1. **High-Speed Interconnects - Lumped Segment models, .**

a)

- ✓ **Write the MNA (modified nodal analysis) equations in the matrix form with one RLCG lumped equivalent circuit (use the model) for the transmission line (TL).**

(Handwritten)

- ✓ **How many MNA variables are introduced due to one lumped section of TL?**

Two new variables are introduced to lumped section out of which one is node voltages and one is current flowing through inductor.

- ✓ **How many MNA variables are introduced if 20 segments are used to represent the TL?**

Total number of introduced variables for 20 segments are, (N * X)-1 , where n is the number of segments and X is the new variable. So (20*3)-1= 59.

- ✓ **In the general case of N segments, how many variables will be added to the MNA due to the TL?**

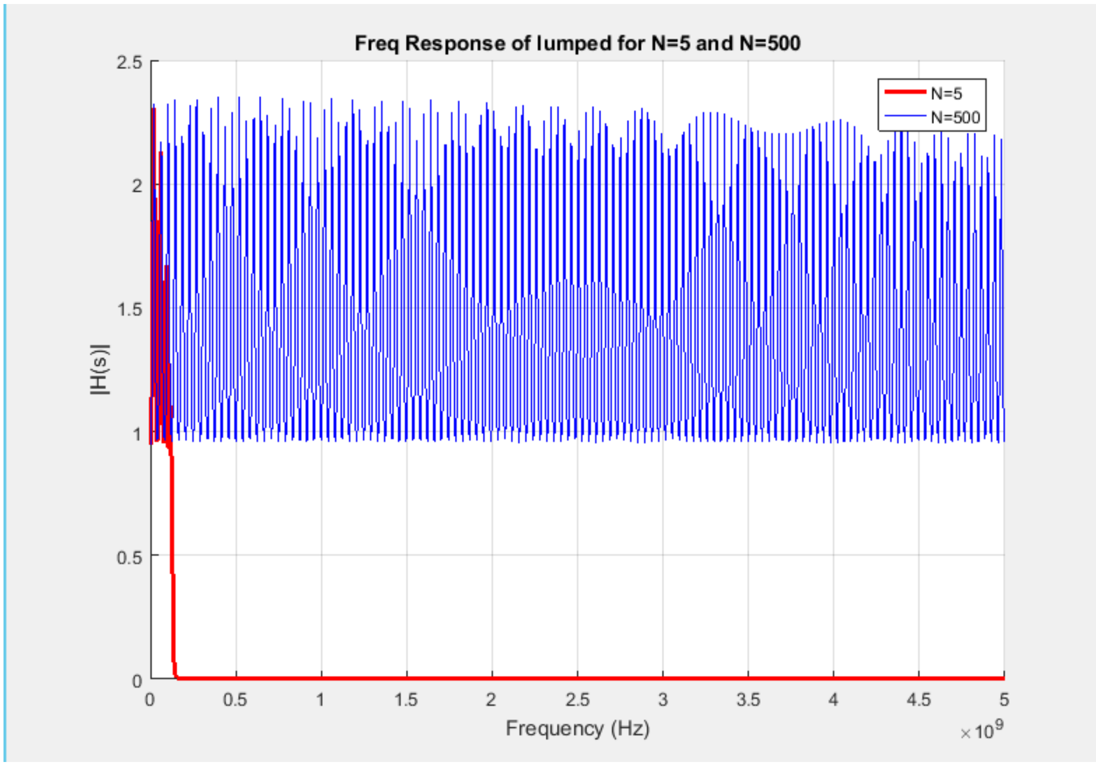
In general case of N segments, **3N-1** variables will be added to MNA due to TL.

b) Write a MATLAB routine to generate a lumped equivalent circuit (should be HSPICE compatible netlist) with N segments for a transmission line with known RLCG parameters and the line length.

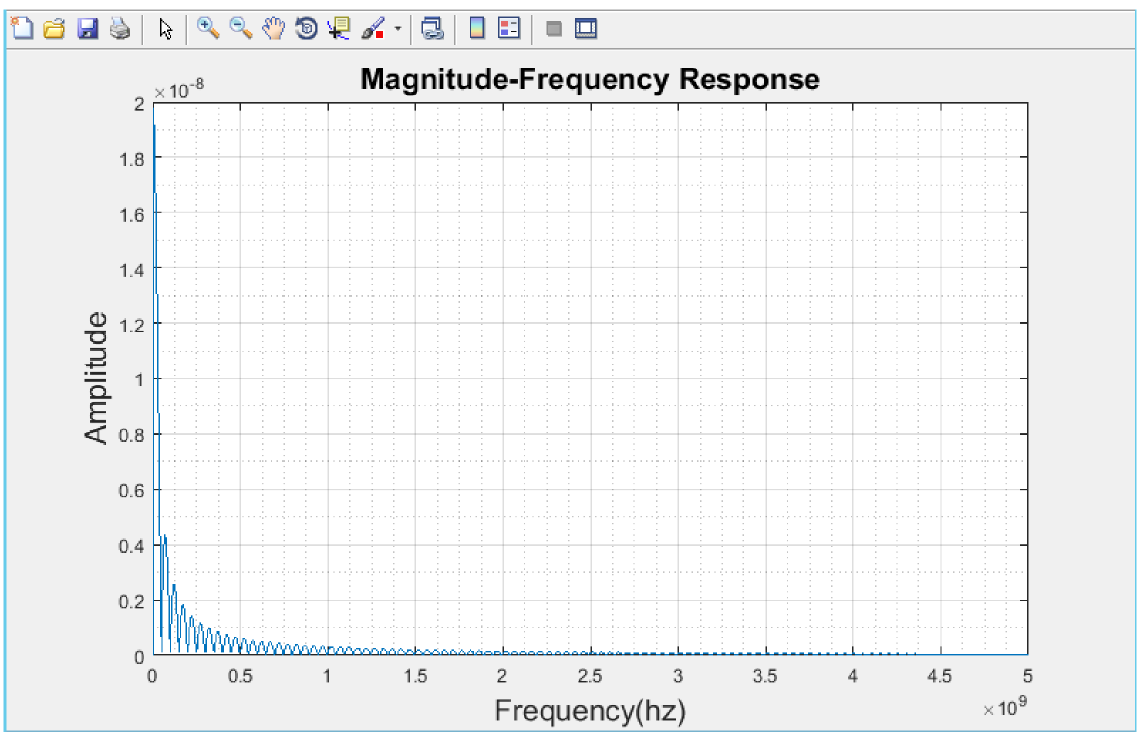
codegfinal.m | sub.m | valuesori.m

```matlab
clc
close all
clear all

global G C b; %global variables

N = input('no of segments');  % N segments
vout = (2*N)+2;


fprintf('Nodes = %d \n\n.OPTION PROBE \n.OPTION POST=2 \n.OPTION INGOLD=2 \n.OPTION ACCURATE\n\n',N)
fprintf('V 1 0 AC 1 \nR1 1 2 5\nR2 %d 0 500\n',vout')


length = 20/N; % Length of TL
R1 = 1*length; % Resistance p.u.l of TL
G1 = 0.015e-3*length;  % Conductance p.u.l of TL
C1 = 4e-12*length; % Capacitance p.u.l of TL
L1 = 90e-9*length;  % Inductance p.u.l of TL

r=3;
c=1;
l=1;
for i=0:N-1
    A=2*i;

    fprintf('R%d %d 0 %d\n',r,2+A,1/(G1/2));
    r=r+1;

    fprintf('C%d %d 0 %d\n',c,2+A,(C1/2));
    c=c+1;

    fprintf('L%d %d %d %d\n',l,2+A,3+A,(L1));
    l=l+1;

    fprintf('R%d %d %d %d\n',r,3+A,4+A,(R1));
    r=r+1;

    fprintf('C%d %d 0 %d\n',c,4+A,(C1/2));
    c=c+1;

    fprintf('R%d %d 0 %d\n',r,4+A,1/(G1/2));
    r=r+1;
end

fprintf('\n.ac lin 1000 1 2e9 \n.Print AC i(v)\n.END\n\n');

```

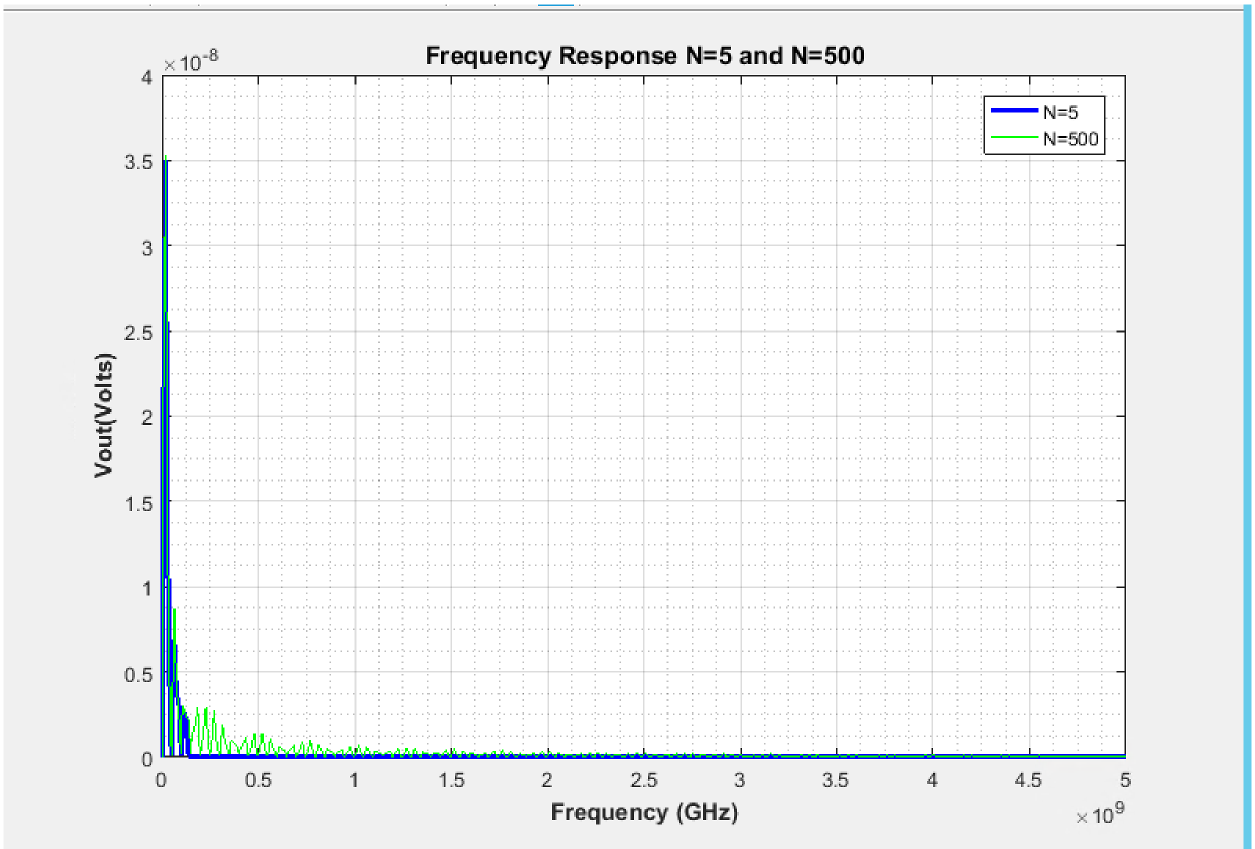
c) **Compute and plot the frequency-responses on a linear scale (from 1Hz to 5GHz at 1000 points) using HSPICE, for netlists generated from the above program, for N=5 and N=500 sections, for the circuit in Fig. 1 (on a same graph) using the routine from 1(b).**



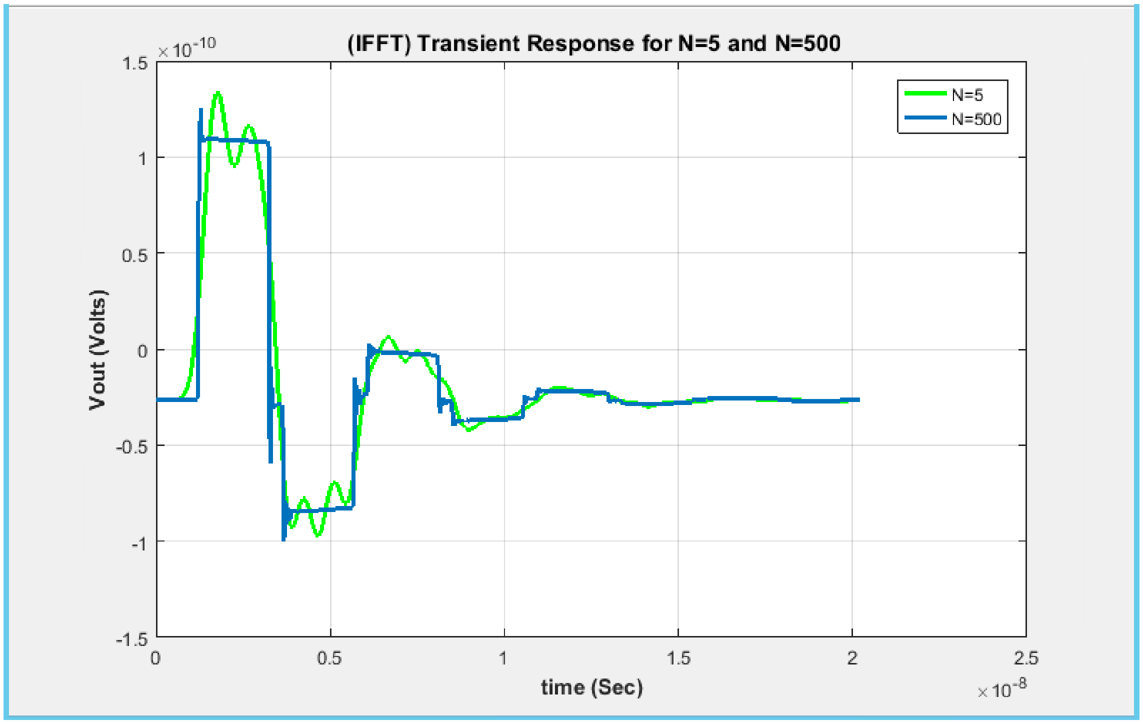
d) **Compute and plot the frequency spectrum of the trapezoidal pulse (FSTP) described in Fig. 1, using the program you developed in Assignment-1.**



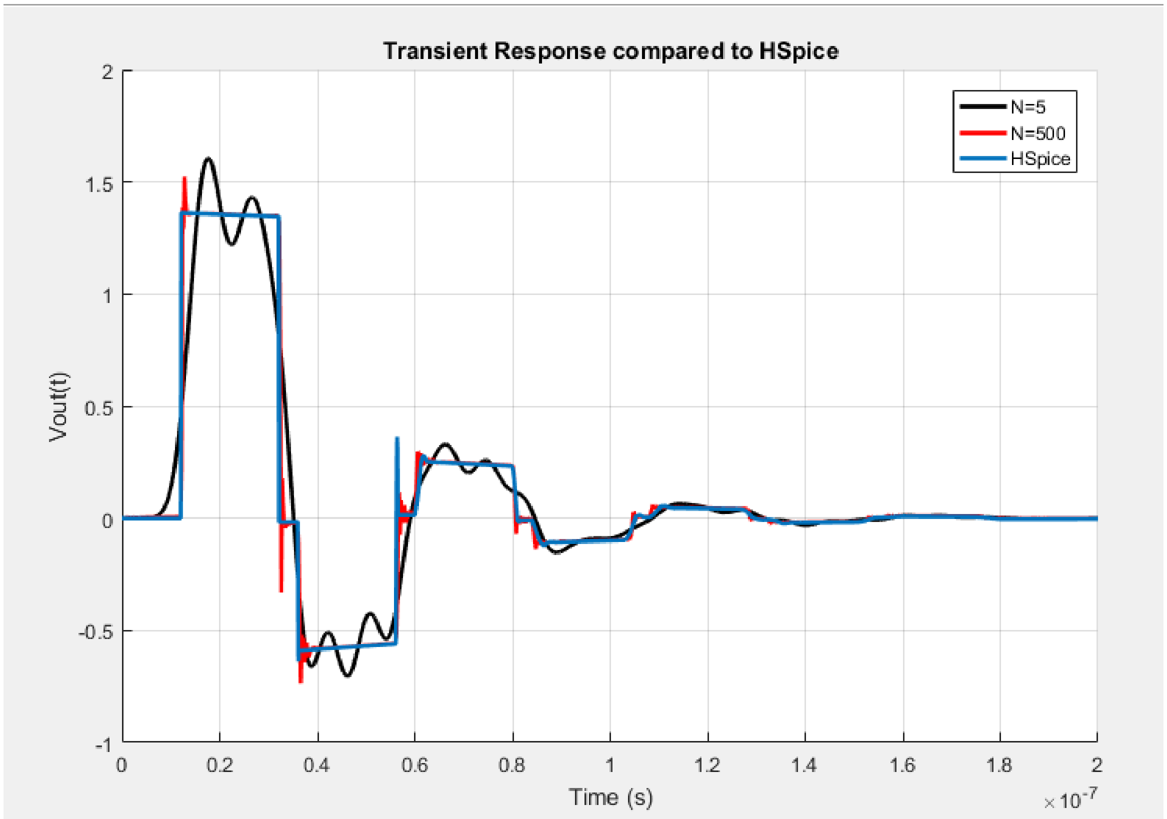
e) Compute and plot the product of the computed FSTP with both the frequency spectrums from part 3(c) [on a same graph but different from that of part 3(c, d)].



f) Perform IFFT (Inverse Fast Fourier Transform - use the built-in Matlab routine; make sure to feed the data input in real-imaginary format) on both the frequency responses of part-3(e) to obtain the corresponding time responses and plot them on a same graph. Couple of notes here, as blind use of the Matlab IFFT function may not yield the expected results. You have to prepare the data properly to feed to the Matlab ifft function. Copule of tips: -Use the option 'symmetric' option in IFFT. -The derived trapezoidal pulse spectrum expression doesn't provide a value for zero freq; use a low starting frequency, say in the Khz region. - If you find the IFFT output out-of-scale, you should be multiplying by the real and imaginary parts of the spectrum (of section e)) by 1/dt, prior to IFFT. - If you find DC offset in IFFT output, simply deduct the dc value from all the entries of the IFFT output vector.



g) Compare these time-domain responses by directly performing the HSPICE transient simulation by using the W element for the transmission line (plot on the same graph of 3(f); you need to port the data from HSPICE to Matlab for this purpose). $\pi\ \pi$ **...2**



h) Based on the observation of the above plots, provide your conclusions on the validity of the ruleof-thumb used to determine the required number of lumped segments.

Thumb Rule:-

Formula used to determine the required number of lumped segments is below.

$$N = \frac{10 * \tau * d}{t_r}$$

$$\tau = \sqrt{(L * C)} = \sqrt{90n * 4p} = 0.6n$$

$$d = 20cm$$

$$t_r = 0.1ns$$

$$N = \frac{10 * 0.6n * 20}{0.1n} = 1200$$

The ideal number of sections comes to 1200. So, in order to preserve the bandwidth we need to consider 1200 lumped segments which is obtained by the rule of thumb. When we use the N as 5 , at that the frequency response is correct for the initial frequency but is wrong at higher frequencies. With N as 500 the frequency response is working at higher frequencies therefore, it looks much closer to the HSpice W element results. This shows us that with increasing N we are getting accurate results.

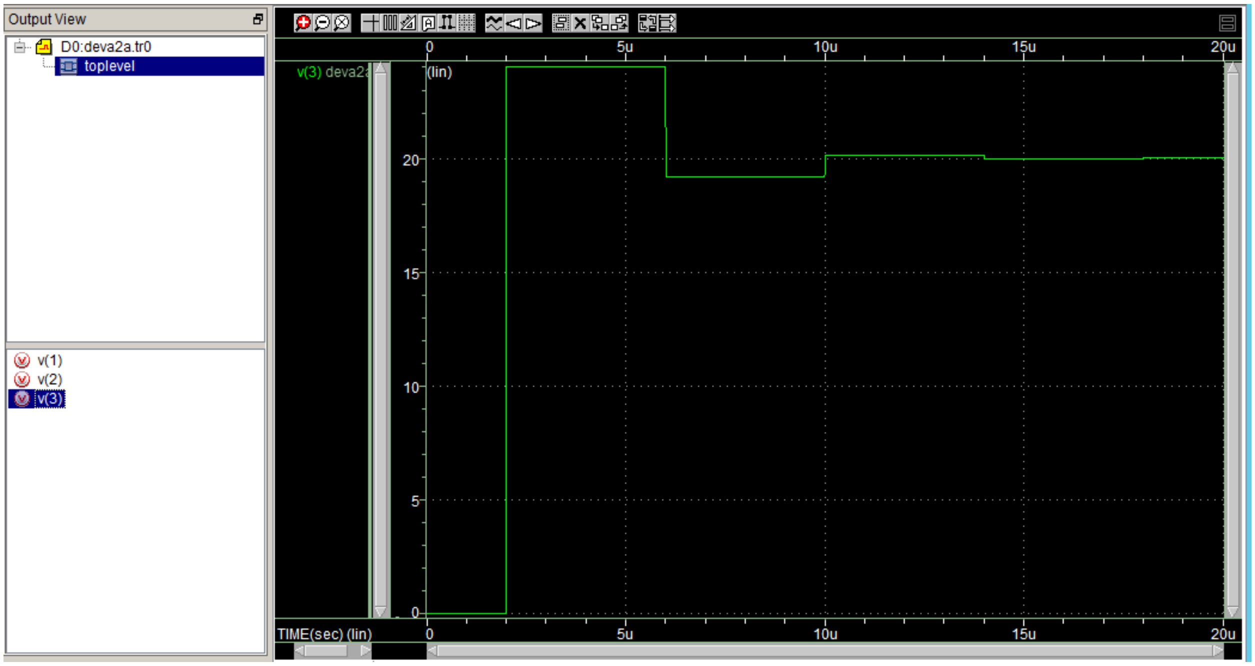
i) Can you also use the U element for this example, instead of W element? Provide your comments

Both W and U elements are used for transmission line simulation but the W element can output accurate simulation results without fine tuning optional parameters.

When running the simulations of U element a warning is issued in the .lis file stating that the T-line delay is too small. Just for that reason we can't use the U element instead of the W element. Even though U element share the same features of W element say, time delay, phase shift, crosstalk and distortion. In our case as we are working with a very low rise time, fall time and pulse width which U element cannot handle, so we cannot use U element instead of W element.

2. Transient Response via Voltage Reflection Diagrams.

a) For the following single lossless interconnect circuit (use Rg=0, RL=75 Ohms), compute the output voltage waveform (show the necessary calculations briefly) from 0 to 20us (show all the transitions points on the waveform). Compare on the same graph, the response using the simulation from HSPICE (T-element).



Calculations:-

$\Gamma_L = \frac{R_L - Z_C}{R_L + Z_C}$ = **0.2;** $\Gamma_G = \frac{R_G - Z_C}{R_G + Z_C}$ = **-1** ;

$V_1^+ = (\Gamma_L * V_1) + V_1$ = **24V**

$V_1^- = (\Gamma_L * V_1) + V_1 + (\Gamma_G * \Gamma_L * V_1^+)$ = **19.2V**

$V_2^+ = (\Gamma_L * V_1) + V_1 + (\Gamma_G * \Gamma_L * V_1^+) + (\Gamma_G^2 * \Gamma_L^2 * V_1^+)$ = **20.21V**

$V_2^- = (\Gamma_L * V_1) + V_1 + (\Gamma_G * \Gamma_L * V_1^+) + (\Gamma_G^2 * \Gamma_L^2 * V_1^+) + (\Gamma_G^3 * \Gamma_L^2 * V_1^+)$ = **19.898V**

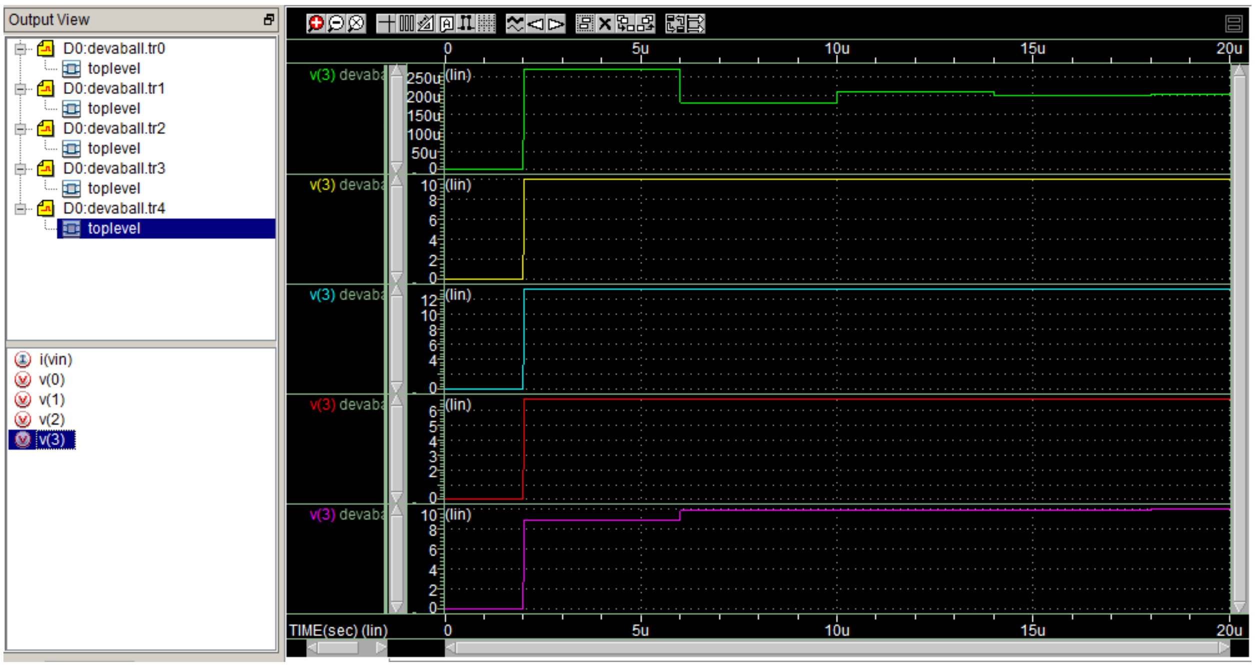
$V_3^+ = (\Gamma_L * V_1) + V_1 + (\Gamma_G * \Gamma_L * V_1^+) + (\Gamma_G^2 * \Gamma_L^2 * V_1^+) + (\Gamma_G^3 * \Gamma_L^2 * V_1^+) + (\Gamma_G^4 * \Gamma_L^4 * V_1^+)$ = **20V**

$\tau_d = \frac{l}{v}$ = **2μs**

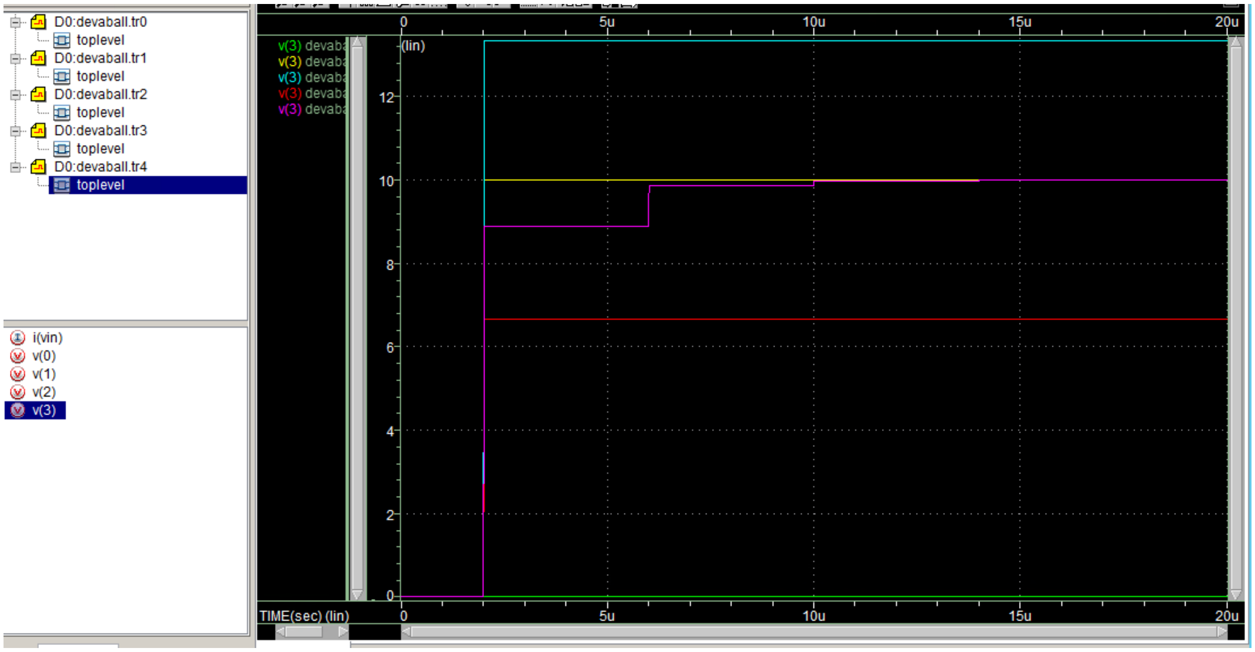
Continuation (Handwritten)

b) **Compare output voltage waveforms simulations using HSPICE for the following cases, by plotting them on a same graph (but different from that of part a): (i) Rg=100, RL=10-4 Ohms; (ii) Rg=50, RL=50 Ohms (iii) Rg=50, RL=100 Ohms; (iv) Rg=100, RL=50 Ohms (v) Rg=100, RL=100 Ohms**

Output Waveform :



Grouped together:



c) Comment on your observations regarding the possible relationships between Rg, RL, Zc, Reflection Coefficient and the overshoot/undershoots in the response.

The relationship between R_g, R_l, Z_c and Reflection Coefficient:-

- When $R_g > Z_c$ and $Rl < Z_c$, there is overshoot and undershoot in output voltage. Due to high mismatch in the load the reflection coefficient is very low where most of the signal is lost and output voltage is very low
- When R_g , R_l and Z_c are matched, there is no overshoot or undershoot everything is balanced properly with a constant reflection coefficient and output is half of the input.
- When R_g is matched to Z_c and $R_l > Z_c$, there is no overshoot or undershoot because one of the side is matched and output is more than the half because input side is matched and reflection co efficient is more.
- When R_l is matched to Z_c and $R_g > Z_c$, there is no overshoot or undershoot because one of the side is matched and output is less than the half because output side is matched and reflection co efficient is less because one end is not matched.
- When R_g and $R_l > Z_c$, there is overshoot or undershoot because none of the side is matched and output is equal to half because of $R_g = R_l$. The reflection coefficient vary as R_g and R_l are not matched Z_c.

3. **MoC based TL Macromodeling.**

a) For the circuit in Fig. 2, Rg= RL=80 Ohms; length of the TL = 10 cm:

- ✓ **Write an an equivalent circuit, in which the TL is represented via the Method of Characteristics.**

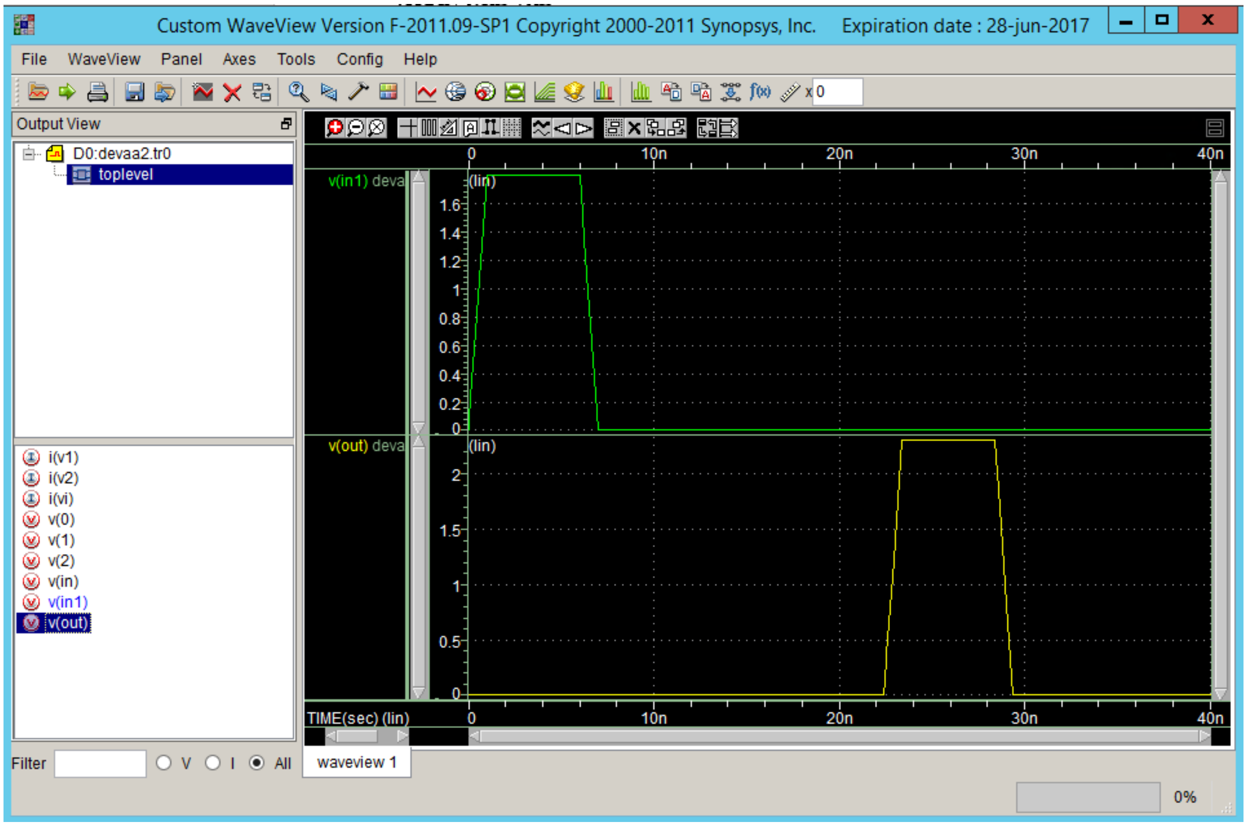
(Handwritten)

- ✓ **Provide the corresponding netlist and simulate using HSPICE.**

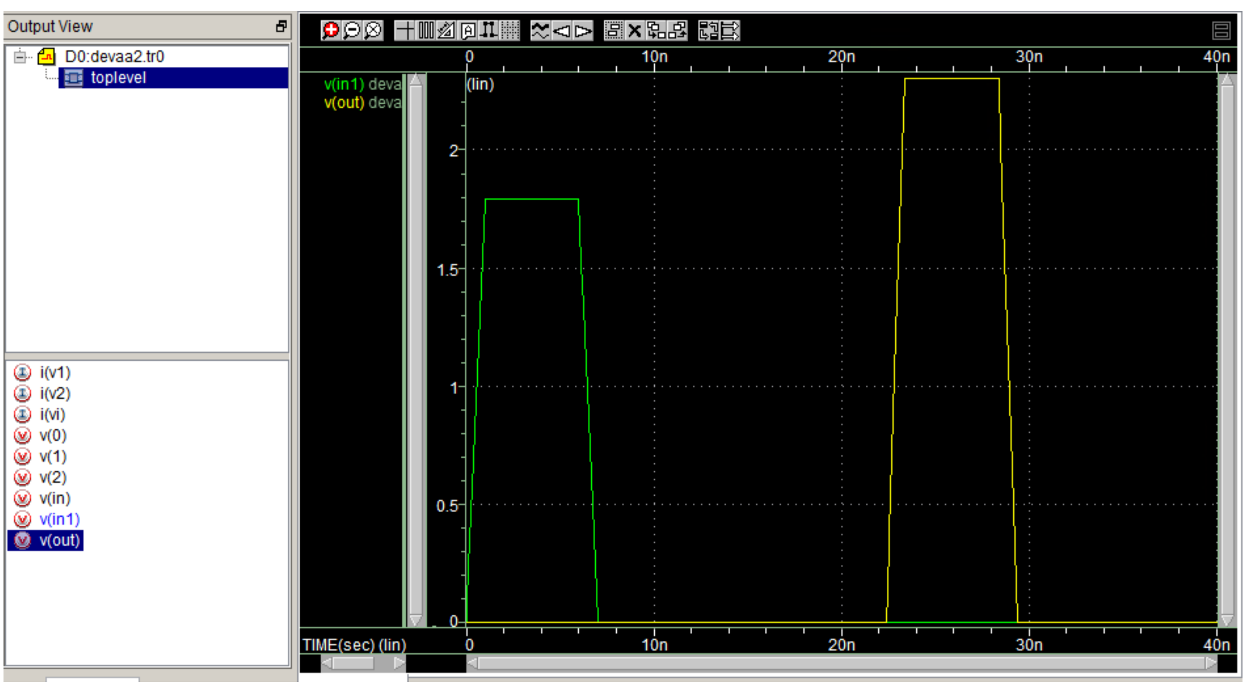
Netlist :

```
*. Moc implementation/interface in HSPICE
*td=22.4e-9 **td=sqrt(LC)d
*Yc=22.4e-3 **Yc=sqrt(C/L)
Vi In 0 PWL (0 0V 1ns 5V 6ns 5V 7ns 0V 10ns 0V)
R1 In In1 80
R2 Out 0 80
V1 In1 1 0V
V2 Out 2 0V
R3 1 0 44.64
R4 2 0 44.64
G1 0 1 DELAY 2 0 TD=22.4e-9 scale=22.4e-3
G2 0 2 DELAY 1 0 TD=22.4e-9 scale=22.4e-3
F1 0 1 DELAY V2 TD=22.4e-9 scale=1
F2 0 2 DELAY V1 TD=22.4e-9 scale=1
.TRAN 0.1ns 40ns
.PRINT TRAN V(Out)
.END
```

Output Waveform :

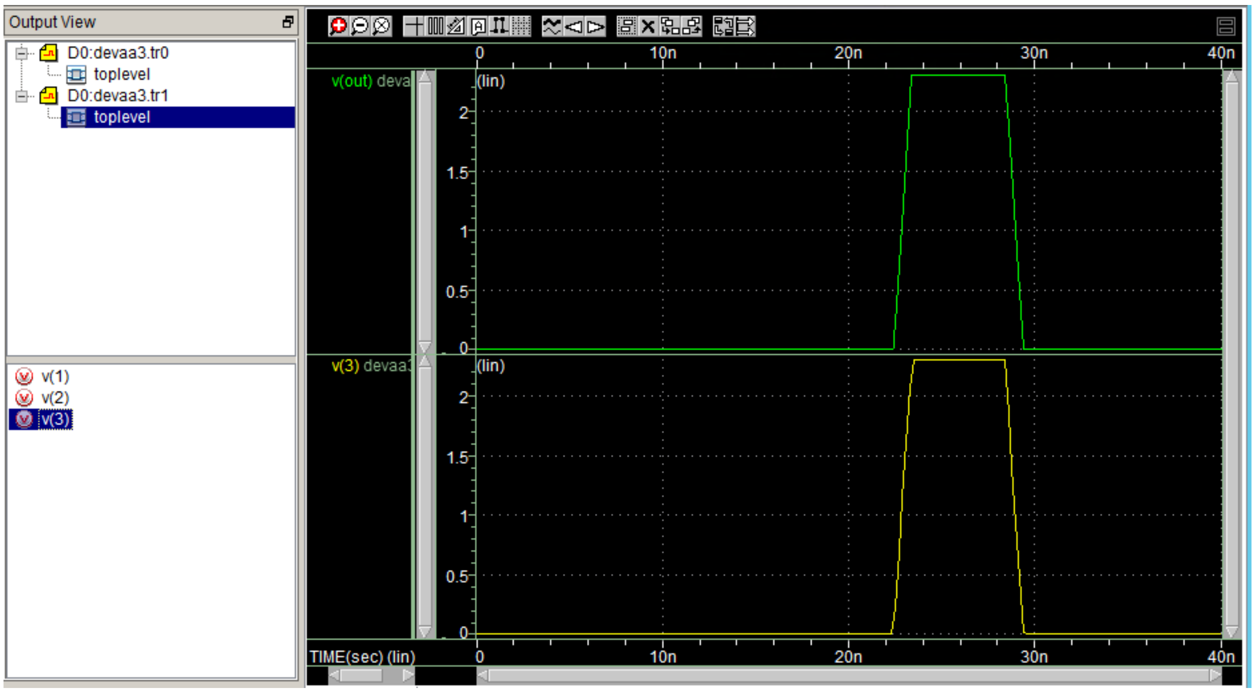


Grouped together :

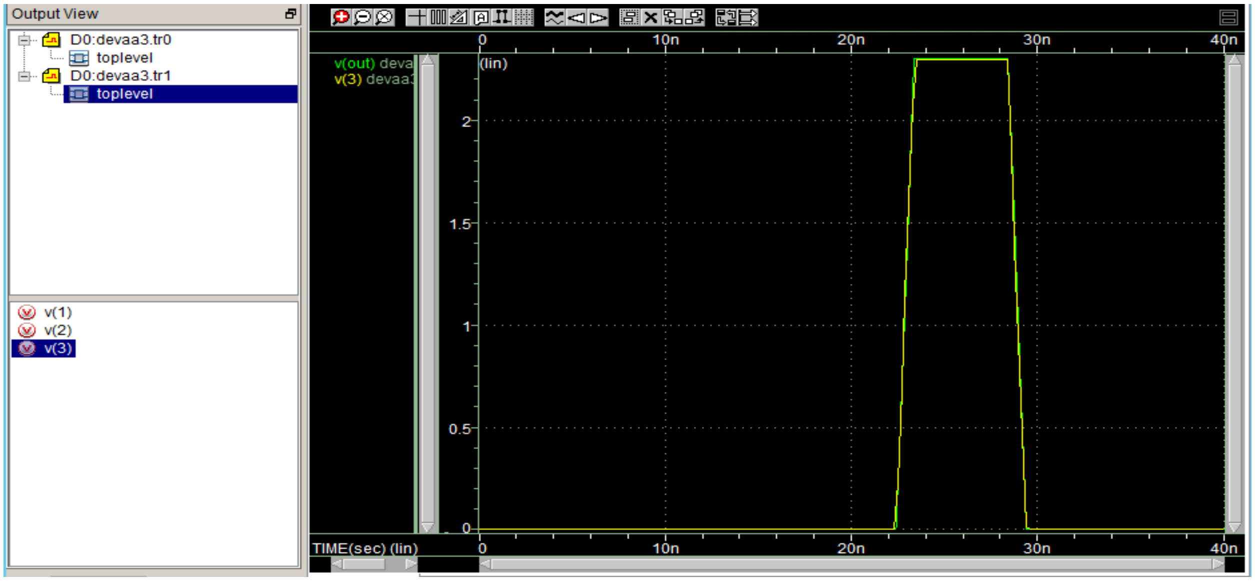


✓ **Compare the above results with the simulation of the circuit in Fig. 2, wherein the TL is represented by T-element. Provide the transient responses for both (i) & (ii) on a same graph (make sure to use different markers to distinguish the cases).**

Output Waveform :



Grouped together :



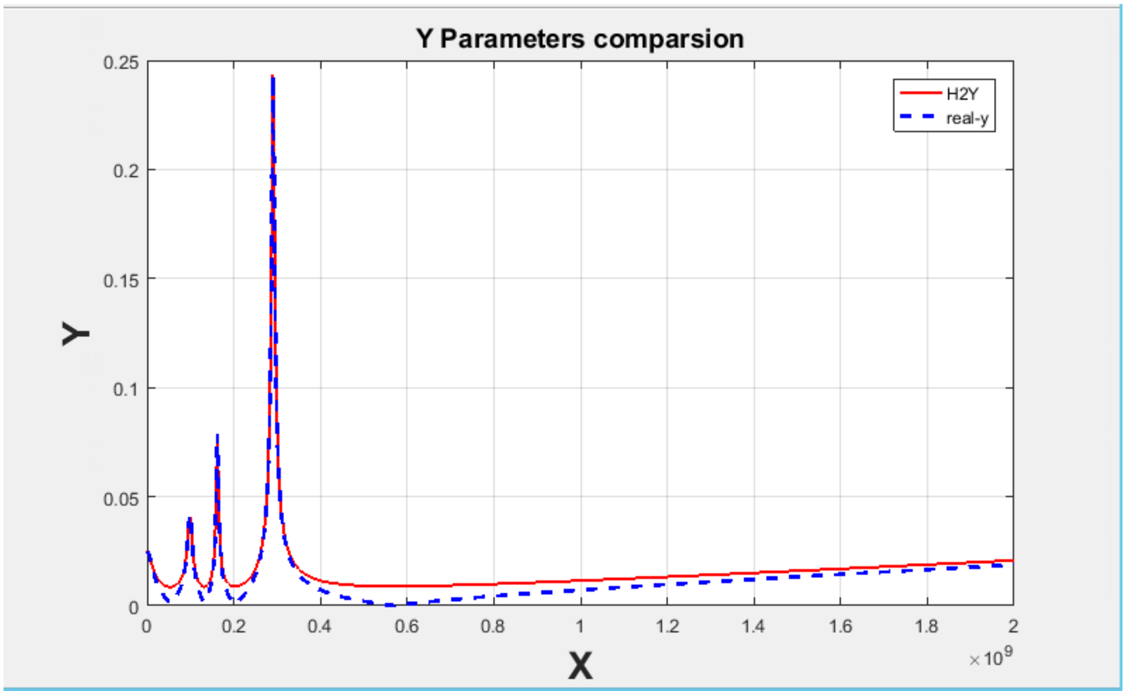
4. **Q4. MRA based TL Macromodeling.**

a) **Write a Matlab program to implement the MRA algorithm.**

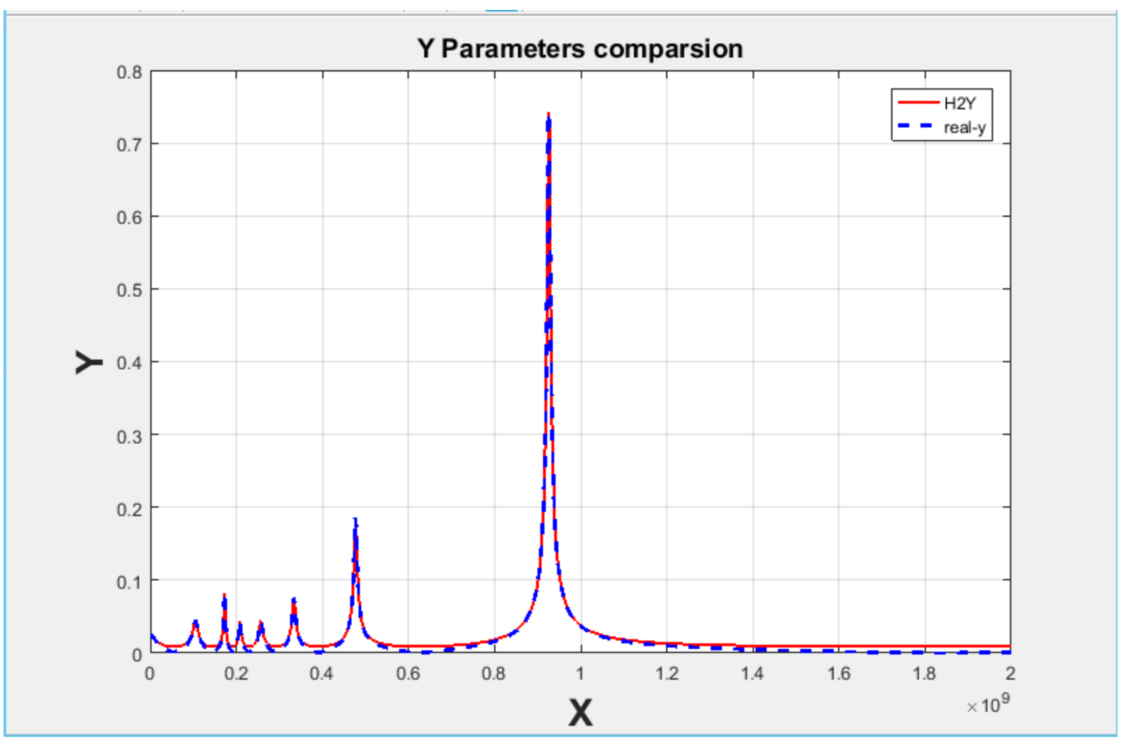
```
frequency= linspace(1, 2e9, 1000);
length=10;
q1=4;
t1=0.02e-3;
w1=100e-9;
o1=8e-12;
d1=[0 -q1;-t1 0];
e1=[0 -w1;-o1 0];
V=4;
L=4;
var= V;
a=zeros(size(frequency));
Q=zeros(size(frequency));
p=zeros(2,2);
q=zeros(2,2);
A=zeros(2,2);
B=zeros(2,2);
C=zeros(2,2);
D=zeros(2,2);
for m=1:1:1000
    m1=frequency(m);
    s1=(1i*2*pi*m1);
    z1=(d1+s1.*e1)*length;
for i=0:1:var
    q = q+ ((factorial(V + L - i)/factorial(V + L))*(factorial(L)/(factorial(L - i)*factorial(i)))).*(-z1)^i;
    C = q;
    p= p + ((factorial(V + L - i)/factorial(V + L))*(factorial(V)/(factorial(V - i)*factorial(i)))).*z1^i;
    A =p;
    D=inv(C)*A;
    P1= [ -A(1,1), C(1,1); -A(2,1), C(2,1)];
    Q1= [A(1,2), -C(1,2); A(2,2), -C(2,2)];
end

B=h2y(D);
a(m)=B(1,1)/B(1,2);
Y= inv(Q1)*P1;
real(m)=Y(1,1);
end

%comparing results in one graph:

plot(frequency,abs(a),'r','LineWidth',1.5);
hold on;
grid;
plot(frequency,abs(real),'--b','LineWidth',2);
hold on;
title('Y Parameters comparsion','FontSize',14,'FontWeight','bold');
xlabel('X','FontWeight','bold','FontSize',20);
ylabel('Y','FontWeight','bold','FontSize',20);
legend('H2Y','real-y');
```

b) **For the TL circuit in Fig. 3, compute the Y11-magnitude response using the MRA approximations of order 4/4, 8/8 and 16/16. Plot the corresponding responses on three different graphs, with each graph containing the comparison with the exact Y-parameters based on the exponential stamp (from 1Hz to 2GHz at 1000 points).**

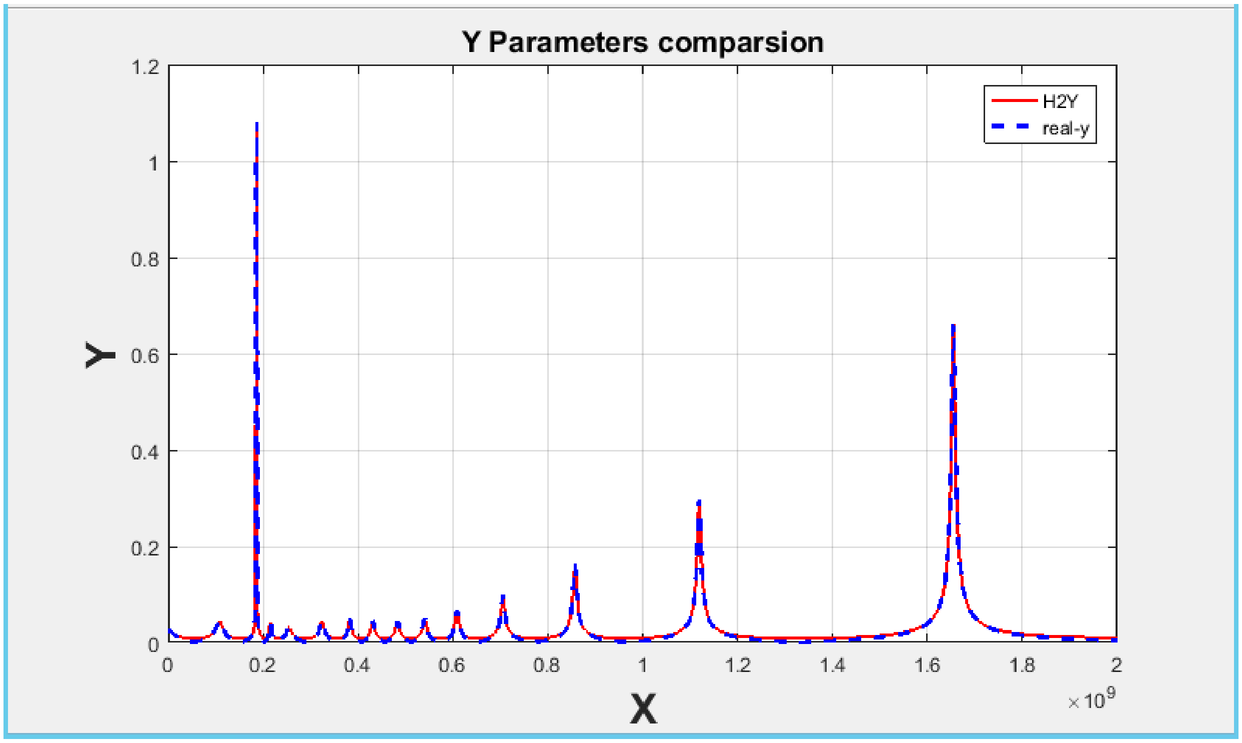
ORDER 4 x 4



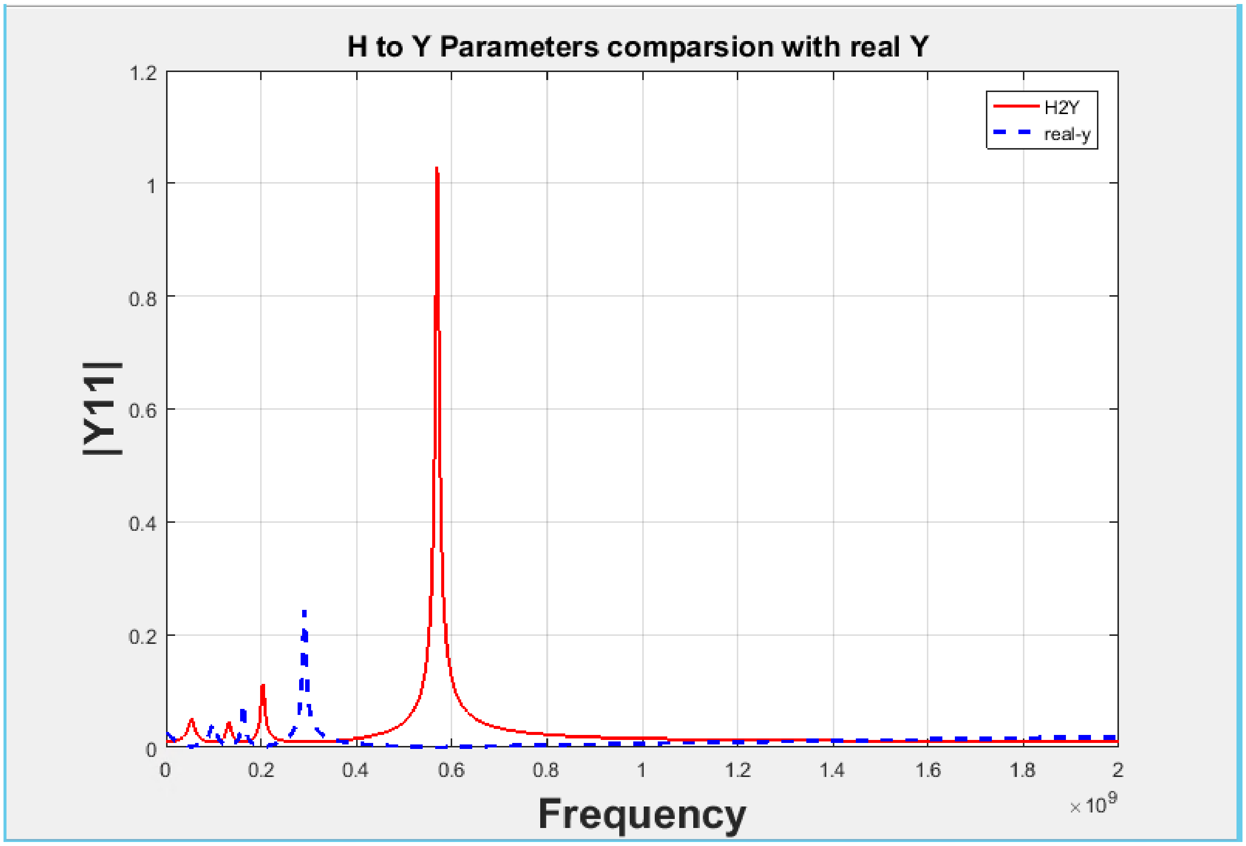
ORDER 8 x 8



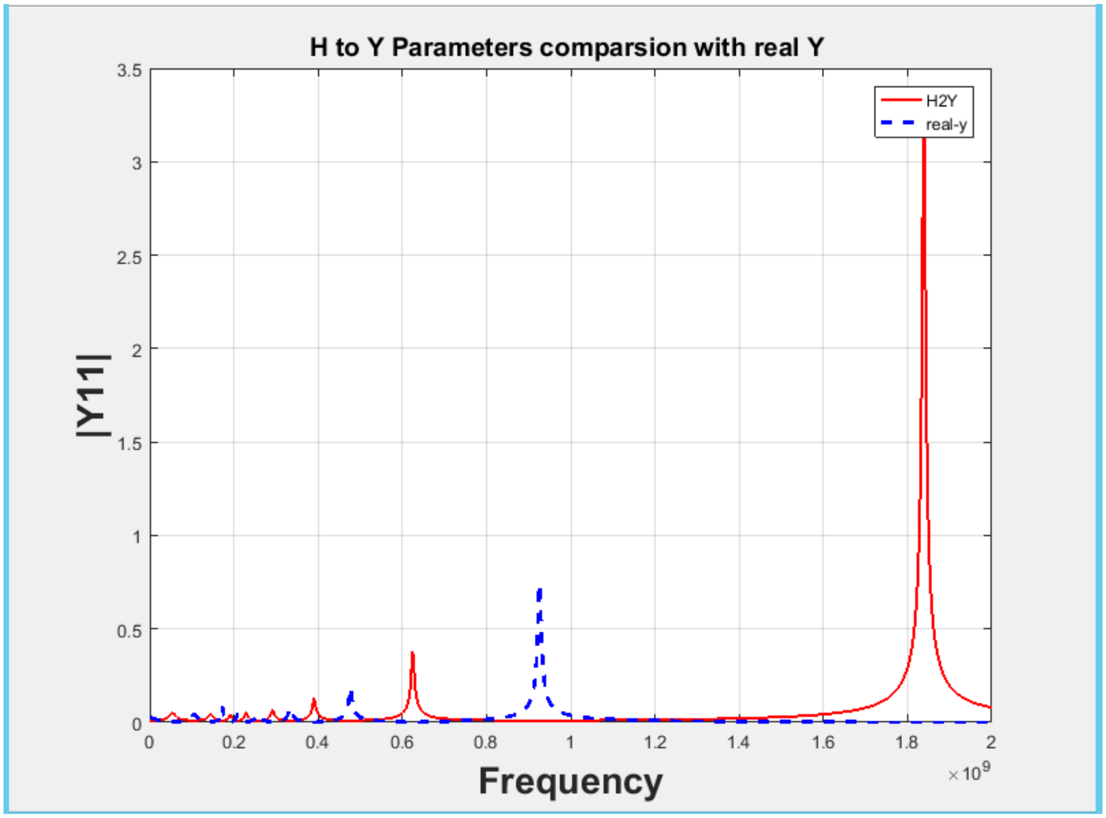
ORDER 16 x 16



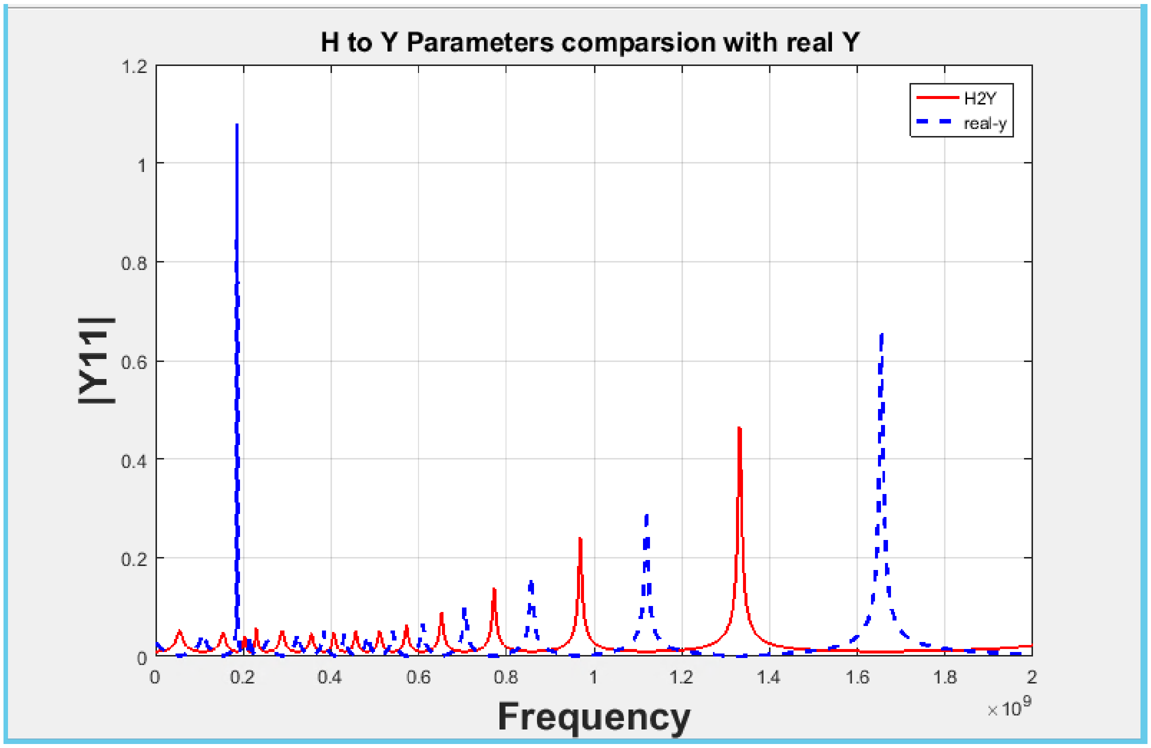
H to Y Parameters comparison with real Y : Order 4 X 4 :



H to Y Parameters comparison with real Y : Order 8 X 8 :

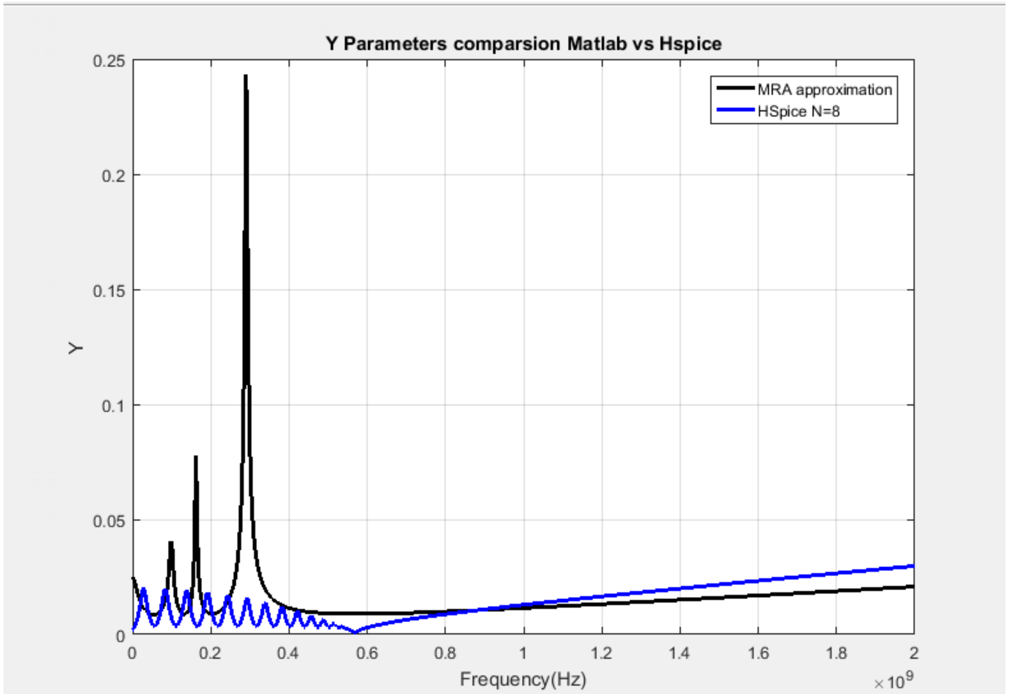


H to Y Parameters comparison with real Y : Order 16 X 16 :

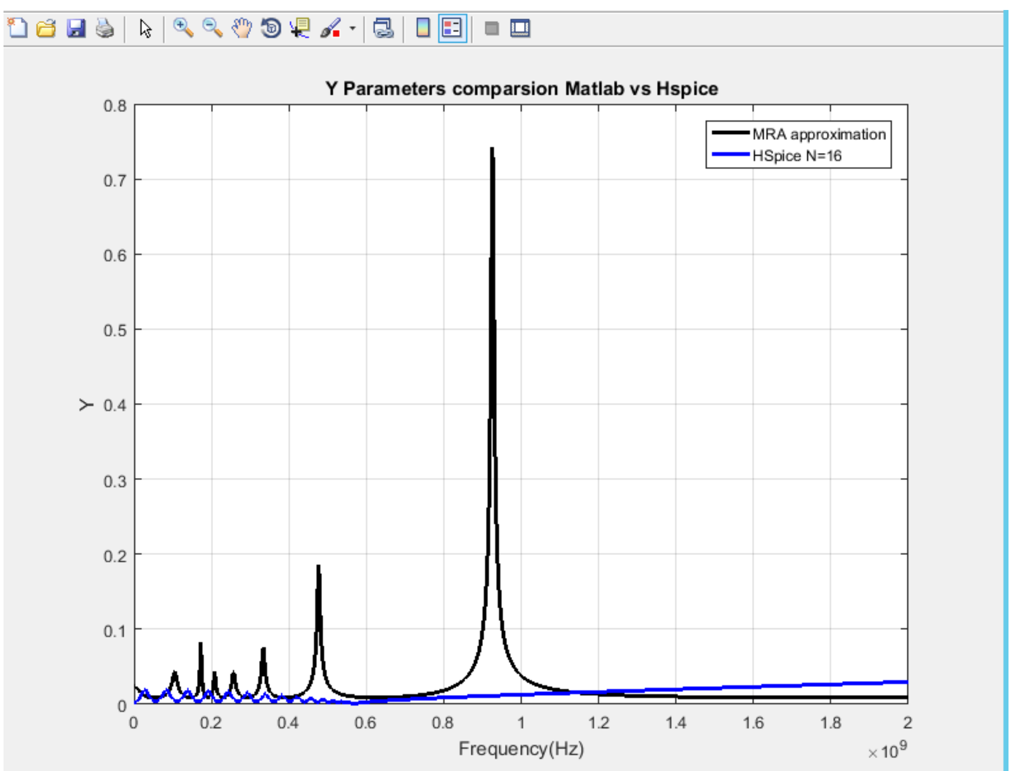


c) Experimentally verify, how many conventional lumped pi-segments will be needed to accurately match each of the above three approximations and report the numbers in a table.

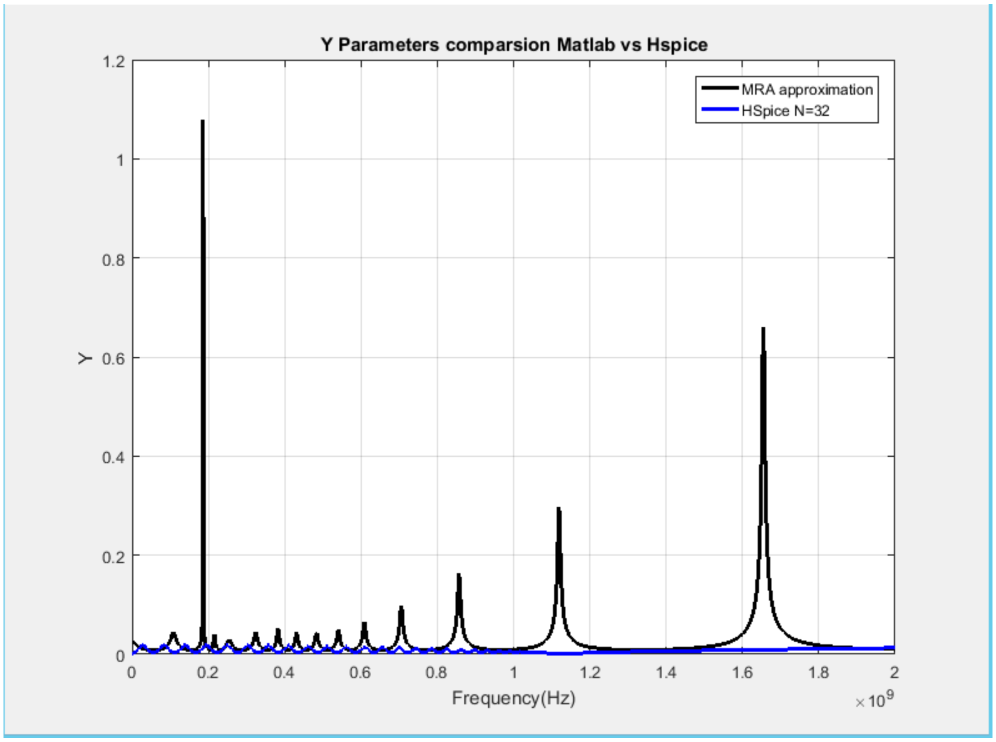
Order 4X4


Y Parameters comparsion Matlab vs Hspice
0.25
0.2
0.15
0.1
0.05
0
Y
MRA approximation
HSpice N=8
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Frequency(Hz)
×10^9

Order 8X8


Y Parameters comparsion Matlab vs Hspice
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Y
MRA approximation
HSpice N=16
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Frequency(Hz)
×10^9

Order 16 X 16



MRA Order	No of lumped model approximations
4	>=8
8	>=16
16	>=32