Advanced Computation:
Computational Electromagnetics

Implementation of Rigorous Coupled-Wave Analysis (RCWA)

1

Outline

- Step 0 – Define problem
- Step 1 – Initialize Program
- Step 2 – Build device on high resolution grid
- Step 3 – Compute convolution matrices
- Step 4 – Compute wave vector expansion
- Step 5 – Compute eigen-modes of free space
- Step 6 – Initialize global scattering matrix
- Step 7 – Main loop through layers
- Step 8 – Compute reflection side scattering matrix
- Step 9 – Compute transmission side scattering matrix
- Step 10 – Update global scattering matrix
- Step 11 – Compute source terms
- Step 12 – Compute reflected and transmitted fields
- Step 13 – Compute diffraction efficiencies
- Step 14 – Verify conservation of power

human does this

computer does the rest

Step 7: Iterate through layers

- Compute **P** and **Q**
- Compute eigen-modes
- Compute layer scattering matrix
- Update global scattering matrix

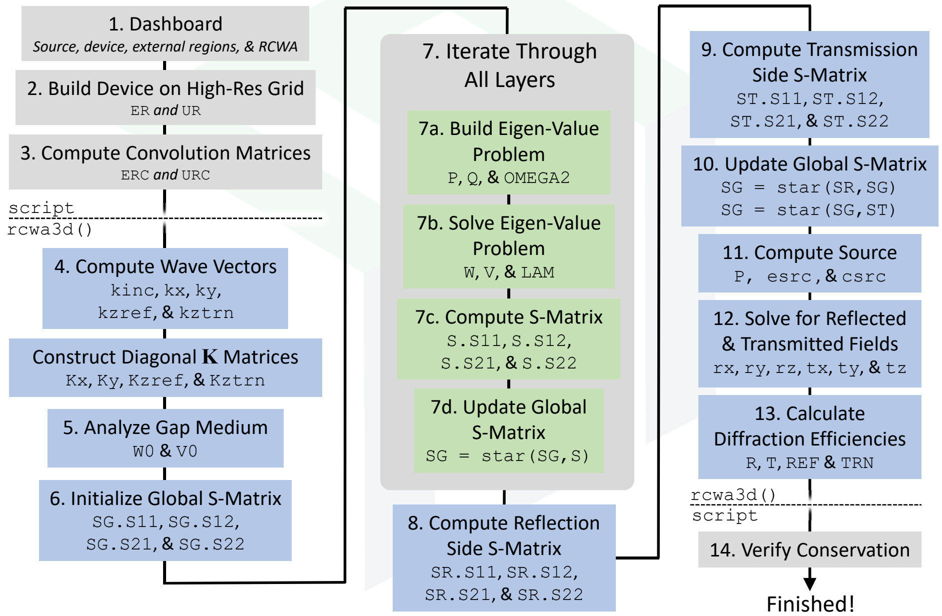
`rcwa3d()`

EMPossible

Slide 2

2

RCWA Block Diagram



EMPossible

Slide 3

3

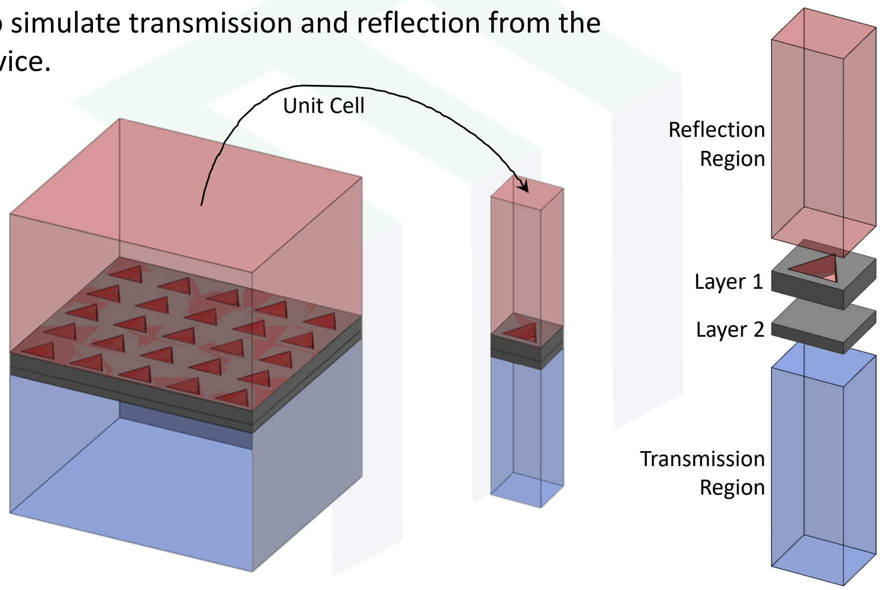
Step-by-Step Implementation of RCWA

Slide 4

4

Problem Definition

Use RCWA to simulate transmission and reflection from the following device.

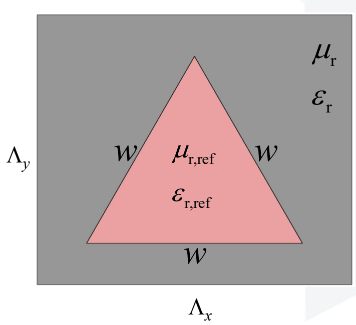


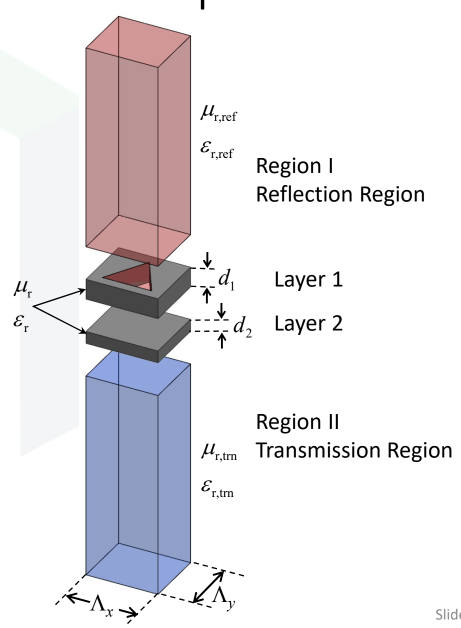
Step 0: Dimensions and Material Properties

$\mu_{\mathrm{r,ref}} = 1.0$
$\varepsilon_{\mathrm{r,ref}} = 2.0$
$\mu_{\mathrm{r}} = 1.0$
$\varepsilon_{\mathrm{r}} = 6.0$
$\mu_{\mathrm{r,trn}} = 1.0$
$\varepsilon_{\mathrm{r,trn}} = 9.0$

$\Lambda_x = 1.75$ cm
$\Lambda_y = 1.50$ cm
$d_1 = 0.50$ cm
$d_2 = 0.30$ cm
$w = 0.8\Lambda_y$

Triangle is centered in unit cell.
Normal incidence.
Field linearly polarized along y axis.
λ_0=2.0 cm.





Step 1: Initialize Program

- Initialize MATLAB
- Define units
- Define constants
  - c_0, μ_0, ε_0, η_0, etc.
- Open a figure window if desired
- Define what is to be simulated
  - Source parameters
    - λ_0, θ, ϕ, , etc. $\vec{P}$
  - Device parameters
    - Dimensions, material properties, etc.
  - RCWA specific parameters
    - Size of real-space grid, number of harmonics, etc.

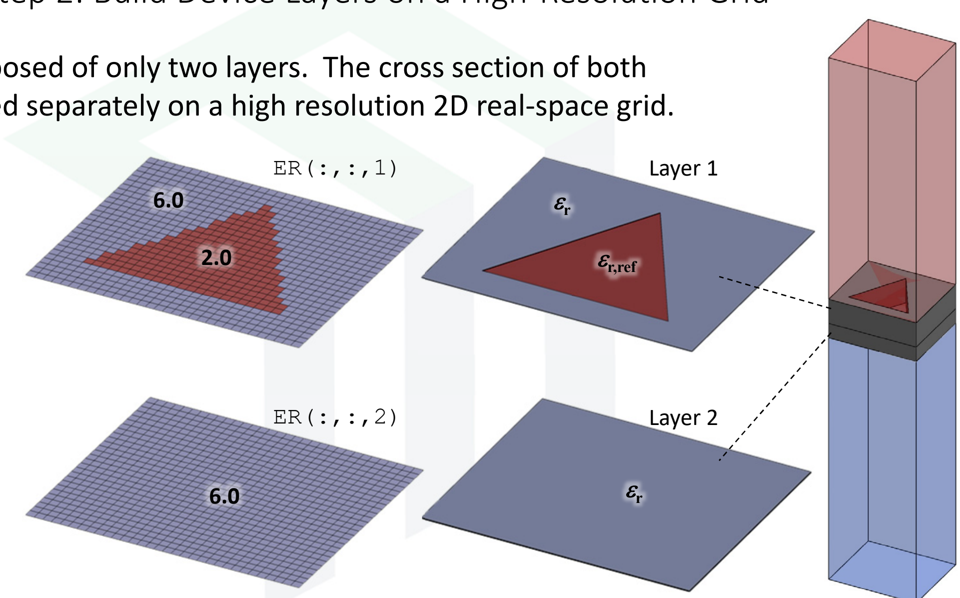
EMPossible

Slide 7

7

Step 2: Build Device Layers on a High-Resolution Grid

This device is composed of only two layers. The cross section of both must be constructed separately on a high resolution 2D real-space grid.



IMPORTANT: Use a very high-resolution grid!

EMPossible

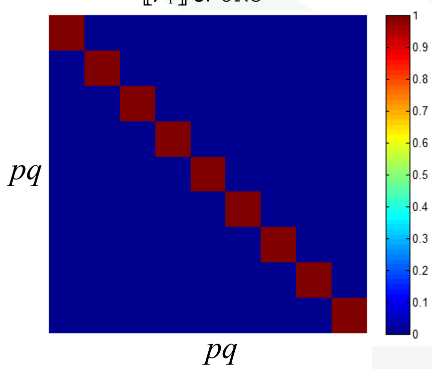
Slide 8

8

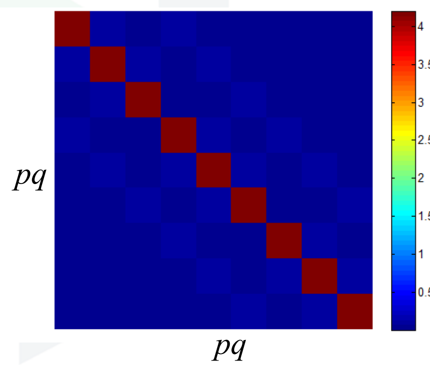
Step 3: Compute Convolution Matrices

Calculate separate convolution matrices for each layer of the device. Using 3×3 spatial harmonics, the convolution matrices for layer 1 are

$[\![\mu_r]\!]$ or `URC`



$[\![\varepsilon_r]\!]$ or `ERC`



Rule of Thumb for # Harmonics: $\# \approx 7\dfrac{\Lambda}{\lambda}$

Store the convolution matrices in arrays that are $N \times N \times$ `NLAY`, where $N = PQ$.

Step 4: Compute Wave Vector Expansion

$$\vec{\tilde{k}}_{\text{inc}} = \vec{k}_{\text{inc}}/k_0 = n_{\text{inc}}\left(\sin\theta\cos\phi\hat{a}_x + \sin\theta\sin\phi\hat{a}_y + \cos\theta\hat{a}_z\right)$$

Wave vector components for λ_0 = 2.0 cm at normal incidence.

$$\tilde{k}_x(m,n) = \tilde{k}_{x,\text{inc}} - mT_{1,x} - nT_{2,x} = \tilde{k}_{x,\text{inc}} - \frac{2\pi m}{k_0\Lambda_x} \qquad m = -M,\cdots,-2,-1,0,1,2,\cdots,M$$

$$\tilde{k}_y(m,n) = \tilde{k}_{y,\text{inc}} - mT_{1,y} - nT_{2,y} = \tilde{k}_{y,\text{inc}} - \frac{2\pi n}{k_0\Lambda_y} \qquad n = -N,\cdots,-2,-1,0,1,2,\cdots,N$$

$$\vec{T}_1 = \frac{2\pi}{\Lambda_x}\hat{a}_x \qquad \vec{T}_2 = \frac{2\pi}{\Lambda_y}\hat{a}_y$$

Note: k_x and k_y from above will be 2D arrays. Remember to use `meshgrid()` to make k_x and k_y 2D arrays before calculating the k_z terms.

Longitudinal wave vector components in reflection and transmission regions.

$$\tilde{k}_{z,\text{ref}}(m,n) = -\left\{\sqrt{\mu^*_{\text{r,ref}}\varepsilon^*_{\text{r,ref}} - \tilde{k}_x^2(m,n) - \tilde{k}_y^2(m,n)}\right\}^* \qquad \tilde{k}_{z,\text{trn}}(m,n) = \left\{\sqrt{\mu^*_{\text{r,trn}}\varepsilon^*_{\text{r,trn}} - \tilde{k}_x^2(m,n) - \tilde{k}_y^2(m,n)}\right\}^*$$

Construct diagonal matrices containing normalized wave vectors.

$\tilde{\mathbf{K}}_x, \tilde{\mathbf{K}}_y, \tilde{\mathbf{K}}_{z,\text{ref}}, \tilde{\mathbf{K}}_{z,\text{trn}}$

```
Kx = diag(sparse(kx(:)));
```

Step 5: Compute Eigen-Modes of Gap Medium

This is a homogeneous layer so the calculation reduces to

$$\tilde{\mathbf{K}}_z = \left(\sqrt{\mathbf{I} - \tilde{\mathbf{K}}_x^2 - \tilde{\mathbf{K}}_y^2}\right)^*$$

$$\mathbf{Q} = \begin{bmatrix} \tilde{\mathbf{K}}_x \tilde{\mathbf{K}}_y & \mathbf{I} - \tilde{\mathbf{K}}_x^2 \\ \tilde{\mathbf{K}}_y^2 - \mathbf{I} & -\tilde{\mathbf{K}}_x \tilde{\mathbf{K}}_y \end{bmatrix}$$

$$\mathbf{W}_0 = \begin{bmatrix} \mathbf{I} & \mathbf{0} \\ \mathbf{0} & \mathbf{I} \end{bmatrix}$$

$$\boldsymbol{\lambda} = \begin{bmatrix} j\tilde{\mathbf{K}}_z & \mathbf{0} \\ \mathbf{0} & j\tilde{\mathbf{K}}_z \end{bmatrix}$$

$$\mathbf{V}_0 = \mathbf{Q}\boldsymbol{\lambda}^{-1}$$

There is no need to construct convolution matrices or to solve an eigen-value problem!

Step 6: Initialize Device Scattering Matrix

$\mathbf{S}_{11}$ is interpreted as reflection at the first interface so it is initialized as all zeros.

$$\mathbf{S}_{11}^{(\text{device})} = \mathbf{0}$$

$\mathbf{0}$ in this case is a $2PQ \times 2PQ$ matrix of 0's, not a single scalar 0.

$\mathbf{S}_{12}$ is interpreted as transmission in the forward direction so it is initialized as a $2PQ \times 2PQ$ identity matrix.

$$\mathbf{S}_{12}^{(\text{device})} = \mathbf{I}$$

$\mathbf{S}_{21}$ is interpreted as transmission in the backward direction so it is initialized as the identity matrix.

$$\mathbf{S}_{21}^{(\text{device})} = \mathbf{I}$$

$\mathbf{S}_{22}$ is interpreted as reflection at the last interface so it is initialized as all zeros.

$$\mathbf{S}_{22}^{(\text{device})} = \mathbf{0}$$

Not the identity matrix!

$$\mathbf{S}^{(\text{device})} = \begin{bmatrix} \mathbf{0} & \mathbf{I} \\ \mathbf{I} & \mathbf{0} \end{bmatrix}$$

Think of this as a thin slice of "nothing."

Step 7: Main Loop Iterates Through Layers

a. Build eigen-value problem for the i^{th} layer

$$\mathbf{P}_i = \begin{bmatrix} \tilde{\mathbf{K}}_x \left[\!\left[\varepsilon_{r,i}\right]\!\right]^{-1} \tilde{\mathbf{K}}_y & \left[\!\left[\mu_{r,i}\right]\!\right] - \tilde{\mathbf{K}}_x \left[\!\left[\varepsilon_{r,i}\right]\!\right]^{-1} \tilde{\mathbf{K}}_x \\ \tilde{\mathbf{K}}_y \left[\!\left[\varepsilon_{r,i}\right]\!\right]^{-1} \tilde{\mathbf{K}}_y - \left[\!\left[\mu_{r,i}\right]\!\right] & -\tilde{\mathbf{K}}_y \left[\!\left[\varepsilon_{r,i}\right]\!\right]^{-1} \tilde{\mathbf{K}}_x \end{bmatrix} \qquad \mathbf{Q}_i = \begin{bmatrix} \tilde{\mathbf{K}}_x \left[\!\left[\mu_{r,i}\right]\!\right]^{-1} \tilde{\mathbf{K}}_y & \left[\!\left[\varepsilon_{r,i}\right]\!\right] - \tilde{\mathbf{K}}_x \left[\!\left[\mu_{r,i}\right]\!\right]^{-1} \tilde{\mathbf{K}}_x \\ \tilde{\mathbf{K}}_y \left[\!\left[\mu_{r,i}\right]\!\right]^{-1} \tilde{\mathbf{K}}_y - \left[\!\left[\varepsilon_{r,i}\right]\!\right] & -\tilde{\mathbf{K}}_y \left[\!\left[\mu_{r,i}\right]\!\right]^{-1} \tilde{\mathbf{K}}_x \end{bmatrix} \qquad \mathbf{\Omega}_i^2 = \mathbf{P}_i \mathbf{Q}_i$$

b. Compute eigen-modes in the i^{th} layer

$$\left[\mathbf{W}_i, \boldsymbol{\lambda}_i^2\right] = \text{eig}\left(\mathbf{\Omega}_i^2\right) \qquad \mathbf{V}_i = \mathbf{Q}\mathbf{W}_i \boldsymbol{\lambda}_i^{-1}$$

Don't calculate $\sqrt{\mathbf{\Omega}_i^2}$!!!

Be sure $\mathbf{\Omega}_i^2$ is a full matrix.

```
[W,LAM] = eig(OMEGA2);
LAM = sqrt(LAM);
```

c. Compute layer scattering matrix for the i^{th} layer

$$\mathbf{S}_{11}^{(i)} = \left(\mathbf{A}_{i0} - \mathbf{X}_i \mathbf{B}_{i0} \mathbf{A}_{i0}^{-1} \mathbf{X}_i \mathbf{B}_{i0}\right)^{-1} \left(\mathbf{X}_i \mathbf{B}_{i0} \mathbf{A}_{i0}^{-1} \mathbf{X}_i \mathbf{A}_{i0} - \mathbf{B}_{i0}\right)$$

$$\mathbf{S}_{12}^{(i)} = \left(\mathbf{A}_{i0} - \mathbf{X}_i \mathbf{B}_{i0} \mathbf{A}_{i0}^{-1} \mathbf{X}_i \mathbf{B}_{i0}\right)^{-1} \mathbf{X}_i \left(\mathbf{A}_{i0} - \mathbf{B}_{i0} \mathbf{A}_{i0}^{-1} \mathbf{B}_{i0}\right)$$

$$\mathbf{S}_{21}^{(i)} = \mathbf{S}_{12}^{(i)}$$

$$\mathbf{S}_{22}^{(i)} = \mathbf{S}_{11}^{(i)}$$

$$\mathbf{A}_{i0} = \mathbf{W}_i^{-1}\mathbf{W}_0 + \mathbf{V}_i^{-1}\mathbf{V}_0$$

$$\mathbf{B}_{i0} = \mathbf{W}_i^{-1}\mathbf{W}_0 - \mathbf{V}_i^{-1}\mathbf{V}_0$$

$$\mathbf{X}_i = e^{-\boldsymbol{\lambda}_i k_0 L_i}$$

```
X = expm(-LAM*k0*L(nlay));
```

d. Update device scattering matrix

$$\mathbf{S}^{(\text{device})} = \mathbf{S}^{(\text{device})} \otimes \mathbf{S}^{(i)}$$

EMPossible

Slide 13

13

Step 8: Compute Reflection Side Connection S-Matrix

This is a homogeneous layer so the layer parameters can be calculated as

$$\mathbf{Q}_{\text{ref}} = \frac{1}{\mu_{\text{r,ref}}} \begin{bmatrix} \tilde{\mathbf{K}}_x \tilde{\mathbf{K}}_y & \mu_{\text{r,ref}}\varepsilon_{\text{r,ref}}\mathbf{I} - \tilde{\mathbf{K}}_x^2 \\ \tilde{\mathbf{K}}_y^2 - \mu_{\text{r,ref}}\varepsilon_{\text{r,ref}}\mathbf{I} & -\tilde{\mathbf{K}}_y \tilde{\mathbf{K}}_x \end{bmatrix}$$

$$\mathbf{W}_{\text{ref}} = \begin{bmatrix} \mathbf{I} & \mathbf{0} \\ \mathbf{0} & \mathbf{I} \end{bmatrix} \qquad \boldsymbol{\lambda}_{\text{ref}} = \begin{bmatrix} -j\tilde{\mathbf{K}}_{z,\text{ref}} & \mathbf{0} \\ \mathbf{0} & -j\tilde{\mathbf{K}}_{z,\text{ref}} \end{bmatrix}$$

$$\mathbf{V}_{\text{ref}} = \mathbf{Q}_{\text{ref}} \boldsymbol{\lambda}_{\text{ref}}^{-1}$$

IMPORTANT: DO NOT USE CONVOLUTION MATRICES FOR EXTERNAL REGIONS.

Compute reflection side connection scattering matrix

$$\mathbf{S}_{11}^{(\text{ref})} = -\mathbf{A}_{i1}^{-1}\mathbf{B}_{i1}$$

$$\mathbf{S}_{12}^{(\text{ref})} = 2\mathbf{A}_{i1}^{-1}$$

$$\mathbf{S}_{21}^{(\text{ref})} = 0.5\left(\mathbf{A}_{i1} - \mathbf{B}_{i1}\mathbf{A}_{i1}^{-1}\mathbf{B}_{i1}\right)$$

$$\mathbf{S}_{22}^{(\text{ref})} = \mathbf{B}_{i1}\mathbf{A}_{i1}^{-1}$$

$$\mathbf{A}_{i1} = \mathbf{W}_0^{-1}\mathbf{W}_{\text{ref}} + \mathbf{V}_0^{-1}\mathbf{V}_{\text{ref}}$$

$$\mathbf{B}_{i1} = \mathbf{W}_0^{-1}\mathbf{W}_{\text{ref}} - \mathbf{V}_0^{-1}\mathbf{V}_{\text{ref}}$$

```
A = W0\Wref + V0\Vref;
B = W0\Wref - V0\Vref;

SR.S11 = -A\B;
SR.S12 = 2*inv(A);
SR.S21 = 0.5*(A - B/A*B);
SR.S22 = B/A;
```

EMPossible

Slide 14

14

Step 9: Compute Transmission Side Connection S-Matrix

This is a homogeneous layer so the layer parameters can be calculated as

$$\mathbf{Q}_{\text{trn}} = \frac{1}{\mu_{\text{trn}}} \begin{bmatrix} \tilde{\mathbf{K}}_x \tilde{\mathbf{K}}_y & \mu_{\text{r,trn}} \varepsilon_{\text{r,trn}} \mathbf{I} - \tilde{\mathbf{K}}_x^2 \\ \tilde{\mathbf{K}}_y^2 - \mu_{\text{r,trn}} \varepsilon_{\text{r,trn}} \mathbf{I} & -\tilde{\mathbf{K}}_y \tilde{\mathbf{K}}_x \end{bmatrix}$$

$$\mathbf{W}_{\text{trn}} = \begin{bmatrix} \mathbf{I} & \mathbf{0} \\ \mathbf{0} & \mathbf{I} \end{bmatrix} \qquad \boldsymbol{\lambda}_{\text{trn}} = \begin{bmatrix} j\tilde{\mathbf{K}}_{z,\text{trn}} & \mathbf{0} \\ \mathbf{0} & j\tilde{\mathbf{K}}_{z,\text{trn}} \end{bmatrix}$$

$$\mathbf{V}_{\text{trn}} = \mathbf{Q}_{\text{trn}} \boldsymbol{\lambda}_{\text{trn}}^{-1}$$

IMPORTANT: DO NOT USE CONVOLUTION MATRICES FOR EXTERNAL REGIONS.

Compute transmission side connection scattering matrix

$$\mathbf{S}_{11}^{(\text{trn})} = \mathbf{B}_{i2} \mathbf{A}_{i2}^{-1}$$

$$\mathbf{S}_{12}^{(\text{trn})} = 0.5\left(\mathbf{A}_{i2} - \mathbf{B}_{i2} \mathbf{A}_{i2}^{-1} \mathbf{B}_{i2}\right)$$

$$\mathbf{S}_{21}^{(\text{trn})} = 2\mathbf{A}_{i2}^{-1}$$

$$\mathbf{S}_{22}^{(\text{trn})} = -\mathbf{A}_{i2}^{-1} \mathbf{B}_{i2}$$

$$\mathbf{A}_{i2} = \mathbf{W}_0^{-1} \mathbf{W}_{\text{trn}} + \mathbf{V}_0^{-1} \mathbf{V}_{\text{trn}}$$

$$\mathbf{B}_{i2} = \mathbf{W}_0^{-1} \mathbf{W}_{\text{trn}} - \mathbf{V}_0^{-1} \mathbf{V}_{\text{trn}}$$

```
A = W0\Wtrn + V0\Vtrn;
B = W0\Wtrn - V0\Vtrn;

ST.S11 = B/A;
ST.S12 = 0.5*(A - B/A*B);
ST.S21 = 2*inv(A);
ST.S22 = -A\B;
```

EMPossible

Slide 15

15

Step 10: Compute Global Scattering Matrix

Perform a double Redheffer star product to connect the device scattering matrix to the external regions.

$$\mathbf{S}^{(\text{global})} = \mathbf{S}^{(\text{ref})} \otimes \mathbf{S}^{(\text{device})} \otimes \mathbf{S}^{(\text{trn})}$$

This is actually performed in two steps.

1. $\mathbf{S}^{(\text{global})} = \mathbf{S}^{(\text{ref})} \otimes \mathbf{S}^{(\text{device})}$
2. $\mathbf{S}^{(\text{global})} = \mathbf{S}^{(\text{global})} \otimes \mathbf{S}^{(\text{trn})}$

EMPossible

Slide 16

16

Step 11: Compute Source Parameters

Construct Delta Vector

$$\boldsymbol{\delta}_{0,pq} = \begin{bmatrix} 0 & \cdots & 0 & 1 & 0 & \cdots & 0 \end{bmatrix}^T$$

'1' at the position that corresponds to the zero-order spatial harmonic to incorporate a unit amplitude source.

Compute Directions of TE and TM Polarization

$$\hat{n} = \hat{a}_z \qquad \hat{a}_{\text{TE}} = \frac{\hat{n} \times \vec{k}_{\text{inc}}}{\left|\hat{n} \times \vec{k}_{\text{inc}}\right|} \qquad \hat{a}_{\text{TM}} = \frac{\vec{k}_{\text{inc}} \times \hat{a}_{\text{TE}}}{\left|\vec{k}_{\text{inc}} \times \hat{a}_{\text{TE}}\right|}$$

For normal incidence, $\hat{a}_{\text{TE}}$ can be chosen to be in any direction in the xy plane. An often convenient choice is $\hat{a}_{\text{TE}} = \hat{a}_y$.

Compute Polarization Vector

$$\vec{P} = \begin{bmatrix} p_x \\ p_y \\ p_z \end{bmatrix} = p_{\text{TE}}\hat{a}_{\text{TE}} + p_{\text{TM}}\hat{a}_{\text{TM}}$$

Note: Best to ensure that $\left|\vec{P}\right| = 1$

Compute Source Field

$$\mathbf{e}_{\text{T}}^{\text{src}} = \begin{bmatrix} p_x \boldsymbol{\delta}_{0,pq} \\ p_y \boldsymbol{\delta}_{0,pq} \end{bmatrix}$$

$p_x \equiv x$ component of electric field polarization vector

$p_y \equiv y$ component of electric field polarization vector

EMPossible

Slide 17

17

Step 12: Compute Reflected and Transmitted Fields

Compute mode coefficients of the source

$$\mathbf{c}_{\text{src}} = \mathbf{W}_{\text{ref}}^{-1}\mathbf{e}_{\text{T}}^{\text{src}}$$

Compute transmission and reflection mode coefficients

$$\mathbf{c}_{\text{ref}} = \mathbf{S}_{11}^{(\text{global})}\mathbf{c}_{\text{src}} \qquad \mathbf{c}_{\text{trn}} = \mathbf{S}_{21}^{(\text{global})}\mathbf{c}_{\text{src}}$$

Compute reflected and transmitted fields

$$\begin{bmatrix} \mathbf{r}_x \\ \mathbf{r}_y \end{bmatrix} = \mathbf{e}_{\text{T}}^{\text{ref}} = \mathbf{W}_{\text{ref}}\mathbf{c}_{\text{ref}} = \mathbf{W}_{\text{ref}}\mathbf{S}_{11}\mathbf{c}_{\text{src}} \qquad \begin{bmatrix} \mathbf{t}_x \\ \mathbf{t}_y \end{bmatrix} = \mathbf{e}_{\text{T}}^{\text{trn}} = \mathbf{W}_{\text{trn}}\mathbf{c}_{\text{trn}} = \mathbf{W}_{\text{trn}}\mathbf{S}_{21}\mathbf{c}_{\text{src}}$$

Compute longitudinal components

$$\mathbf{r}_z = -\tilde{\mathbf{K}}_{z,\text{ref}}^{-1}\left(\tilde{\mathbf{K}}_x\mathbf{r}_x + \tilde{\mathbf{K}}_y\mathbf{r}_y\right) \qquad \mathbf{t}_z = -\tilde{\mathbf{K}}_{z,\text{trn}}^{-1}\left(\tilde{\mathbf{K}}_x\mathbf{t}_x + \tilde{\mathbf{K}}_y\mathbf{t}_y\right)$$

EMPossible

Slide 18

18

Step 13: Compute Diffraction Efficiencies

Compute Reflected Power

$$|\vec{\mathbf{r}}|^2 = |\mathbf{r}_x|^2 + |\mathbf{r}_y|^2 + |\mathbf{r}_z|^2$$

$$\mathbf{R} = \frac{\mathrm{Re}\left[-\tilde{\mathbf{K}}_{z,\mathrm{ref}} / \mu_{\mathrm{r,inc}}\right]}{\mathrm{Re}\left[k_z^{\mathrm{inc}} / \mu_{\mathrm{r,inc}}\right]} |\vec{\mathbf{r}}|^2$$

$$R_{\mathrm{total}} = \sum_{PQ} R(p,q)$$

Diffraction efficiencies of reflected modes.
This equation assumes unit amplitude source.

```
R2 = abs(rx).^2 + abs(ry).^2 + abs(rz).^2;
R  = real(-Kzr/ur1)/real(kinc(3)/ur1)*R2;
R  = reshape(R,M,N);

REF = sum(R(:));
```

Compute Transmitted Power

$$|\vec{\mathbf{t}}|^2 = |\mathbf{t}_x|^2 + |\mathbf{t}_y|^2 + |\mathbf{t}_z|^2$$

$$\mathbf{T} = \frac{\mathrm{Re}\left[\tilde{\mathbf{K}}_{z,\mathrm{trn}} / \mu_{\mathrm{r,trn}}\right]}{\mathrm{Re}\left[k_z^{\mathrm{inc}} / \mu_{\mathrm{r,inc}}\right]} |\vec{\mathbf{t}}|^2$$

$$T_{\mathrm{total}} = \sum_{PQ} T(p,q)$$

Diffraction efficiencies of transmitted modes.
This equation assumes a unit amplitude source.

```
T2 = abs(tx).^2 + abs(ty).^2 + abs(tz).^2;
T  = real(Kzt/ur2)/real(kinc(3)/ur1)*T2;
T  = reshape(T,M,N);

TRN = sum(T(:));
```

EMPossible

Slide 19

19

Step 14: Verify Conservation of Power

It is always good practice to check for conservation of power.

$$R_{\mathrm{total}} + T_{\mathrm{total}} \rightarrow \begin{cases} <1 & \text{loss} \\ =1 & \text{no loss and no gain} \\ >1 & \text{gain} \end{cases}$$

General Conservation Equation

$$R_{\mathrm{total}} + T_{\mathrm{total}} + A_{\mathrm{total}} = 1$$

Even if loss or gain is to be incorporated, turn off the loss or gain at first, test for conservation of power, and then turn it back on.

EMPossible

Slide 20

20