W8_THz simulation

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Using the following parameters:

Plotting THz transmission line using the following parameter:

$$C = 1x10^{-10}F, \qquad L = 250x10^{-9}H, \qquad R = 1200 Ohms, \qquad l = 150x10^{-6}m$$

The input is a sinewave with frequency of 0.1 THz.

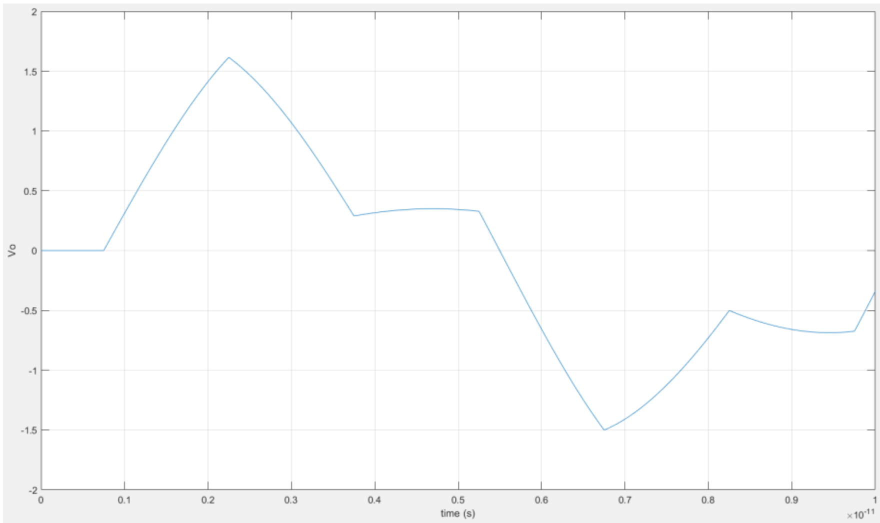

Figure 1 : shows the response using the exact solution.

```
clear
clc
R = 1200;          % Resistance per unit length (Ω/m)
L = 250e-9;        % Inductance per unit length (H/m)
C = 1e-10;         % Capacitance per unit length (F/m)
Rs = 10;
G = 0;
l = 150e-6;        % Length of the transmission line
f_max = 100e9;    % Maximum frequency (100 GHz)
w = 2*pi*f_max;
s = 1i*w;
vs_sine = @(s) w./(s.^2 + w^2);% Laplace transform of sin(wt)
% Transfer function (exact solution)
vo = @(s) 1 ./ (cosh(l .* sqrt((R + L.*s) .* (G + C.*s))));
vo_sine = @(s) vs_sine(s).*vo(s);
time =10e-12;
[y_sine,t] = niltcv(vo_sine,time);
% Plot the frequency response
plot(t, y_sine)
xlabel('time (s)');
ylabel('Vo');
grid on;
```

RLC,

Unit step response.

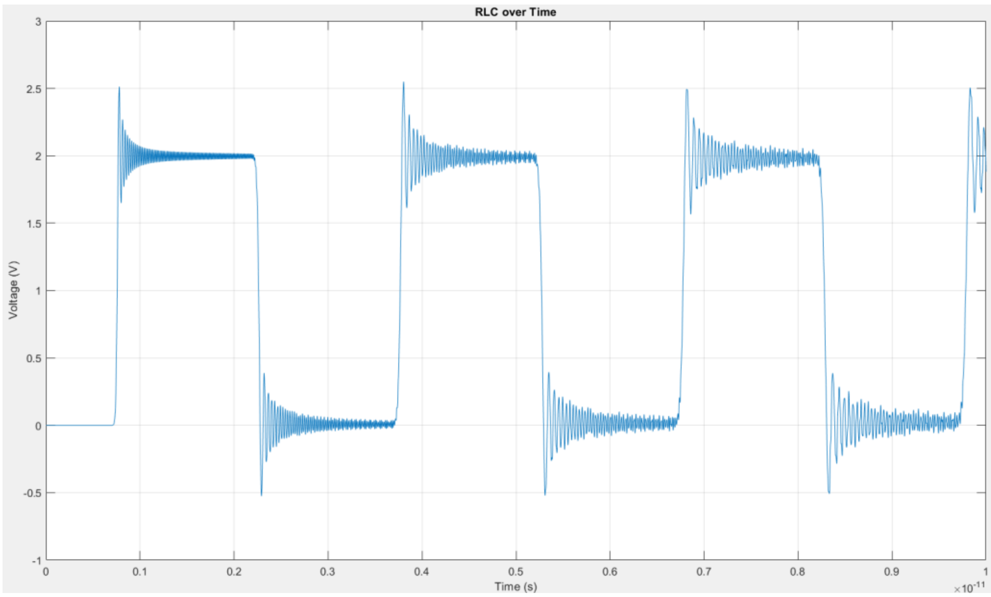

Figure 2 illustrates the output of the transmission line (TL) using the RLC ladder method with a unit step input.

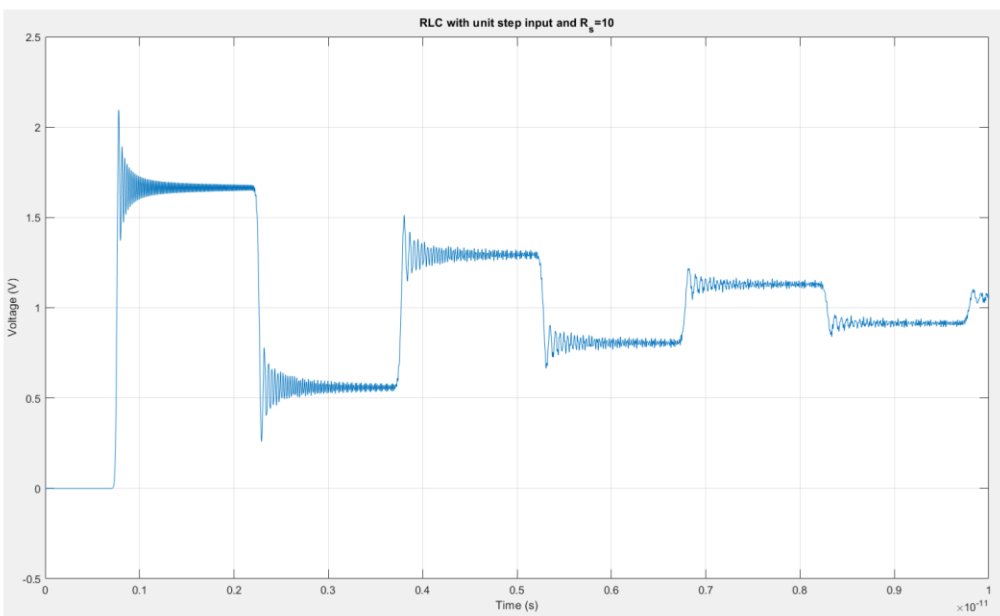

Figure 3 :shows the output of the transmission line (TL) using the RLC ladder method with a unit step input and R_s = 10.

The response due to sinewave with frequency of 0.1 THz.

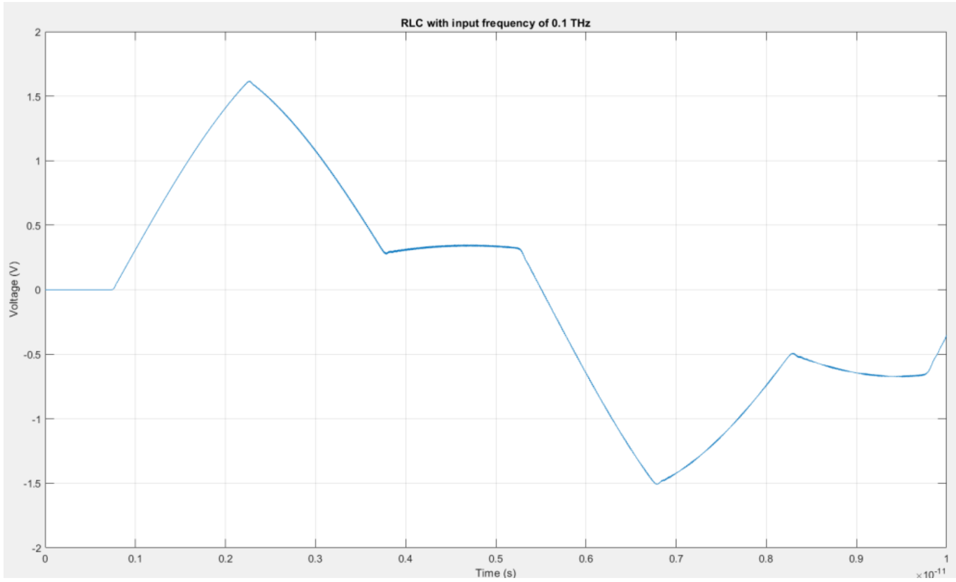

Figure 4 :presents the output of the transmission line (TL) using the RLC ladder method with a sinusoidal input at a frequency of 0.1 THz.

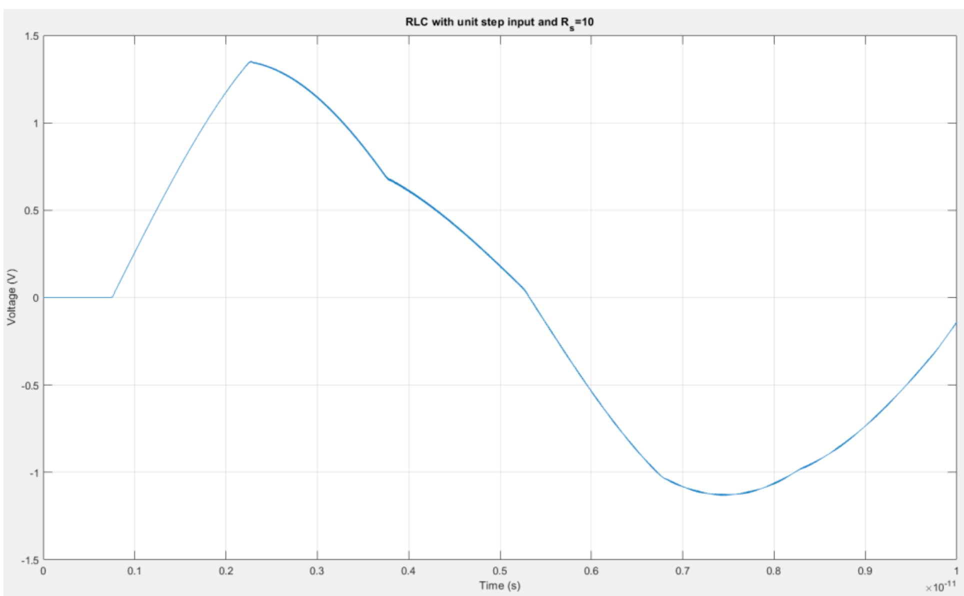

Figure 5:shows the response of the transmission line (TL) using the RLC ladder method with a sinusoidal input at a frequency of 0.1 THz and R_s = 10.

The input is a pulse with a rise time from 0 to 1V of 1ps and the same fall time and it stays at 1V for 5ps using trapezoidal pulse.

A trapezoidal pulse that:

- Rises linearly from 0 V to 1 V over 1 ps,
- Stays at 1 V for 5 ps,
- Falls back to 0 V over 1 ps,
  can be built from ramps and exponentials in the Laplace domain.

Time-Domain Definition

$$v_{pulse}(t) = \begin{Bmatrix} 0, & t < 0 \\ linear\ rise, & 0 \leq t < 1ps \\ 1, & 1ps \leq t < 6ps \\ linear\ fall, & 6ps \leq t < 7ps \\ 0, & t \geq 7ps. \end{Bmatrix}$$

Total duration: 7 ps = 1 ps (rise) + 5 ps (high) + 1 ps (fall).

a function is coded in MATLAB below to implement this pulse.

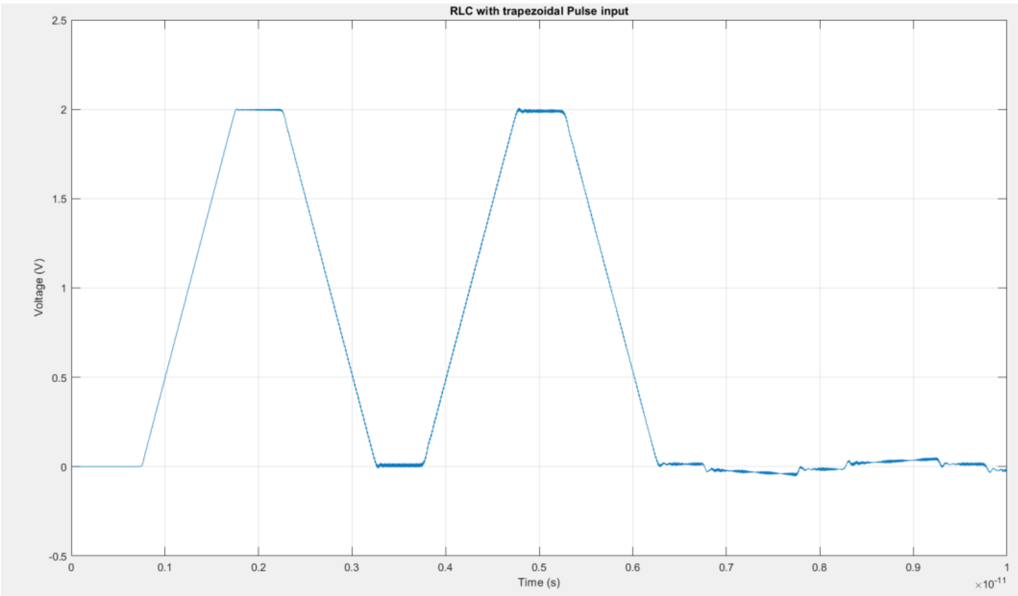

Figure 6: illustrates the output of the transmission line (TL) using the RLC ladder method with a trapezoidal pulse input.

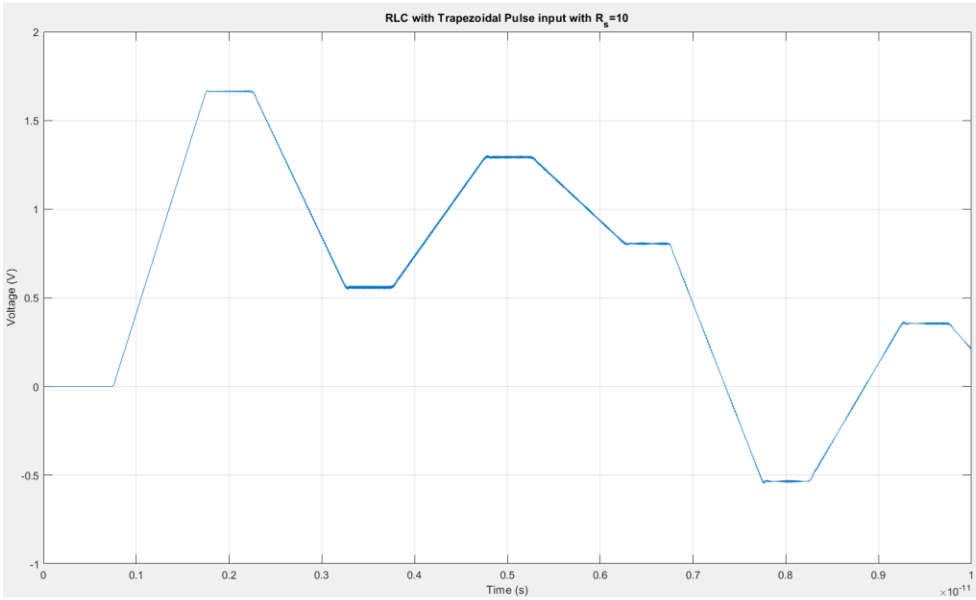

Figure 7: illustrates the output of the transmission line (TL) using the RLC ladder method with a trapezoidal pulse input and R_s=10.

```
function v = trapezoidalPulse(t)
    % Define pulse parameters
    T_r = 1e-12;   % Rise time (1 ps)
    T_p = 5e-12;   % High-level duration (5 ps)
    T_total = 2*T_r + T_p;  % Total pulse duration (7 ps)

    % Piecewise definition of the pulse
    if t < 0
        v = 0;
    elseif t < T_r
        % Linear rise: from 0 to 1 V over T_r
        v = t / T_r;
    elseif t < T_r + T_p
        % Constant high level at 1 V
        v = 1;
    elseif t < T_total
        % Linear fall: from 1 V back to 0 over T_r
        v = (T_total - t) / T_r;
    else
        v = 0;
    end
end
```

```
%RLC input as pulse
clear
clc
len=150e-6;
N = 200; % Number of sections in the transmission line
dz=len/N;
L = 250e-9*dz;   % Inductance
C = 1e-10*dz;    % Capacitance
R = 1200*dz;       % Resistance per section
Rs = 0;       % Source resistance
vs_pulse = @(t) trapezoidalPulse(t);
y0 = zeros(2 * N, 1);
```

```
tspan = linspace(0,10e-12,10e4);
% Solve using ode45
[t, y_pulse] = ode45(@(t, y) fline_noR(t, y, N, L, C, R, Rs, vs_pulse), tspan, y0);
% Plot voltage at the end of the transmission line (VN)
figure(1);
plot(t, y_pulse(:,N*2));
xlabel('Time (s)');
ylabel('Voltage (V)');
title('RLC with Trapezoidal Pulse input');
grid on
```

FDTD

In the FDTD model, resistance R is not included. To compare it with the exact solution and the RLC method, the model must be adapted to account for R= 1200. Previously, in the original code, we performed the following steps: Given $Z_c = 50$, we calculated the lumped inductance (L) and capacitance (C) elements using the following approach.

$$Z_c = \sqrt{\frac{L}{C}}\ , v = 2x10^8 \qquad (1)$$

where, v is the speed of propagation so,

$$L = \frac{Z_c}{v}\ , C = \frac{1}{v\, Z_c} \qquad (2)$$

How to include R, compute Z_c as in the exact solution using the given values for R, L and C:

$$Z_c = \sqrt{\frac{R + L}{G + C}},$$

We find Z_c with the provided R, L, and C values. Since the lumped elements L and C in the model are purely a means to replicate the behaviour of a transmission line, recalculating them based on the adjusted Z_c will generate new values that effectively account for the resistance R.

FDTD improvised with 100 sections.

Unit step response

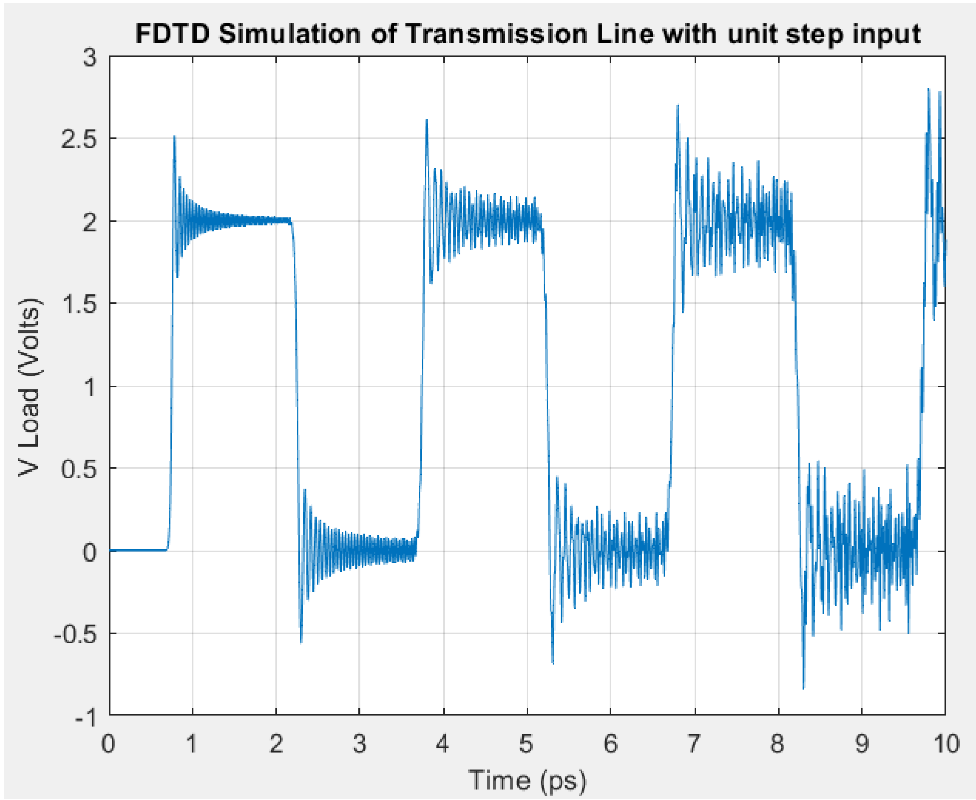

Figure 8 : shows the unit step response using FDTD and 1000000-time steps.

With 10000000 time steps and 100 sections

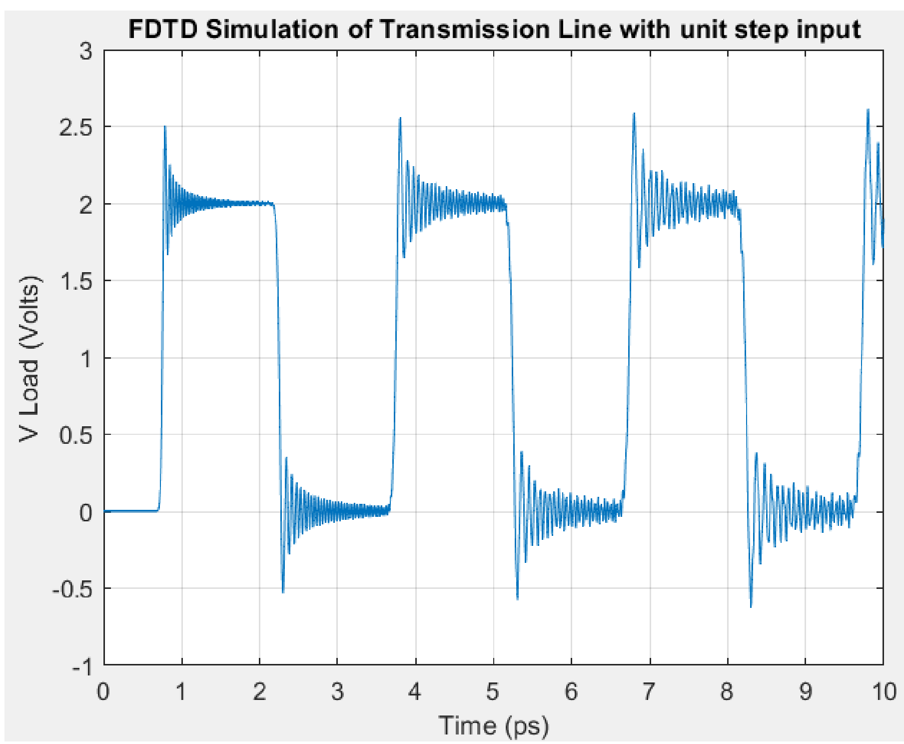

Figure 9: shows the unit step response with 10^7-time steps and 100 sections

The response due to sinewave with frequency of 0.1 THz.

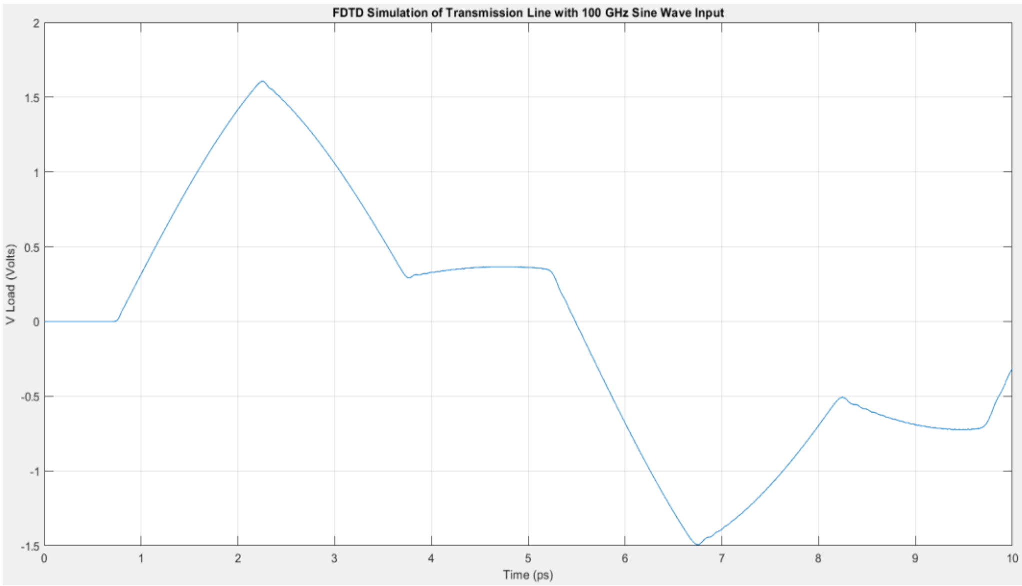

Figure 10: the response due to sinewave at 0.1 THz and 100 segments .

```
clear
clc
L_total = 150e-6;  % Total length of the line (m)
R = 1200;
l = 250e-9;
c = 1e-10;
Zc = sqrt((R+l)/(c));  % Characteristic impedance (Ohms)
v = 2e8;  % Speed of propagation (m/s)
% Compute inductance and capacitance
C = 1 / (v * Zc);
L = Zc/v;
NDZ = 100;  % Number of spatial steps
dz = L_total / NDZ;  % Spatial step delta z
dt = 1e-17;  % Time step delta t
t_max = 10e-12;
t_steps = round(t_max / dt);  % Number of time steps
% allocate voltage and current arrays
V = zeros(NDZ+1, t_steps);
time = (0:t_steps-1)*dt;
Vs = sin(2*pi*100e9.*time);
V(1,:)=Vs.*ones(1,t_steps);
I = zeros(NDZ, t_steps);
% FDTD Loop for Time Stepping
for n = 1:t_steps-1
    %V(1,n+1) = V(1,n);
    V(1, n+1) = sin(2*pi*100e9 * time(n+1));
    for k = 1:NDZ
    if k>1
        V(k,n+1) = V(k,n) + dt/(dz *C)* (I(k-1,n) - I(k,n));  % Update voltag
        dV_k = V(k-1,n) - V(k,n);  % Voltage difference between points
        I(k-1,n+1) = I(k-1,n) + dt/(dz *L) * dV_k;
```

```
    end
    end
    V(NDZ,n+1) =V(NDZ,n)+dt*(I(NDZ-1,n)/(C*dz));
end
y_FDTD = V(NDZ,:);
% Plot the results for the voltage at the load
figure(1)
plot((0:t_steps-1)*dt/1e-12, V(NDZ,:));
xlabel('Time (ps)');
ylabel('V Load (Volts)');
%title('FDTD Simulation of Transmission Line with unit step input');
title('FDTD Simulation of Transmission Line with 100 GHz Sine Wave Input');
grid on;
```

The input is a pulse with a rise time from 0 to 1V of 1ps and the same fall time and it stays at 1V for 5ps using trapezoidal pulse (using the same function that was coded for the RLC method)

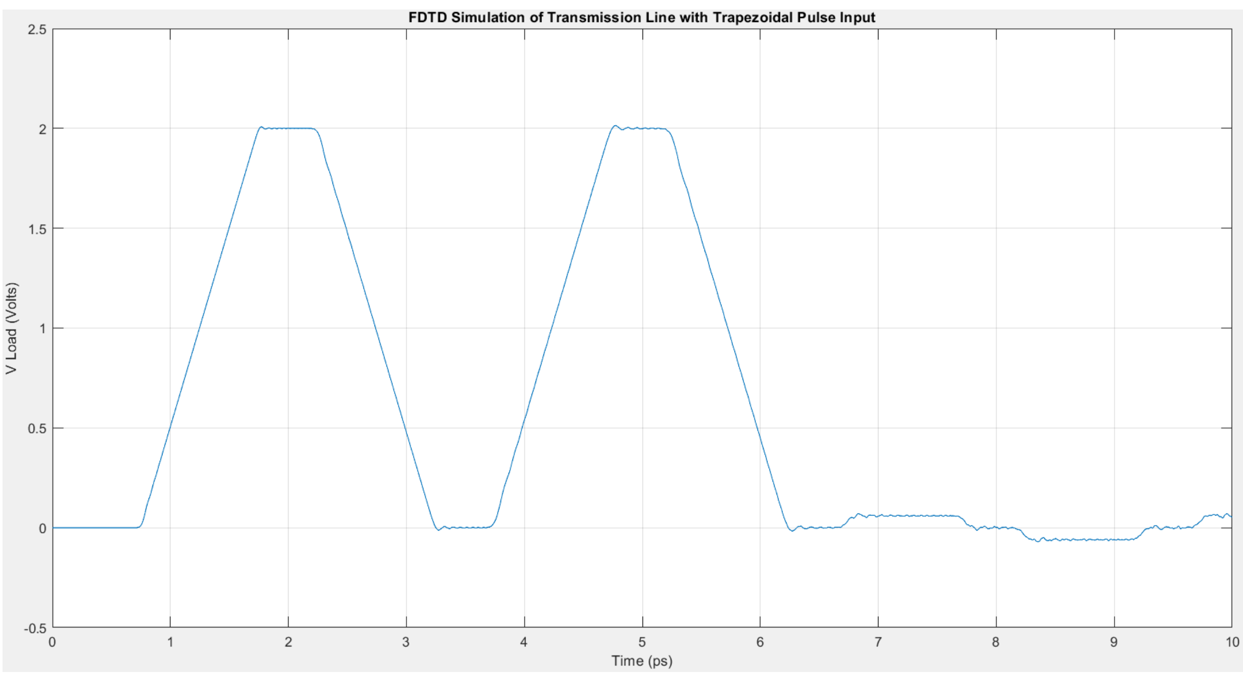

Figure 11: illustrates FDTD simulation of a TL with a pulse input using 100 sections and 10^6 time steps.

```
clear
clc
L_total = 150e-6;  % Total length of the line (m)
R = 1200;
l = 250e-9;
c = 1e-10;
Zc = sqrt((R+l)/(c));  % Characteristic impedance (Ohms)
```

```
v = 2e8;  % Speed of propagation (m/s)
% Compute inductance and capacitance
C = 1 / (v * Zc);
L = Zc/v;
NDZ = 100;  % Number of spatial steps
dz = L_total / NDZ;  % Spatial step delta z
dt = 1e-17;  % Time step delta t
t_max = 10e-12;
t_steps = round(t_max / dt);  % Number of time steps
% allocate voltage and current arrays
V = zeros(NDZ+1, t_steps);
time = (0:t_steps-1)*dt;
%Vs = sin(2*pi*100e9.*time);
%Vs = 1;
%V(1,:)=Vs.*ones(1,t_steps);
V(1,1) = trapezoidalPulse(time(1));
I = zeros(NDZ, t_steps);
% FDTD Loop for Time Stepping
for n = 1:t_steps-1
    %V(1,n+1) = V(1,n);
    %V(1, n+1) = sin(2*pi*100e9 * time(n+1));
    V(1,n+1) = trapezoidalPulse(time(n+1));
    for k = 1:NDZ
    if k>1
        V(k,n+1) = V(k,n) + dt/(dz *C)* (I(k-1,n) - I(k,n));  % Update voltag
        dV_k = V(k-1,n) - V(k,n);  % Voltage difference between points
        I(k-1,n+1) = I(k-1,n) + dt/(dz *L) * dV_k;
    end
    end
    V(NDZ,n+1) =V(NDZ,n)+dt*(I(NDZ-1,n)/(C*dz));
end
y_FDTD = V(NDZ,:);
% Plot the results for the voltage at the load
figure(1)
plot((0:t_steps-1)*dt/1e-12, V(NDZ,:));
xlabel('Time (ps)');
ylabel('V Load (Volts)');
%title('FDTD Simulation of Transmission Line with unit step input');
%title('FDTD Simulation of Transmission Line with 100 GHz Sine Wave Input');
title('FDTD Simulation of Transmission Line with Trapezoidal Pulse Input');
grid on;
```