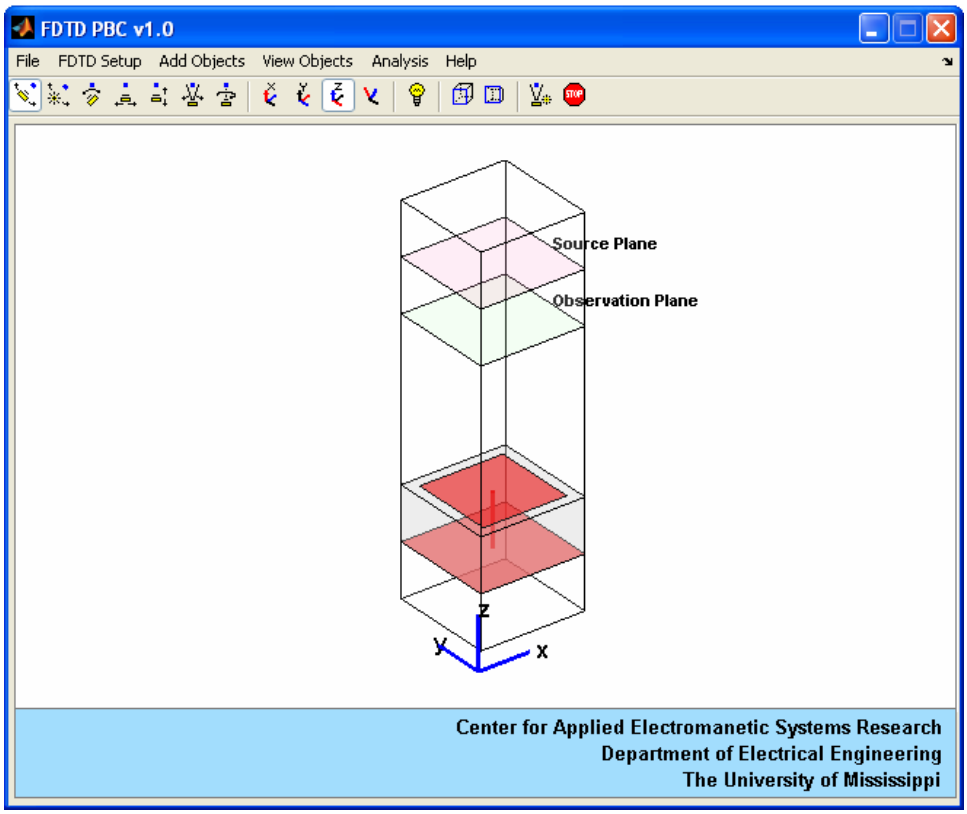
User Manual

Periodic Structure Analysis Using

Spectral Finite Difference Time Domain Code V.1.0



Yanghyo Kim and Fan Yang

The University of Mississippi

September 2008

Table of Contents

1. Introduction

- **Goal of FDTD/PBC code**

The FDTD/PBC algorithm is developed to analyze plane wave scattering from general periodic structures. Both the magnitude and phase of the reflection coefficient are calculated and recorded.

- **FDTD computational domain**

In order to use FDTD method, a 3-D computational domain is created first. The material of each cell within the computational domain needs to be specified accordingly. In general, the material can be free-space (by default), or metal plates/wires (perfect electrical conductor), or dielectrics whose permittivity and permeability are defined by users.

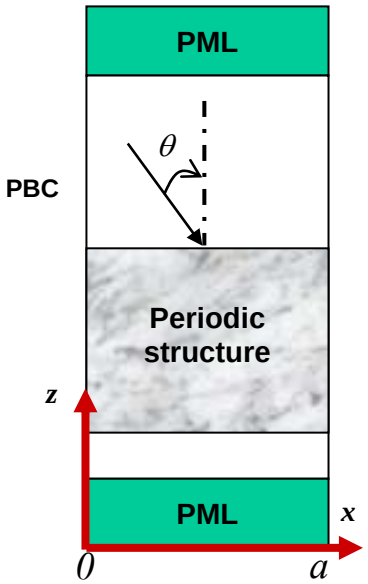


Fig. 1. FDTD computational domain.

As shown Fig. 1, the object structure is periodic along the *x*- and *y*-directions. Thus, the computational domain is truncated using the periodic boundary conditions (PBC) on four sides.

Assume plane waves propagate in the xz plane with an incident angle θ. The perfectly matched layers (PML) are placed on the top and bottom of the structure to absorb the propagating plane waves.

- **FDTD/PBC Code Author:** Dr. Fan Yang, The University of Mississippi
- **Graphic User Interface Designer:** Yanghyo Kim, The University of Mississippi

2. Overview of FDTD/PBC Code

2.1 FDTD/PBC Code Flowchart

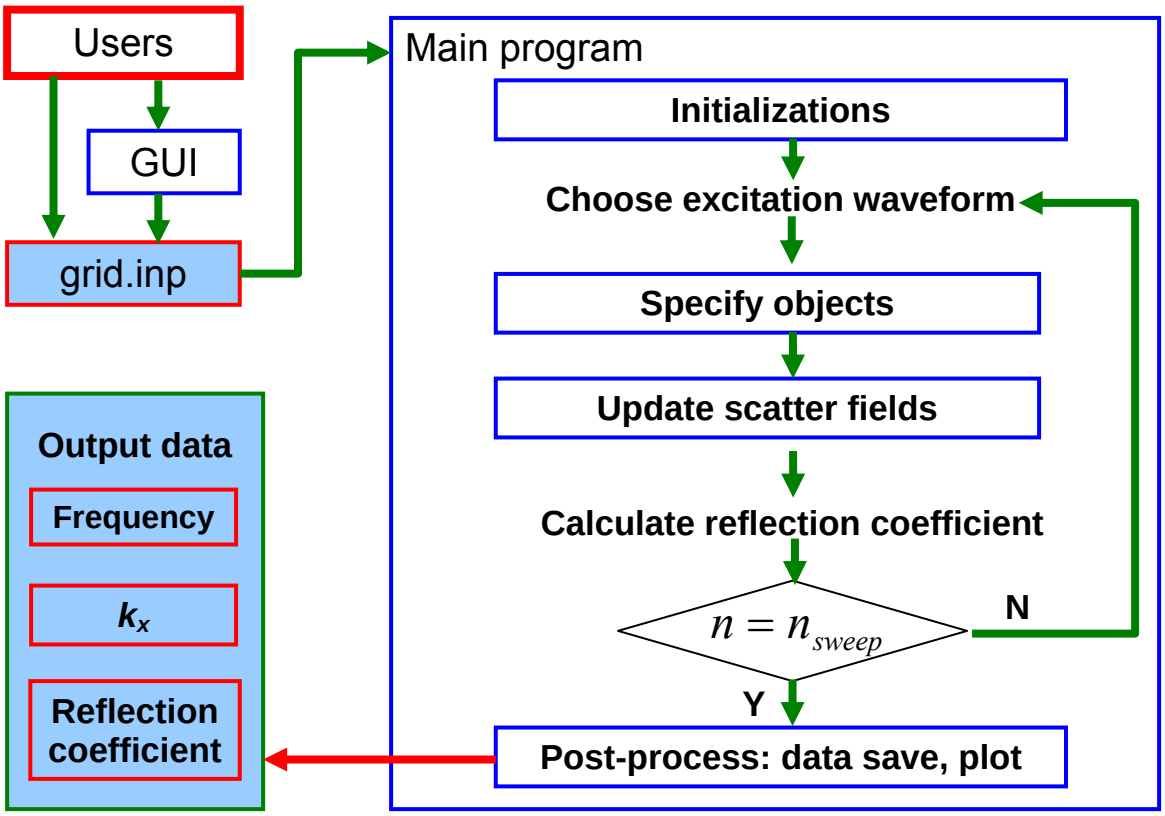


Fig. 2. Flowchart of the FDTD/PBC code.

Figure 2 shows the flowchart of the FDTD/PBC algorithm. Once users decide simulation structure and its parameters, an input file "grid.inp" can be created from either a Graphic User Interface (GUI) or a text editor. The FDTD/PBC program reads data from the input file and starts to calculate the electromagnetic fields and scattering parameters. The simulation stops when it reaches the maximum number of k_x lines ('n_{sweep}'), and then the program generates output files and related figures.

2.2 FDTD/PBC Program and Subroutines

- **Input file: grid.inp**
  - Object geometries, materials, and FDTD parameters.
  - Manually input or GUI input.

- **Graphic user interface (GUI): start.m**
  - Task: Generate grid.inp through a graphic interface.
  - Next: Call main program.

- **Main program: main.m**
  - Task: Control the program flow, determine wave excitation, and calculate reflection coefficient.
  - Call subroutines below.

- **Initialization subroutine: FDTD_init.m**
  - Task: Read FDTD parameters.
    1. Define fundamental constants, FFT number
    2. Read reference frequency, reference cell size
    3. Determine time step, sample rate, frequency
    4. Read total computational size
    5. Read plane wave info: Location, polarization, frequency range
    6. Read simulation control: Single k_x or scan k_x
    7. Read the number of time step
    8. Read location of receiving time step
    9. Define PML region coefficients
  - Use grid.inp, called by main.m.

- **Scatter subroutine: scatter_PBC.m**
  - Task: Calculate the EM fields and control time step loop.
  - Called by main.m
  - Use following subroutines:
    - E field calculation: fdtd_maine.m, fdtd_pmle.m, fdtd_plwe.m
    - H field calculation: fdtd_mainh.m, fdtd_pmlh.m, fdtd_plwh.m
    - Parameter extraction: fdtd_param.m

- **Post-process subroutine: fdtd_post.m**

- Task: Save data to output files and plot figures
- Called by main.m

- **Output file:**
  - Generated by fdtd_post.m
  - Frequency and kx data: freq_fig.dat, kx_fig.dat
  - Reflection coefficient (magnitude and phase)

    Co-polarization: Rm_kfc.dat, Rp_kfc.dat

    Cross polarization: Rm_kfx.dat, Rp_kfx.dat

    Total: Rm_kf.dat, Rp_kf.dat

❖ Remark: Depending on simulation geometry, a reflected field polarization can be different from the source polarization. Therefore, a cross polarization effect has to be considered. This will be further explained in Chapter 10.

3. Start of FDTD/PBC Code

3.1 Software Installation

In order to use the FDTD/PBC program, users need to copy all necessary files to a working folder. By opening MATLAB (Version 7.0 or higher) and selecting the proper directory, users are ready to start the FDTD/PBC program.

3.2 Graphic User Interface (GUI)

There are two ways to run a simulation. The first way is to use the GUI. Users can type "start" on the MATLAB command window.

> start

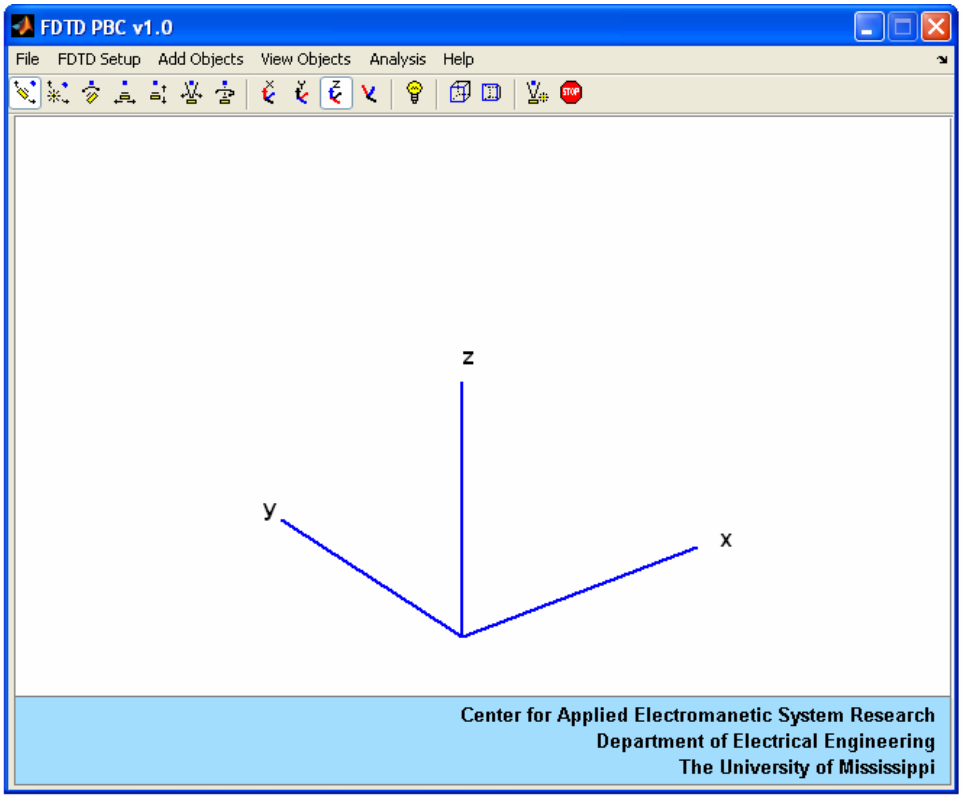


Fig. 3. Graphic User Interface (GUI) of the FDTD/PBC code.

The FDTD/PBC GUI will pop up. Users can easily set up the input parameters with an aid of visual structure. Some examples will be shown in the following chapters to illustrate input parameters. When users click on "Analysis" on the menu, the program

will save current input parameters into ‘grid.inp’ file and begin simulating. When the simulation is over, output files will be generated and stored in the same folder.

3.3 Grid.inp

The second way is to generate the “grid.inp” manually with any text editors. Users can find example files in following chapters. Once it is generated, users should save it and then type “main” on the MATLAB command window to start the FDTD simulation.

```
> main
```

The descriptions of “grid.inp” will be discussed in the following chapters with detailed examples.

4. Input File Descriptions (grid.inp)

4.1 Reference Frequency

The first step in setting up an input file is to determine an FDTD computational domain. The free space wavelength at a reference frequency is used as reference length to describe simulation structure. Most physical dimensions such as cell size, computational domain size, location of plane wave source and sampling field, and dielectric slab structure are represented in term of wavelength.

$$\lambda_0 = C / f_{ref} \tag{1}$$

C is the free space wave speed and f_{ref} is the reference frequency. For example, if the reference frequency is 9.6 GHz, the wavelength λ_0 is 31.25 (mm).

4.2 Cell Size

The second step is to choose a reference cell size (dx, dy, and dz). Usually, the cell size is around 0.01λ to achieve an accurate result. When a high frequency wave propagates through a high permittivity material, the cell size needs to be reduced. An example will be shown in Chapter 6.

4.3 Total Simulation Dimensions

If the reference cell size is specified, users can determine total simulation dimensions along the *x, y, z* directions to include the scattering object. For example, the cell size is 0.01λ (m). If the total dimension along x, y, z directions are 0.01, 0.01, and 0.7 respectively, the total dimension to be simulated is $0.1\lambda \times 0.1\lambda \times 0.7\lambda$ = 3.125 (mm) × 3.125 (mm) × 21.875 (mm) size.

4.4 Location of Plane Wave Source

Once the total dimension is decided, the location of the plane wave source needs to be defined. For instance, if the total z-dimension is 0.7λ, the source excitation can start at z = 0.6λ and the wave will propagate along –z direction. If there is a reflected wave field which goes over the source location, it will be absorbed by the PML on the top.

4.5 Plane Wave Parameters (Polarization & Frequency)

Users can choose either '0' or '90' for the plane wave polarization. '0' is the transverse electric field (TE^z) mode. If a wave incidents on the *xz* plane, it contains (Ey, Hx, Hz) components. '90' is the transverse magnetic field (TM^z) mode. If a wave incidents on the *xz* plane, it has (Hy, Ex, Ez) components.

The frequency range of interest is determined by k_x value, as shown below:

$$\begin{aligned} f_{low} &= k_0 \cdot C / 2\pi = k_x \cdot C / 2\pi \\ f_{up} &= f_{low} + BW \end{aligned} \tag{2}$$

In grid.inp, the upper frequency equals to the summation of the lower frequency and the frequency bandwidth (BW). Depending on the problems, users need to specify the bandwidth in the input file. A modulated Gaussian waveform is used as the excitation signal [3].

4.6 Number of kx and Frequency

K_x is the *x* component of a wave number *k*. If a wave incidents on the *xz* plane,

$$k_x = k_0 \cdot \sin\theta = 2\pi \cdot f / C \cdot \sin\theta \tag{3}$$

In general, k_x is the function of two variables: one is the incident angle, and the other is the frequency. In the FDTD/PBC code, k_x is set as a fixed value [1-3]. For example, if k_x is zero, the output is the reflection coefficient vs. frequency of interest at the normal incidence (θ = 0). In the input file, users can specify the number of different k_x values and the maximum k_x value. If more than one k_x is selected, the output is the frequency spectral of the reflection coefficient. The output file and k_x will be further explained in the Chapter 5 with examples.

4.7 Time Step

For the computational stability, the reference time step is internally defined as below:

$$dt = dx/(2 \cdot C) \tag{4}$$

The number of total FDTD time steps is problem-dependent. Normally, less time steps are required for low permittivity materials (such as ε_r = 2.56), whereas a large number of

time steps are required for high permittivity materials (ε_r = 16, 25, 49, etc). This will be shown in Chapter 6 with examples.

4.8 Location of Sampling Field

The location of the sampling field for parameter extraction can be set up next. Normally, it is placed in between object structure and plane wave source location along the z direction. For example, if the source location is at z = 0.6 λ, the reflected fields can be sampled at z = 0.5 λ.

4.9 Objects of Interest

The next step is to specify the geometry of the structure. In the current FDTD/PBC code, three types of objects are supported in the input file. The first one is a dielectric slab. The coordinates of two corner points of the box need to be specified as well as its dielectric constant.

The second type of geometries is a PEC plate. The plate can be placed in parallel to the *xy*, or *xz*, or *yz* plane. The (*x, y, z*) coordinates of two corner points need to be specified in the input file.

The third type of geometries is a PEC wire, which is assumed to be infinitely thin. The wire should be oriented along *x*, *y*, or *z* direction. The (*x, y, z*) coordinates of two end points need to be specified in the input file.

4.10 End of Input File

The input file ends with the following line:

%Done

5. Output and k_x

There are two different types of output formats: the number of k_x is 1, and the number of k_x is more than 1. In this section, the manners of choosing the number of k_x will be discussed with examples.

5.1 Number of k_x > 1

If the number of k_x is more than 1, the reflection coefficient in the frequency-k_x plane will be plotted at the end of a simulation. The number of different k_x values and maximum k_x value are specified in the input file. Note that the maximum k_x value is provided in terms of an associated frequency, as shown below

$$k_x^{\max} = 2\pi \cdot f^{\max} / C \tag{5}$$

For example, Fig. 4 shows the reflection coefficient of a dielectric slab illuminated by a TE incident wave. f^{max} is set to 20 GHz and the maximum k_x is 418.88 rad/m according to (5). 101 different k_x values are sampled from 0 to the maximum k_x value. The data of the horizontal axis (k_x axis), vertical axis (frequency axis), and reflection coefficients are saved into different output files for future usages.

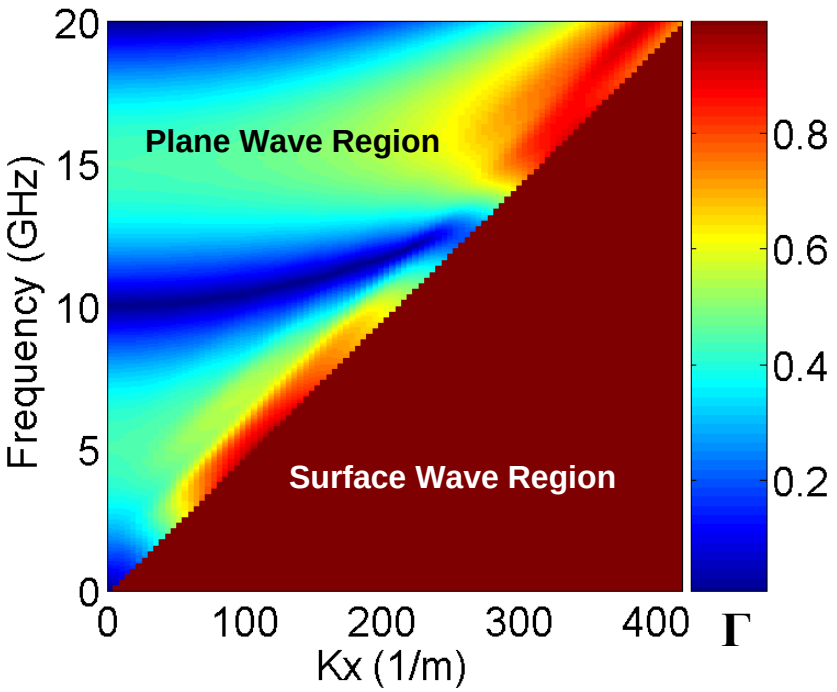


Fig. 4. Reflection coefficient in the frequency-k_x plane.

5.2 Number of k_x = 1

If the number of k_x is 1, two plots will show up after simulation. One is sample field data in the time domain, which can be used to check the convergence of the FDTD simulation. The other plot is the magnitude of reflection coefficient versus frequency. It is identical to the reflection coefficient on a vertical line with the corresponding k_x value in the previous 2-D color figure.

In the previous example, if the number of *kx* is 1 and the f^{max} is 4.8 GHz, the FDTD code will calculate the reflection coefficient for k_x = 100.6 rad/m according to (5). Figure 5 shows the reflection coefficient and the time domain waveform.

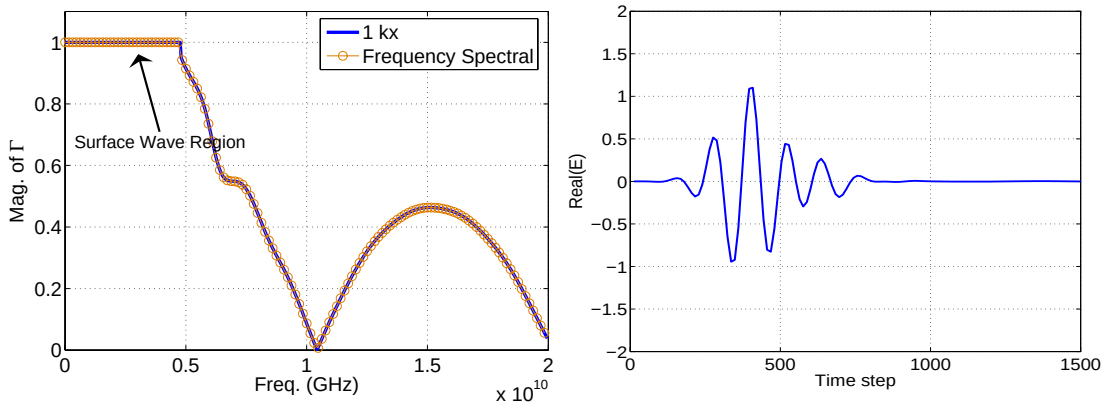


Fig. 5. Reflection coefficient and source incidence.

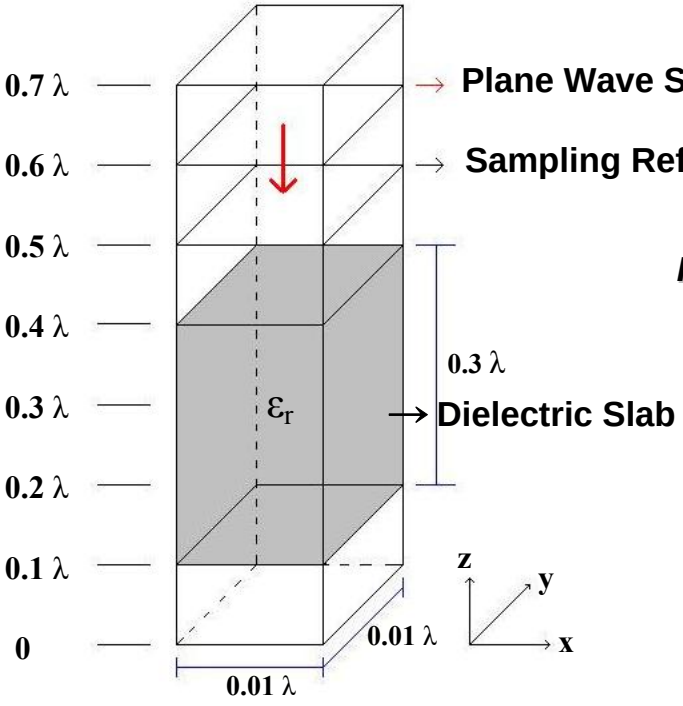
Setting the number of different k_x values to 1 makes a simulation more efficient if users are interested in a specific k_x value. For example, if only a normal incidence case is in interest, one can set the number of k_x to 1 and its value to 0.

From the time domain waveform, it is clear that the field damps to zero at 1500 time steps. This figure helps users determine the number of time steps needed for an accurate simulation.

6. Example I: Dielectric Slab

In this chapter, plane wave incidence on a dielectric slab is discussed. The simulation structure, an input file (grid.inp), and ways to set up the input parameters will be shown below.

6.1 Simulation Model



Remarks:

- **Reference Frequency: 9.6 GHz**
- **Wave Length: λ = c/f = 0.03125(m)**
- **Reference Cell size dx, dy, dz = 0.01 λ**
- **Dielectric constant: 2.56**
- **Thickness 0.01λ × 30 = 9.375(mm)**

Fig. 6. Simulation model.

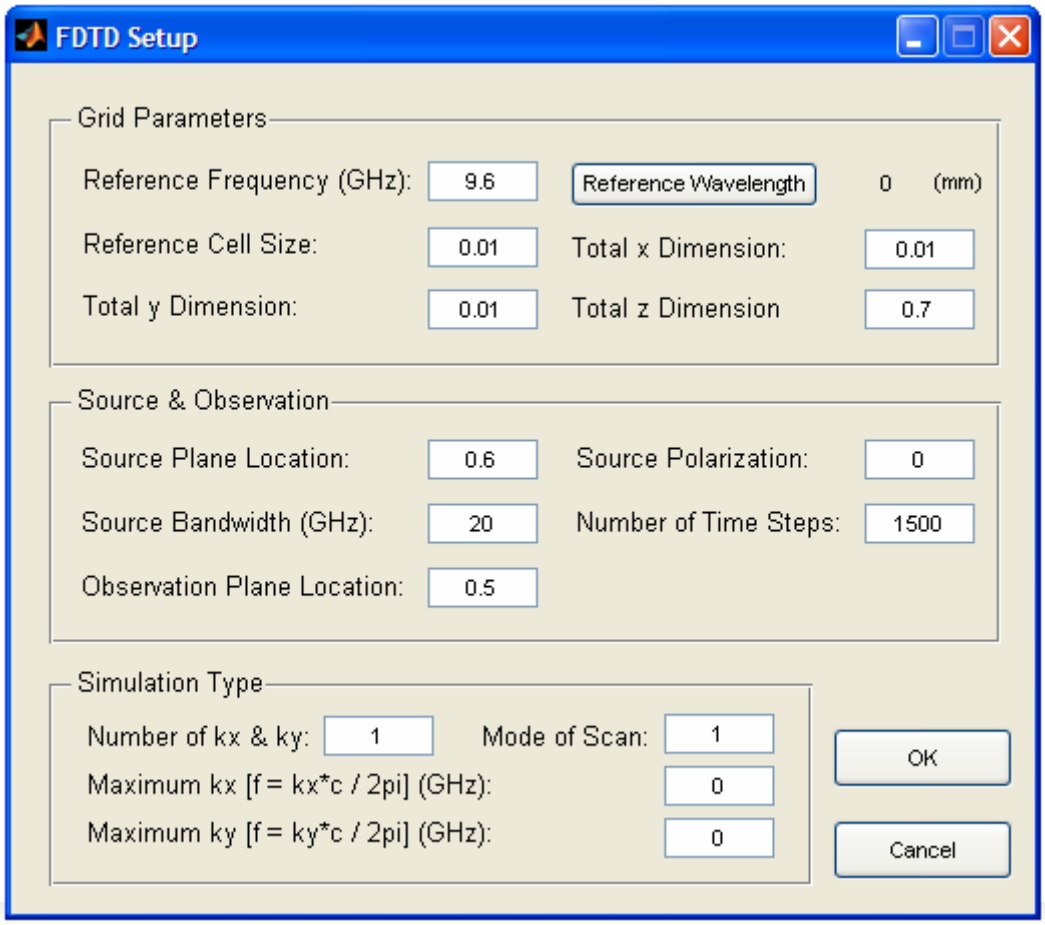
A dielectric slab can be regarded as a periodic structure with arbitrary periodicity. For computational efficiency, only one cell is selected along the *x*- and *y*-directions.

Simulation results based on the different number of time steps, permittivity of dielectric slab, reference cell size, and thickness of dielectric slab are discussed. Users can add any number of dielectric materials in the domain by simply setting up the structures on the GUI or “grid.inp” file.

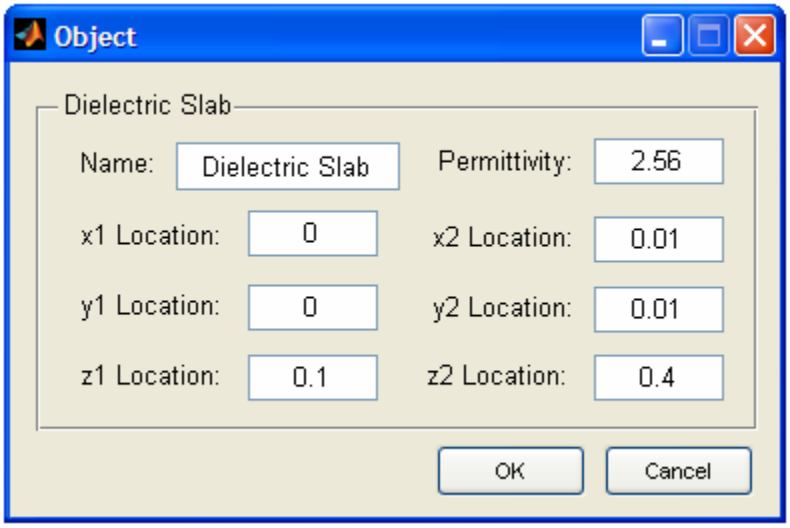
6.2 grid.inp

```
%%%   Frequency, used to describe the structure
9.6e9

%%% Cell size
0.01

%%%   Total dimensions along the x, y, z direction (including scatter
region)
0.01  0.01   0.70

%%% Location of plane wave source
0.60

%%%   Plane wave parameter: E to y direction (TE 0, TM 90), Frequency
of interest
0     0e9   20e9

%%%   Number of Kx & Ky Lines, Frequency, and Mode of Scan
1   0   0   1

%%%   Basic simulation time steps
1500

%%%   Location of sampling field for parameter extraction
0.50

%%% Slab

%Diel
0  0  0.1  0.01  0.01  0.4  2.56

%EndD

%Done
```

Users can also determine the input parameters and dielectric slab parameters on GUI.



(a) FDTD input parameters



(b) Dielectric geometry

Fig. 7. Input parameters on GUI.

6.3 Simulation Results and Manners of Setting up Input Parameters

6.3.1 Time Step Selection

❖ Time steps = 500, 700, 900, 1200, 1500, k_x = (1 0)

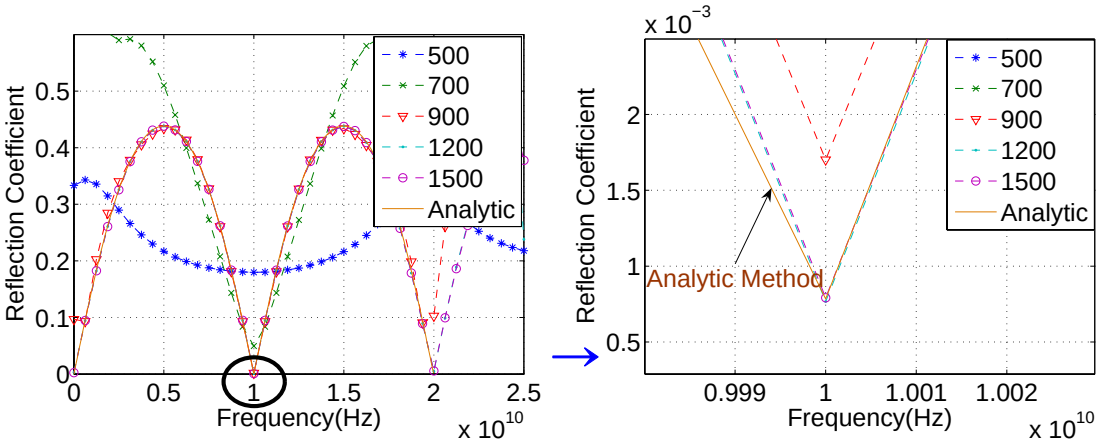


Fig. 8. Reflection coefficient comparison with different time steps.

This result shows that the FDTD/PBC code needs a proper number of time steps for an accurate result. When the number of time steps is small (500, 700, 900), there are not enough samples taken from the reflected fields. Thus the reflection coefficient is not accurate. In contrast, if the number of time steps is large enough (1200, 1500), the result has a good agreement with a result of the analytic method.

6.3.2 Time Step and High Permittivity

❖ ε_r = 36, Time Steps = 2000, 15000, k_x = (1 0)

When there is a high permittivity material in the domain, the result reveals that the FDTD/PBC code requires a greater number of time steps, as shown in Fig. 9. This is because if the permittivity is increased, the wave speed in the dielectric slab gets slower so that it takes more time for the wave to return to the sampling plane. When the number of time steps is increased to 15,000, the result has a good agreement with the analytic method. Therefore, users need large number of time steps in order to get an accurate result.

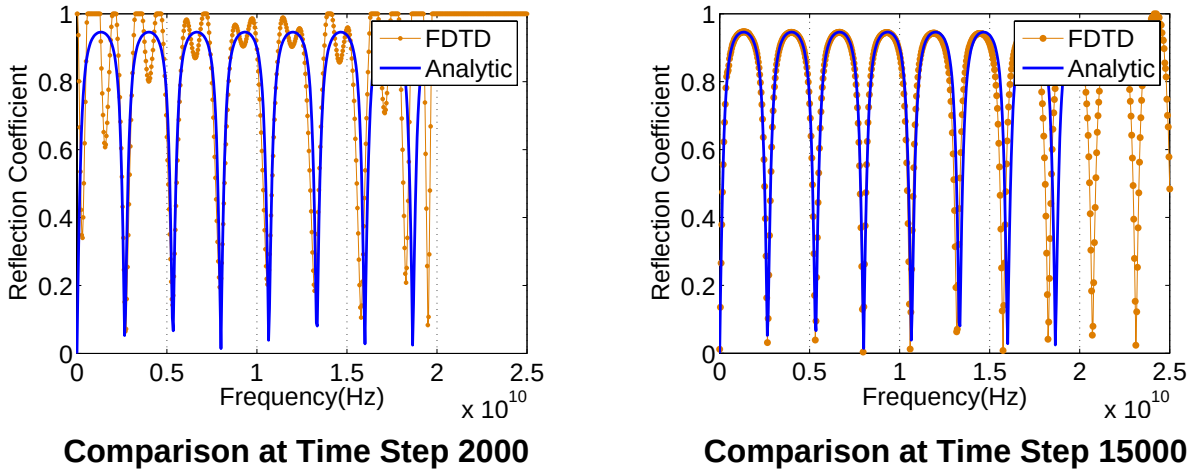


Fig. 9. Reflection coefficient comparison for higher permittivity slab.

On the second plot (Time Step = 15000), there is a little discrepancy for the high frequency range from 15GHz to 20GHz. This is related to the reference cell size, which will be explained shortly.

6.3.3 Cell Size and High Permittivity (At High Frequency)

- $\varepsilon_r = 36$, dx = 0.01λ (Time Step = 15000), dx = 0.005λ (Time Step = 35000), k_x = (1 0)

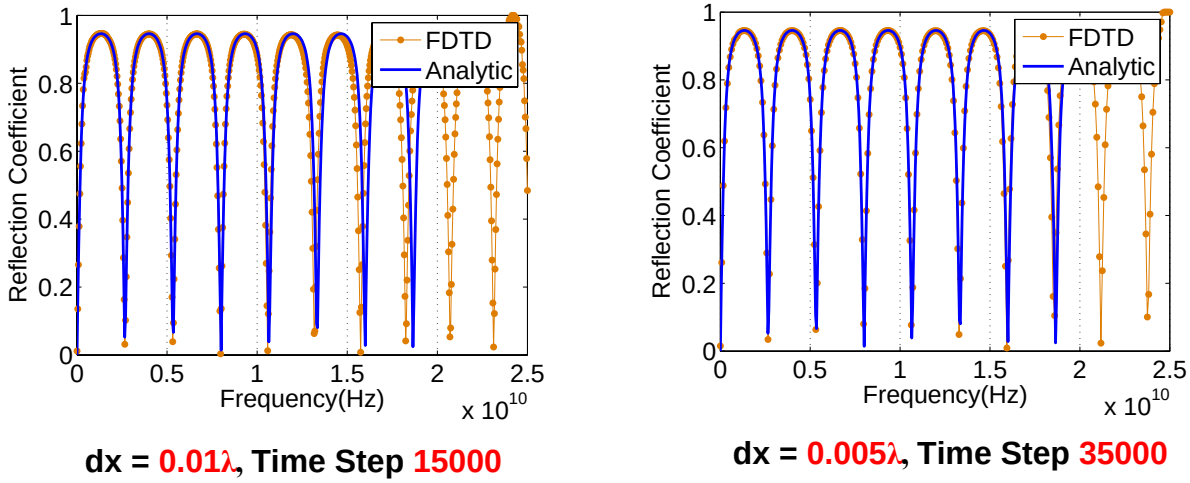


Fig. 10. Reflection coefficient comparison with different cell size.

This result shows that the FDTD/PBC code needs a smaller reference cell size to fix the discrepancy problem in the high frequency range. It is mainly because the number of

cells per guided wavelength is decreased for the high permittivity material at high frequency. Therefore, if the cell size is small enough in this case, the code can take enough samples for an accurate result.

When the cell size is reduced, the time step interval *dt* is reduced as well according to (4). In order to obtain the response for the same Gaussian incident pulse, the number of time steps also needs to be increased. When dx = 0.005λ with time step 35000, the result has a good agreement with the analytic method.

6.3.4 Thickness of Dielectric Slab

- ε_r = 2.56, Thickness = 0.2 λ, 0.35 λ, dx = 0.01 λ, Time Step = 1500, k_x = (1 0)

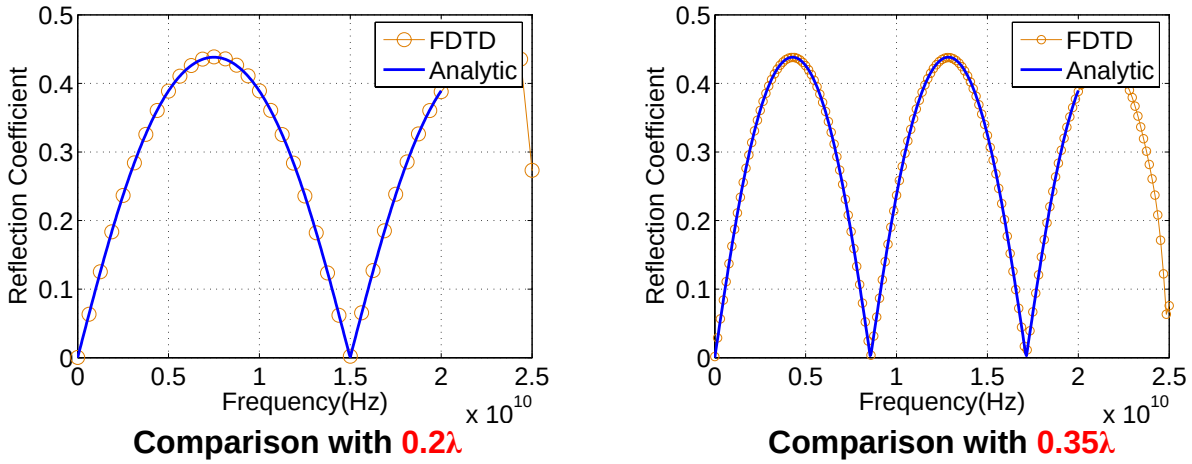


Fig. 11. Reflection coefficient comparison for different thickness.

The FDTD results show good agreement with the analytic method as far as the program takes enough number of time steps for the simulation. Notice that the thickness of the dielectric slab does not affect the maximum magnitude of the reflection coefficient. Instead, it only affects the period of oscillation along the frequency axis.

7. Example II: Frequency Selective Surface

The FDTD/PBC is also used to characterize the reflection/transmission coefficients of a frequency selective surface (FSS) consisting of dipole elements.

7.1 Simulation Model

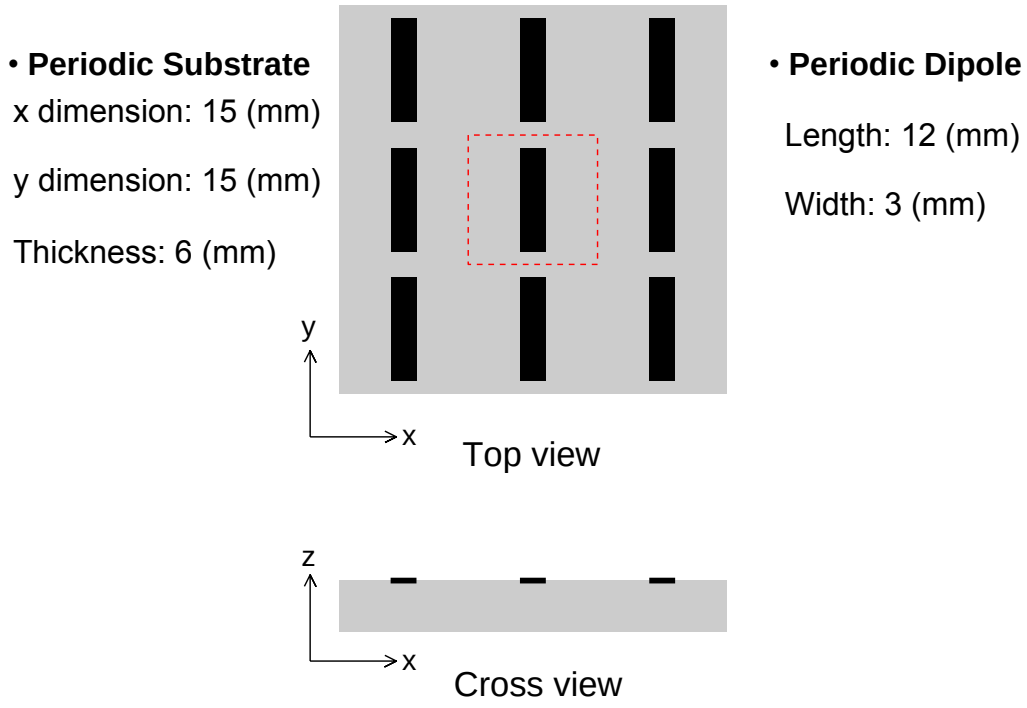


Fig. 12. Frequency selective surface (FSS) on a dielectric slab.

For computational efficiency, only one cell of periodic structure is analyzed inside of the red dashed line in Fig. 12. The location of the periodic dipole is determined by (x1, y1, z1) and (x2, y2, z2).

1) x location

The total x dimension of the periodic cell is 15 (mm), which is 0.15 λ at 3 GHz. The dipole width is 3 (mm), which is 0.03 λ, and it is placed in the middle of the dielectric slab along the x axis. Therefore, x1 is 0.06 and x2 is 0.09 in the domain.

```
%Plate
0.06 0.01 0.16 0.09 0.13 0.16
```

2) y location

The total y dimension of the periodic cell is 15 (mm), which is 0.15 λ. The dipole length is 12 (mm), which is 0.12 λ. Since the reference cell size is 0.01 λ, it cannot be placed exactly in the middle of the dielectric slab along the y axis. Instead, y1 is 0.01 λ and y2 is 0.13 λ in the computation domain. The periodic condition is still satisfied with this condition.

```
%Plate
0.06 0.01 0.16 0.09 0.13 0.16
```

3) z location

The patch is mounted on top of the dielectric slab. Thus z location is the same as the location of the top surface of the dielectric slab, which is 0.16 λ. Therefore, both z1 and z2 are 0.16 in the domain.

```
%Plate
0.06 0.01 0.16 0.09 0.13 0.16
```

Above parameters also can be selected on the GUI interface, as shown in Fig. 13.

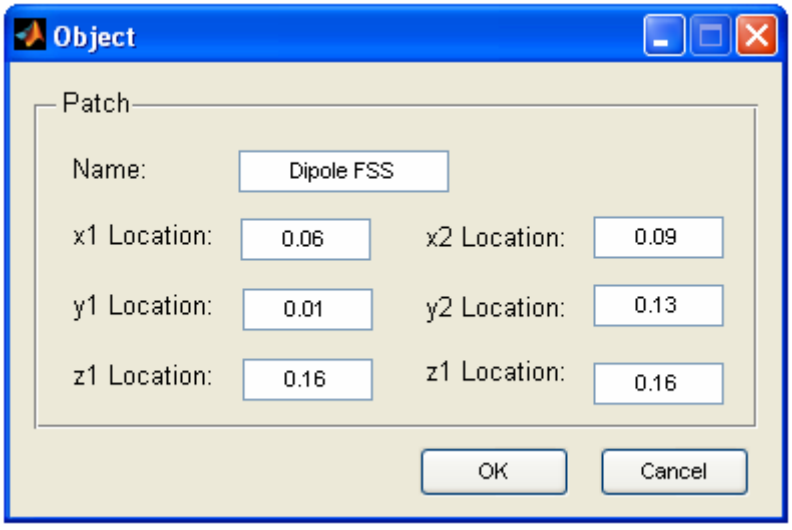


Fig. 13. Periodic patch array setup on GUI.

7.2 Grid.inp

A complete input file is shown below.

```
%%% Frequency, used to describe the structure
3e+009

%%% Cell Size
0.01

%%% Total dimensions along the x, y, z direction (including scatter
region)
0.15   0.15   0.7

%%% Location of plane wave source
0.6

%%% Plane wave parameter: E to y direction (TE 0, TM 90), frequency
of interest
0   0   2e+010

%%% Number of Kx & Ky Lines, Frequency, and Mode of Scan
101   2e+010   0   1

%%% Basic simulation time steps
1500

%%% Location of sampling field for parameter extraction
0.5

%%% Slab

%Diel
0     0     0.1   0.15  0.15  0.16  2.2

%EndD

%Plate
0.06  0.01  0.16  0.09  0.13  0.16

%Done
```

- Wavelength (λ): c / f = 3 x 10^8 / 3 x 10^9 = 0.1 (m)
- Reference cell size: 0.01 λ = 0.001 (m)
- Total x dimension: 0.15 → 15 (mm)
- Total y dimension: 0.15 → 15 (mm)
- Total z dimension: 0.70 → 70 (mm)

- Usually, the distance in between the top of the structure and the source location is 0.25λ ~ 0.5λ.
- Users can set up the parameters on the GUI.

7.3 Simulation Result

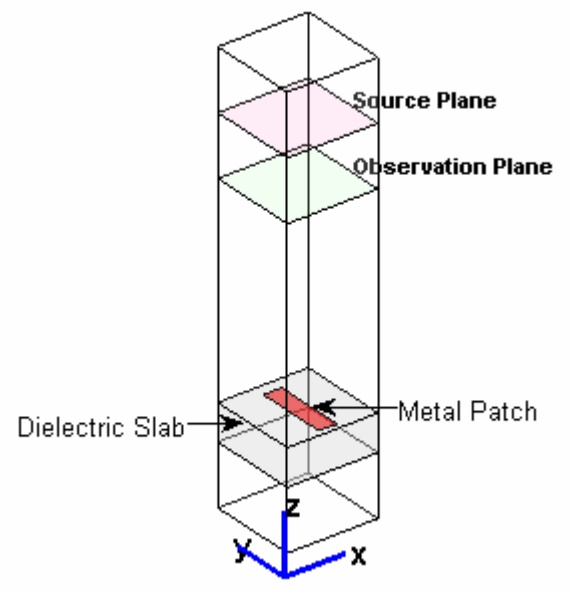


Fig. 14. Simulation structure on GUI.

After setting up all parameters, a graphic figure appears on the main GUI window. The simulated reflection coefficient is shown in Fig. 15. The reflection and transmission regions can be clearly identified. One observation on the result is that there exist some oscillations near the light line ($\theta = 90^\circ$, $k_x = k_0$). This is because the excitation signal is weak in this frequency region. Accurate results can be obtained by reducing the BW of the Gaussian exaction of the plane wave, as discussed in Section 4.5.

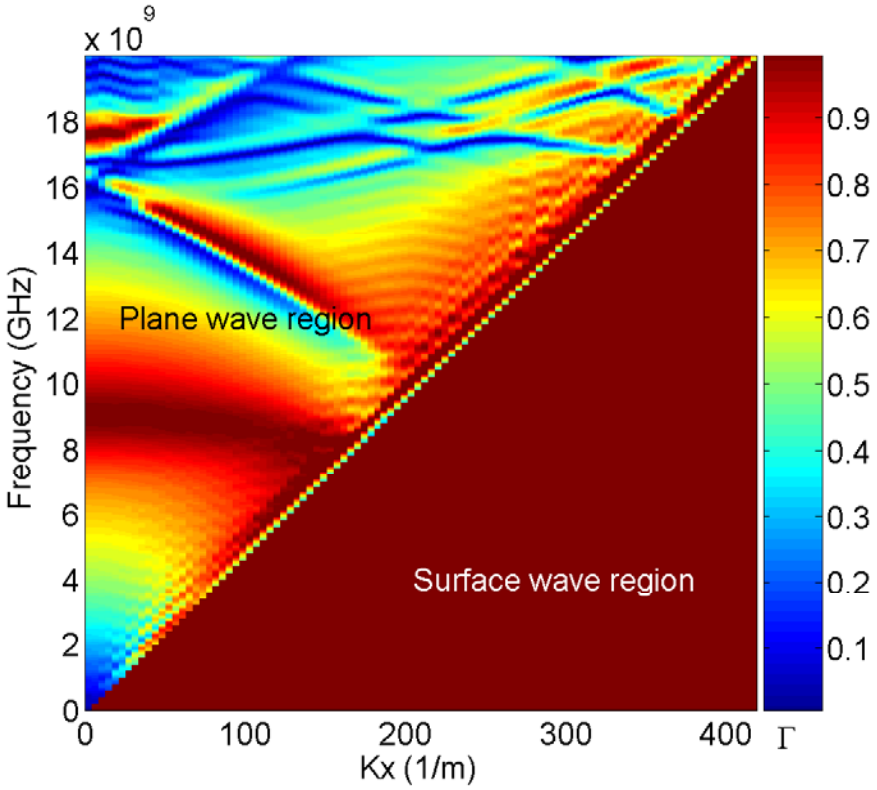


Fig. 15. The reflection coefficient of the dipole FSS.

8. Example III: Loop FSS

Metal wires are popular structures in EM designs, such as vias or feeding probe. To illustrate how to implement wires, the metal dipole in the previous FSS structure is replaced by a metal wire loop. In this example, 4 metal wires are mounted on top of a dielectric slab, and they form the same boundary as the metal patch in the example II. Users can expect a similar result.

8.1 Simulation Model

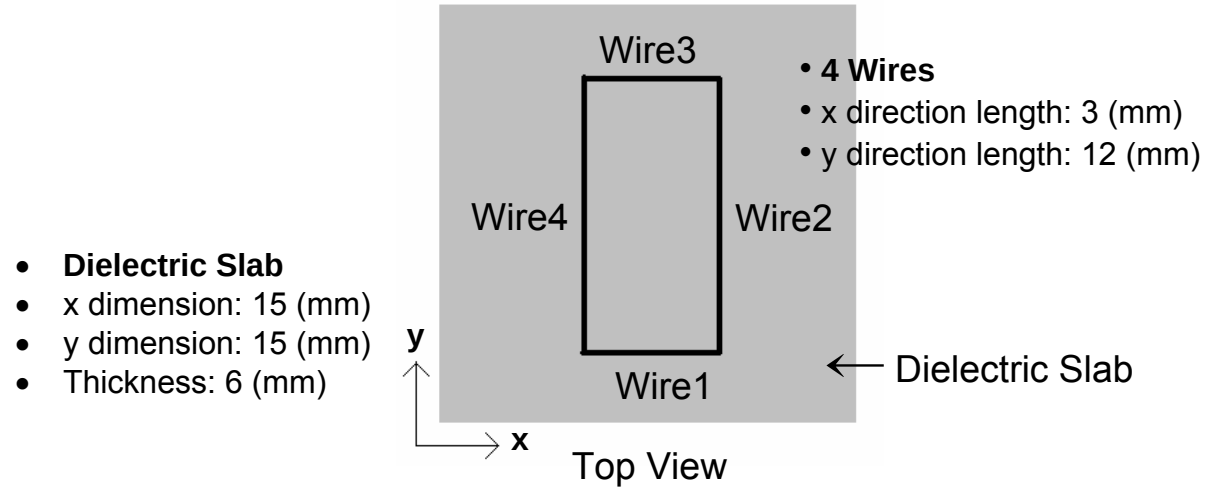


Fig. 16. Metal wire structure on a dielectric slab.

Users can place metal wires in the computational domain by simply setting up x, y, and z location of the wire. Structure components are same as the periodic dipole case, which consists of 6 coordinates. If a wire is placed along x axis, y1 and y2 locations are same, and if a wire is placed along y axis, x1 and x2 locations are same. Since this wire is mounted on the surface, z1 and z2 coordinates are the same as the location of the upper plate of the dielectric slab.

1) Wire 1

- Length: 3 (mm)
- x oriented, same coordinates for y1 and y2, and z1 and z2

```
%Wire
0.06   0.01   0.16   0.09   0.01   0.16
 (x1)  (y1)   (z1)   (x2)   (y2)   (z2)
```

2) Wire 2

- Length: 12 (mm)
- y oriented, same components for x1 and x2, and z1 and z2

```
%Wire
0.09   0.01   0.16   0.09   0.13   0.16
```

Wire 3 and 4 can be defined with the same method. Users can also set up the metal wire structure on the GUI, as shown in Fig. 17.

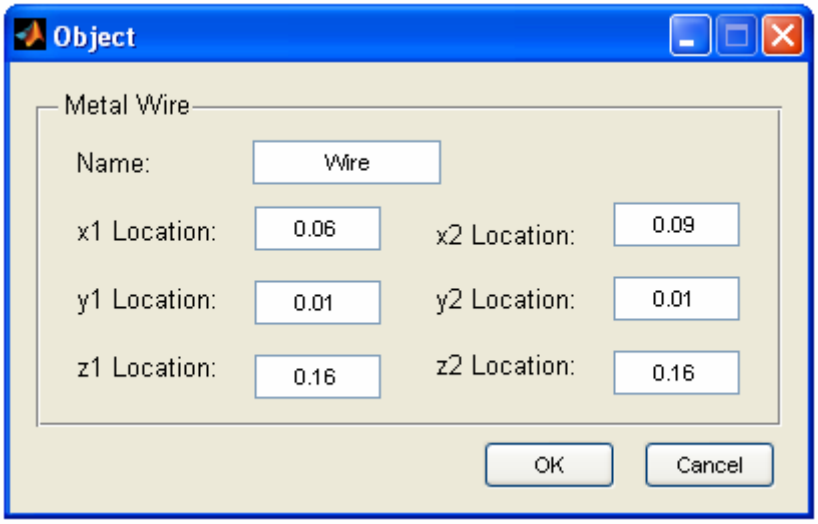


Fig. 17. Metal wire setup on GUI.

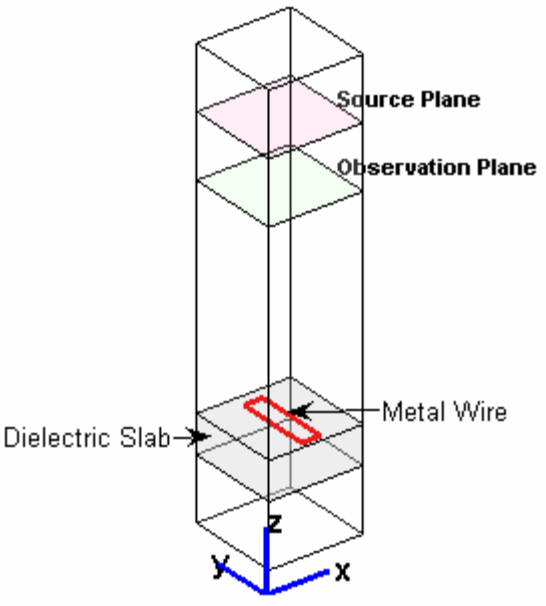


Fig. 18. Simulation structure on GUI.

8.2 grid.inp

A complete input file can be found in the example folder. Basically, all the input parameters are same as the dipole case except the 4 metal wires.

8.3 Simulation Result

After setting up all parameters, a graphic structure is generated as shown in Fig. 18. The simulated result is plotted in Fig. 19 & 20, which is close to the dipole FSS case. The reflection coefficient at a specific angle is extracted from Fig. 19.

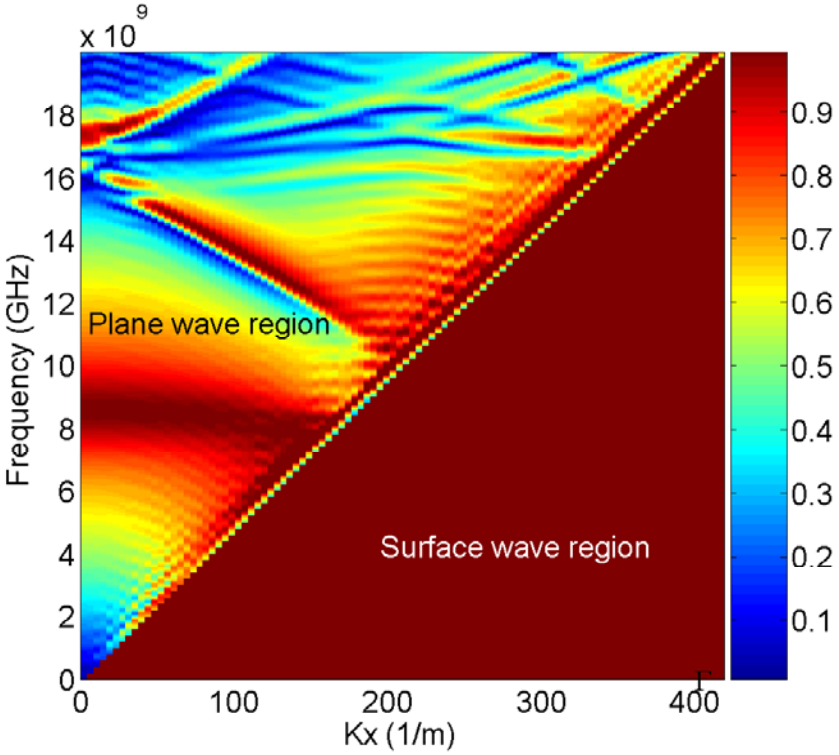


Fig. 19. The reflection coefficient of the loop FSS.

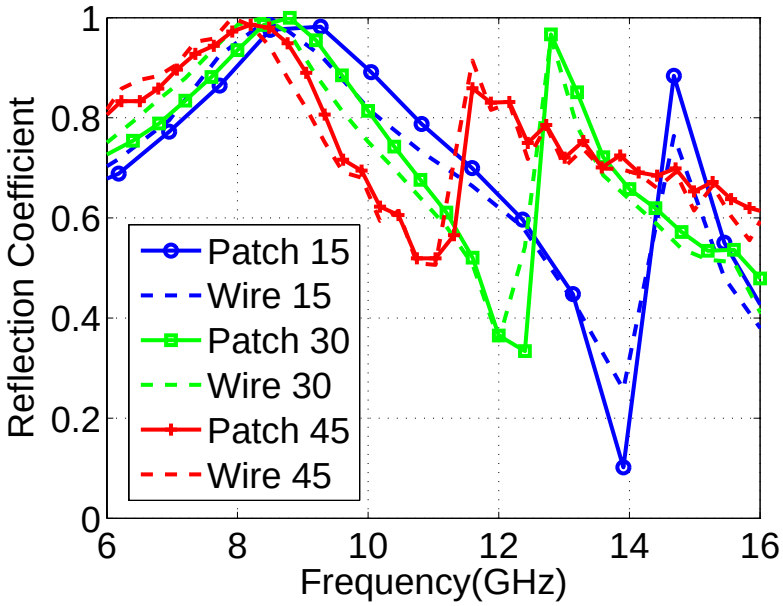
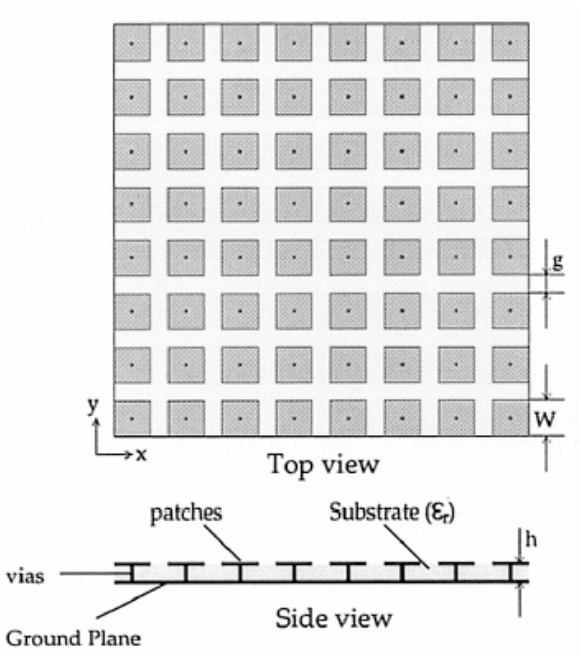


Fig. 20. Comparison of reflection coefficient of periodic dipole FSS and metal wire loop FSS for several incident angles.

9. Example IV: Mushroom-Like EBG Structure

There has been an increasing interest in electromagnetic band-gap (EBG) structures. When a plane wave normally illuminates upon an EBG structure, the phase of the reflected field changes continuously from 180˚ to -180˚ as sweep frequency varies [4]. This property can be utilized as a Perfect Magnetic Conductor (PMC) when a reflection phase is 0˚. In this chapter, a mushroom like EBG structure is analyzed.

9.1 Simulation Model



- Substrate thickness (h): 0.04 λ_{12GHz}
- Substrate permittivity (ε_r): 2.2
- Unit cell length: 0.14 λ_{12GHz}
- Patch width (w): 0.12 λ_{12GHz}
- Side gap width (g): 0.2 λ_{12GHz}
- Normal incident case

Fig. 21. Geometry of a mushroom-like EBG structure [4].

9.2 grid.inp

```
%%% Frequency, used to describe the structure
1.2e+010

%%% Cell Size
0.01

%%% Total dimensions along the x, y, z direction (including
scatter region)
0.14   0.14   0.7
```

```
%%% Location of plane wave source
0.6

%%% Plane wave parameter: E to y direction (TE 0, TM 90),
frequency of interest
0   0   3e+010

%%% Number of Kx & Ky Lines, Frequency, and Mode of Scan
1   0   0   1

%%% Basic simulation time steps
3000

%%% Location of sampling field for parameter extraction
0.5

%%% Slab

%Diel
0  0  0.1  0.14  0.14  0.14  2.2

%EndD

%Plate
0  0  0.1  0.14  0.14  0.1

%Plate
0.01  0.01  0.14  0.13  0.13  0.14

%Wire
0.07  0.07  0.1  0.07  0.07  0.14

%Done
```

This structure includes all three objects discussed before: dielectric slab, metal patch, and metal via. The input file can be also found in the example folder.

9.3 Simulation Result

The simulated result is plotted in Fig. 23. Note that the reflection coefficient is always 1, which means all incident wave energy is reflected. The phase of the reflected field changes from 180˚ to -180˚. At the resonant frequency 17.1 GHz, the reflection phase is 0˚, which is the PMC condition. It is important to point out that the phase is normalized to the phase of a PEC ground plane that locates on top of the dielectric slab, as discussed in [4]. Therefore, the reflection phase for a PEC ground plane need to be simulated as a reference.

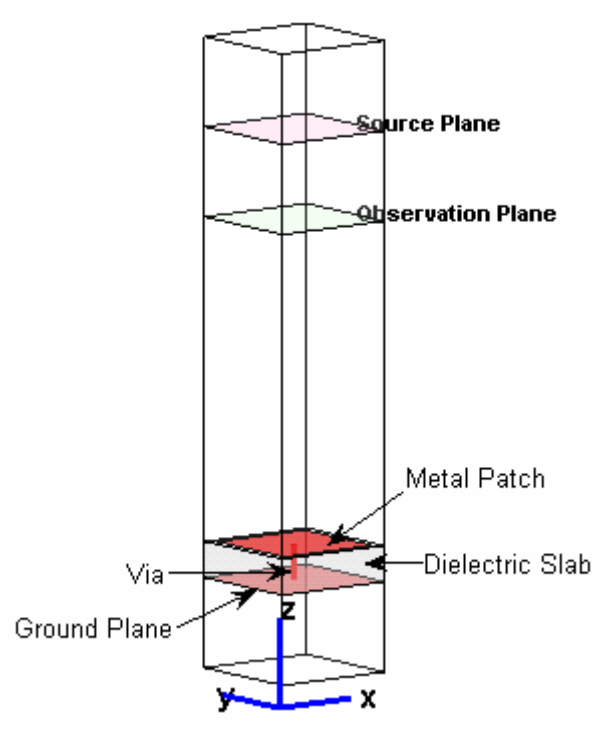
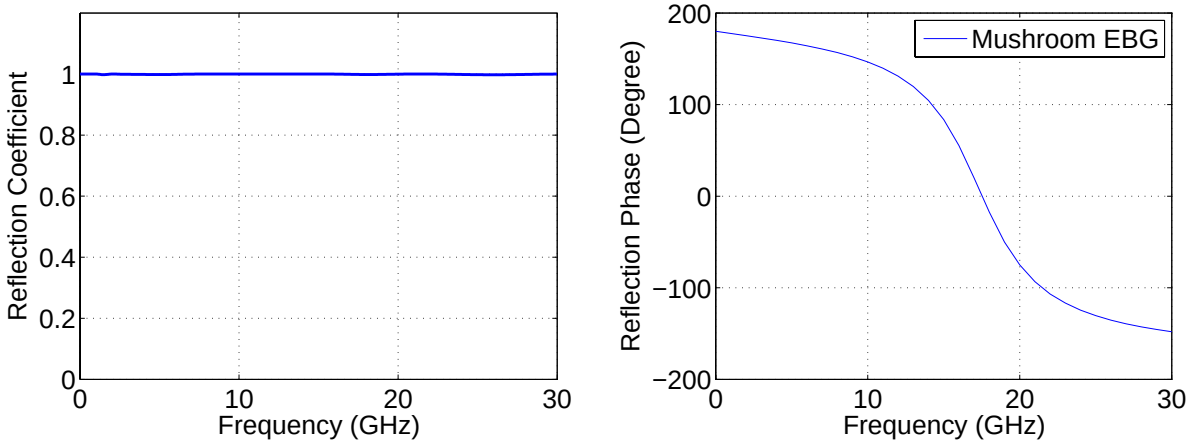


Fig. 22. Simulation structure on GUI.



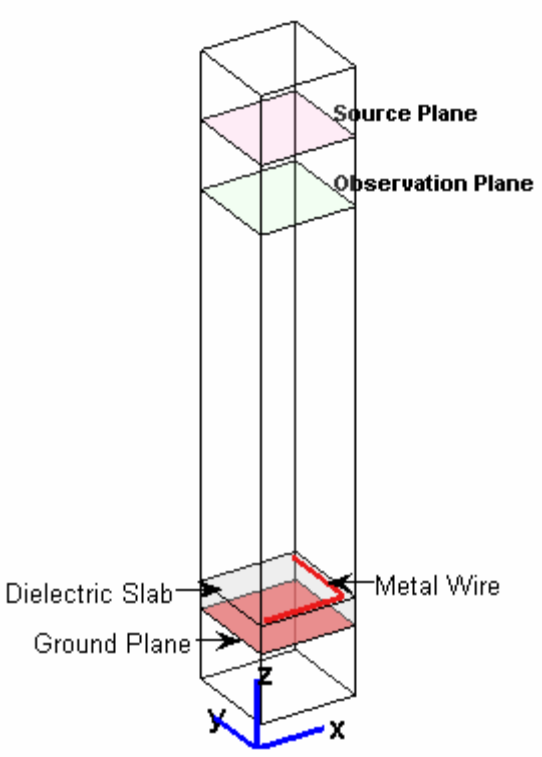
(a) **(b)**

Fig. 23. (a) Magnitude and (b) phase of the reflection coefficient.

10. Example V: Cross Polarization

In previous examples, all structures are symmetric with respect to the incident plane wave so that the reflected wave has the same polarization as the incident wave. However, a cross polarization may occur for general structures. This chapter analyzes a structure that both co- and cross-polarized fields are observed.

10.1 Simulation Model



- Substrate thickness: 0.04 λ_{12GHz}
- Substrate permittivity: 2.2
- Unit cell length: 0.14 λ_{12GHz}
- Normal incident case (TE)
- Wire length (When connected): 0.24 λ_{12GHz}

In this structure, two metal wires, along x-and y-directions, are mounted on the top surface of a grounded dielectric slab. The normal incident wave is polarized along the y-direction. Since the x-oriented wire is connected with the y-oriented wire, electric current will be induced along the x-direction. Thus, an x-polarized reflected field will be generated. Two reflection coefficients will be obtained, as shown in (5).

Fig. 24. Connected metal wire.

$$\Gamma_{yy} = \frac{E_y^{refl}}{E_y^{inc}}, \quad \Gamma_{xy} = \frac{E_x^{refl}}{E_y^{inc}} \tag{5}$$

Since there is a metal ground plane on the back of the dielectric slab, the total reflection energy should equal to the incident energy. Therefore, the following equation should be satisfied:

$$\Gamma_{yy}^2 + \Gamma_{xy}^2 = 1 \tag{6}$$

10.2 Simulation Results

The FDTD simulated results are shown in Fig. 25, where the co-, cross-, and total reflection coefficients are plotted. As expected, the total reflection is always 1, as expected from (6). Around 16 and 29 GHz, the co-polarized field is zero and the cross-polarized field reaches the maximum.

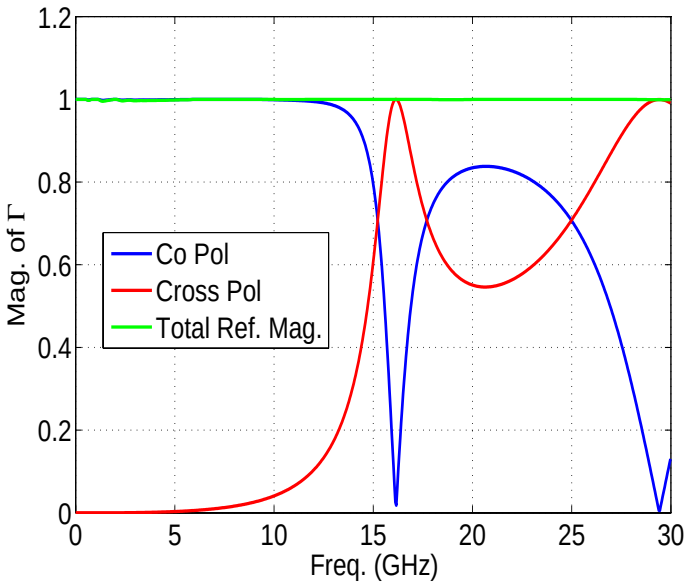


Fig. 25. Reflection coefficient for co- and cross-polarized fields.

11. Summary

This user manual introduces spectral FDTD software developed by the authors to analyze scattering properties of general periodic structures. The program flow chat, input/output files, and several examples are illustrated to explain how to use this electromagnetic software.

This FDTD software is developed for free usage. It is users' own responsibility to use the data generated by this software. If users have problems and find any mistakes in the software, they are welcomed to contact Prof. Fan Yang at fyang@olemiss.edu. Your suggestions and comments are greatly appreciated.

References

[1] A. Aminian, F. Yang, and Y. Rahmat-Samii, “Bandwidth determination for soft and hard ground planes by spectral FDTD: a unified approach in visible and surface wave regions”, *IEEE Trans. Antennas Propag.,* vol. 53, no. 1, pp. 18-28, Jan. 2005.

[2] A. Aminian and Y. Rahmat-Samii, “Spectral FDTD: a novel technique for the analysis of oblique incident plane wave on periodic structures”, *IEEE Trans. Antennas Propag.,* vol. 54, no. 6, pp. 1818-1825, June 2006.

[3] F. Yang, J. Chen, R. Qiang, and A. Elsherbeni, “FDTD analysis of periodic structures at arbitrary incidence angles: a simple and efficient implementation of the periodic boundary conditions”, *2006 IEEE AP-S Digest*, vol 3, pp. 2715-2718, July 2006.

[4] F. Yang and Y. Rahmat-Samii, “Reflection phase characterizations of the EBG ground plane for low profile wire antenna applications,” *IEEE Trans. Antennas Propag.,* vol. 51, no. 10, pp. 2691-2703, Oct. 2003.