Lab number: 1
Lab title: TEM Wave in lossless media
Date lab was performed: 07.04.2020
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.

a = 7.5
1 a)
Values we start with:

$$f\ =\ 7.5\ [GHz],\ \varepsilon_r\ =\ 1\ [F\ /\ m],\ \mu_r = 1\ [H\ /\ m],\ tg\delta = 0\ \Rightarrow\ \sigma\ =\ 0\ [\ S\ /\ m\ ]\ (lossless\ model)$$
$$f\ -\ frequency,\ \varepsilon_r\ -\ permittivity,\ \ \mu_r\ -\ permeability,\ tg\delta\ -\ loss\ tangent,\ \sigma\ -\ conductivity$$

3.7:
$$Z_c\ of\ input\ =\ Z_c\ of\ output\ =\ 376.7303\ [\Omega]$$
$$Z_c\ -\ impedance$$

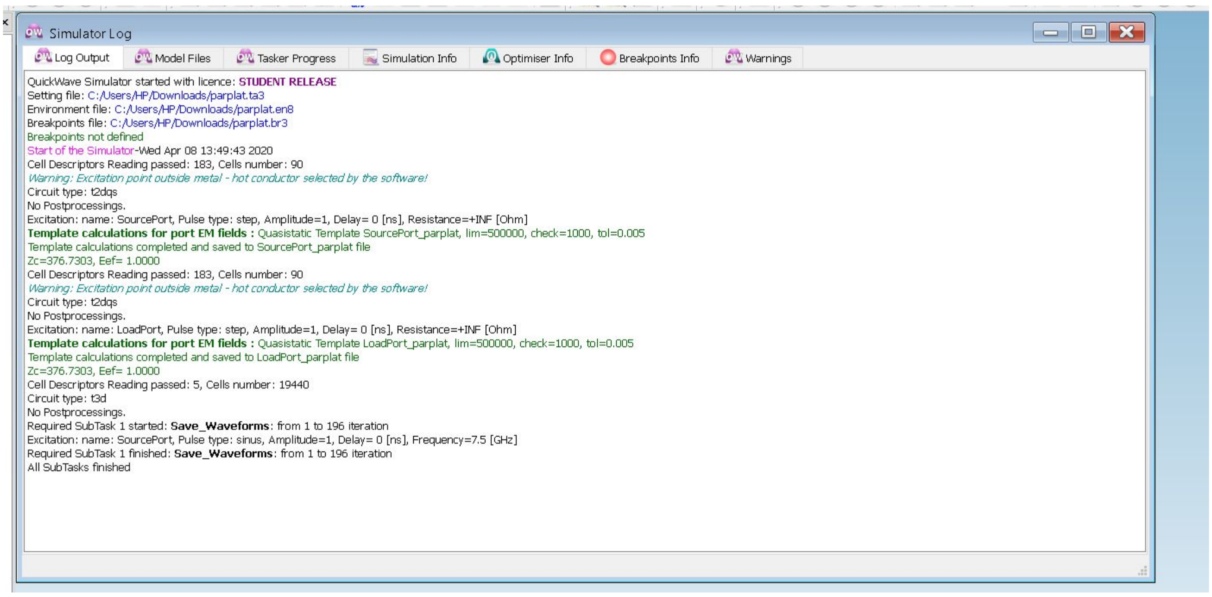


Figure 1: Impedance value for
$$f\ =\ 7.5\ [GHz],\ \varepsilon_r\ =\ 1\ [F\ /\ m],\ \mu_r = 1\ [H\ /\ m],\ tg\delta = 0\ \Rightarrow\ \sigma\ =\ 0\ [\ S\ /\ m\ ]$$

3.8:

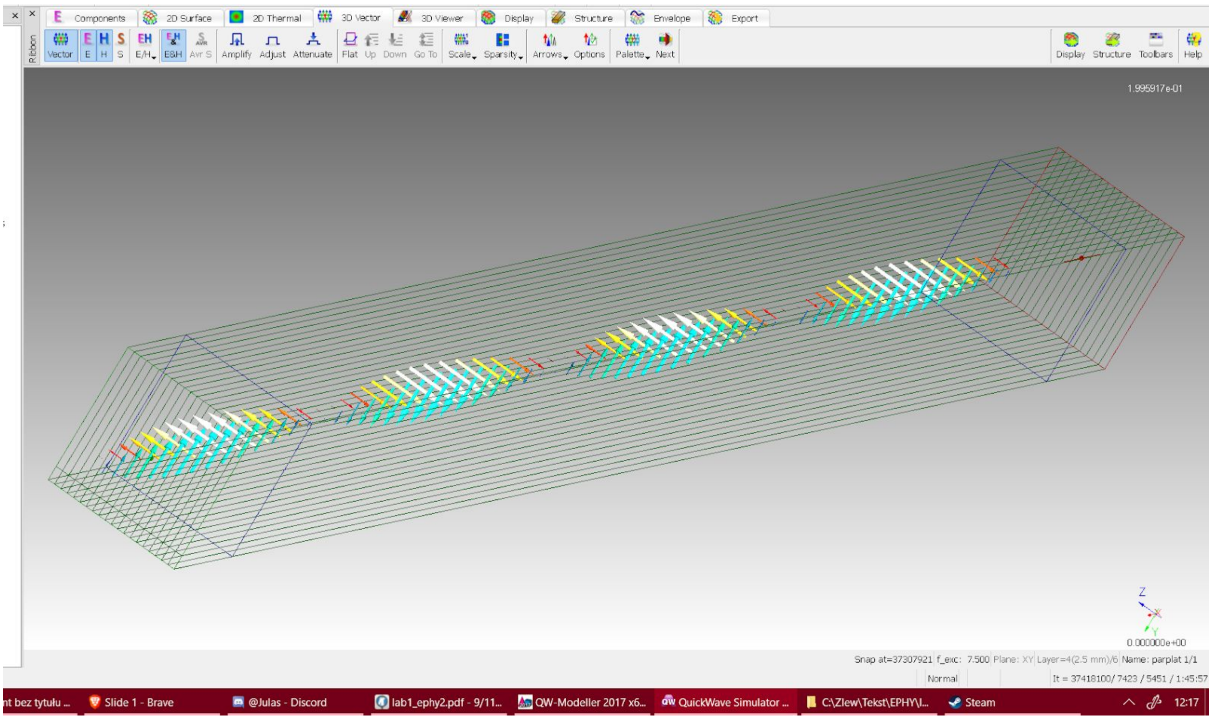


Figure 2: 3D Vector Display for

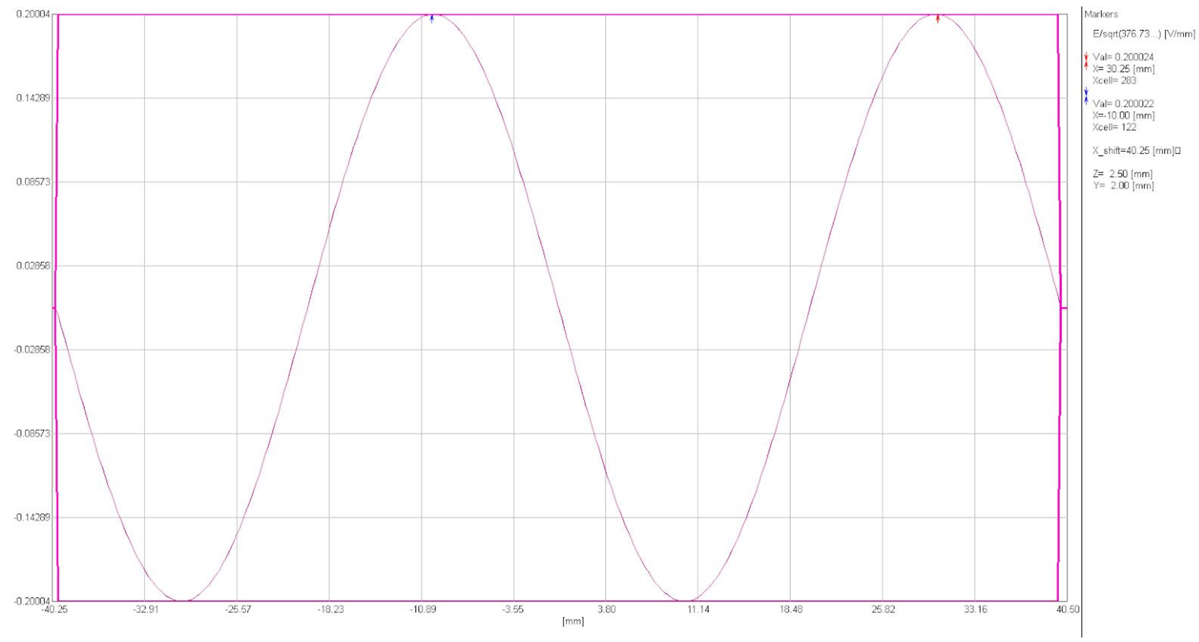
$f = 7.5\,[GHz],\ \varepsilon_r = 1\,[F/m],\ \mu_r = 1\,[H/m],\ tg\delta = 0 \Rightarrow \sigma = 0\,[S/m]$

Electric component: z (We can see that only z axis is visible in electric component in the program)

Magnetic component: y (We can see that only y axis is visible in magnetic component in the program)

Direction of propagation: x (It is the only axis left, after we established that we can see z and y component)

3.9



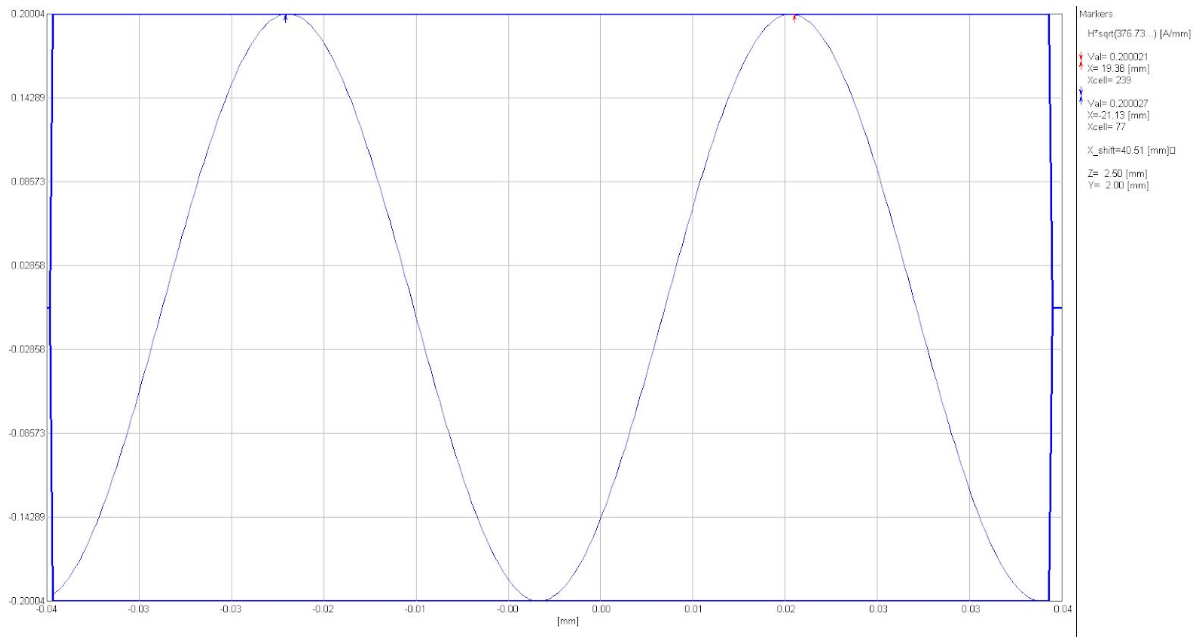


Figure 3: Envelope windows Ez(upper) Hy(lower) for
$f = 7.5\ [GHz],\ \varepsilon_r = 1\ [F/m],\ \mu_r = 1\ [H/m],\ tg\delta = 0 \ \Rightarrow\ \sigma = 0\ [S/m]$

$Wavelength - \lambda =$ X_shift = 40.25 [mm]

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

$\lambda = \frac{2\pi}{\beta} \Rightarrow \beta = \frac{2\pi}{\lambda} \Rightarrow \beta \approx 156.02\ [1/m]$

$\varepsilon = \varepsilon_0 * \varepsilon_r =$

$Analytical\ formula\ for\ \beta = \omega * \sqrt{\mu * \varepsilon} = 2\pi * f * \sqrt{\mu * \varepsilon} \approx 154,92\ [1/m]$

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

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

$Relative\ error = 100\ \% * \frac{\beta_{markers} - \beta_{analytical}}{\beta_{analytical}} \approx 0.7\ \%$

From markers:

$E_n = 0.2\ [V/mm]$

$H_n = 0.2\ [A/mm]$

$E = E_n * \sqrt{Z_0} \approx 2.2\ [V/mm]$

$H = \frac{H_n}{\sqrt{Z_0}} = 0.018\ [A/mm]$

$Z_w = \frac{E_n}{H_n} * Z_0 = 376.7\ [\Omega]$

From analytical formulas:

$Z = \sqrt{\frac{\mu}{\varepsilon}} = 377.0\ [\Omega]$

$Relative\ error = 100\% * \frac{Z - Z_w}{Z} \approx 0.08\ \%$

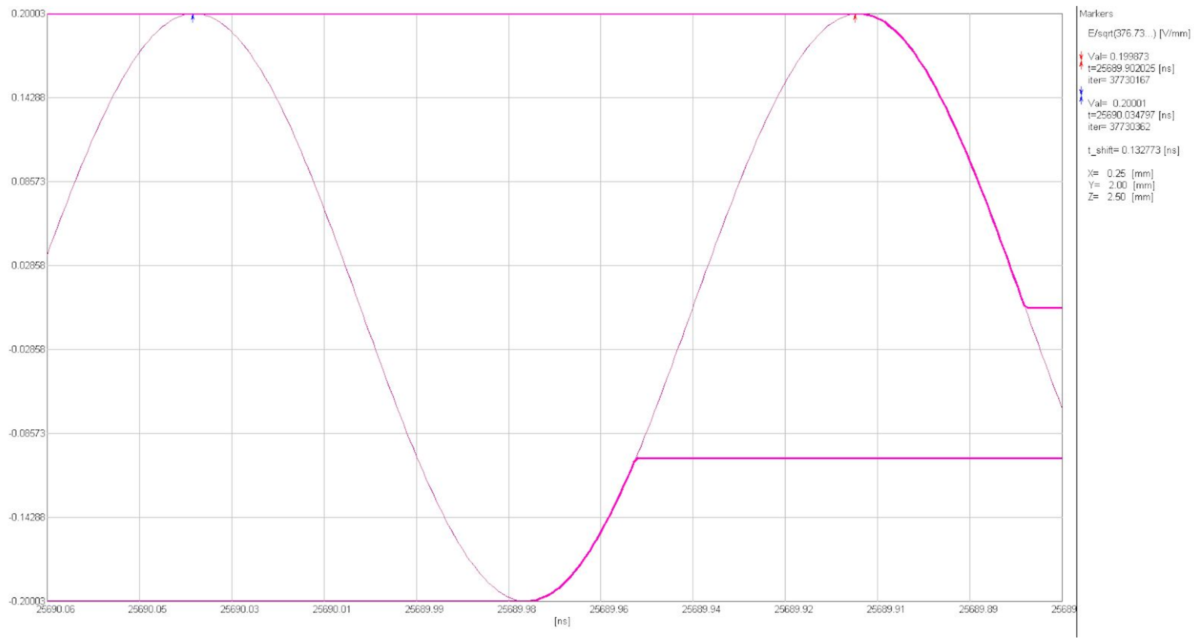


Figure 4: Time domain View Envelope window for
$f = 7.5\ [GHz],\ \varepsilon_r = 1\ [F/m],\ \mu_r = 1\ [H/m],\ tg\delta = 0\ \Rightarrow\ \sigma = 0\ [S/m]$

$T = t_{shift} \approx 0.138\ [ns]$

$T_{real} = \frac{1}{f_{real}} \approx 0.133[ns]$

$Relative\ error = \frac{T - T_{real}}{T_{real}} * 100\% = 3.3\%$

$f = \frac{1}{T} = 7.25\ [GHz]$

$f_{real} = 7.5\ [GHz]$

$Relative\ error = \frac{f_{real} - f}{f_{real}} * 100\% = 3.3\%$

$\beta = 2\pi * f * \sqrt{\mu * \varepsilon} \approx 149.76\ [1/m]$

$\beta_{analytical} = 154,92\ [1/m]$

$Relative\ error = \frac{\beta_{analytical} - \beta}{\beta_{analytical}} * 100\% = 3.3\%$

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

$Relative\ error\ with\ \beta\ from\ 3.7: \frac{\beta_{3.7} - \beta_{3.10}}{\beta_{3.7}} * 100\% \approx 3.31\%$

a = 7.5

1 b)

Values we start with:

$f = 15\ [GHz],\ \varepsilon_r = 1\ [F/m],\ \mu_r = 1\ [H/m],\ tg\delta = 0\ \Rightarrow\ \sigma = 0\ [S/m]\ (lossless\ model)$

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

3.7:

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

$Z_c - impedance$

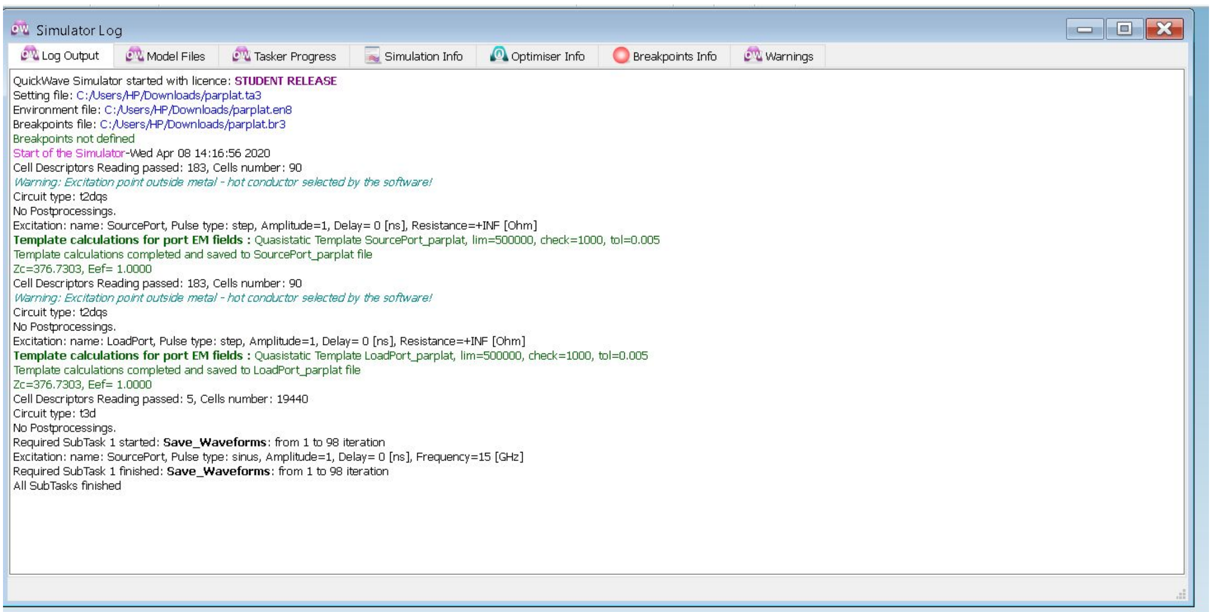


Figure 5: Impedance value for
$f = 15\ [GHz],\ \varepsilon_r = 1\ [F/m],\ \mu_r = 1\ [H/m],\ tg\delta = 0 \Rightarrow \sigma = 0\ [S/m]$

3.8:

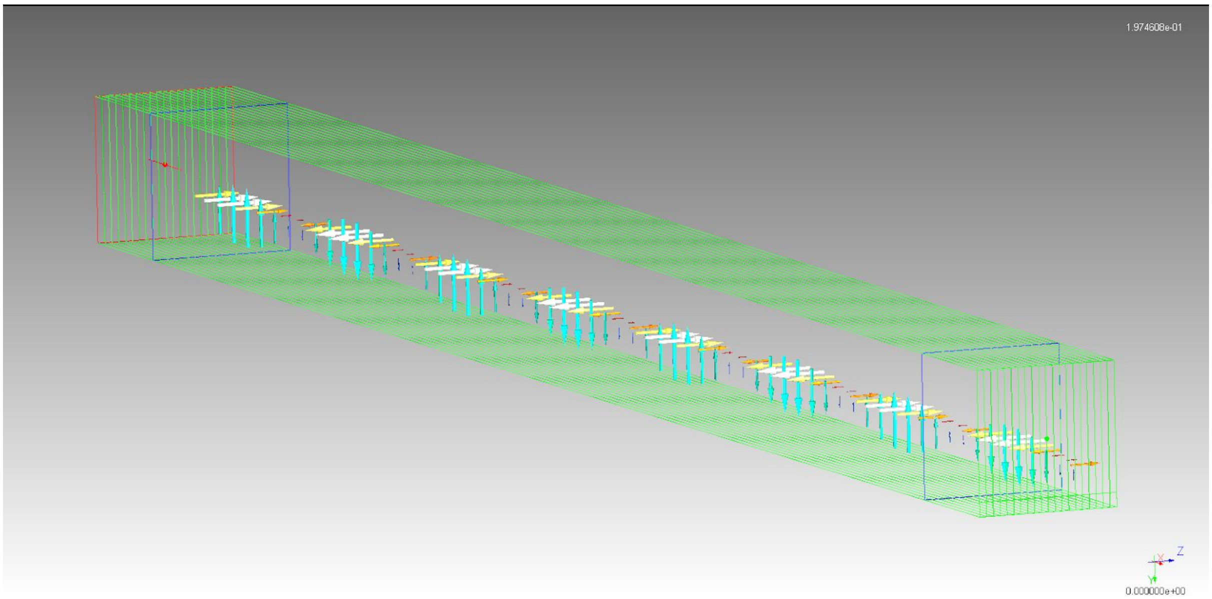


Figure 6: Fields window (3d vector display) for:

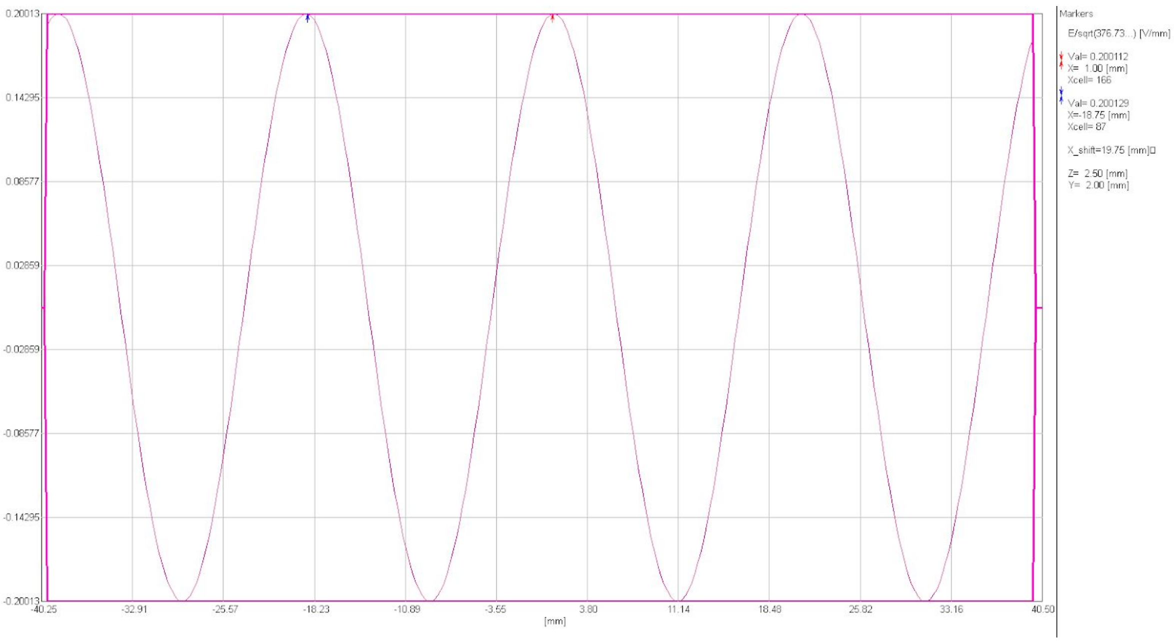
$f = 15\ [GHz],\ \varepsilon_r = 1\ [F/m],\ \mu_r = 1\ [H/m],\ tg\delta = 0\ \Rightarrow\ \sigma = 0\ [S/m]$

Electric component: z (We can see that only z axis is visible in electric component in the program)

Magnetic component: y (We can see that only y axis is visible in magnetic component in the program)

Direction of propagation: x (It is the only axis left, after we established that we can see z and y component)

3.9



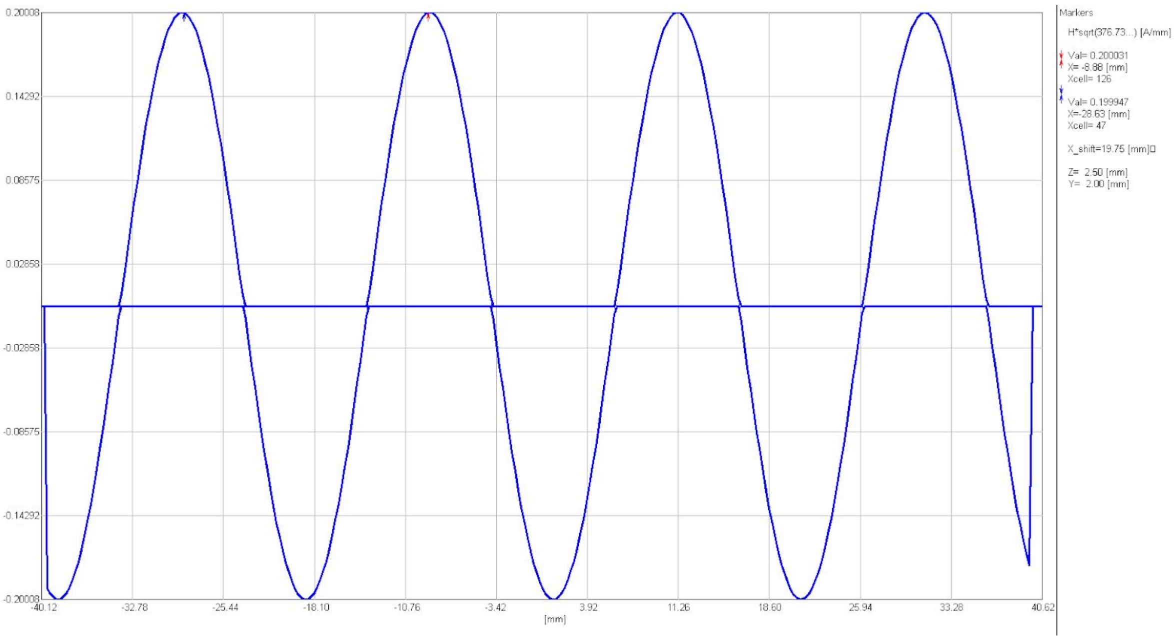


Figure 7: Envelope windows Ez(upper) and Hy(lower) for
$f\ =\ \ [GHz],\ \varepsilon_r\ =\ 1\ [F\ /\ m],\ \mu_r = 1\ [H\ /\ m],\ tg\delta = 0\ \ =>\ \ \sigma\ =\ 0\ [\ S\ /\ m\ ]$

$Wavelength\ -\ \lambda\ =$ X_shift = 19.75 [mm]

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

$\lambda\ =\ \frac{2\pi}{\beta}\ =>\ \beta = \frac{2\pi}{\lambda}\ =>\ \beta\ \approx 318.13\ [\ 1\ /\ m\ ]$

$\varepsilon = \varepsilon_0 * \varepsilon_r$

$Analytical\ formula\ for\ \beta\ =\ \omega\ *\ \sqrt{\mu * \varepsilon} = 2\pi * f * \sqrt{\mu * \varepsilon} \approx 309.84\ [1\ /\ m]$

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

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

$Relative\ error\ =\ 100\ \%\ *\ \frac{\beta_{markers}\ -\beta_{analytical}}{\beta_{analytical}} \approx 2.7\ \%$

From markers:

$E_n = 0.2\ [V\ /\ mm]$

$H_n = 0.2\ [A\ /\ mm]$

$E\ =\ E_n * \sqrt{Z_0} \approx 2.2\ [V\ /\ mm]$

$H = \frac{H_n}{\sqrt{Z_0}} = 0.018\ [A\ /\ mm]$

$Z_w = \frac{E_n}{H_n} * Z_0 =\ 376.7\ [\Omega]$

From analytical formulas:

$Z = \sqrt{\frac{\mu}{\varepsilon}} = 377.0\ [\Omega]$

$Relative\ error\ =\ 100\%\ *\ \frac{Z - Z_w}{Z} \approx 0.08\ \%$

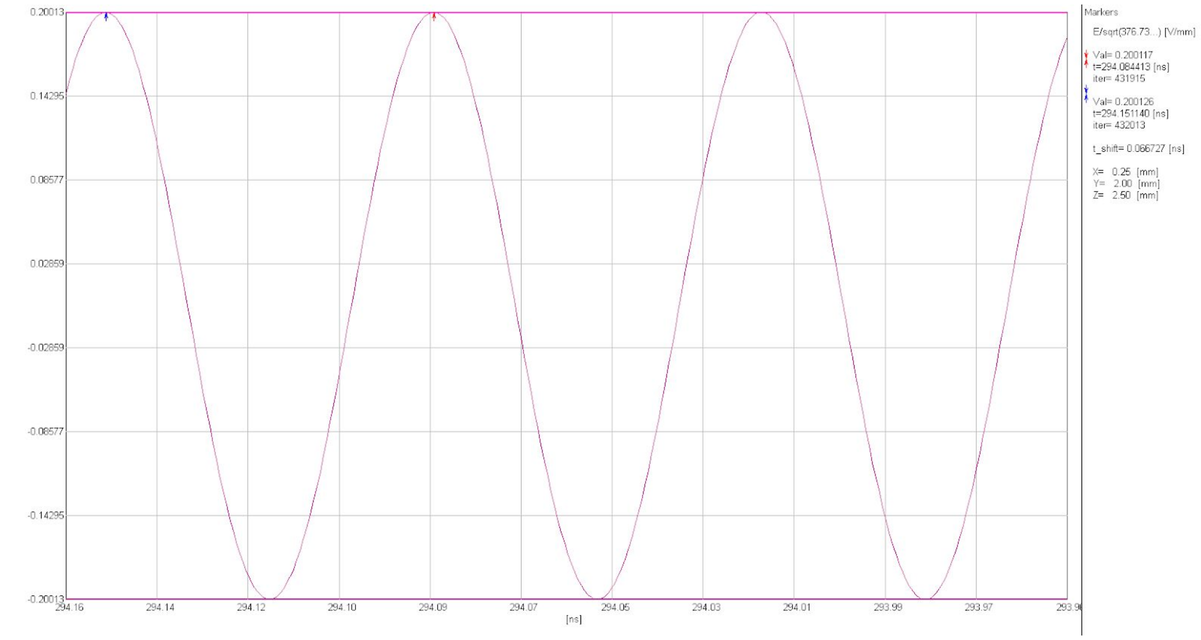


FIgure 8: Time domain Ez component for:

$f\ =\ 15\ [GHz],\ \varepsilon_r\ =\ 1\ [F\ /\ m],\ \mu_r = 1\ [H\ /\ m],\ tg\delta = 0\ \Rightarrow\ \sigma\ =\ 0\ [\ S\ /\ m\ ]$

$T\ =\ t_{shift}\ \approx\ 0.067\ [ns]$

$T_{real} = \frac{1}{f_{real}} \approx 0.066 [ns]$

$Relative\ error\ =\ \frac{T - T_{real}}{T_{real}} * 100\% = 1.5\%$

$f\ =\ \frac{1}{T} = 14.93\ [GHz]$

$f_{real} =\ 15\ [GHz]$

$Relative\ error\ =\ \frac{f_{real} - f}{f_{real}} * 100\% = 0.46\%$

$\beta = 2\pi * f * \sqrt{\mu * \varepsilon} \approx 308.4\ [1\ /\ m]$

$\beta_{analytical} = 309.84\ [1\ /\ m]$

$Relative\ error\ =\ \frac{\beta_{analytical} - \beta}{\beta_{analytical}} * 100\% = 0.46\%$

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

$Relative\ error\ with\ \beta\ from\ 3.7:\ \frac{\beta_{3.7} - \beta_{3.10}}{\beta_{3.7}} * 100\% \approx 3.05\%$

2 b)

Values we start with:

$f\ =\ 7.5\,[GHz],\ \varepsilon_r\ =\ 1\,[F\,/\,m],\ \mu_r = 7.5\,[H\,/\,m],\ tg\delta = 0\ \Rightarrow\ \sigma\ =\ 0\,[\,S\,/\,m\,]\ (lossless\ model)$

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

3.7:

$Z_c\ of\ input\ =\ Z_c\ of\ output\ = Zc = 1031.7184\ [\Omega]$

$Z_c\ -\ impedance$

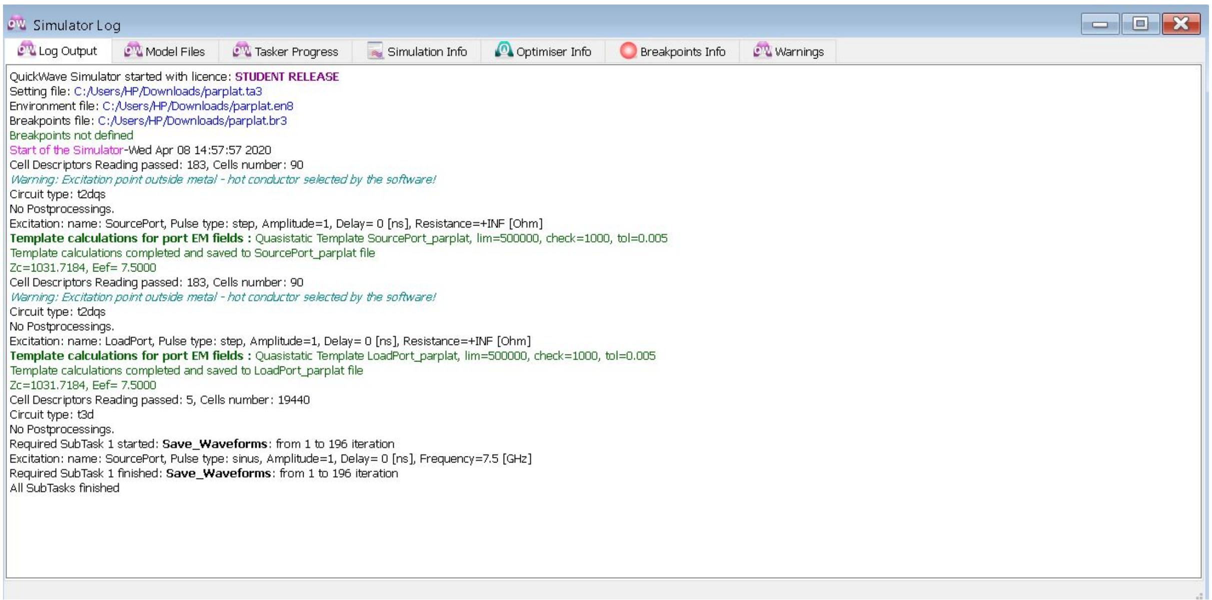


FIgure 9: SImulation log window for

$f\ =\ 7.5\,[GHz],\ \varepsilon_r\ =\ 1\,[F\,/\,m],\ \mu_r = 7.5\,[H\,/\,m],\ tg\delta = 0\ \Rightarrow\ \sigma\ =\ 0\,[\,S\,/\,m\,]\ (lossless\ model)$

3.8:

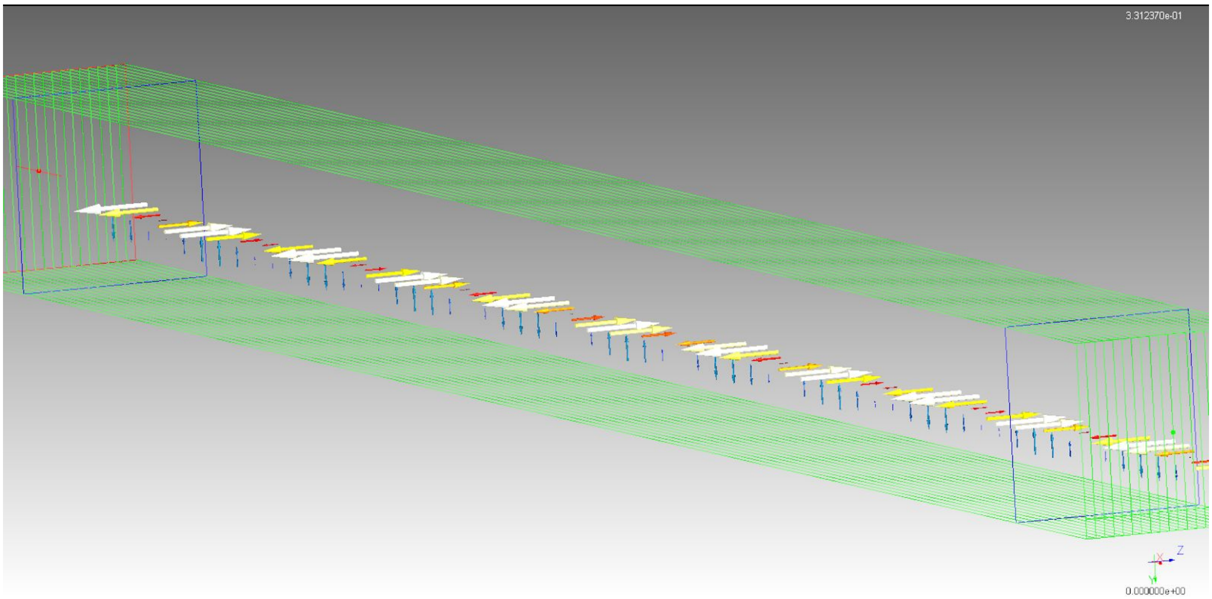


FIgure 10: Fields window (3D vector display)

$f = 7.5\ [GHz],\ \varepsilon_r = 1\ [F/m],\ \mu_r = 7.5\ [H/m],\ tg\delta = 0 \Rightarrow \sigma = 0\ [S/m]$ (*lossless model*)

Electric component: z (We can see that only z axis is visible in electric component in the program)

Magnetic component: y (We can see that only y axis is visible in magnetic component in the program)

Direction of propagation: x (It is the only axis left, after we established that we can see z and y component)

3.9

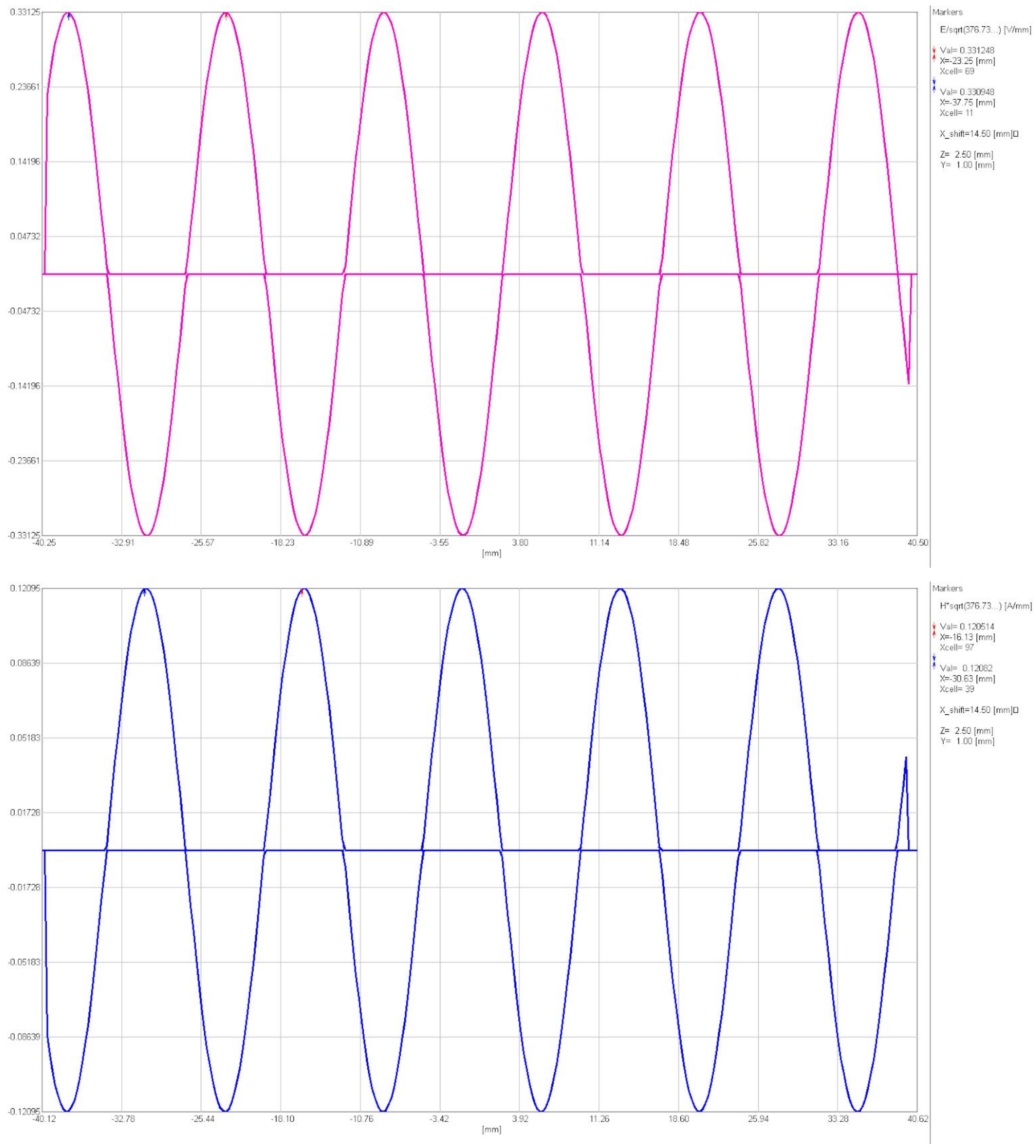


Figure 11: Envelope windows Ez(upper) and Hy(lower)

$f = 7.5\ [GHz],\ \varepsilon_r = 1\ [F/m],\ \mu_r = 7.5\ [H/m],\ tg\delta = 0 \ => \ \sigma = 0\ [S/m]\ (lossless\ model)$

$Wavelength - \lambda =$ X_shift = 14.50 [mm]

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

$\lambda = \frac{2\pi}{\beta} => \beta = \frac{2\pi}{\lambda} => \beta \approx 433.3\ [1/m]$

$\varepsilon = \varepsilon_0 * \varepsilon_r$

$Analytical\ formula\ for\ \beta = \omega * \sqrt{\mu * \varepsilon} = 2\pi * f * \sqrt{\mu * \varepsilon} \approx 394.98[1/m]$

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

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

$Relative\ error = 100\,\% * \frac{\beta_{markers} - \beta_{analytical}}{\beta_{analytical}} \approx 9.7\,\%$

From markers:

$E_n = 0.33\ [V/mm]$

$H_n = 0.12\ [A / mm]$

$E = E_n * \sqrt{Z_0} \approx 6.4\ [V / mm]$

$H = \frac{H_n}{\sqrt{Z_0}} = 0.006\ [A / mm]$

$Z_w = \frac{E_n}{H_n} * Z_0 = 137\ [\Omega]$

From analytical formulas:

$Z = \sqrt{\frac{\mu}{\varepsilon}} = 148\ [\Omega]$

$Relative\ error = 100\% * \frac{Z - Z_w}{Z} \approx 7.4\ \%$

FIgure 12: View envelope window for
$f = 7.5\ [GHz],\ \varepsilon_r = 1\ [F / m],\ \mu_r = 7.5\ [H / m],\ tg\delta = 0 \Rightarrow \sigma = 0\ [S / m]\ (lossless\ model)$

$T = t_{shift} \approx 0.1335\ [ns]$

$T_{real} = \frac{1}{f_{real}} \approx 0.133 [ns]$

$Relative\ error = \frac{T - T_{real}}{T_{real}} * 100\% = 0.05\%$

$f = \frac{1}{T} = 7.49\ [GHz]$

$f_{real} = 15\ [GHz]$

$Relative\ error = \frac{f_{real} - f}{f_{real}} * 100\% = 0.13\%$

$\beta = 2\pi * f * \sqrt{\mu * \varepsilon} \approx 394.4\ [1 / m]$

$\beta_{analytical} = 394.98\ \ [1 / m]$

$Relative\ error = \frac{\beta_{analytical} - \beta}{\beta_{analytical}} * 100\% = 0.15\%$

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

$Relative\ error\ with\ \beta\ from\ 3.7: \frac{\beta_{3.7} - \beta_{3.10}}{\beta_{3.7}} * 100\% \approx 8.98\%$

2 a)

Values we start with:

$f = 7.5\ [GHz],\ \varepsilon_r = 7.5\ [F / m],\ \mu_r = 1\ [H / m],\ tg\delta = 0 \Rightarrow \sigma = 0\ [S / m]\ (lossless\ model)$

f − *frequency*, ε_r − *permittivity*, μ_r − *permeability*, $tg\delta$ − *loss tangent*, σ − *conductivity*

3.7:

Z_c *of input* $=$ Z_c *of output* $= 137.5625\ [\Omega]$

Z_c − *impedance*

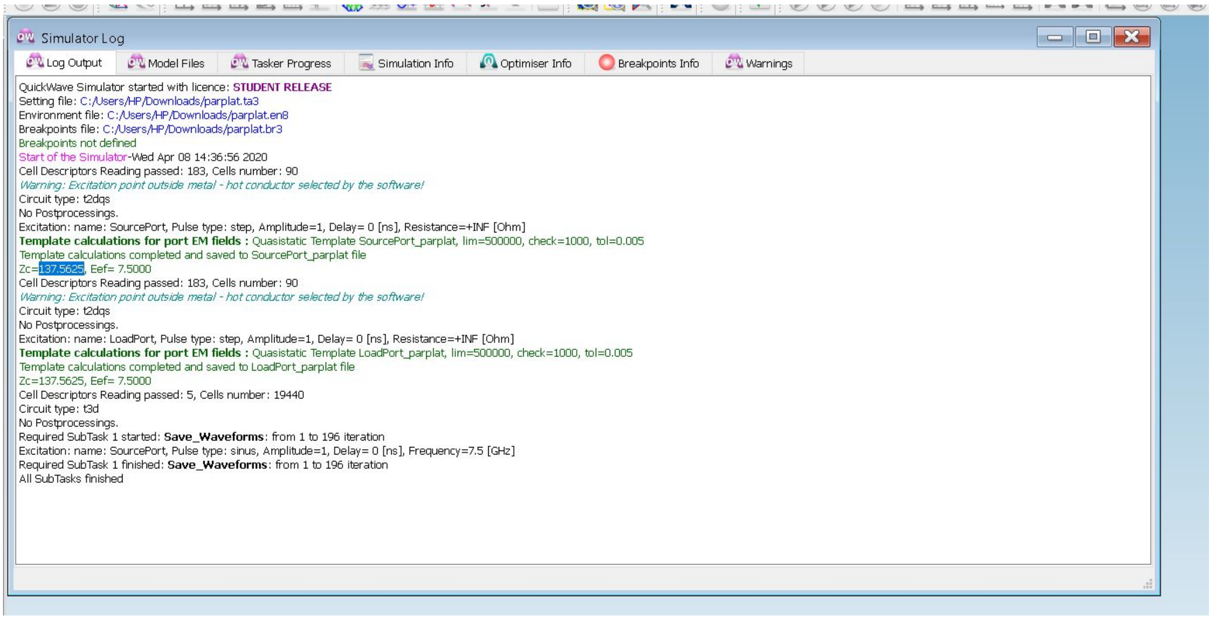


Figure 13: Simulation log window for:

$f = 7.5\ [GHz]$, $\varepsilon_r = 1\ [F/m]$, $\mu_r = 7.5\ [H/m]$, $tg\delta = 0 \Rightarrow \sigma = 0\ [S/m]$

3.8:

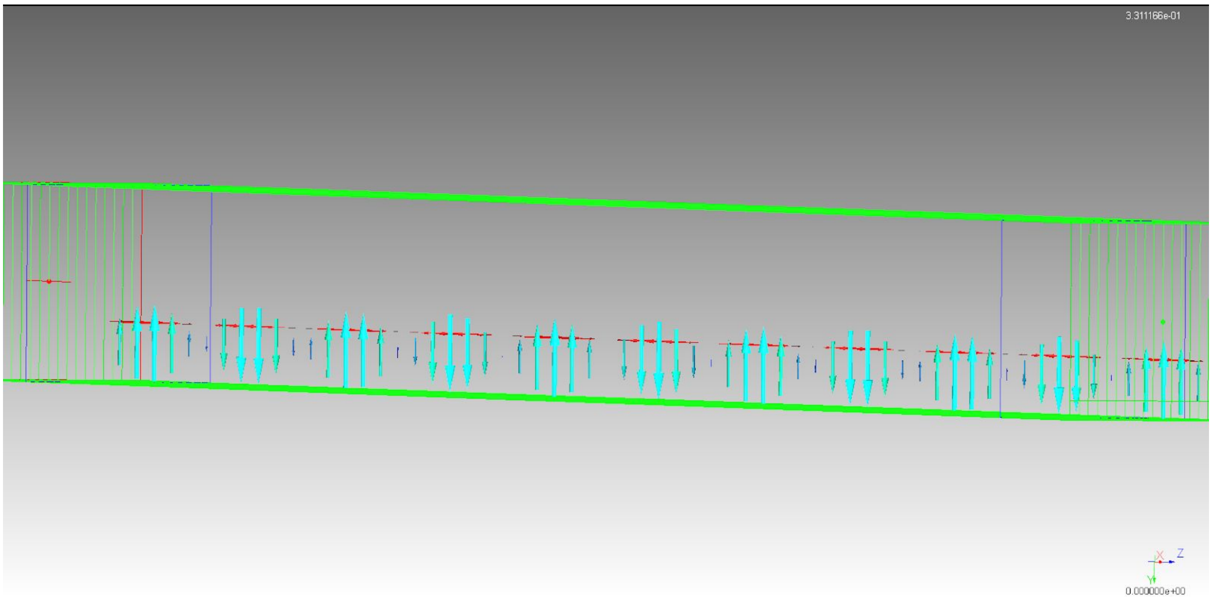
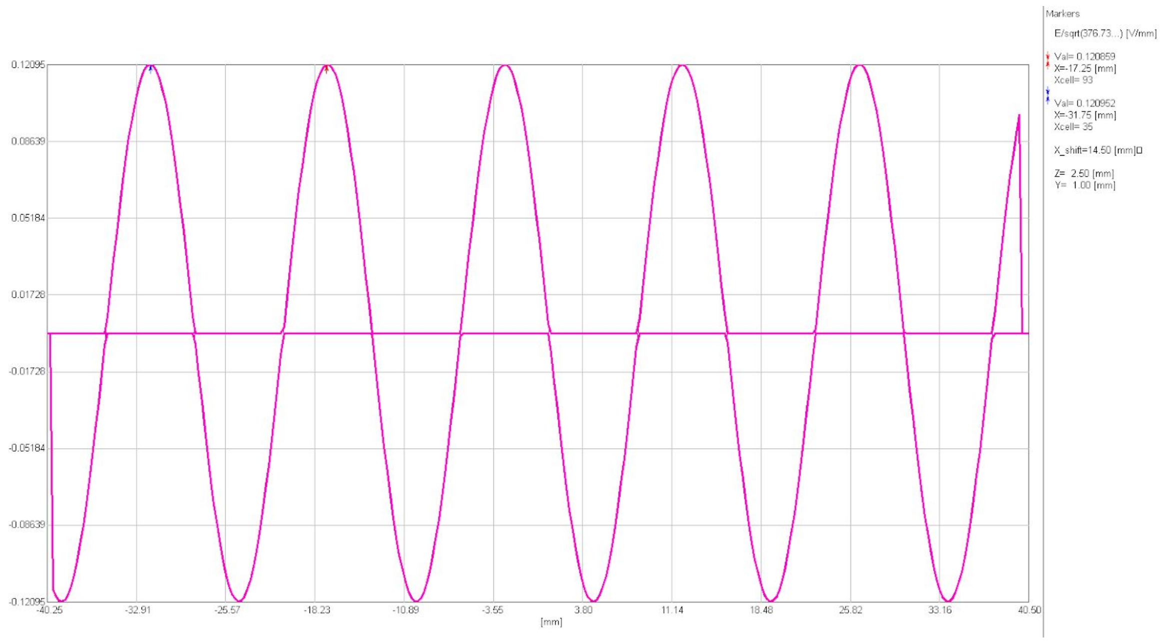


Figure 14: View Fields window (3D vector display) for:
$f = 7.5\ [GHz],\ \varepsilon_r = 1\ [F/m],\ \mu_r = 7.5\ [H/m],\ tg\delta = 0 \Rightarrow \sigma = 0\ [S/m]$

Electric component: z (We can see that only z axis is visible in electric component in the program)
Magnetic component: y (We can see that only y axis is visible in magnetic component in the program)
Direction of propagation: x (It is the only axis left, after we established that we can see z and y component)
3.9



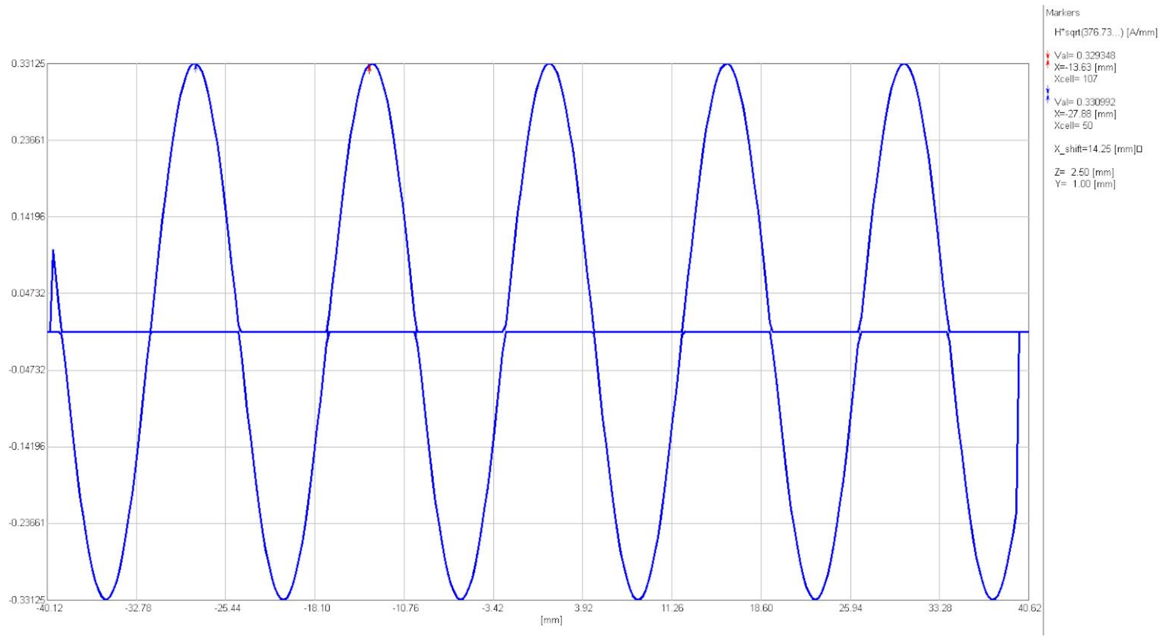


Figure 15: View envelope window for:
$f = 7.5\ [GHz],\ \varepsilon_r = 1\ [F/m],\ \mu_r = 7.5\ [H/m],\ tg\delta = 0 \Rightarrow \sigma = 0\ [S/m]$

$Wavelength - \lambda =$ X_shift = 14.50 [mm]

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

$\lambda = \frac{2\pi}{\beta} \Rightarrow \beta = \frac{2\pi}{\lambda} \Rightarrow \beta \approx 433.3\ [1/m]$

$\varepsilon = \varepsilon_0 * \varepsilon_r$

$Analytical\ formula\ for\ \beta = \omega * \sqrt{\mu * \varepsilon} = 2\pi * f * \sqrt{\mu * \varepsilon} \approx 394.98[1/m]$

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

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

$Relative\ error = 100\ \% * \frac{\beta_{markers} - \beta_{analytical}}{\beta_{analytical}} \approx 9.7\ \%$

From markers:

$E_n = 0.12\ [V\ /\ mm]$

$H_n = 0.33\ [A\ /\ mm]$

$E\ =\ E_n * \sqrt{Z_0} \approx 2.33\ [V\ /\ mm]$

$H = \frac{H_n}{\sqrt{Z_0}} = 0.017\ [A\ /\ mm]$

$Z_w = \frac{E_n}{H_n} * Z_0 =\ 137\ [\Omega]$

From analytical formulas:

$Z = \sqrt{\frac{\mu}{\varepsilon}} = 148\ [\Omega]$

$Relative\ error\ =\ 100\%\ *\ \frac{Z - Z_w}{Z} \approx 7.4\ \%$

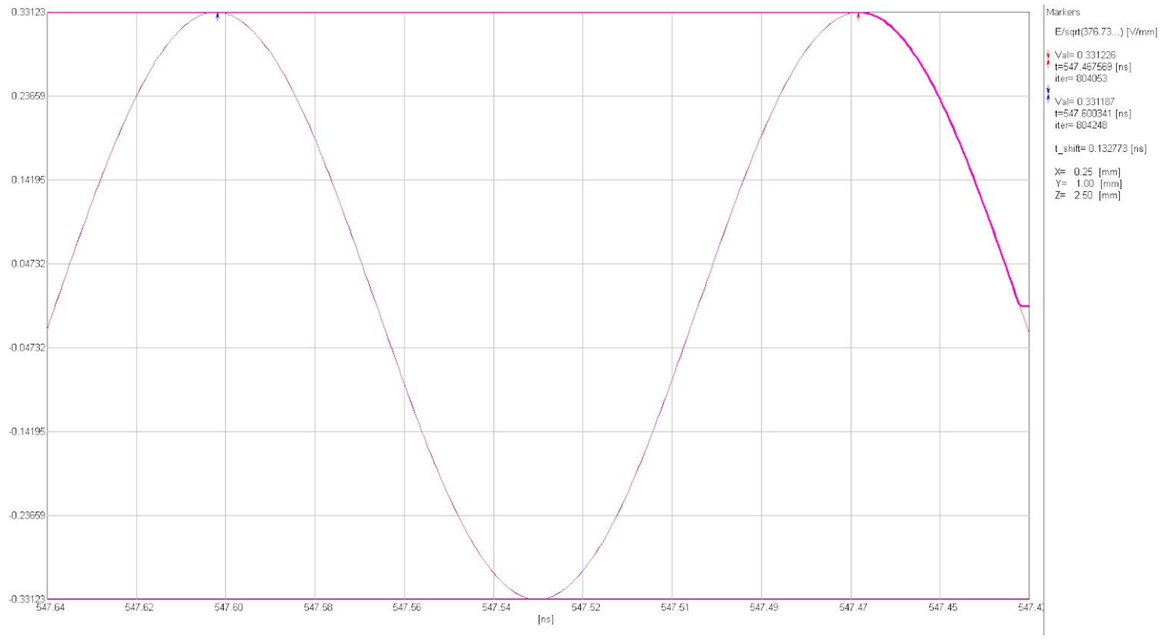


Figure 16: Time domain View Envelope window for:

$f\ =\ 7.5\ [GHz],\ \varepsilon_r\ =\ 1\ [F\ /\ m],\ \mu_r = 7.5\ [H\ /\ m],\ tg\delta = 0\ \Rightarrow\ \sigma\ =\ 0\ [\ S\ /\ m\ ]$

$T\ =\ t_{shift}\ \approx\ 0.1327\ [ns]$

$T_{real} = \frac{1}{f_{real}} \approx 0.133[ns]$

$Relative\ error\ =\ \frac{T - T_{real}}{T_{real}} * 100\% = 0.23\%$

$f\ =\ \frac{1}{T} = 7.53\ [GHz]$

$f_{real} =\ 7.5\ [GHz]$

$Relative\ error\ =\ \frac{f_{real} - f}{f_{real}} * 100\% = 0.4\%$

$\beta = 2\pi * f * \sqrt{\mu * \varepsilon} \approx 396.6\ [1\ /\ m]$

$\beta_{analytical} = 394.98\ \ [1\ /\ m]$

$Relative\ error\ =\ \frac{\beta_{analytical} - \beta}{\beta_{analytical}} * 100\% = 0.41\%$

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

$Relative\ error\ with\ \beta\ from\ 3.7\ :\ \frac{\beta_{3.7} - \beta_{3.10}}{\beta_{3.7}} * 100\% \approx 0.41\%$

Answering the questions at the end:

a) frequency is proportional with x_shift

b) permitivity and permeability changes E and H, but frequency and x_shift does not change
c) it is a sinus shape
d) It is $\frac{\lambda}{2}$