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# Frequency Response Analysis of the Parallel-plate Transmission Line using Various Conductors

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**ABSTRACT**

Transmission lines are special types of cables that are used to conduct alternating current (AC) voltages with frequencies in the radio wave spectrum. One such wire is the parallel-plate transmission line that is generally utilized for short and long-distance signal transmissions as it exhibits minimum power loss over the channel. Its behavior, as it transfers AC voltages, is described by its frequency response that is dependent on many parameters, relevantly its conductivity and dielectric constant. The paper aims to identify and analyze the frequency response of a parallel-plate transmission line using different kinds of conductor and insulating materials. Through the use of the RF Toolbox, specifically, in the Matlab software, the researchers were able to analyze the parallel-transmission line in the frequency domain with respect to the time domain. They were able to generate plots of its frequency response with respect to an input signal's amplitude and phase shift. The data resulting will give insight into how different materials can interact with the frequency response of the signal passing through in the transmission line.

**Key words:** Parallel-plate transmission line, Frequency Response, Dielectric Constant, Conductivity, Matlab, Simulink.

## 1. INTRODUCTION

A transmission line is a type of wire that is specialized in conducting AC voltages with frequencies around the radio wave and microwave ranges. They can be used to transfer either low- or high-frequency electrical signals between two points with minimal interference as possible. The physical structure of a transmission line can be generally described as two conductors separated by a dielectric material. There exist various types of transmission lines such as the open-wire, twin-lead, microstrip, coaxial cable, and the parallel plate configuration which differ from each based on the orientation of the conductors and insulator. Relevantly, the parallel-plate transmission line, also known as the parallel-plate waveguide, is a planar transmission line with geometry similar to that of the microstrip line. It consists of two outer parallel conductors separated by a dielectric material. Common applications of said transmission line include transmission line transformers used to transform high-voltage short duration pulses [1]. The transmission line's geometry is also frequently applied in other disciplines [2].
The behavior of a transmission line depends on many parameters such as its relative permittivity, dielectric thickness, conductor conductivity, length, and the likes. In real-world applications, external components also have a considerable impact on their performance [3]. In this paper, the researchers strive to analyze the effects of various conductor conductivities on the frequency response of parallel-plate transmission lines. The study aims to identify the amplitude and phase differences introduced by gold, copper, and silver conductors. A thorough analysis of conductor modifications in the parallel-plate waveguide can expand the material selection in transmission line design applications. Consequently, this research can bring about improvements and better cost-efficiency in radio and microwave systems.

Over the past decades, various studies have been implemented that concern material modification in the parallel-plate transmission line [4, 5, 6, 7, 8, 9, 10]. This paper differs from said studies such that the researchers are exclusively tackling the impacts of the outer conductor material on the frequency response of the aforementioned transmission line. Also, the research takes on a theoretical approach that only concerns the waveguide itself; external components and phenomena are not considered. To do this, the researchers will emulate the parallel-plate transmission line using the RF Toolbox in Matlab.

## 2. BACKGROUND OF THE STUDY

Transmission line conductors can vary from a range of materials to alloys and composite materials. With this, it is important to note the several factors that are to be considered when implementing a transmission line design. Since most early transmission lines are overhead transmission lines, typically those seen hanging from pole to pole will have its own unique set of factors compared to those modern underground transmission lines. An overhead transmission line should be able to consider factors such as transmission line sag and exposure to different environments which can cause erosion of the cable. An underground transmission line will have to factor in perpendicular line strength and as well as corrosion from different sources. A typical conductor of both types of transmission lines will include Aluminum Conductor Steel-Reinforced (ACSR) cables that are resistant to most factors mentioned as discussed in C.H. Jensen, R.E. Demuth, and R.W. Mowery's work [11]. These ACSR lines are used due to their strength and cost as described by N. Murray, F. Besnard, D. B. McGuire, and K. J. Scissum [12]. Although the transmission lines mentioned beforehand had mostly been used for long-range radio and AC distribution, smaller and more frequency optimized transmission lines are used for precision circuits that rely on relatively high frequencies. More specific applications of these parallel-plate transmission lines are for the cross-communication between electronic components, such can be seen in the works of H. Guckel, P. A. Brennan, and I. Palocz [13] and G. A. Melkov and Yu. V. Egorov [14]. A typical transmission line will factor in the economic costs of the conductor and length to strength characteristics of the conductor. However, a parallel plate transmission line in minuscule applications will only slightly be affected by these factors as they are cost-efficient [15]. With this, the scope of the study will only focus on specific characteristics of the conductor materials in parallel plate transmission lines. The paper will only focus on the frequency response and phase shift when a different conductor material will be used for the parallel plate transmission line. With these data, the researchers will be able to discern which material will be suited for high-frequency transmission. The materials of the conductor to be included in this study consists of copper, silver, and gold.

## 3. STATEMENT OF THE PROBLEM

Power losses are among the complications that hinder the performance of a microwave communication system along with noise. Even though it is negligible within short distances, transmission lines that span over a thousand kilometers impose amplitude and phase attenuations on the transmitted signal. Depending on the frequency of the signal, some decibels (dB) of power are lost per length of the wire. This results in the loss of information between the sender and the receiver within the system. Although signal repeaters can be used, such components can be quite costly and do not address the problem of reducing attenuation.

As such, this paper aims to explore alternative conductor materials that can be integrated within transmission lines. Particularly, the frequency response of conductors made of silver and gold will be compared with that of copper. The researchers will implement a quantitative analysis to compare the efficiency of and power losses introduced by each material.

## 4. SIGNIFICANCE OF THE STUDIES

Parallel-plate transmission lines are versatile components inside an electronic board. The size in comparison to the efficiency of the design will give ample applications in modern electronics with examples such as antennas or pulse generators that are highly efficient [16,17,18]. Furthermore, this study will aim to provide adequate evidence that suggests the proper conductor material for optimal frequency response to yield better efficiency. Specifically, the study will be analyzing the different frequency responses of conductor materials used in parallel plate transmission lines. Using materials that garner a higher conductivity than gold, the researchers will be providing the results for copper, gold, and silver. The following materials will be made into a parallel-plate transmission line and simulated using MATLAB. Analysis of the results will mostly be extracted from the study's amplitude and phase angle plot with respect to a certain frequency range. With this, the optimal conductor to be used will be deduced.

## 5. DESCRIPTION OF THE SYSTEM

To evaluate the frequency response of the given conductor materials the researchers first need to get the specific parameters of each conductor. This study will mainly be requiring the conductivity of each conductor, this can be seen in Figure 5.1 where a table is provided with the conductivity of each material. Table 1 shows the Resistivity and Conductivity of the system.

**Table 1:**Table of Resistivity and Conductivity

| Material | Ohm (Ω.m) at 20 °C Resistivity | Sigma (S/m) at 20 °C Conductivity |
|---|---|---|
| Silver | $1.59 \times 10^{-8}$ | $6.30 \times 10^{7}$ |
| Copper | $1.68 \times 10^{-8}$ | $5.96 \times 10^{7}$ |
| Annealed copper | $1.72 \times 10^{-8}$ | $5.80 \times 10^{7}$ |
| Gold | $2.44 \times 10^{-8}$ | $4.10 \times 10^{7}$ |
| Aluminum | $2.82 \times 10^{-8}$ | $3.5 \times 10^{7}$ |
| Calcium | $3.36 \times 10^{-8}$ | $2.98 \times 10^{7}$ |
| Tungsten | $5.60 \times 10^{-8}$ | $1.79 \times 10^{7}$ |
| Zinc | $5.90 \times 10^{-8}$ | $1.69 \times 10^{7}$ |

The parallel-plate transmission line parameters are given below:

Length = 0.2 m
Width = 0.1 m
Thickness = 1 mm
Relative Permittivity = 2.3
(Benzene)
Relative Permeability = 1
Noise Figure = 0
Zs = ZL = Zo = 50 Ω

The values presented are mostly defaults set by MATLAB. However, the research will only focus on these values. The parallel-plate transmission line parameters significantly affect the output data but since we are only comparing the frequency response of each conductor and not the design of the parallel-plate transmission line, only one set of parameters is adequate in extracting the main data of the study.

## 6. METHODOLOGY

The flow of the study is based on Figure 6.1. The first step is to initialize the code, this is where the researchers declare necessary variables such as bandwidth and parallel-plate transmission line parameters. The researchers then retrieve the S parameter using rfckt.parallelplate(), analyze(), and then extract() to finally get the S-parameter of the given conductor. This is placed inside a for loop to calculate all the s parameters. It is also important to note that the S-parameters are tested and calculated between frequencies of 1 to 3 GHz. The transfer function and rational function is then computed, this will be the basis for the fitted and computed data. Lastly, we plot the s parameters using both the rational and transfer function to the frequency. Figure 1 shows the experiment flow chart.

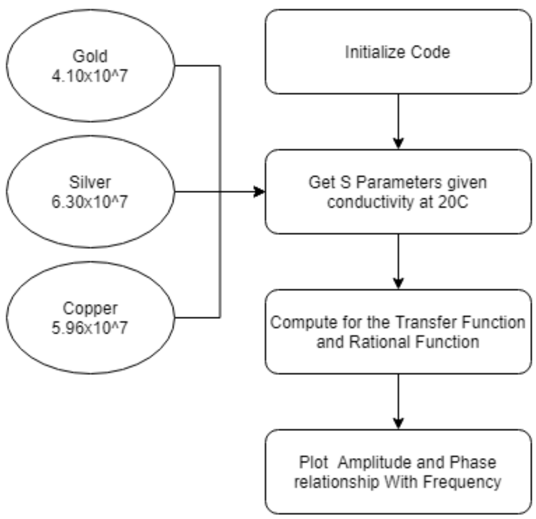


**Figure 1:**Experiment Flow Chart

## 7. REVIEW OF RELATED LITERATURE

The paper of Shimizu, N., Omote, T., Ito, H., and Watabe, M. [19] talks about the problem of Japan and its transmission line conductor erosion in coastal areas when using ACSR or aluminum conductor steel reinforced cables in transmission lines. Usually, this corrosion happens inside the transmission line cables and they call this an inner corrosion wherein it is difficult to detect the exact location of the corrosion. To determine the deterioration of the conductor, the paper uses a formula that includes the salinity and humidity of the area. It suggests that the aluminum-clad be highly resistant to corrosion and suggest the addition of manganese to improve its life span. This paper gives an idea of how a conductor should be erosion-resistant, especially in tropical areas with high humidity such as the Philippines.

The paper of A. Kato et al. [20] mentions the generality of transmission line corrosion near rivers or bodies of water. The paper involves using an alternative conductor to solve the long span transmission line corrosion in these areas. This problem is usually solved with the same concept, develop a special transmission line for these areas. Then the paper states that a new conductor that has high corrosion protection is developed together with higher conductivity. This paper indicates the use of better alternatives to aluminum transmission lines as they are easily corroded in humid areas.

With prolonged high currents of transmission lines develops high tension areas in the span of the length of the transmission lines. With this, the paper of Ahmad, Y. Jin, C. Zhu, I. Javed, and M. Waqar Akram [21] aims to pinpoint the location of such high-tension zones using an analysis of these high current areas. The tension of the overhead transmission line caused by the high current was calculated using the finite element method. The paper gives an insight into how transmission lines should have proper current flow and as such, a material with good current properties will yield to a longer-lasting transmission line.

A study on a balun transmission line by C. Liu, Z. Yin, Y. Yang and W. Huang [22] discussed the advantages of using a balun compared to a regular microstrip transmission line. Their results yield excellent amplitude and phase balance and as well as a significant size reduction wherein it is 10% the size of a standard microstrip transmission line. This half-wave balun operates at 900 MHz and features a low impedance. Even though it is stated that the research paper will include a parallel plate transmission line, this study can give insight into how an efficient balun can be created using the study's design.

This paper by Xiang Zhou, Haibao Mu, Jianlin Wei, Jian He, and Guanjun Zhang [23] discusses the different effects of galloping transmission lines to the power and current abilities of the signal. This galloping, although only occurring in places with low temperatures, can highly damage transmission lines and provide risks to bystanders. With this, the paper introduces a draw-line sensor that monitors the galloping of transmission lines in order to properly maintain it. It is apparent that in the Philippines it can be quite an improbable scenario to have a temperature near that of the winter but it should be noted that transmission lines are a global utility. The paper gives an idea of how galloping can introduce difficulties in the propagation of the signal and why it is recommended to develop a conductor capable of withstanding these effects.

The study of S.-W. Kim, K. Kim, W. Nah, C.-R. Lee, S.-B. Jung, and J.-W. Kim [24] utilizes a percolated network of silver nanowires (AgNW) as a transmission line conductor. The study succeeds by providing a strong and flexible wire that is also transparent. The line can propagate relatively high frequencies of up to 8GHz and is mechanically stable due to its composition. Shown in the study, as the film thickness increases, the electrical losses of the system decreases. With this, the study suggests that the paper will serve as a guideline for fabricating silver transmission lines.

The study of K. Qiao, A. Zhu, B. Wang, C. Di, J. Yu, B. Zhu [25] provides a comparison of alloy wire composite material core conductor (ACCC/HW) to the standard aluminum conductor steel reinforced (ACSR) overhead transmission lines. The lines were subjected to different tests such as high current capabilities, heat relation to sagging, and tensile strength tests. Results show the additional capacity of the ACCC/HW in higher temperatures compared to ACSR and mechanical behavior. The study concludes that ACCC/HW is better at higher temperatures than ASCR but care should be taken in its construction to ensure quality.

The study by S. Z. Sajal and B. D. Braaten [26] discusses the comparison of a graphene-based conductor to copper and aluminum. The paper involves a bend test to determine the number of times it takes to bend and destroy a conductor. This is prevalent in today's electronic cables wherein the cables are constantly stressed from bending and stretching. To find a stronger alternative conductor to protect wiring, the study tests the capabilities of a 97% carbon conductor. It concluded that the graphene-based conductor was 10x stronger than that of a copper cable and 13x stronger than that of the aluminum conductor. With this insight, it can be stated that a graphene-based conductor is a great alternative to copper and aluminum transmission line as it provides similar current and voltage capabilities while giving maximum tensile strength.

In the research of Nguyen, D. Oates, J. Oates, Shin, and Tsuk [27], a nonlinear transmission line was modeled using NbN and YBa2Cu3O7-x thin films. The authors aimed to explain the nonlinear frequency response of such materials when subjected to high levels of the input power of the stripline resonator. Resonators with high Q factors were affirmed to exhibit nonlinear inductance and resistances that are odd functions of the transmission line current. Results show that the transmission lines exhibit hysteresis at input power levels of -6 dBm which is due to nonlinear inductance. For both NbN and YBCO resonators, this effect was said to be suppressed through the nonlinearity in the resistance. For the latter, however, hysteresis was less prominent since the inherent material's resistance is sufficient enough to counteract the inductance. With regards to this paper, the researchers are assured that a change in the conductivity and permittivity of transmission lines results in different frequency responses. At high input powers, there exists a possibility that related graphs will exhibit nonlinear trends such as in the paper.

The paper of Follonier, Knoesen, Miller, and Song [28], proposes an alternative method of determining thin-film dielectric properties at microwave frequencies. The authors suggested the use of parallel-plate transmission line geometry as a waveguide structure to concentrate electric fields in the dielectric thin film. Using calibration techniques and multiline thru-line-reflect (TRL) calibration algorithm, they determined the propagation constant and used it to determine dielectric constants. Results show greater sensitivity to thin-film dielectric properties when compared to other testing structures such as the coplanar waveguide and microstrip transmission lines. This paper proves vital in the researchers' interests as it tackles the behavior of the electric field generated by an unconventional parallel-plate transmission line structure. This paper goes to show that such transmission lines will exhibit different characteristics and, ultimately, frequency responses at distinct configurations.

The investigation of Jaitly, Ramrus, and Strickland [29] assessed the dielectric constants, losses at high frequencies, and pulsed high breakdown voltage strength of fluid impregnated films. To test this, the authors created a parallel-plate transmission line that consisted of two copper wires separated by such a film. They aimed to maximize the energy density of pulse lines by reducing their size and weight through various fluid and laminations. The results of their investigation show that plastic films containing polyvinylidene fluoride (PVDF) exhibit a significant increase in the rise time of the transmission line. On the other hand, impregnated films consisting of mylar and polypropylene showed no notable changes. The result of this investigation is important to the researchers since it confirms that there are significant changes in the frequency response of a transmission line with some dielectric materials. Since there was a change in the rise time of the PVDF, the researchers can expect different outcomes in terms of frequency as they change the permittivity of the parallel-plate transmission line.

In the research of Ali, Lam, Oates, and Sheen [30], the nonlinearity of superconducting strip transmission lines was determined using the Ginzburg-Landau (GL) theory. The authors considered two situations wherein an infinite parallel-plate transmission line was first considered to solve for one-dimensional GL equations, followed by two-dimensions using strip lines. Using such methodology, they were able to compute for nonlinear inductance and the shift of the resonant frequency for components consisting of NbN and YBa2Cu3O7-x. The results of their work show that with large input currents, there was underestimation and overestimation in the magnetic field penetration edge enhancement of the current density, respectively, in the superconducting parallel plates and strip lines. Nevertheless, the GL theory was affirmed to have good agreement with reference values and was a valid model. The results of this research provide a firm insight into the frequency response of a superconducting transmission line. Specifically, they can expect that at very high conductivities, there would be a shift in the resonant frequency.

The paper of Brussard, Pemen, Vermeulen, and Voeten [1] proposes the application of parallel-plate transmission lines in transmission line transformers (TLT). They aimed to increase its voltage gain by limiting the losses caused by secondary mode and reflections. In comparison to coaxial cables, the geometry of the parallel-plate transmission line was deemed suitable for their cause due to its relatively better gain and lower losses. With this, the authors analyzed and designed 4- and 8-line parallel-plate TLT (PPTLT) to determine their voltage amplification. Consequently, results show that their setup achieved near-ideal values; the voltage gains are equal to the number of parallel-plate transmission lines in the PPTLT. This paper is relevant to the researchers since it tackles the geometric orientation of such a transmission line. It sufficiently discusses inherent parameters such as the breakdown voltage, flashover, and frequency response which is relevant to the researcher's transmission line design.

## 8. THEORETICAL CONSIDERATIONS

Using Matlab, the S-parameters and transfer functions of the transmission line models were obtained using the rfckt.parallelplate() command with its ABCD parameters as a basis. To identify the ABCD parameters, the resistance R, inductance L, conductance G, and capacitance C per meter of the transmission line were first calculated using Equation 8.1. σcond represents the conductor conductivity; w is the plate width; d is the plate separation; μ is the dielectric permeability; ε is the dielectric permittivity; δcond is the skin depth of the conductor; ε″ is the imaginary part of ε; ε0 is the permittivity of free space; εr is the relative permittivity of the dielectric, and tan δ is the tangent of the loss angle of the dielectric.

## 9. DATA AND RESULTS

Figures 2 and 3 illustrates the amplitude attenuations of the transmission line of various outer conductors versus frequency. The frequency response was evaluated from 1 to 3 GHz and power loss was expressed in dB.

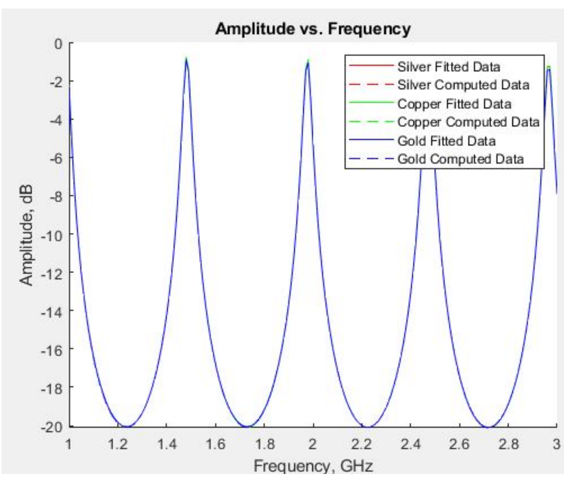


**Figure 2:** Computed and Fitted Amplitude vs. Frequency

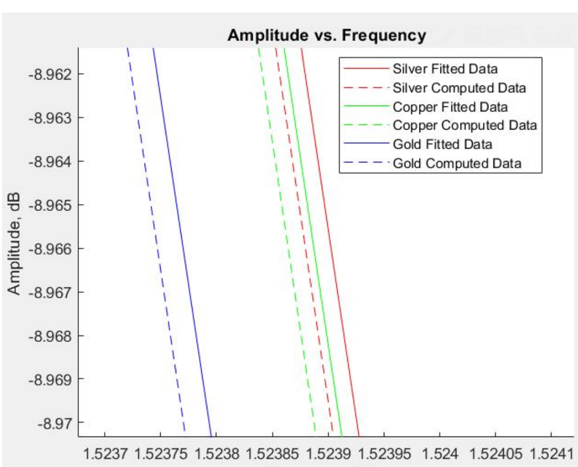


**Figure 3:** Amplitude Attenuation Distinctions

Figure 4, 5, and 6 shows the phase angle attenuations of the transmission line of different outer conductors to frequency. Just like in the previous figures, the frequency response was evaluated from 1 to 3 GHz and the phase attenuation was expressed in radians.

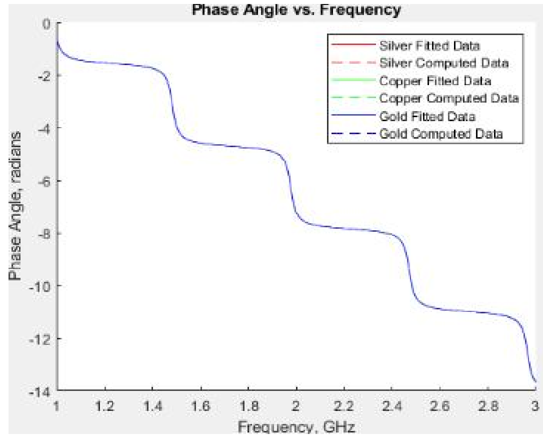


**Figure 4:**Computed and Fitted Phase Angle vs. Frequency

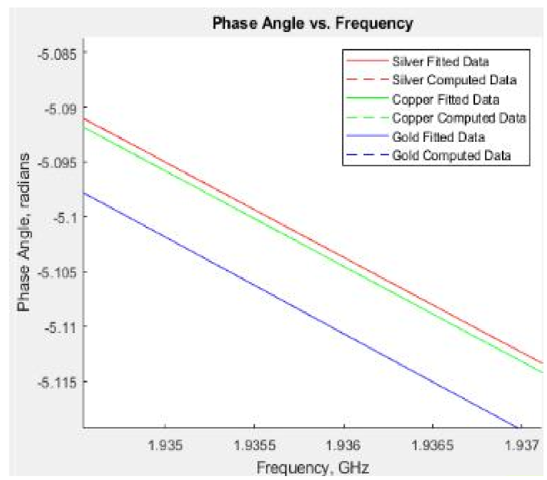


**Figure 5:** Phase Angle Distinctions

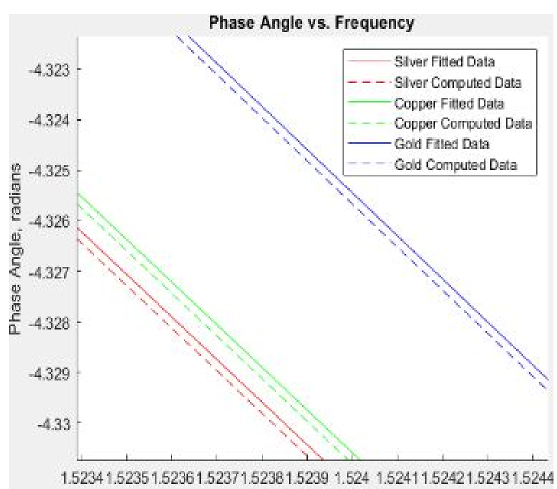


**Figure 6:**Phase Angle Distinctions

## 10. ANALYSIS OF DATA

In Figure 9.1, it can be observed that the frequency response of a parallel-plate transmission line is non-linear with gold, silver, and copper outer conductors. The graph closely exhibits a sinusoidal behavior such that the amplitude attenuations peak and drop at set intervals of frequency. Within the testing range of 1 to 3 GHz, amplitude attenuation approximately peaks at frequencies of 1.23 GHz, 1.73 GHz, 2.22 GHz, and 2.72 GHz with values of -20.0795 dB, -20.0836 dB, -20.085 dB, and -20.0882 dB respectively. On the other hand, the frequency response drops at frequencies roughly around 1.48 GHz, 1.98 GHz, 2.47 GHz, and 2.97 GHz with amplitudes of -0.9021 dB, -1.0691 dB, -1.0391 dB, and -1.2356 dB respectively. In the same figure, it also becomes apparent that a change in the conductor material contributes inconsequential changes in the amplitude attenuation of a transmission line. This is supported by the fact that a 1.5239 kHz transmitted signal introduces a power loss of -8.992 dB for a gold conductor, -8.972 dB for copper, and -8.969 dB for silver. With copper as a reference, there is less than 0.002% percentage change for gold and 0.0003% for silver. As for figure 9.2, it can be discerned that there are negligible differences between the fitted and computed values for amplitude attenuation. Although minuscule, gold induces the highest power loss while silver effects the least.

In Figure 9.3, the researchers plotted the phase to the frequency response of the parallel-plate transmission line. With the parallel-plate transmission line parameters given in Part 5of the study, the output plot shows a distinct phase difference between 1.4-1.5GHz and 1.9-2.0GHz, this means that a sudden change in frequency inside these ranges can result in significant phase changes. Placing the frequency between ~1-1.45 GHz and ~1.45-1.95GHz will yield the smallest phase change. Furthermore, to see the differences in the phase to frequency plot in each of the conductors, Figure 9.4 and 9.5 shows the zoomed-in version of each phase to frequency plots in different locations. Figure 9.4 shows the phases versus frequency plot from 1.9345GHz to 1.9375GHz. It shows that in terms of the phase, the silver conductor shows the highest value followed by copper and gold. Figure 9.5 shows the phase difference in the frequency of 1.5234GHz to 1.5244GHz. Gold was recorded to have the highest phase angle followed by copper and silver. With this, we can state that certain frequencies can yield a varied result in both silver and gold being interchanged as the most and least difference in phase.

## 11. CONCLUSION

A simulation-based algorithm was developed to find appropriate substitutes for the outer conductors of parallel-plate transmission lines to reduce power loss. The amount of amplitude and phase attenuation induced by the materials was evaluated in comparison to that of a copper conductor. Along with copper, the frequency response of a transmission line with gold and silver outer conductors were particularly analyzed. It is of note, however, that the economic practicalities of materials were not assessed. The methodology implemented in the research utilized the RF toolbox of the Matlab software. A transmission line model was generated with a length, width, thickness, relative permittivity, relative permeability, and noise figure of 0.2 m, 0.1 m, 1 mm, 2.3, 1, and 0 respectively. With the transmission line's ABCD parameters as a basis, the transfer functions for each material were computed within the frequency range of 1 to 3 GHz. Rational fitted values of the transfer function were also considered to, to some extent, emulate real-world values. From these values, the amplitude and phase attenuation for gold, silver, and copper were graphed with respect to frequency. Results show that the power loss introduced by said conductors in a parallel-plate transmission line is non-linear. The frequency response exhibits a sinusoidal behavior wherein attenuation peaks and drops occur at set intervals of frequency. Notably, changes in the material of the conductor contribute negligible changes in the amplitude attenuation of the transmission line. With an input frequency of 1.5239 GHz, the percentage changes between gold and silver to copper were 0.002% and 0.0003% respectively. Even still, gold was found to induce the highest power loss while silver was the least. The phase to frequency results gave varying results within where the slopes exponentially change. For when the slope exponentially decreases, silver gives the highest phase difference. When the slope increases exponentially, gold is the conductor with the highest phase difference. With this, it is conclusive that choosing the right conductor will be dependent on the frequency of use.

## 12. RECOMMENDATIONS

In the future, the researchers suggest that the following are looked at: The parameters of the parallel-plate transmission lines are variables to be considered when choosing a conductor, this means that it would give better insight as to what conductor will fit best to a certain transmission line design. The researchers also believe that using more conductors in the study will give more perspective as to what conductivity means in the frequency response analysis in parallel-plate transmission lines. This is because, in the phase to frequency plot, gold and silver were found to have different results when the frequency is shifted, at one point gold had a higher phase angle while in another frequency silver had a higher phase angle. It would also give a better sample size to determine the exact effects of conductivity on the frequency response. It can also be recommended that the researchers explore more types of transmission lines as the results can be different for another type of transmission line. Power lines can also be analyzed but considering the number of wires to be needed in a city power line, the cost to efficiency ratio of the conductors will be heavily in question. This is because gold and silver are significantly more expensive than copper and aluminum. The researchers also believe that varying the dielectric material of the parallel-plate transmission line will also yield interesting results as to just assuming that the dielectric is benzene. The relative permittivity of the parallel-plate transmission line dielectric material can affect the actual frequency response of the transmission line. Lastly, the researchers suggest varying the frequency range used in the study to better approximate the bandwidths of each material. This is because the study only used 1GHz to 3GHz to analyze the frequency response and give more insight as to how the transmission line responds to other frequencies.

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