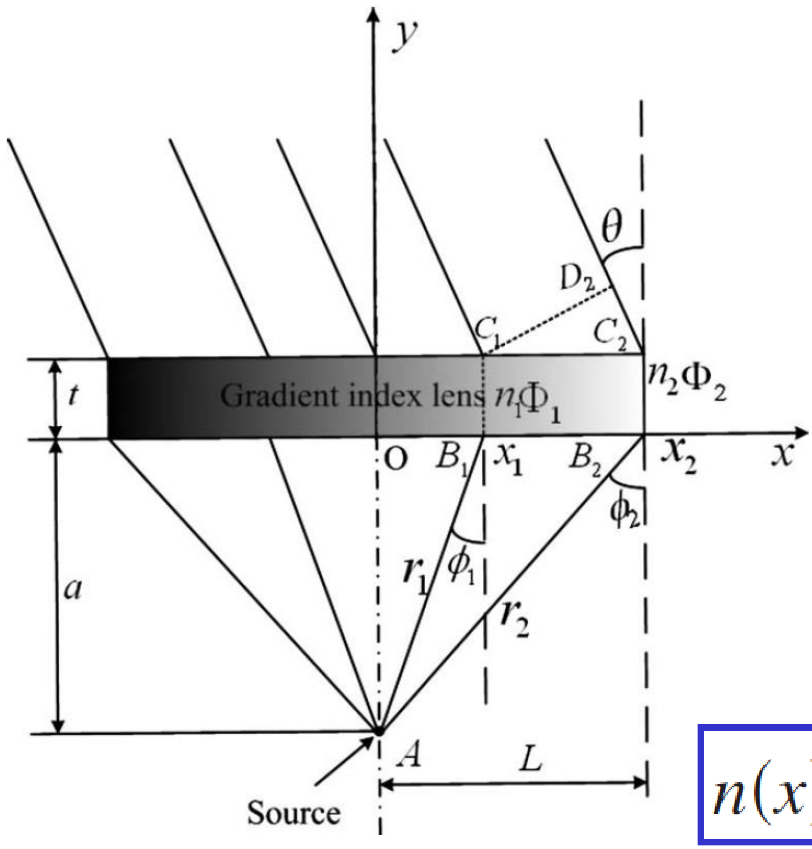
- Realize metamaterial devices by using actual meta structures
- 3D broadband and low loss metamaterial devices for practical applications

Gradient-index metamaterials

- Flat Lenses and Luneburg lens based on geometrical optics
- 3D ground-carpet cloak and flatten Luneburg lens based on quasi-conformal mapping

Flat Lens : High-gain antenna (2D)

◆**Metamaterial Flat Lens Antennas**



Point source

All optical paths from the source to the required wave front should have the same phase delay

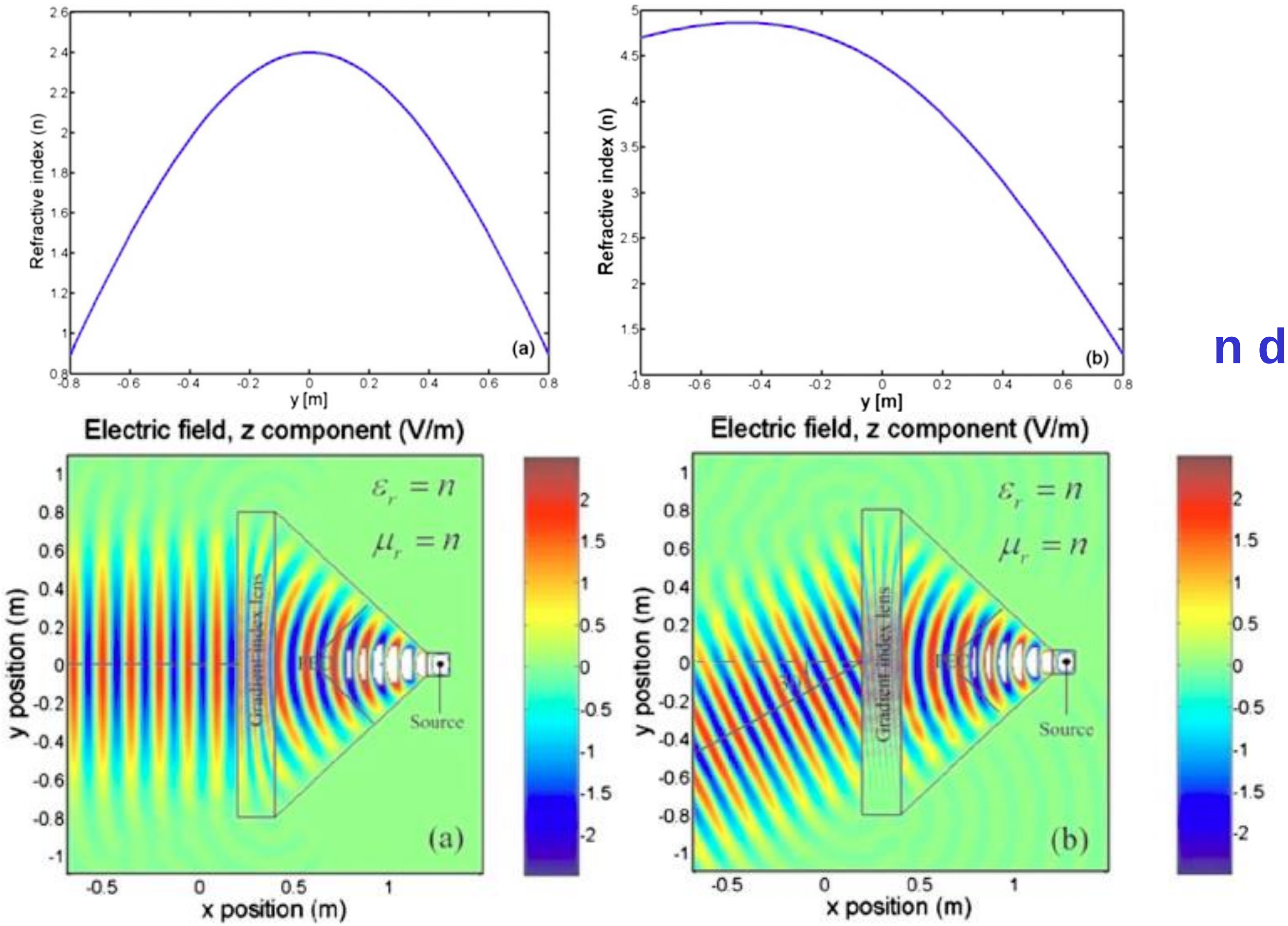
$$\sin\theta + \frac{x}{\sqrt{x^2+a^2}} = -\frac{dn}{dx}t$$

$$n(x) = n_0 - [x\sin\theta + (\sqrt{a^2+x^2} - a)]/t$$

Gradient Index

H. F. Ma, et al., JAP 107, 1, 2010

Flat Lens : High-gain antenna (2D)

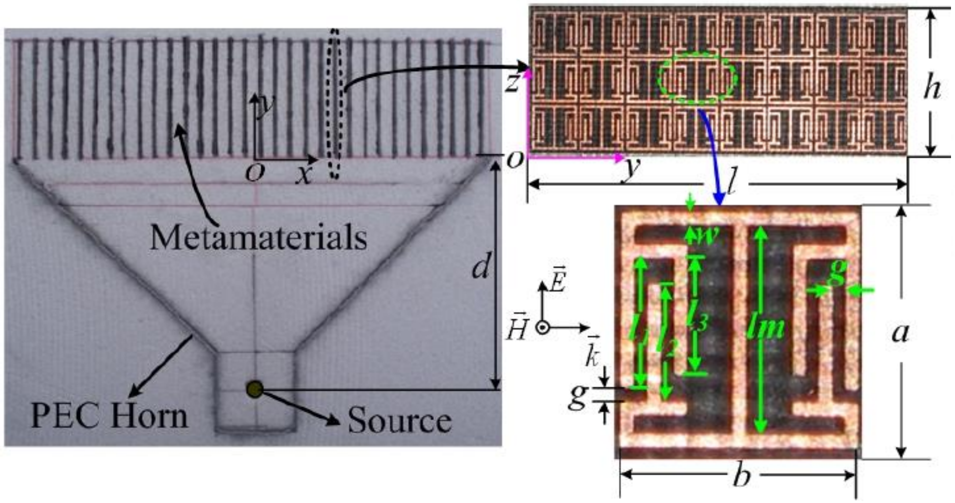


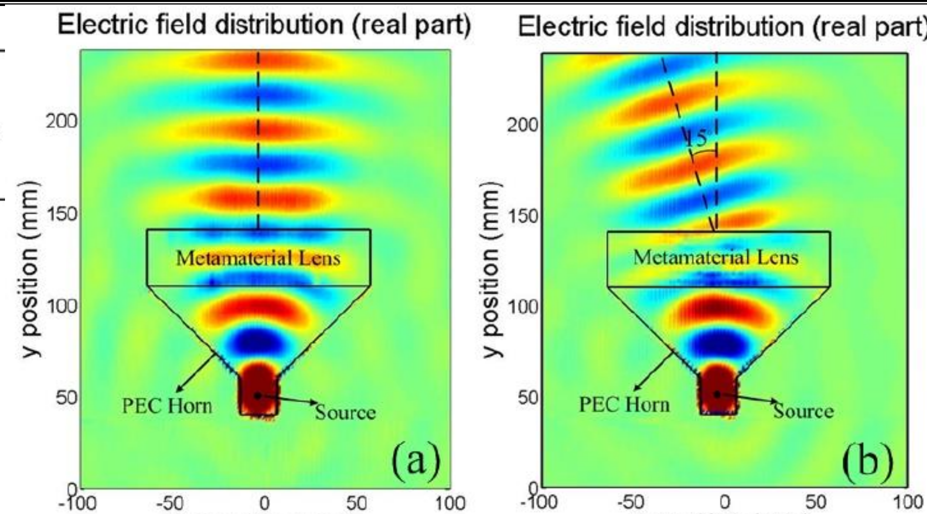
n distributions

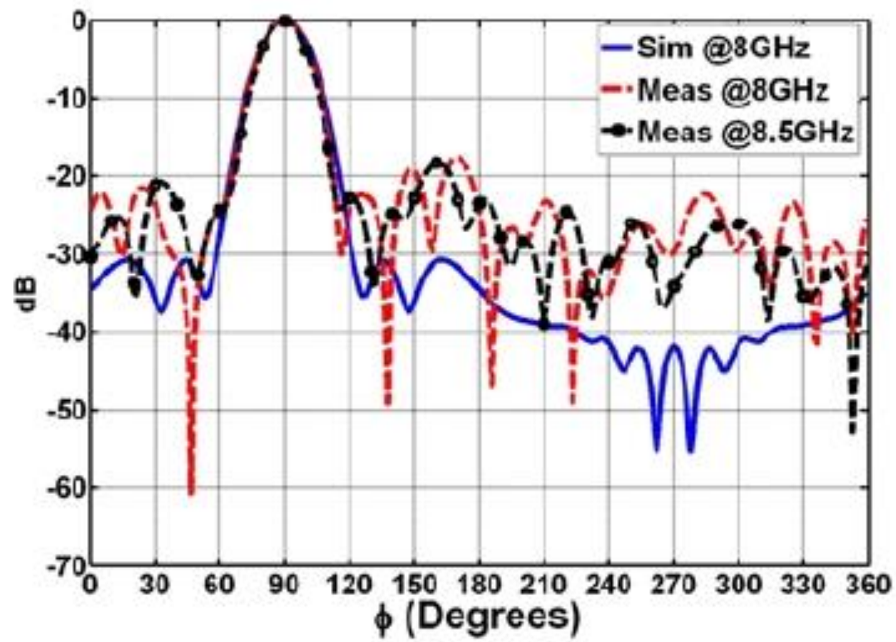
E distributions

Simulations

Flat Lens: High-gain antenna (2D)





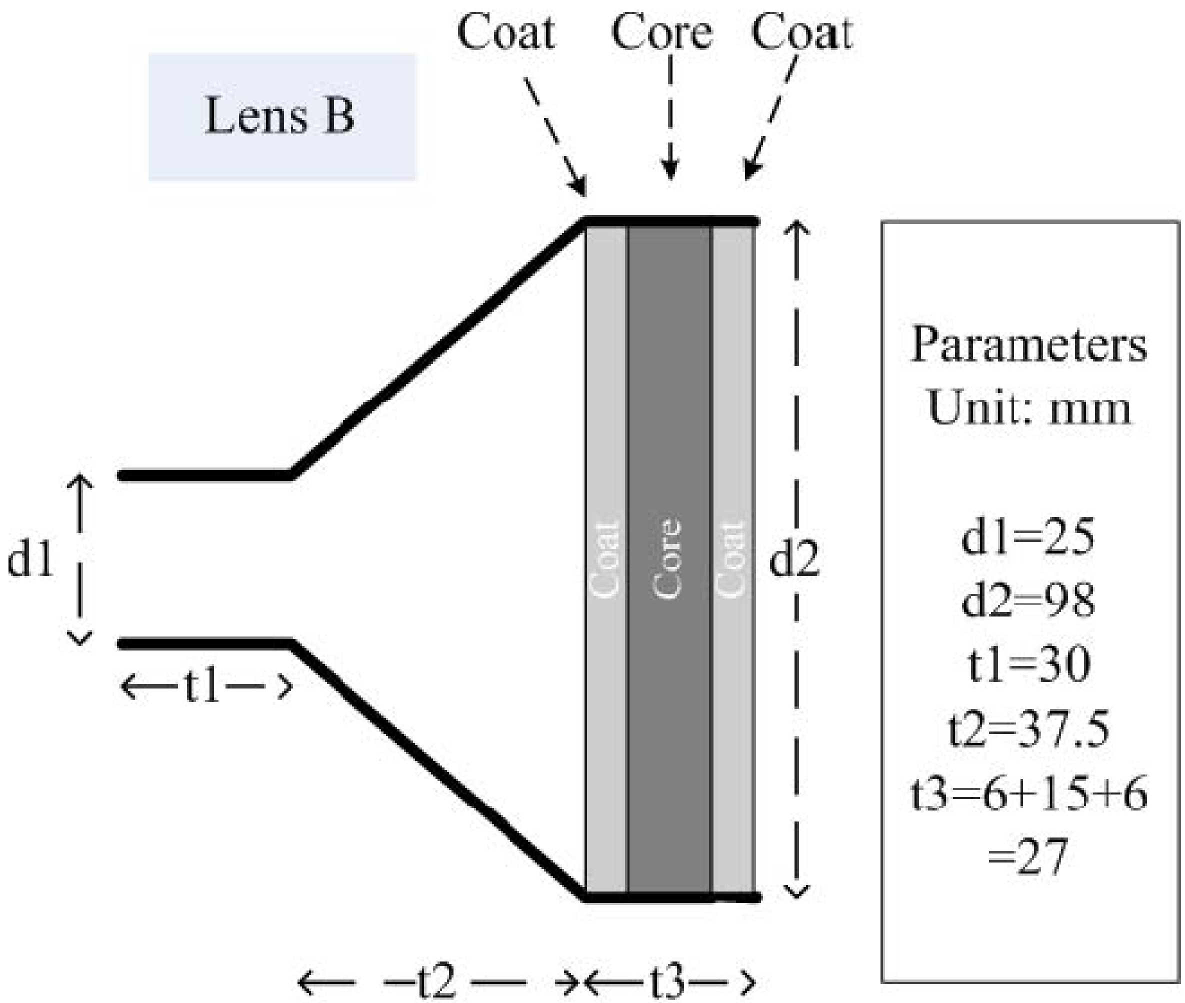


- Both electrical and magnetic responses
- Impedance matching
- Aperture: 12cm, 8GHz

H. F. Ma, T. J. Cui, et al.,
Appl. Phys. Lett. 95, 094107, 2009

Experiment

Flat Lens: High-gain antenna (3D)

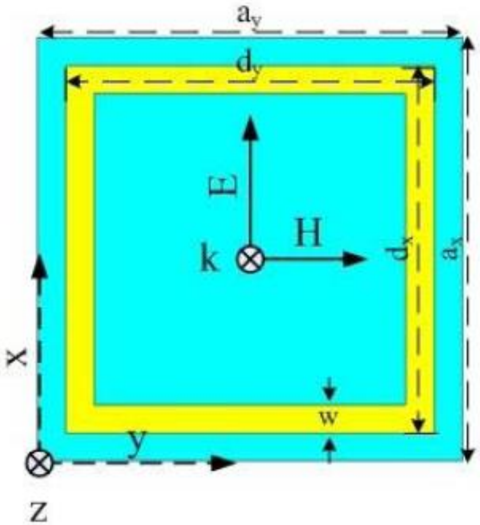


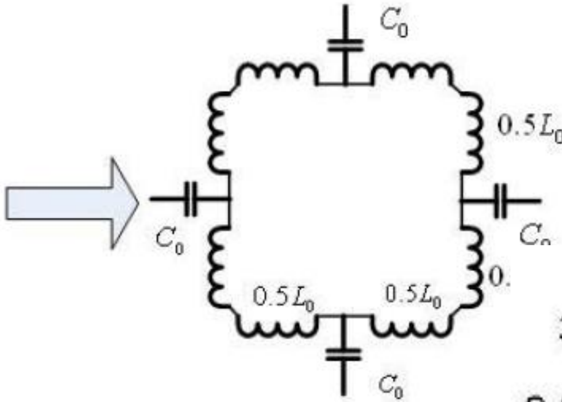
- Coat-Core-Coat Sandwich Structure
- Core: Gradient Index Lens
- Coat: Impedance Matching Layer

X. Chen, H. F. Ma, T. J. Cui, JAP, 110, 044904, 2011

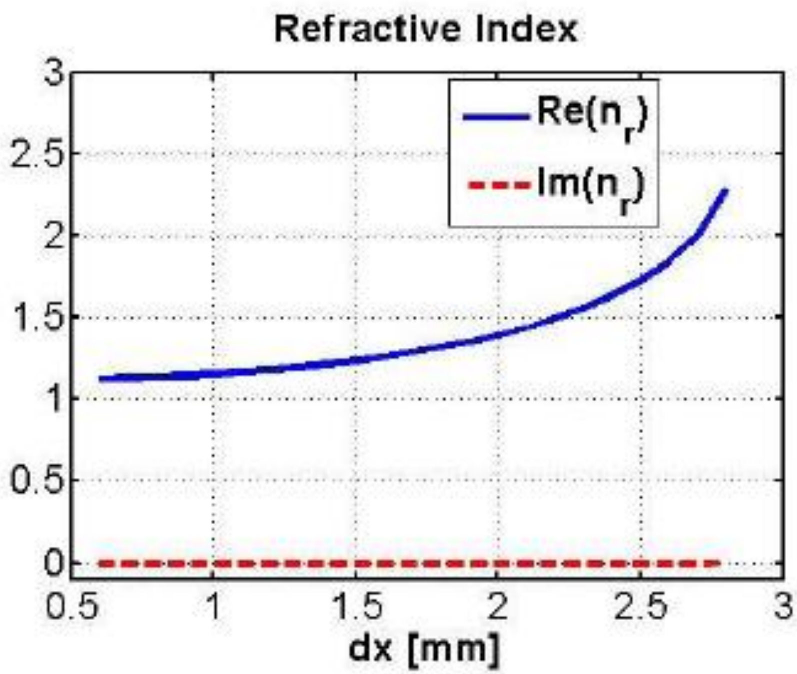
Flat Lens: High-gain antenna (3D)

◆Design of unit cells





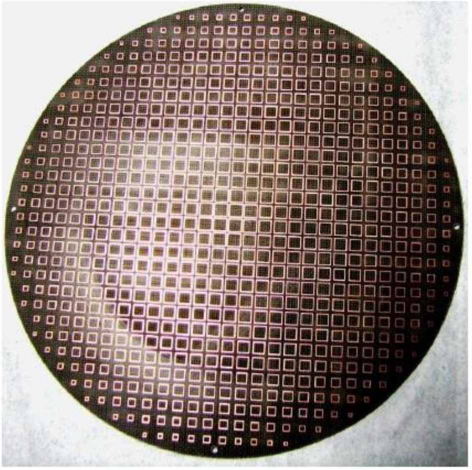
Square-Ring Unit Cell

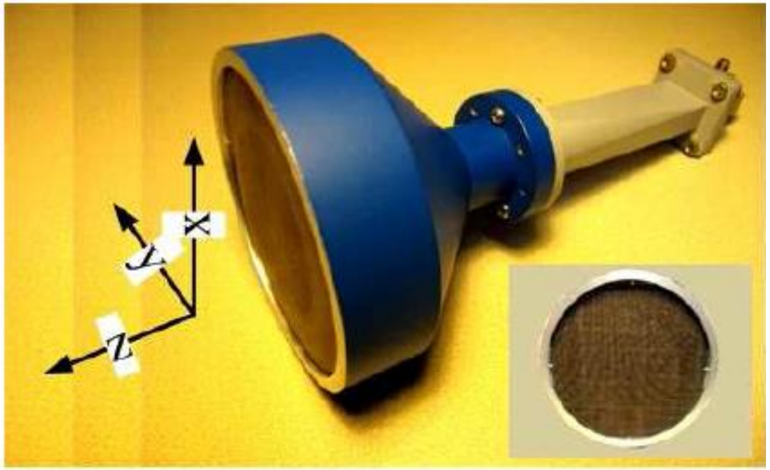


Retrieved Distribution of Refractive Index n

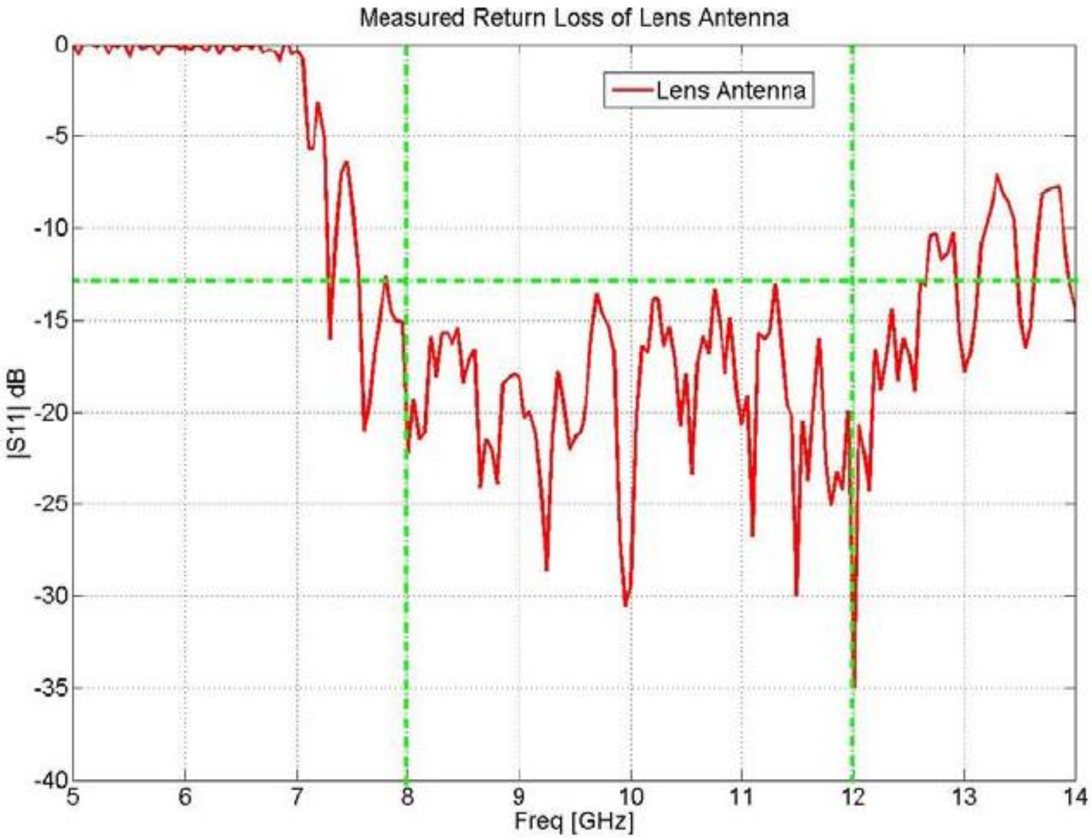
Flat Lens: High-gain antenna (3D)

◆ Fabricated 3D Flat Lens



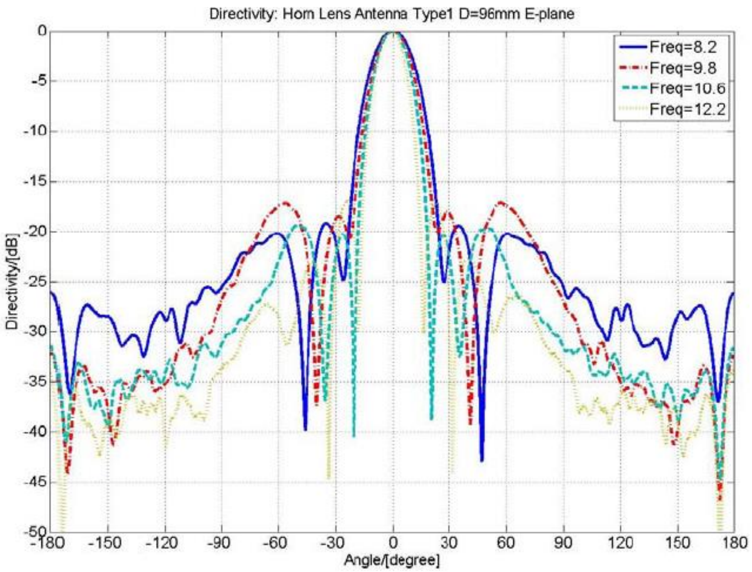


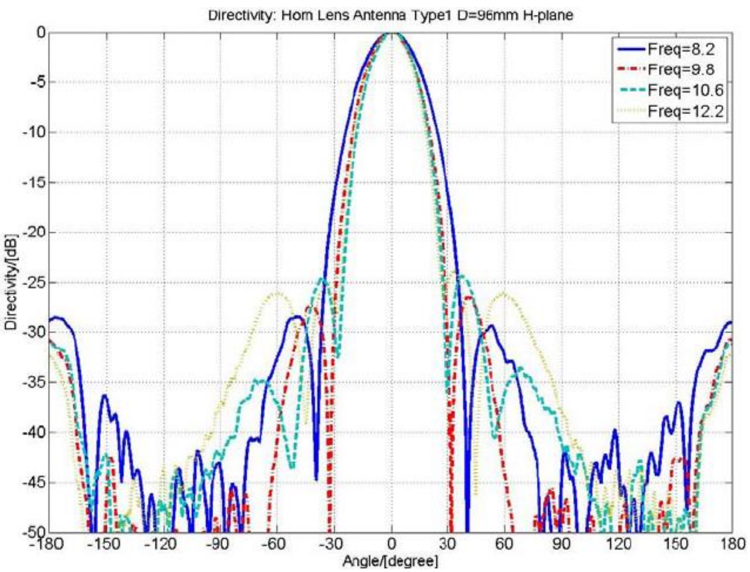
Aperture Size 9.6cm

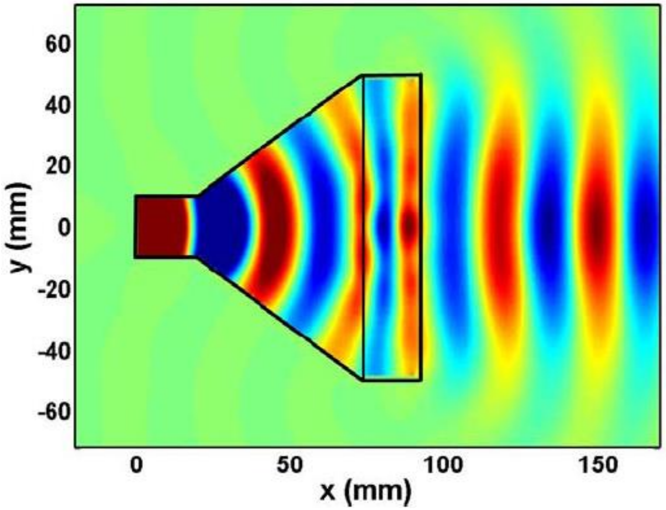


◆ Measured Return Loss: Below -13dB from 8 to 12 GHz

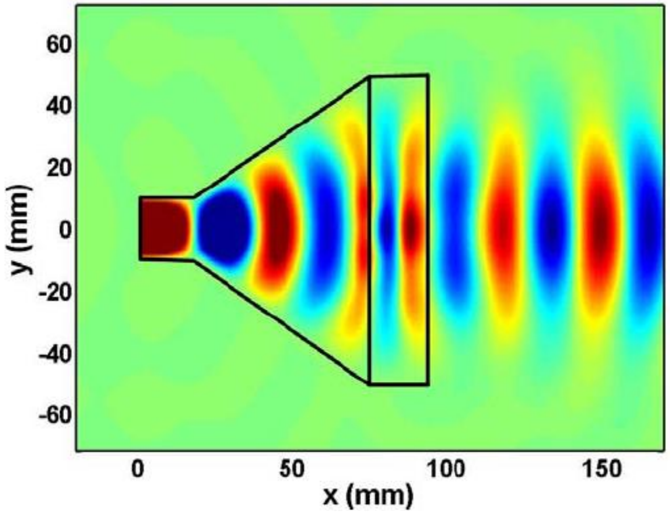
Flat Lens: High-gain antenna (3D)



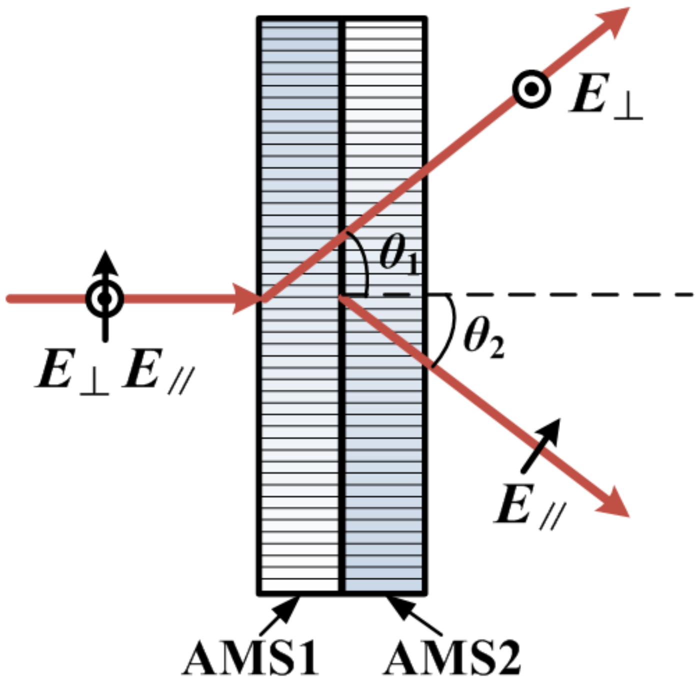




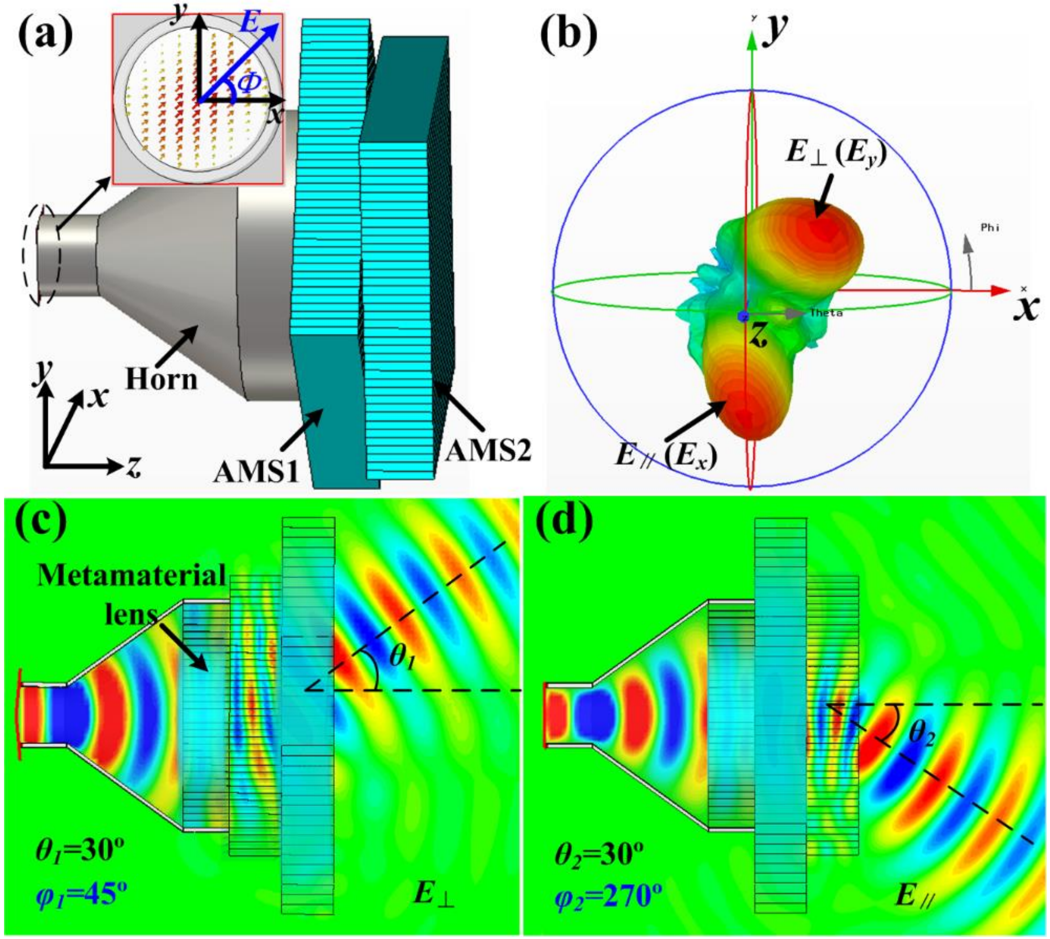
Measured Gain
23 dBi @12 GHz
6dBi higher than the bare horn



Flat Lens: Polarization Beam Splitter



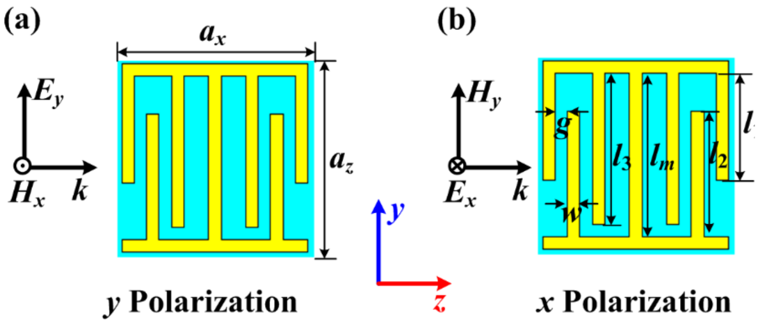
AMS1: Only vertical polarization is deflected.
AMS2: Only horizontal polarization is deflected.

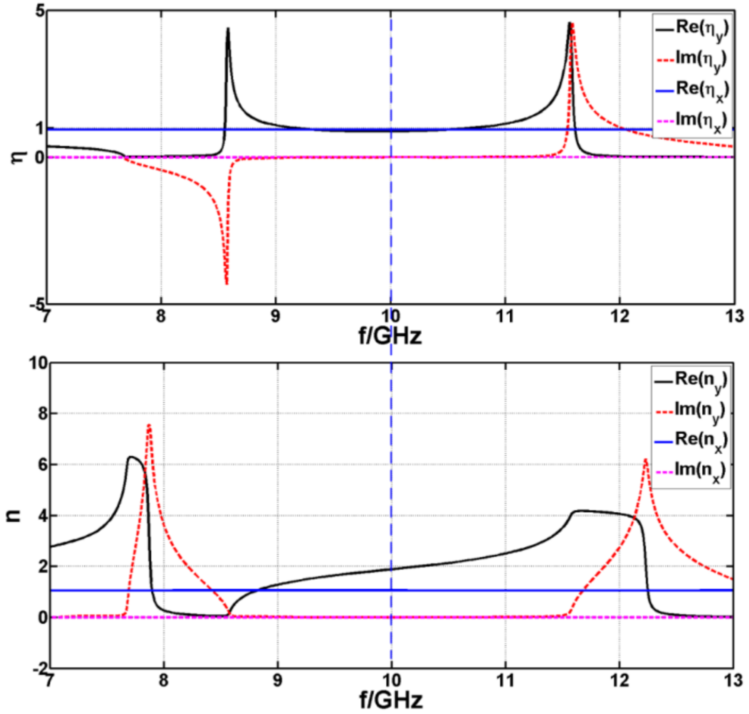


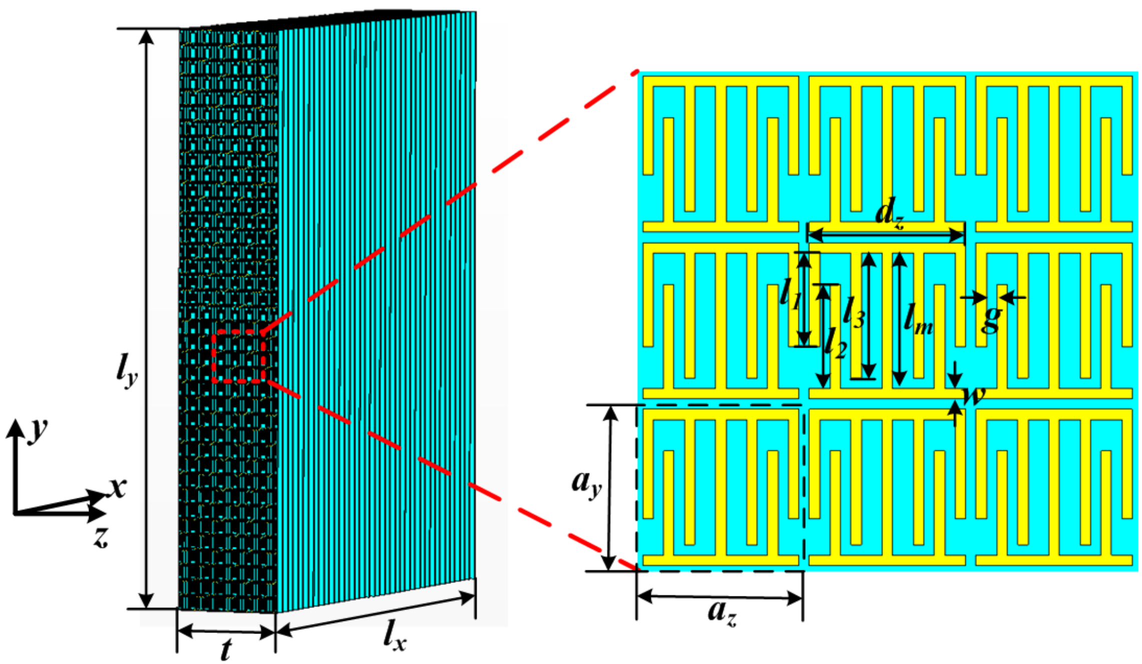
H. F. Ma, T. J. Cui, *et al*. Sci. Rep., 4, 6337, 2014

Anisotropic GRIN metamaterial lens

Flat Lens: Polarization Beam Splitter

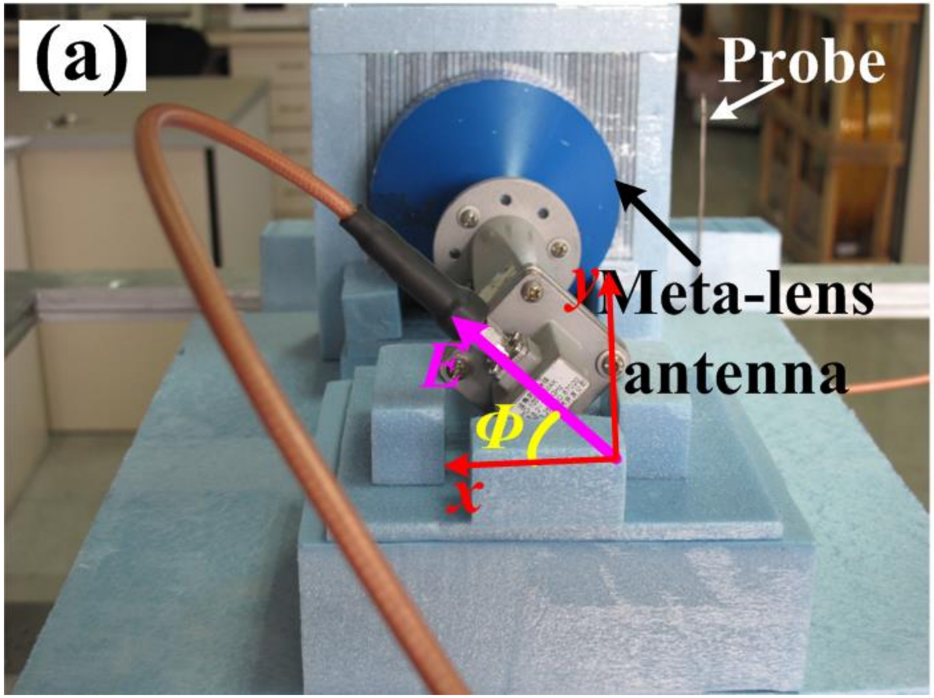


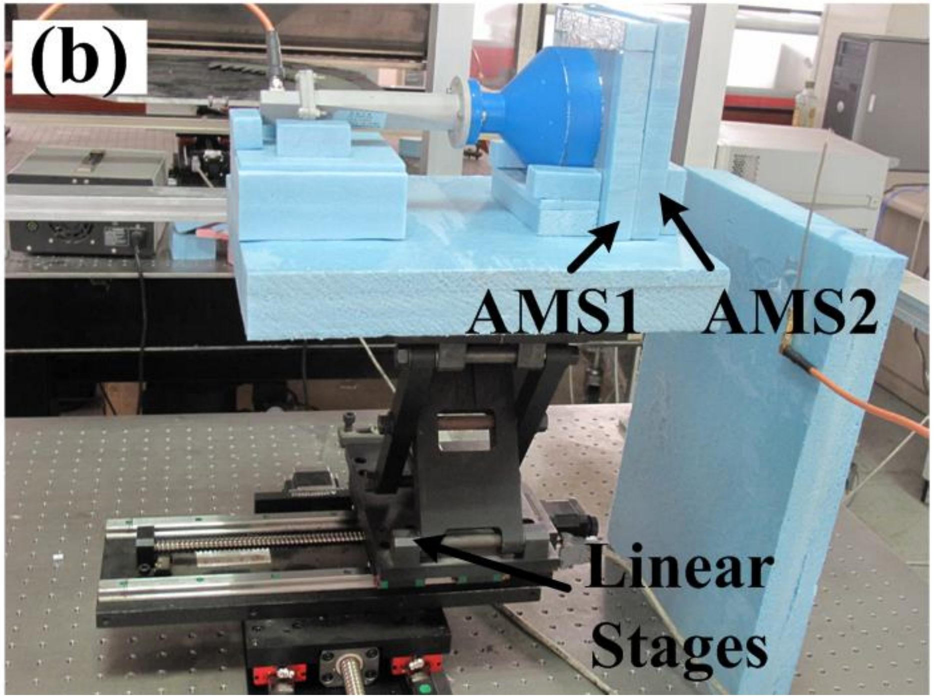




Under *y* polarization: $\eta\approx1$, n is dispersive
Under *z* polarization: $\eta\approx1$, $n=1$

Anisotropic Flat Lens: Polarization Beam Splitter





(a) Φ=45º, **E** can be decomposed to **E**$_x$ ($E_{\parallel}$) and **E**$_y$ ($E_{\perp}$), in which |**E**$_x$|= |**E**$_y$|.

(b) E$_x$ and **E**$_y$ are controlled by AMS1 and AMS2, respectively.

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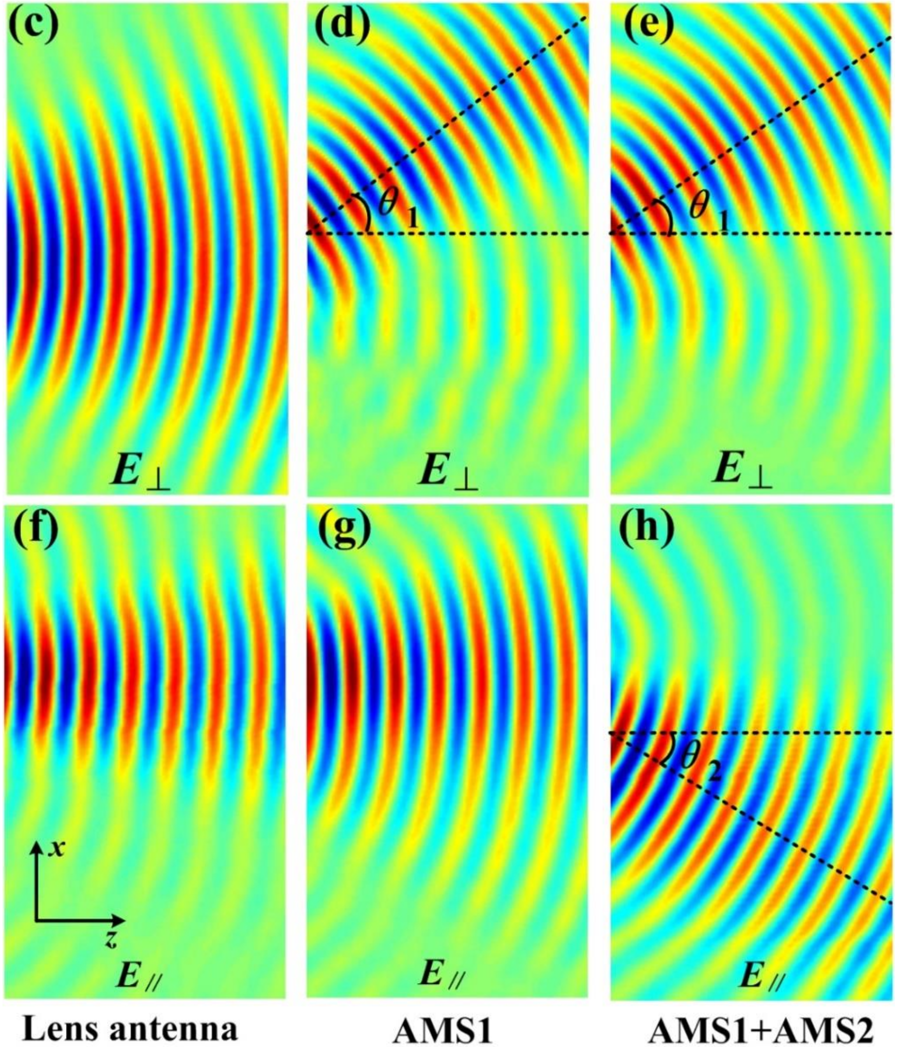
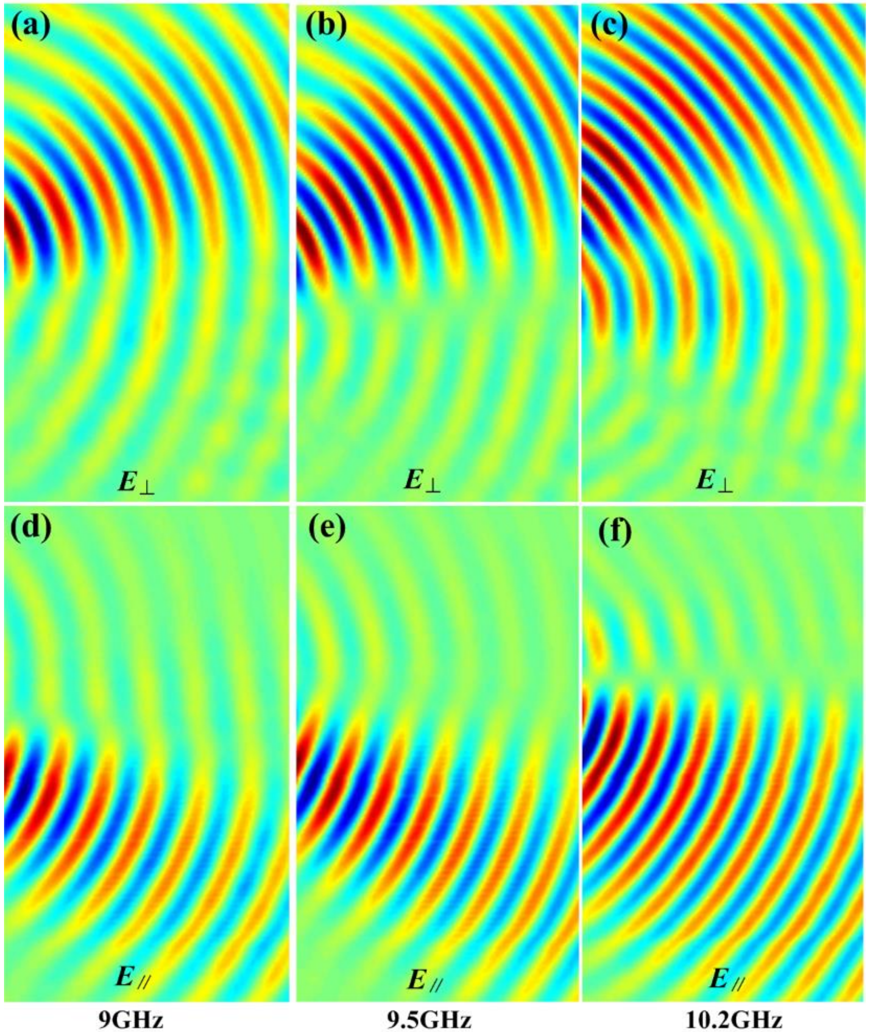
Flat Lens: Polarization Beam Splitter

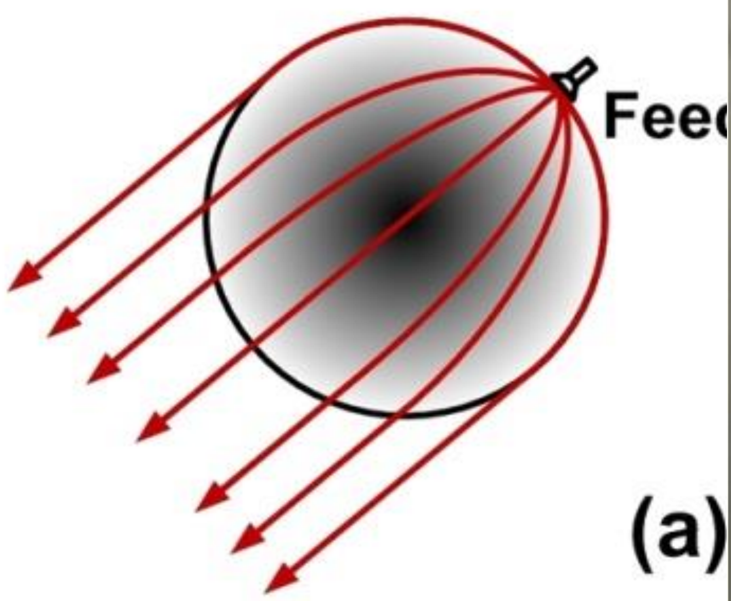


f=10GHz



AMS1+AMS2

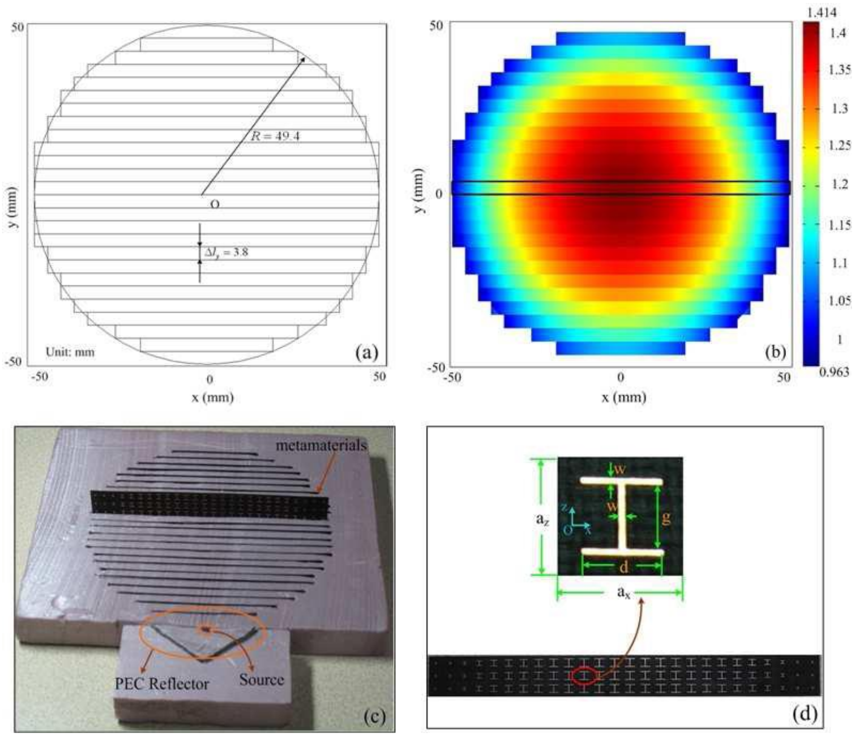
Luneburg Lens

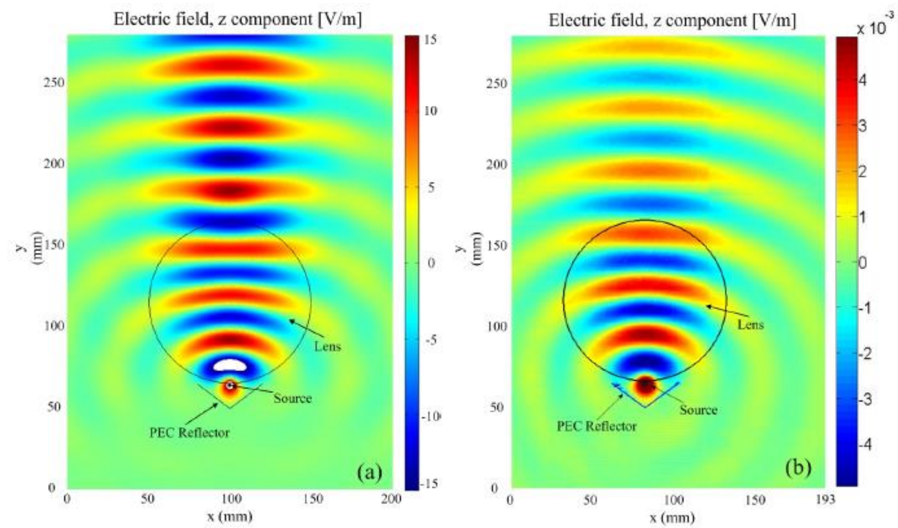


$$n = \sqrt{2 - (r/R)^2}$$

- Expensive
- Discrete Multilayers with spherical shells
- Impedance Mismatch among Layers

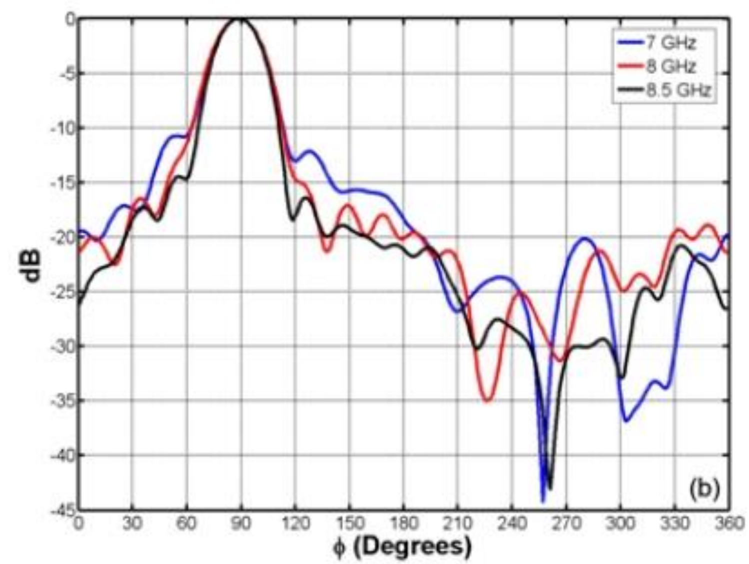
Luneburg Lens: 2D Experiments





Size: R=5cm

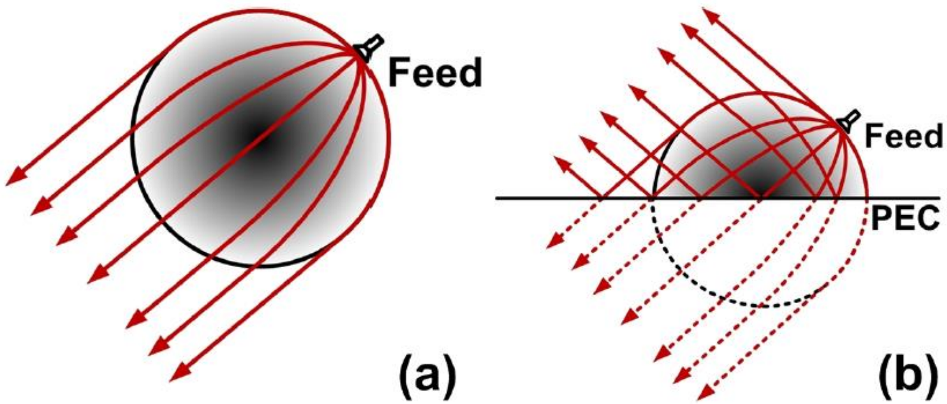
$$n = \sqrt{2 - \left(r/R\right)^2}$$

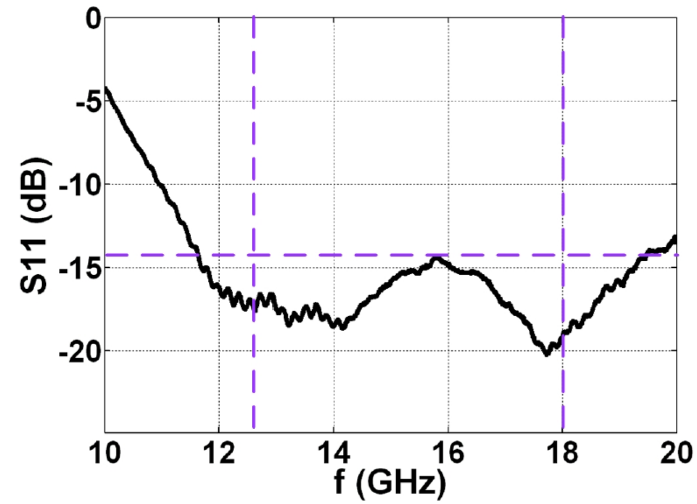


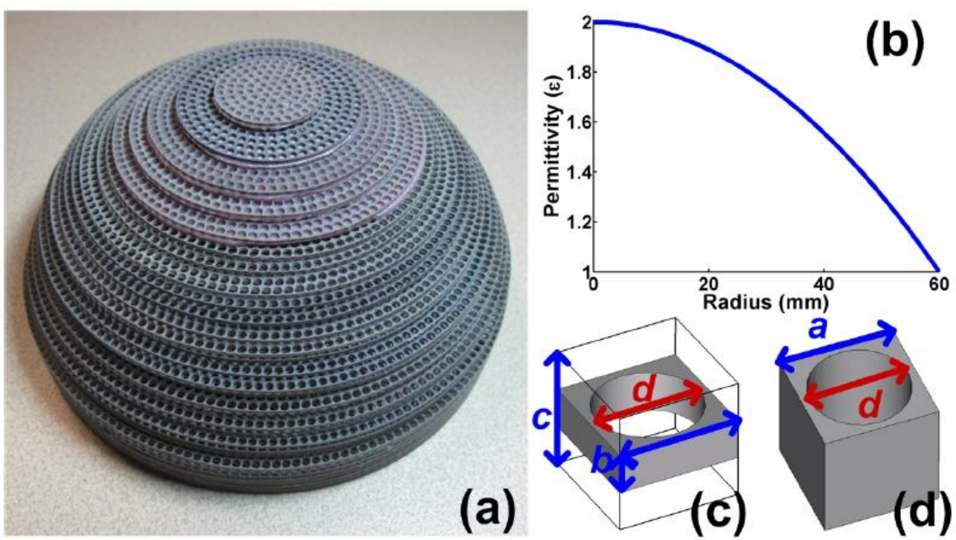
H. F. Ma, T. J. Cui, et. al.

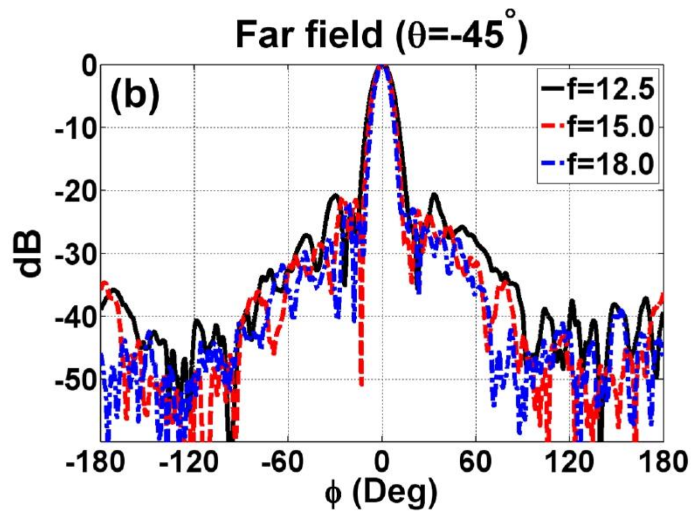
Chin. Sci. Bulletin 55, p. 2066, 2010

Luneburg Lens: 3D Experiments









H. F. Ma, T. J. Cui, et. al. *IEEE Trans. Antennas Propag. 6* (5): 2561-2569, 2013

Flattened Luneburg Lens: **Experiments**

nature COMMUNICATIONS

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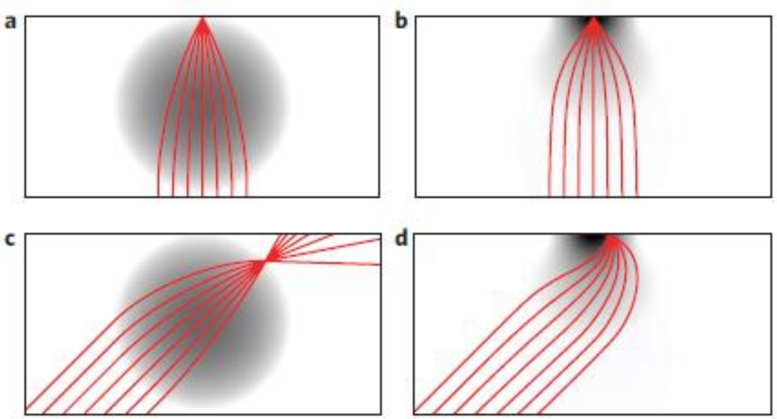
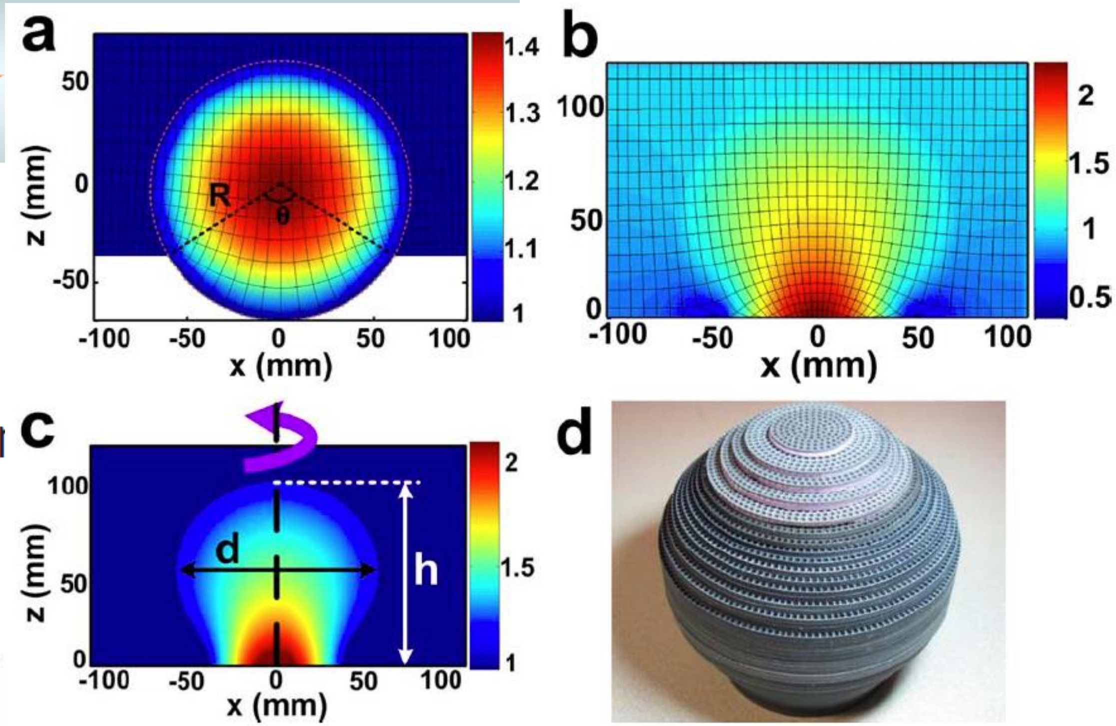
Received 12 Jul 2010 | Accepted 27 Oct 2010 | Published 23 Nov 2010

Three-dimensional broadbar
transformation-optics lens

Hui Feng Ma & Tie Jun Cui



Kundtz & Smith, *Nat. Mater.* **9**, 129, 2010

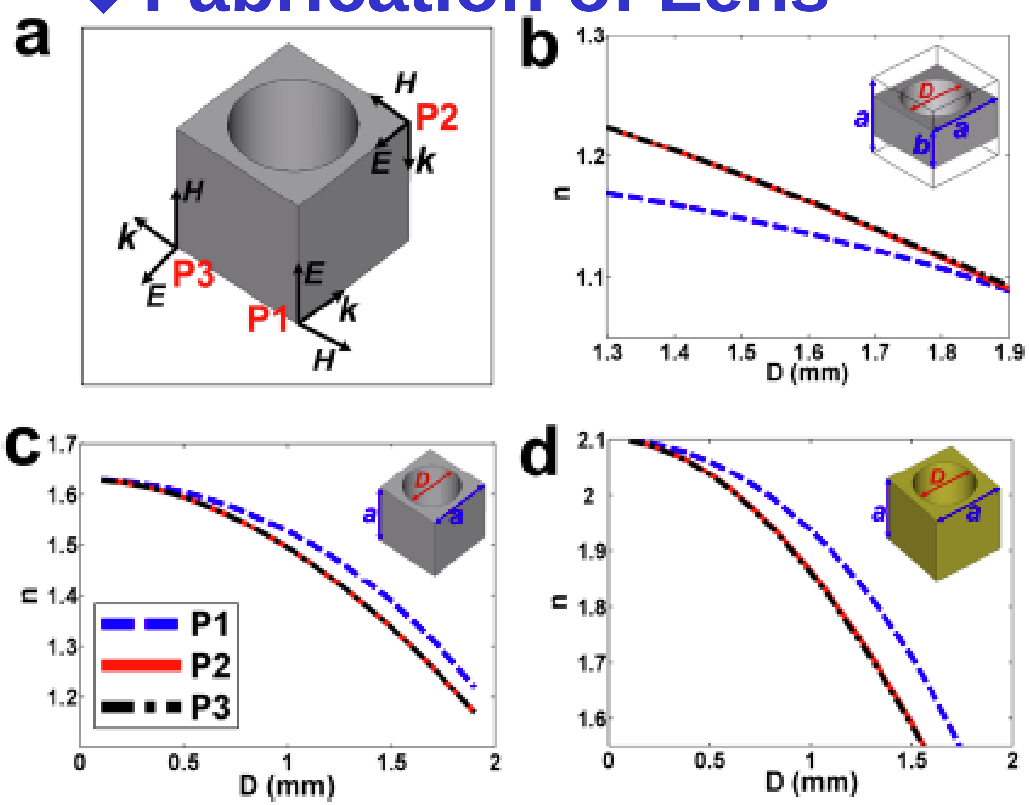


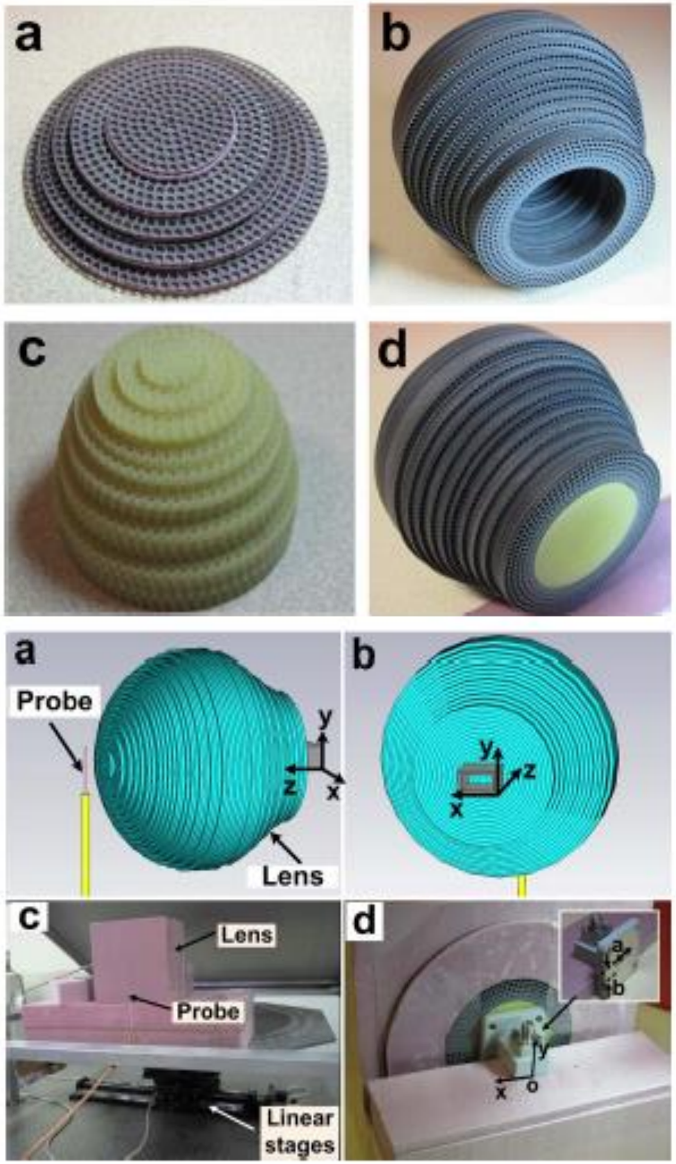
Aperture: 10.8 cm; Height: 10.4 cm

H. F. Ma and T. J. Cui,
***Nat. Commun.*1, 124, 2010**

Flattened Luneburg Lens: Experiments

◆ Fabrication of Lens

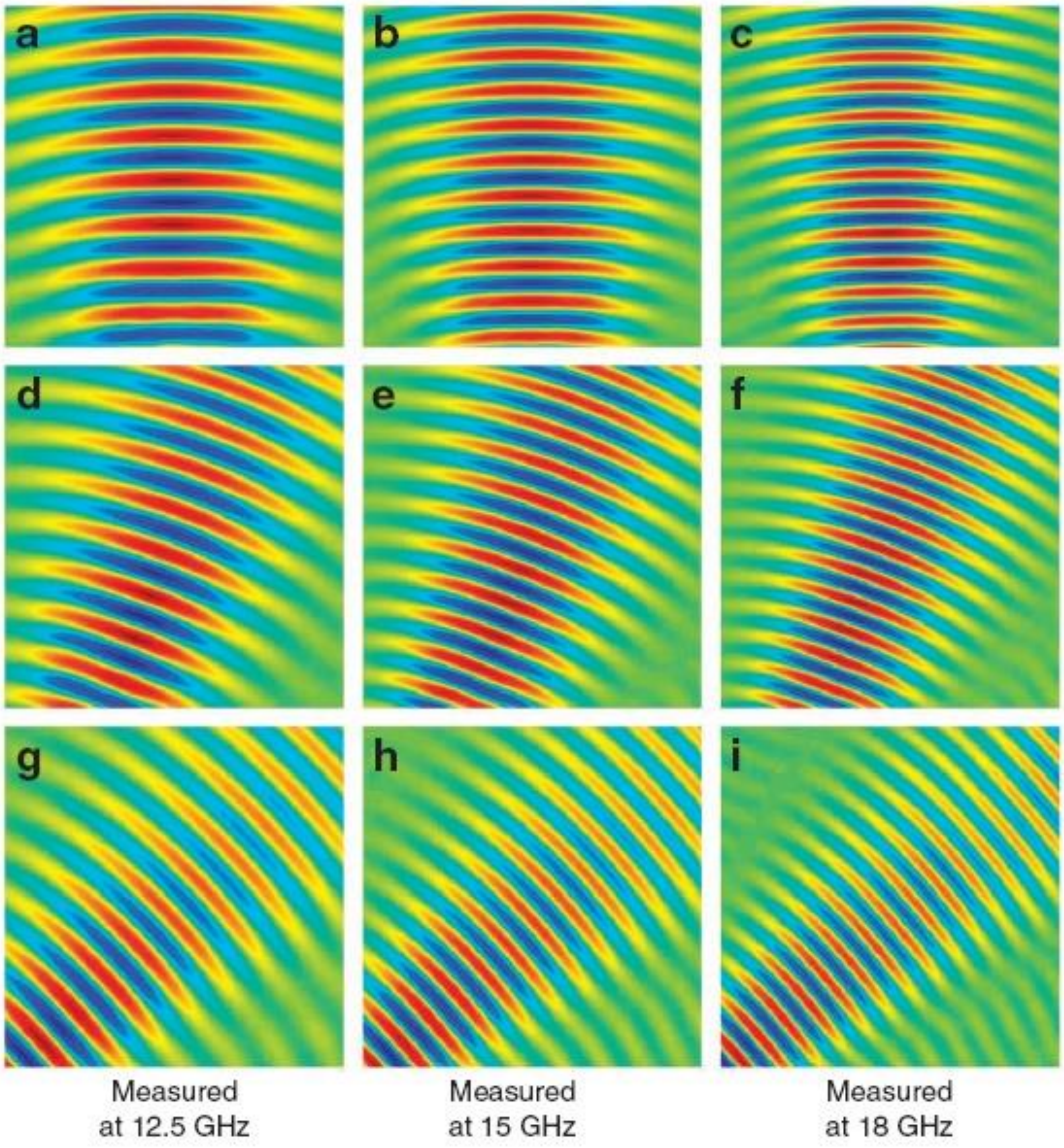




- ◆ Design of Unit Cells
- ◆ Fabrication of Lens
- ◆ Near field measurement

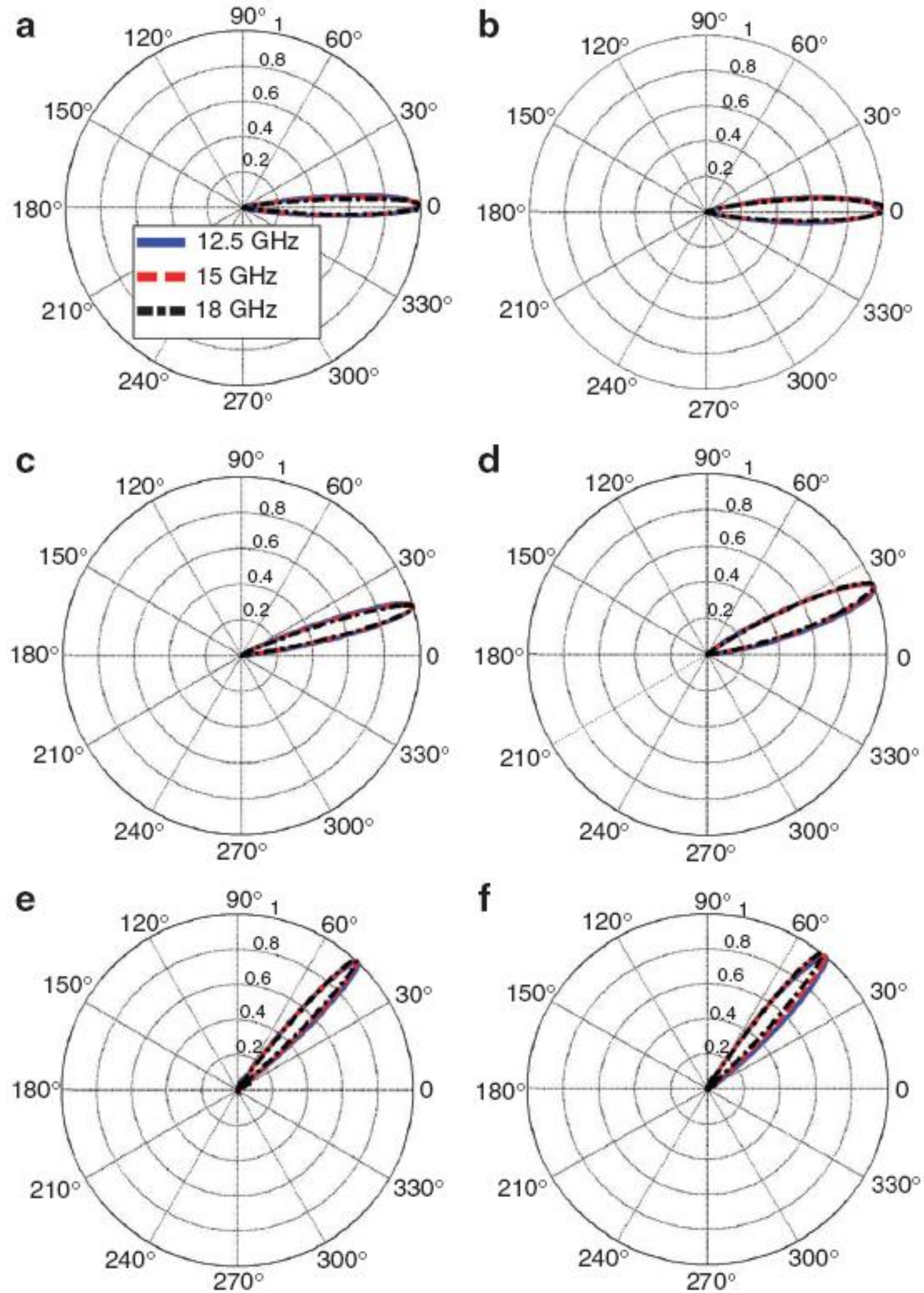
Measured Near Fields

Measured near-field distributions when the feeding positions are different. A beam steering is observed.

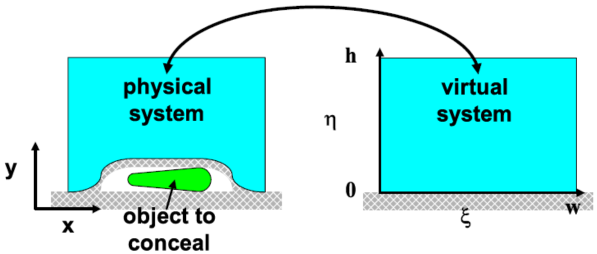


Measured Far Fields

1) High gain (22.7dBi);
2) Dual polarizations;
3) Large radiation angles (up to 50º);
4) Broad band (from 12 to 18 GHz).

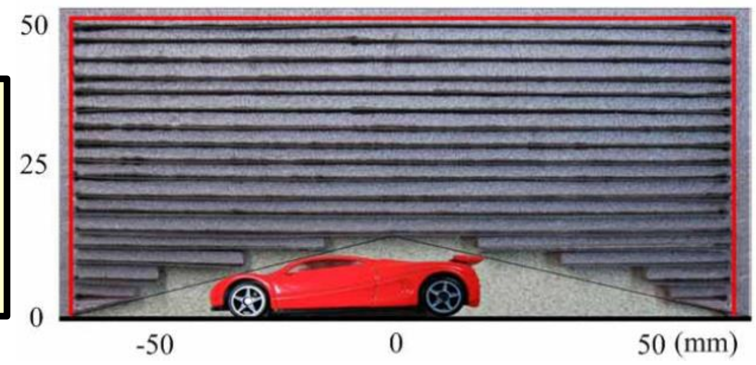


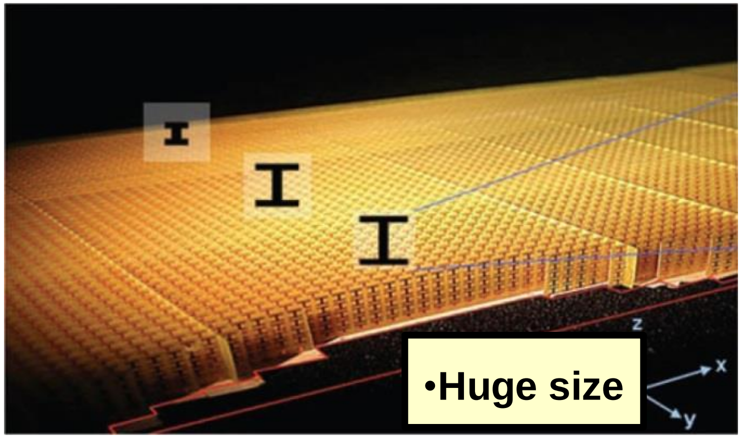
Carpet cloak: Compact 2D Experiments



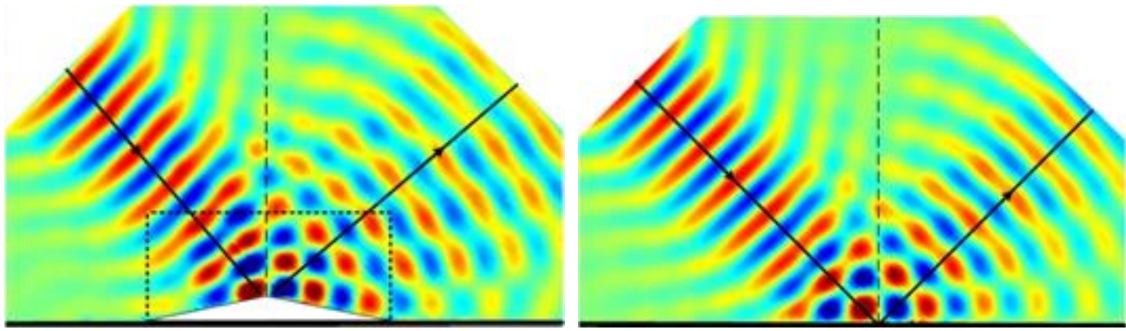
Li and Pendry, *Phys. Rev. Lett.* 101, 203901, 2008.

- Approximately Isotropic
- broad band
- Small loss





- Huge size



Object cloaked

PEC

6 times smaller

R. Liu, et al. Science 323, 336 (2009)

H. F Ma, T. J. Cui, et al. Opt. Express 17, 19947 (2009)

Southeast University

Carpet cloak: 3D Experiments

nature COMMUNICATIONS

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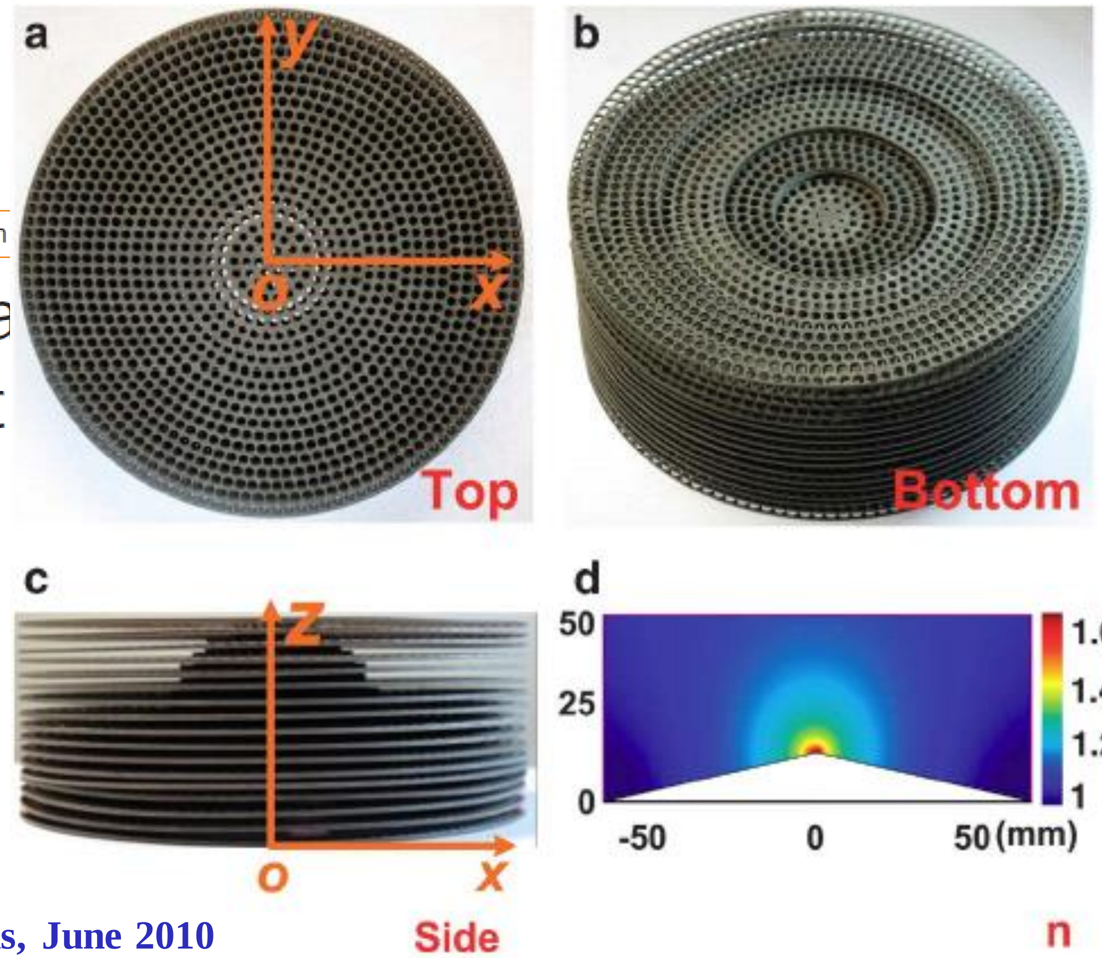
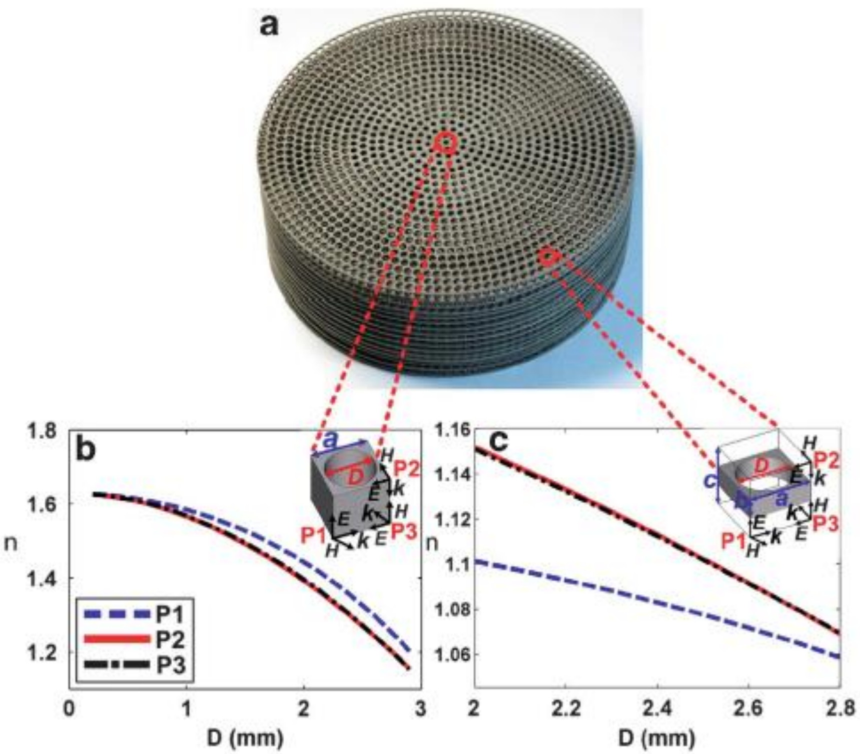
Received 12 Mar 2010 | Accepted 5 May 2010 | Published 1 Jun

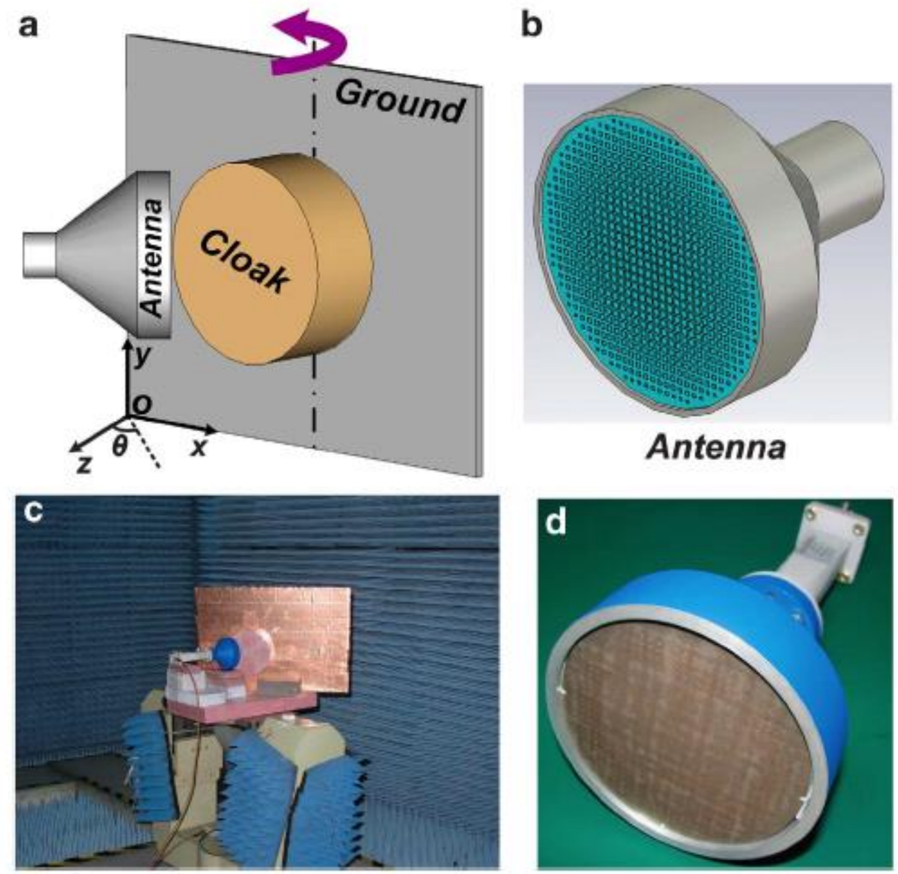
Three-dimensional broa
cloak made of metamat

Hui Feng Ma[1,*] & Tie Jun Cui[1,*]



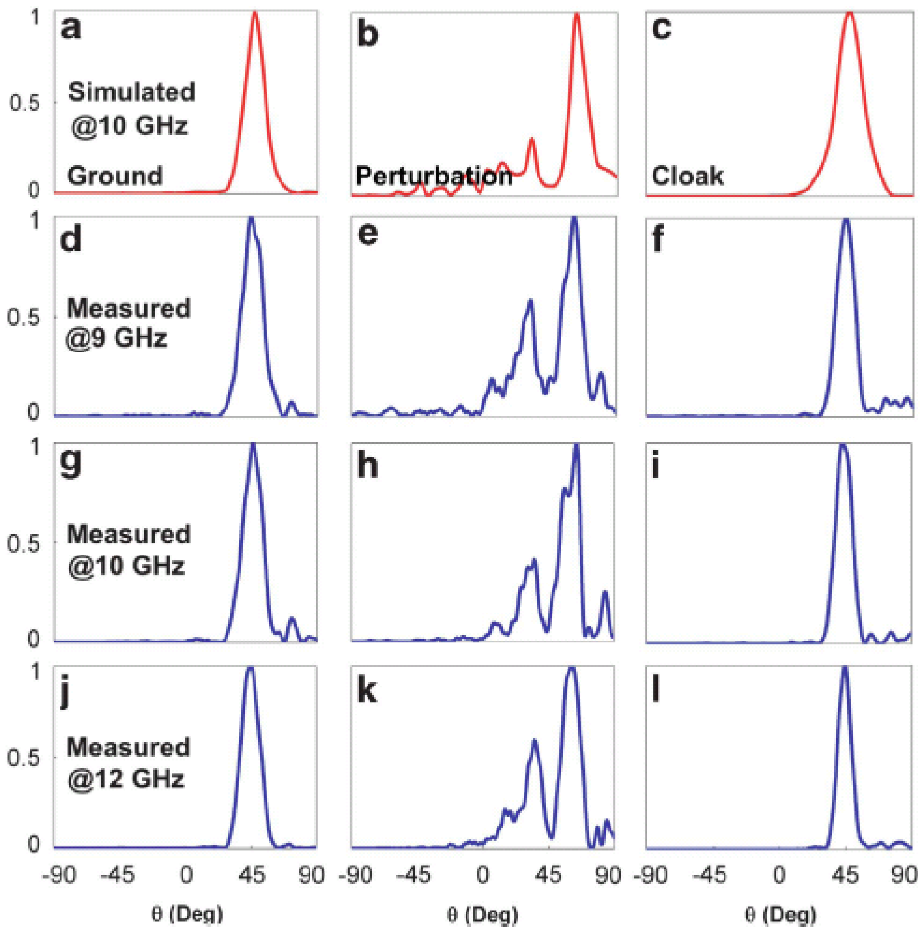
H. F. Ma, T. J. Cui, Nature Communications, June 2010



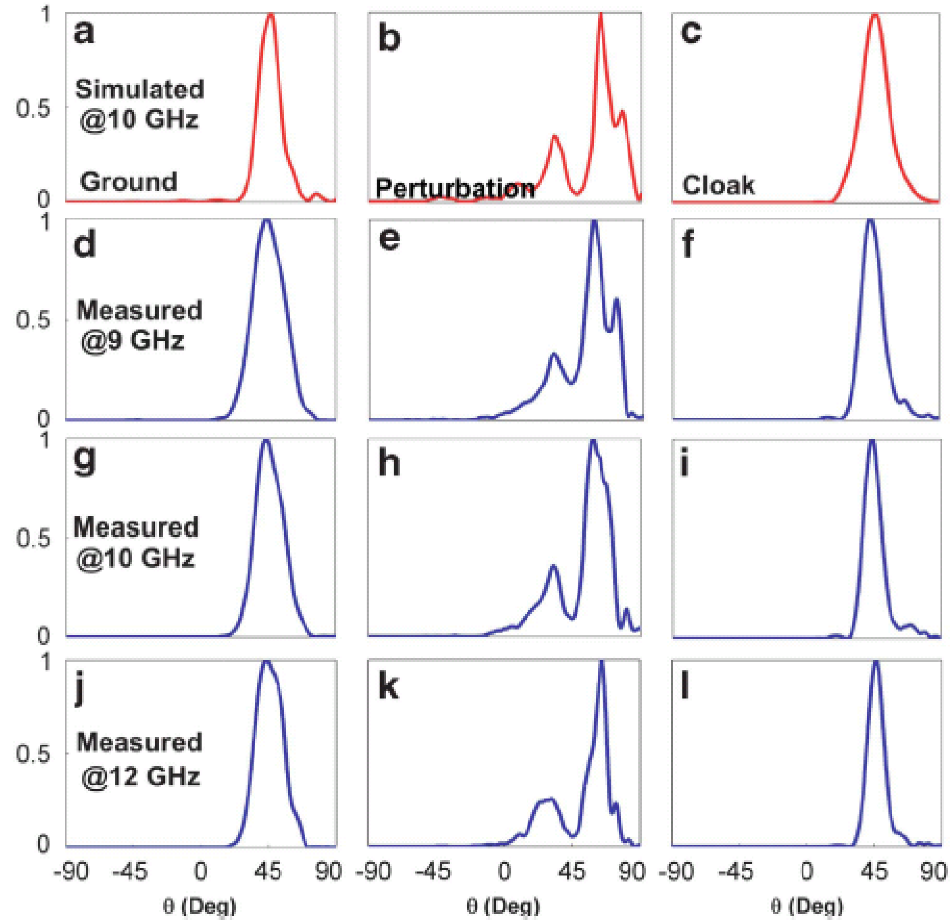


Ten Breakthroughs in China Science in 2010

Measured far-field patterns



Vertical Polarization



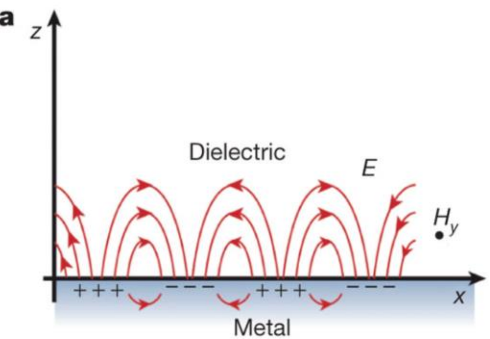
Horizontal Polarization

Spoof surface plasmonic waveguide

- An Ultra-thin corrugated plasmonic waveguide
- High-efficiency conversion between guided waves and SSPPs
- Convert SSPPs to leaky waves

Southeast University

Spoof surface plasmon polaritons (SSPPs)



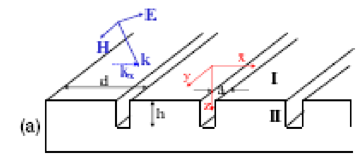
Surface plasmon polaritons (SPPs)

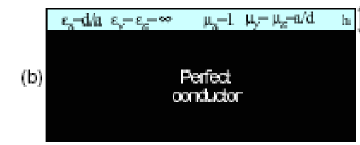
O. Benson,
Nature, 480, 193-199, 2011

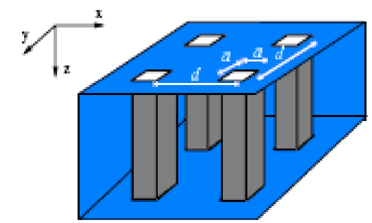
- **Propagating along the interface**
- **Exponential decay in both directions**

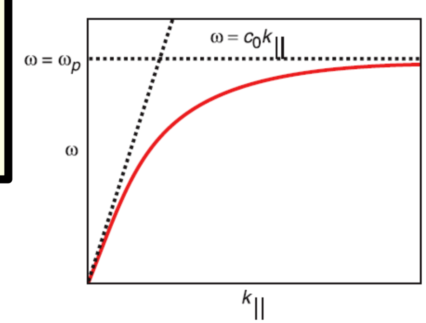
- **Natural SPPs only exist at optical frequencies.**
- **To realize SPPs at lower frequencies (GHz, THz), spoof SPPs can be suppotred by etching structures on metal surface.**
- **The concept of “designer” surface modes opens opportunities to control and direct the radiations at surfaces within a subwavelength region.**

Pendry *et* al. , *Science* 305, 847 (2004).
Garcia-Vidal *et* al., *J. Opt. A: Pure Appl. Opt*. 7, S94 (2005).



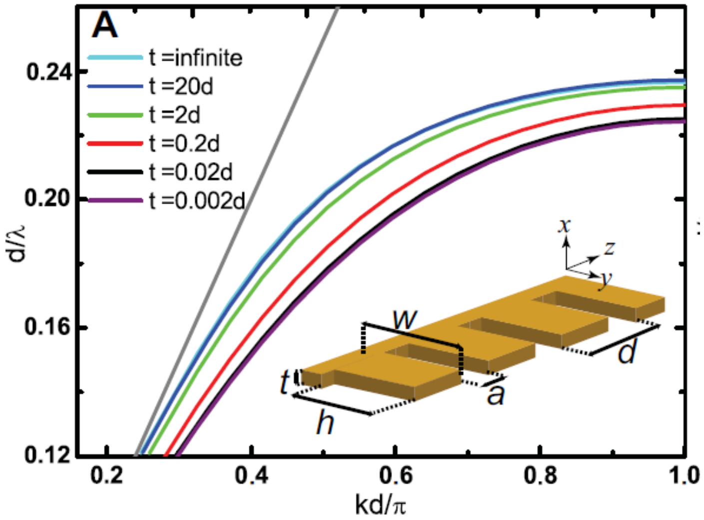


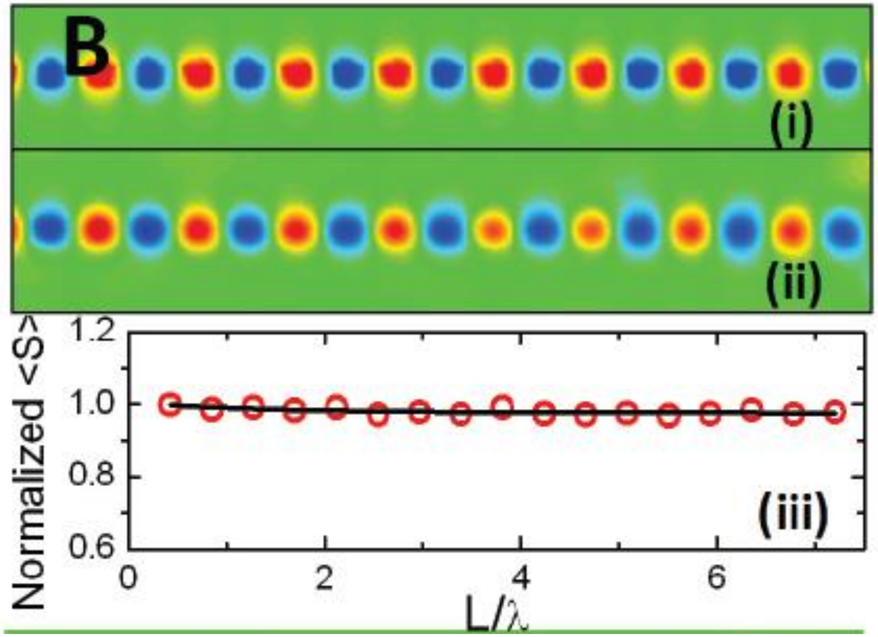


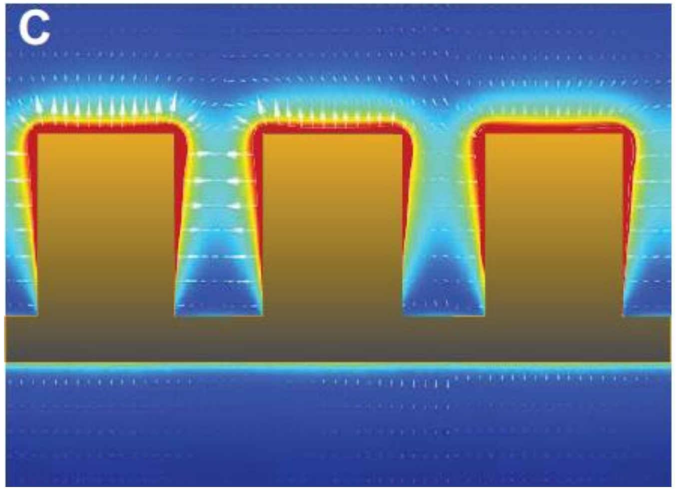


Spoof Surface plasmon polaritons (SSPPs)

Spoof SPPs：Ultra-thin plasmonic waveguide





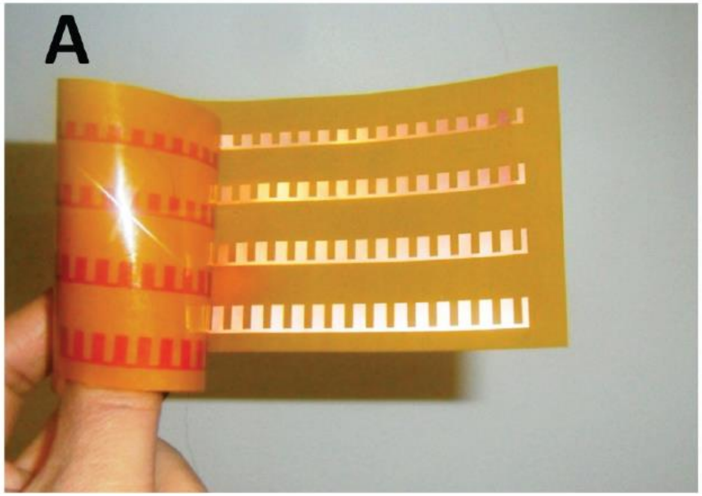


- Experiment results: Wideband (7GHz – 11 GHz)
- Excellent propagation properties with low loss and long propagation distance.

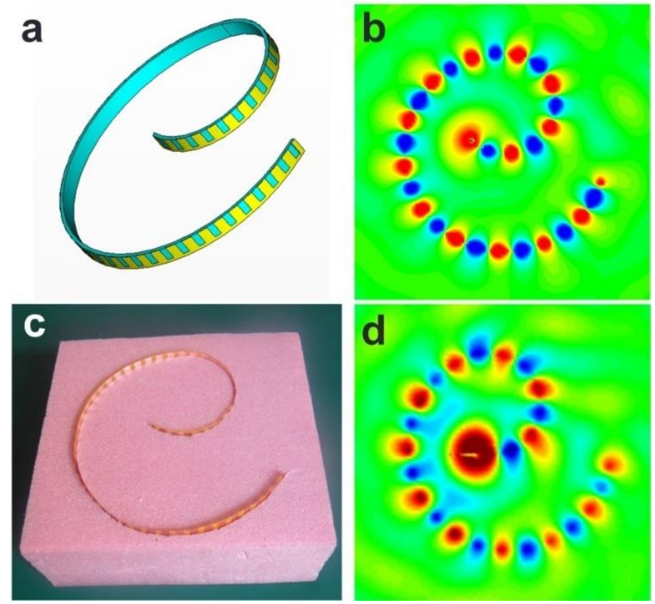
X. Shen, T. J. Cui, et al., PNAS, doi 10.1073, 2013.

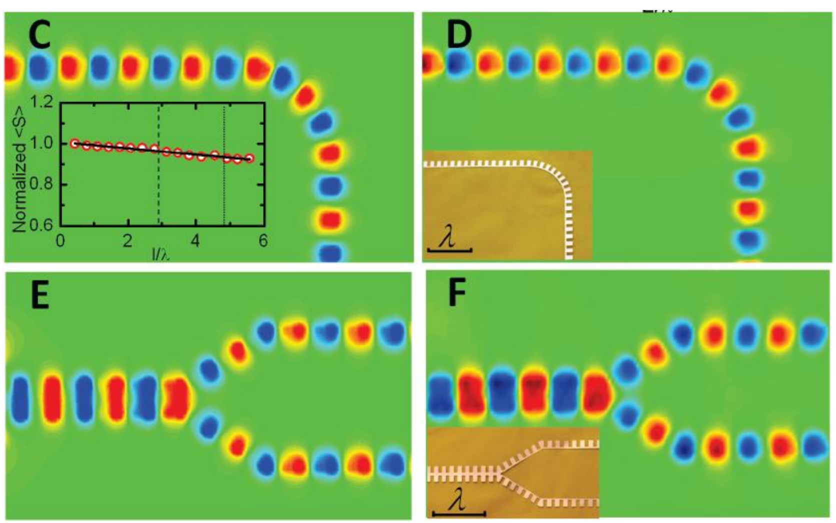
Southeast University

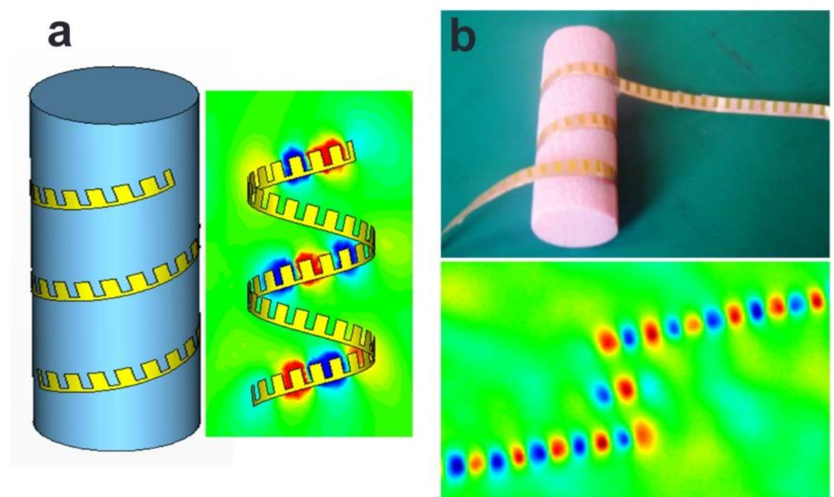
Spoof SPPs：Ultra-thin plasmonic waveguide



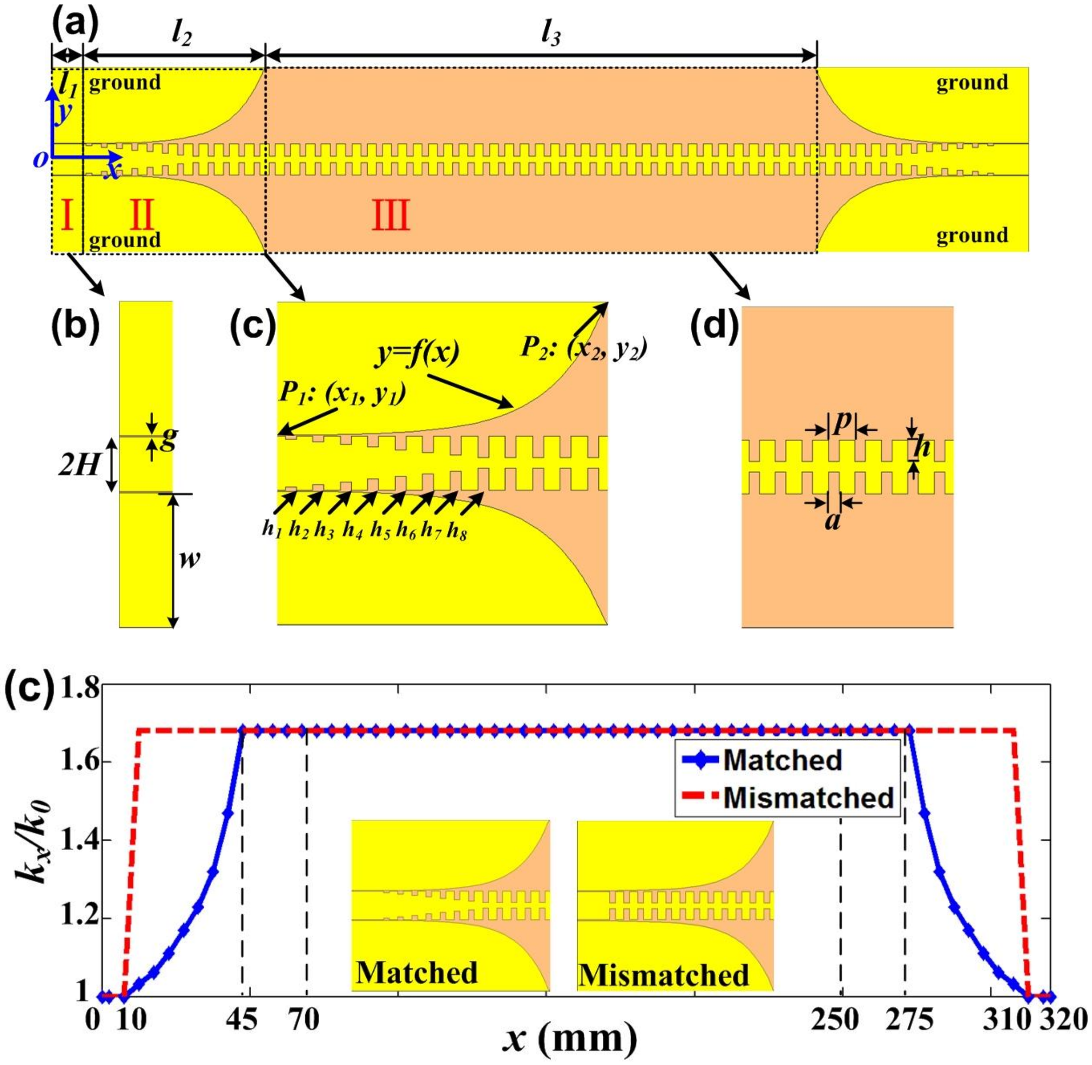
Flexible Copper Clad Laminate (FCCL)





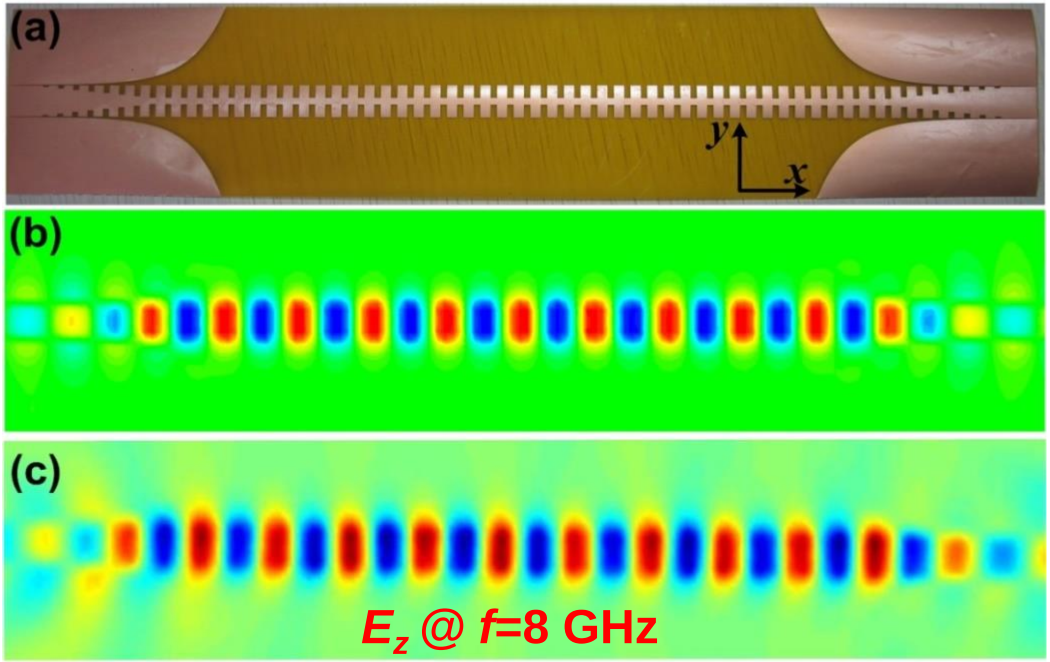


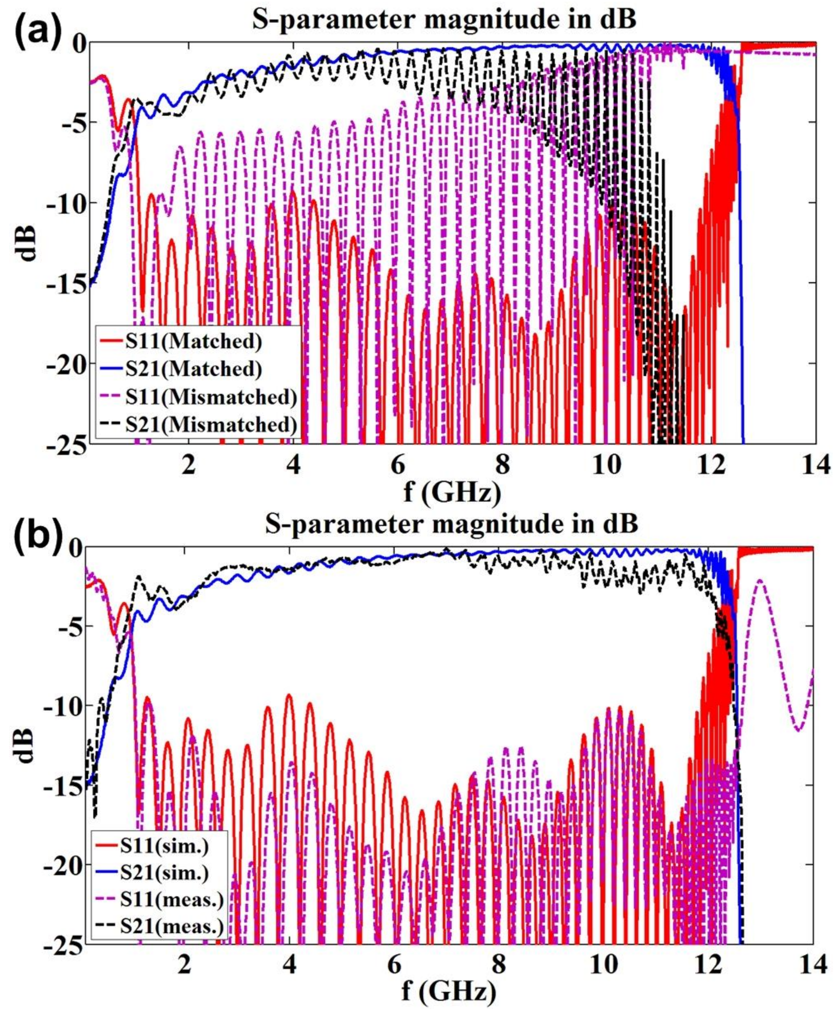
Spoof SPPs：Conversion of Guided Modes and SSPPs



H. F. Ma, et al, Laser & Photonics Review, 8. 146-151 (2014)

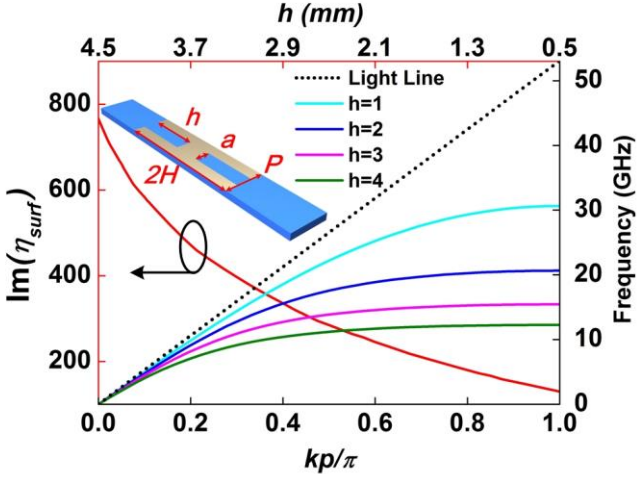
Spoof SPPs: Conversion of Guided Modes and SSPPs





- **High efficiency**
- **Broad band**
- **Direct measurements of reflection & transmission**

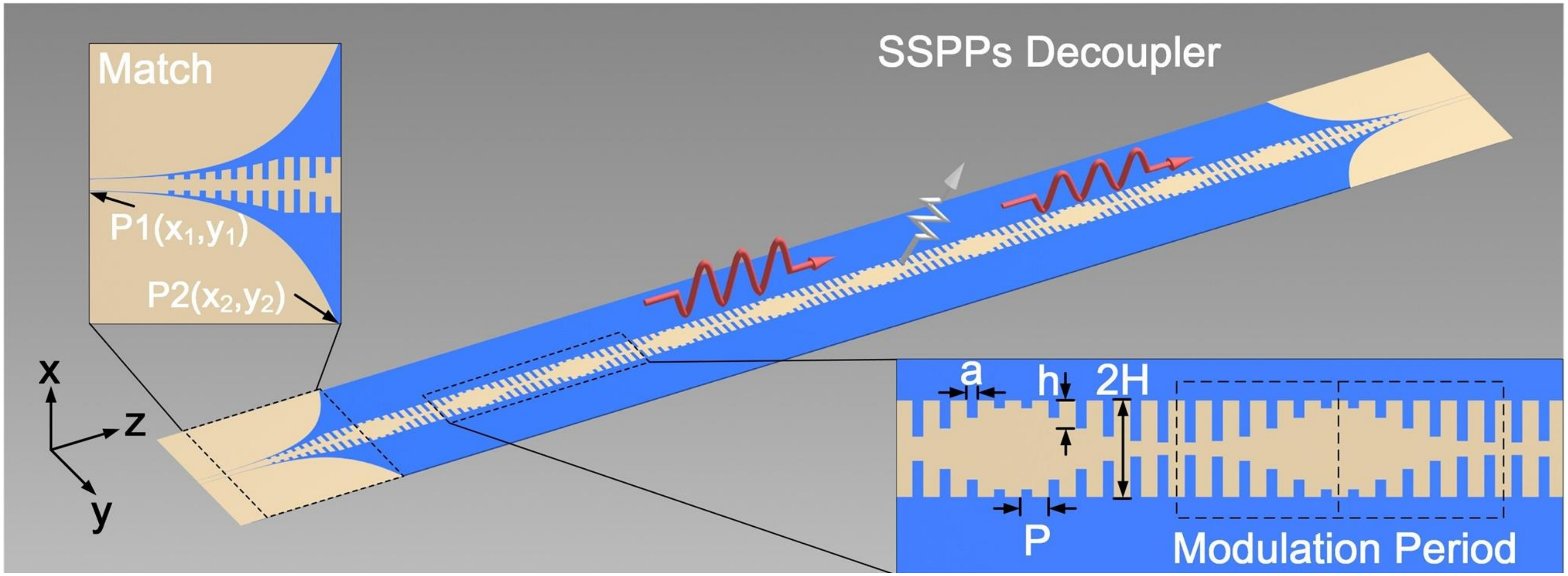
Spoof SPPs: Convert SSPPs to leaky waves



$$\eta_{surf}(z) = jX_s\left[1 + M\cos\left(\frac{2\pi}{A}z\right)\right]$$

$$k_N A = nk_0 A + 2N\pi, \quad N = 0, \pm 1, \pm 2, \cdots$$

$$k_{-1} = nk_0 - \frac{2\pi}{A} = k_0 \cos\theta$$



G. S. Kong, H. F. Ma*, et al., Sci. Rep. 6, 29600, 2016

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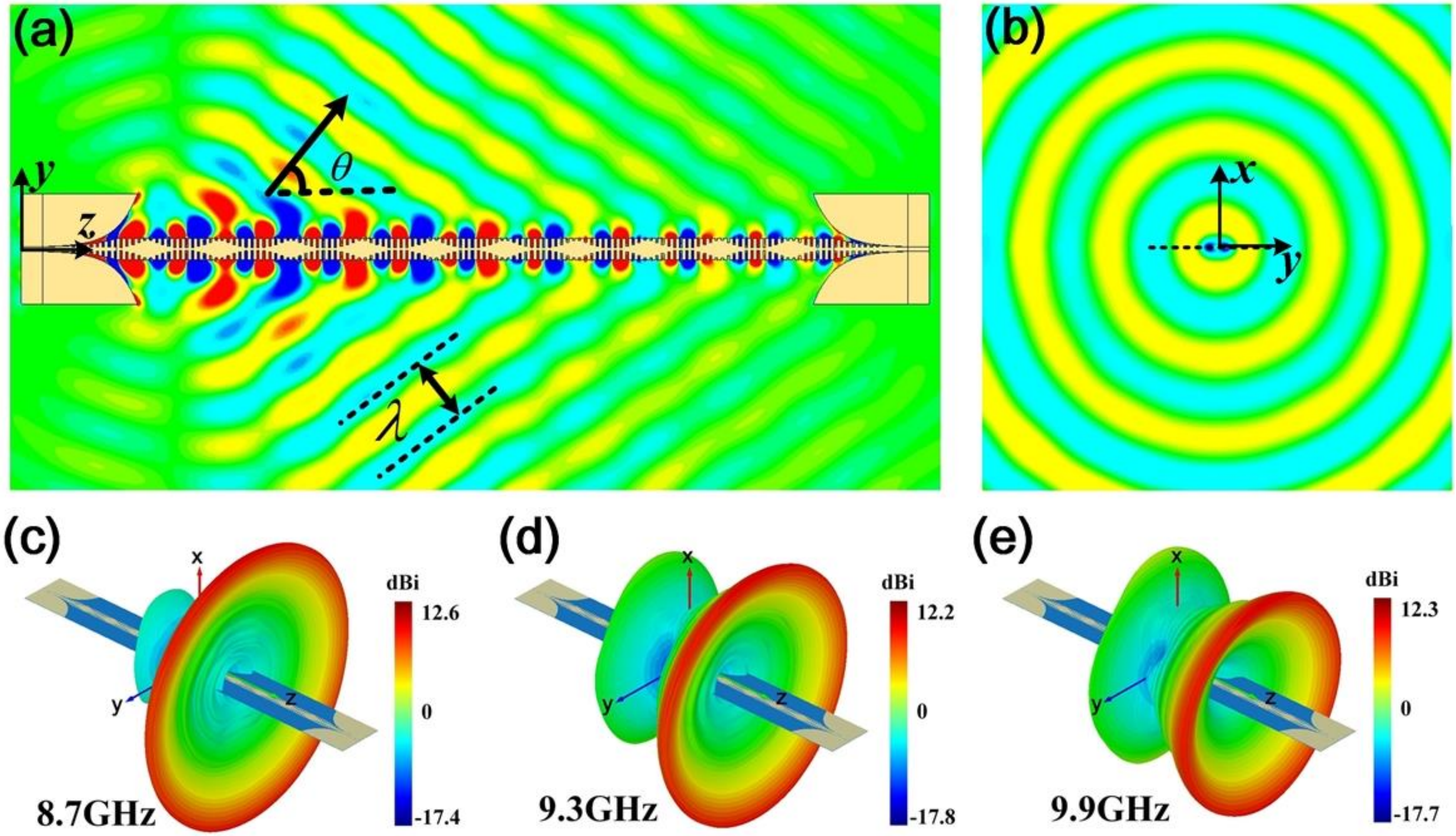
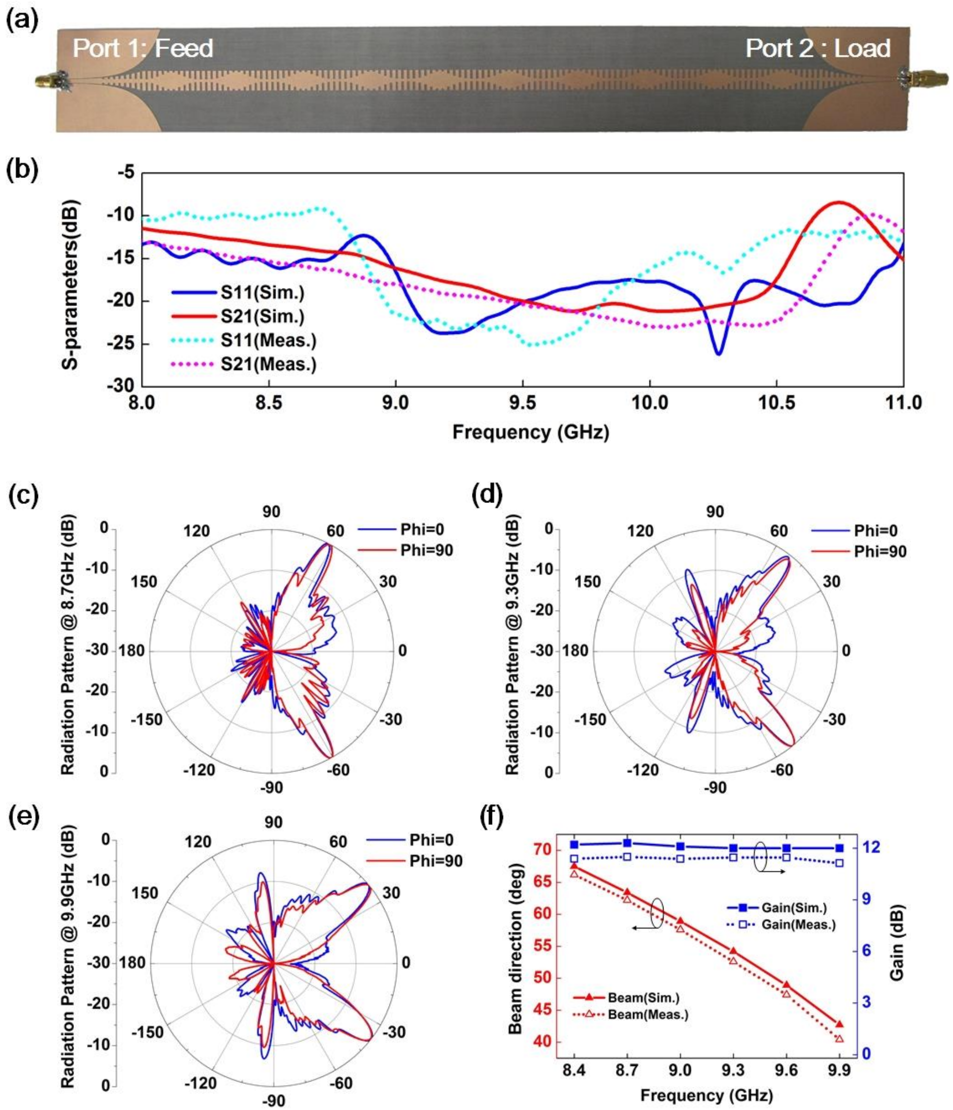
Spoof SPPs：Convert SSPPs to leaky waves



Simulated near-field distributions and far-field radiation patterns

Spoof SPPs：Convert SSPPs to leaky waves



The photograph of the sample and the measured results

θ=55° @ 9.3GHz

- **High radiation efficiency**
- **Beam Scans from 66° to 42° as frequency changes from 8.4GHz to 9.9GHz**

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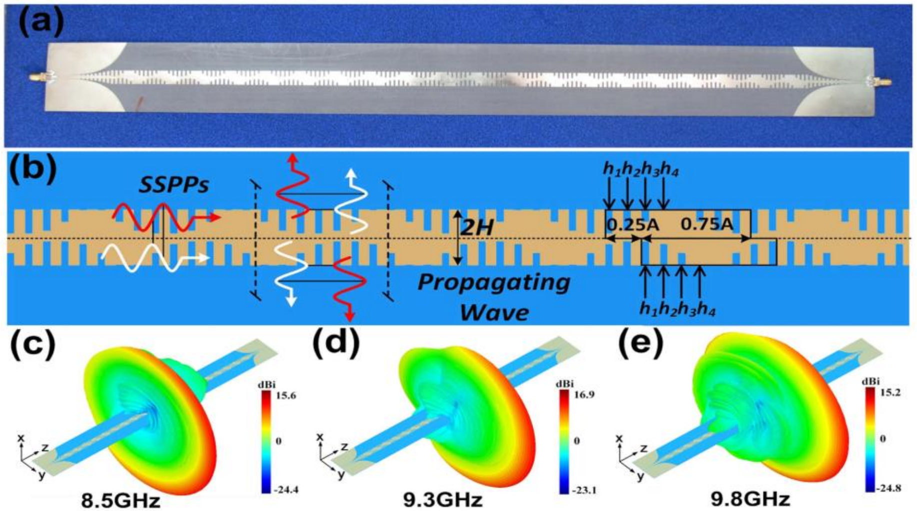
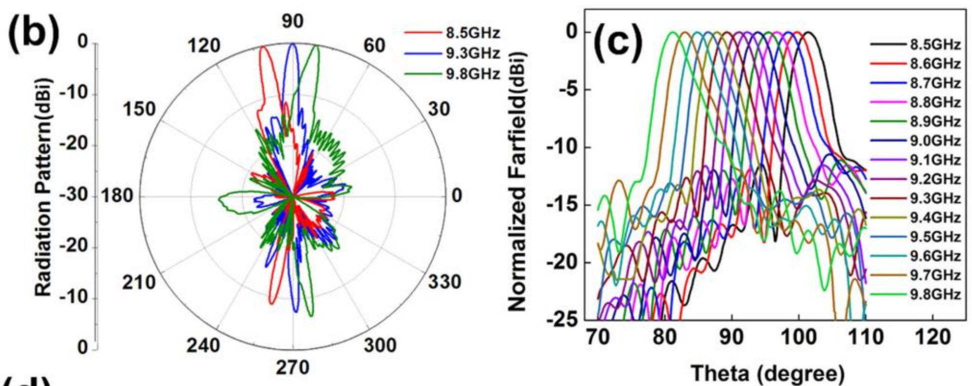
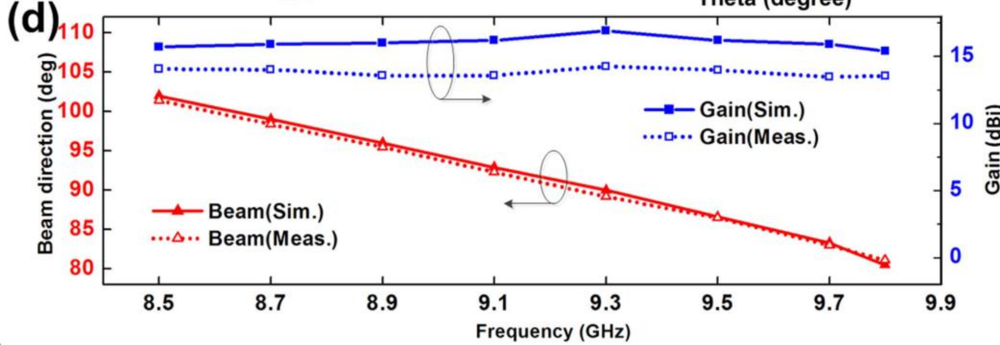
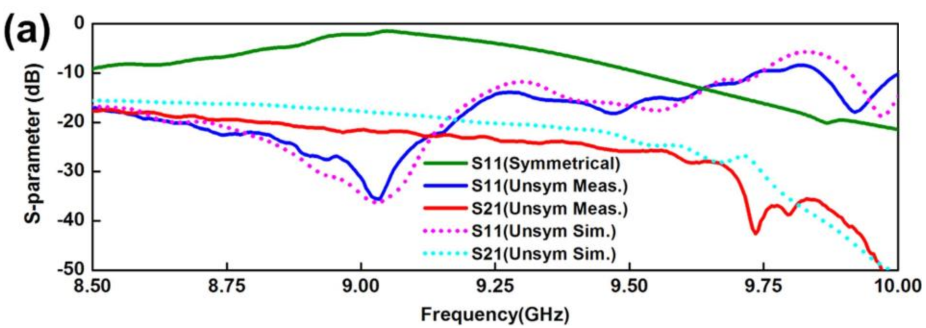
Spoof SPPs：Convert SSPPs to leaky waves









Broadside Radiation @ 9.3GHz

Beam steers from backward quadrant to forward quadrant, through the broadside radiation continuously as frequency changes

Conclusions

- **Inhomogeneous gradient-index metamaterials have been developed in microwave frequencies**
  - **High-performance antennas**
  - **Ground-plane cloaks**
  - **Other devices and experiments**
- **Spoof surface plasmon polaritons can be supported, propagated and radiated by ultra-thin corrugated metal structure in microwave frequency**

Thank you for your attention

Email: hfma@seu.edu.cn