

Christopher Stricklan
02/16/2011
EEL 5390 – Special Topics (FDTD)
HW #3

Problem 1
Maxwell's Equations

$$\nabla \cdot \vec{D}(t) = \rho_v(t) \quad (1)$$

$$\nabla \cdot \vec{B}(t) = 0 \quad (2)$$

$$\nabla \times \vec{E}(t) = -\frac{\partial \vec{B}(t)}{\partial t} \quad (3)$$

$$\nabla \times \vec{H}(t) = \vec{J} + \frac{\partial \vec{D}(t)}{\partial t} \quad (4)$$

Constitutive relations

$$\vec{D} = [\epsilon(t)] * \vec{E}(t) \quad (5)$$

$$\vec{B} = [\mu(t)] * \vec{H}(t) \quad (6)$$

Eliminate Divergence

Our use of the Yee Grid Scheme allows us to eliminate divergence via equations (7) and (8)

$$\nabla \cdot (\epsilon \vec{E}) = 0 \quad (7)$$

$$\nabla \cdot (\mu \vec{H}) = 0 \quad (8)$$

This also allows for the centering of the fields invoked by the curl equations
Figure 1

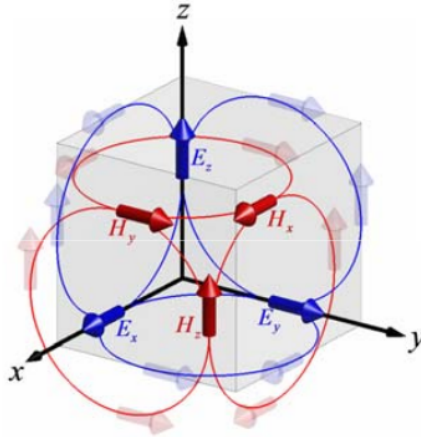


Figure 1: Yee Grid

Substitution

Because we have satisfied the divergence equations by using the Yee Grid Scheme, we are now able to focus on the curl equations with our constitutive relation equations (5) and (6) substituted in. We are also not injecting a Source.

Where $\vec{J} = 0$

$$\nabla \times \vec{E}(t) = -[\mu] \frac{\partial \vec{H}(t)}{\partial t} \quad (9)$$

$$\nabla \times \vec{H}(t) = [\epsilon] \frac{\partial \vec{E}(t)}{\partial t} \quad (10)$$

Normalize Magnetic Field

The Electric and Magnetic Fields are three orders of magnitude different. Rounding errors can propagate through our simulation, therefore we require that we normalize a Field. In this case we are normalizing the Magnetic Field.

$$\begin{aligned} \vec{H} = \sqrt{\frac{\mu_0}{\epsilon_0}} \vec{\tilde{H}} \implies \nabla \times \vec{E} &= -\frac{[\mu_r]}{c_0} \frac{\partial \vec{\tilde{H}}}{\partial t} \\ \nabla \times \vec{\tilde{H}} &= \frac{[\epsilon_r]}{c_0} \frac{\partial \vec{E}}{\partial t} \end{aligned} \quad (11)$$

Expand Curl Equations

$$\begin{aligned} \nabla \times \vec{E} &= -\frac{[\mu_r]}{c_0} \frac{\partial \vec{\tilde{H}}}{\partial t} \implies \\ \frac{\partial E_z}{\partial y} - \frac{\partial E_y}{\partial z} &= -\frac{1}{c_0} \left(\mu_{xx} \frac{\partial \tilde{H}_x}{\partial t} + \mu_{xy} \frac{\partial \tilde{H}_y}{\partial t} + \mu_{xz} \frac{\partial \tilde{H}_z}{\partial t} \right) \\ \frac{\partial E_x}{\partial z} - \frac{\partial E_z}{\partial x} &= -\frac{1}{c_0} \left(\mu_{yx} \frac{\partial \tilde{H}_x}{\partial t} + \mu_{yy} \frac{\partial \tilde{H}_y}{\partial t} + \mu_{yz} \frac{\partial \tilde{H}_z}{\partial t} \right) \\ \frac{\partial E_y}{\partial x} - \frac{\partial E_x}{\partial y} &= -\frac{1}{c_0} \left(\mu_{zx} \frac{\partial \tilde{H}_x}{\partial t} + \mu_{zy} \frac{\partial \tilde{H}_y}{\partial t} + \mu_{zz} \frac{\partial \tilde{H}_z}{\partial t} \right) \end{aligned} \quad (12)$$

$$\begin{aligned} \nabla \times \vec{\tilde{H}} &= \frac{[\epsilon_r]}{c_0} \frac{\partial \vec{E}}{\partial t} \implies \\ \frac{\partial \tilde{H}_z}{\partial y} - \frac{\partial \tilde{H}_y}{\partial z} &= \frac{1}{c_0} \left(\epsilon_{xx} \frac{\partial E_x}{\partial t} + \epsilon_{xy} \frac{\partial E_y}{\partial t} + \epsilon_{xz} \frac{\partial E_z}{\partial t} \right) \\ \frac{\partial \tilde{H}_x}{\partial z} - \frac{\partial \tilde{H}_z}{\partial x} &= \frac{1}{c_0} \left(\epsilon_{yx} \frac{\partial E_x}{\partial t} + \epsilon_{yy} \frac{\partial E_y}{\partial t} + \epsilon_{yz} \frac{\partial E_z}{\partial t} \right) \\ \frac{\partial \tilde{H}_y}{\partial x} - \frac{\partial \tilde{H}_x}{\partial y} &= \frac{1}{c_0} \left(\epsilon_{zx} \frac{\partial E_x}{\partial t} + \epsilon_{zy} \frac{\partial E_y}{\partial t} + \epsilon_{zz} \frac{\partial E_z}{\partial t} \right) \end{aligned} \quad (13)$$

Cross Out Diagonal Tensors

$$\nabla \times \vec{E} = -\frac{[\mu_r]}{c_0} \frac{\partial \vec{H}}{\partial t} \Rightarrow \quad (14)$$

$$\begin{aligned} \frac{\partial E_z}{\partial y} - \frac{\partial E_y}{\partial z} &= -\frac{1}{c_0} \left(\mu_{xx} \frac{\partial \tilde{H}_x}{\partial t} + \cancel{\mu_{xy} \frac{\partial \tilde{H}_y}{\partial t}} + \cancel{\mu_{xz} \frac{\partial \tilde{H}_z}{\partial t}} \right) \\ \frac{\partial E_x}{\partial z} - \frac{\partial E_z}{\partial x} &= -\frac{1}{c_0} \left(\cancel{\mu_{yx} \frac{\partial \tilde{H}_x}{\partial t}} + \mu_{yy} \frac{\partial \tilde{H}_y}{\partial t} + \cancel{\mu_{yz} \frac{\partial \tilde{H}_z}{\partial t}} \right) \\ \frac{\partial E_y}{\partial x} - \frac{\partial E_x}{\partial y} &= -\frac{1}{c_0} \left(\cancel{\mu_{zx} \frac{\partial \tilde{H}_x}{\partial t}} + \cancel{\mu_{zy} \frac{\partial \tilde{H}_y}{\partial t}} + \mu_{zz} \frac{\partial \tilde{H}_z}{\partial t} \right) \end{aligned}$$

$$\nabla \times \vec{H} = \frac{[\epsilon_r]}{c_0} \frac{\partial \vec{E}}{\partial t} \Rightarrow \quad (15)$$

$$\begin{aligned} \frac{\partial \tilde{H}_z}{\partial y} - \frac{\partial \tilde{H}_y}{\partial z} &= \frac{1}{c_0} \left(\epsilon_{xx} \frac{\partial E_x}{\partial t} + \cancel{\epsilon_{xy} \frac{\partial E_y}{\partial t}} + \cancel{\epsilon_{xz} \frac{\partial E_z}{\partial t}} \right) \\ \frac{\partial \tilde{H}_x}{\partial z} - \frac{\partial \tilde{H}_z}{\partial x} &= \frac{1}{c_0} \left(\cancel{\epsilon_{yx} \frac{\partial E_x}{\partial t}} + \epsilon_{yy} \frac{\partial E_y}{\partial t} + \cancel{\epsilon_{yz} \frac{\partial E_z}{\partial t}} \right) \\ \frac{\partial \tilde{H}_y}{\partial x} - \frac{\partial \tilde{H}_x}{\partial y} &= \frac{1}{c_0} \left(\cancel{\epsilon_{zx} \frac{\partial E_x}{\partial t}} + \cancel{\epsilon_{zy} \frac{\partial E_y}{\partial t}} + \epsilon_{zz} \frac{\partial E_z}{\partial t} \right) \end{aligned}$$

Final Analytical Equations

These equations are our final Maxwell Equations that will be used to derive the Finite-Difference Equations for all dimensions. We have one equation for each dimension for both the magentic and electric fields. This gives a total of six equations that will need to be tracked.

Magnetic Field Equations

$$\frac{\partial \tilde{H}_z}{\partial y} - \frac{\partial \tilde{H}_y}{\partial z} = \frac{\epsilon_{xx}}{c_0} \frac{\partial E_x}{\partial t} \quad (16)$$

$$\frac{\partial \tilde{H}_x}{\partial z} - \frac{\partial \tilde{H}_z}{\partial x} = \frac{\epsilon_{yy}}{c_0} \frac{\partial E_y}{\partial t} \quad (17)$$

$$\frac{\partial \tilde{H}_y}{\partial x} - \frac{\partial \tilde{H}_x}{\partial y} = \frac{\epsilon_{zz}}{c_0} \frac{\partial E_z}{\partial t} \quad (18)$$

Electric Field Equations

$$\frac{\partial E_z}{\partial y} - \frac{\partial E_y}{\partial z} = -\frac{\mu_{xx}}{c_0} \frac{\partial \tilde{H}_x}{\partial t} \quad (19)$$

$$\frac{\partial E_x}{\partial z} - \frac{\partial E_z}{\partial x} = -\frac{\mu_{yy}}{c_0} \frac{\partial \tilde{H}_y}{\partial t} \quad (20)$$

$$\frac{\partial E_y}{\partial x} - \frac{\partial E_x}{\partial y} = -\frac{\mu_{zz}}{c_0} \frac{\partial \tilde{H}_z}{\partial t} \quad (21)$$

Finite-Difference Derived Equations

Each equation needs to be derived based on the Yee Grid Model. Remember that adjacent cells will need to be used to perform the calculation of the individual finite-difference equations for Magnetic and Electric fields in each direction x,y,z

Hx - Figure 2 Equation (22)

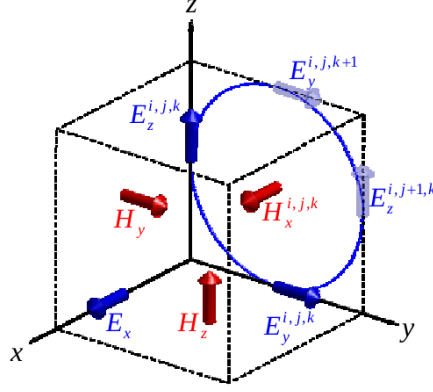


Figure 2: Yee Grid Hx

$$\frac{\partial E_z}{\partial y} - \frac{\partial E_y}{\partial z} = -\frac{\mu_{xx}}{c_0} \frac{\partial \tilde{H}_x}{\partial t} \longrightarrow$$

$$\frac{E_z^{i,j+1,k} |_t - E_z^{i,j,k} |_t}{\Delta y} - \frac{E_y^{i,j,k+1} |_t - E_y^{i,j,k} |_t}{\Delta z} = -\frac{\mu_{xx}^{i,j,k}}{c_0} \frac{\tilde{H}_x^{i,j,k} |_{t+\frac{\Delta t}{2}} - \tilde{H}_x^{i,j,k} |_{t-\frac{\Delta t}{2}}}{\Delta t} \quad (22)$$

Hy - Figure 3 Equation (23)

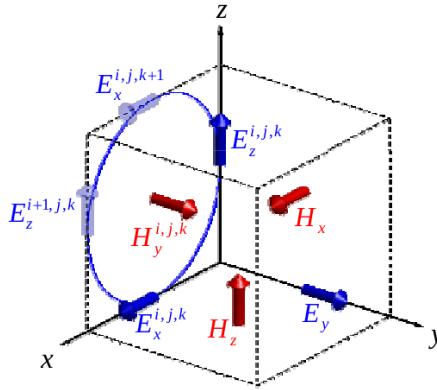


Figure 3: Yee Grid Hy

$$\frac{\partial E_x}{\partial z} - \frac{\partial E_z}{\partial x} = -\frac{\mu_{yy}}{c_0} \frac{\partial \tilde{H}_y}{\partial t} \longrightarrow \quad (23)$$

$$\frac{E_x^{i,j,k+1} |_{t+\frac{\Delta t}{2}} - E_x^{i,j,k} |_t}{\Delta z} - \frac{E_z^{i+1,j,k} |_{t+\frac{\Delta t}{2}} - E_z^{i,j,k} |_t}{\Delta x} = -\frac{\mu_{yy}^{i,j,k}}{c_0} \frac{\tilde{H}_y^{i,j,k} |_{t+\frac{\Delta t}{2}} - \tilde{H}_y^{i,j,k} |_{t-\frac{\Delta t}{2}}}{\Delta t}$$

Hz - Figure 4 Equation (24)

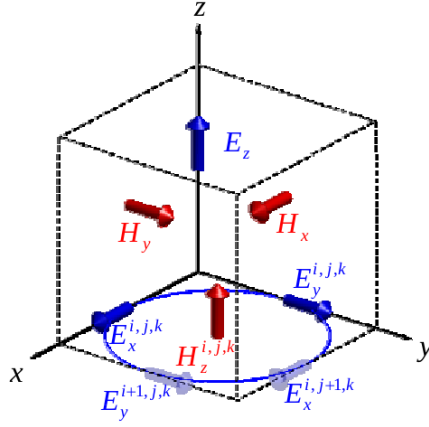


Figure 4: Yee Grid Hz

$$\frac{\partial E_y}{\partial x} - \frac{\partial E_x}{\partial y} = -\frac{\mu_{zz}}{c_0} \frac{\partial \tilde{H}_z}{\partial t} \longrightarrow \quad (24)$$

$$\frac{E_y^{i+1,j,k} |_{t+\frac{\Delta t}{2}} - E_y^{i,j,k} |_t}{\Delta x} - \frac{E_x^{i,j+1,k} |_{t+\frac{\Delta t}{2}} - E_x^{i,j,k} |_t}{\Delta y} = -\frac{\mu_{zz}^{i,j,k}}{c_0} \frac{\tilde{H}_z^{i,j,k} |_{t+\frac{\Delta t}{2}} - \tilde{H}_z^{i,j,k} |_{t-\frac{\Delta t}{2}}}{\Delta t}$$

Ex - Figure 5 Equation (25)

$$\frac{\partial \tilde{H}_z}{\partial y} - \frac{\partial \tilde{H}_y}{\partial z} = -\frac{\epsilon_{xx}}{c_0} \frac{\partial E_x}{\partial t} \longrightarrow \quad (25)$$

$$\frac{\tilde{H}_z^{i,j,k} |_{t+\frac{\Delta t}{2}} - \tilde{H}_z^{i,j-1,k} |_{t+\frac{\Delta t}{2}}}{\Delta y} - \frac{\tilde{H}_y^{i,j,k} |_{t+\frac{\Delta t}{2}} - \tilde{H}_y^{i,j,k-1} |_{t+\frac{\Delta t}{2}}}{\Delta z} = \frac{\epsilon_{xx}^{i,j,k}}{c_0} \frac{E_x^{i,j,k} |_{t+\Delta t} - E_x^{i,j,k} |_t}{\Delta t}$$

Ey - Figure 6 Equation (26)

$$\frac{\partial \tilde{H}_x}{\partial z} - \frac{\partial \tilde{H}_z}{\partial x} = -\frac{\epsilon_{yy}}{c_0} \frac{\partial E_y}{\partial t} \longrightarrow \quad (26)$$

$$\frac{\tilde{H}_x^{i,j,k} |_{t+\frac{\Delta t}{2}} - \tilde{H}_x^{i,j,k-1} |_{t+\frac{\Delta t}{2}}}{\Delta z} - \frac{\tilde{H}_z^{i,j,k} |_{t+\frac{\Delta t}{2}} - \tilde{H}_z^{i-1,j,k} |_{t+\frac{\Delta t}{2}}}{\Delta x} = \frac{\epsilon_{yy}^{i,j,k}}{c_0} \frac{E_y^{i,j,k} |_{t+\Delta t} - E_y^{i,j,k} |_t}{\Delta t}$$

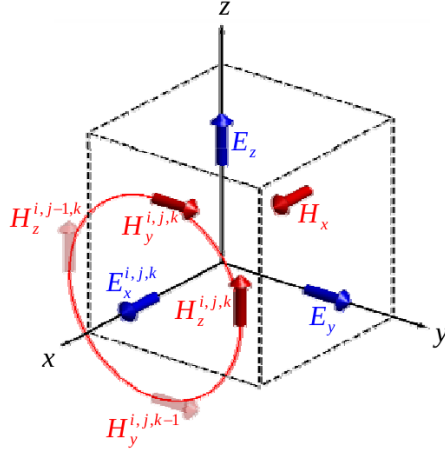


Figure 5: Yee Grid Ex

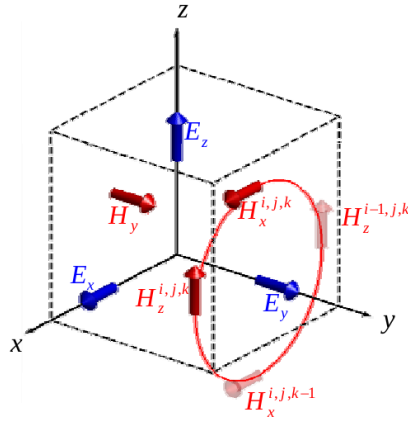


Figure 6: Yee Grid Ey

Ez - Figure 7 Equation (27)

$$\frac{\partial \tilde{H}_y}{\partial x} - \frac{\partial \tilde{H}_x}{\partial y} = -\frac{\epsilon_{zz}}{c_0} \frac{\partial E_z}{\partial t} \longrightarrow$$

$$(27)$$

$$\frac{\tilde{H}_y^{i,j,k} \big|_{t+\frac{\Delta t}{2}} - \tilde{H}_y^{i-1,j,k} \big|_{t+\frac{\Delta t}{2}}}{\Delta x} - \frac{\tilde{H}_x^{i,j,k} \big|_{t+\frac{\Delta t}{2}} - \tilde{H}_x^{i,j-1,k} \big|_{t+\frac{\Delta t}{2}}}{\Delta y} = \frac{\epsilon_{zz}^{i,j,k}}{c_0} \frac{E_z^{i,j,k} \big|_{t+\Delta t} - E_z^{i,j,k} \big|_t}{\Delta t}$$

Summary of Finite-Difference Equations

The six sets equations below are our Finite-Difference equations derived from Maxwell's Equations. These equations we will use to derive equations for 1D, 2D, and 3D update equations for our FDTD algorithms.

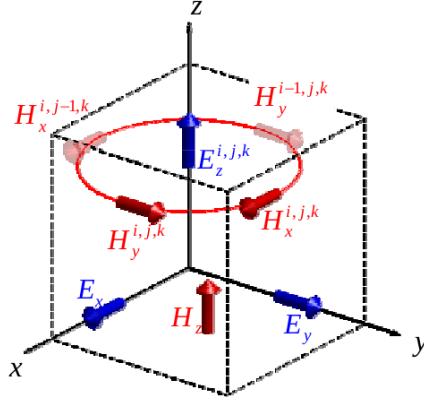


Figure 7: Yee Grid Ez

$$\frac{\partial E_z}{\partial y} - \frac{\partial E_y}{\partial z} = -\frac{\mu_{xx}}{c_0} \frac{\partial \tilde{H}_x}{\partial t}$$

$$\frac{\partial E_x}{\partial z} - \frac{\partial E_z}{\partial x} = -\frac{\mu_{yy}}{c_0} \frac{\partial \tilde{H}_y}{\partial t}$$

$$\frac{\partial E_y}{\partial x} - \frac{\partial E_x}{\partial y} = -\frac{\mu_{zz}}{c_0} \frac{\partial \tilde{H}_z}{\partial t}$$

$$\frac{\partial \tilde{H}_z}{\partial y} - \frac{\partial \tilde{H}_y}{\partial z} = -\frac{\epsilon_{xx}}{c_0} \frac{\partial E_x}{\partial t}$$

$$\frac{\partial \tilde{H}_x}{\partial z} - \frac{\partial \tilde{H}_z}{\partial x} = -\frac{\epsilon_{yy}}{c_0} \frac{\partial E_y}{\partial t}$$

$$\frac{\partial \tilde{H}_y}{\partial x} - \frac{\partial \tilde{H}_x}{\partial y} = -\frac{\epsilon_{zz}}{c_0} \frac{\partial E_z}{\partial t}$$

→

$$\frac{E_z^{i,j,k+1} \big|_t - E_z^{i,j,k} \big|_t}{\Delta y} - \frac{E_y^{i,j,k+1} \big|_t - E_y^{i,j,k} \big|_t}{\Delta z} = -\frac{\mu_{xx}^{i,j,k}}{c_0} \frac{\tilde{H}_x^{i,j,k} \big|_{t+\frac{\Delta t}{2}} - \tilde{H}_x^{i,j,k} \big|_{t-\frac{\Delta t}{2}}}{\Delta t}$$

$$\frac{E_x^{i,j,k+1} \big|_t - E_x^{i,j,k} \big|_t}{\Delta z} - \frac{E_z^{i+1,j,k} \big|_t - E_z^{i,j,k} \big|_t}{\Delta x} = -\frac{\mu_{yy}^{i,j,k}}{c_0} \frac{\tilde{H}_y^{i,j,k} \big|_{t+\frac{\Delta t}{2}} - \tilde{H}_y^{i,j,k} \big|_{t-\frac{\Delta t}{2}}}{\Delta t}$$

$$\frac{E_y^{i+1,j,k} \big|_t - E_y^{i,j,k} \big|_t}{\Delta x} - \frac{E_x^{i,j,k+1} \big|_t - E_x^{i,j,k} \big|_t}{\Delta y} = -\frac{\mu_{zz}^{i,j,k}}{c_0} \frac{\tilde{H}_z^{i,j,k} \big|_{t+\frac{\Delta t}{2}} - \tilde{H}_z^{i,j,k} \big|_{t-\frac{\Delta t}{2}}}{\Delta t}$$

$$\frac{\tilde{H}_z^{i,j,k} \big|_{t+\frac{\Delta t}{2}} - \tilde{H}_z^{i,j-1,k} \big|_{t+\frac{\Delta t}{2}}}{\Delta y} - \frac{\tilde{H}_y^{i,j,k} \big|_{t+\frac{\Delta t}{2}} - \tilde{H}_y^{i,j,k-1} \big|_{t+\frac{\Delta t}{2}}}{\Delta z} = \frac{\epsilon_{xx}^{i,j,k}}{c_0} \frac{E_x^{i,j,k} \big|_{t+\Delta t} - E_x^{i,j,k} \big|_t}{\Delta t}$$

$$\frac{\tilde{H}_x^{i,j,k} \big|_{t+\frac{\Delta t}{2}} - \tilde{H}_x^{i,j,k-1} \big|_{t+\frac{\Delta t}{2}}}{\Delta z} - \frac{\tilde{H}_z^{i,j,k} \big|_{t+\frac{\Delta t}{2}} - \tilde{H}_z^{i-1,j,k} \big|_{t+\frac{\Delta t}{2}}}{\Delta x} = \frac{\epsilon_{yy}^{i,j,k}}{c_0} \frac{E_y^{i,j,k} \big|_{t+\Delta t} - E_y^{i,j,k} \big|_t}{\Delta t}$$

$$\frac{\tilde{H}_y^{i,j,k} \big|_{t+\frac{\Delta t}{2}} - \tilde{H}_y^{i-1,j,k} \big|_{t+\frac{\Delta t}{2}}}{\Delta x} - \frac{\tilde{H}_x^{i,j,k} \big|_{t+\frac{\Delta t}{2}} - \tilde{H}_x^{i,j-1,k} \big|_{t+\frac{\Delta t}{2}}}{\Delta y} = \frac{\epsilon_{zz}^{i,j,k}}{c_0} \frac{E_z^{i,j,k} \big|_{t+\Delta t} - E_z^{i,j,k} \big|_t}{\Delta t}$$

Reduce to One-Dimension

We will reduce our Finite-Difference Equations to 1D. This means that we will have material that is uniform in two directions. This uniform material will cause the fields to be uniform as well. The change in material in our case we will define to be in the z-direction there for in the x and y direction will be uniform. This means that the derivatives in this direction will also equal zero.

$$\frac{\partial}{\partial x} = \frac{\partial}{\partial y} = 0$$

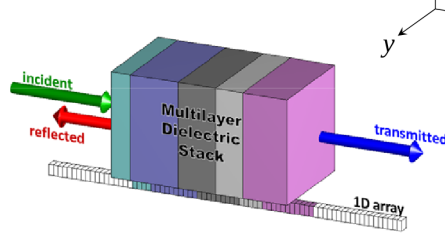


Figure 8: 1D Problem

From our Finite-Difference equations we need to cancel out the x and y derivatives that are zero.

$$\cancel{\frac{\partial E_z}{\partial y}} - \frac{\partial E_y}{\partial z} = -\frac{\mu_{xx}}{c_0} \frac{\partial \tilde{H}_x}{\partial t}$$

$$\frac{\partial E_x}{\partial z} - \cancel{\frac{\partial E_z}{\partial x}} = -\frac{\mu_{yy}}{c_0} \frac{\partial \tilde{H}_y}{\partial t}$$

$$\cancel{\frac{\partial E_y}{\partial x}} - \cancel{\frac{\partial E_x}{\partial y}} = -\frac{\mu_{zz}}{c_0} \frac{\partial \tilde{H}_z}{\partial t}$$

$$\cancel{\frac{\partial \tilde{H}_z}{\partial y}} - \frac{\partial \tilde{H}_y}{\partial z} = \frac{\epsilon_{xx}}{c_0} \frac{\partial E_x}{\partial t}$$

$$\frac{\partial \tilde{H}_x}{\partial z} - \cancel{\frac{\partial \tilde{H}_z}{\partial x}} = \frac{\epsilon_{yy}}{c_0} \frac{\partial E_y}{\partial t}$$

$$\cancel{\frac{\partial \tilde{H}_y}{\partial x}} - \cancel{\frac{\partial \tilde{H}_x}{\partial y}} = \frac{\epsilon_{zz}}{c_0} \frac{\partial E_z}{\partial t}$$

→

$$\cancel{\frac{E_z^{i,j+1,k} |_{t-\frac{\Delta t}{2}} - E_z^{i,j,k} |_t}{\Delta y}} - \frac{E_y^{i,j,k+1} |_{t-\frac{\Delta t}{2}} - E_y^{i,j,k} |_t}{\Delta z} = -\frac{\mu_{xx}^{i,j,k}}{c_0} \frac{\tilde{H}_x^{i,j,k} |_{t+\frac{\Delta t}{2}} - \tilde{H}_x^{i,j,k} |_{t-\frac{\Delta t}{2}}}{\Delta t}$$

$$\frac{E_x^{i,j,k+1} |_{t-\frac{\Delta t}{2}} - E_x^{i,j,k} |_t}{\Delta z} - \cancel{\frac{E_z^{i+1,j,k} |_{t-\frac{\Delta t}{2}} - E_z^{i,j,k} |_t}{\Delta x}} = -\frac{\mu_{yy}^{i,j,k}}{c_0} \frac{\tilde{H}_y^{i,j,k} |_{t+\frac{\Delta t}{2}} - \tilde{H}_y^{i,j,k} |_{t-\frac{\Delta t}{2}}}{\Delta t}$$

$$\cancel{\frac{E_y^{i+1,j,k} |_{t-\frac{\Delta t}{2}} - E_y^{i,j,k} |_t}{\Delta x}} - \cancel{\frac{E_x^{i,j+1,k} |_{t-\frac{\Delta t}{2}} - E_x^{i,j,k} |_t}{\Delta y}} = -\frac{\mu_{zz}^{i,j,k}}{c_0} \frac{\tilde{H}_z^{i,j,k} |_{t+\frac{\Delta t}{2}} - \tilde{H}_z^{i,j,k} |_{t-\frac{\Delta t}{2}}}{\Delta t}$$

$$\cancel{\frac{\tilde{H}_z^{i,j,k} |_{t+\frac{\Delta t}{2}} - \tilde{H}_z^{i,j-1,k} |_{t+\frac{\Delta t}{2}}}{\Delta y}} - \frac{\tilde{H}_y^{i,j,k} |_{t+\frac{\Delta t}{2}} - \tilde{H}_y^{i,j,k-1} |_{t+\frac{\Delta t}{2}}}{\Delta z} = \frac{\epsilon_{xx}^{i,j,k}}{c_0} \frac{E_x^{i,j,k} |_{t+\Delta t} - E_x^{i,j,k} |_t}{\Delta t}$$

$$\frac{\tilde{H}_x^{i,j,k} |_{t+\frac{\Delta t}{2}} - \tilde{H}_x^{i,j,k-1} |_{t+\frac{\Delta t}{2}}}{\Delta z} - \cancel{\frac{\tilde{H}_z^{i,j,k} |_{t+\frac{\Delta t}{2}} - \tilde{H}_z^{i-1,j,k} |_{t+\frac{\Delta t}{2}}}{\Delta x}} = \frac{\epsilon_{yy}^{i,j,k}}{c_0} \frac{E_y^{i,j,k} |_{t+\Delta t} - E_y^{i,j,k} |_t}{\Delta t}$$

$$\cancel{\frac{\tilde{H}_y^{i,j,k} |_{t+\frac{\Delta t}{2}} - \tilde{H}_y^{i-1,j,k} |_{t+\frac{\Delta t}{2}}}{\Delta x}} - \cancel{\frac{\tilde{H}_x^{i,j,k} |_{t+\frac{\Delta t}{2}} - \tilde{H}_x^{i,j-1,k} |_{t+\frac{\Delta t}{2}}}{\Delta y}} = \frac{\epsilon_{zz}^{i,j,k}}{c_0} \frac{E_z^{i,j,k} |_{t+\Delta t} - E_z^{i,j,k} |_t}{\Delta t}$$

With these cross outs we come out with two observations. The first is that the longitudinal field components E_z and H_z are always zero. The second is that the Maxwell's equations have decoupled into two sets of two equations E_x/H_y Mode and E_y/H_x Mode.

$$-\frac{\partial E_y}{\partial z} = -\frac{\mu_{xx}}{c_0} \frac{\partial \tilde{H}_x}{\partial t}$$

$$\frac{\partial E_x}{\partial z} = -\frac{\mu_{yy}}{c_0} \frac{\partial \tilde{H}_y}{\partial t}$$

$$0 = -\frac{\mu_{zz}}{c_0} \frac{\partial \tilde{H}_z}{\partial t}$$

$$-\frac{\partial \tilde{H}_y}{\partial z} = \frac{\epsilon_{xx}}{c_0} \frac{\partial E_x}{\partial t}$$

$$\frac{\partial \tilde{H}_x}{\partial z} = \frac{\epsilon_{yy}}{c_0} \frac{\partial E_y}{\partial t}$$

$$\begin{aligned}
0 &= \frac{\epsilon_{zz}}{c_0} \frac{\partial E_z}{\partial t} \\
&\longrightarrow \\
-\frac{E_y^{i,j,k+1} |_{t+\frac{\Delta t}{2}} - E_y^{i,j,k} |_t}{\Delta z} &= -\frac{\mu_{xx}^{i,j,k}}{c_0} \frac{\tilde{H}_x^{i,j,k} |_{t+\frac{\Delta t}{2}} - \tilde{H}_x^{i,j,k} |_{t-\frac{\Delta t}{2}}}{\Delta t} \\
\frac{E_x^{i,j,k+1} |_{t+\frac{\Delta t}{2}} - E_x^{i,j,k} |_t}{\Delta z} &= -\frac{\mu_{yy}^{i,j,k}}{c_0} \frac{\tilde{H}_y^{i,j,k} |_{t+\frac{\Delta t}{2}} - \tilde{H}_y^{i,j,k} |_{t-\frac{\Delta t}{2}}}{\Delta t} \\
\tilde{H}_z^{i,j,k} &= 0 \\
-\frac{\tilde{H}_y^{i,j,k} |_{t+\frac{\Delta t}{2}} - \tilde{H}_y^{i,j,k-1} |_{t+\frac{\Delta t}{2}}}{\Delta z} &= \frac{\epsilon_{xx}^{i,j,k}}{c_0} \frac{E_x^{i,j,k} |_{t+\Delta t} - E_x^{i,j,k} |_t}{\Delta t} \\
\frac{\tilde{H}_x^{i,j,k} |_{t+\frac{\Delta t}{2}} - \tilde{H}_x^{i,j,k-1} |_{t+\frac{\Delta t}{2}}}{\Delta z} &= \frac{\epsilon_{yy}^{i,j,k}}{c_0} \frac{E_y^{i,j,k} |_{t+\Delta t} - E_y^{i,j,k} |_t}{\Delta t} \\
E_z^{i,j,k} &= 0
\end{aligned}$$

Summary of 1D Finite-Difference Equations

The equations are now broken apart into their respective modes. These modes are physical and propagate independently from each other. In the end though they are numerically the same and will exhibit the same electromagnetic behavior. This allows us to only have to solve one set of two equations. We can also note that since we only changing materials along the z axis we can drop the i and j Array Indices.

Ex/Hy Mode

$$-\frac{\tilde{H}_y^k |_{t+\frac{\Delta t}{2}} - \tilde{H}_y^{k-1} |_{t+\frac{\Delta t}{2}}}{\Delta z} = \frac{\epsilon_{xx}^k}{c_0} \frac{E_x^k |_{t+\Delta t} - E_x^k |_t}{\Delta t} \quad (28)$$

$$\frac{E_x^{k+1} |_{t+\frac{\Delta t}{2}} - E_x^k |_t}{\Delta z} = -\frac{\mu_{yy}^k}{c_0} \frac{\tilde{H}_y^k |_{t+\frac{\Delta t}{2}} - \tilde{H}_y^k |_{t-\frac{\Delta t}{2}}}{\Delta t} \quad (29)$$

Ey/Hx Mode

$$\frac{\tilde{H}_x^k |_{t+\frac{\Delta t}{2}} - \tilde{H}_x^{k-1} |_{t+\frac{\Delta t}{2}}}{\Delta z} = \frac{\epsilon_{yy}^k}{c_0} \frac{E_y^k |_{t+\Delta t} - E_y^k |_t}{\Delta t} \quad (30)$$

$$\frac{E_y^{k+1} |_{t+\frac{\Delta t}{2}} - E_y^k |_t}{\Delta z} = \frac{\mu_{xx}^k}{c_0} \frac{\tilde{H}_x^k |_{t+\frac{\Delta t}{2}} - \tilde{H}_x^k |_{t-\frac{\Delta t}{2}}}{\Delta t} \quad (31)$$

Update Equations We are now going to derive the update equations used during in FDTD algorithm. We have arbitrarily chosen to use Ey/Hx Mode found in Equations (30) and (31)

Update Equation for Ey

$$\frac{\tilde{H}_x^k|_{t+\frac{\Delta t}{2}} - \tilde{H}_x^{k-1}|_{t+\frac{\Delta t}{2}}}{\Delta z} = \frac{\epsilon_{yy}^k}{c_0} \frac{E_y^k|_{t+\Delta t} - E_y^k|_t}{\Delta t}$$

We want to solve for the E-Field at the future time value.

$$\begin{aligned} \frac{\epsilon_{yy}^k}{c_0} \frac{E_y^k|_{t+\Delta t} - E_y^k|_t}{\Delta t} &= \frac{\tilde{H}_x^k|_{t+\frac{\Delta t}{2}} - \tilde{H}_x^{k-1}|_{t+\frac{\Delta t}{2}}}{\Delta z} \\ E_y^k|_{t+\Delta t} - E_y^k|_t &= \frac{c_0 \Delta t}{\epsilon_{yy}^k} \left(\frac{\tilde{H}_x^k|_{t+\frac{\Delta t}{2}} - \tilde{H}_x^{k-1}|_{t+\frac{\Delta t}{2}}}{\Delta z} \right) \\ E_y^k|_{t+\Delta t} &= E_y^k|_t + \left(\frac{c_0 \Delta t}{\epsilon_{yy}^k} \right) \left(\frac{\tilde{H}_x^k|_{t+\frac{\Delta t}{2}} - \tilde{H}_x^{k-1}|_{t+\frac{\Delta t}{2}}}{\Delta z} \right) \end{aligned} \quad (32)$$

Update Equation for Hx

$$\frac{E_y^{k+1}|_t - E_y^k|_t}{\Delta z} = \frac{\mu_{xx}^k}{c_0} \frac{\tilde{H}_x^k|_{t+\frac{\Delta t}{2}} - \tilde{H}_x^k|_{t-\frac{\Delta t}{2}}}{\Delta t}$$

We want to solve for the H-Field at the future time value

$$\begin{aligned} \frac{\mu_{xx}^k}{c_0} \frac{\tilde{H}_x^k|_{t+\frac{\Delta t}{2}} - \tilde{H}_x^k|_{t-\frac{\Delta t}{2}}}{\Delta t} &= \frac{E_y^{k+1}|_t - E_y^k|_t}{\Delta z} \\ \tilde{H}_x^k|_{t+\frac{\Delta t}{2}} - \tilde{H}_x^k|_{t-\frac{\Delta t}{2}} &= \frac{c_0 \Delta t}{\mu_{xx}^k} \left(\frac{E_y^{k+1}|_t - E_y^k|_t}{\Delta z} \right) \\ \tilde{H}_x^k|_{t+\frac{\Delta t}{2}} &= \tilde{H}_x^k|_{t-\frac{\Delta t}{2}} + \left(\frac{c_0 \Delta t}{\mu_{xx}^k} \right) \left(\frac{E_y^{k+1}|_t - E_y^k|_t}{\Delta z} \right) \end{aligned} \quad (33)$$

Update Coefficients

Since the update coefficients don't change during the simulation. We can compute them once before our FDTD Algorithm is actually implemented in loop.

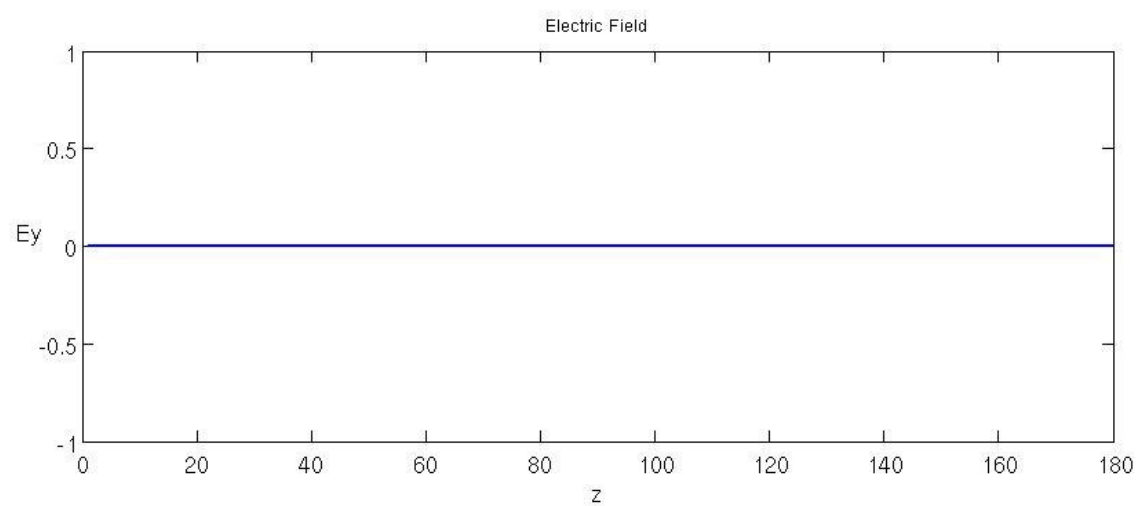
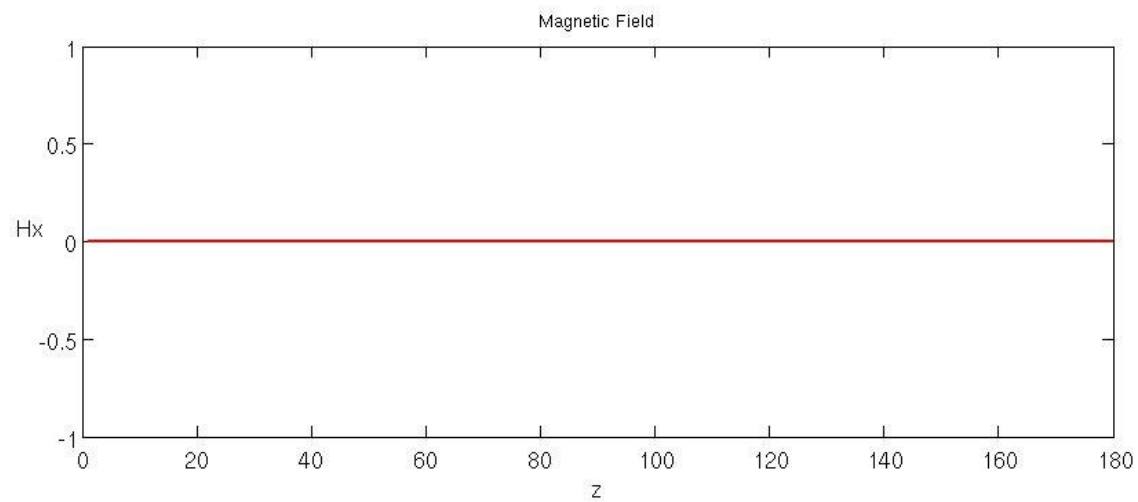
$$\tilde{H}_x^k|_{t+\frac{\Delta t}{2}} = \tilde{H}_x^k|_{t-\frac{\Delta t}{2}} + m_{H_x}^k \left(\frac{E_y^{k+1}|_t - E_y^k|_t}{\Delta z} \right) \quad (34)$$

$$E_y^k|_{t+\Delta t} = E_y^k|_t + m_{E_y}^k \left(\frac{\tilde{H}_x^k|_{t+\frac{\Delta t}{2}} - \tilde{H}_x^{k-1}|_{t+\frac{\Delta t}{2}}}{\Delta z} \right) \quad (35)$$

$$m_{E_y}^k = \frac{c_0 \Delta t}{\epsilon_{yy}^k} \quad (36)$$

$$m_{H_x}^k = \frac{c_0 \Delta t}{\mu_{xx}^k} \quad (37)$$

Problem 2



Appendix – P2 Code

%FDTD1D

%%%

% Initialization

%%%

% Initialize MATLAB

close all; clc;

clear all;

%Constants

c0 = 299792458; %m/s

e0 = 8.854187817*10⁻¹²; %F/m

u0 = 1.256637061*10⁻⁶; %H/m

%Physical Environment

dz = 1.4286*10⁻⁸; %meters

dt = 4.7652*10⁻¹⁷; %secs

%Simulated Environment

Nz = 180;

STEPS = 1000;

%Material Vectors

ER = ones([1 Nz]);

UR = ones([1 Nz]);

%%%

%FDTD Initialization

%%%

% Compute Update Coefficients

mER = (c0*dt/dz)./ER;

mHR = (c0*dt/dz)./UR;

% Initialize Feilds

Ey = zeros([1 Nz]);

Hx = zeros([1 Nz]);

%%%

% Execute Simulation

%%%

for t = 1:STEPS

```

% Calculate H
for nz = 1:Nz-1
    Hx(nz) = Hx(nz) + mHR(nz)*(Ey(nz+1)-Ey(nz));
end
Hx(Nz) = Hx(Nz) + mHR(Nz)*(0 - Ey(Nz));

% Calculate E
Ey(1) = Ey(1) + mER(1)*(Hx(1) - 0);
for nz = 2:Nz
    Ey(nz) = Ey(nz) + mER(nz)*(Hx(nz)-Hx(nz-1));
end

end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Plot Fields
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

fig = figure;
SetFigure(fig, 'HW#3-P2', [680 274 965 826]);

%Plot Magnetic Field
subplot(211)
h = plot(Hx, '-r', 'LineWidth', 2);
title('Magnetic Field');
h = get(h, 'Parent');
set(h, 'FontSize', 14);
xlabel('z');
ylabel('Hx', 'Rotation', 0);
set(gca, 'YTickLabel', {'-1', '-0.5', '0', '0.5', '1'})

%Plot Electric Field
subplot(212)
h = plot(Ey, '-b', 'LineWidth', 2);
title('Electric Field');
h = get(h, 'Parent');
set(h, 'FontSize', 14);
xlabel('z');
ylabel('Ey', 'Rotation', 0);
set(gca, 'YTickLabel', {'-1', '-0.5', '0', '0.5', '1'})

```