Lab number: 2
Lab title: TEM Wave in lossy media
Date lab was performed: 21.04.2020
Names of lab group members: Krzysztof Rudnicki

Theoretical introduction:
We are gonna perform simulation using rectangular dielectric slab with perfect electric conductor at the top and the bottom and perfect magnetic conductors at the lateral walls.
We know from boundary conditions that TEM is how electric polarization and corresponding magnetic component are gonna propagate.
Dielectric medium which files the line is characterized by $\varepsilon_r,\ \mu\ and\ tg\delta$. Input port excites a sinusoidal TEM wave. Frequency (f) is in GHz.
Now, since we are dealing with low lossy dielectric where $tan(\delta) = 0.1$ we have to change some of our equations from the previous task, more specifically equation for $attenuation\ coefficient\ \alpha$:
$\alpha = \frac{\sigma}{2}|Z|$

a = 8.5
Cases:

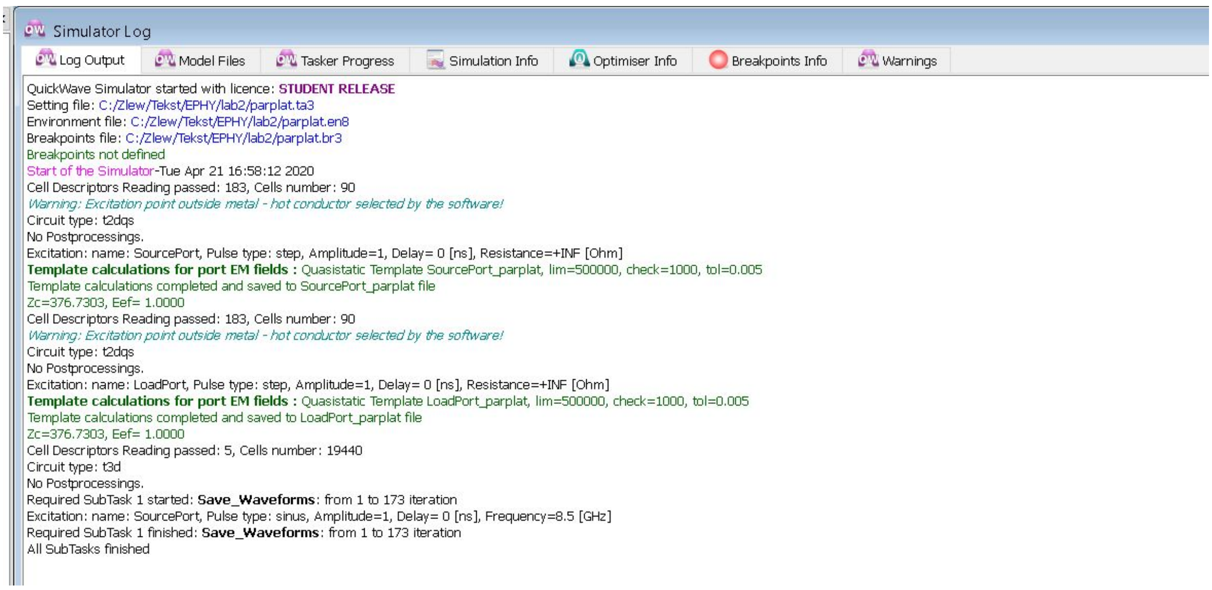
a) $f = 8.5\ [GHz],\ \varepsilon_r = 1\ [F/m],\ \mu_r = 1\ [H/m],\ tan(\delta) = 0.1\ (lossy\ case)$
b) $f = 8.5[GHz],\ \varepsilon_r = 8.5\ [F/m],\ \mu_r = 1\ [H/m],\ tan(\delta) = 0.1$
c) $f = 8.5[GHz],\ \varepsilon_r = 1\ [F/m],\ \mu_r = 8.5\ [H/m],\ tan(\delta) = 0.1$

$f - frequency,\ \varepsilon_r - permittivity,\ \mu_r - permeability,\ tg\delta - loss\ tangent,\ \sigma - conductivity$

$\delta_g R_x = \frac{\Delta_g R}{R_x}$ $\quad u_{rel}(R) = \sqrt{u^2(U) + u^2(I)}$

a)

3.7)


Simulator Log
Log Output | Model Files | Tasker Progress | Simulation Info | Optimiser Info | Breakpoints Info | Warnings

QuickWave Simulator started with licence: STUDENT RELEASE
Setting file: C:/Zlew/Tekst/EPHY/lab2/parplat.ta3
Environment file: C:/Zlew/Tekst/EPHY/lab2/parplat.en8
Breakpoints file: C:/Zlew/Tekst/EPHY/lab2/parplat.br3
Breakpoints not defined
Start of the Simulator-Tue Apr 21 16:58:12 2020
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Warning: Excitation point outside metal - hot conductor selected by the software!
Circuit type: t2dqs
No Postprocessings.
Excitation: name: SourcePort, Pulse type: step, Amplitude=1, Delay= 0 [ns], Resistance=+INF [Ohm]
Template calculations for port EM fields : Quasistatic Template SourcePort_parplat, lim=500000, check=1000, tol=0.005
Template calculations completed and saved to SourcePort_parplat file
Zc=376.7303, Eef= 1.0000
Cell Descriptors Reading passed: 183, Cells number: 90
Warning: Excitation point outside metal - hot conductor selected by the software!
Circuit type: t2dqs
No Postprocessings.
Excitation: name: LoadPort, Pulse type: step, Amplitude=1, Delay= 0 [ns], Resistance=+INF [Ohm]
Template calculations for port EM fields : Quasistatic Template LoadPort_parplat, lim=500000, check=1000, tol=0.005
Template calculations completed and saved to LoadPort_parplat file
Zc=376.7303, Eef= 1.0000
Cell Descriptors Reading passed: 5, Cells number: 19440
Circuit type: t3d
No Postprocessings.
Required SubTask 1 started: **Save_Waveforms**: from 1 to 173 iteration
Excitation: name: SourcePort, Pulse type: sinus, Amplitude=1, Delay= 0 [ns], Frequency=8.5 [GHz]
Required SubTask 1 finished: **Save_Waveforms**: from 1 to 173 iteration
All SubTasks finished

Figure 1: Impedance value for 1a)

$Z_c\ of\ input = Z_c\ of\ output = 376.7303\ [\Omega]$

$Z_c - impedance$

3.8)

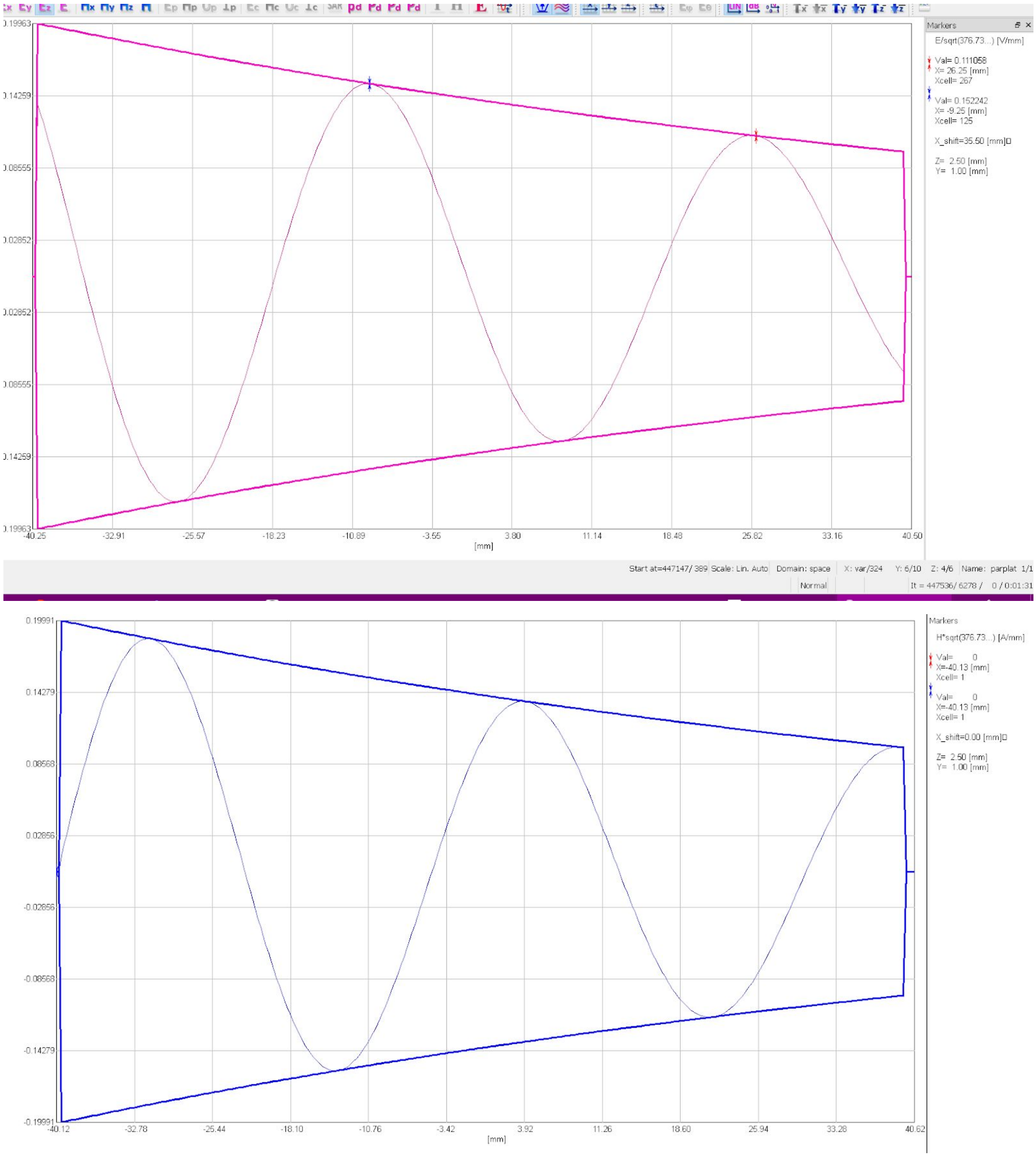


Figure 2: Envelope windows Ez(upper) Hy(lower) for 1a)

$Wavelength\ -\ \lambda\ =$ X_shift = 35.5 [mm]

$Formula\ for\ phase\ coefficient\ \beta\ using\ measured\ \lambda:$

$$\lambda\ =\ \frac{2\pi}{\beta}\ =>\ \beta = \frac{2\pi}{\lambda}\ =>\ \beta\ \approx 176{,}99\ [\ 1\ /\ m\ ]$$

$$Analytical\ formula\ for\ \beta\ =\ \omega\ *\ \sqrt{\mu * \varepsilon} = 2\pi * f * \sqrt{\mu * \varepsilon} \approx 178{,}10\ [1\ /\ m]$$

$\beta_{\ markers} - Phase\ coefficient\ calculated\ from\ lambda\ from\ markers$

$\beta_{\ analytical}\ -\ Phase\ coefficient\ calculated\ from\ analytical\ formula$

$$Relative\ error\ =\ 100\ \%\ *\ \frac{\beta_{\ markers} - \beta_{\ analytical}}{\beta_{\ analytical}} \approx 0{,}6\%$$

$$attenuation\ coefficient\ from\ markers\ \alpha = \frac{1}{x_2 - x_1} ln(\frac{E(x_1)}{E(x_2)}) = 8,890\ [unit\ less]$$

$$attenuation\ coefficient\ from\ analytical\ formula\ \alpha = \frac{\sigma}{2} * |Z| \approx 8.897\ [unit\ less]$$

$$Relative\ error\ \alpha = 100\ \% * \frac{\alpha_{markers} - \alpha_{analytical}}{\alpha_{analytical}} \approx 0.07\ \%$$

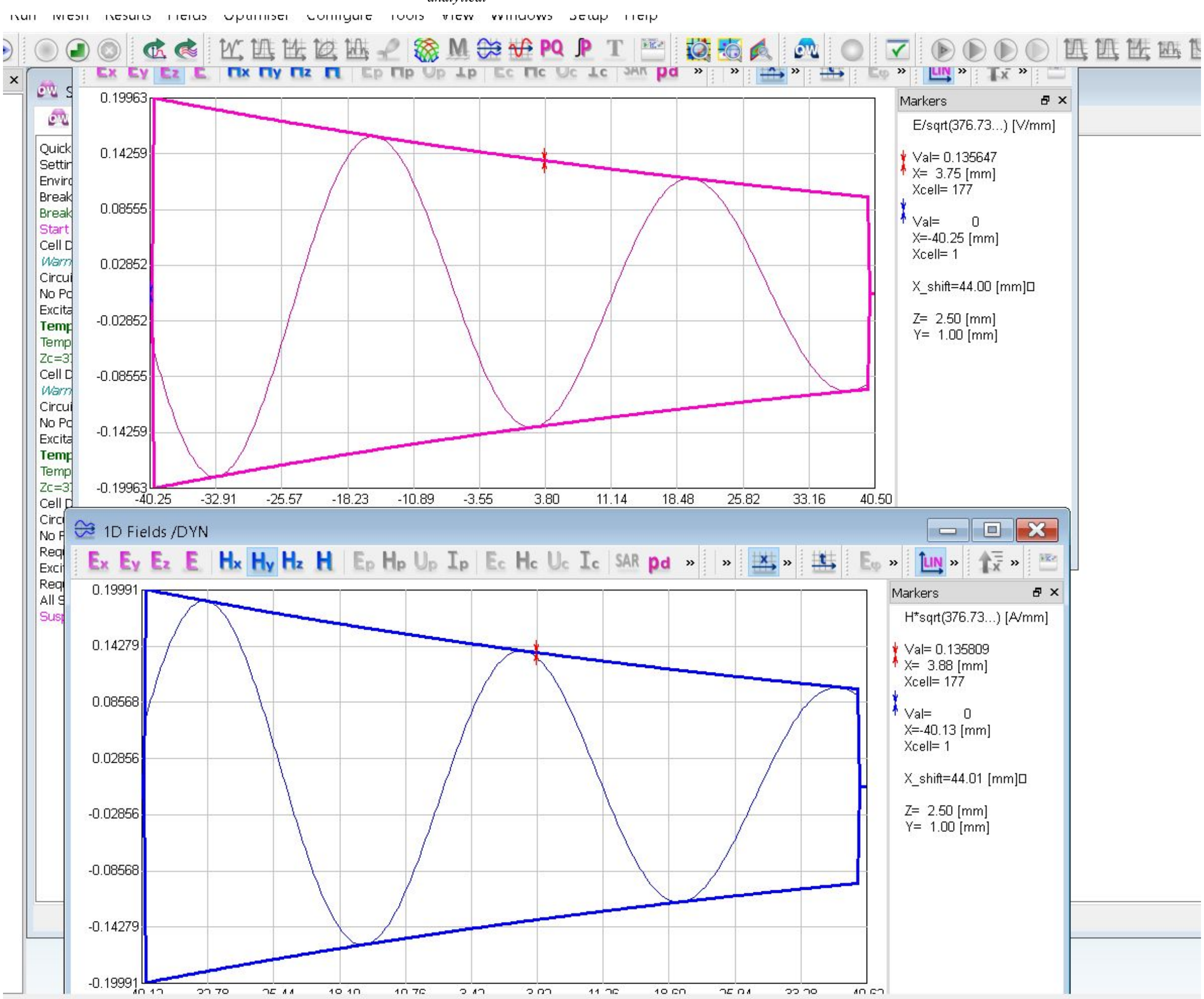


Figure 3: Envelope windows Ez(upper) Hy(lower) with marked En and Hn for 1a)

From markers:

$$E_n = 0.13\ [V\ /\ mm]$$

$$H_n = 0.13\ [A\ /\ mm]$$

$$E = E_n * \sqrt{Z_0} \approx 2,5\ [V\ /\ mm]$$

$$H = \frac{H_n}{\sqrt{Z_0}} = 0.007\ [A\ /\ mm]$$

$$Z_w = \frac{E_n}{H_n} * Z_0 \approx 376,991[\Omega]$$

From analytical formulas:

$$Z = \sqrt{\frac{\mu}{\varepsilon}} = 376.81\ [\Omega]$$

$$Relative\ error = 100\% * \frac{Z - Z_w}{Z} \approx 0.05\ \%$$

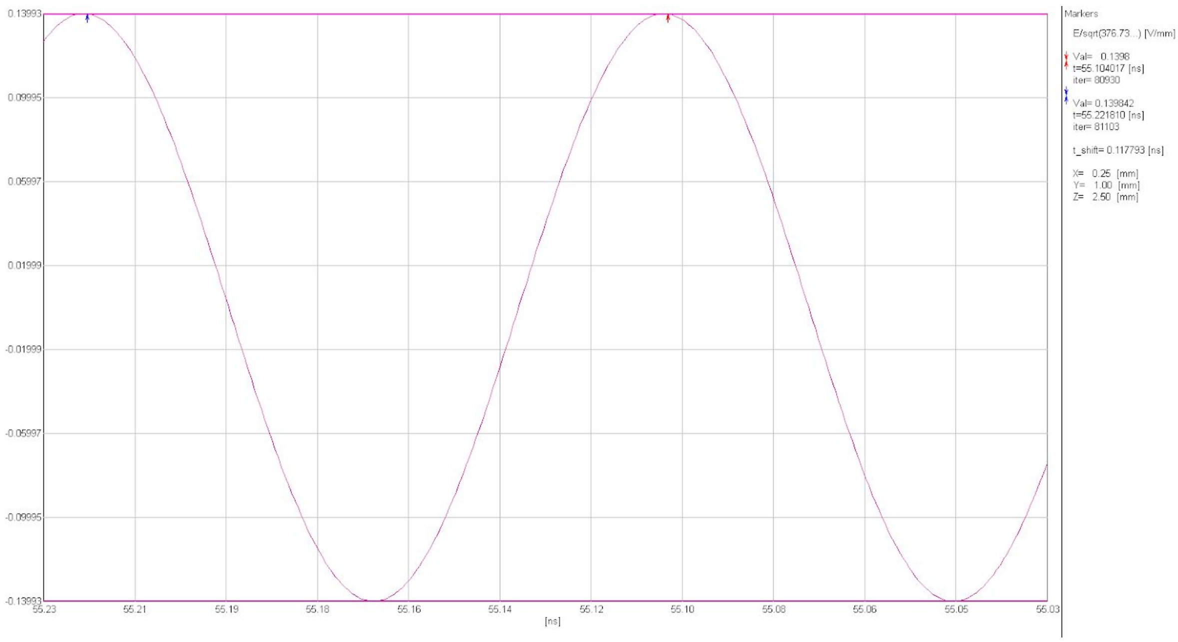


Figure 4: Time domain View Envelope window for 1a)

$T = t_{shift} \approx 0.1178\ [ns]$

$T_{real} = \frac{1}{f_{real}} \approx 0.0,1176[ns]$

$Relative\ error = \frac{T - T_{real}}{T_{real}} * 100\% = 3\%$

$f = \frac{1}{T} \approx 8.476\ [GHz]$

$f_{real} = 8.5\ [GHz]$

$Relative\ error = \frac{f_{real - f}}{f_{real}} * 100\% \approx 0,3\%$

$\beta = 2\pi * f * \sqrt{\mu * \varepsilon} \approx 177,57\ [1/m]$

$\beta_{analytical} \approx 178,10\ [1/m]$

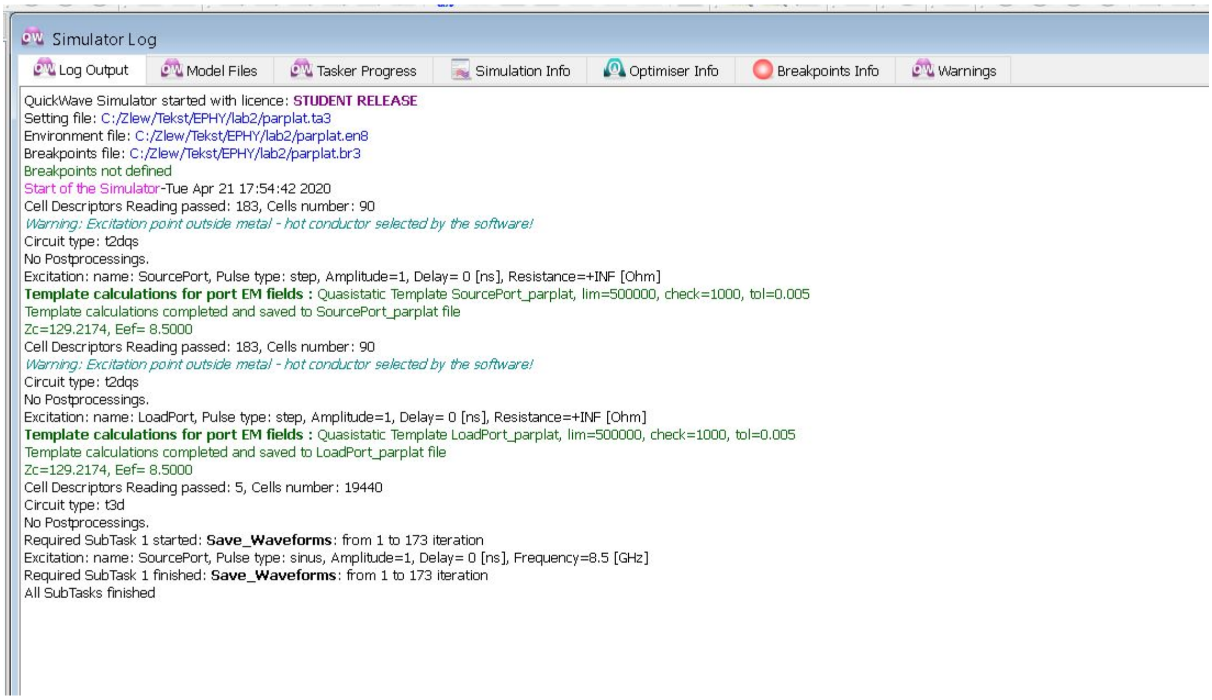
$Relative\ error = \frac{\beta_{analytical} - \beta}{\beta_{analytical}} * 100\% \approx 0,3\%$

$\beta\ compared\ with\ \beta\ from\ 3.7:$

$Relative\ error\ with\ \beta\ from\ 3.7: \frac{\beta_{3.7} - \beta_{3.10}}{\beta_{3.7}} * 100\% \approx 0,33\%$

1 b) $f = 8.5[GHz],\ \varepsilon_r = 8.5\ [F/m],\ \mu_r = 1\ [H/m],\ tan(\delta) = 0.1$

3.7)


Simulator Log

Log Output | Model Files | Tasker Progress | Simulation Info | Optimiser Info | Breakpoints Info | Warnings

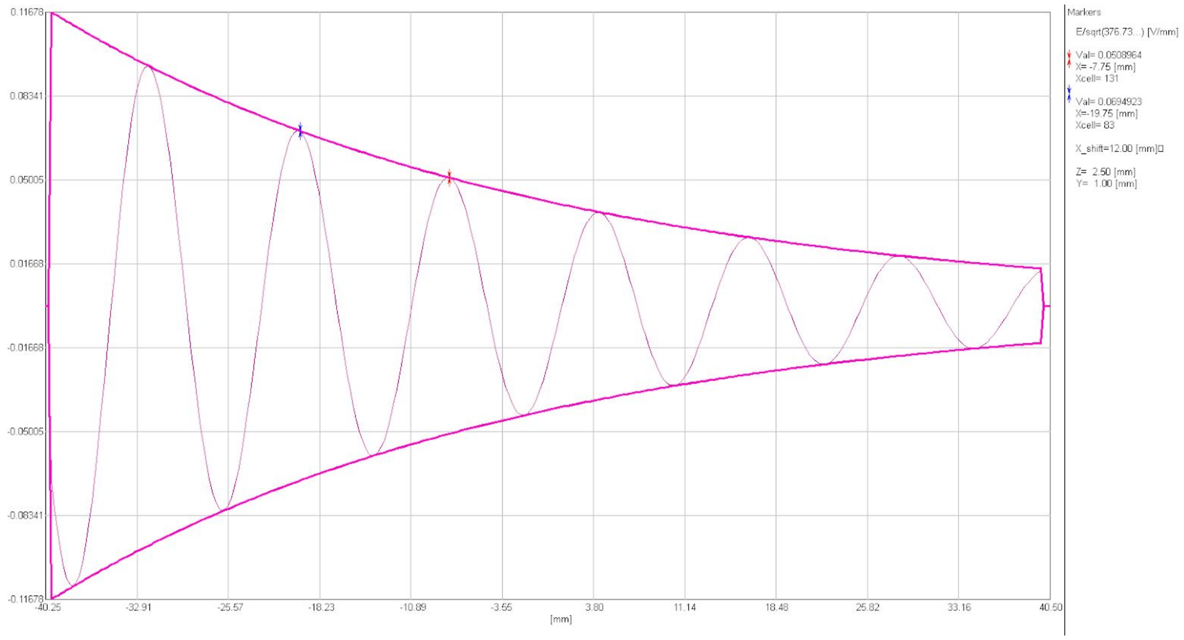
QuickWave Simulator started with licence: STUDENT RELEASE
Setting file: C:/Zlew/Tekst/EPHY/lab2/parplat.ta3
Environment file: C:/Zlew/Tekst/EPHY/lab2/parplat.en8
Breakpoints file: C:/Zlew/Tekst/EPHY/lab2/parplat.br3
Breakpoints not defined
Start of the Simulator-Tue Apr 21 17:54:42 2020
Cell Descriptors Reading passed: 183, Cells number: 90
Warning: Excitation point outside metal - hot conductor selected by the software!
Circuit type: t2dqs
No Postprocessings.
Excitation: name: SourcePort, Pulse type: step, Amplitude=1, Delay= 0 [ns], Resistance=+INF [Ohm]
Template calculations for port EM fields : Quasistatic Template SourcePort_parplat, lim=500000, check=1000, tol=0.005
Template calculations completed and saved to SourcePort_parplat file
Zc=129.2174, Eef= 8.5000
Cell Descriptors Reading passed: 183, Cells number: 90
Warning: Excitation point outside metal - hot conductor selected by the software!
Circuit type: t2dqs
No Postprocessings.
Excitation: name: LoadPort, Pulse type: step, Amplitude=1, Delay= 0 [ns], Resistance=+INF [Ohm]
Template calculations for port EM fields : Quasistatic Template LoadPort_parplat, lim=500000, check=1000, tol=0.005
Template calculations completed and saved to LoadPort_parplat file
Zc=129.2174, Eef= 8.5000
Cell Descriptors Reading passed: 5, Cells number: 19440
Circuit type: t3d
No Postprocessings.
Required SubTask 1 started: **Save_Waveforms**: from 1 to 173 iteration
Excitation: name: SourcePort, Pulse type: sinus, Amplitude=1, Delay= 0 [ns], Frequency=8.5 [GHz]
Required SubTask 1 finished: **Save_Waveforms**: from 1 to 173 iteration
All SubTasks finished

Figure 1b: Impedance value for 1b)

$Z_c\ of\ input = Z_c\ of\ output = 129,2174\ [\Omega]$

$Z_c - impedance$

3.8)



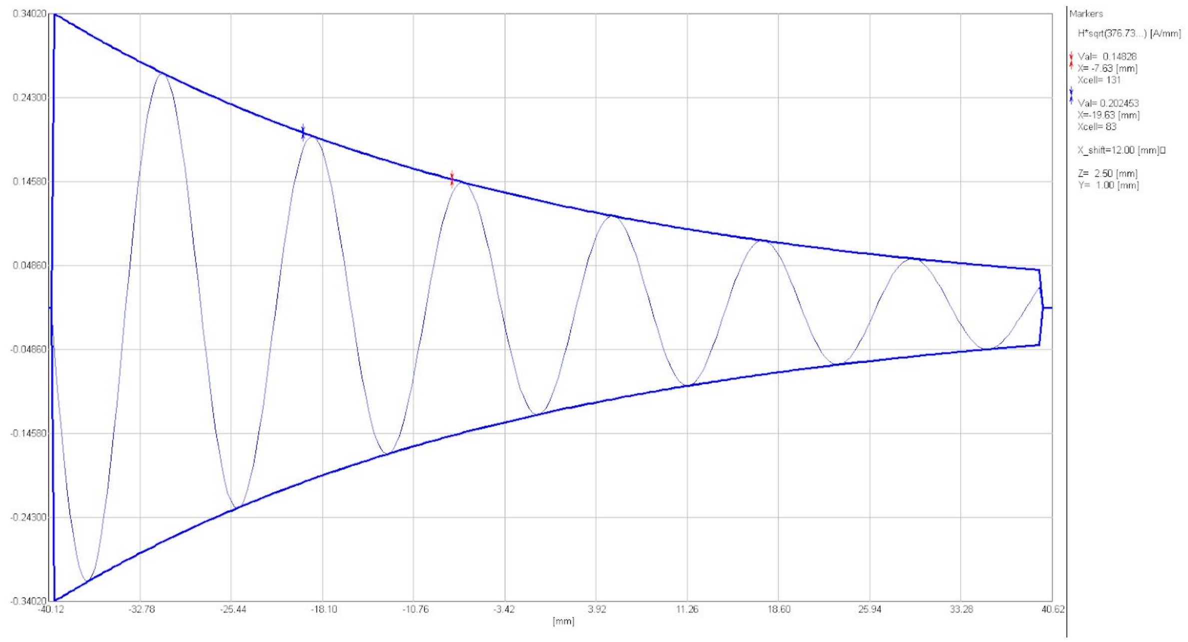


Figure 2b): Envelope windows Ez(upper) Hy(lower) for 1b)

$Wavelength\ -\ \lambda\ =$ X_shift = 12 [mm]

$Formula\ for\ phase\ coefficient\ \beta\ using\ measured\ \lambda:$

$\lambda\ =\ \frac{2\pi}{\beta}\ =>\ \beta = \frac{2\pi}{\lambda}\ =>\ \beta\ \approx 523,599\ [\ 1\ /\ m\ ]$

$Analytical\ formula\ for\ \beta\ =\ \omega\ *\ \sqrt{\mu * \varepsilon} = 2\pi * f * \sqrt{\mu * \varepsilon} \approx 1519,26[1\ /\ m]$

$\beta_{\ markers} - Phase\ coefficient\ calculated\ from\ lambda\ from\ markers$

$\beta_{\ analytical}\ -\ Phase\ coefficient\ calculated\ from\ analytical\ formula$

$Relative\ error\ =\ 100\ \%\ *\ \frac{\beta_{\ markers}\ -\beta_{\ analytical}}{\beta_{\ analytical}} \approx 0.84\%$

$attenuation\ coefficient\ from\ markers\ \alpha\ =\ \frac{1}{x_2 - x_1} ln(\frac{E(x_1)}{E(x_2)}) = 26,3\ [unit\ less]$

$attenuation\ coefficient\ from\ analytical\ formula\ \alpha\ =\ \frac{\sigma}{2} * |Z| \approx 25,939\ [unit\ less]$

$$Relative\ error\ \alpha\ =\ 100\ \%\ *\ \frac{\alpha_{markers}\ -\alpha_{analytical}}{\alpha_{analytical}}\ = 1,4\ \%$$

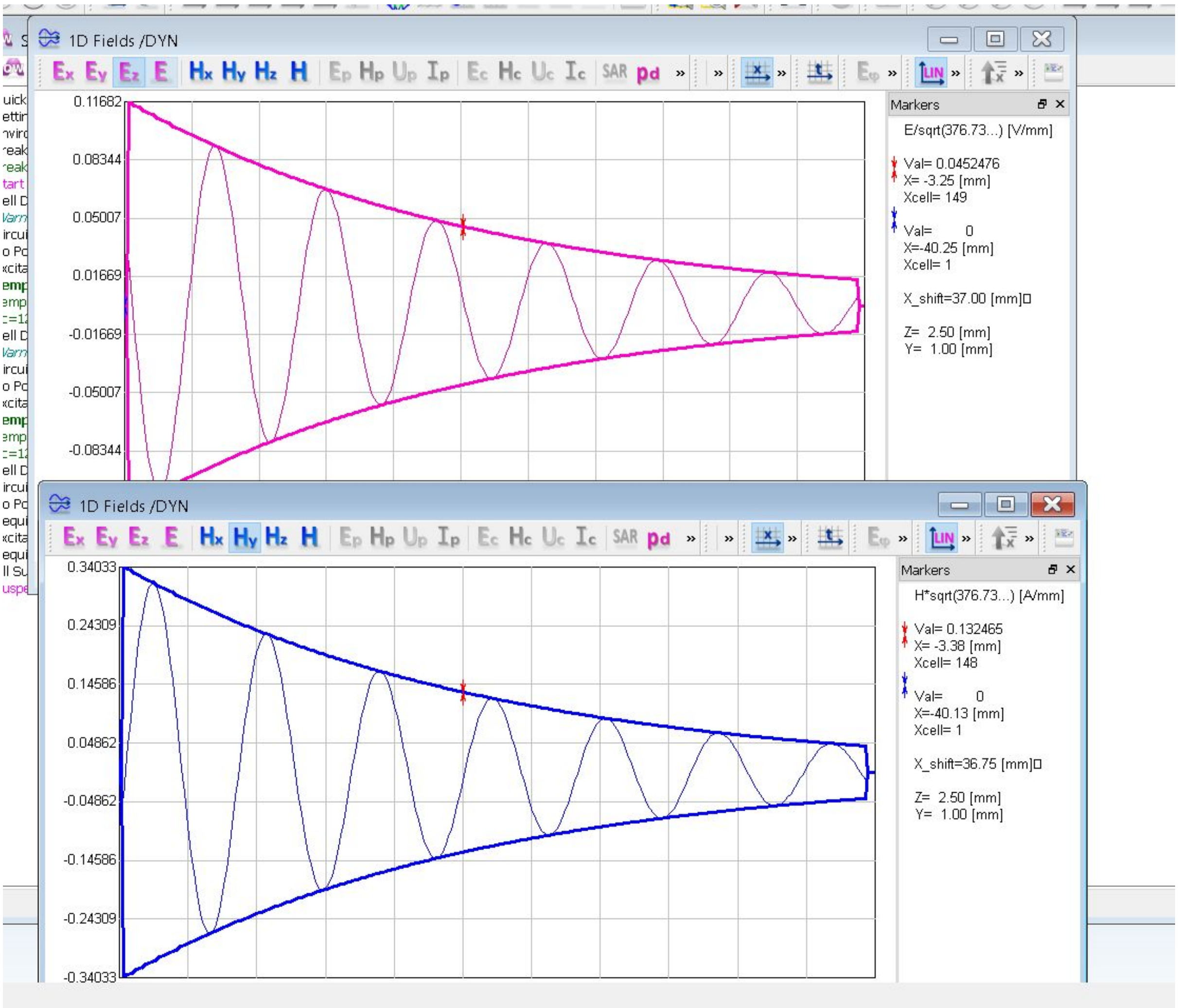


Figure 3b): Envelope windows Ez(upper) Hy(lower) with marked En and Hn for 1b)

From markers:

$$E_n = 0,045\ [V\ /\ mm]$$

$$H_n = 0.13\ [A\ /\ mm]$$

$$E\ =\ E_n * \sqrt{Z_0} \approx 0,88\ [V\ /\ mm]$$

$$H = \frac{H_n}{\sqrt{Z_0}} = 0,007\ [A\ /\ mm]$$

$$Z_w = \frac{E_n}{H_n} * Z_0 \approx\ 128,8[\Omega]$$

From analytical formulas:

$$Z = \sqrt{\frac{\mu}{\varepsilon}} = 130\ [\Omega]$$

$$Relative\ error\ =\ 100\%\ *\ \frac{Z-Z_w}{Z} \approx 0,37\%$$

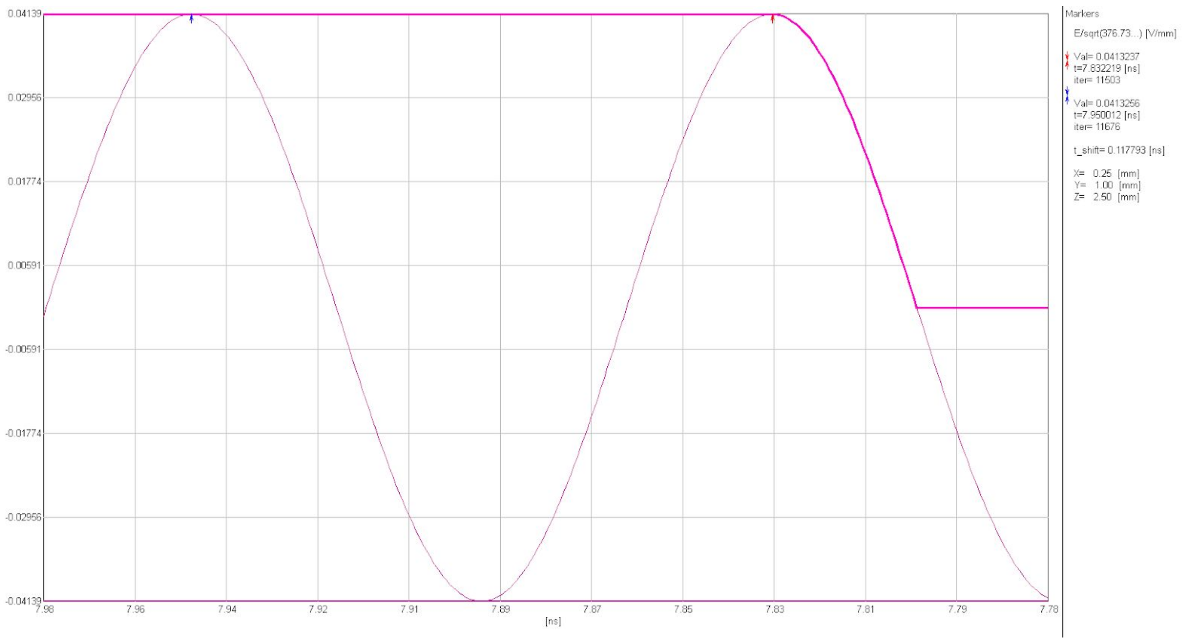


Figure 4b): Time domain View Envelope window for 1b)

$T = t_{shift} \approx 0.1178\ [ns]$

$T_{real} = \frac{1}{f_{real}} \approx 0.0, 1176[ns]$

$Relative\ error = \frac{T - T_{real}}{T_{real}} * 100\% = 3\%$

$f = \frac{1}{T} \approx 8.476\ [GHz]$

$f_{real} = 8.5\ [GHz]$

$Relative\ error = \frac{f_{real} - f}{f_{real}} * 100\% \approx 0, 3\%$

$\beta = 2\pi * f * \sqrt{\mu * \varepsilon} \approx 177, 57\ [1 / m]$

$\beta_{analytical} \approx 178, 10\ [1 / m]$

$Relative\ error = \frac{\beta_{analytical} - \beta}{\beta_{analytical}} * 100\% \approx 0, 3\%$

$\beta\ compared\ with\ \beta\ from\ 3.7 :$

$Relative\ error\ with\ \beta\ from\ 3.7 : \frac{\beta_{3.7} - \beta_{3.10}}{\beta_{3.7}} * 100\% \approx 0, 33\%$

1 c) $f = 8.5[GHz],\ \varepsilon_r = 1\ [F / m],\ \mu_r = 8.5\ [H / m],\ tan(\delta) = 0.1$

3.7)

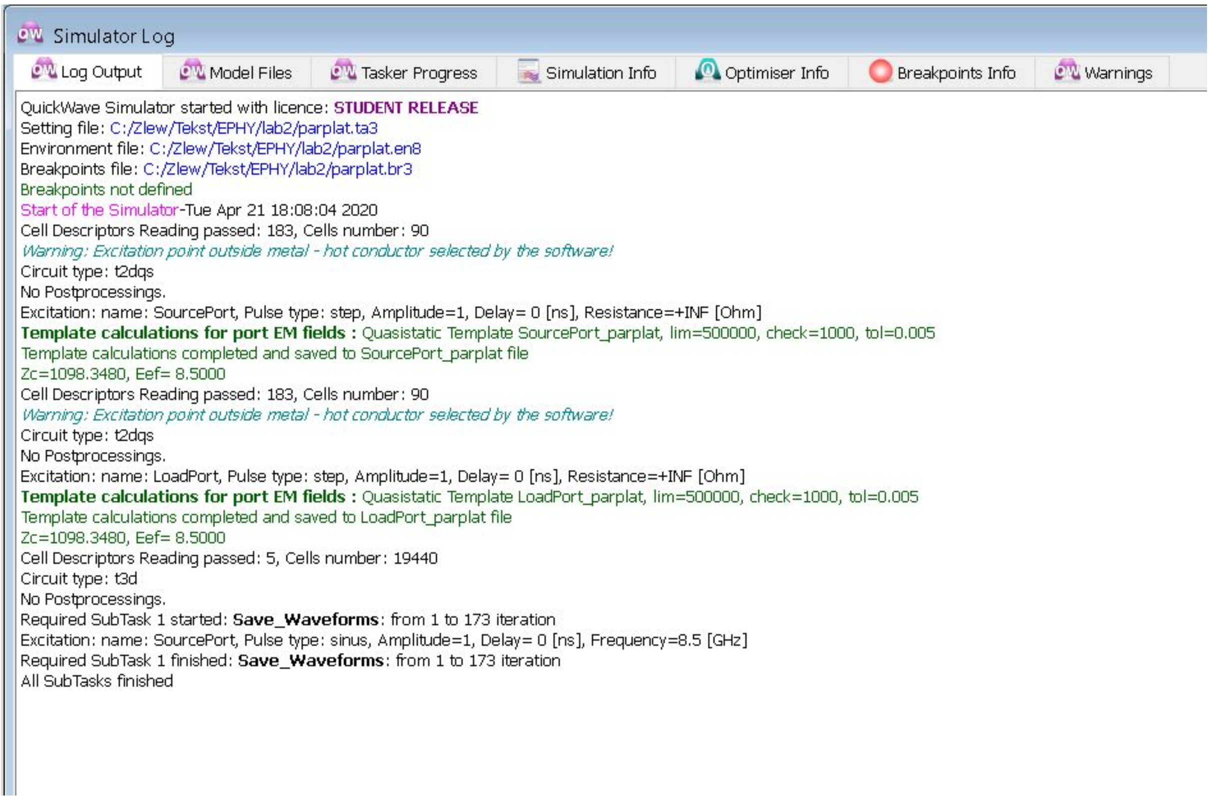
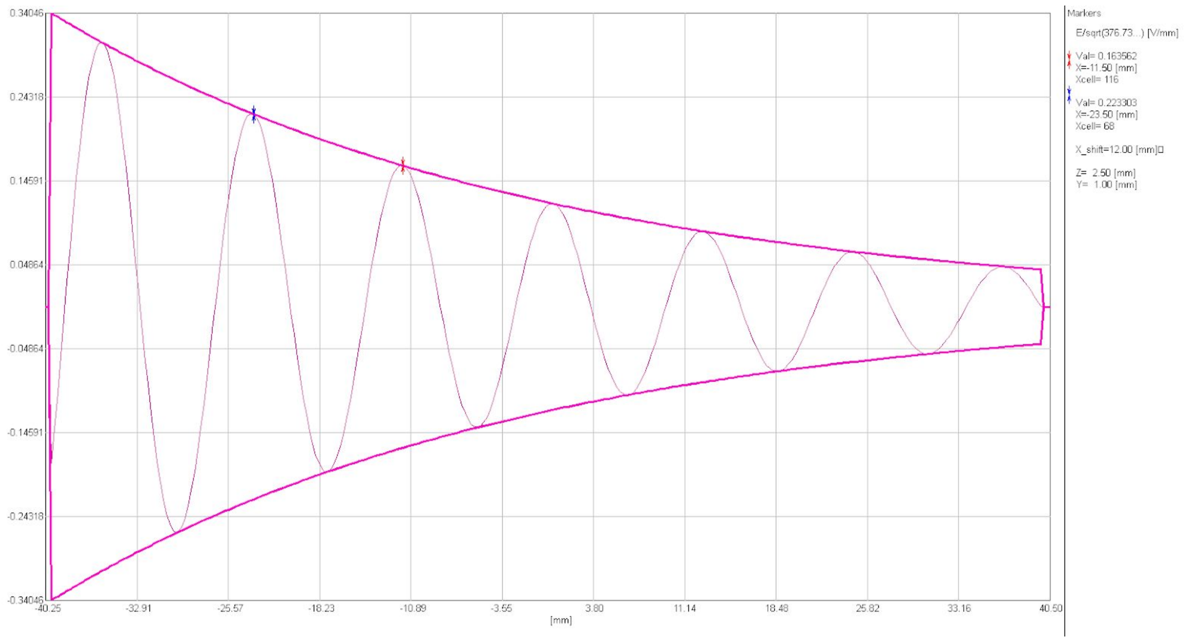


Figure 1c: Impedance value for 1c)

$$Z_c \ of \ input \ = \ Z_c \ of \ output \ = \ 1098,348 \ [\Omega]$$

$$Z_c \ - \ impedance$$

3.8)



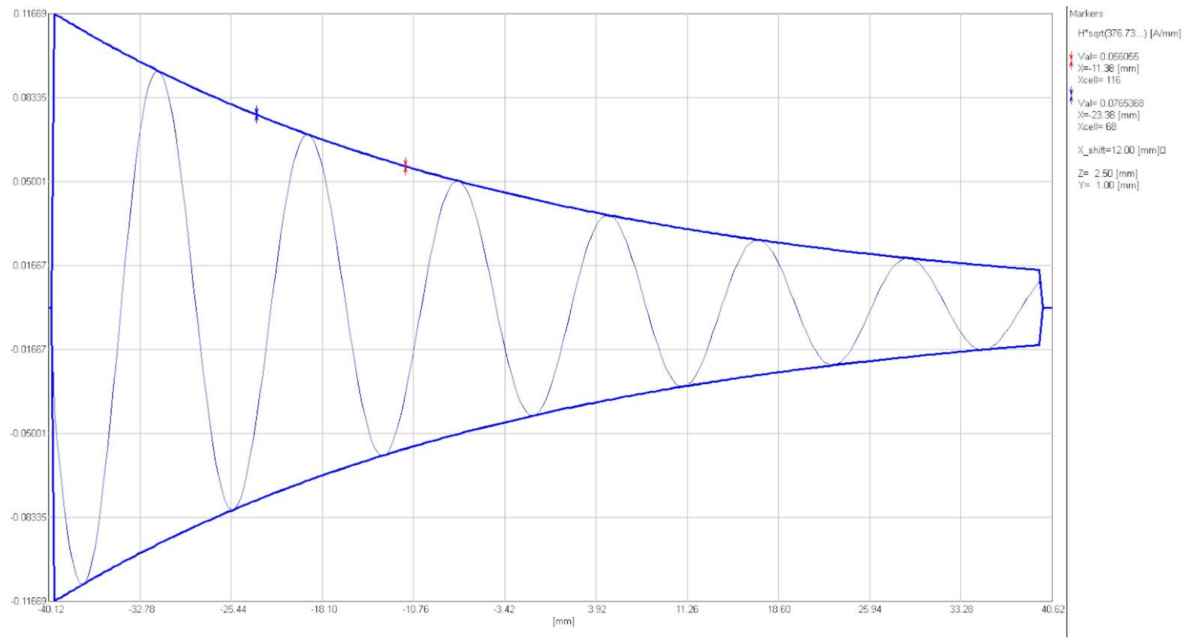


Figure 2c): Envelope windows Ez(upper) Hy(lower) for 1c)

$Wavelength\ -\ \lambda\ =$ X_shift = 12 [mm]

$Formula\ for\ phase\ coefficient\ \beta\ using\ measured\ \lambda:$

$\lambda\ =\ \frac{2\pi}{\beta}\ =>\ \beta = \frac{2\pi}{\lambda}\ =>\ \beta\ \approx 523,599\ [\ 1\ /\ m\ ]$

$Analytical\ formula\ for\ \beta\ =\ \omega\ *\ \sqrt{\mu * \varepsilon} = 2\pi * f * \sqrt{\mu * \varepsilon} \approx 1519,26[1\ /\ m]$

$\beta_{\ markers} - Phase\ coefficient\ calculated\ from\ lambda\ from\ markers$

$\beta_{\ analytical}\ -\ Phase\ coefficient\ calculated\ from\ analytical\ formula$

$Relative\ error\ =\ 100\ \%\ *\ \frac{\beta_{\ markers}\ -\beta_{\ analytical}}{\beta_{\ analytical}} \approx 0.84\%$

$attenuation\ coefficient\ from\ markers\ \alpha\ =\ \frac{1}{x_2 - x_1} ln(\frac{E(x_1)}{E(x_2)}) = 26,5\ [unit\ less]$

$attenuation\ coefficient\ from\ analytical\ formula\ \alpha\ =\ \frac{\sigma}{2} * |Z| \approx 26\ [unit\ less]$

$$Relative\ error\ \alpha\ =\ 100\ \%\ *\ \frac{\alpha_{markers}-\alpha_{analytical}}{\alpha_{analytical}}\ = 2,13\ \%$$

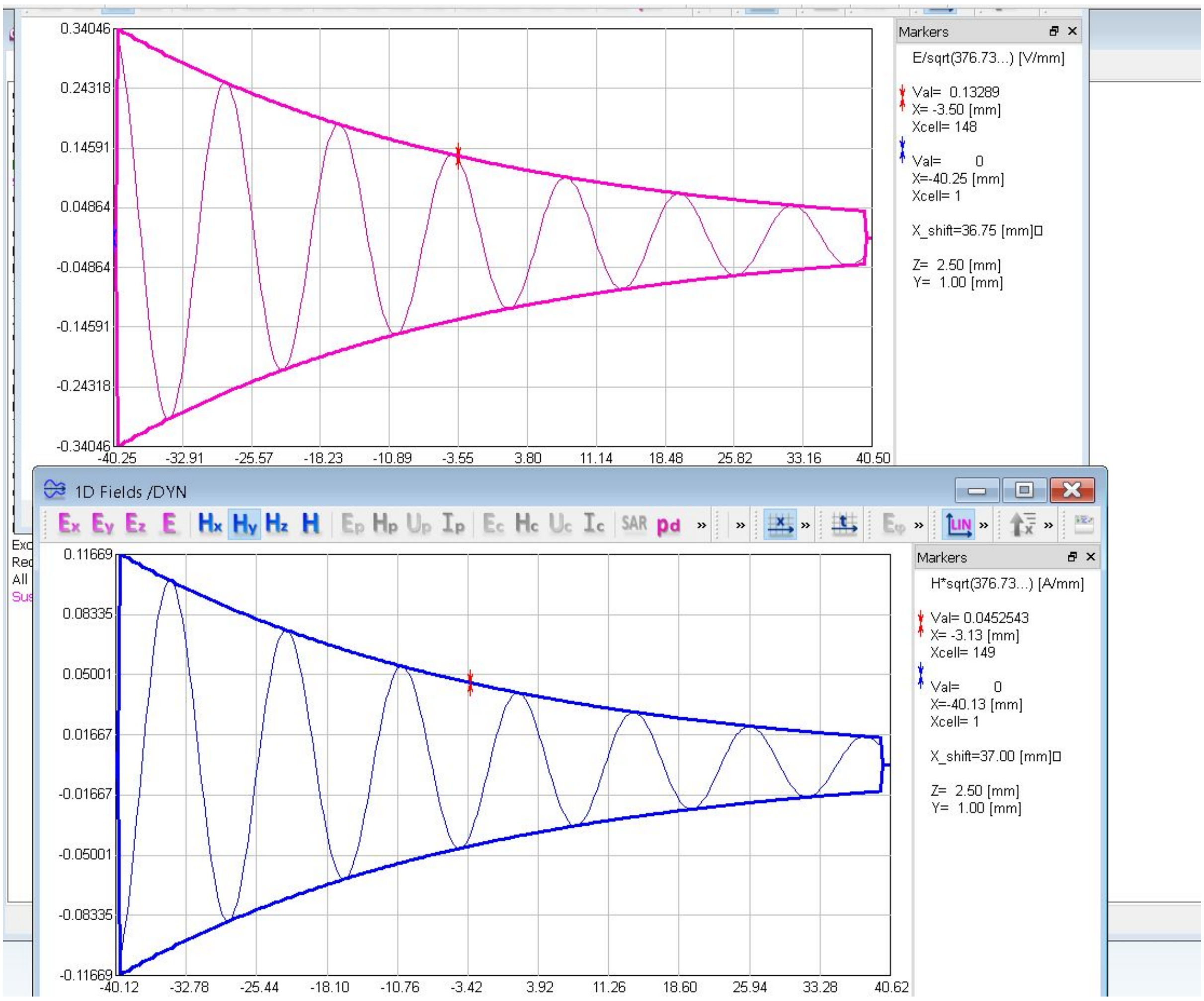


Figure 3c): Envelope windows Ez(upper) Hy(lower) with marked En and Hn for 1c)

From markers:

$E_n = 0,045\ [V\ /\ mm]$

$H_n = 0.13\ [A\ /\ mm]$

$E\ =\ E_n * \sqrt{Z_0} \approx 2,58[V\ /\ mm]$

$H = \frac{H_n}{\sqrt{Z_0}} = 0,002\ [A\ /\ mm]$

$Z_w = \frac{E_n}{H_n} * Z_0 \approx\ 1107,04[\Omega]$

From analytical formulas:

$Z = \sqrt{\frac{\mu}{\varepsilon}} = 1098,6\ [\Omega]$

$Relative\ error\ =\ 100\%\ *\ \frac{Z-Z_w}{Z} \approx 0,77\%$

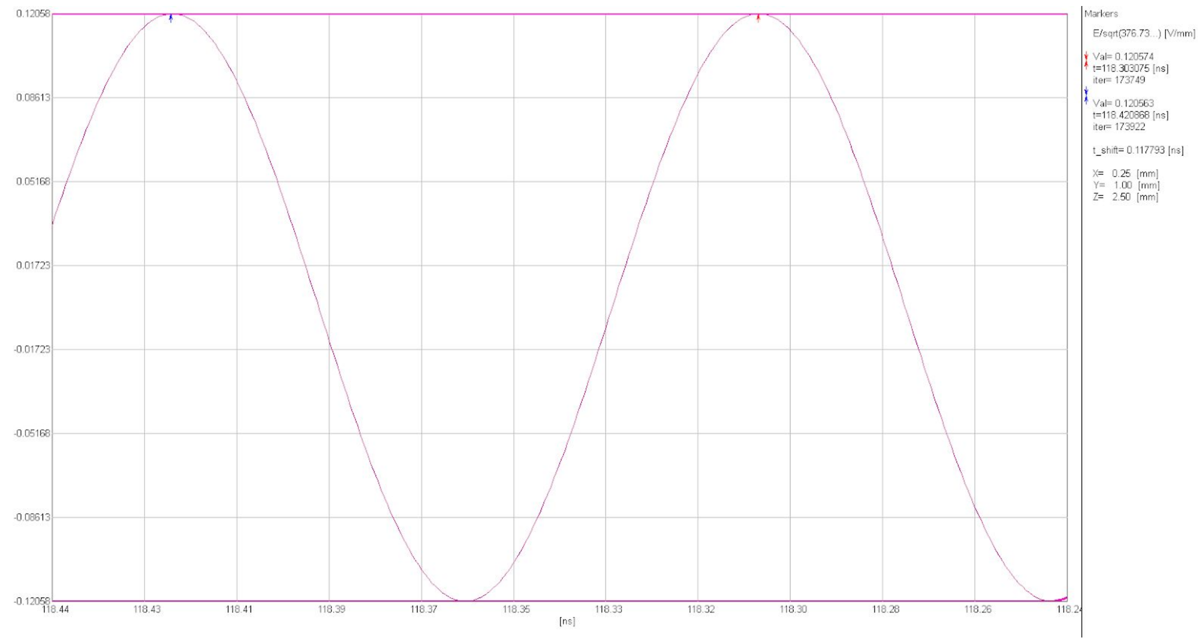


Figure 4c): Time domain View Envelope window for 1c)

$T = t_{shift} \approx 0.1178\ [ns]$

$T_{real} = \frac{1}{f_{real}} \approx 0.0,1176[ns]$

$Relative\ error = \frac{T - T_{real}}{T_{real}} * 100\% = 3\%$

$f = \frac{1}{T} \approx 8.476\ [GHz]$

$f_{real} = 8.5\ [GHz]$

$Relative\ error = \frac{f_{real - f}}{f_{real}} * 100\% \approx 0,3\%$

$\beta = 2\pi * f * \sqrt{\mu * \varepsilon} \approx 177,57\ [1 / m]$

$\beta_{analytical} \approx 178,10\ [1 / m]$

$Relative\ error = \frac{\beta_{analytical} - \beta}{\beta_{analytical}} * 100\% \approx 0,3\%$

$\beta\ compared\ with\ \beta\ from\ 3.7 :$

$Relative\ error\ with\ \beta\ from\ 3.7 : \frac{\beta_{3.7} - \beta_{3.10}}{\beta_{3.7}} * 100\% \approx 0,33\%$

Answering the questions:

a) Envelope in a lossy case has a shape like an exponential function.

b) It does not influence phase shift.