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Transfer Matrix Approach to Propagation of Angular Plane Wave Spectra through Metamaterial Multilayer Structures

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Abstract

The development of electromagnetic (EM) metamaterials for perfect lensing and optical cloaking has given rise to novel multilayer bandgap structures using stacks of positive and negative index materials. Gaussian beam propagation through such structures have been analyzed using transfer matrix method (TMM) with paraxial approximation, and unidirectional and bidirectional beam propagation methods (BPMs). We use TMM to analyze non-paraxial propagation of TE and TM angular plane wave spectra in 1 transverse dimension through a stack containing layers of positive and negative index materials (PIMs, NIMs).

Objective

The objective is to systematically investigate propagation of plane waves and arbitrary (e.g., Gaussian) profiles through a multilayer structure. The understanding of transfer matrices for any structure is important in the design of anti-reflection films and optical filters. The TMM, developed for plane wave incidence, naturally incorporates interface reflections, as well as the polarization state of the electric field. This approach can be used to calculate the reflected and transmitted waves for a single layer structure and can be readily extended to multilayer structures.

Methodology

✓ Use the transfer matrix method (TMM) to analyze the non-paraxial propagation of a collection of TE and/or TM polarized plane waves having an initial Gaussian amplitude profile in 1 transverse dimension (x) through a stack containing layers of positive and negative index materials.

✓Use the angular plane wave spectrum to find the spatial variation of the electric field at any plane (z) during bidirectional propagation through the stack.

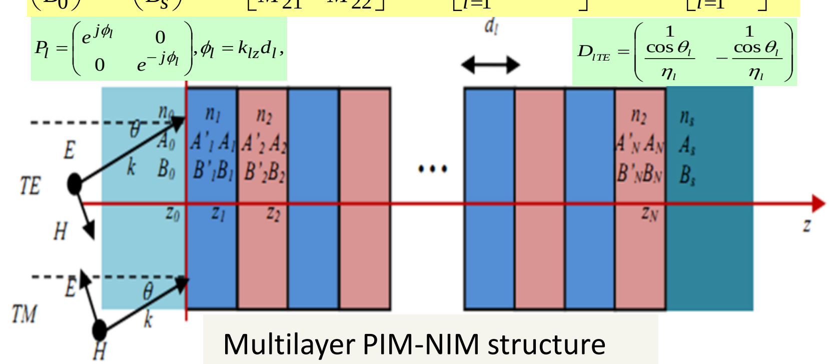
✓Calculate, specifically for the TM case, the spatial variations of both the x and z polarization components.

✓Compare the numerical results from TMM with numerical simulations using FEM and FDTD techniques.

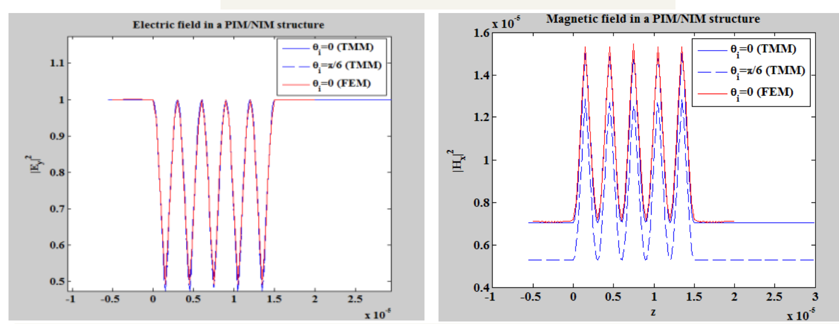
$$\begin{pmatrix}A_0\\B_0\end{pmatrix}=M\begin{pmatrix}A_s\\B_s\end{pmatrix},\ M=\begin{bmatrix}M_{11}&M_{12}\\M_{21}&M_{22}\end{bmatrix}=D_0^{-1}\left[\prod_{l=1}^{N}D_lP_lD_l^{-1}\right]D_s=D_0^{-1}\left[\prod_{l=1}^{N}M_l\right]D_s$$

$$P_l=\begin{pmatrix}e^{j\phi_l}&0\\0&e^{-j\phi_l}\end{pmatrix},\ \phi_l=k_{lz}d_l,$$

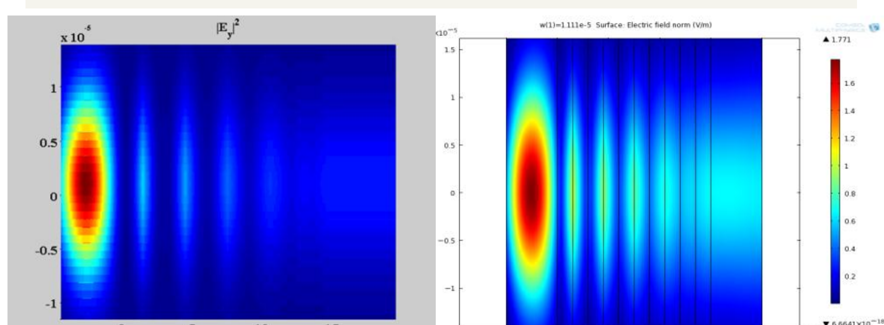
$$D_{lTE}=\begin{pmatrix}1&1\\\frac{\cos\theta_l}{\eta_l}&-\frac{\cos\theta_l}{\eta_l}\end{pmatrix}$$



Multilayer PIM-NIM structure



Typical TE case showing E and H fields in PIM-NIM stack



Typical TMM (l) and FEM (r) simulations of Gaussian beam propagation thru PIM-NIM stack

Advantages of TMM

- ✓ TMM calculations are exact .
- ✓ Less computationally demanding.
- ✓ Not limited by the thickness of the structures
- ✓ Can be performed for arbitrary angular plane wave spectra.
- ✓ Can be used for propagating and non-propagating waves.
- ✓ Can readily give ***E*,*H*** field details at every point during propagation.
- ✓ Can be readily applied to a wide variety of other cases, e.g., beam propagation through induced reflection gratings in nonlinear media.

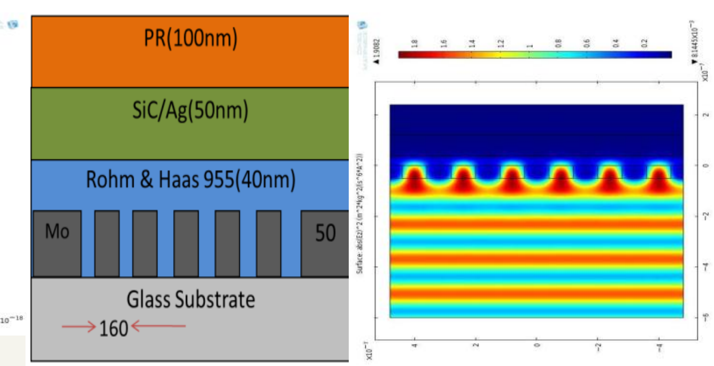
Future work

✓Extend to nonlinear cases.

✓Extend to 2 transverse dimensions .

✓Apply to anti-reflection coating design.

Other related work



Near-field imaging w/ SiC+Ag nanomixture NIM