Frontier Applications of Metamaterials to Magnetic Confinement Fusion

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

- In plasmas $\varepsilon < 1$ and, at $\omega < \omega_p$, $\varepsilon < 0$, 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

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

• Motivation
• Reverse chromatic aberration
• Metamaterial lens
• Numerical optimization
• 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 $f \rightarrow$ 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

\[ C_1 = \varepsilon_0 \varepsilon_{eff} \frac{2D}{\pi} \ln \left[ \frac{1}{\sin \left( \frac{\pi g_1}{2D} \right)} \right] \]

\[ L = \mu_0 \mu_{eff} \frac{D}{2\pi} \ln \left[ \frac{1}{\sin \left( \frac{\pi w}{2D} \right)} \right] \]
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 $\Delta \phi(f)$ in each zone.

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

\[
C_1 = \varepsilon_0 \varepsilon_{\text{eff}} \frac{2D}{\pi} \ln \left[ \frac{1}{\sin \left(\frac{\pi g_1}{2D}\right)} \right]
\]

\[
T = \frac{2}{A + B + C \frac{Z_0}{Z} + D}
\]

\[
\begin{bmatrix}
A & B \\
C & D
\end{bmatrix} = \begin{bmatrix} 1 & 0 \\ j\omega C_1 & 1 \end{bmatrix} \begin{bmatrix} \cos \beta h & jZ \sin \beta h \\ \frac{j}{Z} \sin \beta h & \cos \beta h \end{bmatrix} \begin{bmatrix} 1 & 0 \\ \frac{1}{j\omega L} & 1 \end{bmatrix} \begin{bmatrix} \cos \beta h & jZ \sin \beta h \\ \frac{j}{Z} \sin \beta h & \cos \beta h \end{bmatrix} \begin{bmatrix} 1 & 0 \\ j\omega C_2 & 1 \end{bmatrix}
\]
...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 $\Delta \phi$
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)

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

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 $3\mu\Omega\text{cm}$ after 1h sintering at 150-200°C (bulk Ag 1.6$\mu\Omega\text{cm}$).

- 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 $\rightarrow$ recirculating cooling fluid (freon FC-75)
  – Square patches $\rightarrow$ 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
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.