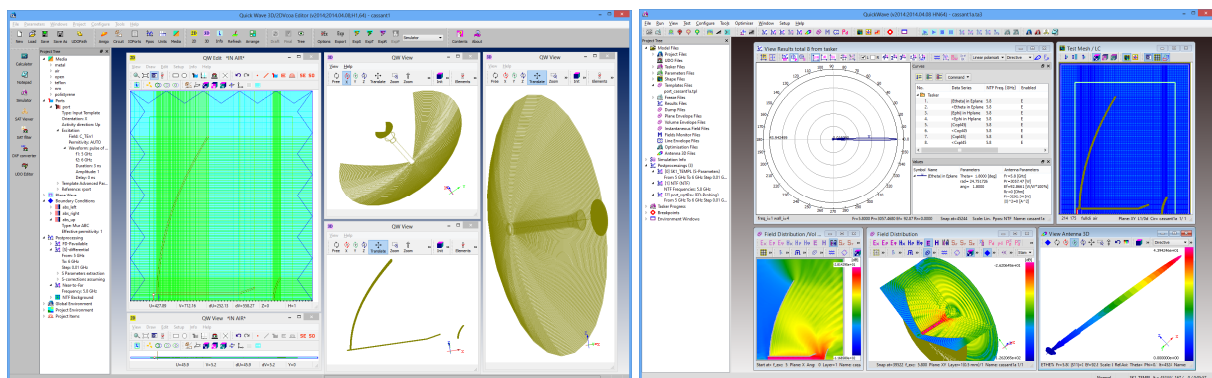


# QUICKWAVE 2014

SOFTWARE FOR ELECTROMAGNETIC DESIGN AND SIMULATIONS

DEMO VERSION

Description of metamaterial examples





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# 1. General Information about QuickWave-3D software

## 1.1 Scope of applications of QW-3D package

*QuickWave-3D* is a general-purpose electromagnetic simulator based on the conformal FDTD method and supplemented with a range of unique models for curved boundaries, media interfaces, modal excitation, and parameter extraction. *QW-3D* history is quite long. The first 2D version of *QuickWave* developed by professor W.Gwarek appeared in 1991. Then in 1997 the first 3D version with graphical user interface was introduced on the world's market by the company named QWED (founded by W.Gwarek, M.Celuch, M.Sypniewski and A.Wieckowski). *QW-3D* quickly gained its first renowned customers like Saab Ericsson Space of Sweden, or two NASA related laboratories National Radio Astronomy Laboratory (Charlottesville, VA) and Jet Propulsion Laboratory (Pasadena CA). It has a well-established position on the world's market since then although QWED did not focus on great number of licenses but rather on approaching specific, challenging problems (often bound to QWED's specialists participation in the customer's projects as consultants). Due to that kind of approach *QW-3D* has a very broad variety of information which can be extracted from the simulations in a form of different pre-processings, co-processings and post-processings. The specific features of *QW-3D* include possibility of simulation of various frequency dependent and anisotropic media in scenarios including various periodic or symmetric boundary conditions. Special attention has been paid to assuring effective analysis of microwave heating problems. The software has been prepared to work in sophisticated regimes, modelling even complicated trajectories of movement of the heated load. Transfer of the heat generated by electromagnetic fields can be modelled with internal Heat Transfer Module or by coupling *QW-3D* simulations to external computational fluid dynamics packages. On our website you can find a document *qw\_features.pdf* ([http://www.qwed.eu/qw\\_features.pdf](http://www.qwed.eu/qw_features.pdf)) in which we have listed specific features of *QW-3D* packages. We encourage the readers to look through it and to find out if some of them can be useful in their work while they are not available in other packages.

Speed of computing has been in the focus of *QW-3D* software developers since its early days. Our tests indicate that we are faster (on the same hardware) than other general purpose packages. We are putting a lot of effort to keep pace with the hardware development. Thus we have a variety of options for the optimum speed of computing on various CPU and GPU configurations. If you are interested please refer to the document *qw\_gpu.pdf* ([http://www.qwed.eu/qw\\_gpu.pdf](http://www.qwed.eu/qw_gpu.pdf)).

*QW-3D* consists of two main units: *QW-Editor* and *QW-Simulator*.

## 1.2 *QW-Editor (supported by QW-AddIn for Autodesk® Inventor® Software)*

*QW-Editor (supported by QW-AddIn for Autodesk® Inventor® Software)* is a unit, which permits graphical definition of 3D structures, mesh generation, and specification of simulation parameters via a convenient system of dialogue boxes. *QW-Editor* contains all necessary basic functions for generation of 3D shapes. They are quite straightforward in application to simple shapes like in the metamaterial examples considered here. It is also possible to introduce complex shapes built out of simple primitives directly in the *QW-Editor*. Such a system assures full control of the user over the shape and meshing so that it leads to scenarios which are optimum from the point of view of the computing efficiency. That kind of approach is most recommended in scientific investigations. However in application to industrial design, engineers typically prefer to use one of popular CAD tools for the shape definition. That kind of



option is available with *QW-AddIn for Autodesk® Inventor® Software* module. That module is addressed to the users who already have a license of *Autodesk® Inventor® Software* (or are prepared to acquire it). *QW-AddIn for Autodesk® Inventor® Software* package generates a set of *QW-Editor* icons in the *Autodesk® Inventor® Software* interface. The shape of the structure to be analysed is generated in (or imported to) *Autodesk® Inventor® Software*. Then the basic parameters describing the task of electromagnetic simulations are introduced using *QW-AddIn for Autodesk® Inventor® Software* functions. The simulation is started directly from the *Autodesk® Inventor® Software*, with *QW-Editor* run being executed without its interface being visible. If you are interested in getting more information about *QW-AddIn for Autodesk® Inventor® Software* please refer to the document *qw\_addin.pdf* ([http://www.qwed.eu/qw\\_addin.pdf](http://www.qwed.eu/qw_addin.pdf)).

The simulation process is initiated in *QW-Editor* (or in the *QW-AddIn for Autodesk® Inventor® Software* if it is used). *QW-Editor* exports to disk a set of files describing the shape to be considered and the required parameters of simulation. Those files are then processed by *QW-Simulator*.

If you are interested in getting more detailed information about the *QW-Editor* and its functionalities please refer to *QW-Editor* manual, available in *QW-Editor Help*.

### **1.3 QW-Simulator**

*QW-Simulator* operation starts from reading the files exported by *QW-Editor*. Then it generates the conformal FDTD mesh and assigns to each cell parameters taking into account the cell filling by a specific material, its shape (considering the local integral approximations for non-rectangular cells appearing at curved boundaries) and its neighbourhood (for possible inclusion of corrections of field singularities). Then the FDTD simulation starts. It should be noted that *QW-3D Simulator* is very flexible in so called co-processings. The user can open arbitrary number of windows for display of field components (in various graphical display systems and at any simulation stage), dissipated power, Poynting vector etc. The decisions about the number and type of the windows showing values deliverable from the instantaneous filed components do not need to be taken prior to launching the simulation. There are some other types of displays which require from the software a priori knowledge about the data to be accumulated during simulations. This concerns mostly the tasks requiring calculation of the Fourier transformation of fields like in the case of the antenna patterns, S-parameters or field distribution at a particular frequency extracted from pulse excitations (so called FD-Monitors). Those tasks need to be predefined in *QW-Editor* in the box of *Parameters–Postprocessings*. Anyway in the cases of both co-processings and post-processings the user has a high flexibility in choosing what and in what graphical form he wants to see. Thus we encourage the users of *QW-Simulator* (including those interested in Metamaterial DEMO examples) to experiment with *QW-Simulator* windows to get the nicest and the most informative pictures. All the useful information about the available features and functionalities of *QW-Simulator*, which can help you to work and get familiar with our tool, have been gathered in QW manuals: *QW-Simulator* manual and *QW-3D User Guide*. In *QW-Simulator* manual you can find a comprehensive description of all the available options and the *QW-3D User Guide* will guide you through the simulation examples that will show you how those options can be used in practice. The manuals are available in *QW-Simulator Help*.



## 2. How the QW-Demo is organized and what is its functionality

*QW-DEMO* contains *QW-3D* software with a limited functionality. The user can run only predefined examples although he can perform most of the functions of the graphical user interface of both *QW-Editor* and *QW-Simulator*. However in *QW-Editor* a modified projects cannot be stored or exported to *QW-Simulator*. When a simulation of a particular DEMO project is launched from *QW-Editor*, the *QW-Simulator* ignores the current output of *QW-Editor*. Instead it reads the files stored previously under the same name and starts simulation of the DEMO example. During the simulation of a DEMO example the user can profit from full flexibility of the *QW-Simulator* graphical outputs. He can open as many windows as he wishes and choose the most convenient type of display, its scale and colour palette. The DEMO users are encouraged to enjoy the flexibility of *QW-Simulator* displays and produce picture they can store for their future work. It is worth mentioning that for each example, all the specific window settings that the user will choose while working with *QW-Simulator* (windows' arrangement and sizes, display type, colour palette, scale, etc.) will be saved in the external file when exiting the *QW-Simulator*, and will be again loaded during the next usage of *QW-Simulator*.

Standard *QW-3D DEMO* contains a variety of examples from different areas of applications. Those examples are described in details in the *QW-3D User Guide*. Please run a few examples from your area of interest and if you have questions please contact QWED support at: [support@qwed.eu](mailto:support@qwed.eu) or [molszewska@qwed.eu](mailto:molszewska@qwed.eu). If you are interested only in the metamaterial examples please continue by reading the next section of this material.



### 3. User Guide for running QW-DEMO Metamaterial examples

The metamaterial examples included in *QW-3D DEMO* are a set of specially prepared examples, discussed in the article:

[1] W.Gwarek "Understanding Propagation and Negative Refraction in Metamaterials Through Time-Domain Simulation" published in *Microwave Magazine*, Vol.15, June 2014. pp. 56 - 65.

Attention: The images generated with the *QW-DEMO* discussed in this document can be used for any purpose and published without prior consent of the authors providing that they contain a clear reference to both, publication [1] and QWED web page [2]:

[2] [http://www.qwed.eu/metamaterial\\_examples.html](http://www.qwed.eu/metamaterial_examples.html).

This section will guide you through those examples indicating step by step what should be done to see the effects described in the article.


The examples are stored in (default path) *C:\Users\Public\QWED\v2014DEMO\qw\_examp\QW\_3D\Standard\Metamaterial* folder, in separate sub-directories from *MM\_Ex1* to *MM\_Ex8*.

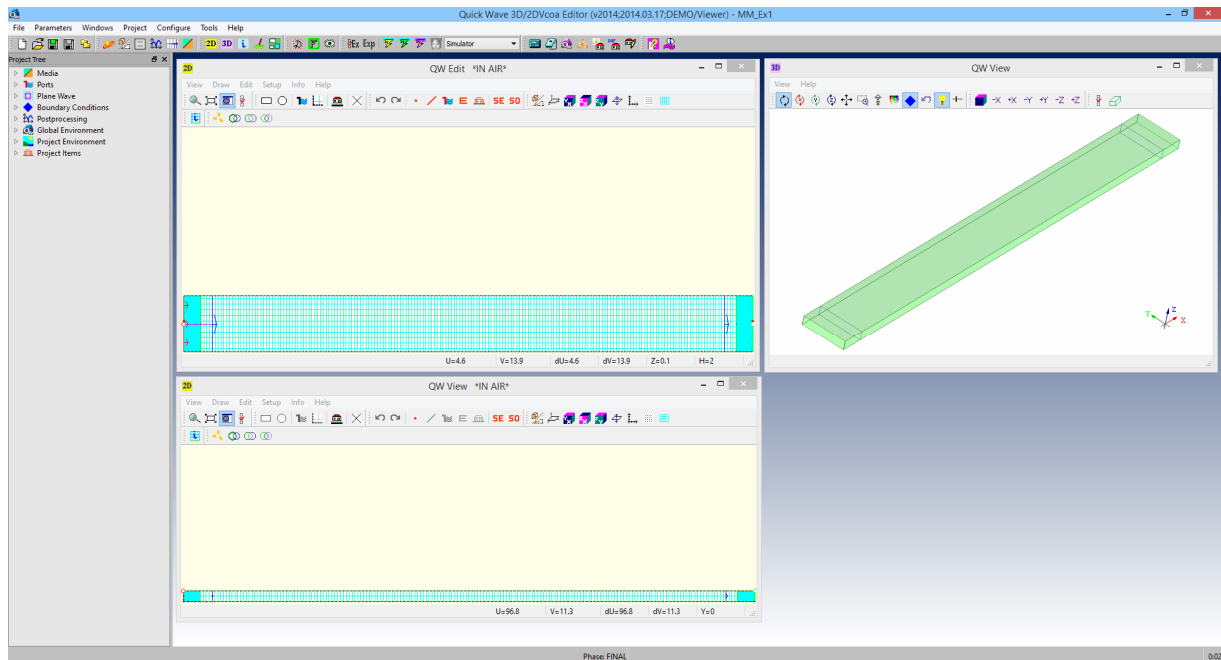
#### 3.1 Example 1

Perform the following operations:

Ex1.1 Open *QW-Editor*. It can be done in a few ways:

- By running *qed.exe* file from DEMO directory (the default path is *C:\Program Files (x86)\QWED\QW\_3D\v2014DEMO\qwin*),
- By using *QW 3D&V2D Editor* shortcut, which is created during the installation. The shortcut can be found on a *Desktop* in *QuickWave 3D&V2D v2014 DEMO* directory or in *Start Menu* under *QuickWave→QuickWave 3D&V2D v2014 DEMO*.


Ex1.2 Press the *File-Load* icon () and open *MM\_Ex1.pro* example from the *MM\_Ex1* folder in DEMO examples directory. The following screen should appear:

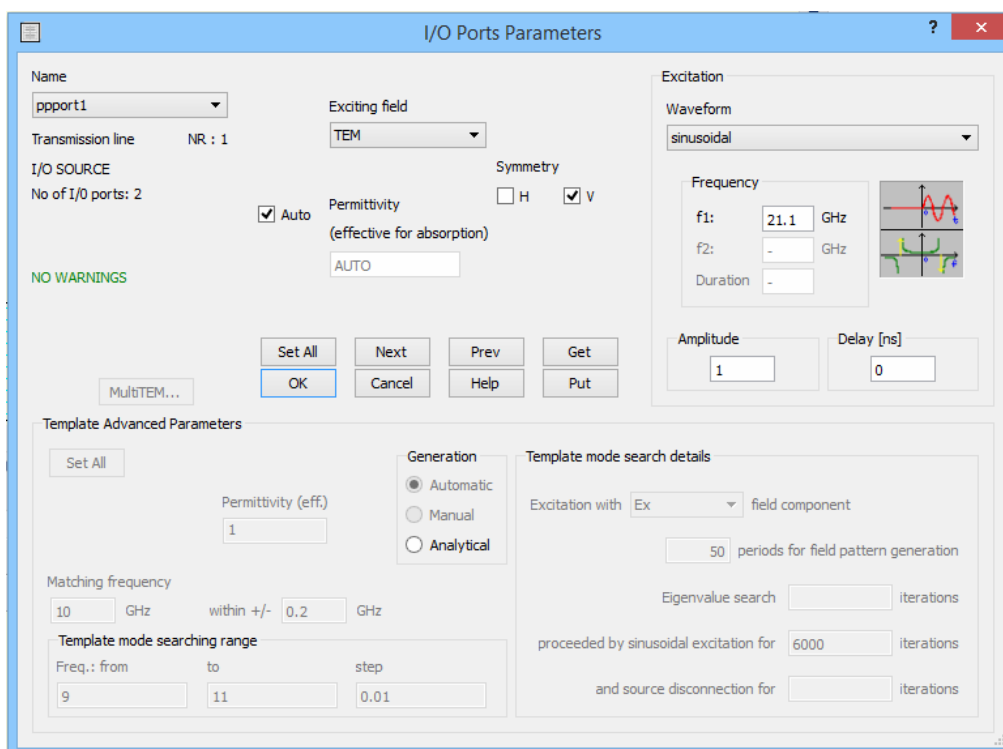


**Figure 1** QW-Editor window with the metamaterial Example 1 loaded.

In this example a TEM line filled with double-Drude medium (named *mmdr1*) is analysed. In the main QW-Editor window you may see three additional windows, showing the project's geometry. Two of them (top left and bottom left) show a 2D views of the TEM line in two different planes (XY and ZX plane) and the third one (top right) presents a perspective view of the structure.

Ex1.3. If you are just interested in running the example proceed to Ex1.10. If you want to find out more about simulation parameters set for this example continue to step Ex1.4



Ex1.4. If you would like to check the excitation parameters set for this example press the *Parameters-I/O Ports* icon (). The following dialogue will appear in the QW-Editor window:



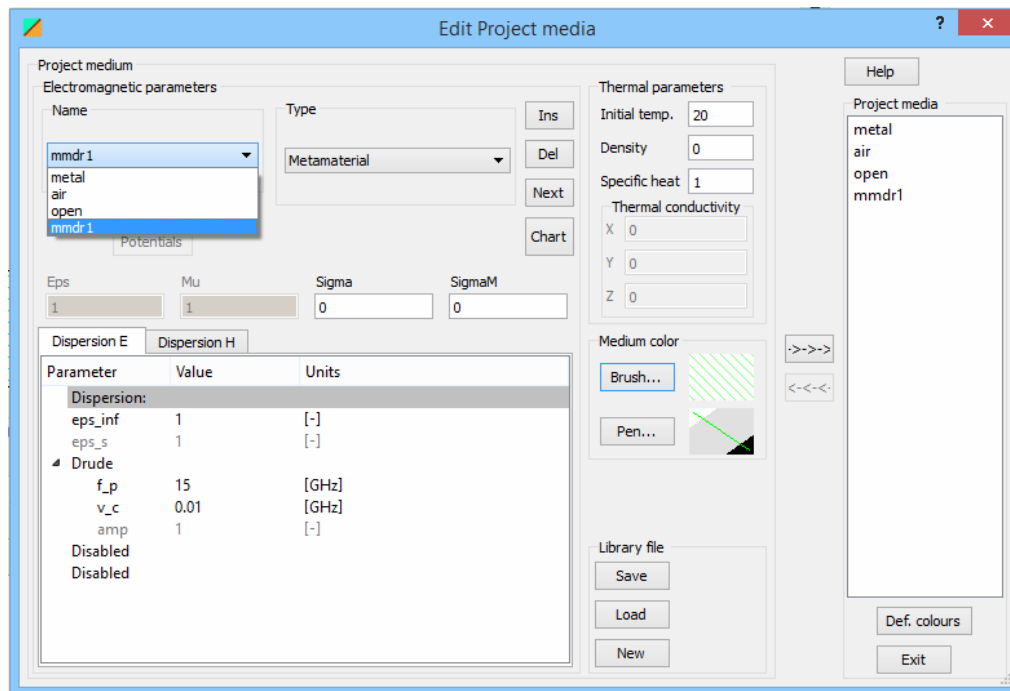
**Figure 2** *Parameters-I/O Ports* dialogue for defining excitation settings - parameters for Example 1.

As you may see the exciting mode has been set to TEM and the sinusoidal signal at frequency 21.1 GHz has been used for excitation. The user is also encouraged to roll out the *Exciting field* and *Waveform* lists to check what other excitation options are available for analysis in QW-3D.

Ex1.5. Exit *Parameters-I/O Ports* dialogue.

Ex1.6. Press *Parameters-Media* icon () to find out more about the media used in Example 1. After pressing  the following dialogue will appear:

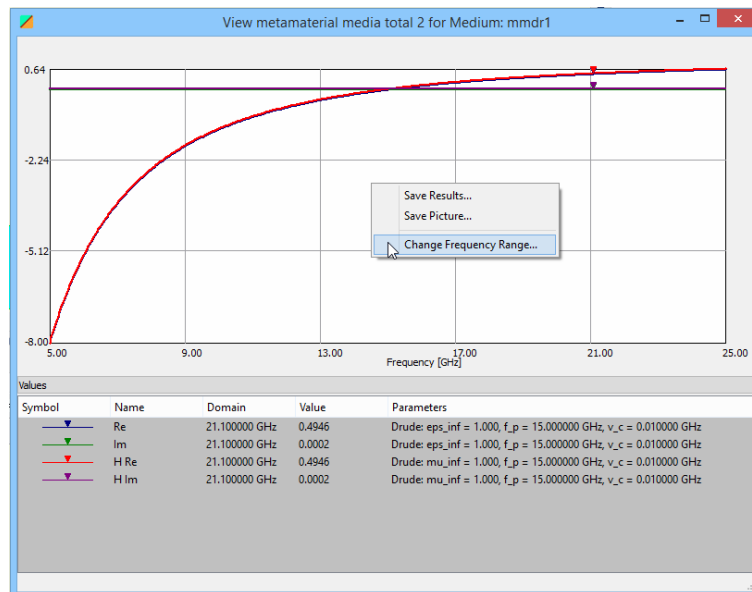




**Figure 3** Parameters-Media dialogue for setting media parameters (*mmdr1* medium parameters) – Example 1.

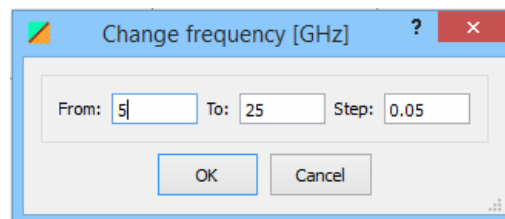
Each medium used in the project requires its parameters to be defined. In this example the TEM line is filled with medium called *mmdr1*. Choose *mmdr1* medium from the list on the left and its parameters will appear below. The medium type was chosen to *Metamaterial* (*Type* list) and both, electric (E) and magnetic (H) dispersion models have been set to *Drude*. In the considered example, single pole dispersion is assumed for both permittivity and permeability, that way the other two poles, also available for analysis in *QW-3D*, are *Disabled*.

After clicking *Chart* button (available for *Dielectric dispersive* and *Metamaterial* media), the window will show the frequency dependence of the real and imaginary part of electric and/or magnetic parameters of the model.



**Figure 4a** Dispersive Media Info window for a Metamaterial after pressing Chart button.


The frequency range and step in the chart can be changed via *Change Frequency Range...* option available in the context menu after pressing right mouse button:

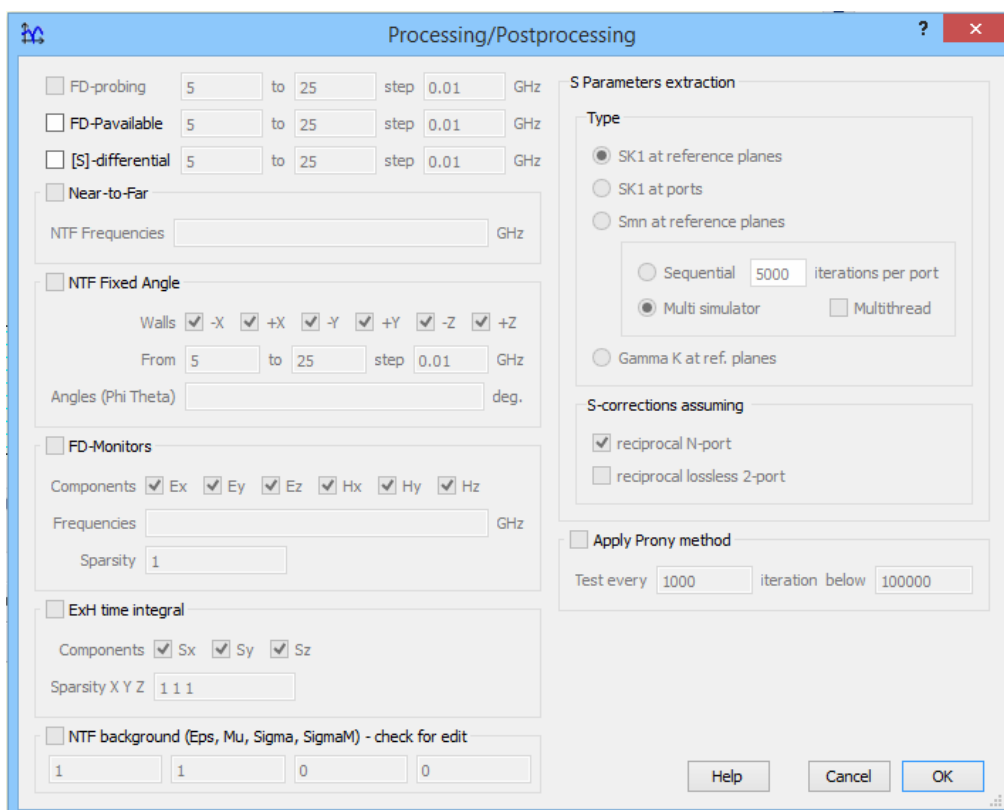


**Figure 4b** Change frequency dialog box.

You may feel free to check what other medium types are available for analysis in QW-3D package (Type list).

Ex1.7. Exit *Parameters-Media* dialogue.


Ex1.8. Press *Parameters-Postprocessing* icon () to check what simulation post-processings have been enabled for Example 1. The following dialogue will appear:



**Figure 5** *Parameters-Postprocessing* dialogue for enabling simulation post-processings – Example 1.

You can notice that in this example none of the available post-processings has been chosen. This is because only the field distribution (co-processing) is under interest for the considered structure.

Ex1.9. Exit *Parameters-Postprocessing* dialogue.

Ex1.10. Press *File-Export, Run & Start* icon (  ) to start *QW-Simulator* and run the simulation. After pressing the icon *QW-Simulator* window will appear:

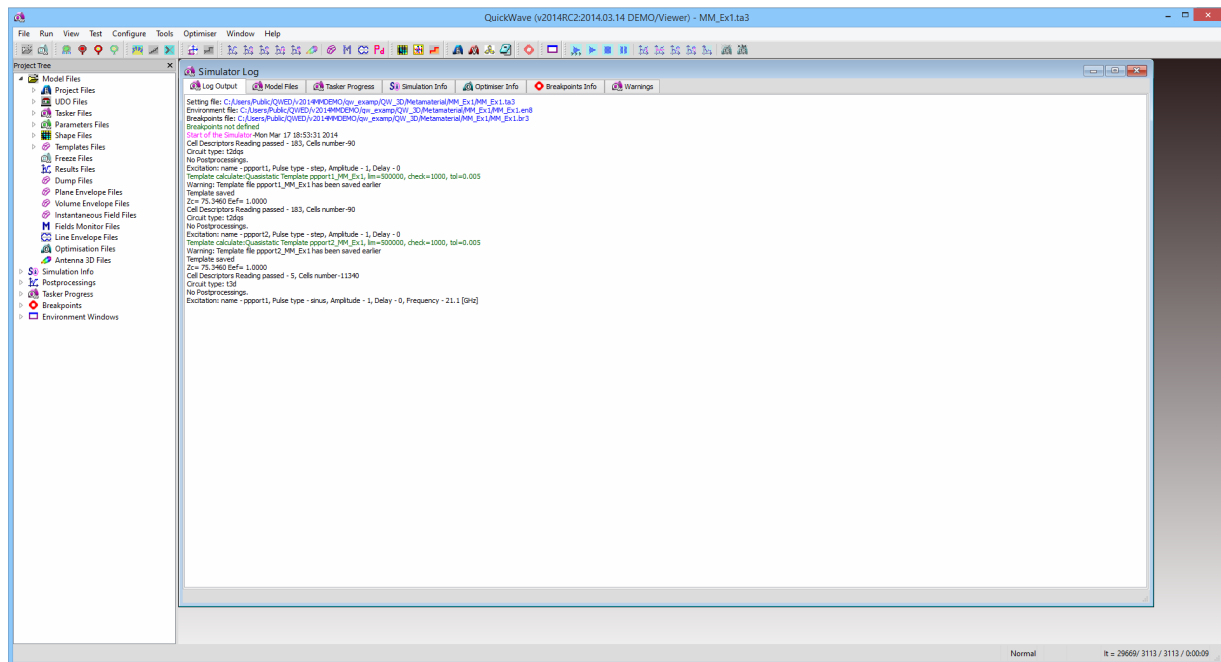





Figure 6 QW-Simulator window for metamaterial Example 1.

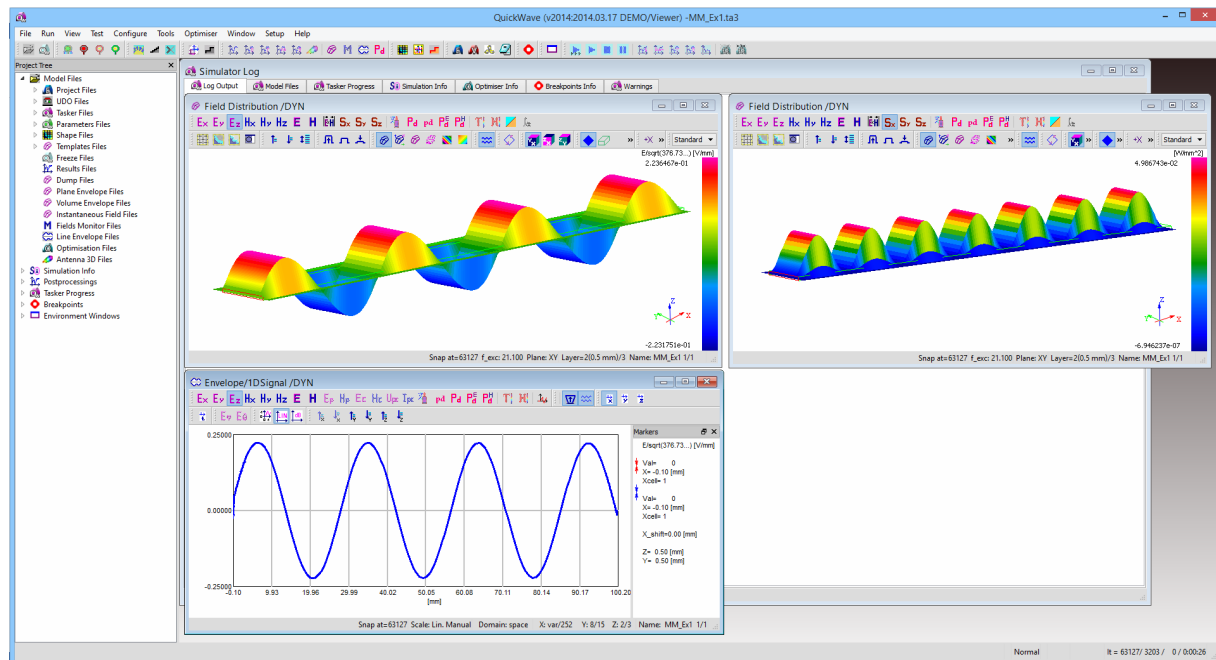
What may be interesting and useful for the user are: the number of FDTD iterations that have been already performed, simulation speed in iterations per second and the total simulation time elapsed, which are given in the status bar in the right bottom corner of the *QW-Simulator* window.

Ex1.11. Press *View-Fields* icon () to see the distribution of the electric field in the slab.


Ex1.12. Press *View-Fields* icon () for the second time to view the distribution of x-component of the Poynting vector in the slab.

Ex1.13. Press *View-Envelope* icon () to see the distribution of the electric field along the slab on one-dimensional display.





Ex1.14. After performing steps Ex1.11-Ex1.13 the following windows' setup will appear:



**Figure 7** QW-Simulator window with fields' distribution windows in Example 1.


Ex1.15. On the top left display you can see an instantaneous distribution of the  $E_z$  component of the electric field, in one of three planes (XY plane chosen). The top right display enables the investigation of the x-component of the Poynting vector, in the same plane. The lower display presents the distribution of the electric field  $E_z$  component along the 0x axis. As you can see the pictures available in all three windows move smoothly during the simulation. This is because the displays use an option enabling the results dynamically changing with every FDTD iteration (  icon pressed).




Ex1.16. If you would like to find out how to suspend the simulation for a moment and then resume your investigations continue to the next step. Otherwise proceed to step Ex1.18.

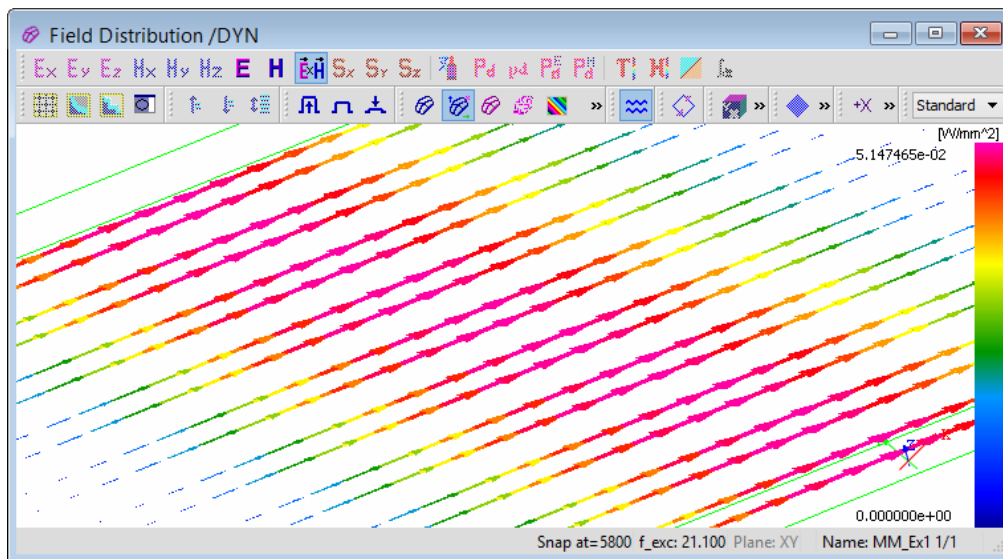
Ex1.17. Press *Run-Suspend* icon (  ) at any time when you want to suspend the simulation for some time. If you want to resume the simulation and your observations press *Run-Resume* icon (  ). You can also stop the simulation by pressing *Run-Stop* icon (  ) and start it once again if required by pressing *Run-Start* icon (  ).

Ex1.18. As you can see in *QW-Simulator* all three pictures move in +X direction. The  $S_x$  component of the Poynting vector, presented in the top right window, is positive along the line, which means that the energy flows from the source towards the load.

Ex1.19. If you would like to watch the envelope of the displayed components, use simple keyboard shortcuts. For enabling envelope calculations in *View-Fields* window, press the mouse button on the display to make it active and then press *E* button on the keyboard. For the envelope in *View-Envelope* window press *E+Shift* combination, while the window is active.

Ex1.20. The user is encouraged to press *View-Fields* icon () once again. The vector display, as in the following picture, showing Poynting vector will be opened. You can see the direction of the energy flow indicated with arrowheads and the direction of the wave phase, which is indicated with arrows motion.

We also encourage you to watch the distribution of the total electric and magnetic fields. They can be enabled by pressing **E** and **H** icons respectively. The magnitude of the fields' displays can be amplified () , adjusted () or attenuated () to fit the user preferences.




**Figure 8** *View-Fields* windows with vector display showing the Poynting vector

Ex1.20. You can close and open the windows at will. We encourage you to feel free in using other options available in those two kinds of windows (more information about available options can be found in *QW-Simulator* manual in Section S 2.4 and Section S 2.5, respectively). This will give you an insight in the calculation possibilities that gives *QW-3D*. In case of any questions do not hesitate to ask us ([support@qwed.eu](mailto:support@qwed.eu)).


Ex1.21. Press *Exit* button when you finish the observations and want to close the *QW-Simulator*. The windows' settings, their arrangement, etc. for a particular example will be saved in the external file and will be loaded when opening those windows in *QW-Simulator* for the next time.

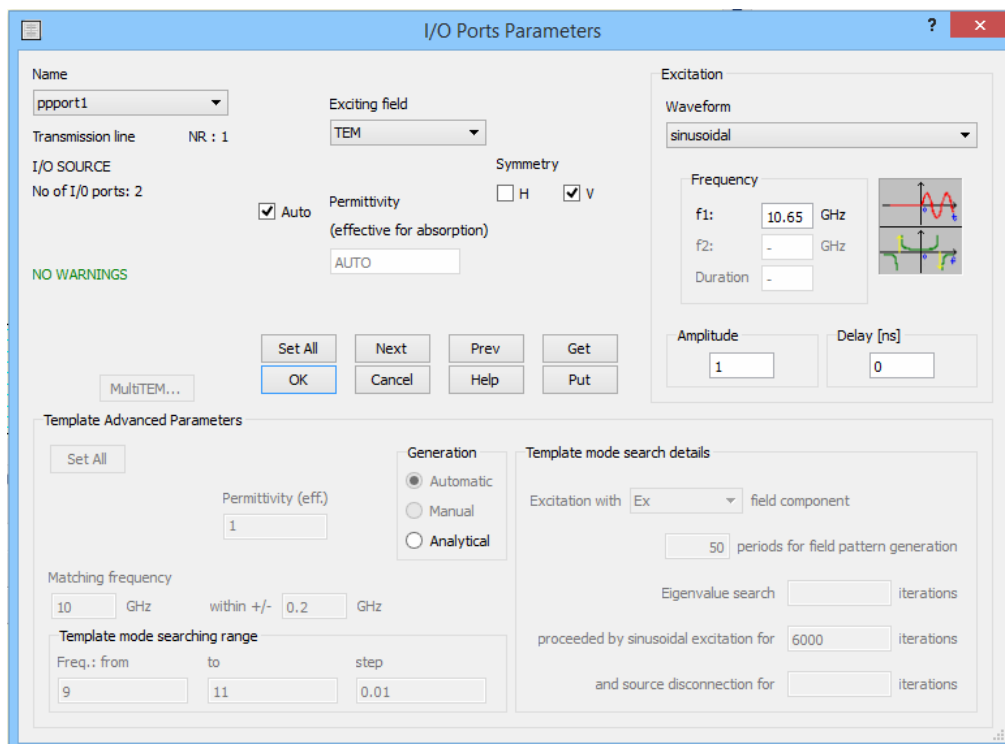
## 3.2 Example 2

Perform the following operations:

Ex2.1. Press the *File-Load* icon () and open *MM\_Ex2.pro* example from *MM\_Ex2* folder in the DEMO examples directory. The screen as in Figure 1 should appear.

Ex2.2. If you want to run the simulation immediately proceed to Ex2.6. If you are interested in checking how the excitation has been changed comparing to Example 1 continue to the next step.

Ex2.3. Press *Parameters-I/O Ports* icon () . The following dialogue will appear:





**Figure 9** *Parameters-I/O Ports* dialogue settings for Example 2.


As you can see sinusoidal frequency has been changed to 10.65 GHz, for which the LH wave is expected.


Ex2.4. Exit *Parameters-I/O Ports* dialogue.

Ex2.5. The media and post-processings settings in *Parameters-Media* and *Parameters-Postprocessing* dialogues remain as for Example 1.

Ex2.6. Press *File-Export, Run & Start* icon (  ) to start *QW-Simulator* and run the simulation.

Ex2.7. Press *View-Fields* icon (  ) to watch the distribution of the electric field in the slab.

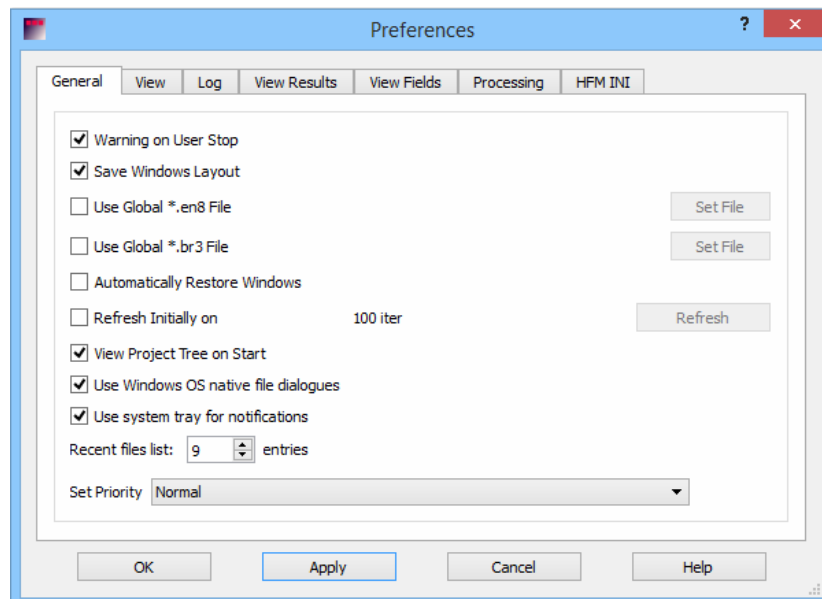
Ex2.8. Press *View-Fields* icon (  ) for the second time to observe the distribution of x-component of the Poynting vector in the slab.

Ex2.9. Press *View-Envelope* icon (  ) to see the distribution of the electric field along the slab on one dimensional display.



Ex2.10. If you would like to watch the field distribution from the very beginning of the simulation continue to the next step, if not proceed to step Ex2.13.

Ex2.11. Open *Configure-Preferences* dialogue (Figure 10) and check option *Automatically Restore Windows*. When the simulation starts for the next time, this option automatically opens all the windows that have been previously opened (for a particular example), before first FDTD iteration is performed.

The settings from *Configure-Preferences* dialogue are stored in computer Registry, so this option will be valid for all examples.

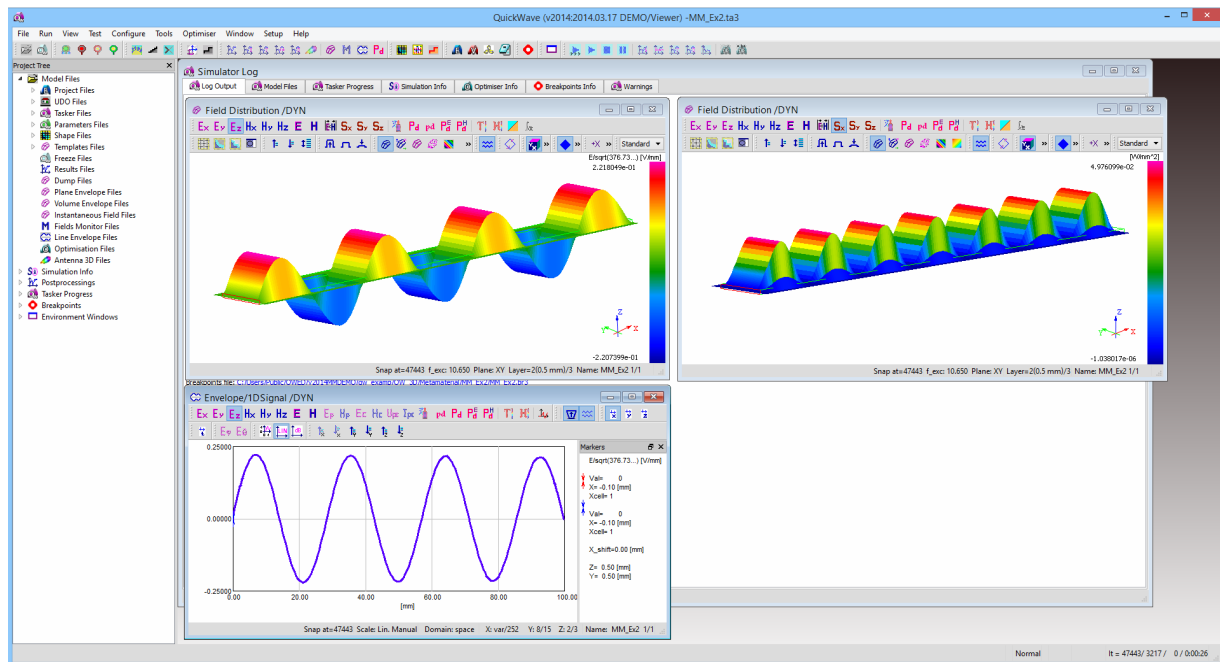


**Figure 10** *Configure-Preferences* dialogue.

Ex2.12. Stop the simulation using *Run-Stop* icon (  ). The information about which windows were opened will be stored. Then run the simulation once again using *Run-Start* icon (  ). The windows will be restored automatically before simulation starts.

Ex2.13. After performing the above steps the following windows' setup will appear:








**Figure 11** QW-Simulator window with fields' distribution windows in Example 2.

In the default setup the windows are organised as in Example 1: top left presents the distribution of  $E_z$  component of the electric field in XY plane, top right presents x-component of the Poynting vector in XY plane, and bottom left shows the distribution of the  $E_z$  component along 0x axis. The user can freely relocated the dialogues according to his preferences.

Ex2.14. Looking at all the displays we can clearly say that the wave phase moves in  $-X$  direction. At the same time you can see that the  $S_x$  component of the Poynting vector is positive along the line, which means that the energy moves from the source towards the load (in  $+X$  direction).

Ex2.15. Here, we also encourage you to press *View-Fields* icon () once again. The vector display for Poynting vector, as in Figure 8 will appear. Compare the direction of arrowheads (the energy flow direction) and the direction of arrows motion. You are also free to watch the distribution of the total electric () and magnetic () fields.


Ex2.16. If you want to enable envelope calculations in any window, press *E* (for *View-Fields* window) or *E+Shift* (for *View-Envelope* window) buttons on the keyboard.

Ex2.17. If you want to explore other options available in *QW-Simulator* please feel free to do that.

Ex2.18. Exit *QW-Simulator*.

### 3.3 Example 3

Perform the following operations:

Ex3.1. Press the *File-Load* icon () and open *MM\_Ex3.pro* example from *MM\_Ex3* folder in the DEMO examples directory. The following screen should appear:

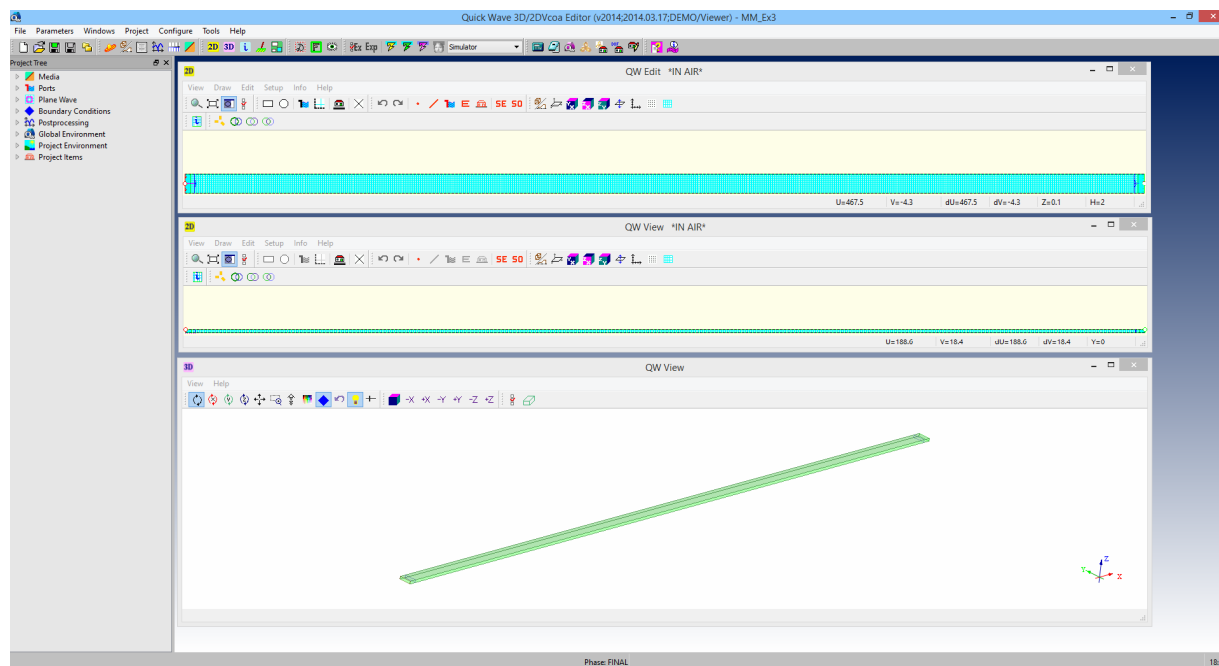

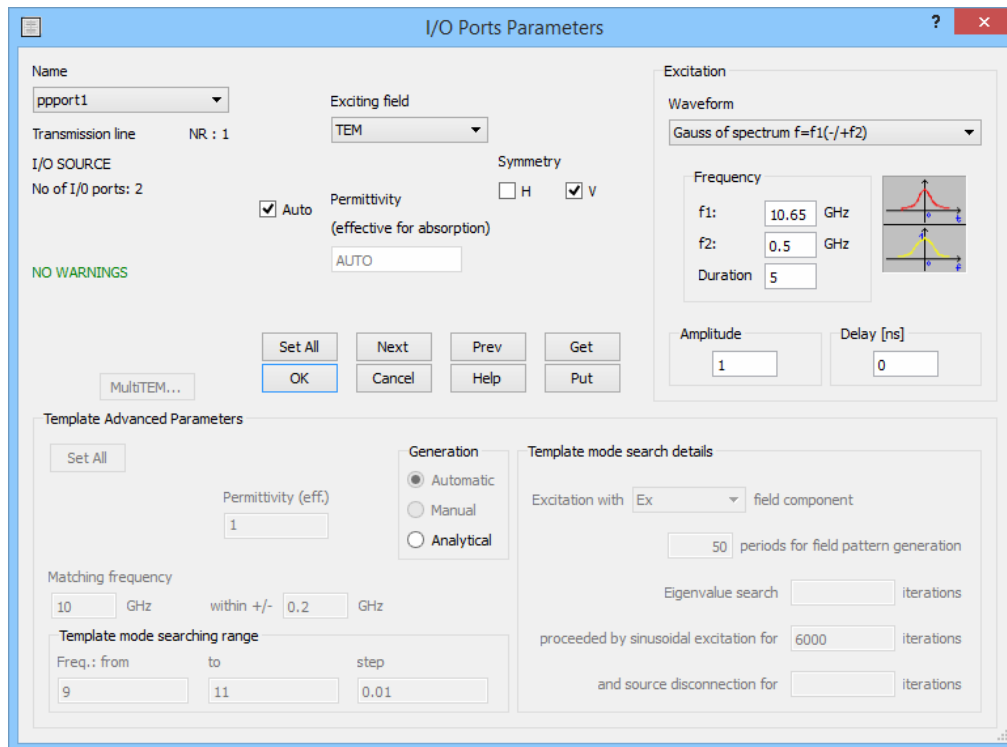


Figure 12 QW-Editor window with the metamaterial Example 3 loaded.

Ex3.2. If you are interested in checking the excitation parameters set for this example follow the next step, if not proceed to step Ex3.6.

Ex3.3. Press *Parameters-I/O Ports* icon () . The following dialogue will appear:




**Figure 13** *Parameters-I/O Ports* dialogue settings for Example 3.


As you can see the excitation has been set to Gaussian pulse with the spectrum centred at 10.65 GHz with the 3dB bandwidth of 1GHz.

Ex3.4. Exit *Parameters-I/O Ports* dialogue.

Ex3.5. The media and post-processings settings in *Parameters-Media* and *Parameters-Postprocessing* dialogues remain as for Example 1 and Example 2.

Ex3.6. Press *File-Export,Run & Start* icon (  ) to start *QW-Simulator* and run the simulation. After pressing the icon, *QW-Simulator* window will appear.

Ex3.7. Continue to step Ex3.8. or Ex3.9. to view the wave propagation in the double-Drude medium slab.

Ex3.8. Press *View-Fields* icon (  ) to watch the electric field distribution ( $E_z$  component) in the slab in XY plane. The following window will appear:

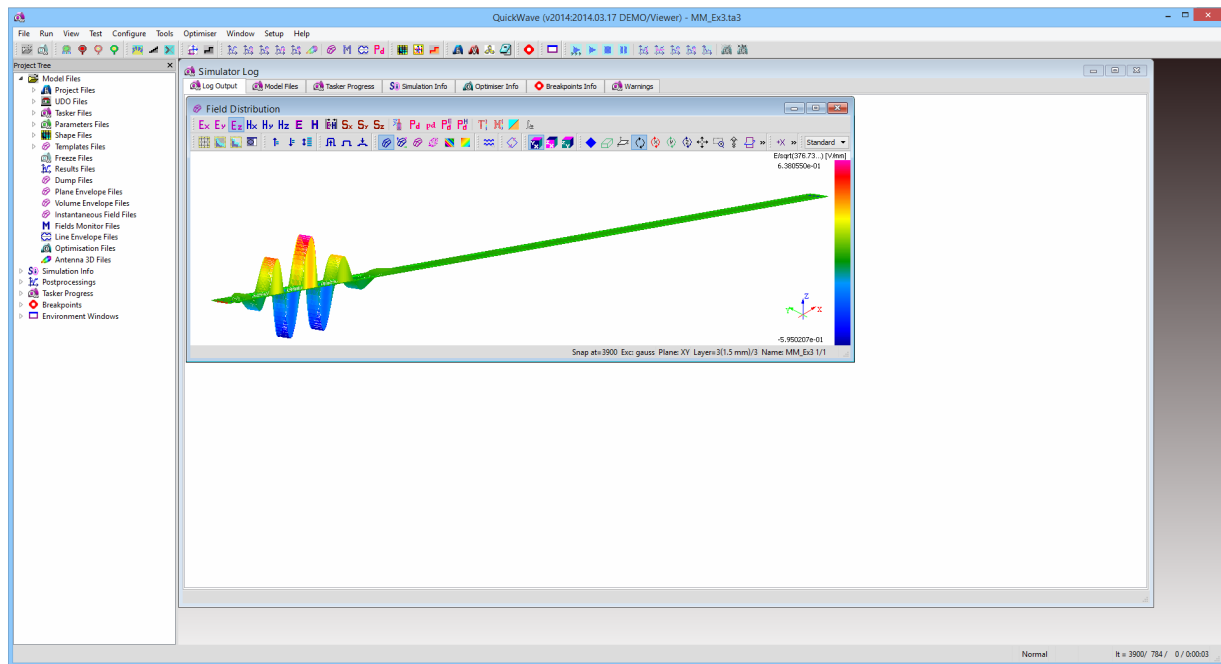



Figure 14 QW-Simulator window with View-Fields window in Example 3 (picture snapped at 3900 iterations).

Ex3.9. Press *View-Envelope* icon () to see the electric field distribution in the slab along Ox axis. The following window will appear:

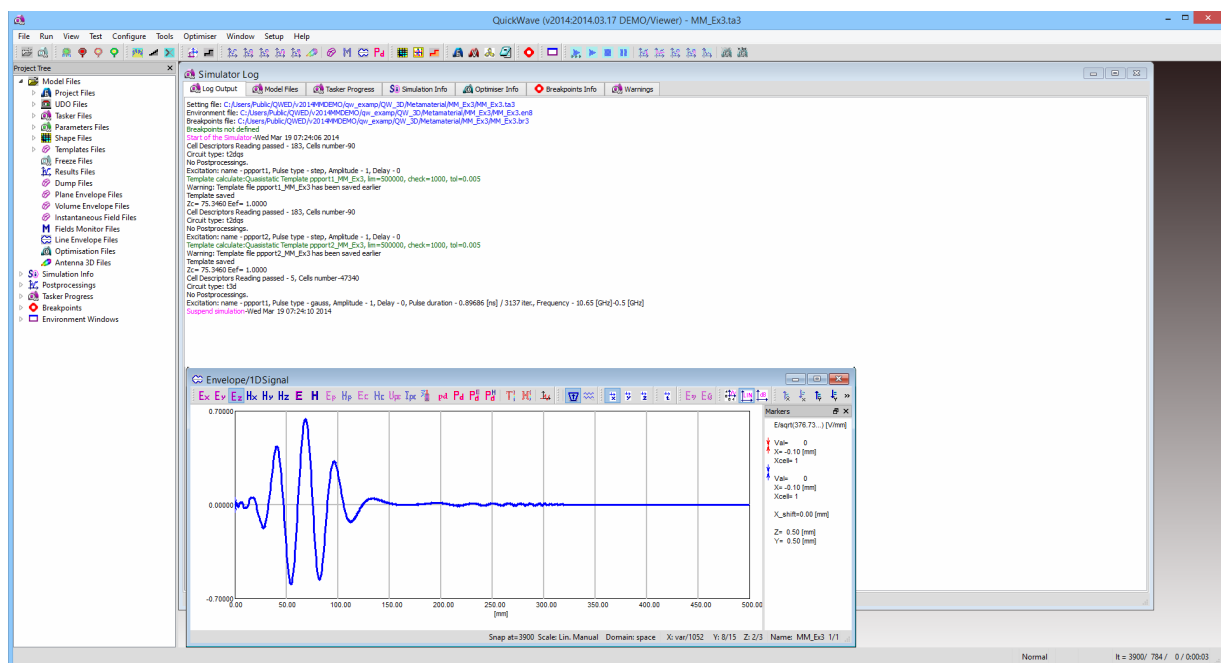





Figure 15 QW-Simulator window with View-Envelope window in Example 3 (picture snapped at 3900 iterations).

Ex3.10. If you would like to see the pulse propagation from the first FDTD iteration continue to the next step, if not proceed to step Ex3.12.

Ex3.11. Stop the simulation using *Run-Stop* icon (  ) and then run it once again using *Run-Start* icon (  ). Previously opened windows will be restored automatically.

Ex3.12. The opened displays are refreshed every 200 iterations. This is set in *Refresh Settings* option available in the context menu after clicking right mouse button (Figure 16). With such refreshing the user can easily distinguish the direction of pulse envelope propagation. If you now press *Dynamic Draw* icon (  ) or *D* on the keyboard, the display will be refreshed every FDTD iteration and you will be able to observe the direction of wave propagation inside the pulse envelope. Pressing *D* for the second time will disable *Dynamic Draw* option and the display will be updated according to settings from *Refresh Settings* dialogue.

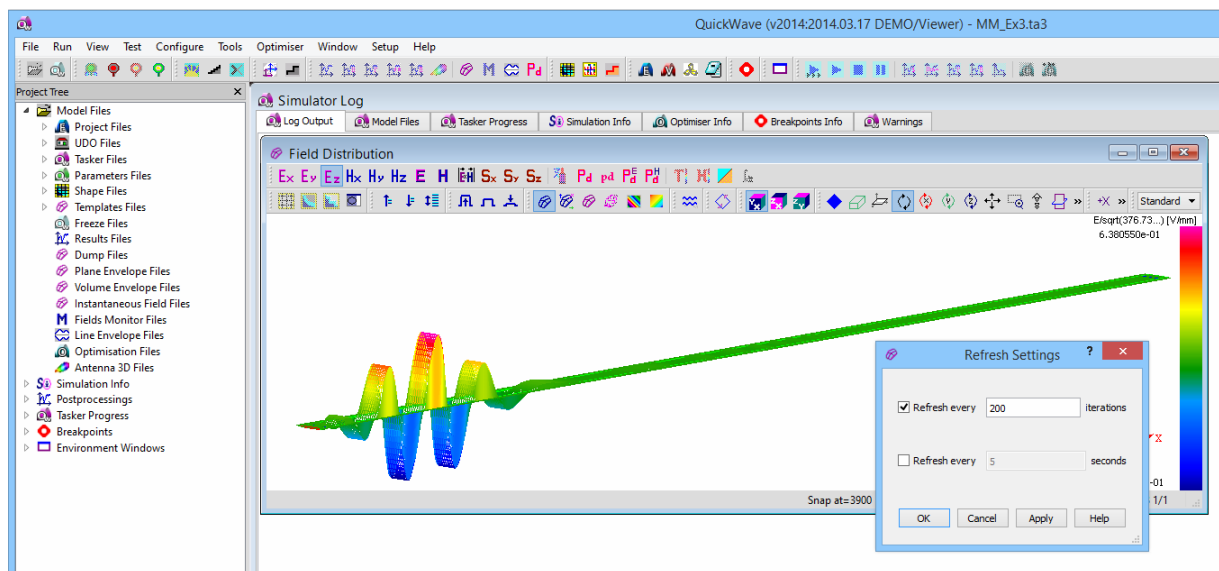



Figure 16 *Refresh Settings* dialogue for *View-Fields* window.

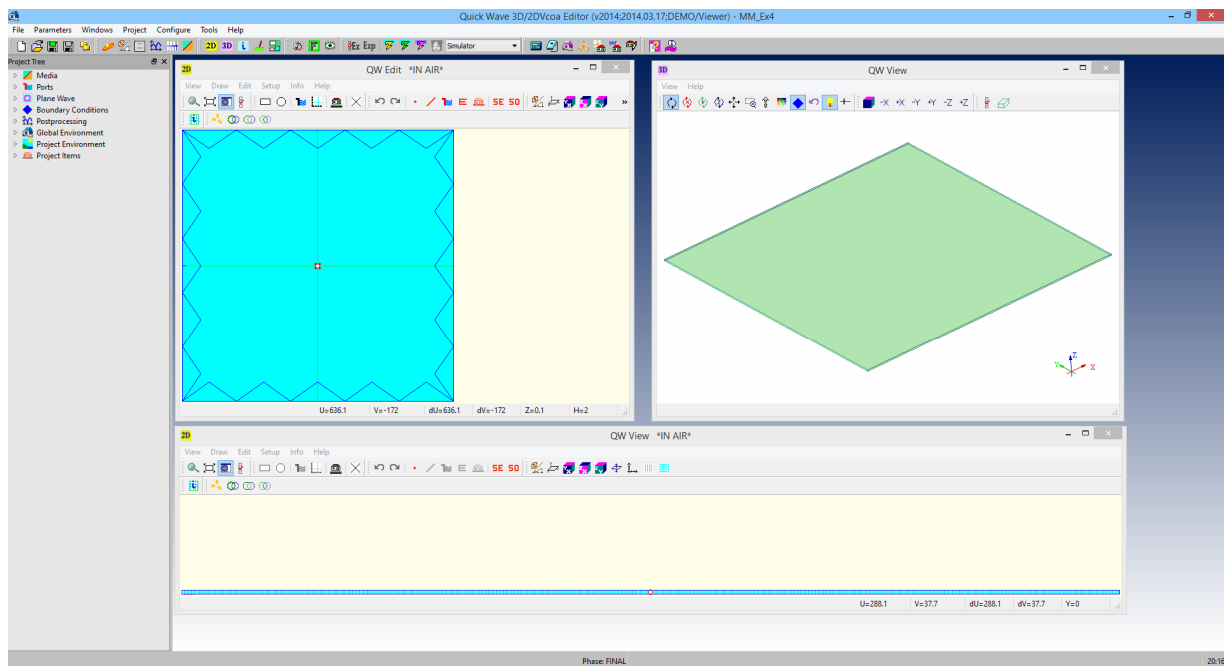
Ex3.13. When watching the pulse propagation along the line you can clearly see that the wave inside the pulse envelope moves backward while the envelope travels from the source towards the load.

Ex3.14. Exit *QW-Simulator*.

### 3.4 Example 4

Perform the following operations:

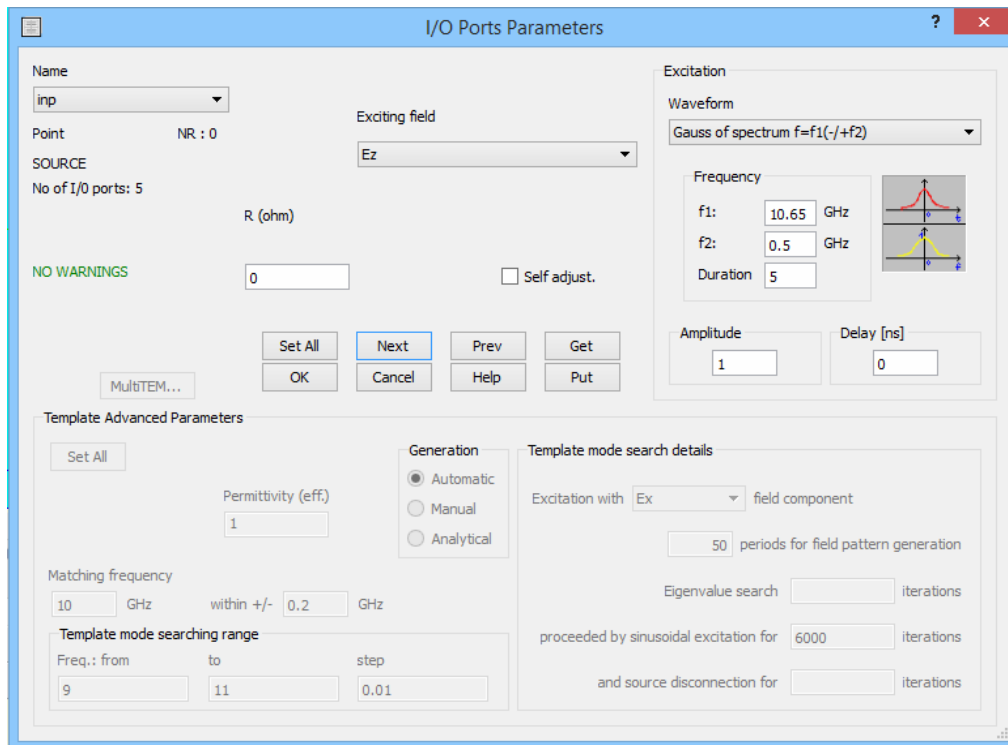
Ex4.1. Press the *File-Load* icon (  ) and open *MM\_Ex4.pro* example from *MM\_Ex4* folder in the DEMO examples directory. The following screen should appear:



**Figure 17** QW-Editor window with the metamaterial Example 4 loaded.


Ex4.2. If you are interested only in running the simulation proceed to step Ex4.4. If you would like to get some information about how the considered structure is excited continue to the next step.


Ex4.3. Press *Parameters-I/O Ports* icon () . The following dialogue will appear:



**Figure 18** Parameters-I/O Ports dialogue settings for Example 4.

The source excites a Gaussian pulse as already considered in Example 3.

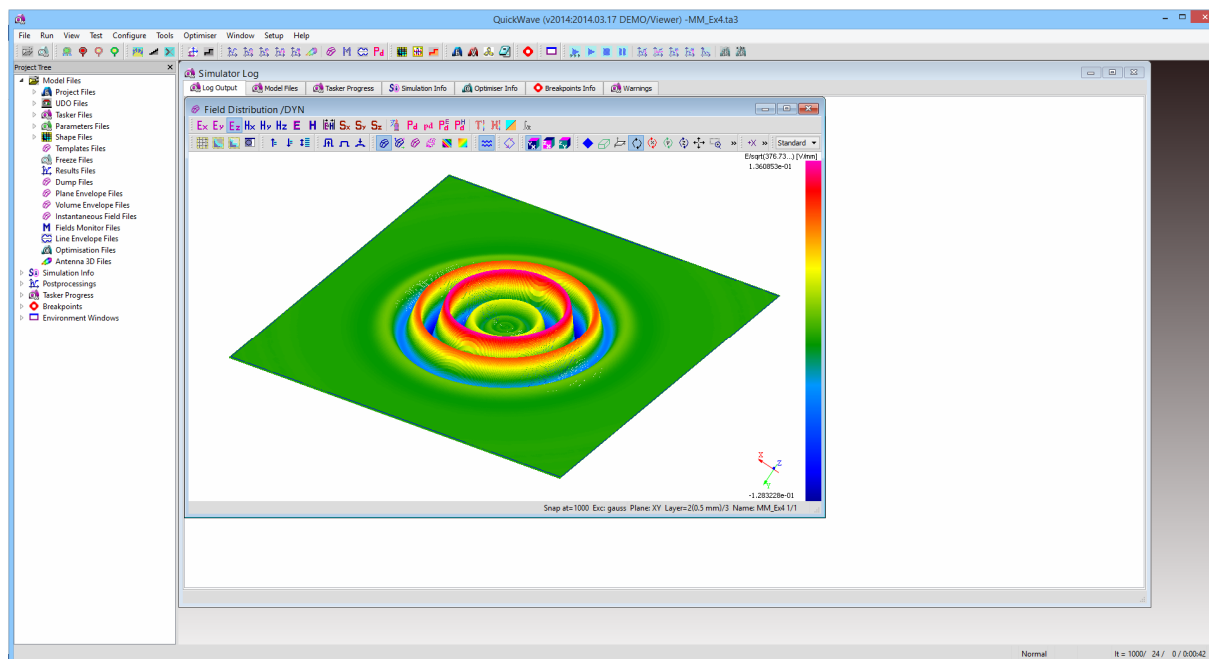
Ex4.4. Press *File-Export,Run & Start* icon (  ) to start *QW-Simulator* and run the simulation.

Ex4.5. Press *View-Fields* icon (  ) to watch the propagation of a Gaussian pulse in the metamaterial plate.

Ex4.6. If you are interested in starting the observation from the first FDTD iteration continue to the next step, if not proceed to step Ex4.8.

Ex4.7. Stop the simulation using *Run-Stop* icon (  ) and then run it once again using *Run-Start* icon (  ). The *View-Fields* windows will be restored automatically.

Ex4.8. The picture presented in Figure 19 shows *View-Fields* display after 1000 iterations. Feel free to adjust the window location and its dimensions to your preferences. The display is refreshed every 30 iterations, what is set in *Refresh Settings* dialogue, available after right mouse button clicking. The default refresh setting allows noticing the direction of the pulse envelope propagation. If you want to observe the wave propagation inside the pulse, press *D* button on the keyboard to enable updating the display every iteration.




**Figure 19** QW-Simulator window with View-Fields window in Example 4 (picture snapped at 1000 iterations).

Ex4.9. While watching the pulse propagation in the metamaterial plate, you can easily notice that the wave inside the envelope travels towards the source, but the pulse envelope travels from the source outwards.

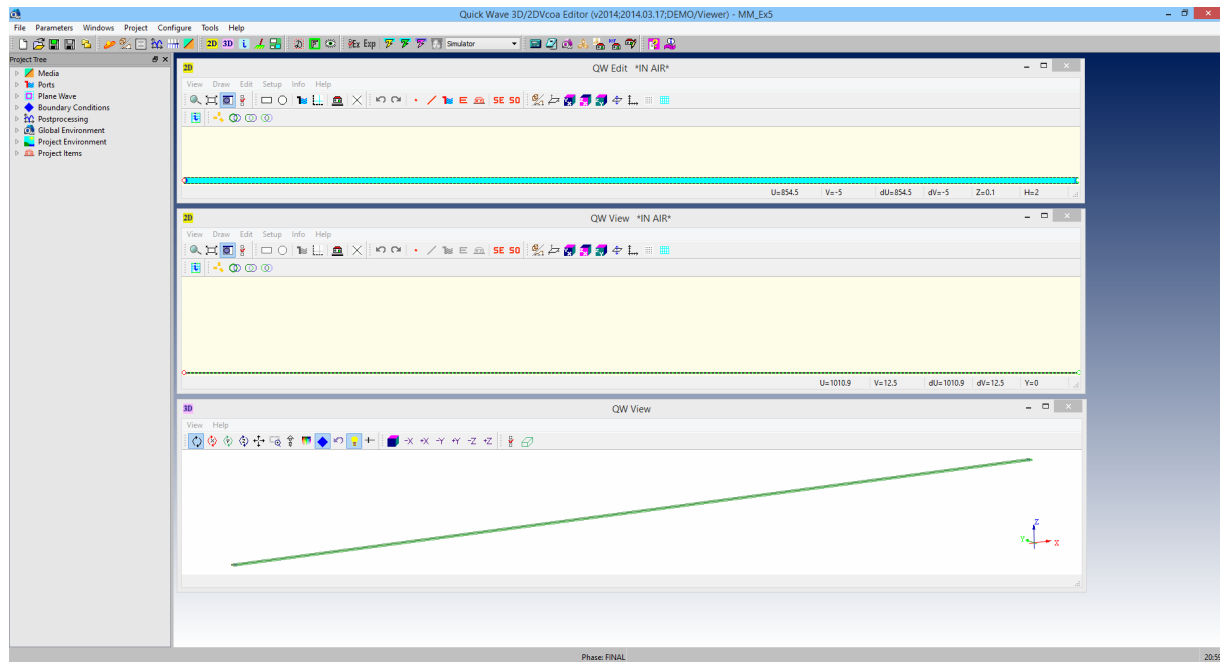
Ex4.10. Exit QW-Simulator.

### 3.5 Example 5

Perform the following operations:


Ex5.1. Press the *File-Load* icon () and open *MM\_Ex5.pro* example from *MM\_Ex5* folder in the DEMO examples directory. The following screen should appear:






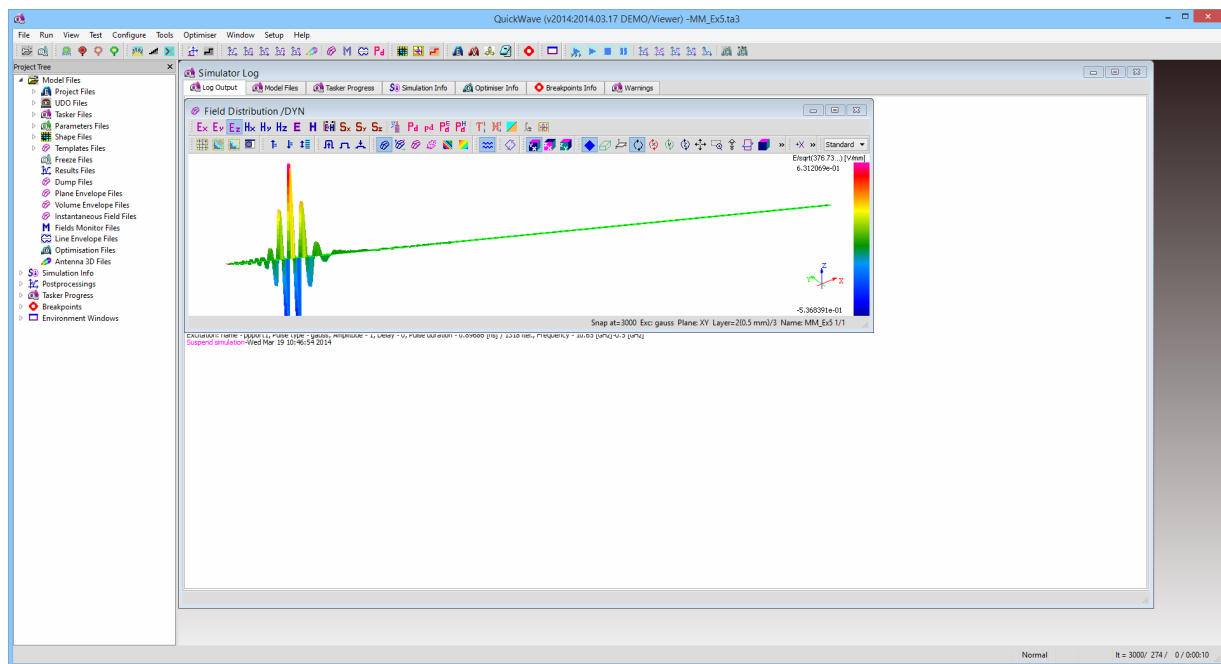
**Figure 20** QW-Editor window with the metamaterial Example 5 loaded.

Ex5.2. Settings for *Parameters-I/O Ports*, *Parameters-Media*, and *Parameters-Postprocessing* dialogues are the same as in Example 3. If you wish to check the settings feel free to do that, if not continue to the next step.


Ex5.3. Press *File-Export, Run & Start* icon (  ) to start QW-Simulator and run the simulation.

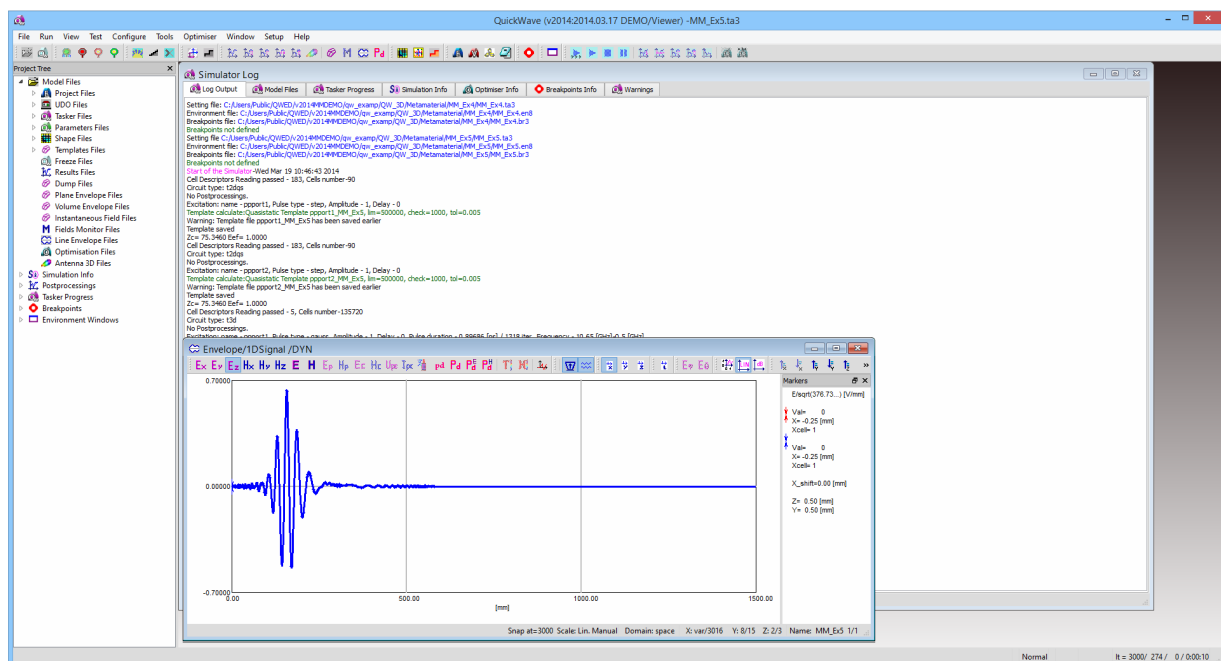
Ex5.4. If you want to watch the pulse propagation on a two dimensional display continue to the next step and then to step Ex5.7. If you want to view the propagation on one-dimensional display proceed to step Ex5.6.

Ex5.5. Press *View-Fields* icon (  ). The following window, showing the distribution of the electric field in the slab, will appear in QW-Simulator:



**Figure 21** QW-Simulator window with *View-Fields* window in Example 5 (picture snapped at 3000 iterations).

Ex5.6. Press *View-Envelope* icon (  ). The following window, showing the distribution of the electric field in the slab, will appear in QW-Simulator:




**Figure 22** QW-Simulator window with *View-Envelope* window in Example 5 (picture snapped at 3000 iterations).

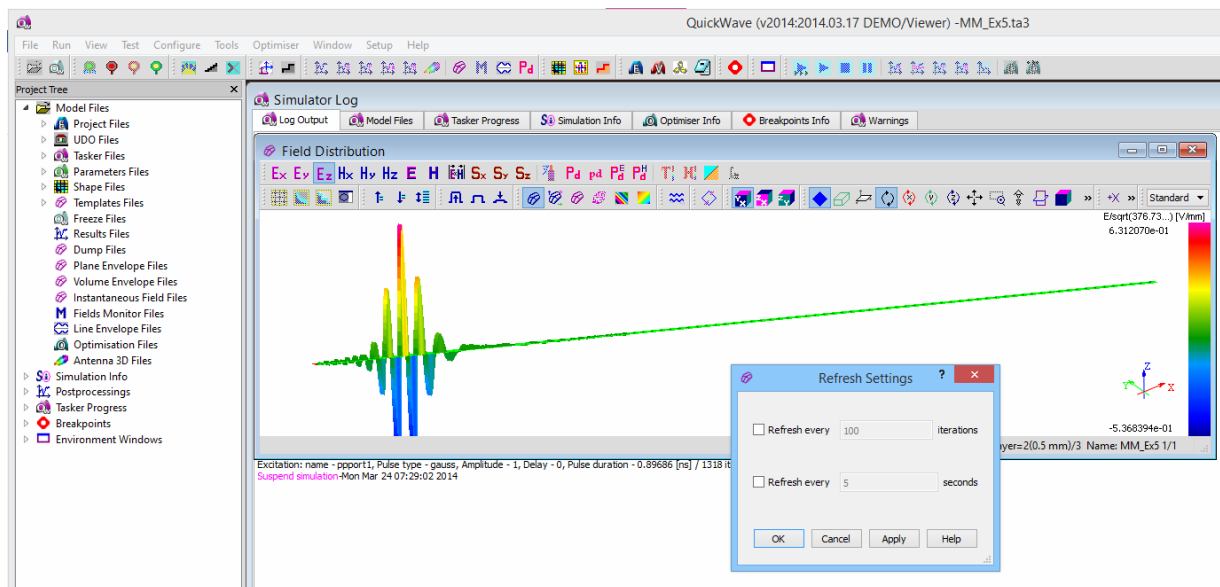
Ex5.7. If you want to start watching the field distribution from the first FDTD iteration, it can be done by stopping and then starting the simulation once again.

Ex5.8. The opened windows can be optionally moved and resized according to your preferences.

Ex5.9. In both displays (*View-Fields* and *View-Envelope*) *Dynamic Draw* option, enabling results changing with every FDTD iteration, has been activated. If the simulation speed is satisfactory for you continue the observation and proceed to step Ex5.13. If you would like to speed up the simulation by decreasing the number of the display's updates please proceed to the next step.

Ex5.10. Press *Dynamic Draw* icon (  ) to deactivate this option.

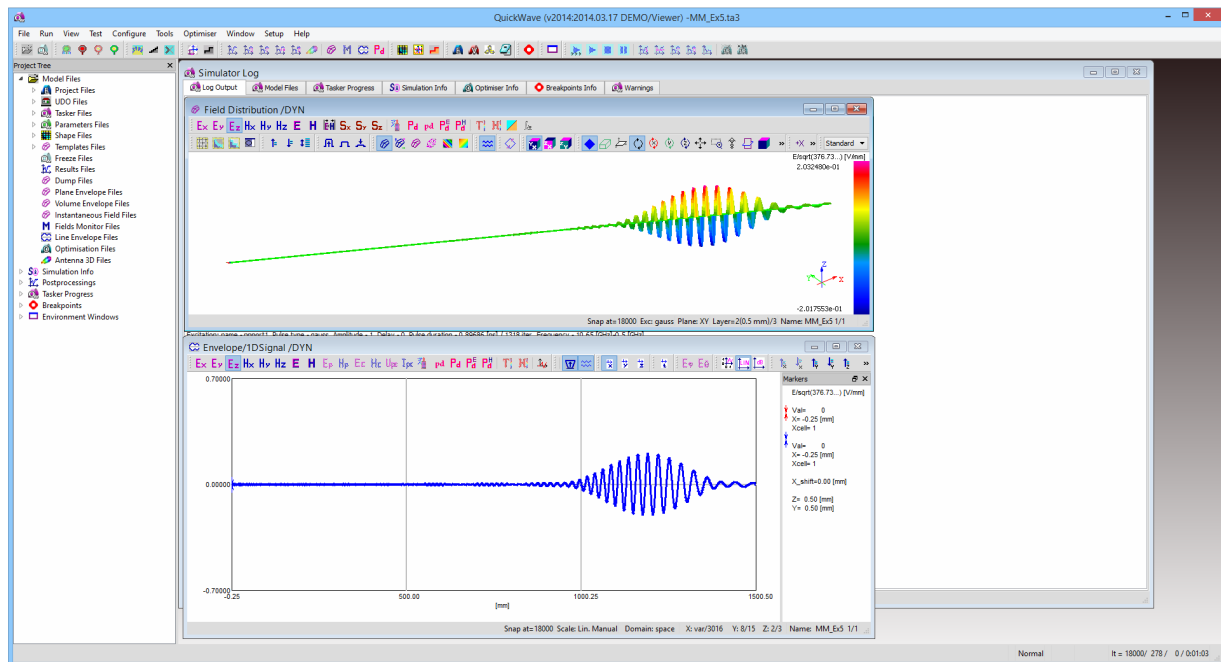
Ex5.11. Press right mouse button on the display (either in *View-Fields* or *View-Envelope* window) and choose *Refresh Settings* option. The following dialogue will appear:



**Figure 23** *Refresh Settings* dialogue in *View-Fields* window.

Ex5.12. You may choose if the display is refreshed every  $N$  iterations or every  $M$  seconds. Checking one of these options and setting  $N$  or  $M > 1$  will speed up the simulation since the results will not be updated every iteration. We do not suggest any values for  $N$  and  $M$  parameters so that the user can fit the settings to his own preferences. We encourage you to try some different combinations to see their influence on the display and simulation speed.

Ex5.13. After 18000 FDTD iterations performed you will get the following display, either for *View-Fields* or *View-Envelope* window:




**Figure 24** QW-Simulator window with *View-Fields* and *View-Envelope* windows in Example 5 (picture snapped at 18000 iterations).

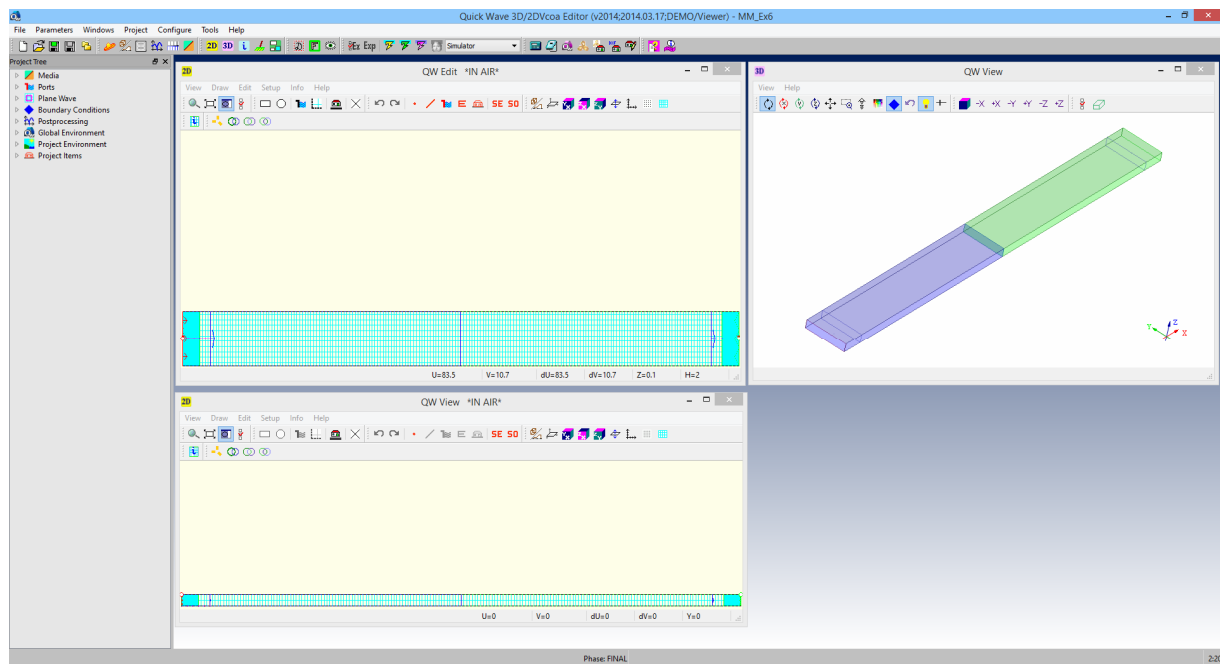
Ex5.14. While watching the pulse propagation along the slab you can notice a significant pulse distortion, from the shape as in Figure 21 and Figure 22 (after 3000 iterations) to the one in Figure 24 (after 18000 iterations).

Ex5.15. Exit QW-Simulator.

### 3.6 Example 6


Perform the following operations:


Ex6.1. Press the *File-Load* icon () and open *MM\_Ex6.pro* example from *MM\_Ex6* folder in the DEMO examples directory. The following screen should appear:





**Figure 25** QW-Editor window with the metamaterial Example 6 loaded.

Ex6.2. The excitation in *Parameters-I/O Ports* dialogue has been set as in Example 2.

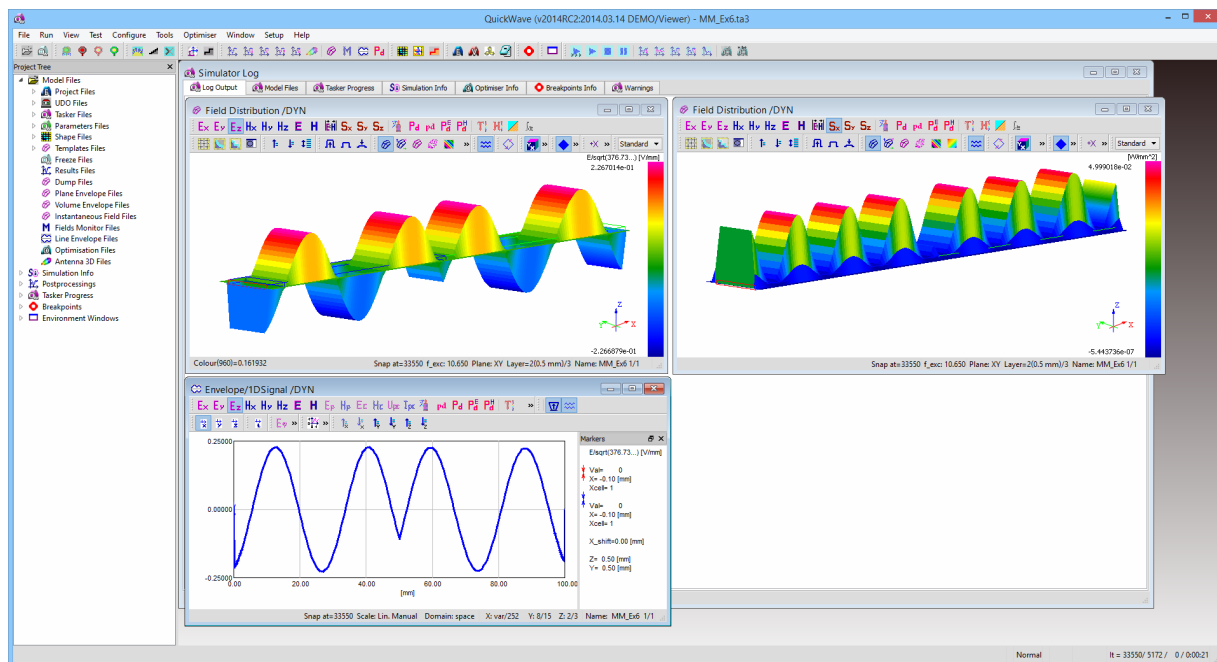
Ex6.3. Press *File-Export, Run & Start* icon (  ) to start *QW-Simulator* and run the simulation.

Ex6.4. Press *View-Fields* icon (  ) to watch the distribution of the electric field in the slab.

Ex6.5. Press *View-Fields* icon (  ) for the second time to see the distribution of x-component of the Poynting vector in the slab.


Ex6.6. Press *View-Envelope* icon (  ) to view the distribution of the electric field along the slab on one-dimensional display.

Ex6.7. After performing steps Ex6.4-Ex6.6 the following windows' setup will appear in *QW-Simulator*:




**Figure 26** QW-Simulator window with fields' distribution windows for Example 6.

Ex6.8. If you want to start watching the field distribution from the first FDTD iteration, stop and then start the simulation once again. The displays will be opened automatically.

Ex6.9. All the opened windows have *Dynamic Draw* option enabled (  pressed) to assure convenient field distribution observation. The user may feel free to change the refresh settings, according to his preferences, through *Refresh Settings* dialogue.

Ex6.10. The user may feel free to rearrange and resize the windows to best fit his own preferences.


Ex6.11. When investigating the wave propagation along the slab you can clearly see that on both sides of the slab the phase of the wave travels towards media boundary. At the same time the  $S_x$  component of the Poynting vector is positive along the slab, which means that the energy flows always from the source towards load.

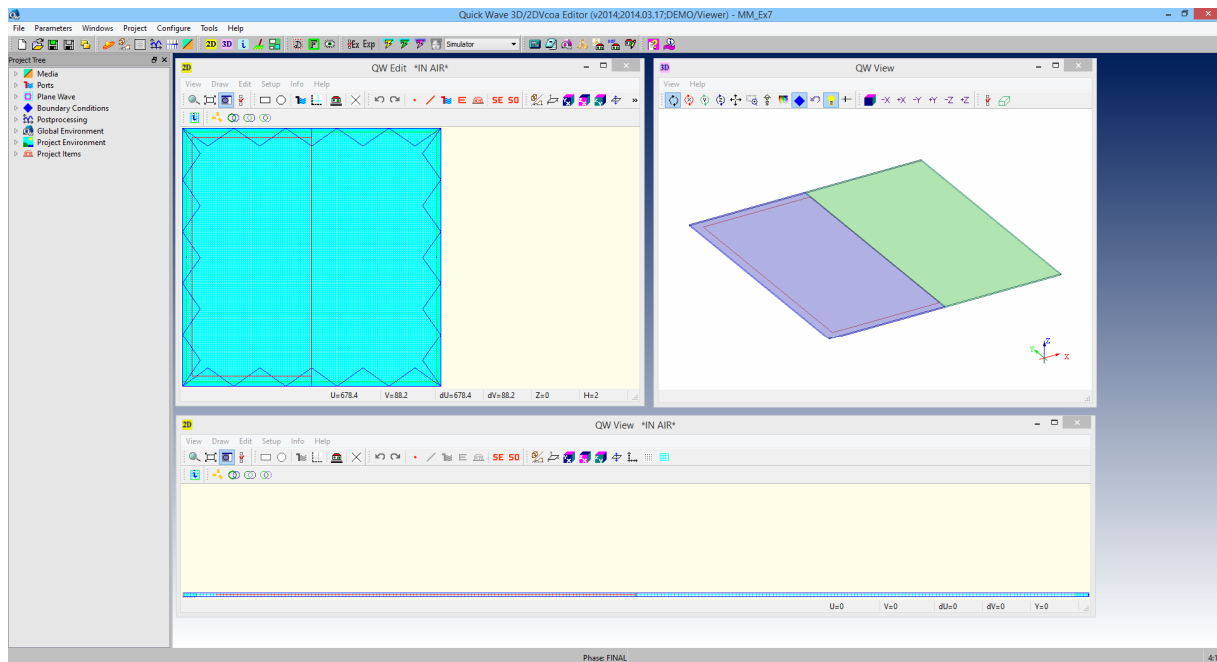
Ex6.12. You can confirm the energy flow direction by watching the distribution of the Poynting vector on vector type display. To perform this observation press *View-Fields* icon (  ) once again. The required display will appear in bottom right corner. What may be also interesting, is watching the distribution of the total electric and magnetic field, enabled by pressing **E** or **H** icon respectively.

Ex6.13. Exit *QW-Simulator*.

### 3.7 Example 7


Perform the following operations:

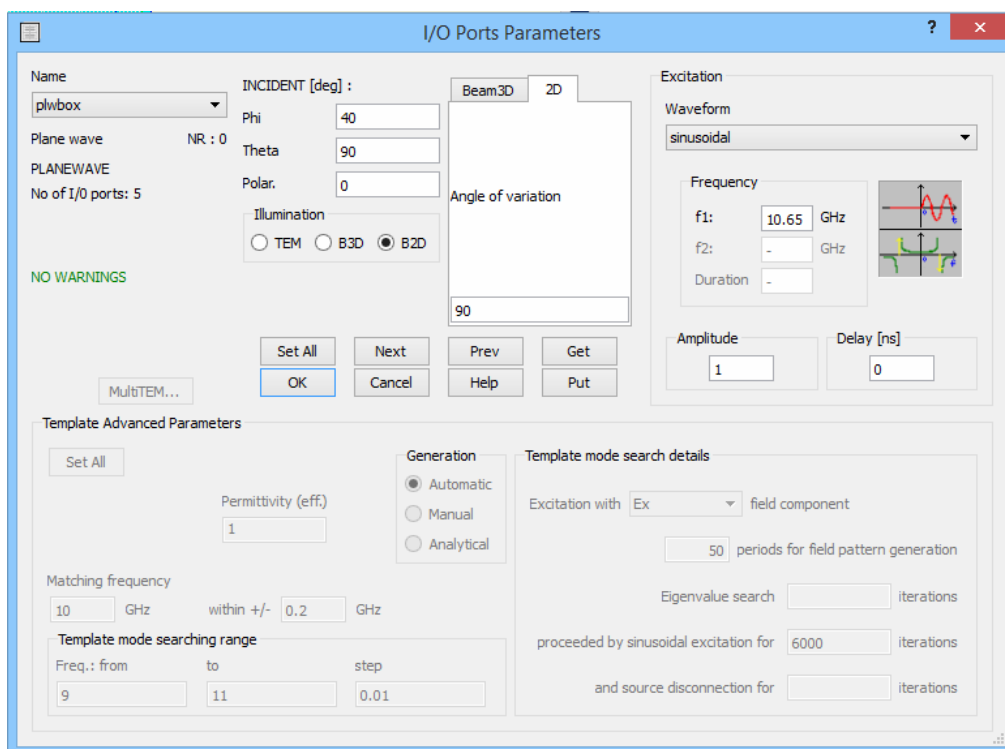
Ex7.1. Press the *File-Load* icon () and open *MM\_Ex7.pro* example from *MM\_Ex7* folder in the DEMO examples directory. The following screen should appear:



**Figure 27** QW-Editor window with the metamaterial Example 7 loaded.

Ex7.2. If you are just interested in running the simulation proceed to step Ex7.6. If you want to check the excitation settings continue to the next step.

Ex7.3. Press *Parameters-I/O Ports* icon () . The following dialogue will appear:



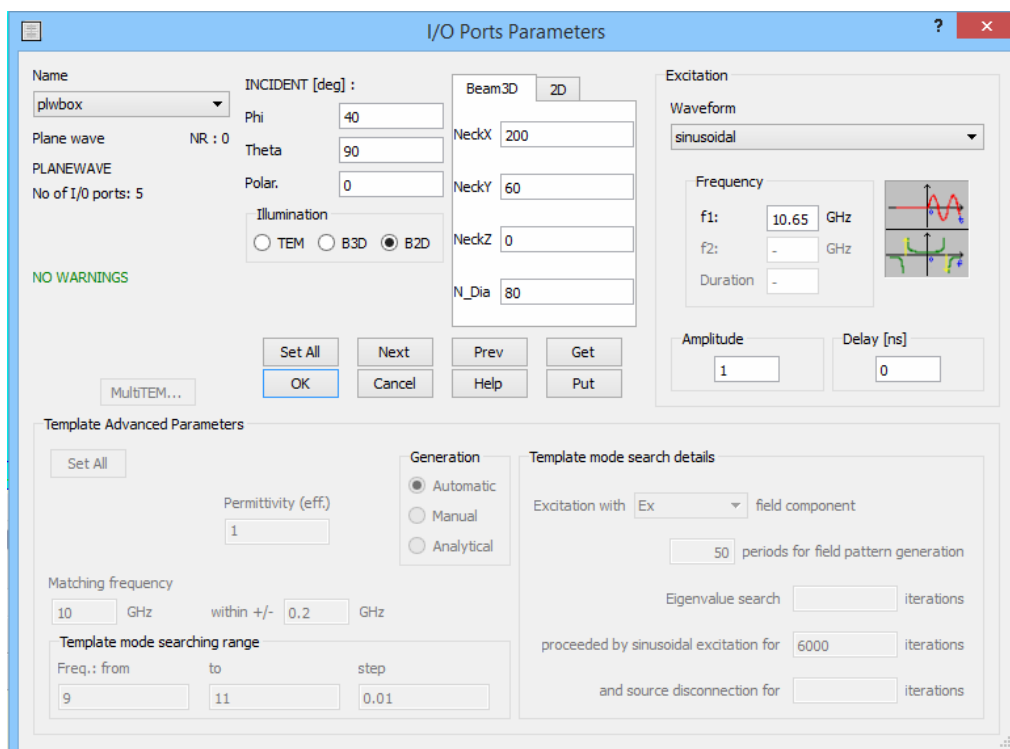
**Figure 28** Parameters-I/O Ports dialogue settings for Example 7.

Ex7.4. The illumination has been set to 2D Gaussian beam sinusoidal in time ( $f=10.65$  GHz). The *Incident Angles* have the meaning of the angles in spherical coordinates system, thus setting  $\Phi=40^\circ$  and  $\Theta=90^\circ$  means that the wave is propagating in XY plane and the incident angle is  $40^\circ$ . The *Angle of Variation* determines the direction in which the Gaussian shape is produced. The value  $90^\circ$  means that the beam has no phase shift along Z axis.


Ex7.5. Press *Beam3D* tab in *Parameters-I/O Ports* dialogue. Here the position of the neck centre of the beam (in all three directions) and its diameter are defined.


*Attention:* In the considered example only left and bottom walls (X- and Y-) of the plane wave box (an auxiliary surface used for exciting an incident plane wave, marked with red lines in *QW-Editor*) are active.



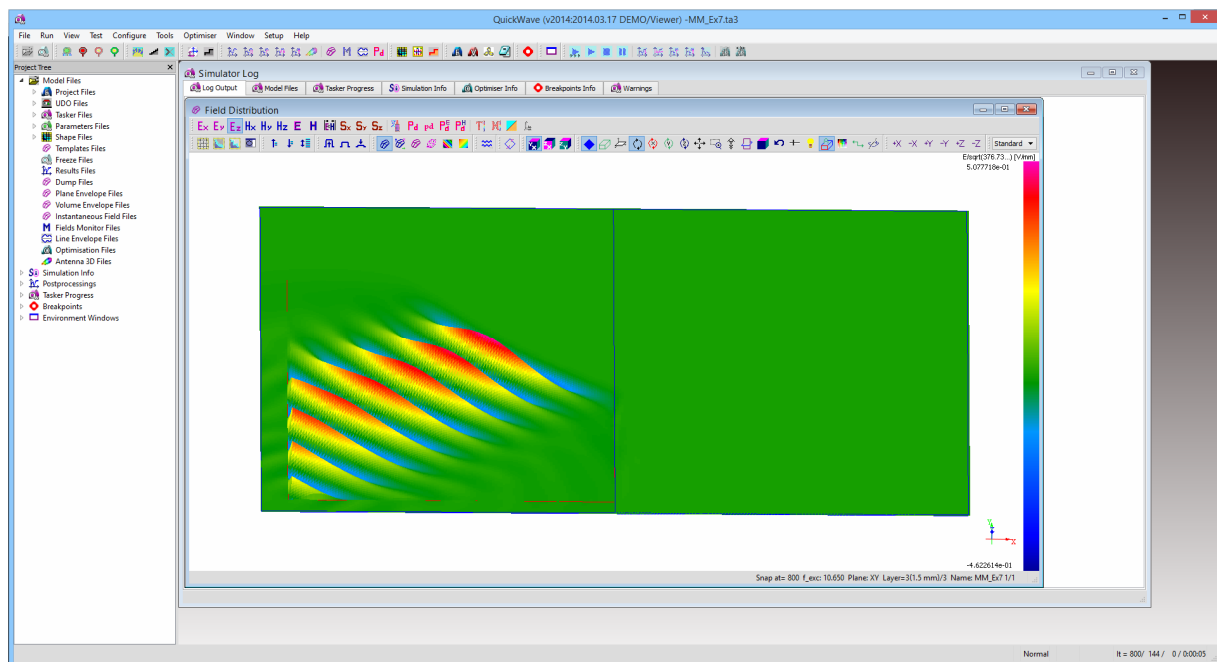


**Figure 29** Parameters-I/O Ports dialogue settings for Example 7.

Ex7.6. Press *File-Export, Run & Start* icon (  ) to start *QW-Simulator* and run the simulation.

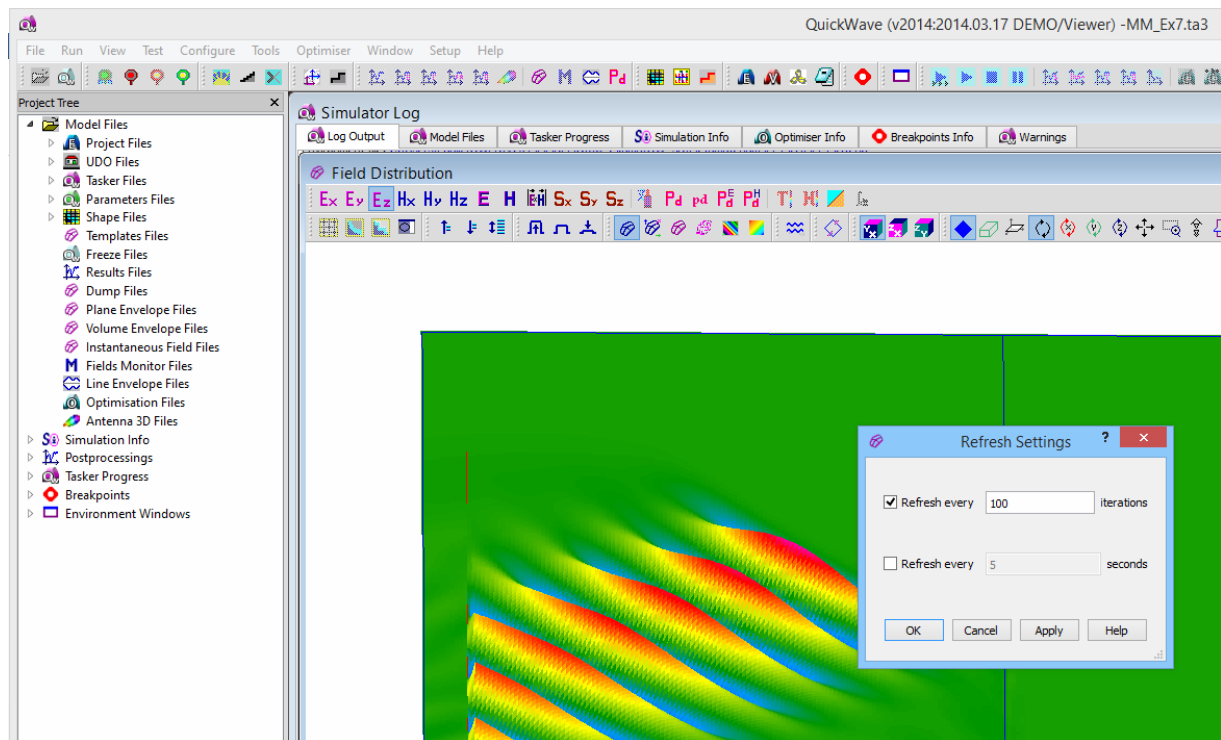
Ex7.7. Press *View-Fields* icon (  ) to view the pulse propagation. If you want to start the observation from the first FDTD iteration, stop the simulation and then start it once again.

Ex7.8. The following window, showing electric field distribution, will appear in *QW-Simulator*:




**Figure 30** QW-Simulator window with *View-Fields* window for Example 7 (picture snapped at 800 iterations).

Ex7.9. The display is refreshed every 100 iterations (see figure below). If you want to change refresh settings continue to the next step, if not continue the observation and proceed to step Ex7.11.

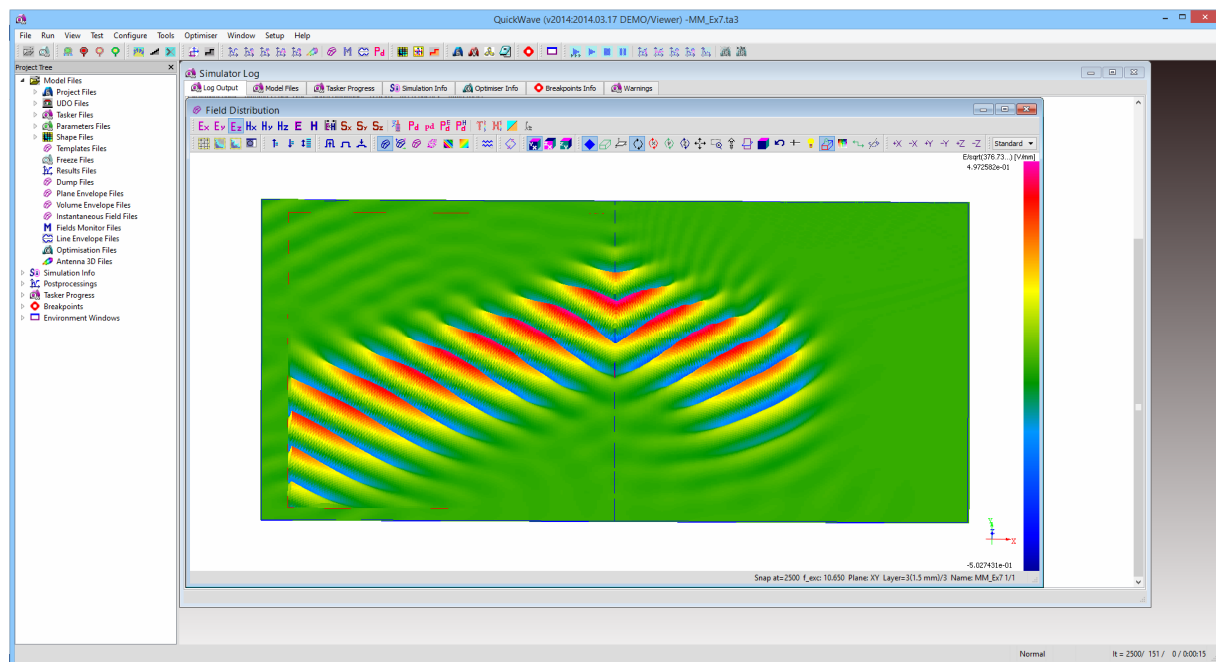


**Figure 31** *Refresh Settings* dialogue in *View-Fields* window for Example 7.

Ex7.10. If you want to change settings in *Refresh Settings* dialogue press right mouse button on the display and choose *Refresh Settings* option. Otherwise, if you want display to be updated every FDTD iteration press *Dynamic Draw* icon (  ) or *D* on the keyboard.

Ex7.11. You may change the window dimensions and position to best fit your preferences.

Ex7.12. After 2000 iterations (counter in the right bottom corner of *QW-Simulator* window) you will get the following picture:




**Figure 32** QW-Simulator window with View-Fields window snapped at 2500 iterations.

Ex7.13. When watching the pulse propagation you can notice that at the boundary between vacuum and the double-Drude material the wave refracts at a negative angle.

Ex7.14. Exit QW-Simulator.

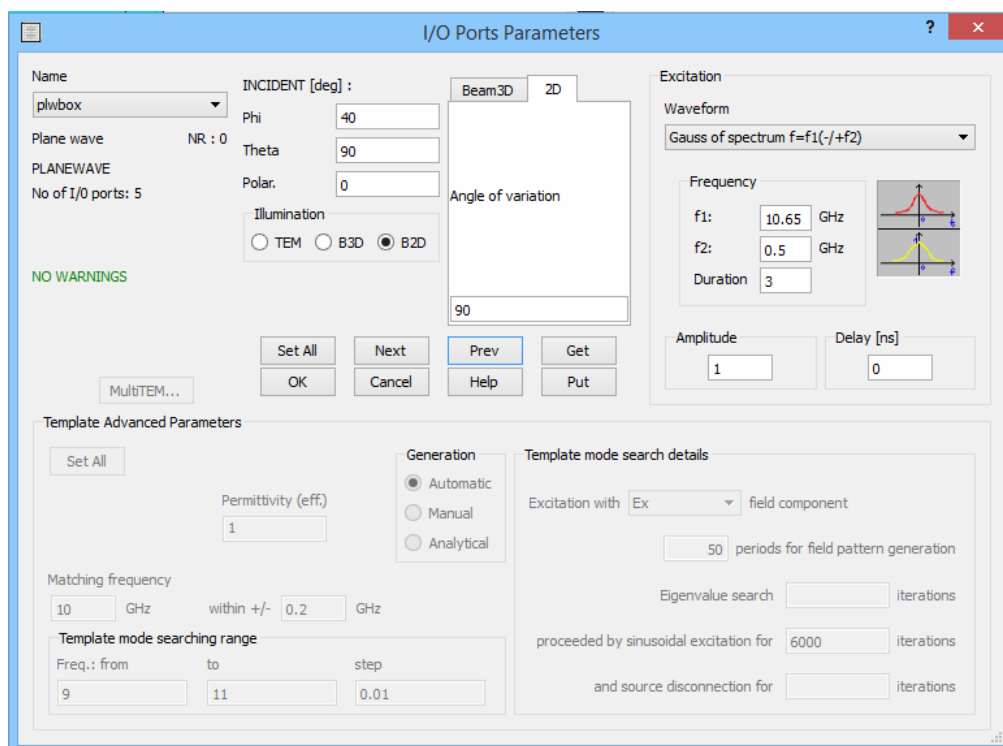
### 3.8 Example 8

Perform the following operations:

Ex8.1. Press the *File-Load* icon () and open *MM\_Ex8.pro* example from *MM\_Ex8* folder in the DEMO examples directory. The screen as in Example 7 will appear.

Ex8.2. If you just want to run the simulation proceed to step Ex8.6. If you want to check how the excitation has been changed comparing to Example 7 continue to the next step.

Ex8.3. Press *Parameters-I/O Ports* icon (). The following dialogue will appear:

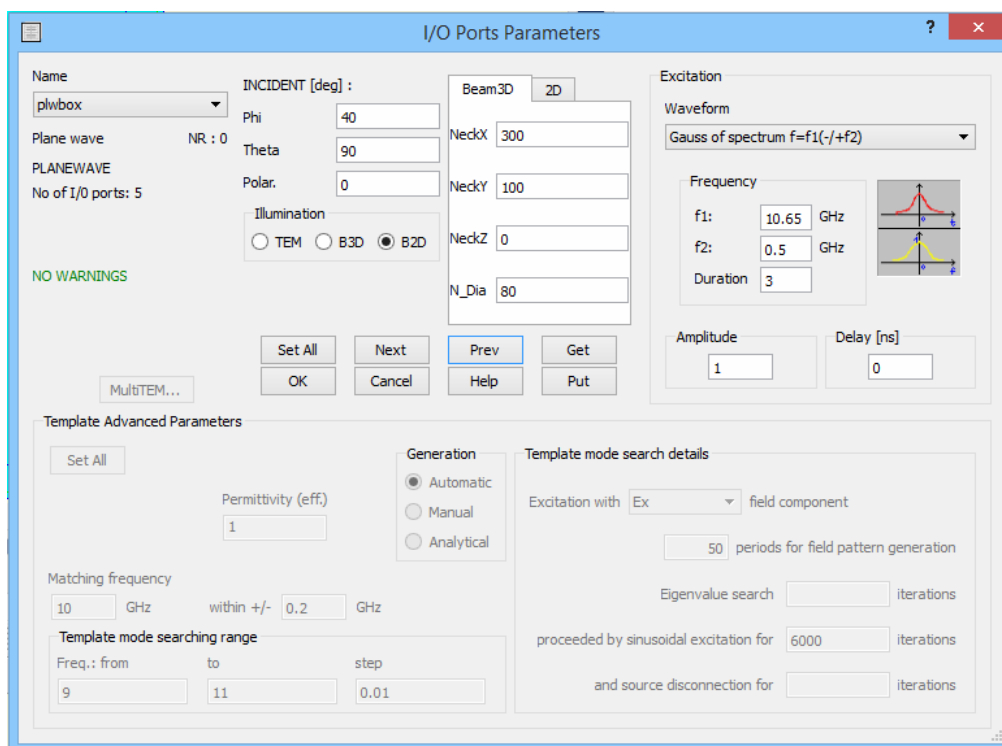


**Figure 33** *Parameters-I/O Ports* window with excitation settings from Example 8.


Ex8.4. In this example the excitation has been set to a pulse that is Gaussian in space and Gaussian in time. The incidence plane and angle remain the same as in Example 7.


Ex8.5. Press *Beam3D* tab in *Parameters-I/O Ports* dialogue to check the position of the neck centre of the beam.

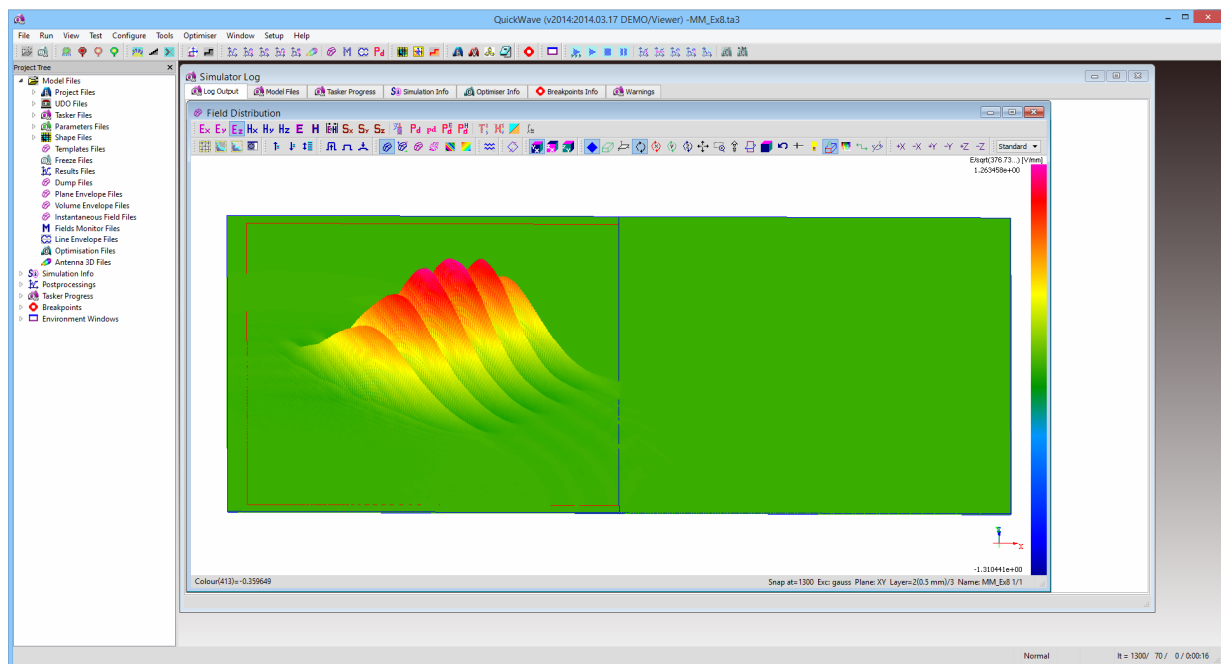
**Attention:** In the considered example only left and bottom walls (X- and Y-) of the plane wave box (an auxiliary surface used for exciting an incident plane wave, marked with red lines in *QW-Editor*) are active.



**Figure 34** Parameters-I/O Ports window with excitation settings from Example 8.

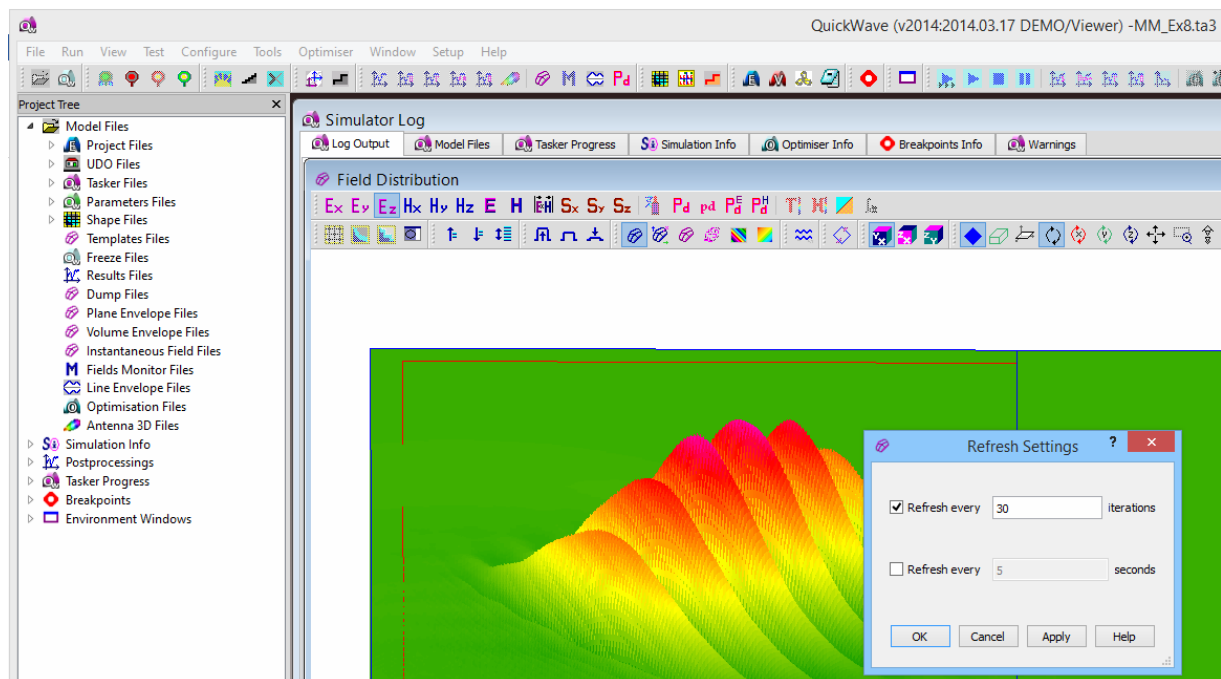
Ex8.6. Press *File-Export, Run & Start* icon (  ) to start *QW-Simulator* and run the simulation.

Ex8.7. Press *View-Fields* icon (  ) to view the pulse propagation. If you are interested in watching the pulse propagation from the first iteration, stop the simulation and after that run it once again. The following window, showing electric field distribution, will appear in *QW-Simulator*:




**Figure 35** QW-Simulator window with *View-Fields* window snapped at 1300 iterations.

Ex8.8. The *Refresh Settings* have been set as shown in the following figure:



**Figure 36** *Refresh Settings* dialogue in *View-Fields* window for Example 7.

Ex8.9. If you want to change the refresh settings continue to the next step. If not continue the observation and proceed to step Ex8.11.

Ex8.10. If you want to change settings in *Refresh Settings* dialogue press right mouse button on the display and choose *Refresh Settings* option. Otherwise, if you want display to be updated every FDTD iteration press *Dynamic Draw* icon (  ).

Ex8.11. After 4500 iterations performed you will get the following picture:

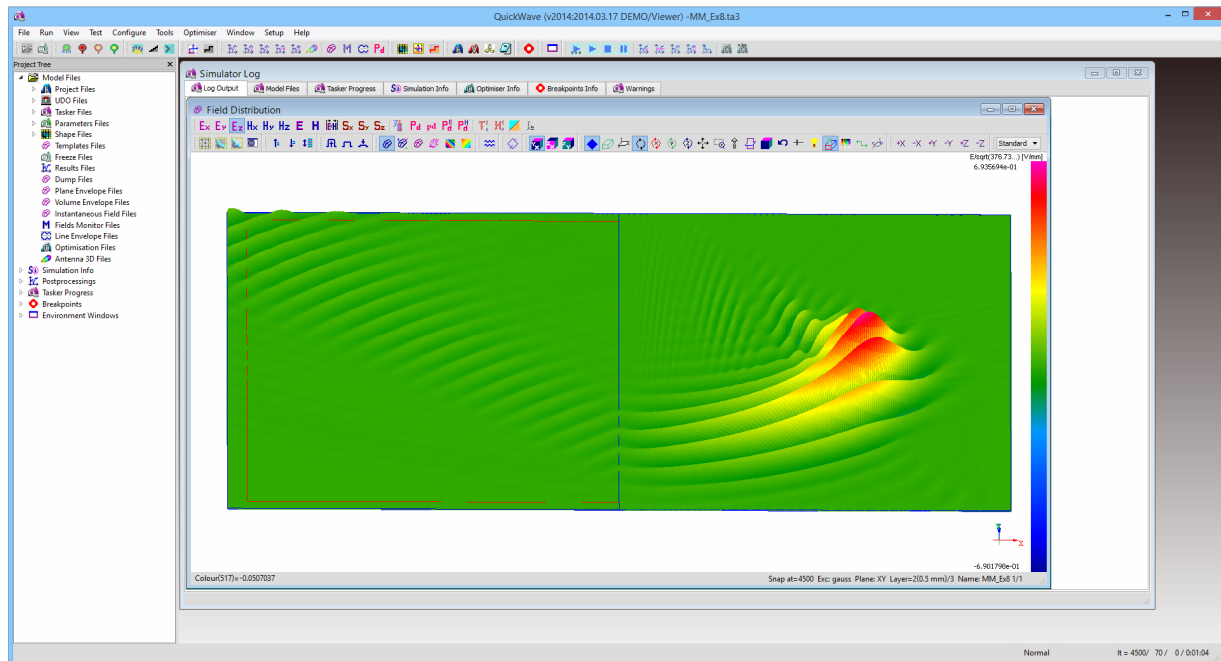


Figure 37 QW-Simulator window with View-Fields window snapped at 4500 iterations.

Ex8.12. As you can notice, the pulse refracts at a negative angle when reaching the media boundary. Also you can easily distinguish the pulse distortion mentioned in the article.

Ex8.13. Exit QW-Simulator.

## 4. Discussion of some special features of QW-Simulator

At the end of this discussion of metamaterial examples we would like to bring your attention to two special and quite unique features of *QW-Simulator* broadening its scope of applications. One of those features is applicable in very big scenarios while the other one in very small ones.

### 4.1. Freeze function


In FDTD analysis we sometimes deal with very large problems running for hours and in some exceptional cases even for days. As it was pointed out before, during simulation the user can decide about opening several windows to watch details of the field distribution in the structure. But this possibility is normally terminated when the simulation ends. Not in *QW-Simulator*. It is possible to “FREEZE” the simulation at any point and then resume at your convenience from the state at which it was, when the freeze was performed. We can watch this option at the example of simulation of Example 8.






F8.1. Load *MM\_Ex8.pro* example to the *QW-Editor*.


F8.2. Run the simulation using *File-Export, Run & Start* icon () .


F8.3. We suggest you to open *View-Fields* window () after about 1500 iterations to notice the simulation stage (the pulse will be almost reaching the media boundary). We will now perform the freeze operation.


F8.4. Press *File-Freeze* icon () to freeze the simulation. The freeze file (\*.sfr) will be saved in (default) *MM\_Ex8* directory. The default name is the project name: *MM\_Ex8.sfr* .


F8.5. Exit *QW-Simulator*.

F8.6. Run the *QW-Simulator* once again but without starting the simulation (we want the simulation to be started from freeze file). This can be done in the three ways:

- Return to *QW-Editor* and use *File-Export & Run* icon () . *QW-Simulator* will be run without starting the simulation
- By running *ker1.exe* file from *DEMO* directory (the default path is C:\Program Files (x86)\QWED\QW\_3D\v2014DEMO\qwin),
- By using *QW 3D&V2D Simulator* shortcut, which is created during the installation. The shortcut can be found on a *Desktop* in *QuickWave 3D&V2D v2014 DEMO* directory or in *Start Menu* under *QuickWave→QuickWave 3D&V2D v2014 DEMO*.

F8.7. Press *File-Open* icon () in *QW-Simulator*. The *Open* dialogue will appear. From the extensions list choose *Simulator Freeze Files (\*.sfr)* to see all the available freeze files. Load *MM\_Ex8.sfr* file from the directory where it was saved (default: C:\Users\Public\QWED\v2014DEMO\qw\_examp\QW\_3D\Standard\Metamaterial\MM\_Ex8).

F8.8. Press *Run-Start* icon () . The simulation will start. When you look at the status bar in the bottom right corner of the *QW-Simulator* window, you will notice that the simulation was started not from zero iteration but from around 1500<sup>th</sup> iteration (exactly, the iteration in which the freeze was performed).

F8.9. Open *View-Fields* window by pressing  icon. You will notice that the pulse is reaching the media boundary, thus the simulation was started from the point at which *Freeze* was made.

F8.10. Exit *QW-Simulator* when you finish the observation.

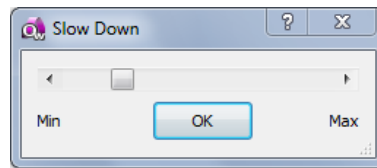
F8.11. We encourage you to try the *Freeze* option also on other examples.

## 4.2. Slow down function

Sometimes we would like to watch the transients of the fields in a particular part of the scenario. When the scenario is not very big and our computer is very fast we may face the problem of too-fast moving fields. In such a case we can use the slow-down function (*Run-Slow Down...* command), which brings up a slider (Figure 38) that allows artificially slowing down the simulation. This may be useful in tutorial



applications of the software and when using *QW-3D* for real-time simulations in classes when teaching electrodynamics. We encourage you to feel free in trying this option.



**Figure 38** *Slow Down* dialogue.