Modelling the Electromagnetic Response of Wire Media with Anomalous Refractive Index using CST Microwave Studio

Antennas and Propagation Group

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**Metamaterials Overview**

**Definition:**
- Artificial (microstructured) materials composed by arrangements of elements properly designed and structured to achieve unusual and advantageous electromagnetic responses.

**Metamaterials vs Conventional Materials:**

- Complex arrangement of atoms or molecules
- Metamaterial with artificially structured “atoms”
- Continuous medium
- 2nd level of homogenization!!!

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Lisboa, June 15, 2012
Double wire medium metamaterials

Applications of double wire medium metamaterials:

- Anomalous refraction of light colors;
- Suppression of Chromatic Aberrations;
- Ultraconfined Waveguiding;
- Imaging devices with super-resolution;
Exotic Property of the Double Wire Medium

Motivation: A double wire medium has extra degrees of freedom when compared to conventional media.

The double wire medium permits achieving a regime of low loss anomalous refraction!
Validation of the Effective Medium Model

\[ \varepsilon_{ii}(\omega, k_i) = 1 + \left( \frac{1}{(\varepsilon_m - 1) f_v} - \frac{(\omega / c)^2 - k_i^2}{\beta_p^2} \right)^{-1}, \quad i = 1, 2 \]

\[ \overline{\varepsilon}_{\text{eff}} = \hat{u}_y \hat{u}_y + \varepsilon_{11} \hat{u}_1 \hat{u}_1 + \varepsilon_{22} \hat{u}_2 \hat{u}_2 \]

\[ \overline{\varepsilon}_{\text{eff}}(\omega, k) \]

\[ k = (k_x, k_y, k_z) \]

CST takes into account all the microscopic details of the material.

Chromatic Aberrations
Chromatic Aberrations

- Single-material glass lenses are unable to focus all the spectral components of light into the same convergence point;
- The image produced by such lenses is distorted (chromatic aberration).

**Focal length**

**Lensmaker’s equation:**

\[
\frac{1}{f} = (n_g - 1) \left( \frac{1}{R_1} + \frac{1}{R_2} \right)
\]

\(f\) varies with \(\omega\)!

(chronatic aberration)

How can \(f\) be made independent of frequency?

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Suppression of Chromatic Aberrations

\( f \) is independent of \( \omega \) provided:

\[
\frac{\partial n_1}{\partial \omega} = -\frac{R_1}{R_2} \frac{\partial n_2}{\partial \omega}
\]

\( \frac{\partial n_1}{\partial \omega}, \frac{\partial n_2}{\partial \omega} > 0 \) (Usual glasses)

\( R_1, R_2 > 0 \) and \( \frac{\partial n_1}{\partial \omega} > 0 \)

\[\frac{\partial n_2}{\partial \omega} < 0\]

\( A \) material with anomalous dispersion is required!

\( R > 0 \) Convex Surface

\( R < 0 \) Concave Surface

(see from the air)

\( \text{• regimes of anomalous dispersion in conventional materials imply very significant loss.} \)

How can we overcome this limitation?
Low Loss Anomalous Dispersion of Light Colors
Refraction of light by a prism

Snell’s law in free-space

\[ n_1 \sin(\alpha) = \sin(\theta_t) \]

In “usual” glass prisms:

\[ \omega \uparrow \Rightarrow n_1 \uparrow \Rightarrow \theta_t \uparrow \]

Shorter wavelengths are more refracted than longer wavelengths.

In a double wire medium prism:

\[ \omega \uparrow \Rightarrow n_{\text{eff}} \downarrow \Rightarrow \theta_t \downarrow \]

Longer wavelengths are more refracted than shorter wavelengths!

\[ n_{\text{eff}} = \sqrt{\frac{3}{2} + \frac{1}{2} \left( 1 + 8 \left( \frac{\beta c}{\omega} \right)^2 \right)^{1/2}} \]


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Refraction of light by a metamaterial prism (FDFD)

Al wires (optical regime)

\[ \alpha = 14^\circ \]
\[ 2w_0 = 3\lambda_{0.75\mu m} \]
\[ a = 100\text{nm} \]
\[ r_w = 15\text{nm} \]
\[ \varepsilon_m = 1 - \frac{\omega_p^2}{\omega(\omega - j\omega_c)} \]
\[ \omega_p / 2\pi = 3570[\text{THz}] \]
\[ \omega_c / 2\pi = 19.4[\text{THz}] \]

Low loss anomalous dispersion occurs at optical frequencies!

\[ n_{xw} = n'_{xw} + jn''_{xw} \]
Refraction of light by a prism (CST)

**Transient Solver**

**Boundary Conditions:**
- *x*-direction: open boundaries;
- *y*-direction: periodic boundaries;
- *z*-direction: open boundaries.

\[ \lambda = 0.56 \mu m \]

Gaussian beam illuminating the metamaterial prism

\[ \omega \uparrow \Rightarrow \theta_i \downarrow \]
Refraction of light by a prism (CST Vs FDFD)

- CST enables the validation of both the analytical and numerical results obtained from our homogenization models;

Can this anomalous property be used to eliminate the chromatic aberrations?
Suppression of Chromatic Aberrations
Suppression of Chromatic Aberrations (contd.)

\( f \) is independent of \( \omega \) provided:

\[
\frac{\partial n_1}{\partial \omega} = - \frac{R_1}{R_2} \frac{\partial n_2}{\partial \omega}
\]

\[ f \sim 7.8 \mu m \]

\[ a = 100 nm \quad 2r_w = 30 nm \]

\[ R_1 = 46.24 \mu m \quad R_2 = 9.25 \mu m \]

\[
\frac{1}{f} = (n_g - 1) \left( \frac{1}{R_1} + \frac{1}{R_2} \right)
\]

Achromatic biconvex metamaterial lens

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Modelling the Metamaterial Lens (CST)

**Transient Solver**

**Boundary Conditions:**
- $x$-direction: open boundaries;
- $y$-direction: open boundaries;
- $z$-direction: periodic boundaries.

Illustrative example of the achromatic biconvex metamaterial lens
Desired focal length \( f \sim 7.8 \mu m \)

Both the FDFD and CST results predict a focal length \( f \approx 7.8 \mu m \) at \( \lambda = 0.75 \mu m \) and \( \lambda = 0.38 \mu m \)
Modelling the Metamaterial Lens (contd.)

Single glass lens

Achromatic biconvex metamaterial lens

The metamaterial based lens nearly suppresses the chromatic aberrations of all colors.

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Conclusions and final remarks
CST is a useful tool for our research work

- Enables the validation of the analytical or numerical results obtained from our homogenization models;

- Models and simulates the electromagnetic response of complex structures;

CST predicts the physical response with great accuracy!