Metamaterial Design Considerations for Casimir Force Control

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Outline (Practical Issues)

- Background
- The goal: repulsive Casimir force
- How do we get there with metamaterials?
  - Properties of constituents (limitations)
  - Properties of metamaterials (opportunities)
  - Utilization of combination for maximum benefit
  - New Frontier

What is a Metamaterial?

Metamaterials: Artificially constructed materials with properties derived from their sub-wavelength structures, ~~not~~ AND from the materials they are made of.

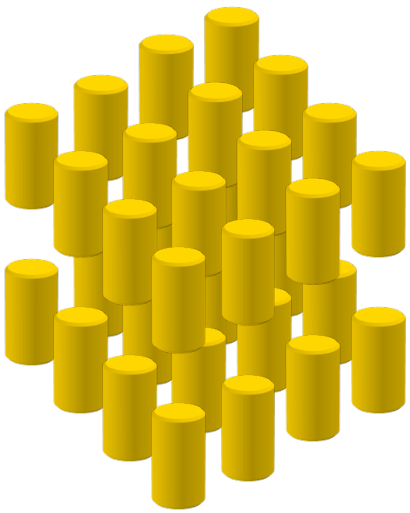
A material that exhibits an electromagnetic response not found in natural materials.

$$\mu < 0$$
$$\varepsilon < 0$$

A material with a deliberately engineered and/or tunable EM response.

$$\varepsilon < 0 \quad \text{-or-} \quad \varepsilon > 0$$

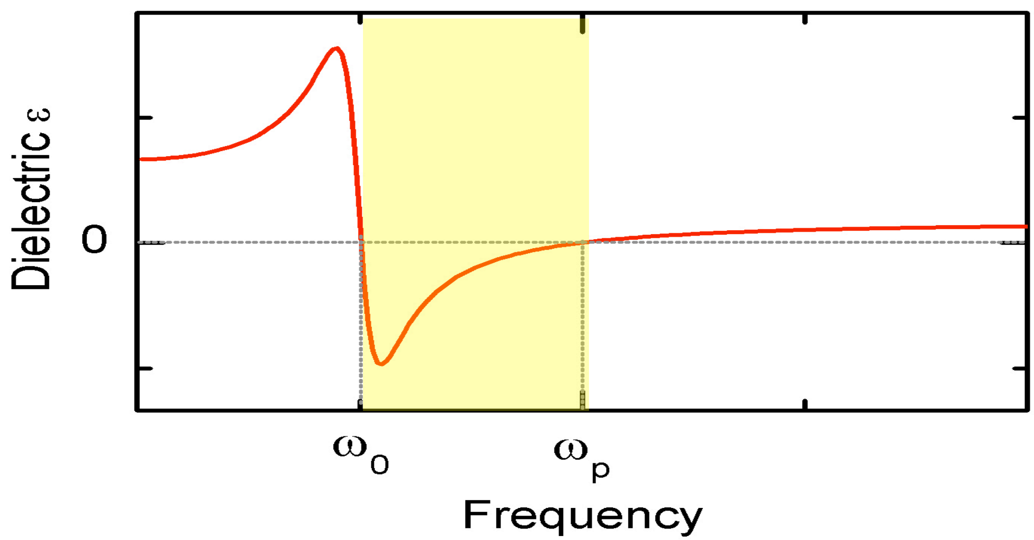
Electric Response



- **Drude-Lorentz:** cut wires

$$\varepsilon(\omega) = 1 - \frac{\omega_p^2 - \omega_0^2}{\omega^2 - \omega_0^2 + i\omega\Gamma}$$

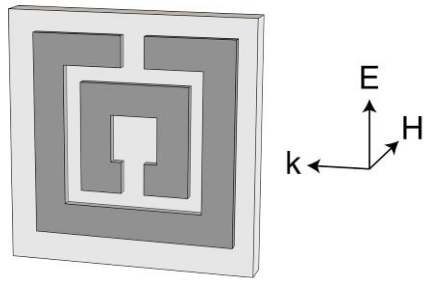
$\varepsilon < 0$ when $\omega_0 < \omega < \omega_p$

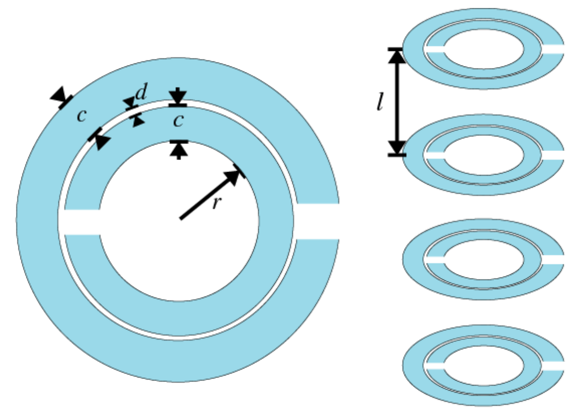


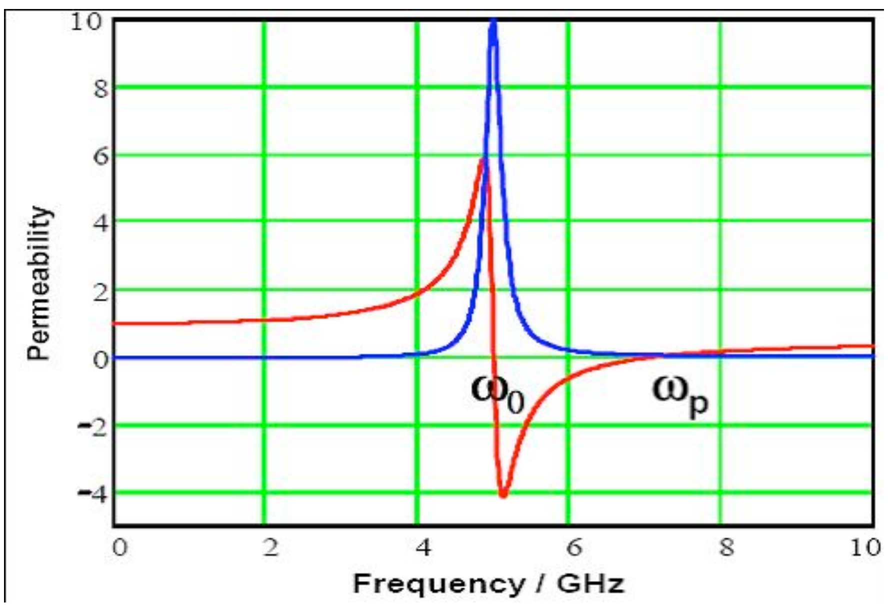
J.B. Pendry *et al.*, *Phys. Rev. Lett.* **76**, 4773 (1996).

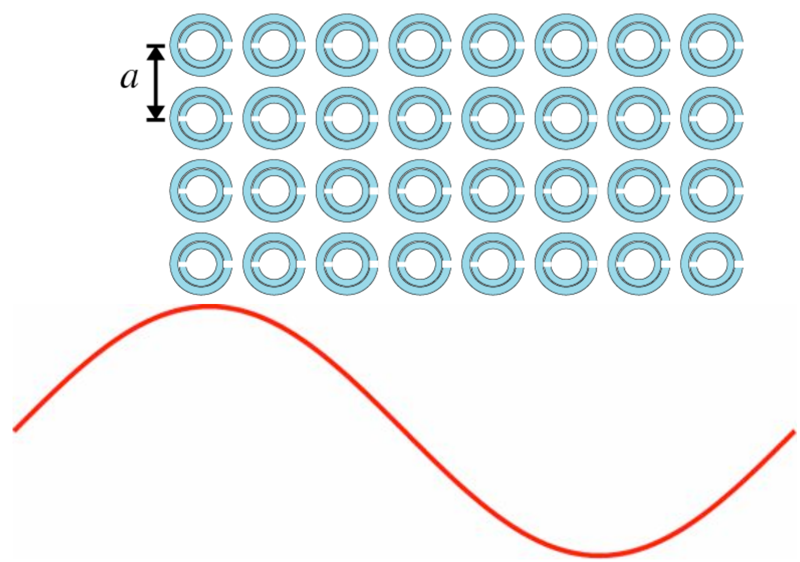
Magnetic Response

$$\mu_{eff} = 1 - \frac{\frac{\pi r^2}{a^2}}{1 + \frac{2\sigma i}{\omega r \mu_0} - \frac{3}{\pi^2 \mu_0 \omega^2 C r^3}}$$



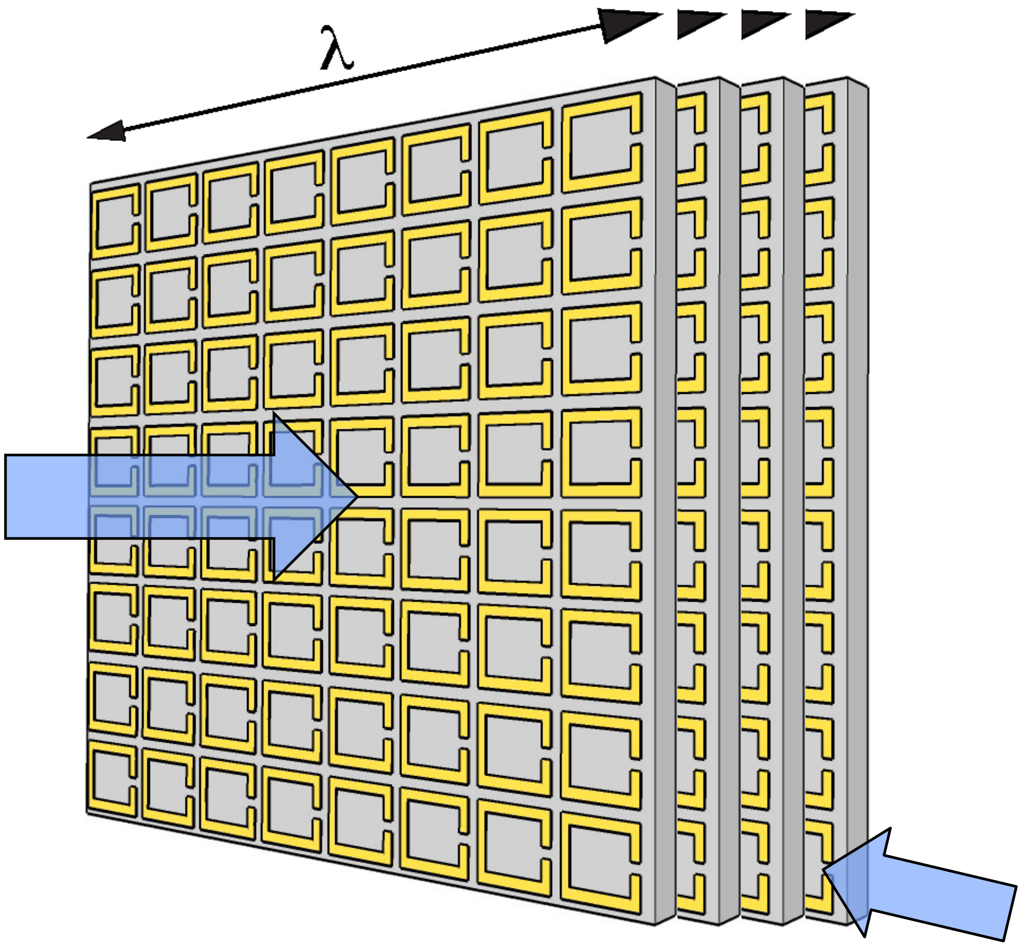


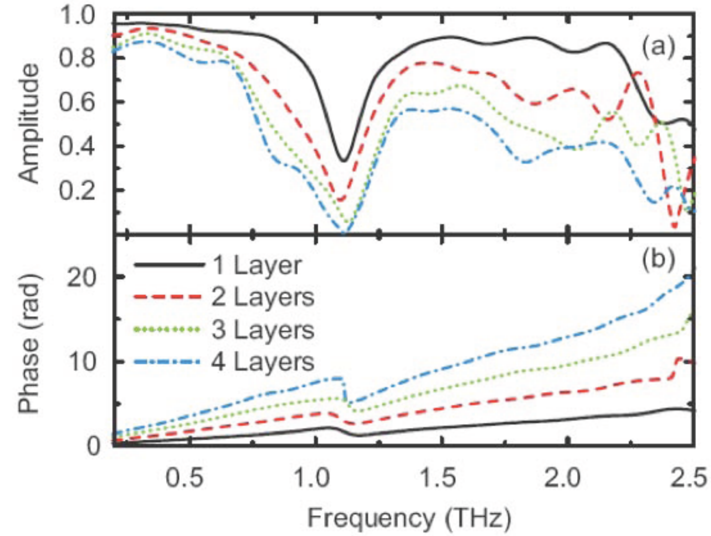


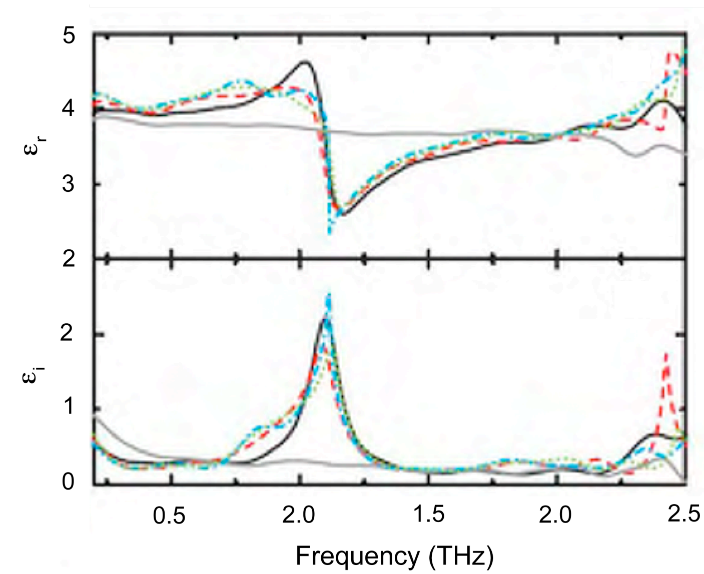


J.B. Pendry *et al*., *IEEE Trans. Microwave Tech.* **47,** 2075 (1999).

Effective Medium

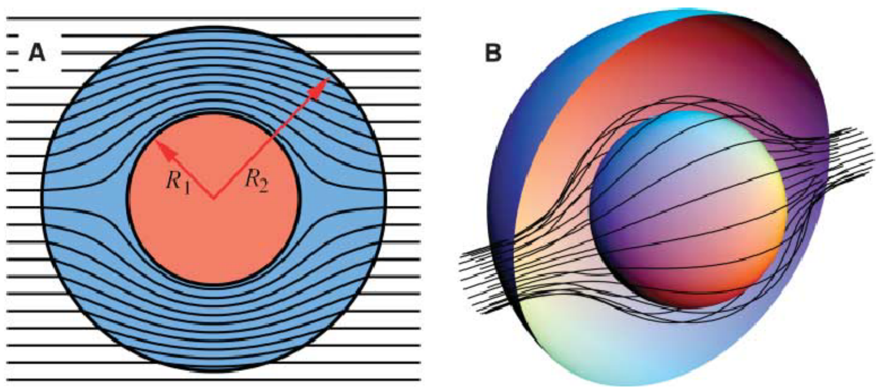




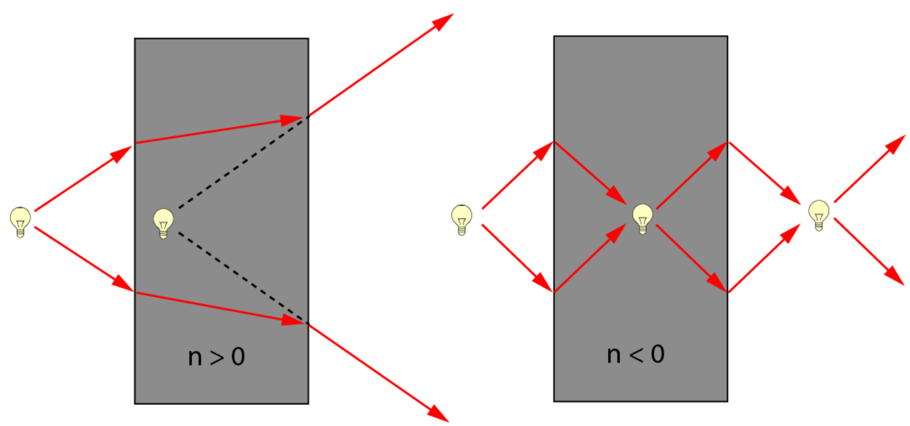


Azad *et al.*, *THz Sci Tech.* **2,** 15 (2009).

Novel Phenomena



J.B. Pendry *et al.* *Science* **312,** 1780 (2006)



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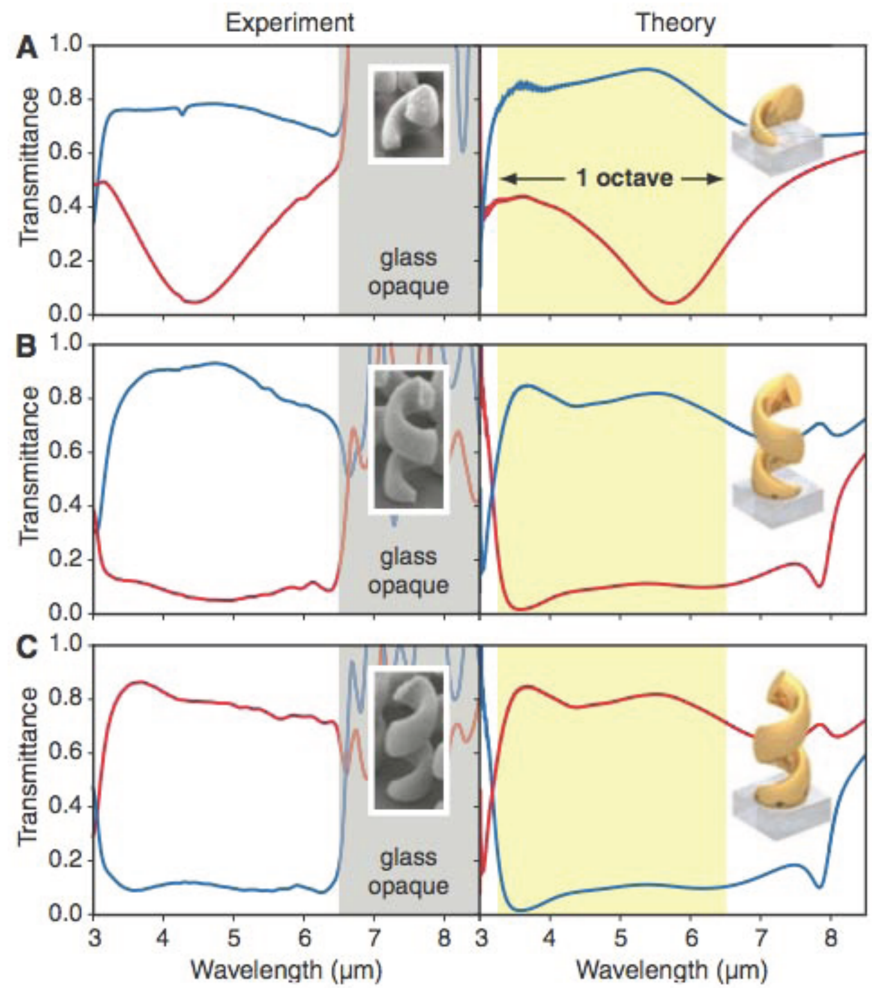

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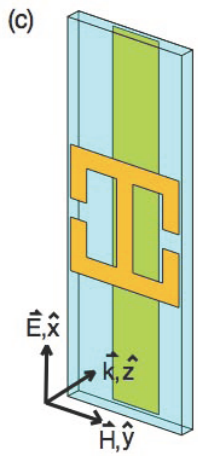
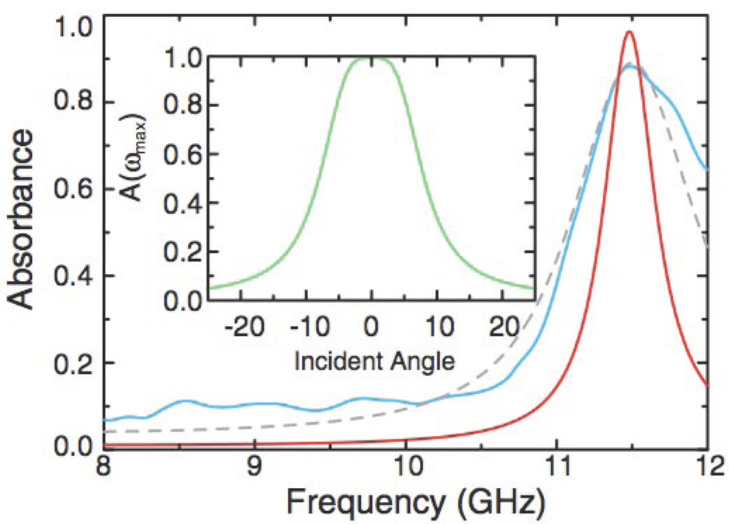
Novel Phenomena





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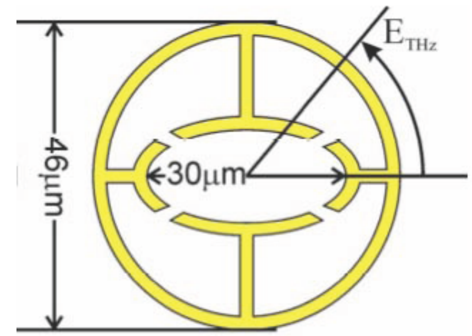

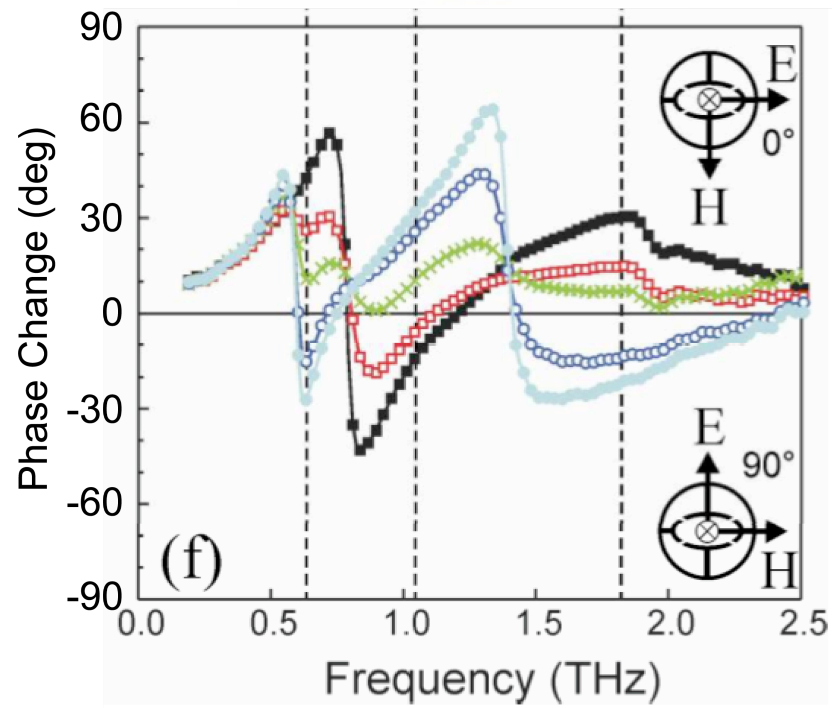

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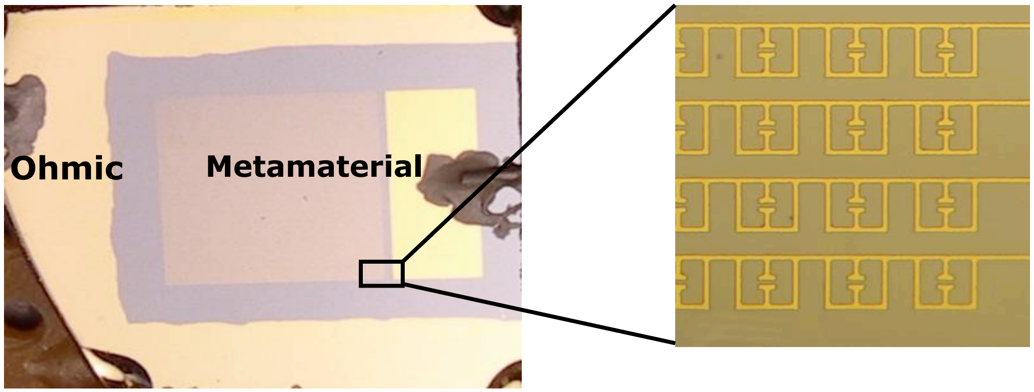
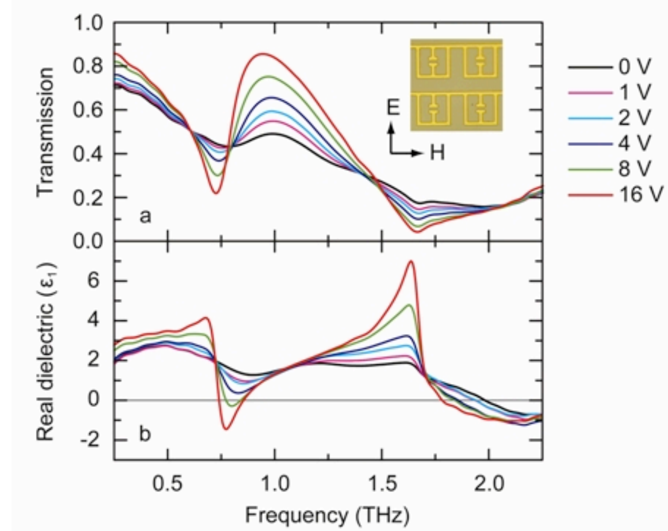
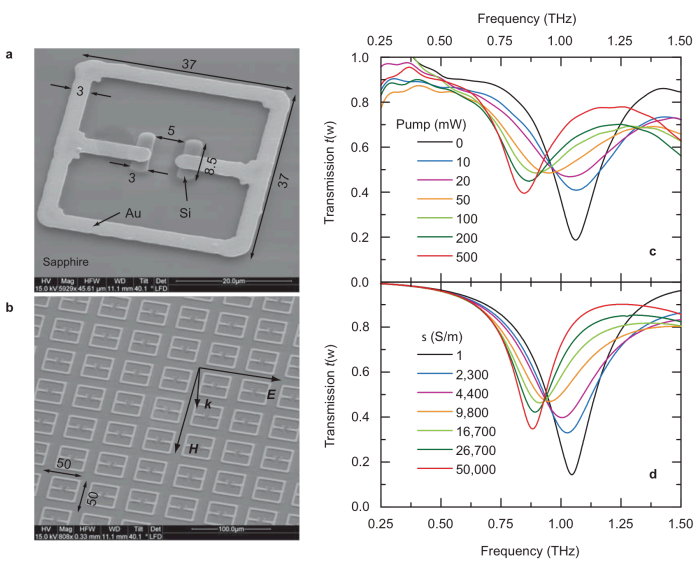
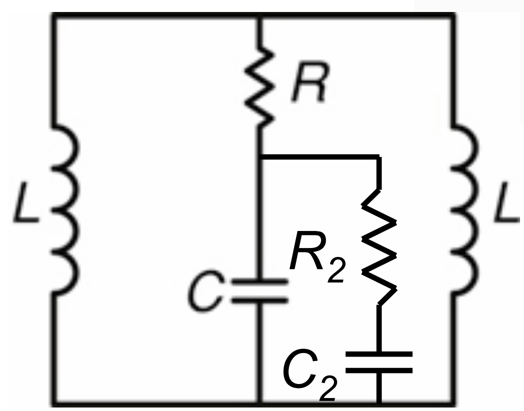
Dynamic Behavior

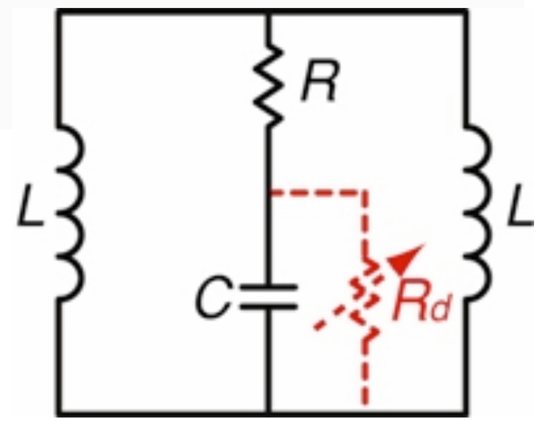




Chen *et al.* *Nature* **444,** 597 (2006)







Chen *et al.* *Nature Photonics* **285,** 295 (2008)

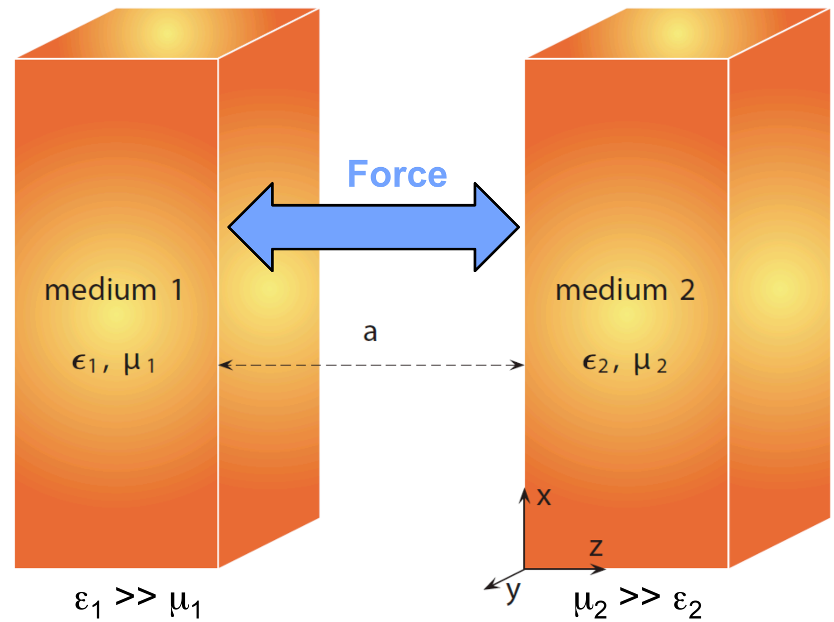
Goal: Casimir Force Neutralization & Reversal

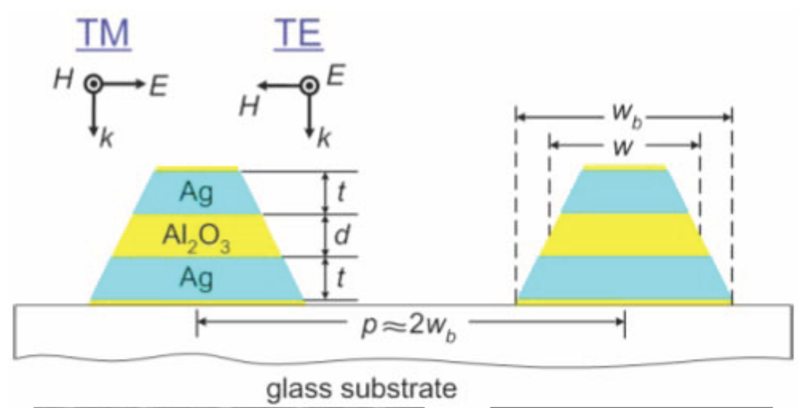
- **Metamaterials → offers numerous directions for modifying electromagnetic properties**

- **→ Possible route to Casimir force manipulation**

Henkel *et al.*, *Europhys. Lett.* **72**, 929 (2005)
Da Rosa *et al.* *PRL* **100**, 183602 (2008)
Zhao *et al.* *PRL* **103**, 103602 (2009)

Boyer *PRA* **9**, 2078 (1974)





Cai *et al.* *Optics Express* **15**, 3333 (2007)

The Equations Reveal the Needs

$$\frac{F(d)}{A} = 2\hbar \int_0^\infty \frac{d\xi}{2\pi} \boxed{\int} \frac{d^2\mathbf{k}_{||}}{(2\pi)^2} K_3 \mathrm{Tr} \frac{\boxed{\mathbf{R}_1} \cdot \mathbf{R}_2 e^{-2K_3 d}}{1 - \mathbf{R}_1 \cdot \mathbf{R}_2 e^{-2K_3 d}}$$

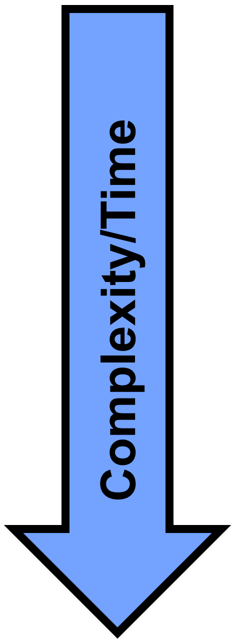
$$\epsilon(i\xi) = 1 + \frac{2}{\pi} \boxed{\int_0^\infty} \frac{\omega \epsilon''(\omega) d\omega}{\omega^2 + \xi^2}$$

Every k matters → homogeneity & isotropy (effective media?)

Every ω counts, more weight at high end

What is R_i?

Practical Limit 1: Simulation – Getting ε, μ, R

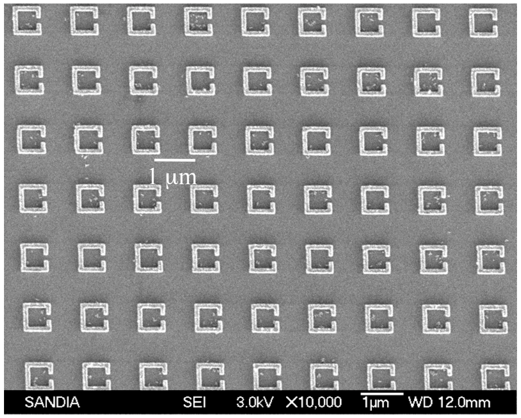


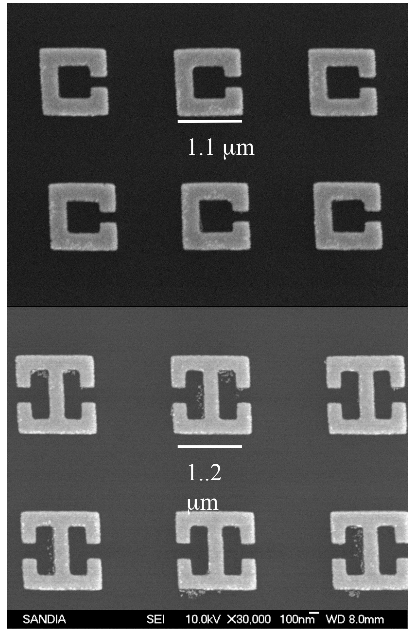
- 2D periodic, normal incidence → S-params
- 2D periodic, oblique incidence → S-params
- 2D random, normal incidence
- 2D random, oblique incidences
- 3D periodic, normal incidence to layers
- 3D periodic, various incidences/layer configs

- Extraction of "effective" parameters from S-parameters

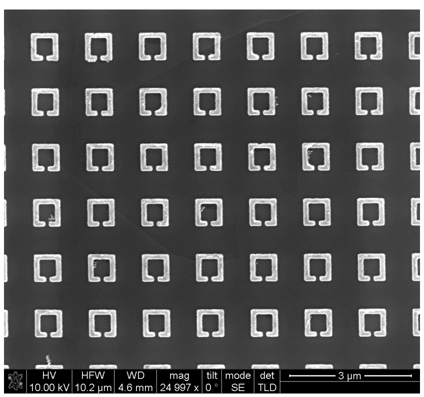
Practical Limit 2: Fabrication

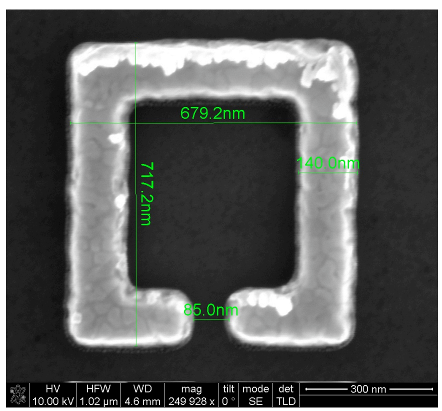
Au on GaAs, Si or BaF_2:

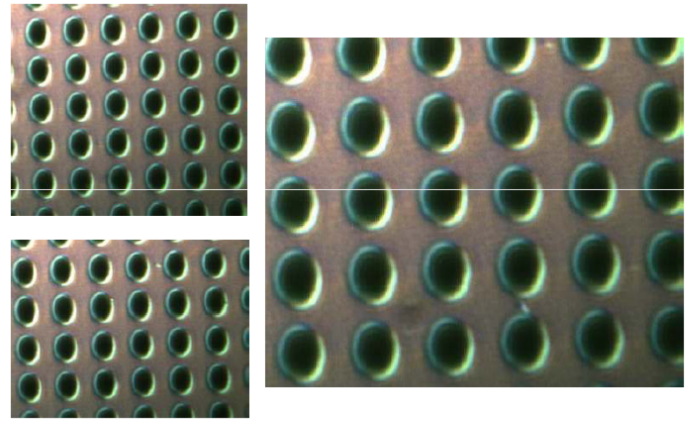


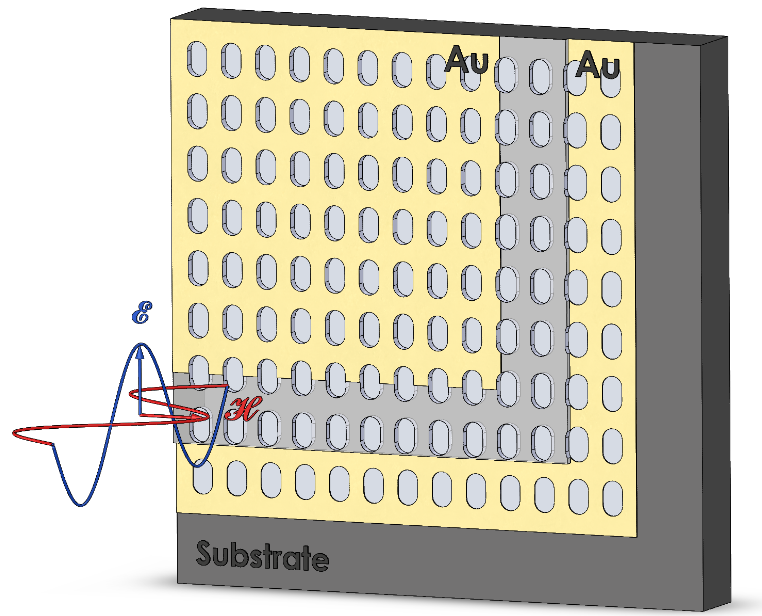


Au on InSb:









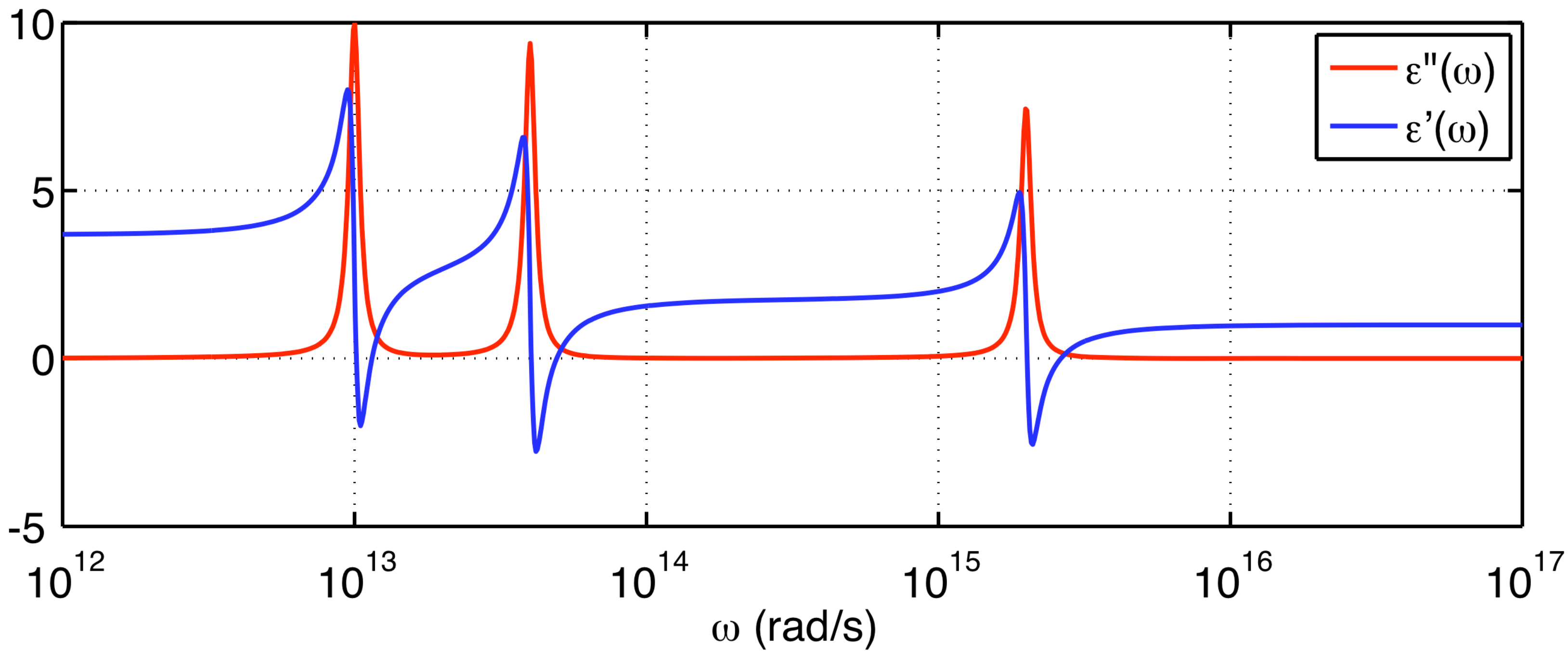
Zhang *et al.* *PRL* **95,** 137404 (2005)

Practical Limit 3: Base Materials

- Visible and IR dielectrics
  - Thermal SiO2
  - HDP SiO2
  - TEOS
  - PECVD SiN
  - Oxi-Nitride
  - SiC
  - Ge
  - BaF_2 sol-gel (preliminary) Al_2O_3
  - $SrTiO_3$
  - TiO_2
  - HfO_2
- Metals
  - Au
  - Al
  - AlCu
  - Ag
  - Ni
  - Ti
  - Cr
  - Pt
  - Pd
- Polymers:
  - BCB
  - PE
  - PMMA
  - ZEP
  - Polyimide
- Substrates:
  - Si
  - GaAs
  - BaF_2
  - ZnSe
  - Glass

Natural Materials Properties

- **Predominant electric response**
  - **Dielectrics → polarizability**
  - **Resonant but wide spectral distribution**
  - **Metals → conductivity**



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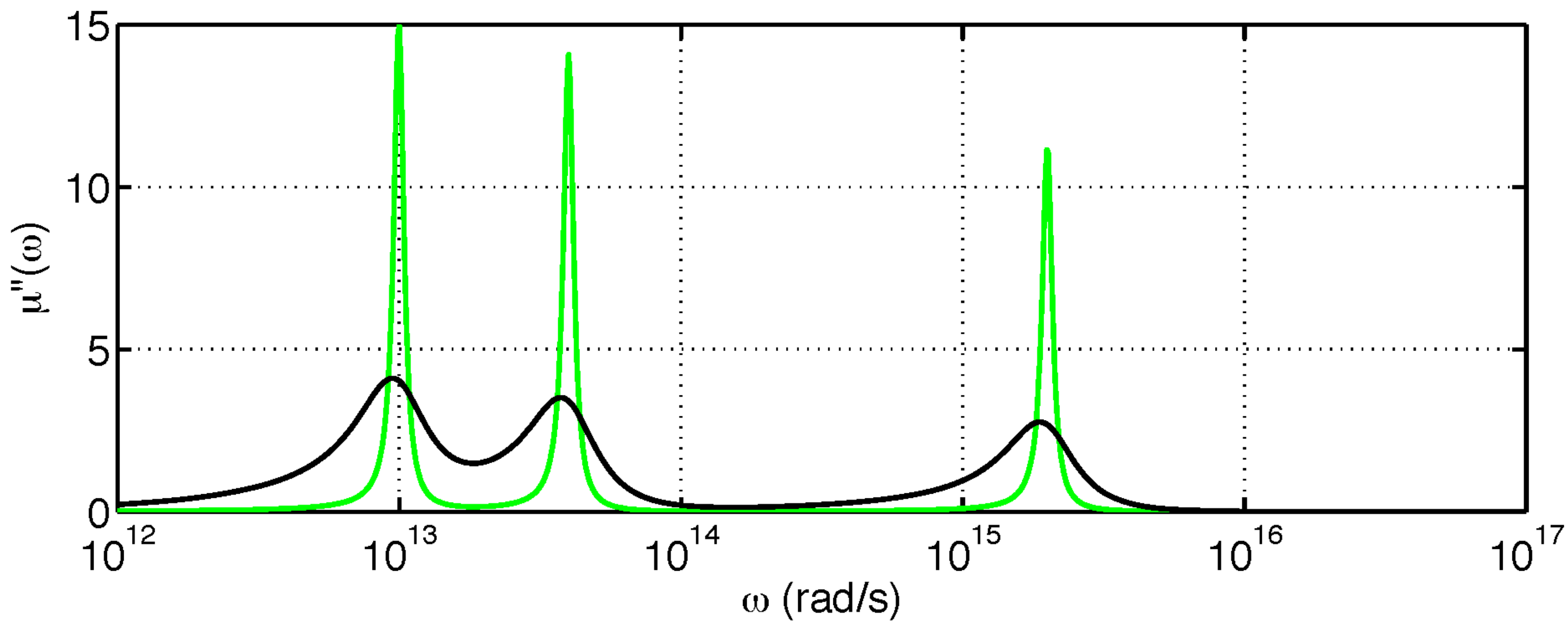
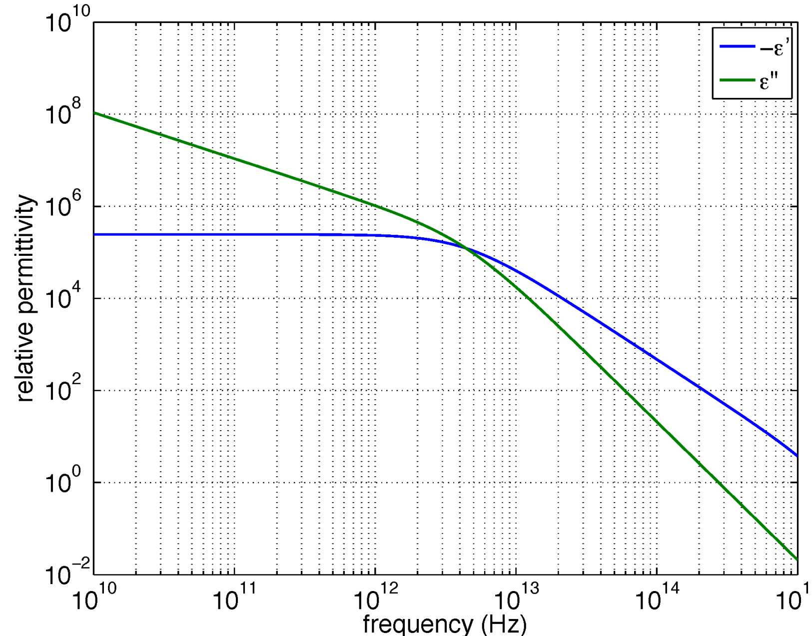
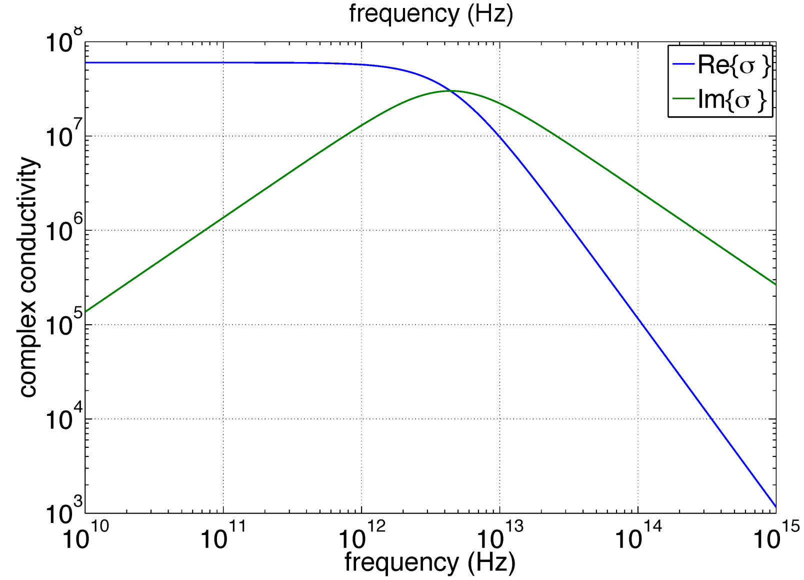


Natural Materials Properties

- Predominant electric response
  - Dielectrics → polarizability
  - Resonant but wide spectral distribution
  - Metals → conductivity
- Suppressed magnetism
  - Few materials with strong response
  - Non-existent by infrared
- Bi-anisotropy uncontrollable
- Fundamental constants (ω_p)



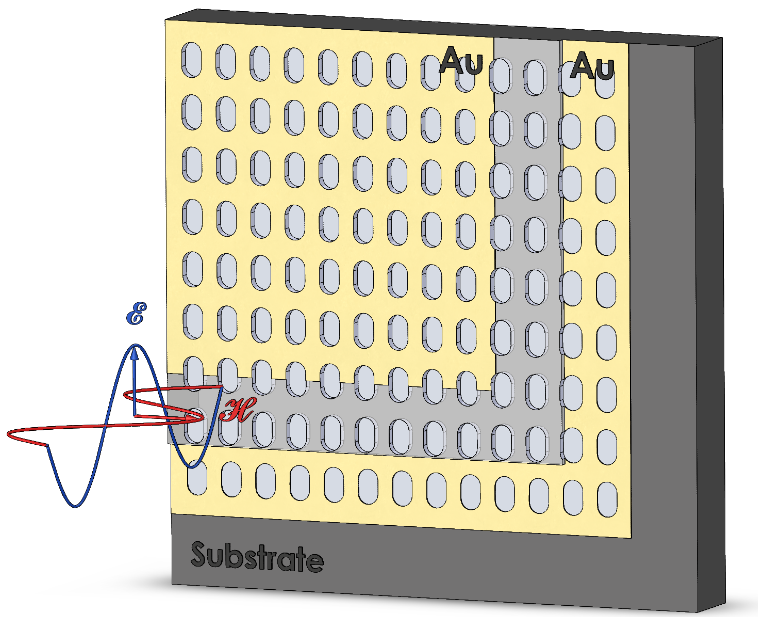


Metamaterial Resources

- **Geometry**
  - Circulating current (magnetism) driven by $\mathcal{H}$ or $\mathcal{E}$
  - Suppression of ε (effective)
  - Bi-anisotropy – chiral, etc.

- **Natural materials properties**
  - Loss (damping)
  - Tend toward air at UV
  - Limited scale of Casimir integration
  - High electric polarizability can enable magnetic polarizability

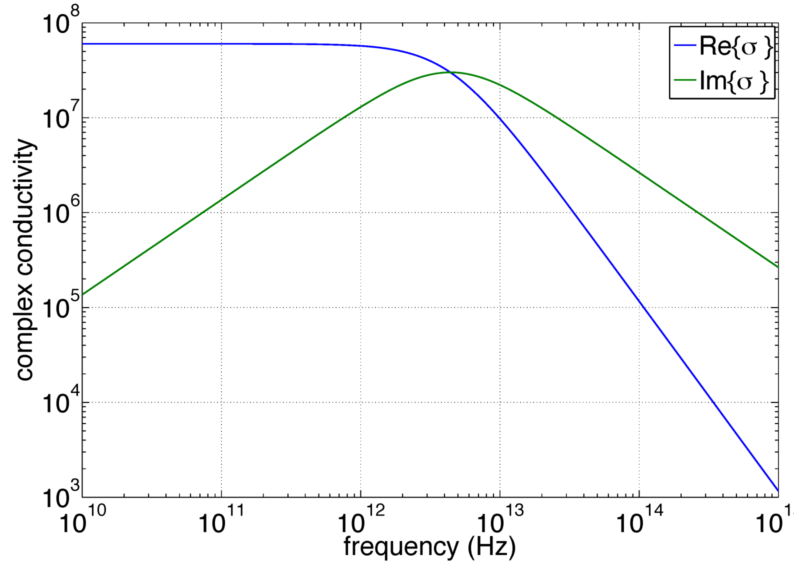
$$\begin{bmatrix} \mathbf{D} \\ \mathbf{B} \end{bmatrix} = \begin{bmatrix} \varepsilon & \xi \\ \zeta & \mu \end{bmatrix} \begin{bmatrix} \mathbf{E} \\ \mathbf{H} \end{bmatrix}$$

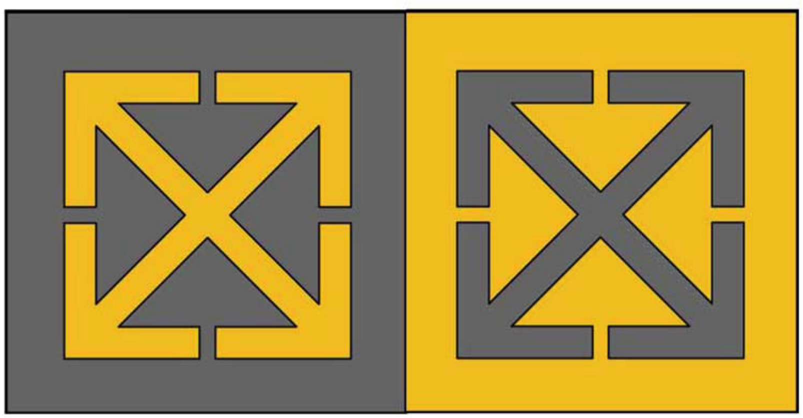


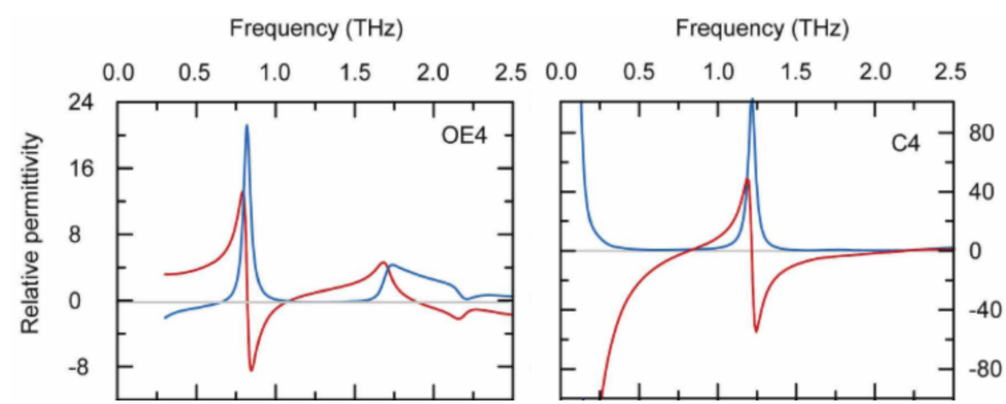
Need to realize full utilization of resources

Metamaterials with diminished permittivity

- Discontinuous metallized metamaterial→finite resonant μ and ε
- Further suppression of ε via frequency-dependent conductivity, decreasing at high frequencies



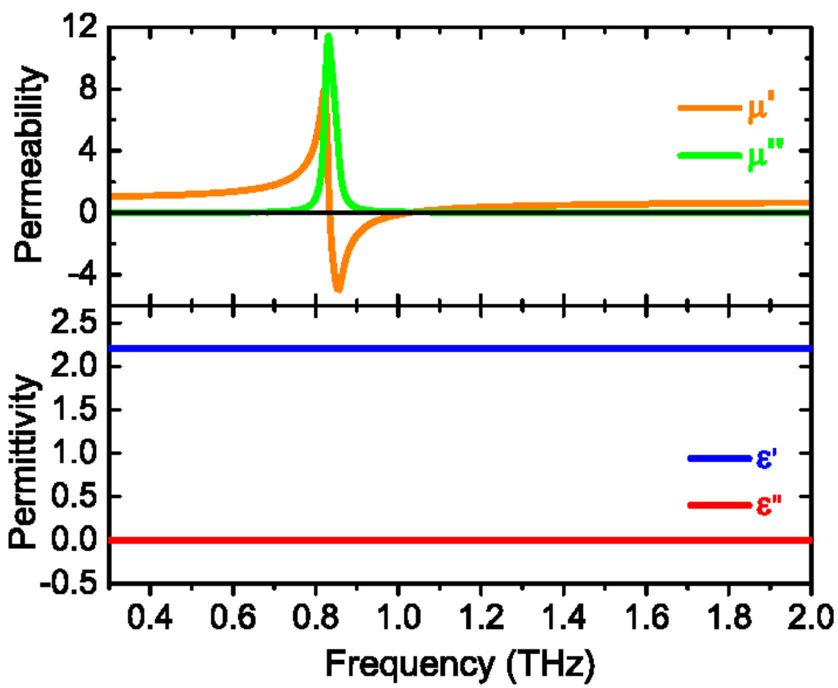


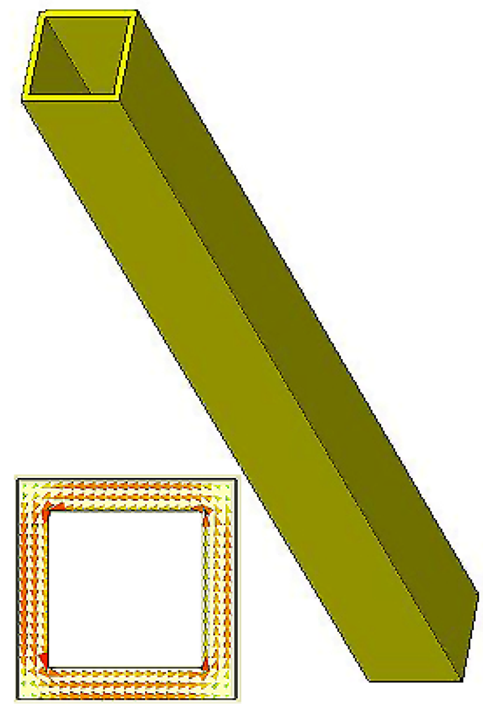


Chen *et al.* *Optics Express* **15**, 1084 (2007)

All-dielectric metamaterials

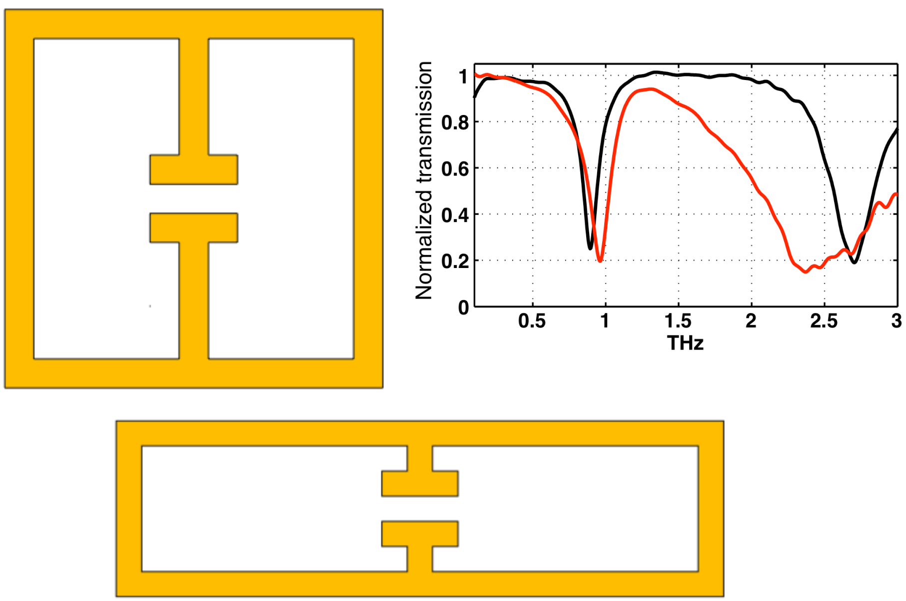
- All-dielectric MM → path to magnetism without metal
- No Drude background → low ε
- Requires high index contrast, difficult at high frequencies
- Low indices; however, also means less Casimir attraction to overcome (Question: which dominates?)





Combining Conductivity & Geometry

- **High σ → high ε**
- **High σ → strong resonance**
- Drude conductivity → damped high frequency response
- Geometry can separate resonances and create bands of μ alone



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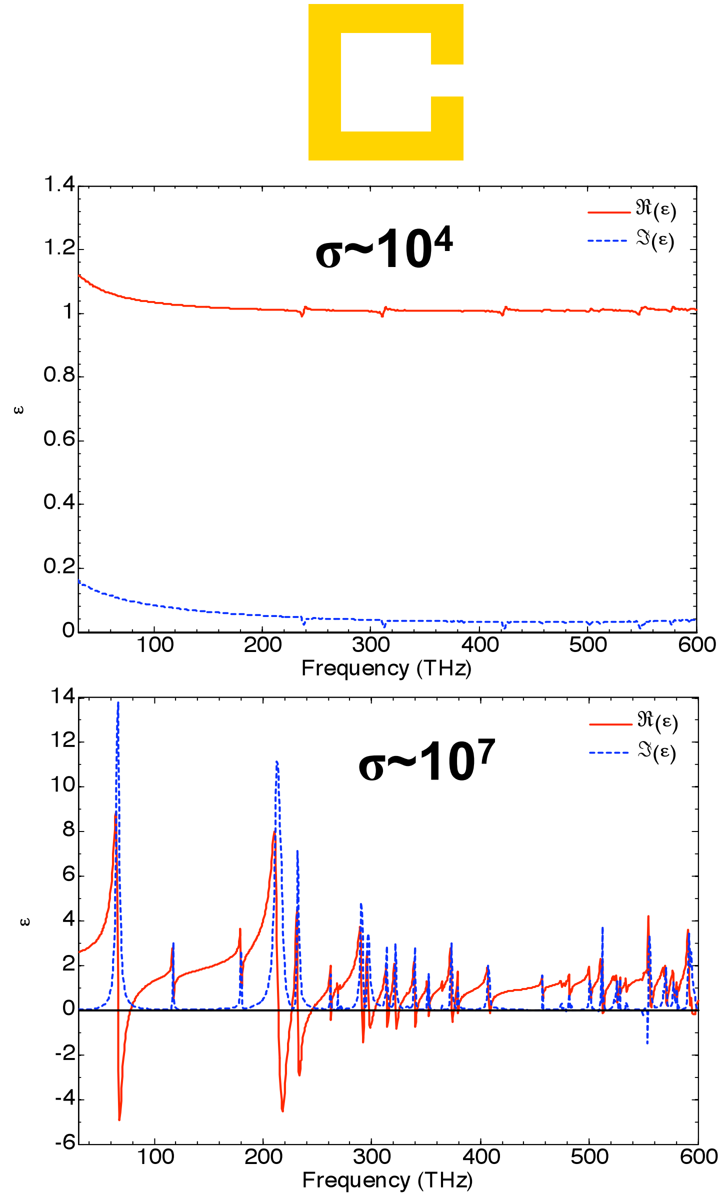
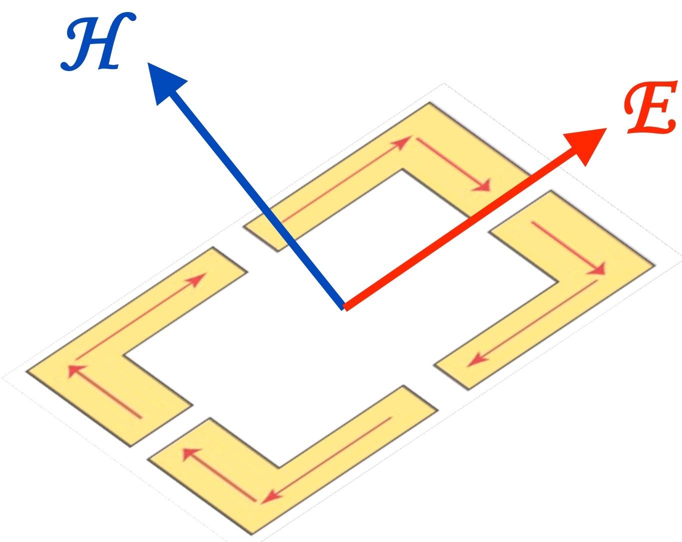
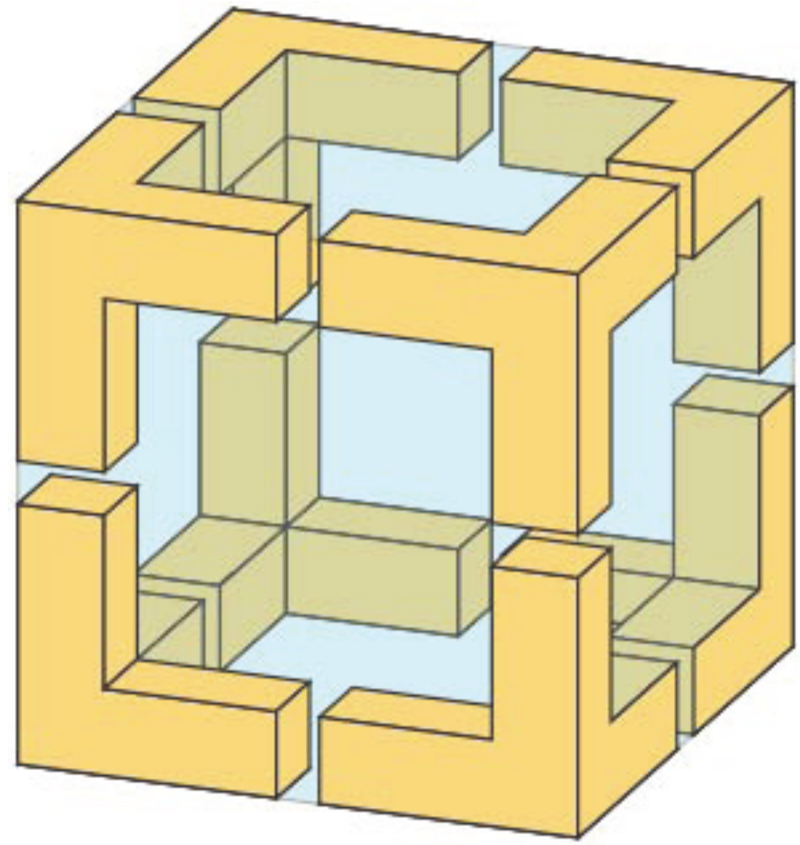


Magnetic Only Resonance

- Electric modes confined to high frequency
- Magnetic-only response associated with fundamental mode (circulating current).





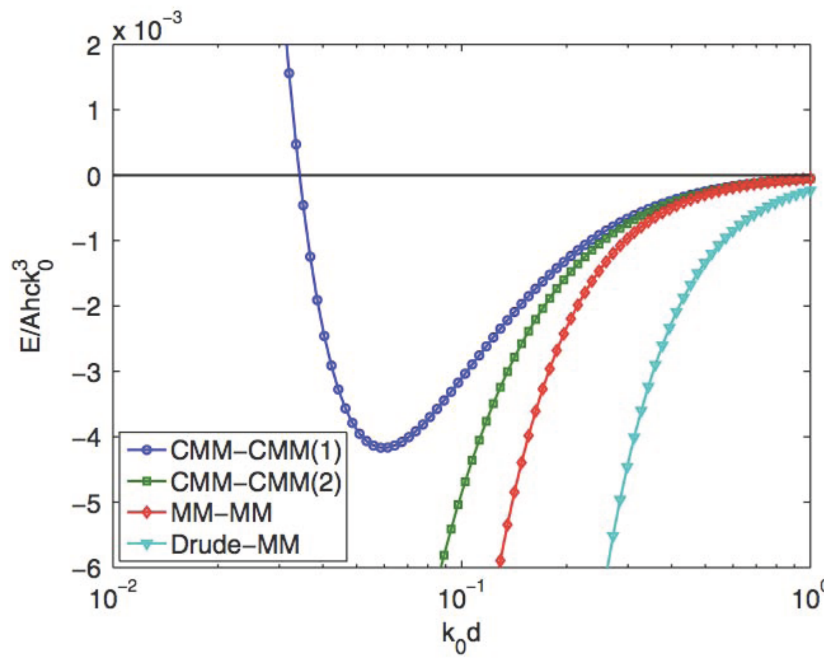
Padilla . *Opt. Express* **15,** 1639 (2007)

Other metamaterials approaches

Bi-Anisotropic metamaterials

- A new approach to Casimir force neutralization and repulsion
- Recent work demonstrated this possibility through a subset of bi-anisotropy: chirality
- More general strategies should be numerous albeit complex

$$\begin{bmatrix}\mathbf{D}\\ \mathbf{B}\end{bmatrix}=\begin{bmatrix}\varepsilon\varepsilon & \xi\, i\kappa\\ \xi\, i\kappa\,\mu & \mu\end{bmatrix}\begin{bmatrix}\mathbf{E}\\ \mathbf{H}\end{bmatrix}\begin{bmatrix}\mathbf{E}\\ \mathbf{H}\end{bmatrix}$$

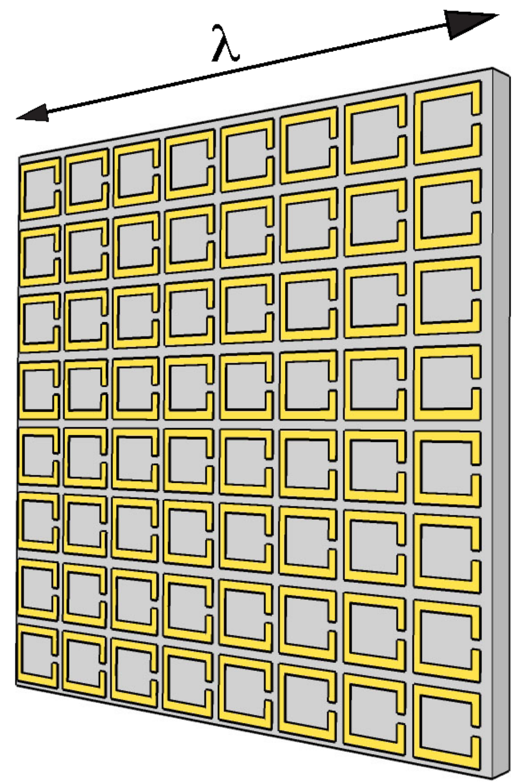


Zhao *et al*. *PRL* **103**, 103602 (2009)

Requirements for Metamaterial Casimir Force Reversal

$$\begin{bmatrix} \mathbf{D} \\ \mathbf{B} \end{bmatrix} = \begin{bmatrix} \varepsilon & \xi \\ \zeta & \mu \end{bmatrix} \begin{bmatrix} \mathbf{E} \\ \mathbf{H} \end{bmatrix}$$

- High μ, low ε,
- Role of ξ and ζ ?
- Isotropy → scalar ε, μ, ξ, and ζ
- Broadband/Multiband response
- Homogeneity (effective medium)
- Independent control over ε, μ, ξ, and ζ
- Within the scope of reality



$$\mu = \begin{bmatrix} \mu_x & 0 & 0 \\ 0 & \mu_y & 0 \\ 0 & 0 & \mu_z \end{bmatrix} \qquad \varepsilon = \begin{bmatrix} \varepsilon_x & 0 & 0 \\ 0 & \varepsilon_y & 0 \\ 0 & 0 & \varepsilon_z \end{bmatrix}$$

Conclusion

Metamaterial approach is difficult but wide open with opportunity

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