A CAD Tool for Design and Analysis of Non-uniform Transmission Lines

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Abstract—Transmission line Impedance Tapers are critical components in signal transmission systems, aiding in impedance matching and minimizing signal reflections. Accurate simulations are essential for analyzing the electrical performance of these tapers. This work presents a CAD tool developed using Python, enabling the simulation of different transmission line tapers using analytical and numerical methods. The CAD tool provides engineers and researchers with an intuitive graphical interface to visualize and analyze the behavior of transmission line tapers effectively.

Index Terms—Impedance Taper, Non-Uniform Transmission Line, Sigmoid

INTRODUCTION

Impedance taper or nonuniform transmission line (NTL) is a critical component in microwave engineering, used for matching and transforming the impedance of transmission lines and components. These tapers play a crucial role in various applications, such as RF and microwave systems, by ensuring efficient signal propagation and minimizing signal reflections. A CAD tool is developed using the Python Tkinter GUI module, which facilitates the simulation and analysis of transmission line tapers.

Impedance taper or nonuniform transmission line (NTL) has been extensively studied and applied in various microwave applications since the 1950s [1]- [2]. Various attempts have been made for efficient analysis of NTLs [3], [4].

However, there needs to be a tool/ software available to ease the problem. This motivates the authors to develop a software tool to facilitate the design and analysis of nonuniform taper lines. The software will comprehensively review past and recent developments in impedance taper design, analysis, and optimization, including different types of tapers and techniques. The proposed CAD tool will be a valuable resource for researchers, engineers, and students working in microwave engineering. The CAD tool is freely available at https://zenodo.org/records/12164713 under Creative Commons License 4.0.

I. ANALYTICAL METHOD:

We can analyze different types of impedance tapers with the help of Telegraphers' Equation. Unlike the uniform transmission line (UTL), the characteristic impedance of the nonuniform transmission line (NTL) is not constant over the lengths [5]. Now applying Telegraper's Equation,

$$\frac{\partial V}{\partial x} = -j\omega L(x) I(x) \quad \text{and} \quad \frac{\partial I}{\partial x} = -j\omega C(x) V(x) \quad (1)$$
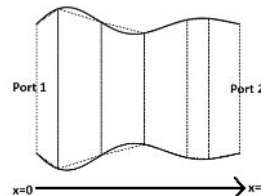

Fig. 1. Approx. using Linear Non-uniform Transmission Line

The first-order equations (1) can be converted to second-order equations as

$$\frac{d^2 V(x)}{dx^2} - \frac{f'(x)}{f(x)}\frac{dV(x)}{dx} + \beta_0^2 V(x) = 0 \quad (2a)$$

$$\frac{d^2 I(x)}{dx^2} + \frac{f'(x)}{f(x)}\frac{dI(x)}{dx} + \beta_0^2 I(x) = 0, \quad (2b)$$

where $\beta_0 = \frac{\omega}{v_p}$ is propagation coefficient, v_p is the phase velocity, and $Z_c(x) = f(x)$ is the characteristic impedance.

If the differential equation (2) is analytically solvable, then we solve it to get Voltage and Current Expression as a function of x. Then, we can get the ABCD parameters from the voltage and current equations. If these equations (2) are not analytically solvable, then we go for a numerical approach to get the ABCD parameters. From that, by using (3) we can get the s parameters.

$$S_{11} = \frac{AZ_{02} + B - CZ_{02}Z_{01} - DZ_{01}}{AZ_{02} + B + CZ_{02}Z_{01} + DZ_{01}} \quad (3a)$$

$$S_{21} = \frac{2\sqrt{Z_{01}Z_{02}}}{AZ_{02} + B + CZ_{02}Z_{01} + DZ_{01}} \quad (3b)$$

II. NUMERICAL METHOD

One can approximate the actual nonuniform line as cascade connections of small UTLs. A smaller length of UTL is better for the approximation. One better approximation is considering NTL as cascade connections of linear sections (LTL)(as in Fig. 1). In this, multiple sections of tapers of small width are taken and approximated with the LTL [3]. Then, for each such section, we used the LTL model to find the ABCD parameters. For the ABCD parameter of the whole taper, we just used

$$[ABCD]_{Total} = \prod_{i=1}^{n} [ABCD]_i$$

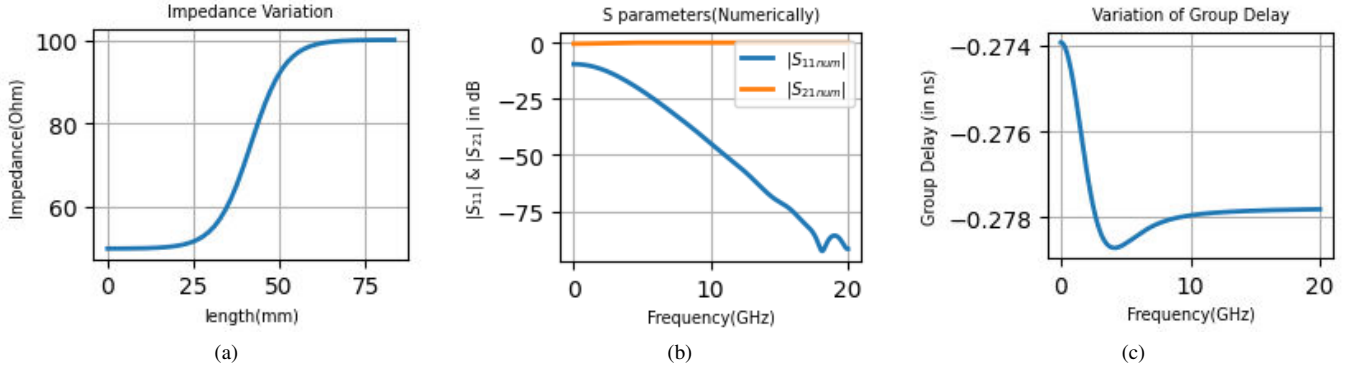The s-parameters are calculated from ABCD parameters using (3).

Fig. 2. Results of Logistic Taper (a) Impedance Variation, (b) S-parameter variation, and (c) Group Delay Variation

III. COMPUTER AIDED DESIGN SOFTWARE

Using this tool [6], one can analyze impedance tapers like-Linear, Parabolic, Exponential, etc. Also, numerical analysis is implemented for tapers like Sigmoid taper, Lifted Cosine taper [7], and Triangular Taperetc. Multiple Sigmoid functions include logistic taper, inverse tan, hyperbolic tan, and Error function. This CAD tool can also help in time domain analysis.

For example, the results of the Logistic Taper analysis are given. The impedance profile of Logistic Taper is given as [8]

$$Z_c(x) = Z_1 - \frac{a}{(1 + e^{gL/2})} + \frac{a}{(1 + e^{g(L/2-x)})} \qquad 0 \le x \le L$$

$$a = (Z_2 - Z_1)\frac{(1 + e^{gL/2})(1 + e^{-gL/2})}{(e^{gL/2} - e^{-gL/2})},$$

where $g < 1$ is a factor for different slopes at the midpoint.

In Fig. 2a, variation of impedance through a length of $L = 85$ mm is plotted for $Z_1 = 50\ \Omega$, $Z_2 = 100\ \Omega$, and $g = 0.2$. In Fig. 2b, s parameters variation is plotted against a frequency range of (0-20 MHz), and Group Delay vs frequency is also plotted in Fig. 2c. Time domain analysis can also be done as in Fig. 3.
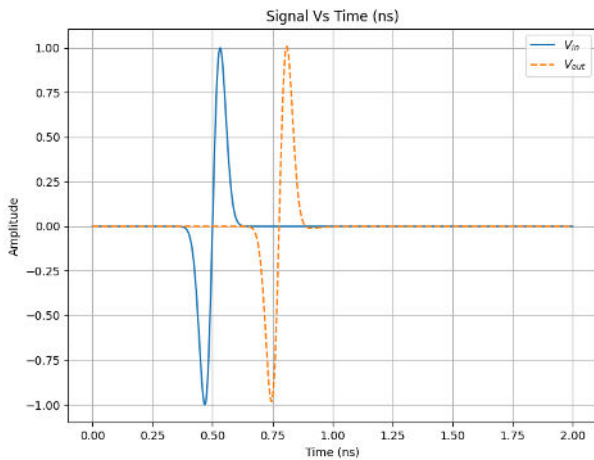

Fig. 3. Time domain Analysis of Logistic Taper

IV. CONCLUSION

This CAD tool covers a variety of parameters, starting from scattering parameters, group delay, transmission delay product (which is a measure of better transmission of pulse), and time domain analysis. With all the conventional tapers, the sigmoid taper, whose pulse transmission is very effective, is analysed. In the next versions of the software, we are trying to implement non-uniform sections for numerical analysis.

V. ACKNOWLEDGMENTA AND FUTURE PLAN

Finally, Sankhadeep would like to thank the IEEE MTT-S Undergraduate Scholarship and Dr. Rakesh Sinha for motivating and guiding him in continuing his research in this field.

Looking ahead, Sankhadeep is interested in exploring career opportunities in the fields of microwave and RF, and he plans to pursue a PhD in this area.

REFERENCES

[1] R. E. Collin, "The optimum tapered transmission line matching section," *Proceedings of the IRE*, vol. 44, no. 4, pp. 539–548, 1956.
[2] R. W. Klopfenstein, "A transmission line taper of improved design," *Proceedings of the IRE*, vol. 44, no. 1, pp. 31–35, 1956.
[3] K. Lu, "An efficient method for analysis of arbitrary nonuniform transmission lines," *IEEE Transactions on Microwave Theory and Techniques*, vol. 45, no. 1, pp. 9–14, 1997.
[4] M. Ahmed, "Impedance transformation equations for exponential, cosine-sqaared, and parabolic tapered transmission lines," *IEEE Transactions on Microwave Theory and Techniques*, vol. 29, no. 1, pp. 67–68, 1981.
[5] M. M. A. A. M. Affandi, S. Mahdi, "Analysis of some non-uniform transmission lines with selected applications," *ICECS*, pp. 153–162, 1994.
[6] S. Das and R. Sinha, "Nonuniform transmission line analyzer," Jun. 2024. [Online]. Available: https://doi.org/10.5281/zenodo.12164713
[7] R. Chatterjee and A. De, "Theory of optimum taper for distortionless pulse transmission," *IEEE Transactions on Microwave Theory and Techniques*, vol. 70, no. 4, pp. 2124–2134, 2022.
[8] Wikipedia contributors, "Sigmoid function — Wikipedia, the free encyclopedia," 2023, [Online; accessed 8-November-2023]. [Online]. Available: https://en.wikipedia.org/w/index.php?title=Sigmoid_function&oldid=1181896352