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Modeling of Electromagnetic Wave Interactions With Bi-isotropic and Bi-anisotropic Meta-materials Using A New Wavefield Decomposition Finite Difference Time Domain (WD-FDTD) Technique

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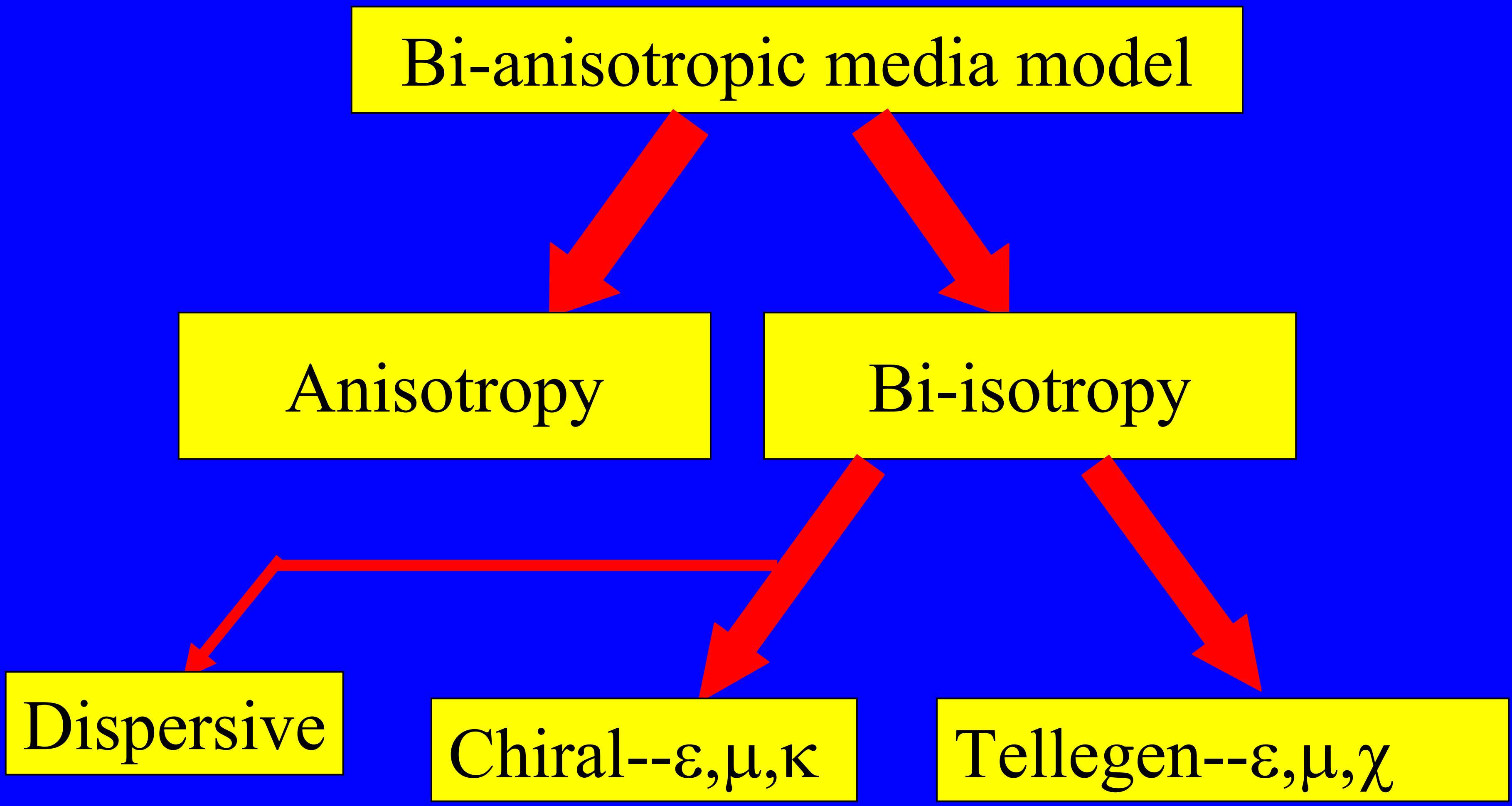
PSU EM Research Group

- First group to apply wavefield decomposition techniques to FDTD
- First group to successfully develop dispersive FDTD formulation for general bi-anisotropic media (BIA-FDTD)
- First group to use new BIA-FDTD formulation to model electromagnetic wave interactions with dispersive chiral meta-materials
- Work has been recognized for its contribution to the EM modeling community
  - ➔ Received ACES Best Paper Award
  - ➔ IEEE Antennas and Propagation Society Conference Student Paper Competition Finalist

Subclasses of Bi-anisotropic Media



BI-FDTD Code

Chiral Model + Tellegen → General BI Media Model

+

Dispersive $\varepsilon, \mu, \kappa, \chi$ → General Dispersive BI Media Model

BIA-FDTD Code

General BI Media Model + Anisotropy Effects → General BIA Media Model

\+ Dispersive $\bar{\bar{\varepsilon}},\bar{\bar{\mu}},\bar{\bar{\kappa}},\bar{\bar{\chi}}$ → General Dispersive BIA Media Model

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Objectives

- To derive a simple yet powerful way to model electromagnetic wave interactions with Bi-isotropic (BI) and Bi-anisotropic (BIA) media using the FDTD method
- To be able to extend the scheme to dispersive BI and BIA materials
- **Final product:** A very general and versatile FDTD code which can be used to model BIA media and its subclasses
- **Application:** A modeling tool for the analysis and design of microstrip antennas with BI and BIA substrates/superstrates

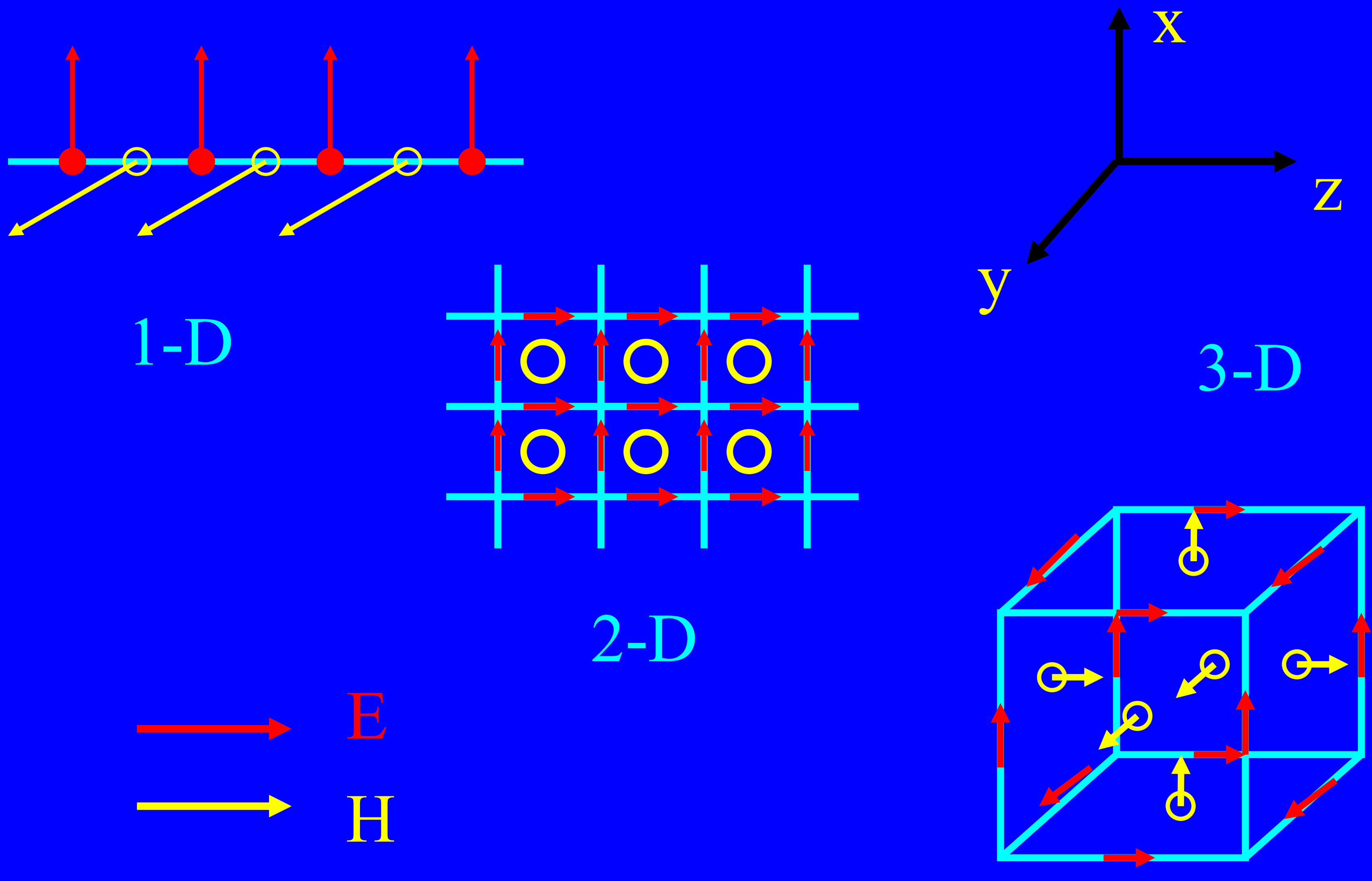
Bi-Anisotropic Media

$$\vec{D} = \bar{\bar{\varepsilon}}\,\vec{E} + \bar{\bar{\xi}}\,\vec{H}$$

$$\vec{B} = \bar{\bar{\zeta}}\,\vec{E} + \bar{\bar{\mu}}\,\vec{H}$$

where $\bar{\bar{\varepsilon}}, \bar{\bar{\xi}}, \bar{\bar{\zeta}}$ and $\bar{\bar{\mu}}$ **are tensor quantities in general**

Field Components in FDTD

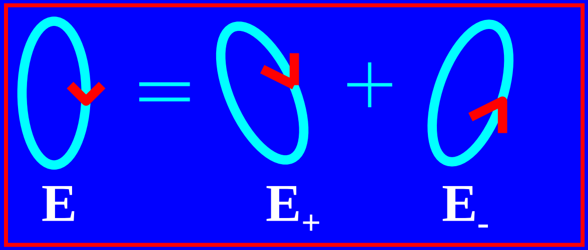


BI-FDTD Formulation

- Decomposing the electric and magnetic fields

$$\vec{E} = \vec{E}_+ + \vec{E}_-$$

$$\vec{H} = \vec{H}_+ + \vec{H}_-$$



- *Wavefields* : circularly polarized wave
- BI medium as an equivalent isotropic medium with ε_+,μ_+ and ε_-,μ_-

$$\mu_\pm = \mu(\cos\theta \pm \kappa_r)e^{\mp j\theta}$$

$$\varepsilon_\pm = \varepsilon(\cos\theta \pm \kappa_r)e^{\pm j\theta}$$

$$\cos\theta = \sqrt{1-\chi_r^2}$$

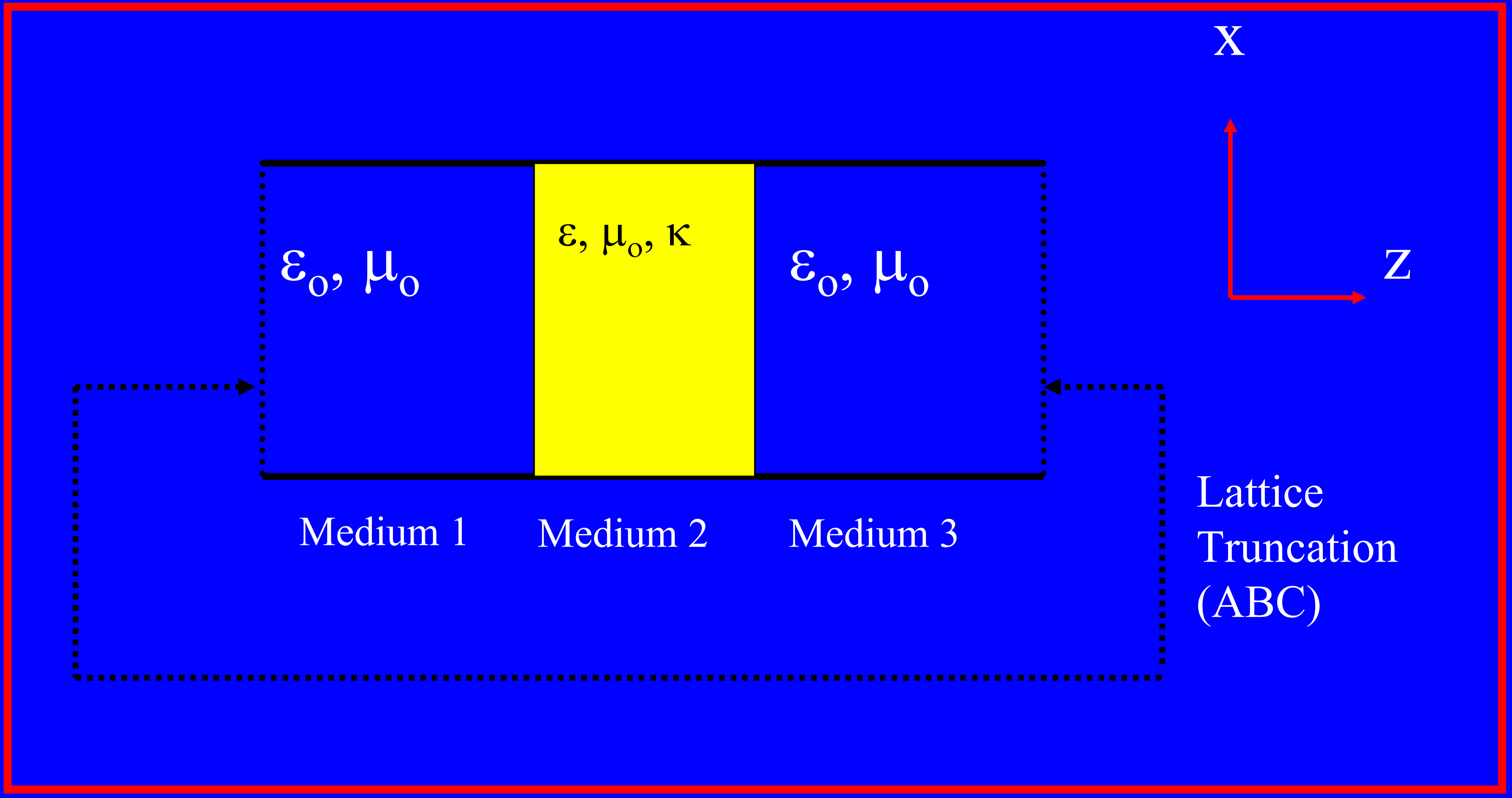
BI-FDTD Formulation

- Wavefields are independent and uncoupled in a homogenous BI Medium

$$\nabla \times E_{\pm} = -j\omega\mu_{\pm} H_{\pm}$$
$$\nabla \times H_{\pm} = j\omega\varepsilon_{\pm} E_{\pm}$$

- $E_{\pm}$, $H_{\pm}$ satisfy Maxwell's equations in the equivalent media whenever E and H satisfy Maxwell equations in original BI medium

Test Case--Chiral Slab



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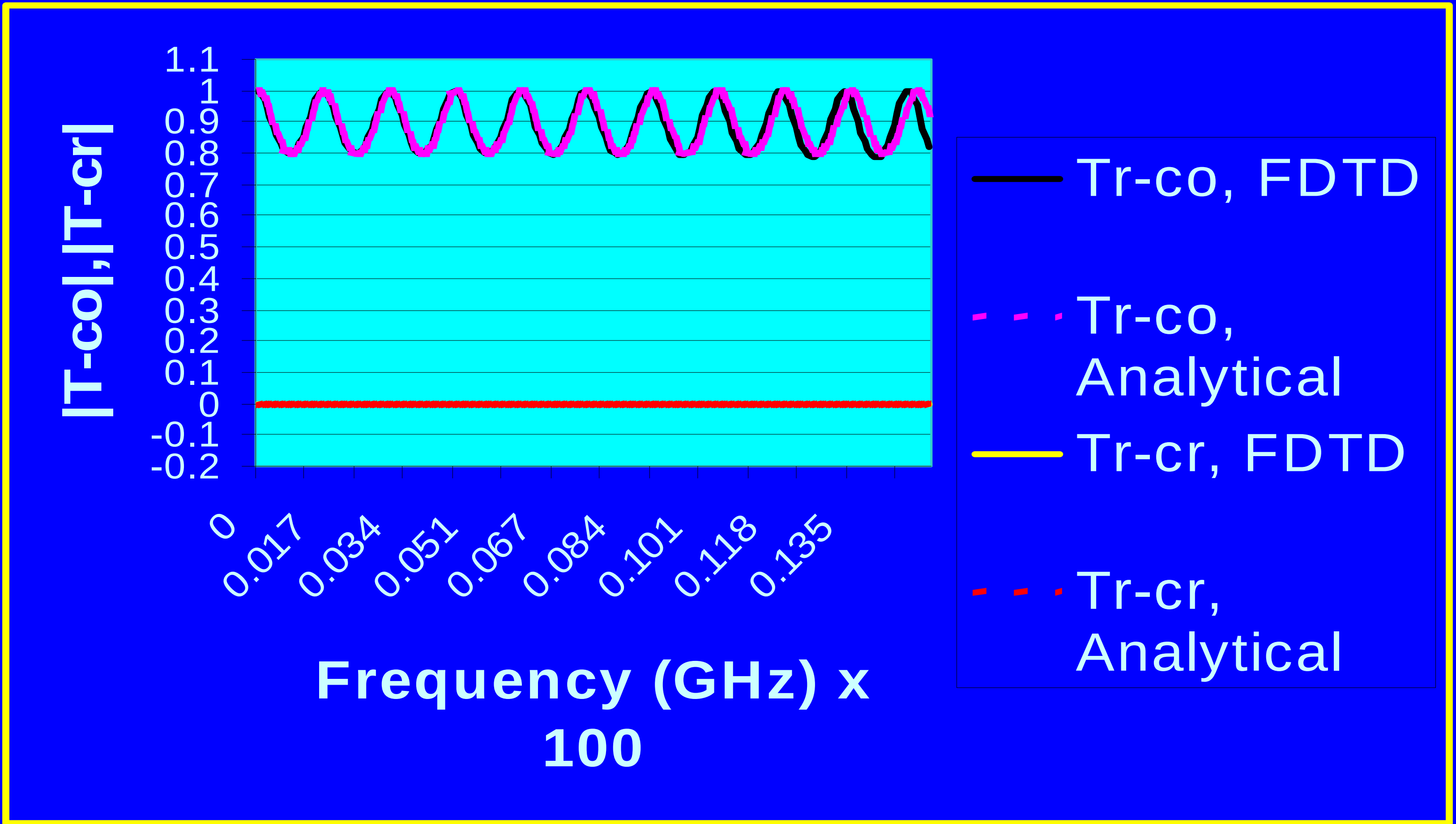
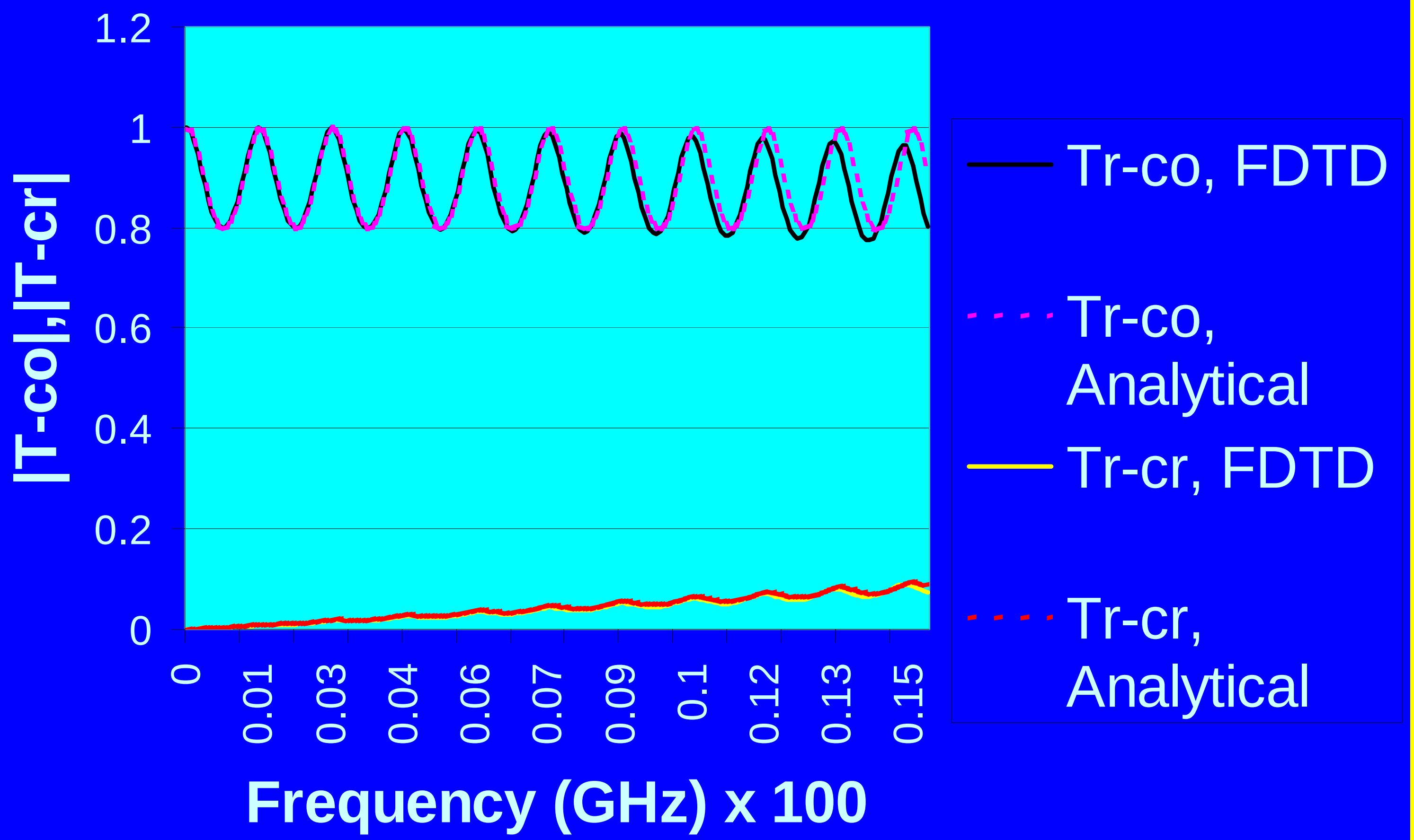
Results



$\kappa_r = 0.0$

Results



$\kappa_r = 0.003$

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Anisotropic BI-FDTD

Equivalent Material Properties:

$$\begin{bmatrix} D_{x\pm} \\ D_{y\pm} \\ D_{z\pm} \end{bmatrix} = \begin{pmatrix} \varepsilon_{xx\pm} & \varepsilon_{xy\pm} & \varepsilon_{xz\pm} \\ \varepsilon_{yx\pm} & \varepsilon_{yy\pm} & \varepsilon_{yz\pm} \\ \varepsilon_{zx\pm} & \varepsilon_{zy\pm} & \varepsilon_{zz\pm} \end{pmatrix} \begin{bmatrix} E_{x\pm} \\ E_{y\pm} \\ E_{z\pm} \end{bmatrix}$$

$$\begin{bmatrix} B_{x\pm} \\ B_{y\pm} \\ B_{z\pm} \end{bmatrix} = \begin{pmatrix} \mu_{xx\pm} & \mu_{xy\pm} & \mu_{xz\pm} \\ \mu_{yx\pm} & \mu_{yy\pm} & \mu_{yz\pm} \\ \mu_{zx\pm} & \mu_{zy\pm} & \mu_{zz\pm} \end{pmatrix} \begin{bmatrix} H_{x\pm} \\ H_{y\pm} \\ H_{z\pm} \end{bmatrix}$$

Dispersive BI-FDTD

For the dispersive BI-FDTD formulation ε, μ, and κ are frequency dependant. The parameters ε and μ use a Lorentzian model and for the chirality parameter, κ, a Condon Model is used.

$$\varepsilon_{\pm} = \varepsilon(\omega)\left(1 \pm \kappa_r(\omega)\right)$$

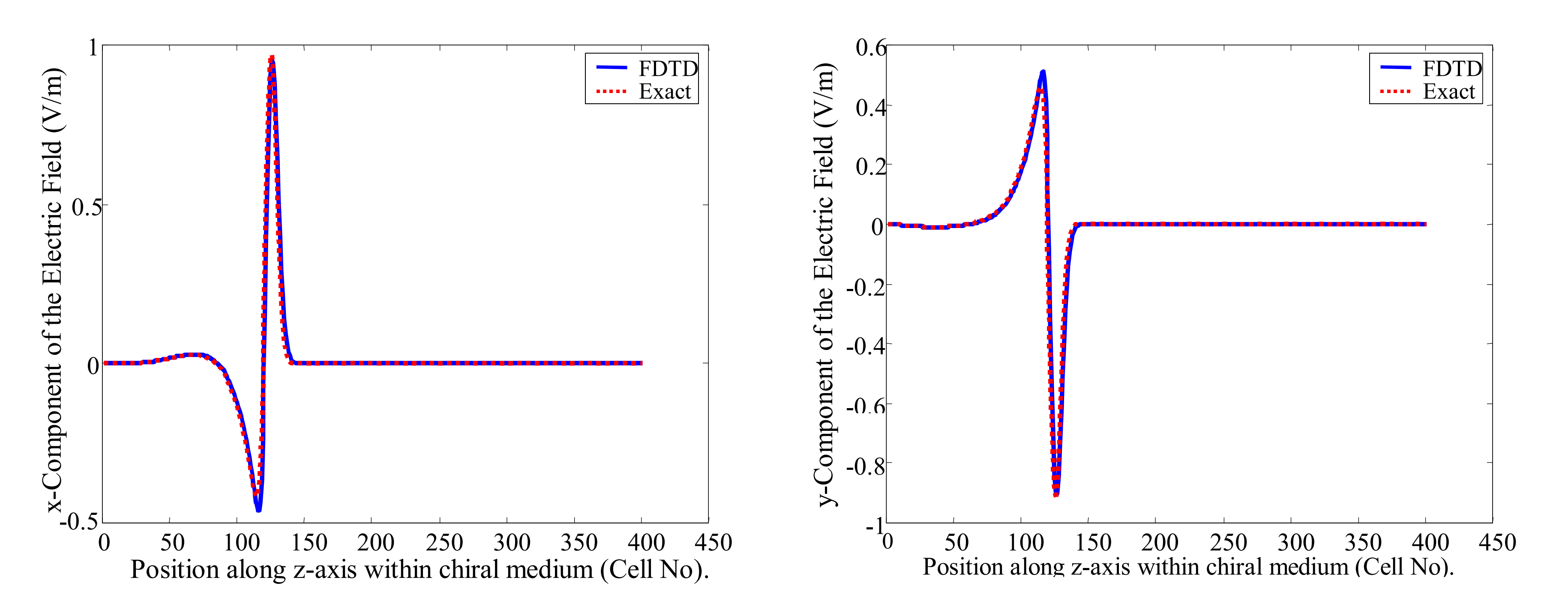
$$\mu_{\pm} = \mu(\omega)\left(1 \pm \kappa_r(\omega)\right)$$

$$\varepsilon(\omega) = \varepsilon_o\left(\varepsilon_\infty + \frac{(\varepsilon_s - \varepsilon_\infty)\omega_{oe}^2}{\omega_{oe}^2 + j2\delta_e\omega - \omega^2}\right)$$

$$\mu(\omega) = \mu_o\left(\mu_\infty + \frac{(\mu_s - \mu_\infty)\omega_{oh}^2}{\omega_{oh}^2 + j2\delta_h\omega - \omega^2}\right)$$

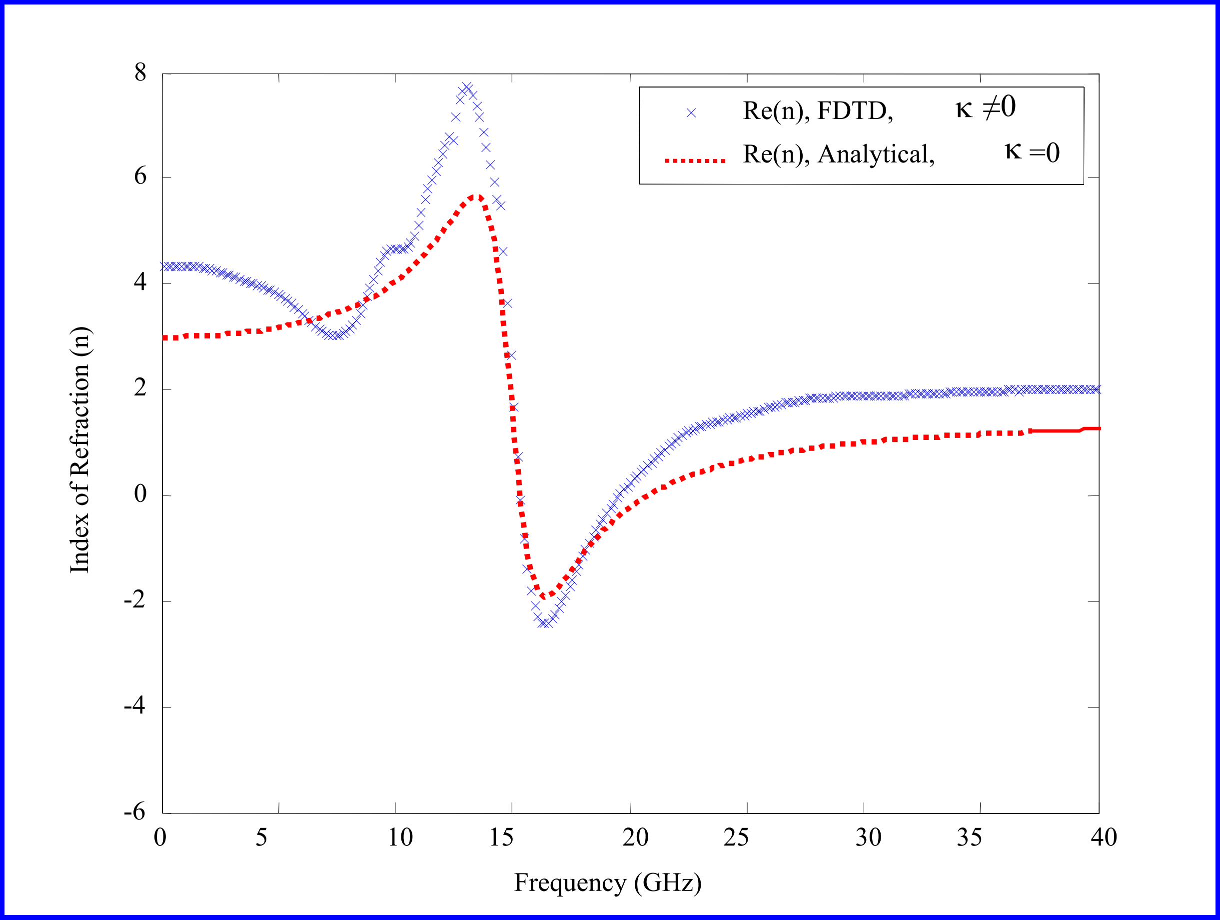
$$\kappa(\omega) = \frac{j\omega\omega_{oc}}{\omega_{oc}^2 + j\delta_c\omega_{oc}\omega - \omega^2}$$

EM Wave Propagation in a Dispersive Chiral Half-Space



Dispersive Chiral Slab

This represents an example of a new left-handed meta-material that exhibits magneto-electric coupling



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Contributions

- **The unique properties of BI and BIA media present many opportunities for the design of novel meta-materials**

- **Some applications include:**
  - Loaded dielectric and ferrite antennas, plasma antennas, chirostrip antennas, BIA antennas
  - Left-handed or double-negative meta-materials
  - Coatings for scatterers
  - Depolarizers, modulators, sensors, etc…

- **A new WD-FDTD approach is being developed at PSU to provide a powerful analysis tool to aid in the design of devices which incorporate BI and BIA meta-materials**