E-B Excitation Module

Application Examples

A. Rectangular Waveguide

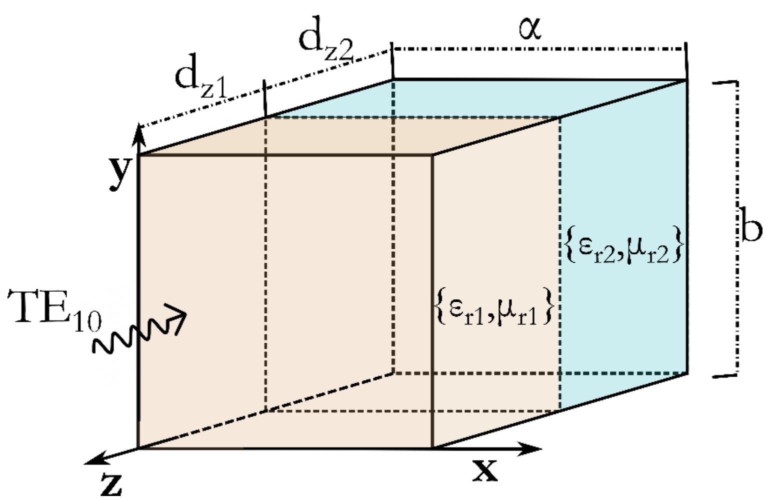

Figure 1 Rectangular Waveguide

The first application example is that of rectangular waveguide filled with two layers of different dielectric media and terminated with a short (Figure 1). The dimensions of the waveguide cross section α and b, t thicknesses and the electromagnetic parameters of the two layers are listed in Table 1. The rectangular waveguide is excited by the TE_{10} mode of frequency above the cutoff.

Table 1. Parameters of Rectangular Waveguide.

α	b	d_{z1}	d_{z2}	ε_{r1}	μ_{r1}	ε_{r2}	μ_{r2}
2m	1m	1m	0.333m	1	1	2-2j	1

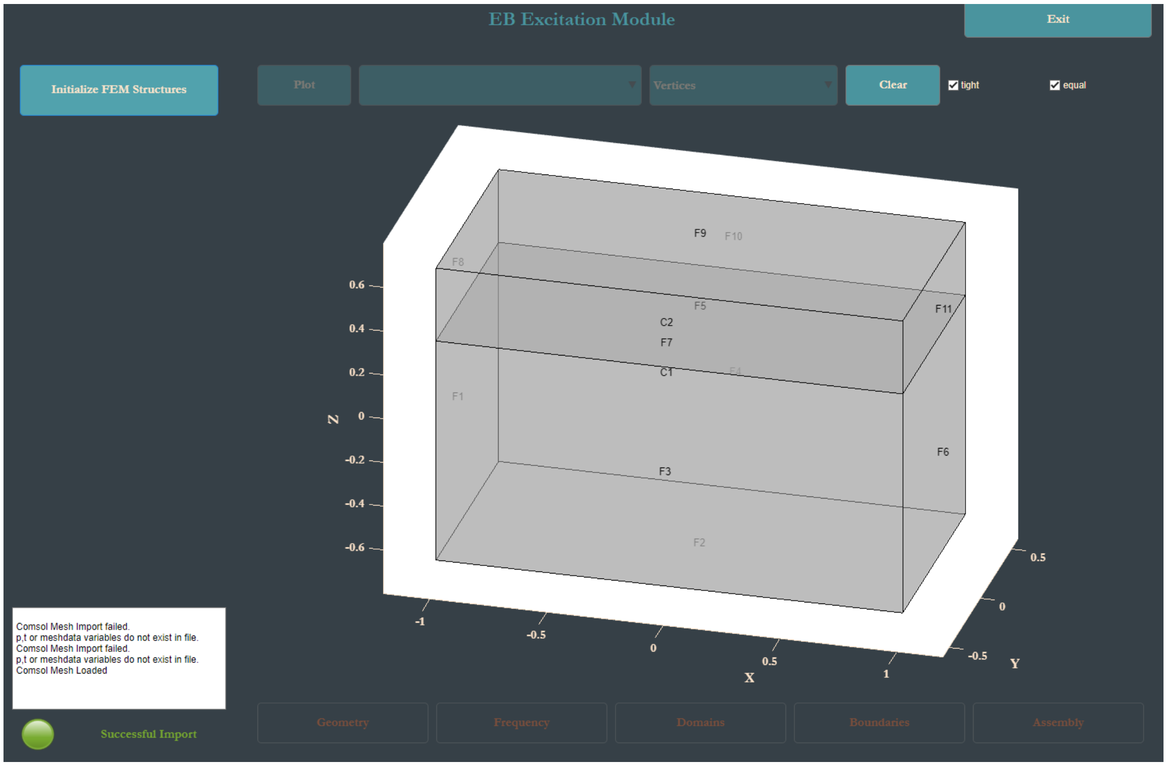

Figure 2 .Successful import of tetrahedral finite element mesh for the Rectangular Waveguide application example.

Geometry

The first step in the construction of the **E**-**B** Excitation Module model is to import a tetrahedral finite element mesh of the structure, by selecting the **Mesh** button in the entry form and selecting the **"Rectangular Waveguide Mesh.mat"** file found in the path: **"Examples\Excitation Module\A. Rectangular Waveguide\Mesh".** Information about this tetrahedral mesh can be found in Table 2.

Sucessful import of the tetrahedral mesh is acknowledged in the Messaging Text Area of the **E**-**B** Excitation Module and the structure is plotted in the center of the central panel area (Figure 2). To initialize the model's finite element structures, the **Initialize**

Table 2. "*Rectangular Waveguide Mesh.mat*" Information

#Vertices	#Elements	#Edges	#Facets	#Domains	#Boundaries
23169	129805	156464	262712	2	11

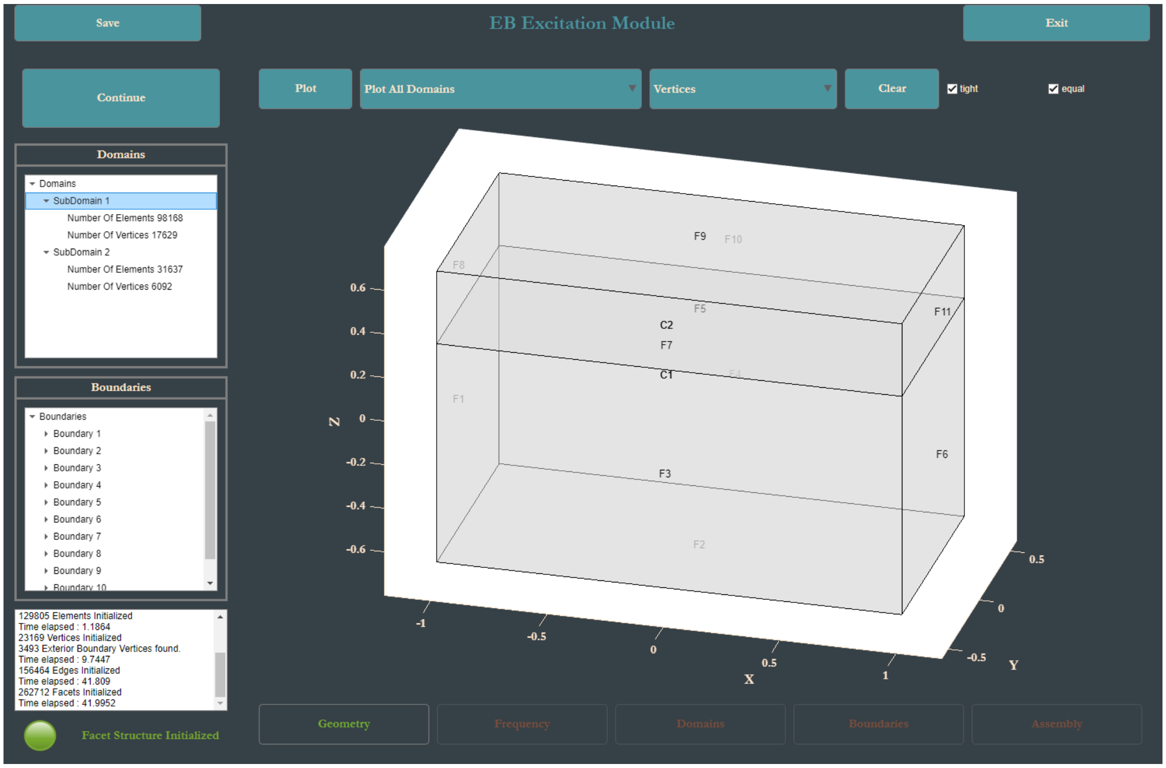

Figure 3. Successful Initialization of Finite Element Structures for the Rectangular Waveguide application Example.

Finite Element Structures button is clicked on and the sucessful initialization of the finite element structures leads to display of the Domains and Boundaries trees in center of the left panel area (Figure 3).

Frequency

Engaging the **Continue** button will progress to the model's frequency definition panel. The user may select either a single frequency simulation, selecting the **Single Frequency** check box or a frequency range simulation by de-selecting the **Single Frequency** check.

To analyze the electromagnetic wave propagation in the rectangular waveguide in the frequency range 100 MHz to 105 MHz, the single frequency is de-selected, the frequency range input mode is set to the **Start: Step: Stop** method. The frequency range consisting of five frequencies 100 MHz, 101 MHz, 102 MHz, 103 MHz 104MHz and 105 MHz is defined by setting the **Start** value equal to 100 MHz, the **Step** value equal to 1 MHz and the **Stop** value equal to 105 MHz and clicking on the **Done** button (Figure 4).

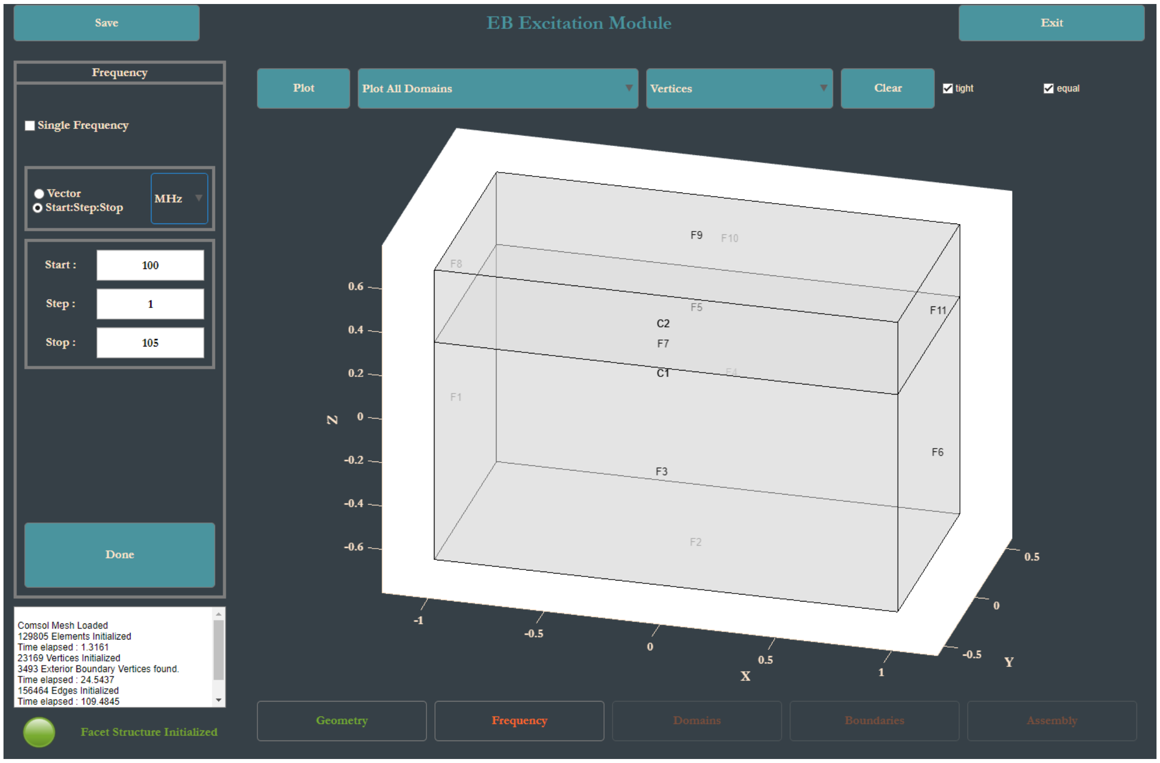

Figure 4. Frequency Range Definition for the Rectangular Waveguide application example.

Opting for a frequency range simulation rather than a single frequency simulation will lead to significantly increased demand of computational resources (time and RAM memory) and for low performance computing system, the latter option is advised.

Domains

The next step in the construction of the rectangular waveguide model is the definition of the electromagnetic media that fill the subdomains of the computational domain. The rectangular waveguide contains two isotropic electromagnetic media, air and a dielectric medium assigned to the domains 1 and 2 respectively, which for the given frequency range are non-dispersive. To assign air as the medium of a domain, the user must select the domain from the domain drop down selection, select the **Isotropic** check box and leave the **Dispersive** check box de-selected. No further action

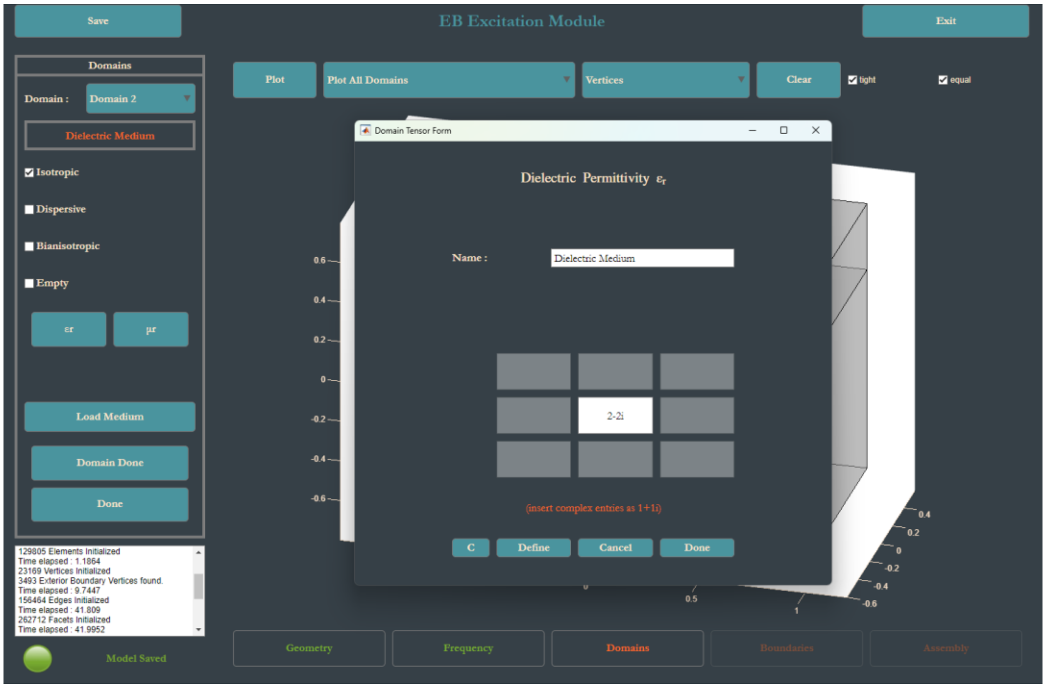

Figure 4. Domain Tensor Form for non-Dispersive Dielectric Substrate ε_r

is required as air's electromagnetic properties are the preset default for an isotropic medium in the **E-B** Excitation. To assign the substrate dielectric to a domain, the user follows the same course of action and clicks on the ε_r button to import the complex scalar dielectric permittivity of the second dielectric layer (Figure 4):

$$\varepsilon_r^* = 2 - 2i$$

The dielectric substrate does not exhibit magnetic behavior, and no action is required for the definition of the relative magnetic permeability. After validating the selection of every domain's medium, the user must click on the **Done** button to continue to the model's boundary condition definitions.

Boundaries

All the exterior metallic surfaces of the rectangular waveguide are modeled as *Perfect Electric Conductor* boundaries, while one of the exterior boundaries functions as a port for the structure. Table 3 lists the rectangular waveguide model's boundaries along with their corresponding boundary conditions. Boundary 2 must be assigned to the *Port Boundary* Condition, by selecting the Port entry in the boundary type drop down selection (Figure 5).

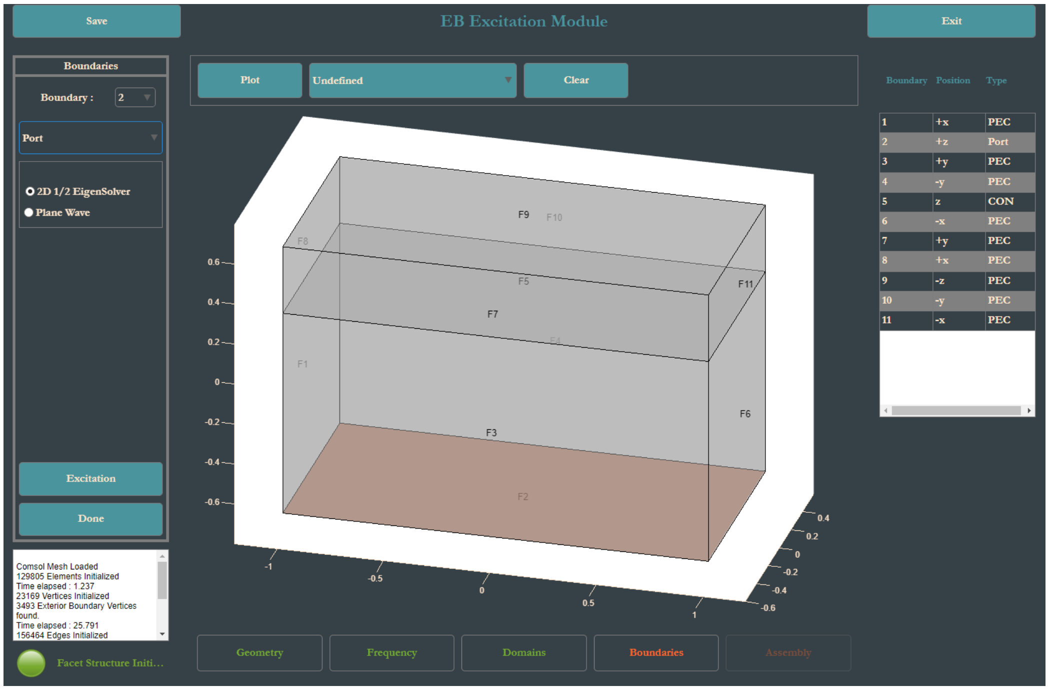

Figure 5. Port Boundary Condition

Table 3 Rectangular Waveguide application example Boundary Conditions.

Boundary	Axis	Position	Boundary Condition
1	$-\hat{x}$	external	PEC
2	$-\hat{z}$	external	Port
3	$-\hat{y}$	external	PEC
4	$\hat{y}$	external	PEC
5	$\hat{z}$	internal	Continuity
6	$\hat{x}$	external	PEC
7	$-\hat{y}$	external	PEC
8	$-\hat{x}$	external	PEC
9	$\hat{z}$	external	PEC
10	$\hat{y}$	external	PEC
11	$\hat{x}$	external	PEC

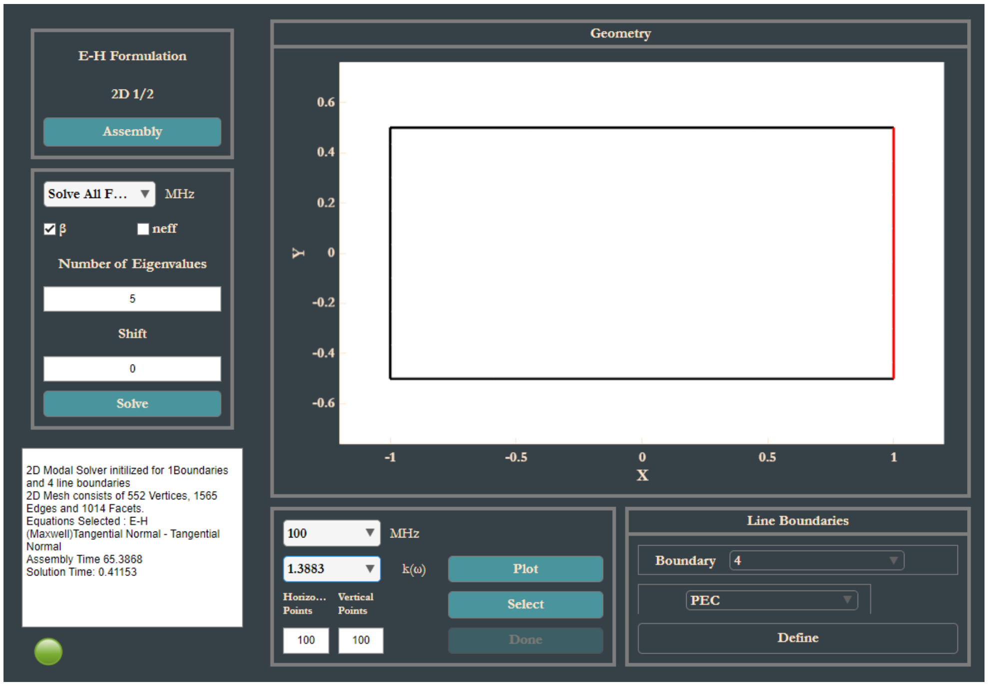

Figure 6. 2D Modal Eigen Solver (post solution) – Rectangular Waveguide.

To obtain the field distribution of the TE_{10} rectangular waveguide mode that excites the structure, the user must utilize the 2D ½ Eigen Solver by selecting the corresponding button on the top of the boundary panel and engaging the **Excitation** button, which prompts the 2D Modal Eigen Solver app (Figure 6).

The first step in obtaining the TE_{10} rectangular waveguide mode consists of assigning the boundaries of the surface domain to the appropriate boundary conditions. As all metallic surfaces of the rectangular waveguide are modeled as *Perfect Electric Conductor* boundaries, all line boundaries in the two-dimensional cross section of the rectangular waveguide must be assigned to the *Perfect Electric Conductor* boundary condition as well. The user must first select each of the line boundaries in the Line Boundaries panel on the lower right corner of the 2D Modal Eigen Solver app, wait until the corresponding line is highlighted (green color) in the plot area, select the PEC entry from the drop-down selection and then click on the **Define** button.

Subsequently, the user can proceed to the assembly process of the 2D ½ Eigen Solver problem, by clicking on the **Assembly** button. To solve the eigenproblem and obtain the propagation constant and field distribution of the TE_{10} rectangular waveguide mode for each of the five frequencies in the problem's frequency range, the user may solve the problem for every single frequency sequentially or all the frequency

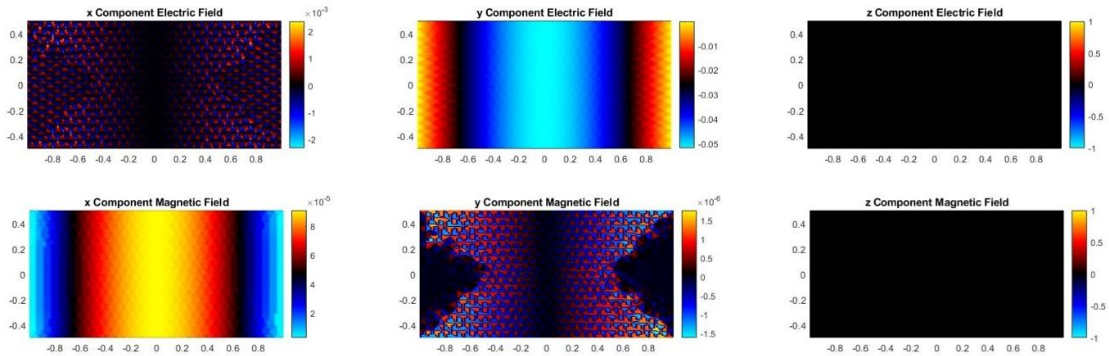

Figure 7. 2D Modal Eigen Solver- Eigenvector corresponding to eigenvalue 1.3883 at 100MHz. (Upper Left Corner) real part E_x component, (Upper Center) real part E_y component, (Upper Right Corner) real part E_z component. (Lower Right Corner) real part H_x component, (Left Center) real part H_y component, (Left Right Corner) real part H_z component.

range by selecting the corresponding option from the drop-down selection directly above the **Solve** button. The first option allows the user to choose different values of eigenvalue shift for each frequency, while the second option solves the eigenvalue problem for all frequencies with the same shift value. As the propagation constant (eigenvalues) of the TE_{10} rectangular waveguide mode are always found as the smallest in absolute eigenvalues, a single shift selection equal to zero and selecting **Solve All Frequencies** in the solution drop down selection suffices. For a computationally efficient solution, the user is advised to solve the problem for a small number of eigenvalues (**Number of Eigenvalues** field). Finally, the eigenvalue type of the eigenproblem is set to the propagation constant by selecting the **β** check box.

Engaging the **Solve** button results in obtaining the eigenpair sets (one for each of the frequencies in the frequency range), that can be examined by the user in the results panel. The correct eigenvalues for each frequency are listed in Table 4, while Figure 7

Table 4 Rectangular Waveguide TE_{10} Eigenvalues.

Frequency	Eigenvalue
100MHz	1.3883
101MHz	1.4198
102MHz	1.4509
103MHz	1.4816
104MHz	1.512

105MHz	1.5421

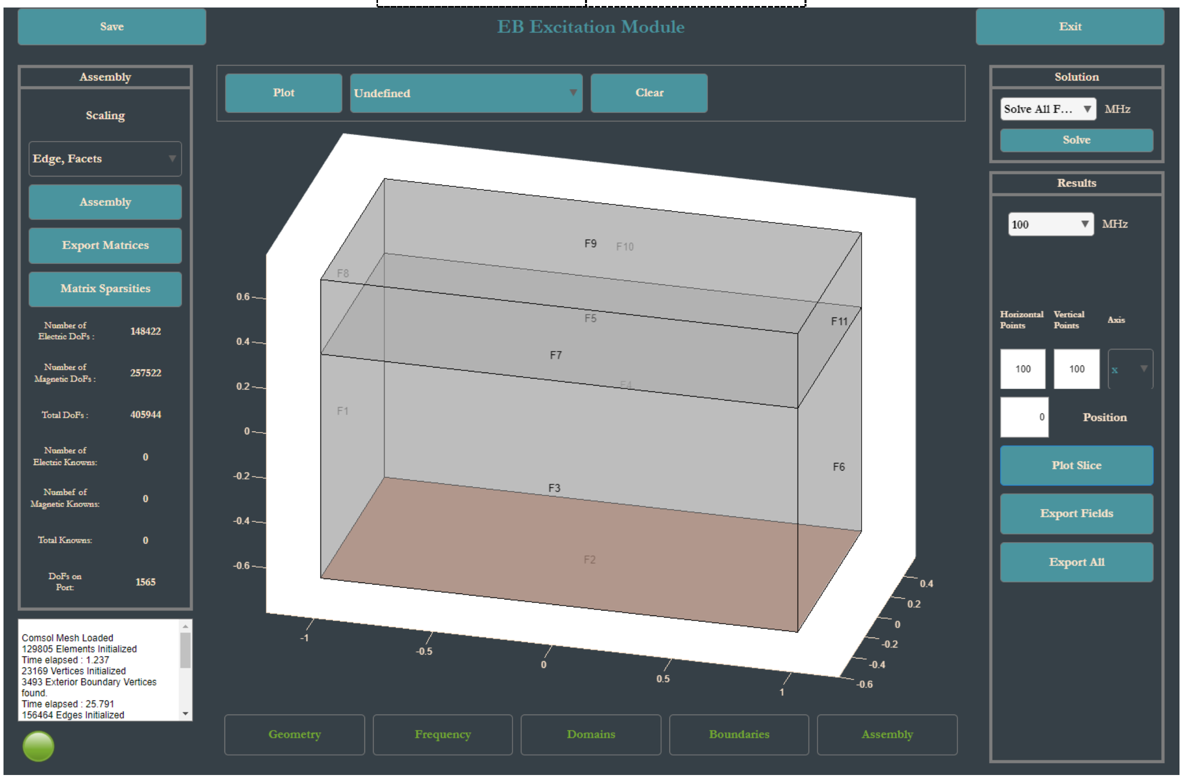

Figure 8. E-B Excitation Module – Assembly and Solution Panel (post solution).

displays the eigenvector corresponding to the TE_{10} eigenvalue equal to 1.3883 at 100MHz. To complete this step, the user must assign each of the correct eigenpairs to the port boundary, by selecting the frequency in the frequency drop down selection and the corresponding eigenvalue in the **k(ω)** drop down selection directly below and clicking on the **Select** button. When this process has been completed for all frequencies in the frequency range, the user can successfully exit the 2D ½ Modal Eigen solver app and return to the **E-B** Excitation Module by clicking on the **Done** button.

Assembly

Following the definition of the model's boundaries, the **E-B** Excitation module allows the user to proceed to the assembly process and solution of the wave propagation problem (Figure 8). These steps require minimal input from the user, as the problem's algebraic form is formed simply by clicking on the **Assemble** button. When the assembly process is completed, the Solution panel in the right panel area is enabled and the solution of the wave propagation problem is achieved by clicking on the **Solve** button (Figure 9).

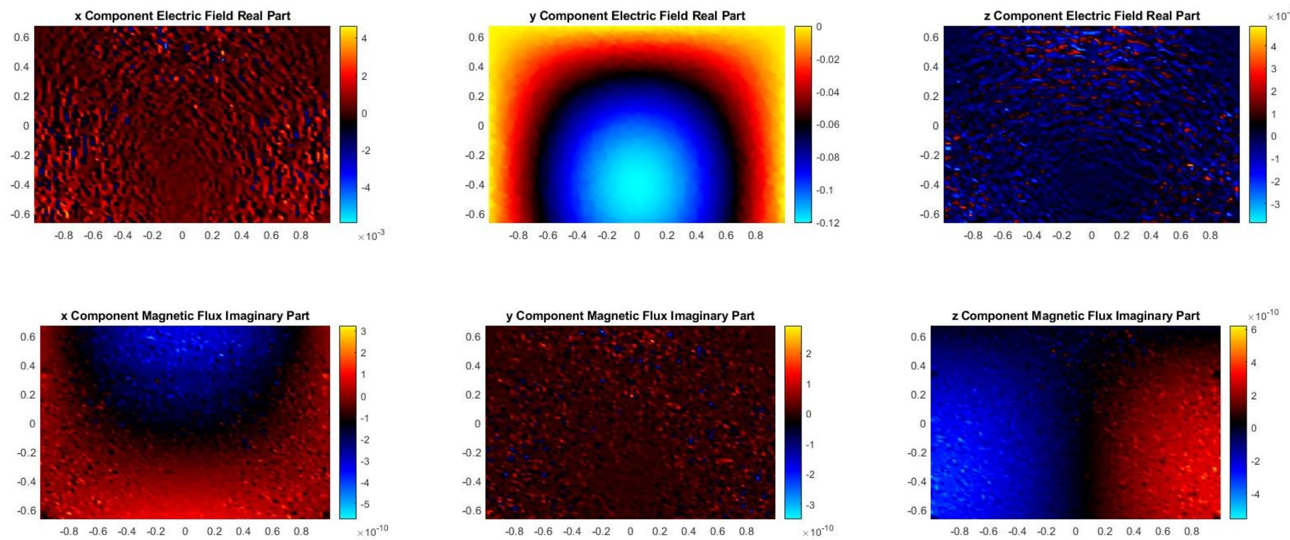

Figure 9. Electromagnetic Wave Propagation of the TE_{10} Rectangular Waveguide Mode in the Rectangular Waveguide application example at 100MHz – xz plane at y=0. (Upper Left Corner) real part of E_x component, (Upper Center) real part of E_y component, (Upper Right Corner) real part of E_z component, (Lower Left Corner), imaginary part of Bx component, (Lower Center) imaginary part of B_y component, (Lower Right Corner) imaginary part of B_z component.

B. Silicon Over Insulator Waveguide

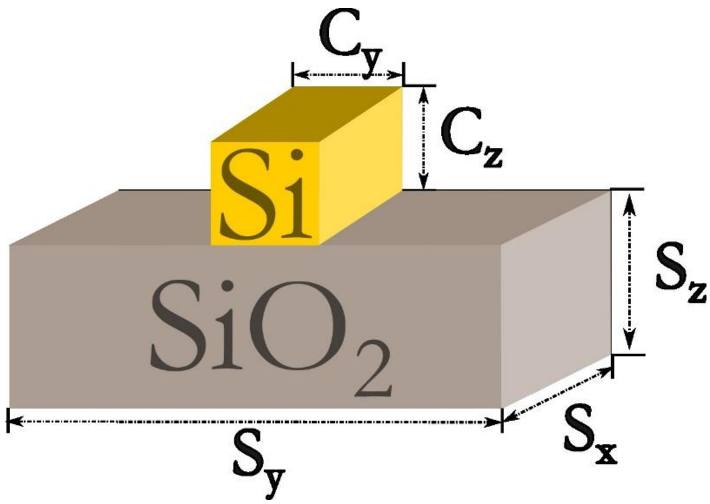

Figure 10. Silicon Over Insulator Waveguide.

The Silicon over Insulator (SOI) waveguide (Figure 10) is an optical waveguide [1] operating in the THz frequency regime. The waveguide is constructed by placing a silicon core of dimensions C_x and C_y over an infinite silicon oxide substrate. The electromagnetic wave is confined mainly in the Silicon core, while the supported electromagnetic wave modes are hybrid, meaning that both the electric and magnetic components have non zeros longitudinal components.

Geometry

The first step in the construction of the **E**-**B** Excitation Module SOI model is to import a tetrahedral finite element mesh of the structure, by selecting the **Mesh** button in the entry form and selecting the **"SOI Mesh.mat"** file found in the path: **"Examples\Excitation Module\B. SOI Waveguide\Mesh".** The dimensions of the SOI waveguide designed for operation at wavelength λ equal to 1550 nm and the dimensions of the computational domain (L_x, L_y, L_z along axes **x**, **y**, **z**) are listed in Table 5, while information about the tetrahedral mesh of the SOI mesh file can be found in

Table 6. The propagation axis of the structure coincides with the **x** axis and the longitudinal dimension of the computational domain equals half of a wavelength.

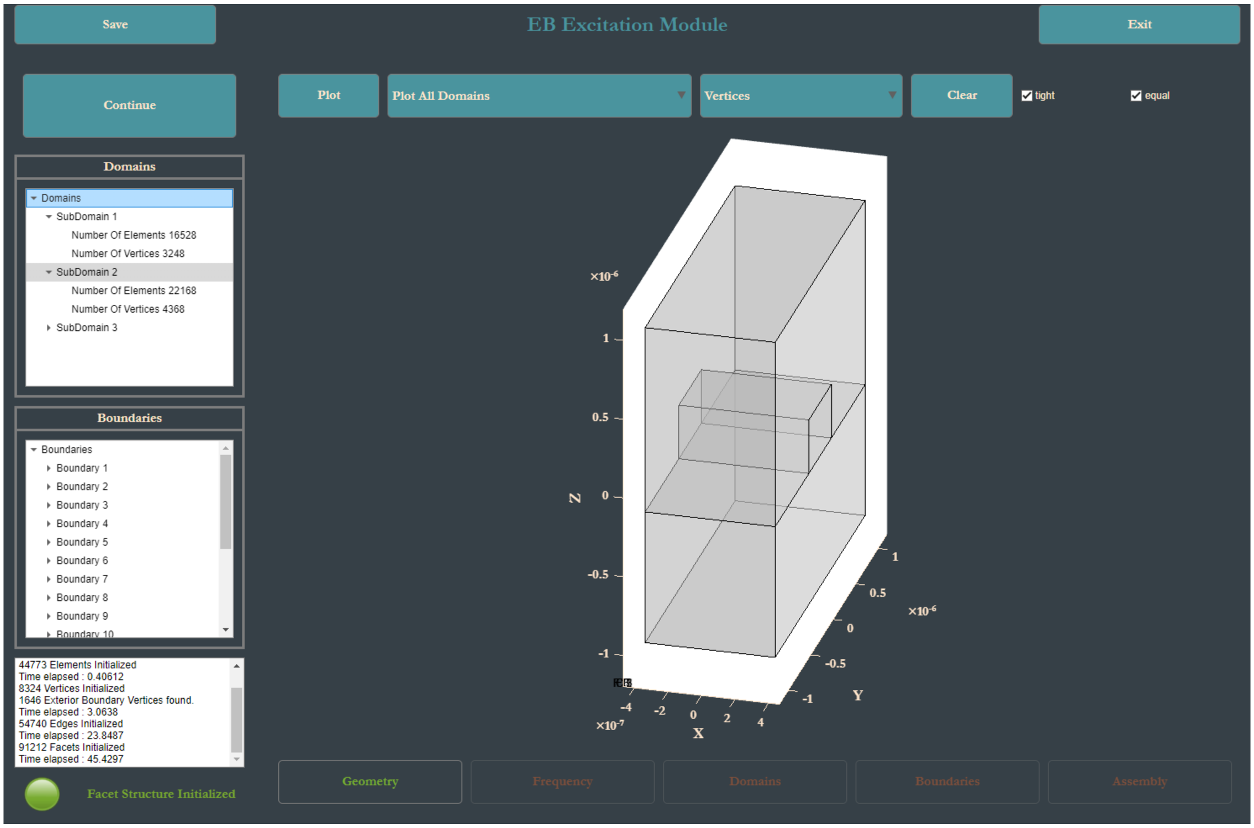

Figure 11. E-B Excitation Module - Silicon Over Insulator Waveguide Geometry.

Table 5. Parameters of Rectangular Waveguide.

S_x	S_y	S_z	C_y	C_z	L_x	L_y	L_z
0.775μm	2μm	830nm	500nm	340nm	0.775μm	2μm	2μm

Table 6. “SOI Mesh.mat” Information

#Vertices	#Elements	#Edges	#Facets	#Domains	#Boundaries
8324	44773	54740	91212	3	18

Frequency

The model is set up in single frequency mode by selecting the **Single Frequency** check box. The frequency input that corresponds to the wavelength of operation equals to 193.4165 THz (Figure 11).

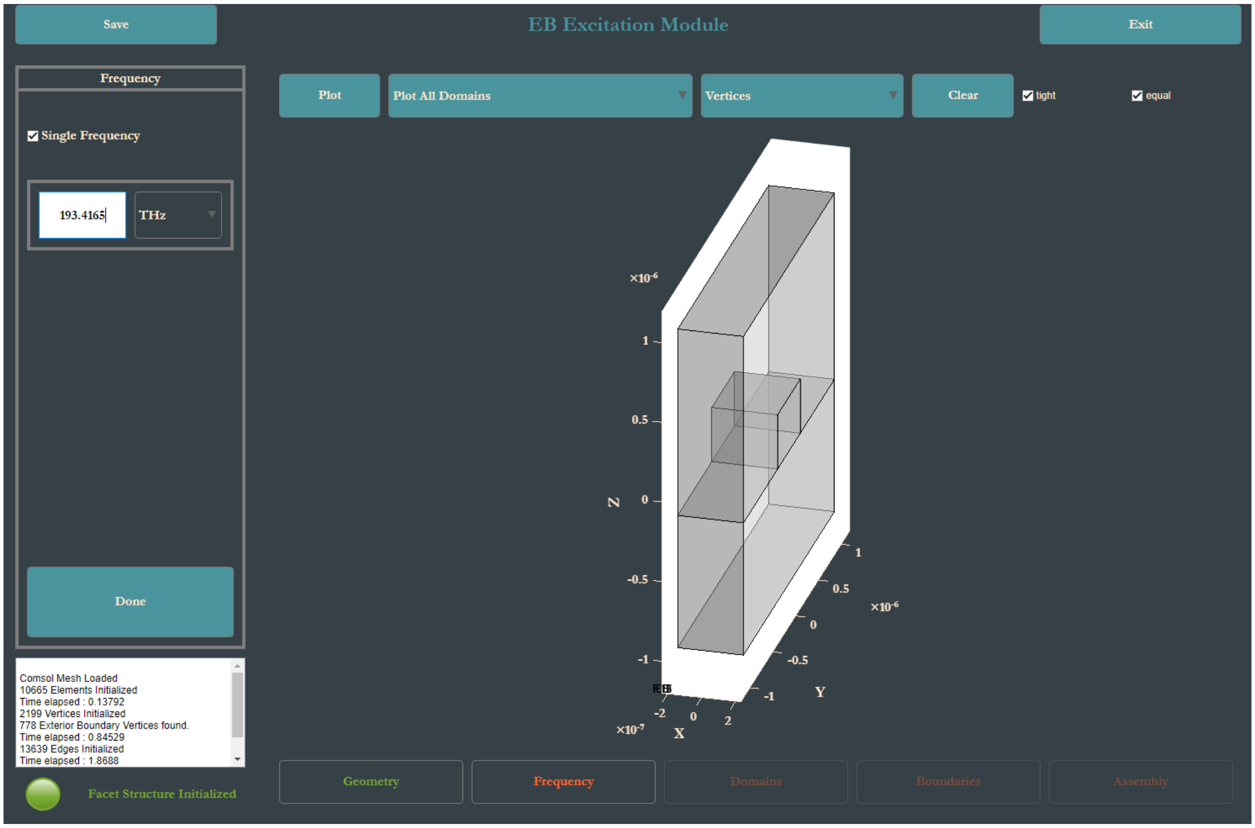

Figure 12. E-B Excitation Module - Silicon Over Insulator Waveguide Frequency.

Domains

The computational domain consists of three subdomains. The first subdomain is the silicon oxide substrate, the second the air surrounding the SOI waveguide and the third the silicon core. All three media filling these subdomains are isotropic and do not exhibit magnetic properties. The relative dielectric permittivity ε_{rSi} of silicon at the model's frequency is 11.9025, while the silicon oxide substrate has relative dielectric permittivity ε_{rSiO2} equal to 2.1025.

Boundaries

The SOI waveguide supports three hybrid electromagnetic modes each propagating with a different effective refractive index. In the case of this SOI waveguide mode, the first mode (in terms of smaller effective refractive index) excites the structure through one of the structure's **x** axis boundaries and exits the other, while the structure is surrounded by open space. To obtain the electromagnetic field distribution of the

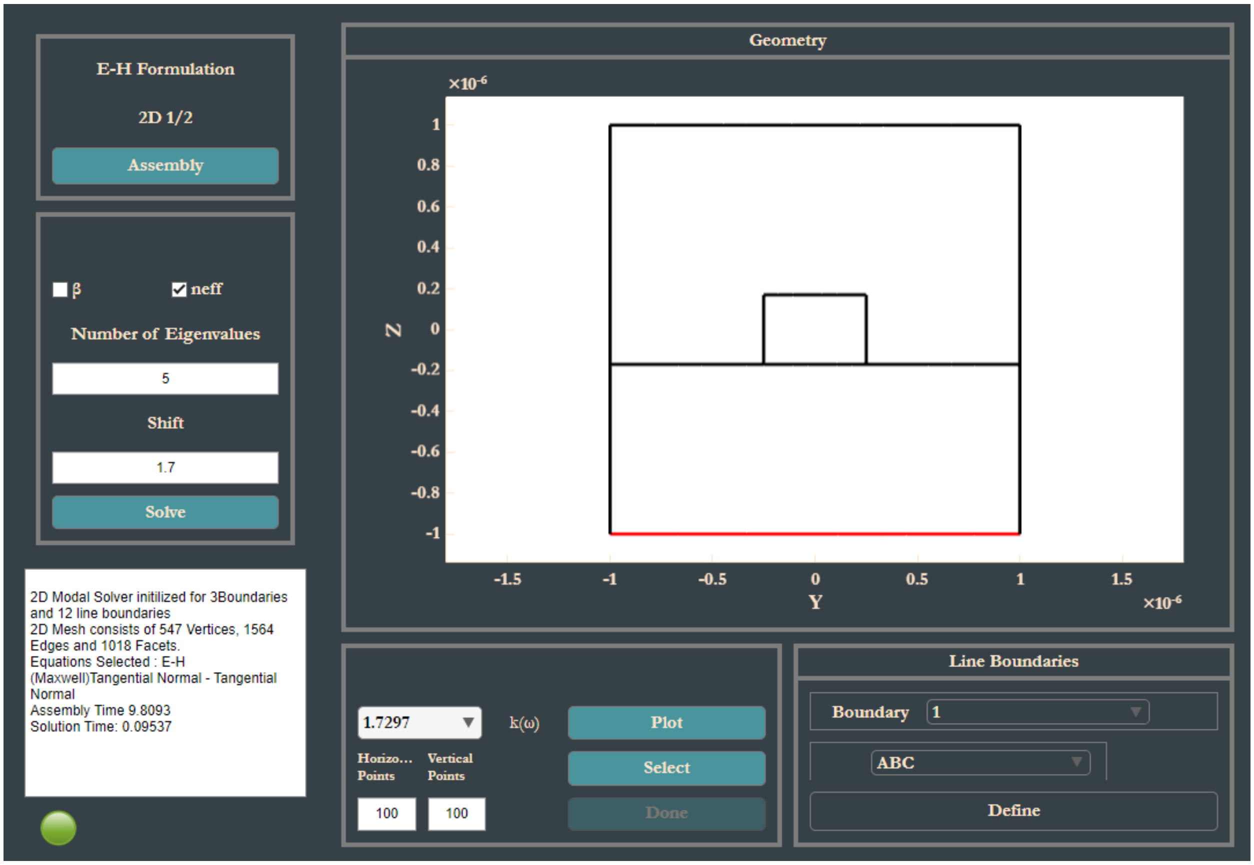

Figure 13. 2D Modal Eigen Solver app (post solution) - Silicon Over Insulator Waveguide

hybrid mode and the propagation characteristics of the SOI waveguide, a cross section of the structure must firstly be examined by means of the 2D Modal Eigen Solver app. The three boundaries that comprise the cross section of the SOI waveguide are boundaries 3, 10 and 17 (see Table 7). The user must first assign each of these three boundaries to the *Port Boundary Condition* and select the **2D ½ EigenSolver** button. After this, the user must engage the **Excitation** button for any of the three boundaries, which in turn prompts the 2D Modal Eigen Solver app (Figure 13).

The first step in setting up the two-dimensional eigenvalue problem in the 2D Modal Eigen Solver app is to assign the line boundaries to appropriate boundary conditions. As the SOI waveguide supported modes are strongly concentrated in the silicon core, the exterior line boundaries can be assigned to the *Perfect Electric Conductor* boundary condition without any loss of accuracy. Line boundaries 1, 2, 6, 7, 9 and 12 form the exterior of the two-dimensional computational domain. To assign each of

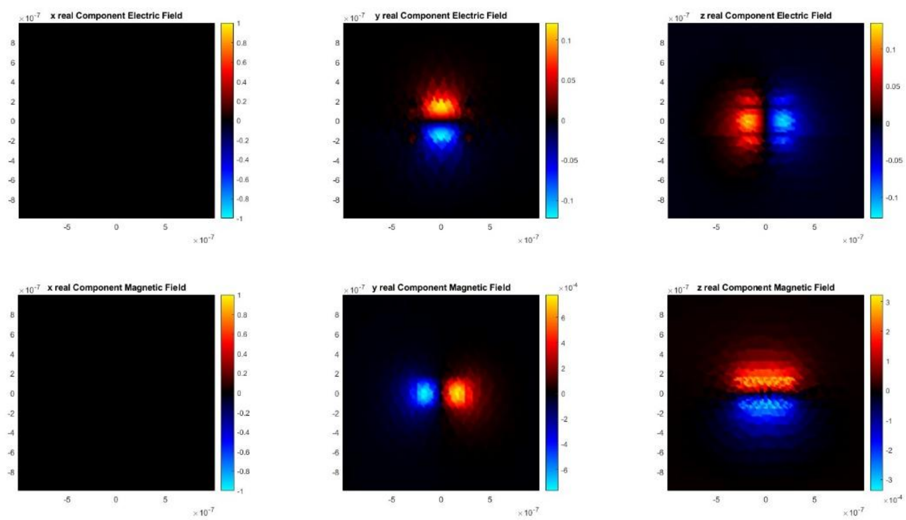

Figure 14. SOI Waveguide – Eigenvector with eigenvalue n_{eff} = 1.7297. Real part components. (Upper Left Corner) E_x, (Upper Center) E_y, (Upper Right Corner) E_z, (Lower Left Corner) H_x, (Lower Center) H_y, (Lower Right Corner) H_z.

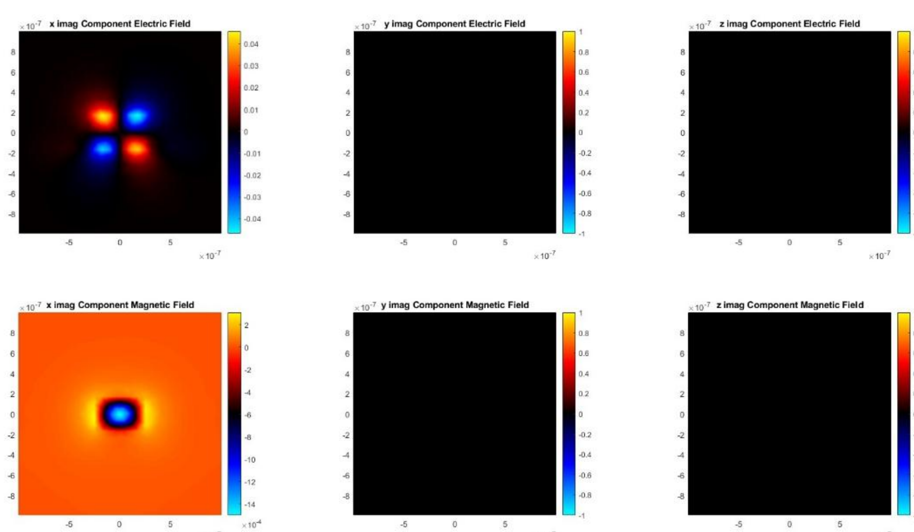

Figure 15. SOI Waveguide – Eigenvector with eigenvalue n_{eff} = 1.7297. Imaginary part components. (Upper Left Corner) E_x, (Upper Center) E_y, (Upper Right Corner) E_z, (Lower Left Corner) H_x, (Lower Center) H_y, (Lower Right Corner) H_z.

these line boundaries to the *Perfect Electric Conductor* boundary condition, the user must select the PEC entry in the drop-down selection in the Line Boundary panel on the lower right corner of the windows and click on the **Define** button.

Following the completion of the assembly process (**Assembly** button), the user must select the **neff** check box, switching the type of the eigenvalues of the problem from the propagation constant to the effective refractive index. The three hybrid modes supporting propagation in the SOI waveguide correspond to the effective refractive indices 1.7, 2.44, 2.68. As the three-dimensional model of the SOI waveguide is excited by the first hybrid mode, the eigenvalue shift should be set to the 1.7 value. The user can visually examine the resulting eigenvectors in the results panel and select the correct eigenpair. In the case of this application example, the eigenvalue equal to 1.7297 (Figure 14 and Figure 15) corresponds to the first hybrid mode.

Returning to the **E**-**B** Excitation module, the rest of the boundaries of the model require boundary condition assignments. All interior boundaries are left to the default *Continuity* boundary condition, while all exterior boundaries along the **y** and **z** axis are assigned to the *Absorbing Boundary Condition.* The three remaining exterior boundaries, located in the opposite side (to the port condition boundaries) along the **x** axis, form the output port of the structure. As a result, these boundaries must be assigned to the

Table 7. SOI Waveguide Boundaries

Boundary	Axis	Boundary Condition
1	$-\hat{z}$	ABC
2	$-\hat{y}$	ABC
3	$-\hat{x}$	Port
4	$\hat{x}$	Port ABC
7	$\hat{y}$	ABC
9	$-\hat{y}$	ABC
10	$-\hat{x}$	Port

11	$\hat{\boldsymbol{x}}$	Port ABC
13	$\hat{\boldsymbol{z}}$	ABC
16	$\hat{\boldsymbol{y}}$	ABC
17	$-\hat{\boldsymbol{x}}$	Port
18	$\hat{\boldsymbol{x}}$	Port ABC

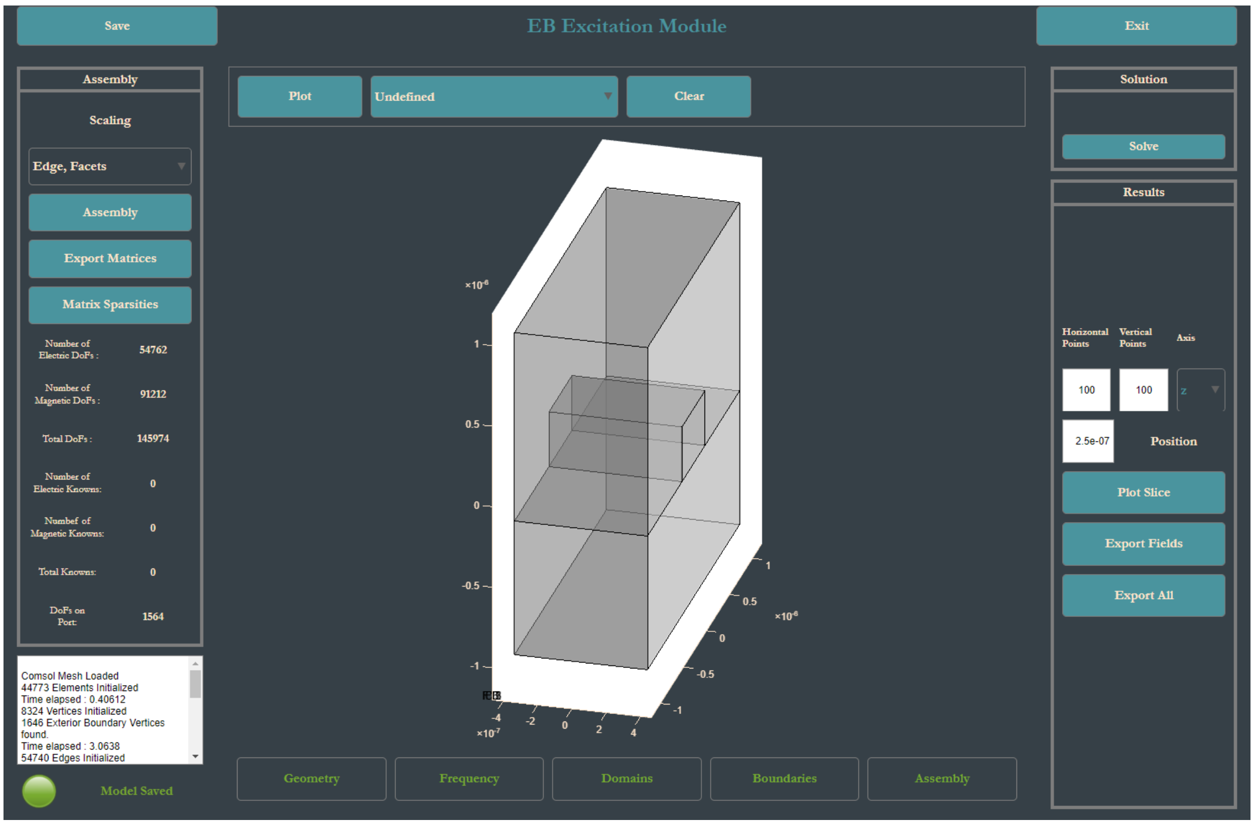

Figure 16. E-B Excitation Module- Assembly.

Port ABC boundary condition by selecting the **Port ABC** entry from the boundary type drop down selection. As this no-feed port will output the same hybrid mode that enters the structure, the propagation constant β for all *Port ABC* boundaries must be set equal to the eigenvalue obtained from the 2D Modal Eigen Solver times the vacuum wave propagation constant k_0, by selecting the **Propagation Constant** button and clicking on the β button. The input value for the β parameter of the first mode eigenvalue (n_{eff} = 1.7297) equals 7.0116 1e6.

Assembly

The final step of assembling and solving the SOI Waveguide problem (Figure 16) leads to the algebraic solution of a 145974 Degrees of Freedom problem, with the resulting electric **E** and magnetic flux density **B** depicted in Figure 17.

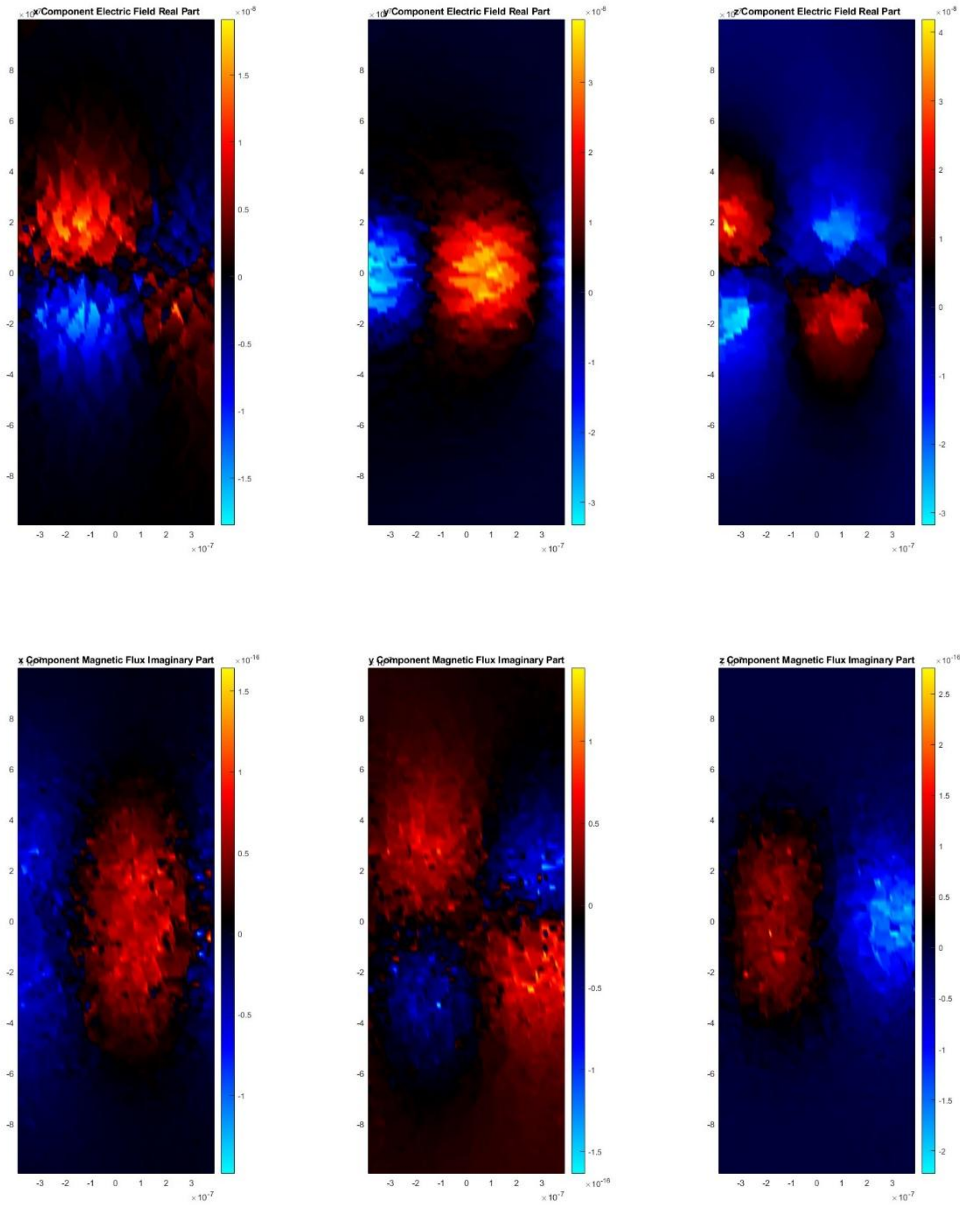

Figure 17. Electromagnetic Propagation in SOI Waveguide at 193.4 THz. xy plane at z = 0.25 μm. (Upper Left Corner) real part E_x component, (Upper Center) real part E_y component, (Upper Right Corner) real part E_z component,

(Lower Left Corner) imaginary part B_x component, (Lower Center) imaginary part B_y component, (Lower Right Corner) imaginary part B_z component.

[1] Tong, X. C. (2014). *Advanced materials for integrated optical waveguides* (Vol. 46, pp. 509-543). Cham: Springer International Publishing.