Analysis of Lossy Multiconductor Transmission Lines (MTL) Using Adaptive Cross Approximation (ACA)

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Abstract ─ In this article, an efficient adaptive cross approximation (ACA) algorithm is employed for the lossy of MTL such as propagation matrix, attenuation loss, dielectric loss and characteristic impedance are evaluated. ACA solver is stable and convenient to solve the compression and approximation of low-rank matrix because adaptive refinement is used to generate the optimal mesh. The integral equation (IE) solver along with adaptive cross approximation (ACA) is used to reduce the computational time and memory size. In the proposed algorithm, the complexities become linear. Therefore, the ACA provides less memory size and less computation cost. The results are compared with the latest state of the art existing work for validation.

Index Terms ─ Adaptive cross approximation, attenuation constant, characteristic impedance, integral equation, losses in multiconductor transmission line (MTL), propagation constant.

I. INTRODUCTION

In the past few decades, electromagnetic compatibility (EMC) has received considerable attention in the scientific community. The numerical schemes are used for the analysis of frequency dependent multiconductor transmission line (MTL) problems. The MTL parameters are generally attained from the computational electromagnetics. The traditional and advanced techniques for MTL are applied in various fields. But the integral equations have some numerical difficulties associated with its integral formula, singularity problems, complex assembly of the populated matrix and time-consuming [1-7].

In the existing literature, various mathematical methods for the simulation of MTL are discussed, for example, finite difference time domain (FDTD) [8], finite element method (FEM) [9] and method of moment (MOM) [10]. The integral equation with the MOM is widely used in EMC problems [11-12].

MOM is a powerful method for solving complex geometries such as those found in EMC problems. The algebraic integral equation method is used for conducting and non-conducting surface under the boundary condition. The discretization process is carried out with the help of MOM, which is considered the most efficient technique. MOM is used to discretize the integral equation into matrix form with subblock basis function [13-15].

The singular value decomposition (SVD) method reduces the computational complexities of deficient low-rank matrix [16]. ACA is an algebraic nature algorithm, which relies on the rank-deficient property between the orders of the basis function of well-separated groups. The grouping of basis function for the iterative solver is used to overwhelm the shortcomings of the traditional method. Therefore, the basis function for the block structure of the dense matrix is developed. Moreover, the groups (subblocks) have the low-rank matrix attribute and the ACA is applied on these properties to reduce the computational performance [17-23].

Based on the existing literature, it can be concluded that ACA is an efficient methodology for the numerical analysis of MTL, therefore used in this paper. The S-matrix, Z-matrix and Y-matrix are achieved from the ACA approach which are used for the analysis of MTL parameters. The lossy transmission line parameters such as dielectric loss, propagation constant loss and characteristic impedance are calculated through the proposed algorithm. The active impedance matching technique, FET transistors named as CGH40006P, is used for the matching of transmission line. To validate effectiveness of the ACA approach, the simulations are carried out in the ANSYS EM-environment and the ADS software. Finally, the results are compared to validate the dominant performance of proposed scheme.

The organization of the rest of the paper is as follows. In Section I, literature review is discussed about MTL. In Section II, the mathematical equation of MTL is described. Section III covers the comprehensive procedure about the adaptive cross approximation, implementation of dielectric constant, characteristic impedance and propagation constant. In Section IV,

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lossy model simulation and validation of results are presented. Finally, Section V concludes the work.

II. MULTICONDUCTOR TRANSMISSION LINE MODEL

In this section, we considered a MTL having M-conductors with one conductor grounded. The total length of the transmission line (TL) is L which is divided into small number of segmets. However, a unit meter length is considered for the analysis. According to the Telegram's equation, lossy transmission line constraints are given [6].

V(z) is the line voltage of $(n \times 1)$ vectors and $I(z)$ is the line current of n vectors. The i^{th} element under the test is voltage V_i and current I_i, respectively. The second order simultaneous equation of the MTL is:

$$\begin{cases} \dfrac{\partial^2 \boldsymbol{V}(z)}{\partial z^2} = \boldsymbol{ZYV}(z), \\ \dfrac{\partial^2 \boldsymbol{I}(z)}{\partial z^2} = \boldsymbol{YZI}(z), \end{cases} \quad (1)$$

where:

$$\begin{cases} \boldsymbol{Z} = \boldsymbol{R} + j\omega \boldsymbol{L} \\ \boldsymbol{Y} = \boldsymbol{G} + j\omega \boldsymbol{C} \end{cases}.$$

The basic model of the MTL line is illustrated in Fig. 1.

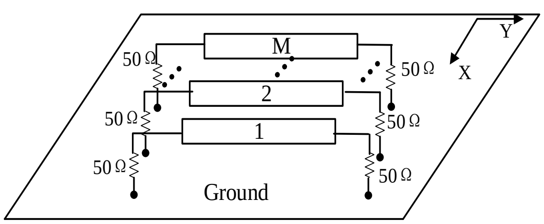

Fig. 1. Simple MTL model.

The Green's function of the MTL for the Helmholtz equation is:

$$E_r(z) = \frac{-jk_1}{2\pi} \int_\Omega G(r,r') \frac{\partial E(r')}{\partial n} dl' - \frac{-j}{2\pi k_1} \int_\Omega G(r,r') E(z) dl', \quad (2)$$

where:

$$G(r,r') = \frac{1}{|r-r'|} \left(e^{-jk_1|r-r'|} \right).$$

$K_1 = \omega\sqrt{\varepsilon\mu_0} = \omega\sqrt{\mu_0\,\sigma^r}$ is a constant, ω is the angular frequency, μ_0 is the permeability, σ^r is the conductivity of the conductor, S^r is the cross sectional area of under test conductor, $\frac{\partial E(r)}{\partial z}$ is the electric voltage of the excited field and ε is complex permittivity of the lossy line.

The basis function for the MTL is:

$$E_z = \sum_{r=1}^{M} \sum_{i=1}^{N^{(r)}} \alpha_i^{(r)} b_i^{(r)}(r), \quad (3)$$

where b_i is the basis function, $N^{(r)}$is the total number of segments and α is the coefficient.

A. Dielectric loss model

In this subsection, the dielectric loss model is presented. The MTL model is frequency dependent. The material for the models are lossy and the properties of the material are shown in the Table 1. The properties of the dielectric material are taken as same for all cables and calculated with the help of ACA techniques. The characteristic of lossy material verses frequency is shown in Fig. 2.

From the equation (2), the dielectric parameter is $K_1 = \omega\sqrt{\mu_0\,\sigma^r}$. The complex conductivity for the lossy model is:

$$\sigma_c = Y_c \frac{d}{A}, \quad (4)$$

where:

$$\sigma_c = \sigma + j\omega\varepsilon_r.$$

The complex permittivity at the angular frequency is:

$$\varepsilon_c = \varepsilon' - j\varepsilon'' = \varepsilon' - j\frac{\sigma_c}{\omega\varepsilon_0}. \quad (5)$$

The k^{th} iteration of the lossy model for complex permittivity is:

$$\varepsilon_c = \sum_{i=1}^{k} \left(\frac{j\omega\tau\varepsilon_h}{1 + j\omega\tau} \right). \quad (6)$$

where:

ε_h is the dielectric at high frequency,
ε_l is the low frequency dielectric constant,
$\omega = 2\pi f$ is an angular frequency,
τ is the relaxation time.

The loss tangent for the lossy model is:

$$\tan(\delta) = \frac{\varepsilon_l - \varepsilon_h}{(\omega\tau\varepsilon_h + \frac{\varepsilon_l}{\omega\tau})}. \quad (7)$$

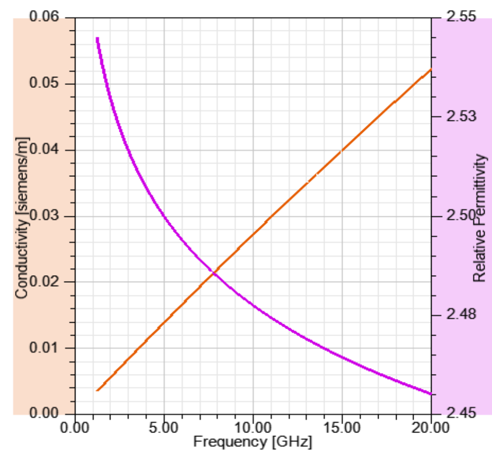

Fig. 2. Lossy material property.

Table 1: Properties of lossy material

Parameter	Value
Relative Permeability	2.5
Relative Permitivity	1
Bulk Conductivity	0
Dielectric Loss Tangent	0.1
Magnetic Loss Tangent	0
Landa G Factor	2

B. Characteristics impedance and propagation constant

The equation (1), describes the compact form of the MTL. The condition for the lossy MTL is $R \ll \omega L$ $and\ G \ll \omega C$. The propagation loss matrix is:

$$\gamma = \frac{R}{2}\sqrt{\frac{C}{L}} + \frac{G}{2}\sqrt{\frac{C}{L}} + j\omega\sqrt{LC}, \quad (8)$$

where:

$$\mathrm{Re}(\gamma) = \alpha = \frac{R}{2}\sqrt{\frac{C}{L}} + \frac{G}{2}\sqrt{\frac{C}{L}},$$

$$\mathrm{Im}(\gamma) = \beta + j\omega\sqrt{LC},$$

α is the attenuation constant which consists of two losses. The first and second terms describe the conductor loss and the dielectric loss respectively. β is the propagation constant. The characteristic impedance for the lossy MTL is:

$$Z_c = \sqrt{\frac{L}{C}}\left\{1 - \frac{jR}{2\omega L} + \frac{jG}{2\omega C}\right\}, \quad (9)$$

where Z_c is characteristics impedance.

B.1. Perfectly matched

In this subsection, the perfectly matched condition of transmission line is discussed. The condition for the perfectly matched load is $Z_o = Z_L$, which means that no energy is reflected back, and maximum power is delivered to the load.

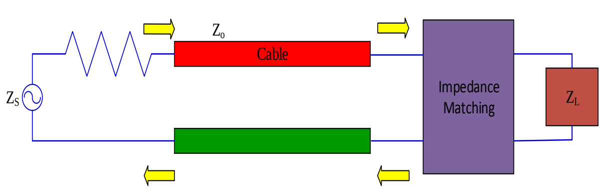

Fig. 3. Simple impedance matching model.

The active impedance matching technique is used for the perfectly matched transmission line in Fig. 3. The FET transistor CGH40006P [24] is used for the active matching technique. The high electron mobility transistor (HEMT), gallium nitride (GaN) is a type of FET unmatched transistor. The HEMT offers high gain and broad bandwidth capabilities for making the ideal and linear compressed amplifier. The HEMT has high power and high reliability, which provides a high degree of freedom and the versatile nature of properties. This FET transistor works in a wide range of frequencies between 1GHz-10GHz. The complex source impedance and load impedance are according to the datasheet.

III. ADAPTIVE CROSS APPROXIMATION

ACA is an iterative procedure for approximation of the low-rank matrix and approximate the original matrix without filling the entire matrix entries. However, ACA is a suboptimal algorithm, which gives a more significant number of independent vectors than other optimal algorithms.

In this paper, the sparse matrix is obtained from the integral equation of the MTL. This matrix is fully populated. The sparse matrix is converted into low-rank matrix. ACA technique is used to compress the matrix and evaluate the useful information, which is relevant for the low-rank matrix. This low-rank matrix is also called the Subblocks. This low-rank matrix is very suitable to calculate the behavior of transmission line at different frequencies with the help of an ACA approach. Therefore, the ACA approach is more suitable to solve the low-rank matrix. The post-processing calculation gives the S-Matrix, Z-Matrix, characteristic impedance, propagation, and attenuation constant. In this paper, the ACA is implemented for the low-rank matrix $P^{p\times q}$, which gives better compression quality. The matrices obtained from the ACA are propagation loss matrix, dielectric loss matrix, and characteristic impedance matrix.

Let $P \coloneqq \{p_1, p_2, \dots\dots, p_M\}\ and\ Q \coloneqq \{q_1, q_2, \dots\dots, q_M\}$ be the two low-rank matrix. ACA approximation is a rank deficient matrix by a product of two matrices in an iterative process:

$$A = [P]^{p\times k}[Q]^{k\times q}. \quad (10)$$

Let $p \times q$ block matrix which is compressed by ACA in k steps (number of iterations), where k is less than M. So the matrix P has $p \times k$ dimension, and the matrix Q has $q \times k$ dimension. At every step of the algorithm (number of iteration), each row and column are calculated by the previous value (last iteration). Each number of entries are updated and then calculate the approximation error. This process continues until the approximation error is smaller than the predefined value. The convergence criteria for the ACA algorithm are maximum delta and number of passes. The improvement of solution needs more number of passes per refinement to concise the solution. Therefore, the ACA algorithm has less memory size and computation cost. ACA is more efficient, so the memory requirement and computation time becomes linear which is $k(p+q)$ and $k^2(p+q)$ respectively. A number of operations are required for the approximation of the low-rank matrix by the ACA are $\varphi(PQ)$.

The matrix $p \times q$ is divided into subblocks $p_1 \times q_1$, $p_2 \times q_2$ which is geometrically well-separated. The admissible condition for the dense populated matrix is:

$$\eta dist(p_1, q_1) \geq \min\{diamp_1, diamq_1\}. \qquad (11)$$

The subblock concerning to $p_1 \times q_1$, is called admissible block. The block patches must satisfy (10), If not satisfied, this matrix cannot be compressed and the process should be repeated to fulfill the admissible condition. For an admissible pair, the ACA provides the vector $p_k := \frac{\hat{p}_k}{(\hat{p}_k)_{ik}} \epsilon P^p$ and $q_k \epsilon P^q$ with the iteration process:

$$\hat{p}_k := p_{jk} - \sum_{i=1}^{k} (q_i)_{jk} p_i, \qquad (12)$$

$$p_k := p_{ik} - \sum_{i=1}^{k} (p_i)_{jk} q_i. \qquad (13)$$

The maximum condition for the number of entries as:

$$0 \neq \left|(\hat{p}_k)_{ik}\right| \geq \left|(\hat{p}_k)_i\right|. \ \forall \text{ i=1,2,…..M}. \qquad (14)$$

The accuracy ε can be found by inspecting the norm of p_k *and* q_k to satisfy the required k-rank of approximation if:

$$\|p_{k+1}\|_2 \|q_{k+1}\|_2 \leq \varepsilon \|PQ^T\|. \qquad (15)$$

The simple flow diagram for the adaptive cross approximation is shown in Fig. 4.

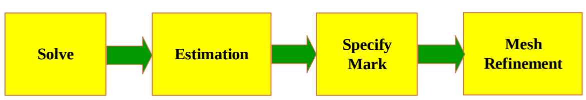

Fig. 4. Simple flow chart of ACA.

IV. NUMERICAL SIMULATION

In this section, numerical simulations are performed to check the effectiveness and correctness of the ACA algorithm for the frequency dependent losses parameters. The simulations of proposed algorithm are carried out in ANSYS HFSS, which is based on MOM. The FEM is implemented based on Q2D-Quasi solver. Both results are compared to check the validity of the algorithm. For proposed model, there are 14-conductors in the MTL. The start and stop frequencies are 0.5GHz and 10GHz respectively. The tolerance for the ACA is 0.002 (maximum value of delta, which is helpful for the convergence to solution). The specification of each cable is in Table 2. The model of MTL is in Fig. 5. The efficiency in term of memory computation is shown in Fig. 6.

A. Dielectric loss

The dielectric loss has a vital role in the performance of MTL. Dielectric loss depends upon the properties of the material such as imperfect conductivity and imperfect conductor. The dielectric loss is calculated through ACA algorithm. The results are compared with the lossless and losses at Tan(0.1) and Tan(0.2). The compared result is shown in Fig. 7.

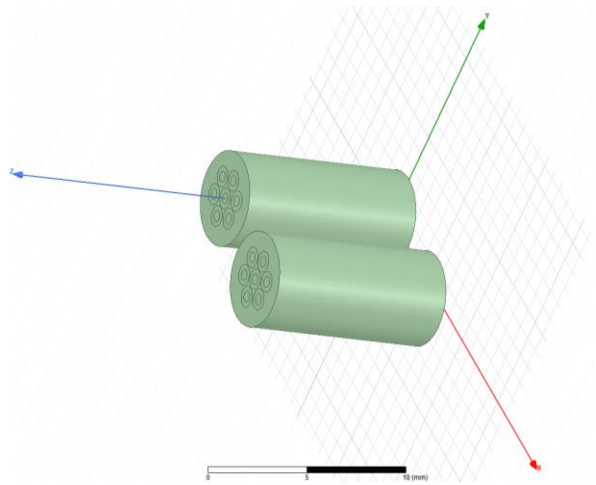

Fig. 5. Simulation model of the stranded cable.

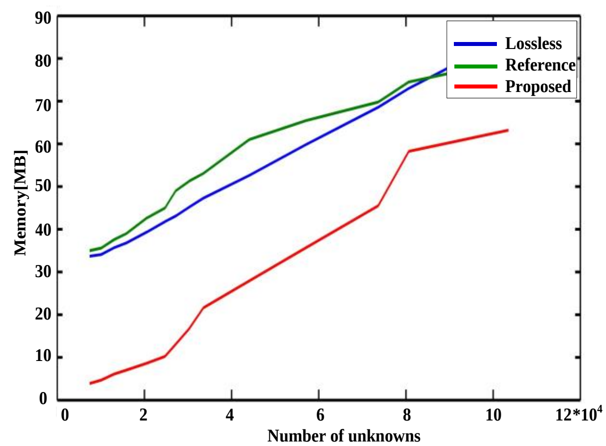

Fig. 6. Memory comparison of ACA.

Table 2: Parameters of lossy MTL model

Parameter	Value
Conductor Diameter	2mm
Dielectric Diameter	4mm
Conductor Material	PEC
Dielectric Material	Lossy Material
Height	10mm
Transparency	0.6
Frequency	10GHz
Number of Adaptive Passes	15

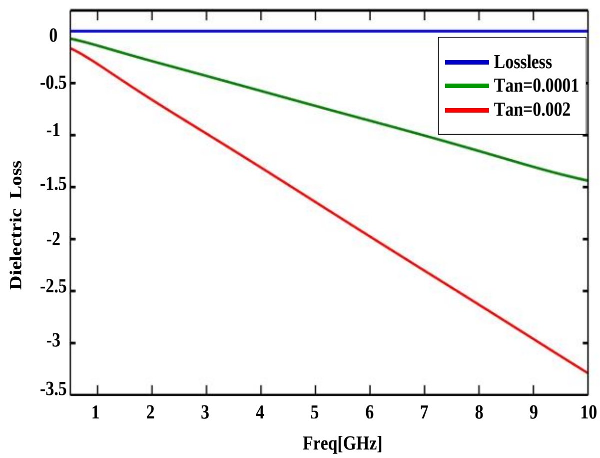

Fig. 7. Dielectric Loss of MTL.

B. Characteristics impedance and attenuation loss

In this subsection, the propagation matrix and characteristic impedance matrix of the MTL are calculated. The parameters of lossy MTL model are shown in Table 1. In this simulation, number of iterations (number of adaptive passes) is 15 with frequency ranges from 0.5 to 10GHz and 951-sweep point steps. The number of adaptive passes and maximum delta value can be adjusted according to the convergence of solution. This data gives the real and imaginary point to analyze the propagation loss (attenuation loss and phase loss) and characteristic impedance. To verify the algorithm result, comparison takes place with the commercial software, Quasi 2D solver, finite element method [25] and the IEEE paper [26]. Both models are drawn in ANSYS environment with same parameters and is compared the result. The comparison is shown in Fig. 8 which depicts the numerical result for the propagation loss. The X- and Y-axis are normalized values.

The magnitude and angle of characteristic impedance are shown in Fig. 9 and Fig. 10. Adaptive cross approximation summary in Table 3 shows lossless and lossy model behavior at different tangent loss. Moreover, the memory usage is also given in Table 3 which shows the required memory to compute the matrix assembly and structure assembly (Tetrahedra) at different number of passes.

Table 3: ACA algorithm

Adaptive Passes	Lossless			Lossy Model (Tanα=0.1)			Lossy Model (Tanα=0.0001)		
	Matrix Assembly (MB)	Matrix Size	Tetrahedra	Matrix Assembly (MB)	Matrix Size	Tetrahedra	Matrix Assembly (MB)	Matrix Size	Tetrahedra
1	33.7	7446	1463	35	7420	1458	35.3	8868	1466
2	34.1	10092	1899	35.6	10094	1894	36.6	11540	1900
3	35.7	13066	2375	37.6	12834	2333	38.4	14120	2310
4	36.8	15856	2835	39	15634	2792	40.3	16872	2737
5	39.3	20468	3624	42.6	19958	3538	43.8	21384	3441
6	41.8	24722	4368	45	22842	4046	47.7	27284	4378
7	43.1	27164	4794	49	29208	5150	49.4	29838	4796
8	45.6	30286	5337	51.3	32400	5687	52.2	33242	5342
9	47.3	33532	5895	53.1	36332	6347	53.9	37182	5973
10	52.6	44012	7619	61	47428	8194	57.2	41538	6667
11	59.9	57160	9798	65.5	53062	9134	60.1	45982	7387
12	68.6	73640	12529	69.8	59836	10259	63.2	50908	8163
13	73	80634	13715	74.5	66298	11326	67.7	56548	9074
14	85.1	103500	17513	79.5	74308	12653	71.2	62752	10055
15	91.1	115004	19417	85.9	82404	14011	75.8	69216	11066

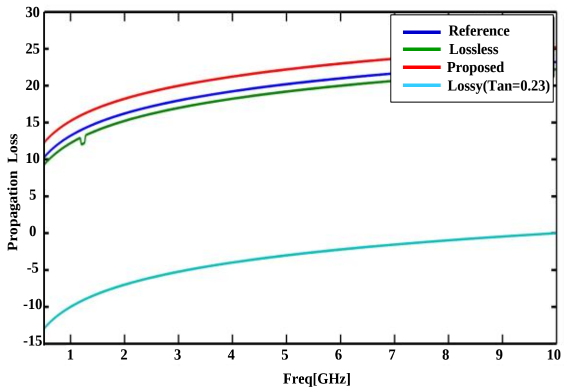

Fig. 8. Comparison of normalized propagation loss.

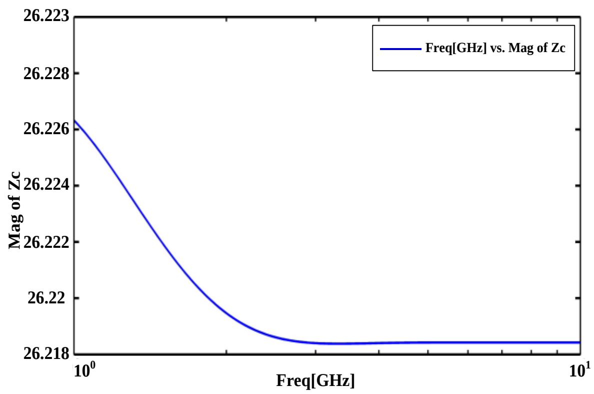

Fig. 9. The Magnitude of Zc versus freuquency.

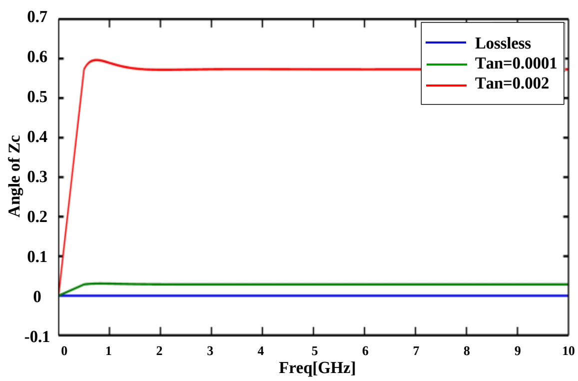

Fig. 10. The angle of Zc versus frequency.

C. Active matching techniques

In this subsection, active impedance matching of MTL is disscued. For this purpose, FET transistor CGH40006P based active matching technique is used. The datasheet of FET transistor CGH40006P is given [24]. The complex source and load impedances are 3.54-j*14.86 and 9.44+j*11.68 respectively at 4 GHz. The S-parameter is obtained from ANSYS HFSS environment, which is based on ACA approach. This S-parameter is exported into ADS software and circuit is designed in ADS environment.

To match the source impedance and load impedance of the MTL at 50 ohms, the acting impedance matching technique is used to optimize S-parameters matrix result. First set the goal which is mag(S(1,1)) linearly, to get optimized matching. The condition for the magnitude of S-matrix is to set the value nearly equal to zero. Furthermore, to achieve the goal, set the random type of optimization which is based on the Min/Max continuous value. In the circuit, the open TL stub is also used to tune the minimum and maximum value. In the impedance matching, two matching methods are adopted. The smith chart and transmission matching by active matching techniques are shown in Fig. 11 and Fig. 12.

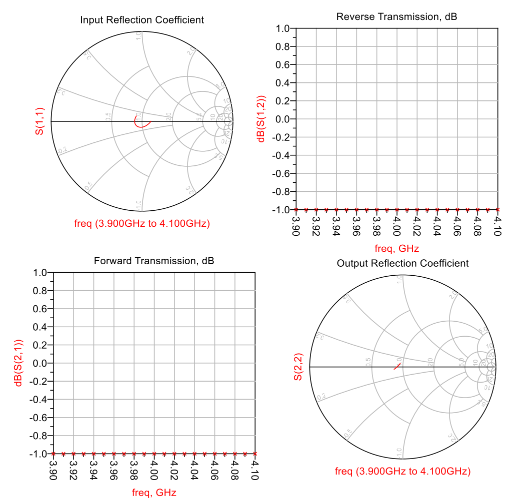

Fig. 11. Impedance matching with Smith chart.

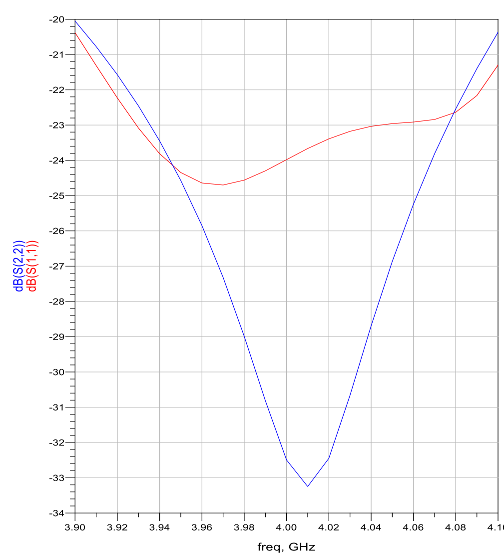

Fig. 12. Impedance matching with the transmission line.

V. CONCLUSION

In this article, the performance parameters of lossy MTL is discussed. The frequency dependent losses such as characteristic impedance, propagation loss and dielectric loss are calculated based on the ACA approach. The ACA algorithm is reliable that provides an efficient compression quality and simple procedure of compression. Moreover, ACA is a useful and efficient algorithm, which is capable to reduce the computation time, set-up time, and required less memory.

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