Radiation Pattern due to Higher Order Modes in Cylindrical Waveguides

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06/01/15 – 07/14/15
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Introduction:

The broader objective of the project is to find ways to increase the field of view of radio interferometer. The field of view of a radio interferometer is limited by the primary beam of individual antenna. The beam of a radio telescope is proportional to the wavelength as the diameter of the telescope is fixed. For higher frequency the beam reduces. So the field of view reduces (see figure: 1). In this project we have investigated the multimode feed horn as possible solution to the problem. Specifically, for the project, we aimed at (a) obtaining the radiation pattern of different modes and their radiation efficiencies and (b) ways to control complex amplitude of modes in waveguide. CST microwave studio is used to simulate far-field pattern when different modes in a circular waveguide are excited. We developed MATLAB programs to verify scatter parameters provided by CST. We also developed MATLAB programs to estimate the radiated power from CST field pattern.

\[ \text{Beam} \sim \frac{\lambda}{D} \]

\( \lambda = \text{wavelength} \)

\( D = \text{diameter of the antenna} \)

Figure 1: Field of view of a radio interferometer
1. **Modes of a Circular Waveguide:**

The field pattern inside the waveguide can be considered as a combination of different modes. This mode can be transverse electric (TE) and transverse magnetic (TM). Figure 2 shows field pattern of two modes inside the waveguide.

![Field patterns of different modes](image)

2. **Radiation pattern of different modes:**

To find the radiation pattern of different modes we used CST microwave studio, which has a CAD based user interface where we can design mechanical structure of antennas and waveguides and simulate their radiation pattern. CST solves the Maxwell’s equations in numerical fashion to obtain the field pattern and scatter parameters.

a) **Waveguide design and simulation**

A cylindrical waveguide model was created in CST microwave studio. The inner, outer diameters and length of the waveguide are set as parameters. The material of the waveguide is selected as perfect electric conductor (PEC). The inner radius is set to $R_{in} = 95\text{mm}$ and the outer radius is set to $R_{out} = 100\text{mm}$. The cutoff frequency of a circular waveguide depends upon the inner radius and the modes. For this specific configuration the lowest cutoff frequency we got is $0.925\text{GHz}$ for TE11 mode. We kept the length of the waveguide of 600 mm (see Fig. 3). CST’s waveguide ports are used to excite the waveguide.

After completing the mechanical design of the waveguide we set the frequency to 0 to 10 GHz for simulation. Initially, two waveguide ports were placed on either side of the waveguide (see Fig. 4). The port is set to excite one mode (TE11). The mesh size is set to $1/10^\text{th}$ of the wavelength. The transient solver is used for the simulation, with accuracy set to -30 dB and scatter parameter (S parameter) normalized to reference impedance of $50\Omega$. The
field pattern at 5 GHz and 10 GHz in the waveguide is shown in Fig. 3 & 4 respectively. The $|S11|$ vs frequency is shown in Fig. 7.

Figure 3: Cylindrical Waveguide Design

Figure 4: Cylindrical Waveguide with Two Waveguide Ports

Figure 5: Electric Field Pattern for 5 GHz
To understand the behavior of $S_{11}$ as a function of frequency we developed a simple network model of the waveguide-port system in MATLAB. We know the cutoff frequency of circular waveguide for TE11 is given by

$$f_{cutoff} = \frac{1.8412 \times c}{2 \times \pi \times r}$$

Where $c = 3 \times 10^8$ m/sec and $r =$ radius of the circular section of the waveguide in meters. The cutoff frequency for TE11 is 0.925 GHz for $r = 95$ mm. The characteristic impedance of a circular waveguide can be measured as
Here 377 Ohm is the approximate free space impedance, \( f \) is the frequency. The circular waveguide is considered as a transmission line terminated with load \( Z_L \). The input impedance of a transmission line is given by

\[
Z_{in} = Z_0 \frac{(Z_L + iZ_0\tan(\beta L))}{(Z_0 + iZ_L\tan(\beta L))}
\]

where Beta is \( \frac{2\pi}{\lambda} \), lambda is the wavelength in the waveguide, and \( L \) is the length of the transmission line. The \( S_{11} \) is then obtained using the equation

\[
S_{11} = \frac{Z_{in} - Z'_0}{Z_{in} + Z'_0}
\]

Figure 8: S parameter for circular waveguide with two ports
Figure 9: Impedance plot of circular waveguide with two ports

Where $Z_0'$ is the reference impedance (= 50 Ohms) used by CST. The computed characteristics impedance is shown in Fig. 9 and S11 is shown in Fig. 8. The computed S11 matches well with the CST simulation.

b) Radiation pattern:

To get the radiation pattern of different modes, we placed a port on one side and kept the other end open (see Fig. 10). The field pattern in the waveguide for TE11 and the S11 for this case are shown in Fig 11 & 12 for 5 and 10 GHz respectively. We simulate the S parameter in CST first (See Figure: 13). Then we have tried the simulation in MATLAB and plot the S parameter and input impedance over frequencies for Mode: 1 (See Figure: 14 & 15).
Figure 10: Cylindrical Waveguide with Single Port

Figure 11: Electric Field Pattern for 5 GHz, Single Port

Figure 12: Electric Field Pattern for 10 GHz, Single Port
Figure 13: S parameter plot for Single Port

Figure 14: MATLAB Simulation of S Parameter for Single Port
We then excited the waveguide with different modes (1 to 10) to analyze its S parameters and far field patterns for different frequencies. We also have developed an analytical model of the waveguide to reproduce the S parameter so that we can verify the CST simulation. The figures attached below shows the simulation results of S parameters from CST and MATLAB and far field from CST. For every mode the waveguide has different cutoff frequency. Figure: 16 show the different cutoff frequency of the waveguide for different modes.

Figure 15: MATLAB Simulation of Input Impedance at Port 1
Figure 16: Different cutoff frequencies of the waveguide for different modes
**MODE 1**

Mode: 1 is TE 11 mode. The cutoff frequency is 0.925 GHz. Figure: 17 shows the plot of S parameter in CST. Figure: 18 shows S parameter plot obtained from MATLAB model. Figure: 19 and Figure: 20 shows far field pattern obtained from CST and plotted in MATLAB for 5 GHz.

**CST Simulation**

![CST Simulation](image)

*Figure 17: S parameter plot from CST for Mode: 1*

**MATLAB Simulation**

![MATLAB Simulation](image)

*Figure 18: S parameter plot from MATLAB model for Mode: 1*
Far field Pattern for 5 GHz

Figure 19: Contour plots of far field at 5 GHz for Mode: 1

Figure 20: 3-D plot of far field at 5 GHz for Mode: 1
MODE 2

Mode: 2 is TE 11 mode with orthogonal polarization. The cutoff frequency is 0.925 GHz. Figure 21 shows the plot of S parameter from CST. Figure 22 shows S parameter plot from MATLAB model. Figure 23 and Figure 24 show far field obtained from CST and plotted using MATLAB for 5 GHz.

CST Simulation

MATLAB Simulation
Far field Pattern for 5 GHz

Figure 23: Contour plot of the far field at 5 GHz for Mode: 2

Figure 24: 3-D plot of far field at 5 GHz for Mode: 2
**MODE 3**

Mode: 3 is TM 01 mode. The cutoff frequency is 1.21 GHz. Figure: 25 show the plot of S parameter from CST. Figure: 26 shows S parameter plot from MATLAB model. Figure: 27 and Figure: 28 show far field obtained from CST and plotted using MATLAB for 5 GHz.

**CST Simulation**

![CST Simulation](image)

*Figure 25: S parameter plot in CST for Mode: 3*

**MATLAB Simulation**

![MATLAB Simulation](image)

*Figure 26: S parameter plot from MATLAB model for Mode: 3*
Far field Pattern for 5 GHz

Figure 27: Contour plot of the far field at 5 GHz for Mode: 3
Figure 28: 3-D plot of far field at 5 GHz for Mode: 3

**MODE 4**

Mode: 4 is TE 21 mode. The cutoff frequency is 1.53 GHz. Figure: 29 shows the plot of S parameter from CST. Figure: 30 shows S parameter plot from MATLAB model. Figure: 31 and Figure: 32 show far field obtained from CST and plotted using MATLAB for 5 GHz.

**CST Simulation**

Figure 29: S parameter plot in CST for Mode: 4

**MATLAB Simulation**
Figure 30: S parameter plot from MATLAB model for Mode: 4

Far field Pattern for 5 GHz
Figure 31: Contour plot of the far field at 5 GHz for Mode: 4

Figure 32: 3-D plot of far field at 5 GHz for Mode: 4
Mode: 5 is TE 21 mode (orthogonal polarization). The cutoff frequency is 1.53 GHz. Figure: 33 shows the plot of S parameter from CST. Figure: 34 shows S parameter plot from MATLAB model. Figure: 35 and Figure: 36 show far field obtained from CST and plotted using MATLAB for 5 GHz.

**CST Simulation**

![CST Simulation](image1)

**MATLAB Simulation**

![MATLAB Simulation](image2)
Far field Pattern for 5 GHz

Figure 35: 3-D plot of far field at 5 GHz for Mode: 5

Figure 36: Contour plot of the far field at 5 GHz for Mode: 5
MODE 6

Mode: 6 is TE 01 mode. The cutoff frequency is 1.92 GHz. Figure: 37 shows the plot of S parameter from CST. Figure: 38 shows S parameter plot from MATLAB model. Figure: 39 and Figure: 40 show far field obtained from CST and plotted using MATLAB for 5 GHz.

CST Simulation

![CST Simulation Graph]

Figure 37: S parameter plot from CST for Mode: 6

MATLAB Simulation

![MATLAB Simulation Graph]

Figure 38: S parameter plot from MATLAB for Mode: 6
Far field Pattern for 5 GHz

Figure 39: 3-D plot of far field at 5 GHz for Mode: 6

Figure 40: Contour plot of the far field at 5 GHz for Mode: 6
MODE 7

Mode: 7 is TM 11 mode. The cutoff frequency is 1.92 GHz. Figure: 41 shows the plot of $S$ parameter from CST. Figure: 42 shows $S$ parameter plot from MATLAB model. Figure: 43 and Figure: 44 show far field obtained from CST and plotted in MATLAB for 5 GHz.

CST Simulation

![Figure 41: S parameter plot from CST for Mode: 7](image)

MATLAB Simulation

![Figure 42: S parameter plot from MATLAB model for Mode: 7](image)
Far field Pattern for 5 GHz

Figure 43: 3-D plot of far field at 5 GHz for Mode: 7

Figure 44: Contour plot of the far field at 5 GHz for Mode: 7
MODE 8

Mode: 8 is TM 11 mode (orthogonal polarization). The cutoff frequency is 1.92 GHz. Figure: 45 shows the plot of S parameter from CST. Figure: 46 shows S parameter plot from MATLAB model. Figure: 47 and Figure: 48 show far field obtained from CST and plotted using MATLAB for 5 GHz.

CST Simulation

![CST Simulation Graph]

Figure 45: S parameter plot from CST for Mode: 8

MATLAB Simulation
Figure 46: $S$ parameter plot from MATLAB model for Mode: 8

Far field Pattern for 5 GHz

Figure 47: 3-D plot of far field at 5 GHz for Mode: 8
MODE 9

Mode: 9 is TE 31 mode. The cutoff frequency is 2.11 GHz. Figure: 49 shows the plot of S parameter from CST. Figure: 50 shows S parameter plot from MATLAB model. Figure: 51 and Figure: 52 show far field obtained from CST and plotted using MATLAB for 5 GHz.

CST Simulation
MATLAB Simulation

Figure 50: S parameter plot from MATLAB model for Mode: 9

Far field Pattern for 5 GHz
MODE 10

Mode: 10 is TE 31 mode (orthogonal polarization). The cutoff frequency is 2.11 GHz. Figure: 53 shows the plot of S parameter from CST. Figure: 54 shows S parameter plot from
MATLAB model. Figure: 55 and Figure: 56 show far field obtained from CST and plotted using MATLAB for 5 GHz.

**CST Simulation**

![CST Simulation Graph](image)

*Figure 53: S parameter plot from CST for Mode: 10*

**MATLAB Simulation**

![MATLAB Simulation Graph](image)

*Figure 54: S parameter plot from MATLAB model for Mode: 10*

**Far field Pattern for 5 GHz**
Figure 55: 3-D plot of far field at 5 GHz for Mode: 10

Figure 56: Contour plot of the far field at 5 GHz for Mode: 10
c) Calculation of Radiated Power:

We developed a MATLAB program to calculate the radiated power using the far field patterns provided by CST. Table:1 and Table: 2 show radiated power for different modes for 5 GHz and 10 GHz respectively. The RMS excitation power was set by CST to 0.5 W. In table below, radiated power larger than 0.5 W is due to numerical inaccuracies in the simulation. This numerical inaccuracy was inferred by comparing the mode impedance with free space impedance. The difference in impedance provides a measure of power transmitted to free space.

Radiated Power for Different Modes for Frequency = 5 GHz

<table>
<thead>
<tr>
<th>Modes</th>
<th>Radiated Power (in Watts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>TE11</td>
</tr>
<tr>
<td>2</td>
<td>TE11</td>
</tr>
<tr>
<td>3</td>
<td>TM01</td>
</tr>
<tr>
<td>4</td>
<td>TE21</td>
</tr>
<tr>
<td>5</td>
<td>TE21</td>
</tr>
<tr>
<td>6</td>
<td>TE01</td>
</tr>
<tr>
<td>7</td>
<td>TM11</td>
</tr>
<tr>
<td>8</td>
<td>TM11</td>
</tr>
<tr>
<td>9</td>
<td>TE31</td>
</tr>
<tr>
<td>10</td>
<td>TE31</td>
</tr>
</tbody>
</table>

Table 1: Radiated Power for Different modes at 5 GHz

Radiated Power for Different Modes for Frequency = 10 GHz

<table>
<thead>
<tr>
<th>Modes</th>
<th>Radiated Power (in Watts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>TE11</td>
</tr>
<tr>
<td>2</td>
<td>TE11</td>
</tr>
<tr>
<td>3</td>
<td>TM01</td>
</tr>
<tr>
<td>4</td>
<td>TE21</td>
</tr>
<tr>
<td>5</td>
<td>TE21</td>
</tr>
<tr>
<td>6</td>
<td>TE01</td>
</tr>
<tr>
<td>7</td>
<td>TM11</td>
</tr>
<tr>
<td>8</td>
<td>TM11</td>
</tr>
<tr>
<td>9</td>
<td>TE31</td>
</tr>
<tr>
<td>10</td>
<td>TE31</td>
</tr>
</tbody>
</table>

Table 2: Radiated Power for Different modes at 10 GHz
The radiation efficiency for the 10 modes are shown in Fig. 57. We found that radiation efficiency for 10 modes (1 to 10) is almost similar within 10% (limited by simulation accuracy).

To find ways to control different modes of a waveguide we designed a slot antenna and excited the waveguide with the slot antenna.

3. **Slot Antenna:**

Slot antennas are quite popular in radar, navigation and other high frequency usage. The main advantage of using slot antennas is that they are simpler to fabricate, have low loss and high efficiency. The slot antenna generally has a narrow width.

We first designed a cross polarized slot antenna based on the theory developed by Li, Hummer & Chang (1991). We kept the length of the slot as $\lambda/2$ and the width a fraction of $\lambda/2$ (see Figure: 58 and 59). The slot antenna was tuned to 5 GHz. The dimensions of the designed antenna are given in Table 3. The slot antenna was then constructed in CST microwave studio. Figure: 61 & 62 show the slot antenna model in CST. Our goal is to get the S parameter and far field pattern of the slot antenna. The S parameter obtained from CST (See Figure: 64) shows that the slot antenna is tuned at 5 GHz. The far field patterns of the slot antenna obtained from CST are shown in Figure: 65 & 66. We excited the waveguide with a single TE11 mode to get the far field pattern. Contour and 3D plots of the far field were also made using MATLAB, which are shown Figure: 67 & 68.
Table 3: Measurements of slot antenna

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value in mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>L</td>
<td>29.949</td>
</tr>
<tr>
<td>a</td>
<td>0.428</td>
</tr>
<tr>
<td>R</td>
<td>26.533</td>
</tr>
<tr>
<td>d</td>
<td>33.243</td>
</tr>
</tbody>
</table>
Figure 60: Slot Antenna tuned at 5 GHz

Figure 61: Back View of Slot Antenna tuned at 5 GHz
Figure 62: Front View of Slot Antenna tuned at 5 GHz

Figure 63: S parameter plot of the slot antenna from CST
Figure 64: Far field plot of the slot antenna at 5 GHz from CST

Figure 65: Far field plot of the slot antenna at 5 GHz from CST
Figure 66: Contour plot of the Far field pattern at 5 GHz made using MATLAB

Figure 67: 3D plot of far field pattern of the slot antenna at 5 GHz made using MATLAB
**Configuration I: Cylindrical Waveguide Excited by Slot Antenna**

We attached the slot antenna with our original cylindrical waveguide to get the far field pattern and field pattern inside the waveguide. The CST model of a centrally placed slot antenna (configuration I) is shown in Figure: 68, 69 & 70.

![Figure 68: Cylindrical waveguide with the slot antenna](image)

The S parameter plot shown in Fig. 71, indicates a slight offset in frequency – ie the antenna in this setup is tuned at 4.97 GHz. For the present experiment, this shift in frequency is not significant.

![Figure 69: Back view of the waveguide with slot antenna](image)
Figure 70: Front view of the waveguide with slot antenna

Figure 71: S parameter plot of waveguide with slot antenna from CST

Figure: 72 & 73 show the far field plot of the waveguide with the centrally located slot antenna for single polarization for TE11 mode at the slot antenna input. The contour and 3D plot of the far field obtained using MATLAB are shown in Figure: 74 & 75.
Figure 72: Far field plot of the waveguide with centrally located slot antenna using CST

Figure 73: Far field plot of the waveguide with centrally located slot antenna using CST
Figure 74: Contour plot of Far field pattern for configuration I

Figure 75: 3D plot of far field for configuration I
**Configuration II: Waveguide with an off-center slot antenna:**

We then repeated the same experiment with an off-center slot antenna. We have shifted the center of the slot feed along the radius of the cylindrical waveguide (See Figure: 76, 77 & 78). The S parameter plot (see Fig. 79) shows that the antenna is tuned at 5 GHz. The far field patterns with TE11 mode excitation at the slot antenna input are shown in Figs. 80, 81, 82 & 83. The far field pattern is asymmetric compared to the centrally fed slot antenna excitation.

![Figure 76: Cylindrical waveguide with the off-center slot antenna](image1)

![Figure 77: Back view of the waveguide with off-center slot antenna](image2)
Figure 78: Front view of the waveguide with off-center slot antenna

Figure 79: S parameter plot of waveguide with the off-center slot antenna from CST
Figure 80: Far field plot of configuration II from the CST

Figure 81: Far field plot of configuration II from CST
Figure 82: 3D plot of far field pattern of configuration II.

Figure 83: Contour plot of the far field pattern for configuration II.
Discussion and Conclusion:

Fig. 84 shows the field pattern inside the waveguide for Configuration I and II. These field patterns can be written as a linear superposition of waveguide modes. The complex amplitudes for the first 10 modes are obtained by multiplying the mode field patterns of the cylindrical waveguide with the field patterns shown in Fig 84 and integrating over the cross section of the waveguide. The cross section was selected 100 mm inside the open end of the waveguide to obtain the complex amplitudes. Plots of the absolute value of complex amplitudes for the two configurations are shown in Fig 85. The amplitudes for the 10 modes are very different. This means that it may be possible to design probes such that each probe can produce modes with an associated set of complex amplitude. By combining the probe outputs with complex weights it may be possible to control the field pattern in the waveguide and thus the far field pattern. This will be our future direction of investigation.
4. Appendix:

1. MATLAB Code for S11 Calculation for Port 1 and Port 2

```matlab
%Frequency from 0 to 10 GHz
f = 0:0.01:10;
f_fc = zeros(1,1001);
Z = zeros(1,1001);

%Characteristic Impedance Calculation
for i = 1:1001
    f_fc(i) = (0.925/f(i))^2;
    Z(i) = 377/sqrt(1-f_fc(i));
end

%Initialization
S11 = zeros(1,1001);
S11_dB = zeros(1,1001);
c = 3000*10^8;
Zin = zeros(1,1001);
BL = 2*pi*f*10^9*(600/c).*sqrt(1-f_fc);

%S11 calculation for port 1 and port 2
for i = 1:1001
    Zin(i) = (Z(i)*((50+j*(Z(i)*tan(BL(i))))/ (Z(i)+j*(50*tan(BL(i))))));
    S11(i) = abs((Zin(i)-50.0)/(Zin(i)+50.0));
    S11_dB(i) = 20*log10(S11(i));
end

%Plots
figure (1);
plot(f, Z);
xlabel('Frq in GHz');
ylabel('Characteristic Impedence in Ohm');
title('Characteristic Impedence vs Frequency');

figure (2);
plot (f, Zin);
xlabel('Frq in GHz');
ylabel('input Impedence in Ohm');
title('Input Impedence vs Frequency');

figure (3);
plot(f, S11_dB);
axis([0 10 -5 5]);
xlabel('Frfquency in GHz');
ylabel('S11 in dB');
title('S11 vs Frequency plot for circular waveguide');
```
2. MATLAB Code for S11 Calculation for Port 1 and Port 2

%Frequency from 0 to 10 GHz
f = 0:0.01:10;
f_fc = zeros(1,1001);
Z = zeros(1,1001);

%Characteristic Impedance Calculation
for i = 1:1001
    f_fc(i) = (0.925/f(i))^2;
    Z(i) = 377/((sqrt(1-f_fc(i))));
end

%Initialization
S11 = zeros(1,1001);
S11_dB = zeros(1,1001);
c = 3000*10^8;
Zin = zeros(1,1001);
BL = 2*pi*f*10^9*(600/c).*sqrt(1-f_fc);

%S11 calculation for port 1 only
for i = 1:1001
    Zin(i) = (Z(i)*((377+j*(Z(i)*tan(BL(i))))/ (Z(i)+j*(377*tan(BL(i))))));
    S11(i) = abs((Zin(i)-Z(i))/(Zin(i)+Z(i)));
    %The reference impedance for S11 used by CST is 50 Ohms since
    %we selected that in the simulator. So I changed Z(i) to 50 Ohms.
    %Anish
    %S11(i) = abs((Zin(i)-50.0)/(Zin(i)+50.0));
    S11_dB(i) = 20*log10(S11(i));
end

%Plots
figure (1);
plot(f, Z);
xlabel('Frq in GHz');
ylabel('Characteristic Impedence in Ohm');
title('Characteristic Impedence vs Frequency');

figure (2);
plot (f, Zin);
xlabel('Frq in GHz');
ylabel('input Impedence in Ohm');
title('Input Impedence vs Frequency');

figure (3);
plot(f, S11_dB);
%axis([0 10 -3 1.5]);
xlabel('Frqquency in GHz');
ylabel('S11 in dB');
title('S11 vs Frequency plot for Cir waveguide With Open Port 2');
3. MATLAB Code to Plot and Calculated Radiated Power of The Far Field

%Plot the beam from CST ffs file

clear all
close all

% Cell Library for the file names.
data1 = ['cylwaveguide_mode01_f5GHz.ffs'; 'cylwaveguide_mode02_f5GHz.ffs'; 'cylwaveguide_mode03_f5GHz.ffs';
'cylwaveguide_mode04_f5GHz.ffs'; 'cylwaveguide_mode05_f5GHz.ffs'; 'cylwaveguide_mode06_f5GHz.ffs';
'cylwaveguide_mode07_f5GHz.ffs'; 'cylwaveguide_mode08_f5GHz.ffs'; 'cylwaveguide_mode09_f5GHz.ffs';
'cylwaveguide_mode10_f5GHz.ffs'];

data2 = ['cylwaveguide_mode01_f10GHz.ffs'; 'cylwaveguide_mode02_f10GHz.ffs'; 'cylwaveguide_mode03_f10GHz.ffs';
'cylwaveguide_mode04_f10GHz.ffs'; 'cylwaveguide_mode05_f10GHz.ffs'; 'cylwaveguide_mode06_f10GHz.ffs';
'cylwaveguide_mode07_f10GHz.ffs'; 'cylwaveguide_mode08_f10GHz.ffs'; 'cylwaveguide_mode09_f10GHz.ffs';
'cylwaveguide_mode10_f10GHz.ffs'];

celldata = cellstr(data2);

Etheta_cu = zeros (37,73);
Ephi_cu = zeros (37,73);

%Loop to calculate cumulative Etheta and Ephi

for n = [1, 4, 7, 9]
    filename = celldata{n};
    Beam = getEfromCST2014ffs(filename);
    prad = radpwr(Beam);
    %cumulative Etheta and Ephi
    Etheta_cu = Etheta_cu + Beam.Etheta;
    Ephi_cu = Ephi_cu + Beam.Ephi;
end

%Plot of Cross section of the Radiated Power

figure(1)
cntrlevels=[0,-1,-2,-3,-5,-10,-15,-20,-25,-30];
axisvalue=[-90,90,-90,90];
%Subtracting pi from theta since the beam is in the negative z axis
%in CST
theta1 = (Beam.theta - pi).*cos(Beam.phi)*180/pi;
theta2 = (Beam.theta - pi).*sin(Beam.phi)*180/pi;
Powpatt = Etheta_cu.*conj(Etheta_cu) + ...
    Ephi_cu.*conj(Ephi_cu);
Powpatt = 10*log10(Powpatt/max(max(Powpatt)));
[C, h] = contour(theta1, theta2, Powpatt, cntrlevels);
clabel(C,h);
colorbar;
% 3-D Plot of the Radiated Power

figure(2)
% Subtracting pi from theta since the beam is in the negative z axis
% in CST
theta1 = (Beam.theta - pi).*cos(Beam.phi)*180/pi;
theta2 = (Beam.theta - pi).*sin(Beam.phi)*180/pi;
Powpatt = Etheta_cu.*conj(Etheta_cu) + ...
    Ephi_cu.*conj(Ephi_cu);
Powpatt = 10*log10(Powpatt/max(max(Powpatt)));
mesh(theta1, theta2, Powpatt);
caxis([-30,0]);
colorbar;
axisvalue=[[-90,90,-90,90];
axis(axisvalue);
axis square;
view(60,45);

% Reads the Etheta and Ephi components of the fields of M elements
% and put them in a four dimensional array (dipole, freq, theta, phi).
% The input file from CST should be in CST source format output of
% the field pattern and broadband selected in CST.

function ffs = getEfromCST2014ffs(filename)
    collen = 6;
    % Get the beam values from these files
    fid = fopen(filename);
    [radP, accP, stimP, freq] = readheader(fid);

    for fcnt = 1:length(freq)
        A = ' '; %
        while ~strncmp(A, '// >> Total', 11)
            A = fgetl(fid);
        end
        A = fgetl(fid);
        B = strsplit(A);
        phisamp = str2num(B{1});
        thetasamp = str2num(B{2});
        while ~strncmp(A, '// >> Phi,', 10)
            A = fgetl(fid);
        end
        A = fgetl(fid);
        B = strsplit(A);
        phisamp = str2num(B(1));
        thetasamp = str2num(B(2));

        while ~strncmp(A, '// >> Phi.', 10)
            A = fgetl(fid);
        end
        B = fscanf(fid,'%f', [collen, phisamp*thetasamp]);
        B = reshape(B', thetasamp, phisamp, collen);
        phi = B(:,:,1)*pi/180;
        theta = B(:,:,2)*pi/180;
        Etheta(:,:,1) = B(:,:,3) + j*B(:,:,4);  % in V/m
        Ephi(:,:,1) = B(:,:,5) + j*B(:,:,6);
    end
    fclose(fid);
ffs.theta = theta;
ffs.phi = phi;
ffs.freq = freq/1e9; %in GHz.
ffs.Etheta = Etheta;
ffs.Ephi = Ephi;

function [radP, accP, stimP, freq] = readheader(fid)
    A1 = '';
    while ~strncmp(A1, '// #Frequencies', 16)
        A1 = fgetl(fid);
    end
    A1 = fgetl(fid);
    nfreq = str2num(A1);
    while ~strncmp(A1, '// Radiated', 11)
        A1 = fgetl(fid);
    end
    for cnt1 = 1:nfreq
        A1 = fgetl(fid);
        radP(cnt1) = str2num(A1);
        A1 = fgetl(fid);
        accP(cnt1) = str2num(A1);
        A1 = fgetl(fid);
        stimP(cnt1) = str2num(A1);
        A1 = fgetl(fid);
        freq(cnt1) = str2num(A1);
        A1 = fgetl(fid);
    end
end

%Function to calculate the radiated power
function Prad = radpwr(dipole)
    theta = dipole.theta;
    phi = dipole.phi;
    freq = dipole.freq;
    Etheta(:,:,1) = dipole.Etheta(:,:,1); %in V/m
    Ephi(:,:,1) = dipole.Ephi(:,:,1);
    pwr = (abs(Etheta).^2 + abs(Ephi).^2)/(120*pi*2);
    Prad = trapz(theta(:,1), (trapz(phi(1,:), pwr, 2)).*sin(theta(:,1)));
    fprintf('Total Radiated Power from the Beam = %7.4f (W) \n', Prad);
end