Understanding the Propagation of Electromagnetic Waves through General Coaxial Structures using Numerical Simulations

Abstract:

Effective propagation of electromagnetic (EM) waves has a wide variety of applications. Here we study the practical requirements necessary for maximizing the bandwidth of frequencies in general Co-axial waveguide structures and also maintain mode purity. In this regard, well known antenna array design is verified using Numerical Simulations. Further these antenna designs were optimized for efficient coupling. Signal processing methods were also explored to enhance the SNR (signal-to-noise-ratio) and the utility of such EM waveguide systems. Finally, the effect of change in the dimensions of the coaxial waveguide on the transfer of energy through the waveguide is also analyzed using numerical simulations.

1 Introduction:

Waveguides are structures that guide waves such as Electromagnetic or Sound waves. The geometry of these structures allow them to confine the waves within them and thereby the waves propagate along the waveguide with no or minimal loss of energy. This allows waveguides to act as mediums of propagation which can carry information. In the case of waveguides used for carrying electromagnetic waves, the surfaces are made of conductors which completely reflect the incident electromagnetic waves. There are different geometric structures which can function as a waveguide among which the Rectangular Waveguide and Coaxial Waveguide are the most common. A coaxial cable is a commonly observed example for a waveguide. In this paper, we will study the behavior of general coaxial structures when excited with high frequency electromagnetic waves.

On exciting the coaxial waveguide, the geometry of the waveguide results in setting up of various modes of propagation each of which travels at a different speed. This results in temporal distribution of energy. This phenomenon is called Dispersion. In order to avoid this, pure mode excitation of the waveguide is required. Each of these modes of propagation has a characteristic cutoff frequency above which they propagate. Moreover, the value of the cutoff frequency of a mode depends on the geometry of the waveguide. Therefore, to have pure-mode excitation, the cutoff frequency of the first higher order mode that gets excited determines the maximum frequency that can be present in the input signal that is to be transmitted.

In order to increase this bandwidth, an Antenna Array design can be used. Through this design, the bandwidth of the coaxial waveguide can be significantly improved.

The excitation of the coaxial waveguide is done using Antennas or Probes which are fed using coaxial cables. Thus, the coupling of energy between the coaxial feeding cables with the coaxial waveguide system should be optimized to ensure maximum transfer of energy. This can be done by optimizing the geometry of the Antenna. The commonly used Antenna for exciting Waveguides are Monopole antennas which extend radially throughout the Annular space between the conductor surfaces. The dimensions of these antennas were varied to produce the maximum energy transfer. In particular, the length and the radius of the antenna were varied. Also, the effect of a sudden change in the dimensions of the coaxial waveguide on the energy transfer was also analyzed using Numerical Simulations.

In this paper, we investigate how to improve the bandwidth of frequencies that a generic coaxial structure can transport while maintaining mode purity with minimal energy loss. Therefore, we begin with reviewing the Theory of Coaxial Waveguides and studying the parameters that determine the bandwidth of frequency that is supported in section 2. In Section 3, we use Numerical Simulations to verify the Antenna Array design[1]. In section 4, we describe the use of Signal Processing algorithms in improving the Signal-to-Noise Ratio(SNR) of the received signal. Section 5 provides the results of the optimization of the probe geometry in order to maximize the energy transfer.

2 Theory of Coaxial Waveguides:

Coaxial Waveguides are made of two concentric cylindrical surfaces made of a conducting material and are thus characterized by 2 parameters - Inner diameter and Outer diameter (refer Fig 2.1). When excited with high frequency electromagnetic waves like Microwaves, different *modes* of wave propagation set in each of which have a characteristic c*utoff frequency*. The cutoff frequency of a mode is the minimum frequency which must be present in the input signal so that wave propagation occurs in that mode. These modes can be classified into two families – Transverse Electric (TE) and Transverse Magnetic (TM). Apart from these, there is one fundamental mode which is called Transverse Electric and Magnetic (TEM). Waves belonging to Transverse Electric mode family do not have Electric field component in the direction of propagation, while waves belonging to Transverse Magnetic mode family do not have Magnetic field in the direction of propagation. Similarly, the Transverse Electric and Magnetic mode does not have both Electric and Magnetic field in the direction of propagation.

The cutoff frequencies of these different modes depend on the geometry of the coaxial structure. Each of these modes have different *Phase Velocity* and *Group velocity* as shown in fig 2.2. These plots show the *Dispersion Characteristics* of the Coaxial Waveguide. As can be seen from the graph, the modes can be further classified into TE_{p1} modes, TE_{p2} modes, TM_{p2} modes etc… Even though the value of the cutoff frequencies of the different modes change with respect to the geometry coaxial structure, the order in which the modes get excited on increasing the frequency of the input signal remains same. The TEM mode is present at all frequencies while the TE_{p1} modes are the first higher order modes to get excited followed by TM_{02} mode and higher order modes.

In order to obtain pure mode excitation, the input signal must have a bandwidth that is less than the cutoff frequency of the first mode of the TE_{p1} mode family – TE_{11} mode. The cutoff frequency of TE_{11} mode is given by where, is the velocity of light in the medium, is the outer radius and is the inner radius of the coaxial waveguide respectively. Therefore, large coaxial structures can only support bandwidth of a few hundred MHz. In order to extend this bandwidth, an Antenna Array design can be used. The idea is based on the observation that modes belonging to the TE_{p1} mode family are *Axisymmetric* and thus can be suppressed by using two antennas per wavelength placed circumferentially around the structure (refer Fig 2.3). But TM_{02} mode which is the next higher order mode to be excited is *Non-Axisymmetric*. Therefore the cutoff frequency of the TM_{02} mode determines the bandwidth of the signal that can be supported by the waveguide without dispersion. Also, the number of antennas required to suppress all the higher order modes depend on the highest mode of the TE_{p1} mode family that is supported while maintaining a bandwidth less than the cutoff frequency of TM_{02} mode.

The cut-off frequency of the TM_{02} mode is given by . Also, the cutoff frequency of the TE_{p1} mode family is linearly dependent on the cutoff frequency of TE_{11} mode - . Therefore, the highest order of TE_{p1} mode (P) which is supported by the coaxial waveguide for the chosen bandwidth and the corresponding number of antennas (N) required is given by and .

In order to achieve mode purity, the maximum frequency () present in the input signal must be less than the cut-off frequency of TM_{02} mode. On the other hand, the axial resolution of the signal obtained is inversely proportional to the maximum frequency present in the input signal. In fact, the relationship is given by.

Thus, in order to attain mode purity of TEM mode, the higher order modes of the TE_{p1} mode family have to be suppressed by using multiple antennas. The number of antennas required to suppress all the higher order modes supported by the coaxial waveguide for the chosen bandwidth depends on the highest order mode that is supported. This, in turn, depends on the inner and outer radii of the coaxial waveguide. The dimensions of some coaxial structures and the corresponding bandwidth details have been tabulated in Table 1.

Table 1 Dimensions of a few large Coaxial Structures and the corresponding number of probes required.

Diameter of Inner conductor (ID)	Diameter of Outer conductor (OD)	No. of Probes required	Axial Resolution	Bandwidth
200mm	240mm	34	20mm	7.5GHz

	300mm	14	50mm	3GHz
400mm	440mm	68	20mm	7.5GHz

3 Numerical Simulations:

In order to verify the validity of the antenna array design, a 3D numerical simulation software COMSOL Multiphysics (v 4.3a) was used. COMSOL Multiphysics is a Finite Element Analysis (FEA), solver and simulation software package for various physics and engineering approach. For our study, the Frequency Domain solver in the RF Module has been used. Numerical Simulations were also used to optimize the probe design for exciting the coaxial waveguide system in order to transfer the maximum amount of energy into the waveguide. Also, the effect of change in waveguide dimensions on the received signal has also been analyzed.

Numerical Simulations is a very convenient method of verifying a concept and also for optimizing the design of any system. This is mainly due to the flexibility that these software provide for changing the dimensions of the system and analyzing its effects. These software help us to study the system behavior in a quick and at a low cost. But it is important to remember that the results obtained from numerical simulations must be analyzed and used carefully since even unrealistic systems can be simulated using software. Therefore, suitable precautions were taken in order to retain the validity of the results obtained from these simulations and some of them have been listed below.

1. The ratio of the largest to smallest dimensions in a model is inversely proportional to the quality of the mesh generated. Also, choosing a base unit closer to the average dimensions used improves the mesh quality.
2. The number of mesh elements is related to the Simulation time and Memory required. Hence, smaller models should be designed whenever possible.
3. The antenna must be introduced after an axial offset in order to allow for numerical errors to remain small.
4. The coaxial feeding cable must have a reasonable length in order to clearly resolve the reflections received from the defects and the excitation port.
5. These frequency domain simulations assume a hard window for the input pulse which is unrealistic since any real signal will have a finite rise-time. This introduces a significant amount of “noise” in the received signal. Therefore, appropriate post processing must be performed to clean the received signal.

At first, the numerical simulation of a simple TDR system was carried out. In this, a coaxial waveguide of dimensions – Inner conductor radius b and Outer conductor radius and length - was excited using a single monopole antenna obtained by extending the inner conductor of the coaxial feeding cable (refer

Fig 3.1). A perfect short was introduced at the farther end of the waveguide in order to act as a perfect reflector. The annular region of the coaxial cable and waveguide were set as air and the inner and outer conductors were set to Perfect Electrical Conductor (PEC). The annular boundary of the coaxial waveguide closer to the antenna was set to a perfect absorbing boundary condition in order to minimize the number of reflections in the received signal.

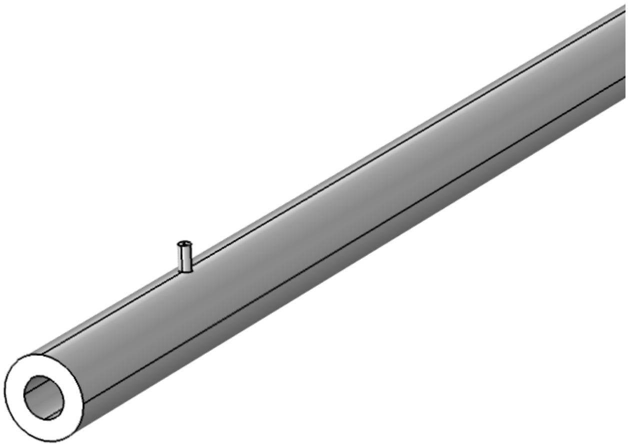


Figure 3.1 Simulation model of a coaxial waveguide structure with inner diameter 10mm and outer diameter 20mm

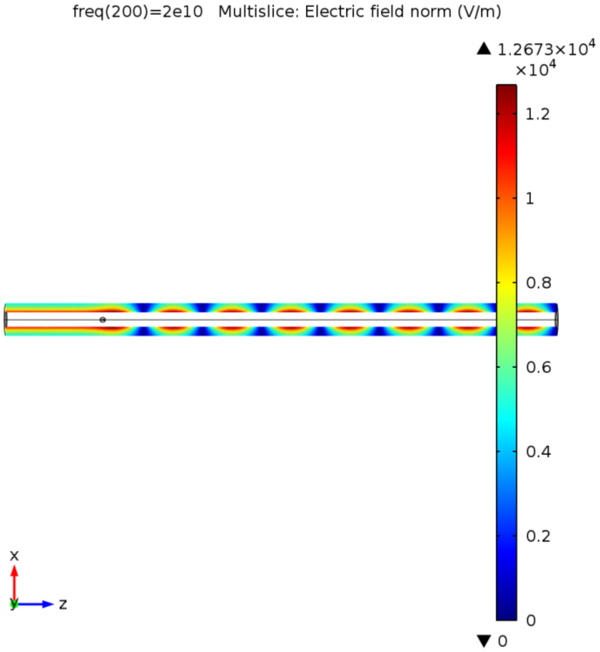


Figure 3.2 Electric field along the y-plane for the coaxial waveguide excited using a single probe

In order to keep things simple, a Physics-controlled mesh of element-size “Finer” was chosen. The frequency range for the simulation was fixed as 0-20 GHz. A frequency domain direct linear solver was used for all the simulations. The results from the simulations were scattering parameters in the frequency domain. This data was analyzed using a script written in GNU Octave (v 3.2.4) which converted the frequency domain scattering parameters to the time domain signals by using Inverse Fast Fourier Transform. The reflection coefficients (or S11 parameters) received by the antenna was converted to a time domain signal to analyze using Time Domain Reflectometry (TDR). The signals from these simulations are plotted against axial distance using TDR analysis (See Fig. 3.3).

Figure 3.3 Signal from Simulation model of a coaxial waveguide with inner and outer conductor radii as 10mm and 20mm respectively when excited by a single monopole antenna. The time domain signal is plotted against the axial distance in this plot.

In order to verify the validity of the Antenna Array approach, a numerical simulation was performed with a much larger coaxial waveguide structure. A simulation model of the coaxial structure was created in COMSOL. The dimensions of the simulation model used were, the radii of the outer and inner conductor of the coaxial waveguide system are given by and respectively. A length of was used for the simulation. Monopole antennas obtained by extending the inner conductor of the coaxial feeding cables were used as antennas. The coaxial cable was modeled as each having an inner radius, and an outer radius, . The inner conductor of the coaxial feeding cable was extended to touch the inner conductor surface and thus extending the full annular distance between the conductors. The annular region of the coaxial cable and waveguide were set to a material of relative permittivity and the inner and outer conductors were set to Perfect Electrical Conductor (PEC). The annular boundary of the coaxial waveguide closer to the antenna array was set to a perfect absorbing boundary condition in order to minimize the number of reflections in the received signal. The annular boundary at the farther side was set to PEC in order to simulate a perfect reflector.

From equations discussed in Section 2, we see that a minimum of 12 probes is required in order to suppress all the higher order modes of TE_{p1} mode family. Therefore, two simulations models were made with the exact same dimensions but with one model having 12 probes while the other model had only 1 probe. This was done to compare the received signals from both these models and verify the effectiveness of the array approach in suppressing the higher order modes. The two simulation models used in this set of numerical simulations are showed in Fig. 2.1 and Fig. 2.2.

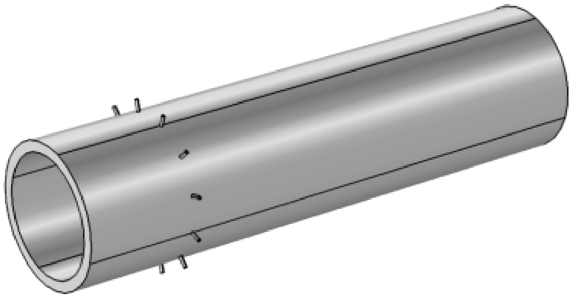


Figure 3.1 Simulation model of a coaxial waveguide having antenna array of 12 monopole antennas uniformly spaced around the circumference

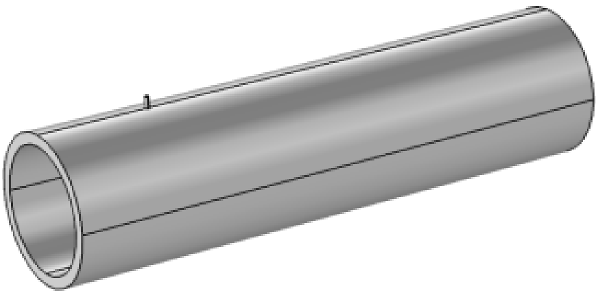


Figure 3.2 Simulation model of a coaxial waveguide having antenna array of 12 monopole antennas uniformly spaced around the circumference

In order to keep things simple, a Physics-controlled mesh of element-size “Finer” was chosen. The frequency range for the simulation was fixed as 0-1.9 GHz. A frequency domain direct linear solver was used for all the simulations.

The results from the simulations were scattering parameters in the frequency domain. This data was analyzed using a script written in GNU Octave (v 3.2.4) which converted the frequency domain scattering parameters to the time domain signals by using Inverse Fast Fourier Transform. The individual reflection coefficients (or S11 parameters) received by the antennas were added algebraically in the frequency domain and this sum was converted to a time domain signal to analyze using Time Domain Reflectometry (TDR). Prior to the transformation, a Hanning window of appropriate window width was applied on the received signal in order to simulate a realistic rise-time for the input pulse. Also, the received signal was zero-padded in order to perform Sinc interpolation as the axial resolution was poor. These two steps proved to be very useful in enhancing the Signal-to-Noise Ratio (SNR) of the received time domain signal.

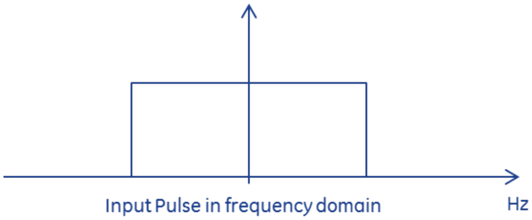
The signals from these simulations are plotted against axial distance using TDR analysis (See Fig. 2.3). The blue line denotes the plot obtained from the simulation model having single probe while the red plot denotes the plot obtained from the simulation model having 12 probes. In both the plots, the first reflection occurs approximately at 0.1m which corresponds to the reflection from the antenna while the second reflection that occurs at approximately 0.5m corresponds to the reflection from the PEC boundary wall condition. Also, in the blue plot, the second reflection is axially spread over a larger distance compared to the red plot. This is attributed to the presence of certain unsuppressed higher order modes which are dispersive. Due to the same fact, the red plot shows a sharper peak and thus has a bigger Signal-to-Noise Ratio (SNR) compared to the blue plot. Another feature to be noticed is the use of 12 circumferentially distributed probes produce a net smaller reflection at the antennas compared to the single probe system.

The results from these simulations clearly verify that the use of an array of probes helps improve the SNR and also allows a higher bandwidth for the input signal.

Figure 2.3 Time Domain Reflectometry signals for a Coaxial Waveguide structure. The peak occurring at 0.1 m corresponds to the reflection from the antennas while the reflection occurring at 0.5 m corresponds to reflection from PEC boundary.

4 Signal Processing

Signal Processing is a powerful method to improve the Signal-to-Noise Ratio (SNR) of a signal. There are various algorithms available but we will be using two simple processing steps to improve the SNR of the signal. In our study, the frequency domain solver numerically solves for the discrete set of given frequencies. This corresponds to an input pulse which is in the shape of a rectangle in the frequency domain. The numerical software imposes a hard transition from 0-1 in the input signal. On the contrary, real signals have a finite rise-time and hence any real signal would be as shown in Fig. 3.2. This unrealistic condition is one of the causes for a poor SNR in the received signal. This “noise”, which is actually an artifact of the unrealistic condition imposed by the numerical software, can be removed by imposing a simple Hanning window. Figure 3.3 and Figure 3.4 demonstrates the effectiveness of employing a Hanning window in improving the SNR of the signal.



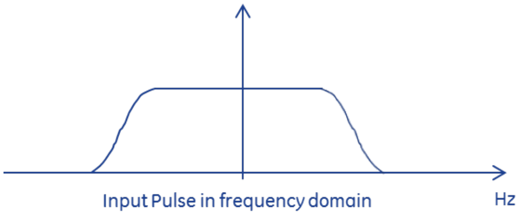
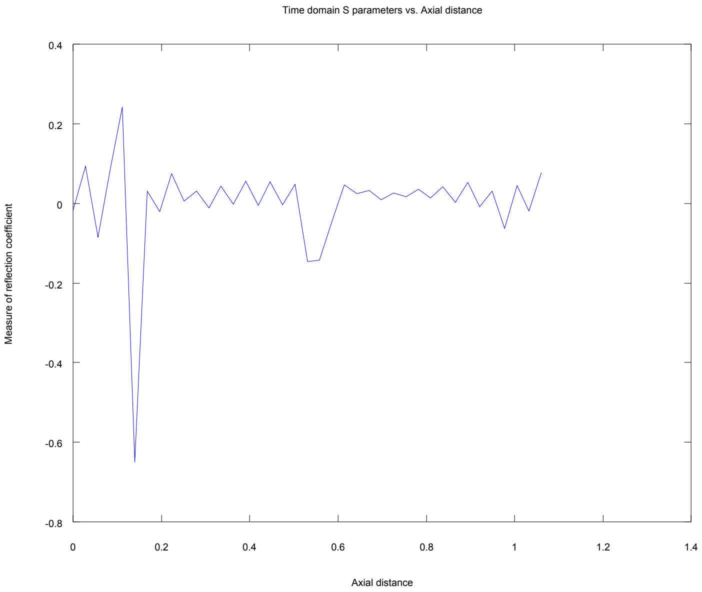


Figure 4.1 Input signals in Frequency domain considered by the numerical simulation software.

Figure 4.2 Input signals in Frequency domain with finite rise time which can be produced in reality.



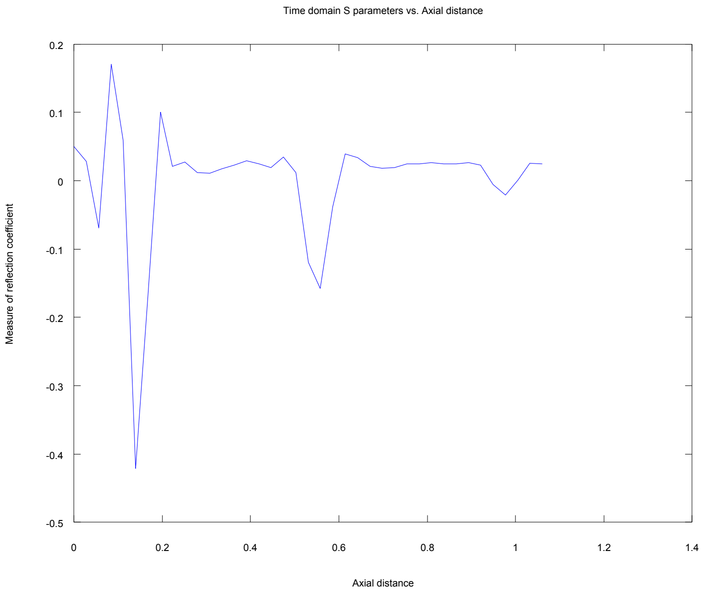


Figure 3.3 Signal from the previous numerical simulation before processing

Figure 3.4 Signal after applying a Hanning window of appropriate window width

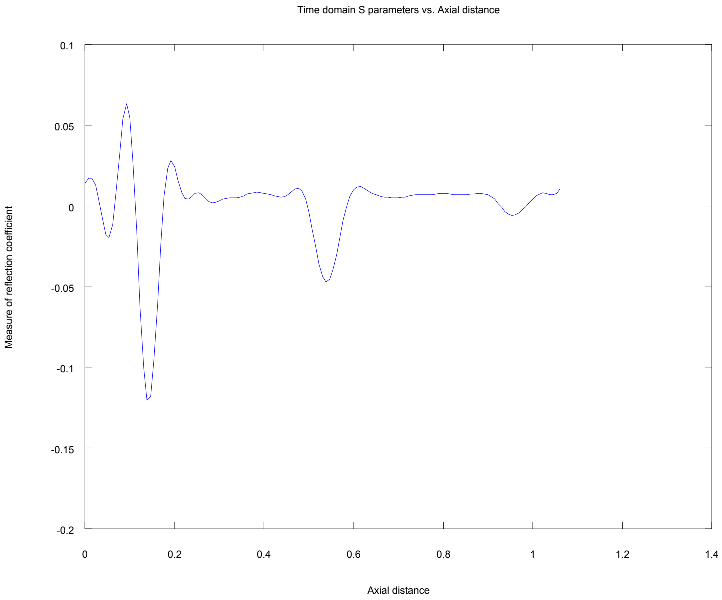


Figure 3.4 Signal after applying a Hanning window of appropriate window width along with Sinc interpolation using Zero

Padding

Also, since the bandwidth used is low, the received signal has a low resolution. Thus, we can employ *Sinc* interpolation of the signal by *zero padding* the signal with required number of higher frequencies. The use of an appropriate window significantly improves the SNR.

5 Probe Optimization

In order to improve the coupling between the coaxial feeding cable and the coaxial waveguide, the radius of the cylindrical probe was varied to obtain the optimal radius of the probe. This optimization was done using Numerical Simulations. The simulation model was created with a small section of the coaxial waveguide of length which was terminated with scattering/absorbing boundary conditions on either side. The dimensions of the coaxial waveguide were: inner radius] and outer radius . The coaxial waveguide was fitted with a single antenna which was fed by a coaxial cable of length, inner radius and outer radius. Also, a radial gap of was left near the outer conductor so that the antenna does not make contact with the outer conductor for large radius of the antenna. Also, the length of the antenna was taken as .

A set of simulations were performed where the radius of the antenna was varied to analyze the effect of radius of cylindrical probe on the amplitude of reflection from the antenna. Three simulations were performed with, and (a large radius). The results of the simulations were analyzed similar to the procedure followed in the previous section. Fig. 5.2 shows the results of the three simulations plotted on a common axis to compare their relative effect. The red plot on the graph which corresponds to a monopole antenna having a radius that is equal to the outer radius of the coaxial feeding cable, suffers the least reflection from the point of excitation. Also, when the radius of the probe is larger than the outer radius of the coaxial cable, an imperfect short is formed since the large radius of the probe brings it in close proximity to the outer conductor of the coaxial waveguide. This imperfect short is seen as a negative peak in the graph whose amplitude increases on increasing the radius of the antenna. Hence, a cylindrical probe with radius equal to the outer radius of the coaxial cable would provide the best coupling among the designs considered in these simulations.

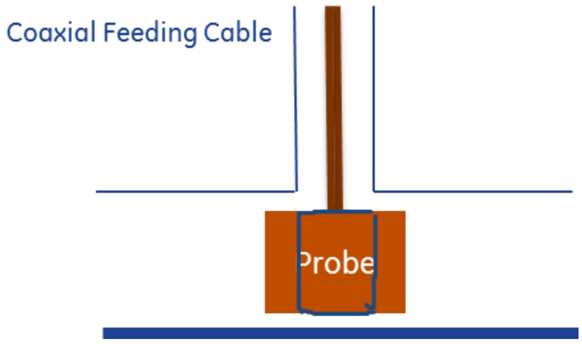


Figure 5.1 Cross-sectional view of the cylindrical probe along with a section of the coaxial waveguide

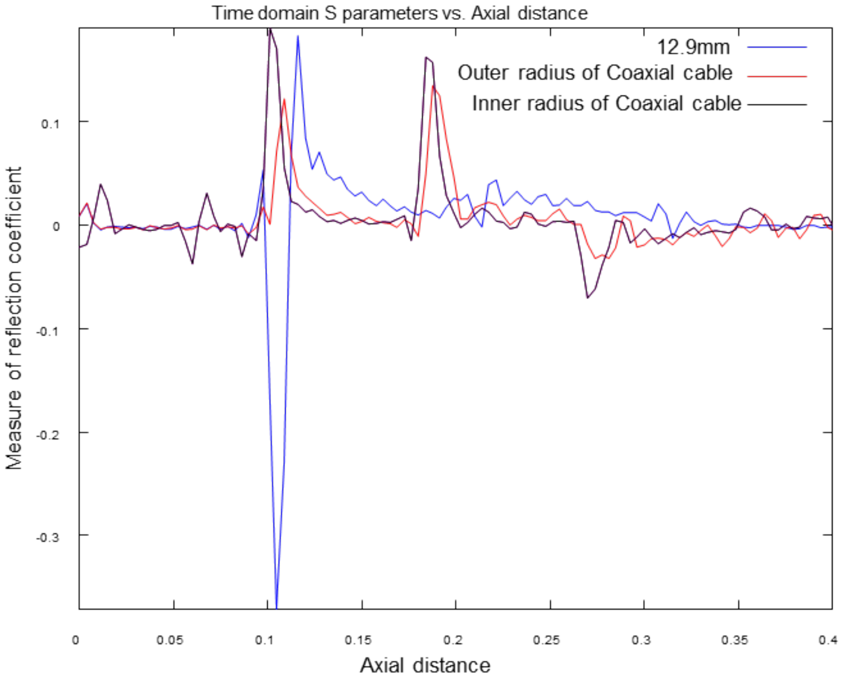


Figure 5.2 Effect of radius on the amplitude of reflection at the antenna for a Monopole antenna.

In the second set of simulations, the radial gap was varied to analyze its effect on the coupling produced. Three simulations were performed with, and . The results of the simulations were analyzed similar to the procedure followed in the previous section. Fig. 5.3 shows the results of the three simulations plotted on a common axis to compare their relative effect. All the three plots have approximately equal coupling. The imperfect short produced due to the increase in radius appears as a negative peak or a truff in the plot. This peak occurs at a farther distance with increase in radial gap, as expected. Hence, varying the radial gap near the outer conductor surface only shifts the position of the negative peak and does not have a significant effect on the coupling obtained.

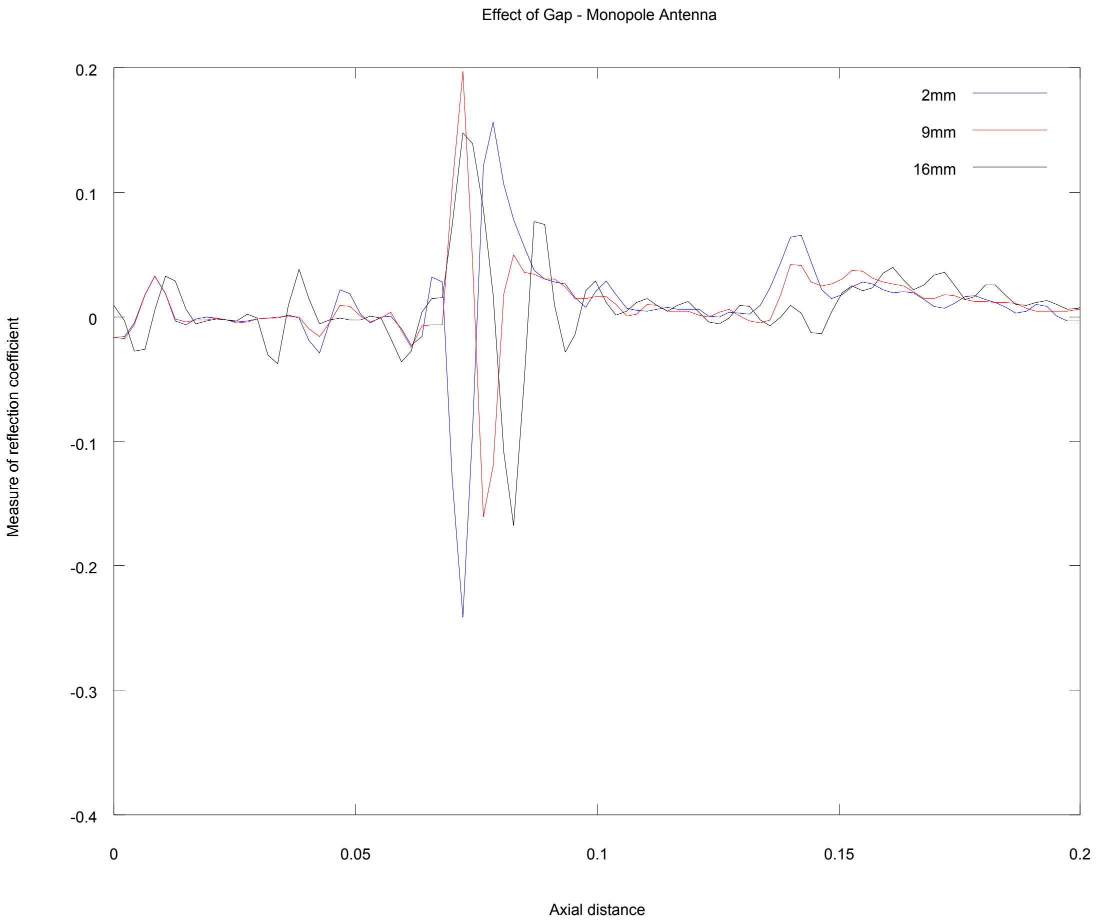


Figure 1 Signal from simulation model analyzing the effect of gap on the received signal

6 Conclusions

Coaxial Structures can act as Waveguides that can be used to carry Electromagnetic waves. In this paper, we studied the practical requirements that are necessary for maximizing the bandwidth of frequencies that a general coaxial structure can support while maintaining mode purity. An Antenna Array design for pure mode excitation of TEM mode was verified using Numerical Simulations performed on COMSOL Multiphysics (v 4.3a). These Antennas used for exciting the coaxial waveguide were optimized in order to transfer the maximum amount of energy from the coaxial feeding cables into the coaxial waveguide. The signals obtained from these numerical simulations were filtered using Signal Processing algorithms like – Windowing and Zero Padding, in order to improve the SNR of the received signal. The effect of change in the dimensions of the coaxial waveguide on the transfer of energy through the waveguide was also analyzed using Numerical Simulations.

References

[1] *Microwave Engineering* 3rd Edition by David M. Pozar, John Wiley Publications.