Characterization and Measurement of Cable Losses Using Fractional-order Circuit Model

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Abstract—**5G communication technology is used in very demanding applications, such as high-performance mobile devices, Internet of Things (IoT) applications, and wearable devices. Therefore, unlike the previous technologies, 5G technology requires massive bandwidth, mainly within three key frequency ranges, Sub-1 GHz, 1-6 GHz, and above 6 GHz. However, these challenges require more accurate and wide-band characterization of the circuits designed for 5G systems. To be specific, the losses, which can be neglected at lower frequencies, may substantially affect the performance of these circuits in the high frequency bands. This requires a comprehensive understanding and proper characterization of the loss mechanism within all frequency band of 5G. This paper investigates the viability of using the most common and easily accessible material FR-4 in circuits designed for 5G applications, and thus focuses on the proper modeling of the microstrip lines built around FR-4. For this purpose, we have used the fractional-order model of the lossy dielectric material, and ended up with a more accurate and simple model which fits well within a wide frequency range, from 1GHz to 16GHz.**

Index Terms—**Fractional-Order Calculus, 5G Communication Technology.**

I. INTRODUCTION

AS A RESULT of very demanding specifications of 5G systems, a comprehensive understanding and proper modeling of electrical circuits designed for this technology are required. On the other hand, due to the interdisciplinary nature of fractional calculus, there has been a growing research interest in using fractional-order calculus as a powerful tool in biochemical, medical and electrical engineering applications. In biomedical systems, it is shown that the accurate modelling of the biological cells and tissues require the utilization of fractional-order calculus [1-3].

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Manuscript received September 24, 2018; accepted October 29, 2018.
DOI: 10.17694/bajece.473637

In another implementations, there are two types of the fractionalorder memristor: the capacitive and the inductive fractionalorder memristor [4]. Fractional order circuits for emulating the mechanical impedance model of the human respiratory system is discussed elsewhere [5].

The fractional-order model calculus is also applied to the modeling of electrical circuits. Among these, the fractionalorder model of transmission lines are presented in [6-7] based on the RLGC model approach. Basically, two main approaches have been presented for the RLGC based model of transmission line in the literature. In the first approach, the loss elements, which are due to the skin effect of the line and the dielectric absorbtion, are modeled by the serial resistance of the copper, R and the conductance G. However, this integer-order model produces inaccurate results and seem to characterize the transmission line loss for only high loss cases, where the main source of nonideality is due to the dispersion of the dielectric material [8].

On the other hand, fractional-order mathematical models developed for the reactive circuit elements, may provide more accurate representation of the electrical characteristics. The use of the fractional-calculus concept leads to the fractionalorder RLGC model of the transmission line, where the involved inductor and capacitor are used as the fractionalorder elements. In this model, fractional inductance is employed to model the skin effect, while the fractional order capacitance is used to model various nonidealities related to the dielectric [3, 5]. Following up in this direction, we use the fractional order model to characterize the FR-4 PCB loss to obtain more accurate model of this easily accessible element in the hope of using this element in wide bandwidth 5G applications.

In this paper, we have studied the proper modeling of the most common and widely available material FR-4, which offers reduced cost but suffers from higher loss. This may be useful in designing low-cost circuits for 5G technology built around high loss PCB materials. The fractional-order model provides higher accuracy and incorporates less number of model parameters. RLGC parameters of both models can be extracted from the measurement data. The evaluations of the models are performed based on a design of a microstrip transmission line with FR4 substrate with permittivity 4.4, substrate height of 1.0mm and loss tangent of 0.025 at microwave frequencies between 1 to 16 GHz. This paper is organized as follows: Section II describes the fundamental concepts related to the modeling of Transmission Lines. In Section III, the results and the comparison of the conventional integer-order and fractional-order models are given. Finally, the conclusion is presented in Section IV.

II. TRANSMISSION LINE MODELS

II. 1 Conventional RLGC Model of the Transmission Line

Fig. 1(a) shows the Transmission Line model for integer order model. Per-unit model parameters can be given explicitely as follows:

$$\left.\begin{array}{c} R \approx R_o + R_s\sqrt{f}(1+i) \\ L \approx L_o \\ C \approx C_0 \\ G \approx G_0 + G_d w \end{array}\right\} \quad (1)$$

where f is the frequency in Hz, R_0 is the DC resistance of the line, R_s is the skin-effect resistance term, G_0 is the DC shunt conductance and G_d is the conductance used to model dielectric-loss [9, 10].
According to the model, the propagation constant (γ) and characteristic impedance (Z_0) of the transmission line are defined as [10]

$$Z_0 = \frac{R + j\omega L}{\gamma} = \sqrt{(R + j\omega L)/(G + j\omega C)} \quad (2)$$

$$\gamma = \alpha + j\beta = \sqrt{(R + j\omega L)(G + j\omega C)} \quad (3)$$

where α is the wave attenuation constant (Np/m) and β is the phase constant (rad/m).

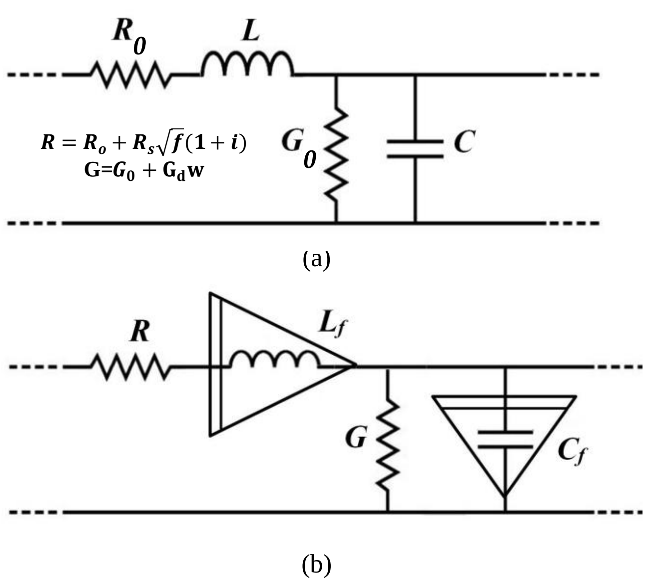


Fig. 1. (a) Classical RLGC unit cell equivalent model of transmission line. (b) Fractional-order equivalent model.

II. 2 Fractional-order Model of the Transmission Line

While the integer-order RLGC unit cell is the classical approach used to model transmission lines, researchers have been focused on using fractional-order models, in the last decade [6, 7, 11]. Fig. 1(b) shows the Transmission Line RLGC model based on fractional-order elements. In this figure, the fractional-order capacitor is of the order α_C with $\alpha_C \epsilon(0,1]$ and the fractional inductor is in the order α_L and $\alpha_L \epsilon(0,1]$. These elements are defined with the following relationships [2]:

$$i(t) = C_f \frac{d^{\alpha_C}}{dt^{\alpha_C}} v(t) \quad (4)$$

$$v(t) = L_f \frac{d^{\alpha_L}}{dt^{\alpha_L}} i(t) \quad (5)$$

For a general transmission line segment, the characteristic impedance Z_f and propagation constant γ are calculated as, respectively, as [11].

$$Z_f = \sqrt{\frac{Z_{Lf}}{Y_{Cf}}} = \sqrt{\frac{R_0 + (j\omega)^{\alpha L} L_f}{G_0 + (j\omega)^{\alpha C} C_f}} \quad (6)$$

$$\gamma_f = \sqrt{\left(R_0 + (j\omega)^{\alpha L} L_f\right)\left(G_0 + (j\omega)^{\alpha C} C_f\right)} \quad (7)$$

At high frequencies, the characteristic impedance, Z_f and propagation constant, γ_f can be evaluated using the following simplified expressions:

$$Z_f = \sqrt{L_f/C_f}\, \omega^{\frac{\alpha L - \alpha C}{2}} \left[\cos\frac{(\alpha_L - \alpha_C)\pi}{2} + \mathrm{j}\sin\frac{(\alpha_L - \alpha_C)\pi}{2}\right] \quad (8)$$

$$\gamma_f = \sqrt{L_f C_f}\, \omega^{\frac{\alpha L + \alpha C}{2}} \cdot \left[\cos\frac{(\alpha_L + \alpha_C)\pi}{2} + \mathrm{j}\sin\frac{(\alpha_L + \alpha_C)\pi}{2}\right] \quad (9)$$

II. 3 Extraction of Transmission Line Parameters Using S-Parameters

In order to extract the per-unit parameters of the RLGC model from the measurements, the measured S-parameters of the transmission line are first converted to the ABCD parameters. For this purpose, we use the inverse of the following relationship between two-port S-parameters and the ABCD matrix [10]

$$\begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} = \begin{bmatrix} \frac{A + B/Z_0 - CZ_0 - D}{A + B/Z_0 + CZ_0 + D} & \frac{2(AD - BC)}{A + B/Z_0 + CZ_0 + D} \\ \frac{2}{A + B/Z_0 + CZ_0 + D} & \frac{-A + B/Z_0 - CZ_0 + D}{A + B/Z_0 + CZ_0 + D} \end{bmatrix} \quad (10)$$

On the other hand, the ABCD matrix for a uniform transmission line with length l can be calculated in terms of the the characteristic impedance and the propogation constant as follows [12]:

$$ABCD = \begin{bmatrix} \cosh(\gamma l) & Zo \cdot \sinh(\gamma l) \\ \sinh(\gamma l)/Zo & \cosh(\gamma l) \end{bmatrix} \quad (11)$$

Given these basic relationships, we can now develop the procedure defined in Table I in order to retrieve the parameters of the transmission line model. Note that this procedure can be applied both to classical integer-order and the fractional-order RLGC models.

TABLE I
PROCEDURE FOR THE EXTRACTION OF THE FRACTIONAL-ORDER TRANSMISSION LINE PARAMETERS.

S-parameters(S_{11},S_{21}) are measured using vector network analyzer.

↓

ABCD parameters, γ, and Z_0 are obtained from Eqn. 10.

↓

Using γ and Z_0, RLCG parameter are derived (Eqn.14).

↓

R_0, R_s, G_0, G_d parameters of the classical model are extracted from the respective characteristics using curve fitting (Eqn. 3).

↓

α, β, L_f, C_f parameters of the fractional-order model are extracted from Z_0 and γ using curve fitting (Eqns.8&9)

↓

Derivation of the main S-parameters (S_{11}, S_{21}) from fractional order model (Using Eqns.8&9 in Eqn.11)

In the second step of the procedure in Table 1, we use a modified version of the method in [13] in order to extract the parameters Z_0 and γ from the ABCD-parameters.

The complex propagation constant $\gamma = \alpha + j\beta$ is mathematically defined by:

$$\gamma = \alpha + j\beta = \frac{\sinh^{-1}\sqrt{BC}}{l} \tag{12}$$

and Z_0 is, in turn, computed from the complex prorogation constant using the following equation:

$$Z_c = \frac{\gamma}{(G + j\omega C)} \tag{13}$$

where G=ωCtanδ.

Finally, the RLGC parameters can be extracted from measurements using the followign relationships:

$$R=\mathrm{Re}\{\gamma/Zc\},\quad L=\mathrm{Re}\{\gamma Zc\}/\omega,\quad C=\mathrm{Im}\{\gamma/Zc\}/\omega,\quad G=\mathrm{Re}\{\gamma/Zc\}. \tag{14}$$

III. EXTRACTION OF THE TRANSMISSION LINE PARAMETERS

In order to evaluate usefulness of the fractional order model, we have fabricated a microstrip line structure. The microstrip line geometries with FR-4 substrates are illustrated in Fig. 2.

For the microstrip line, the dimensions are set to l=25 mm; w=2 mm; h=1.0 mm; and t=0.035 mm. This transmission line is simulated in a high-frequency structure simulator (HFSS) and is optimized for the frequency range from 1 GHz to 16 GHz.

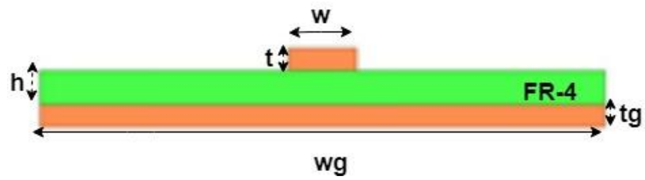


Fig. 2. Cross-section of the microstrip structure wşth FR-4 substrate.

Setup equipment employed are Keysight (m9374a) 20 GHz Vector Network Analyzer, Agilent 85052B/8719D 3.5mm calibration kit and RS Pro SMA connector.

TABLE II
EXTRACTED PARAMETERS FOR INTEGER-ORDER AND FRACTIONAL-ORDER RLGC MODEL

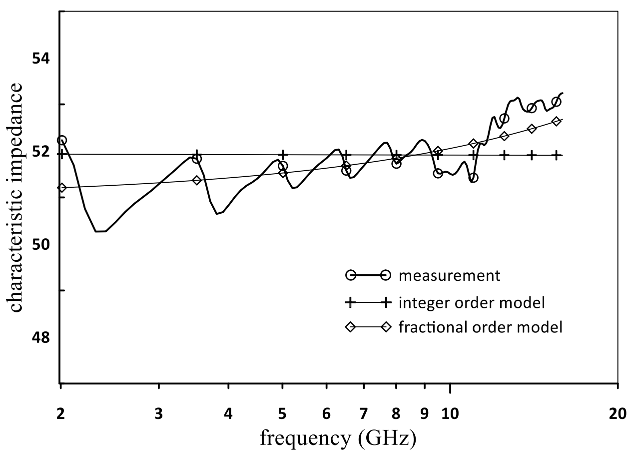
Integer RLGC Model		
Parameter	Value	Unit
R_0	0.16	Ω/m
R_s	3.47	mΩ/m·Hz
L_0	302.49	nH/m
C_0	0.118	nF/m
G	0.017	S/m
G_d	2.37	Ps/m·Hz

Fractional RLGC Model		
Parameter	Value	Unit
R_0	1	Ω/m
L_f	355	$(nVs^{-\alpha})$A/m
C_f	4.62	$(nAs^{-\beta})$/V/m
G	0.017	S/m
α_L, α_C	0.834, 0.79	-

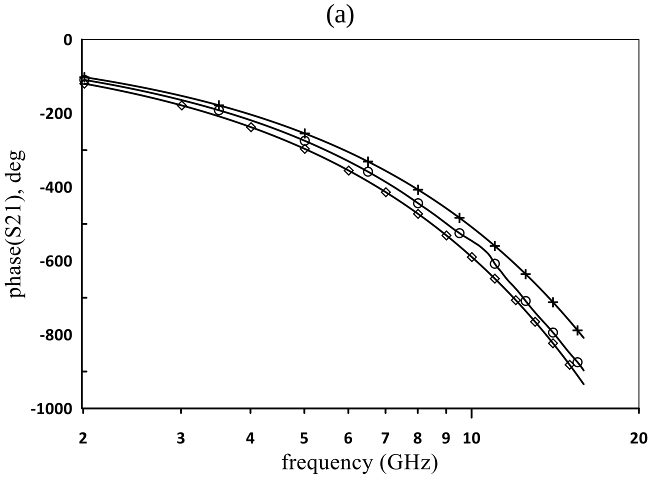
The per-unit parameters of both integer and fractionalorder models are derived from the experimental measurements using the procedure described in Table I. The values of the parameters thus obtained are given in Table II. Since the model equations are highly nonlinear, the optimization problem has many local minima, thus the parameters given in Table II should be considered as near optimum values.

The evaluations of the model accuracies are performed based on the characteristic impedance, Z_0 and the s-parameter, S_{21}. The experimental results, the simulated characteristics using the integer and fractional order models are all given in Figs. 3 & 4. Experimental results and the characterictics obtained from the model for the characteristic impedance, Z_0 are given in Fig. 3(a), while the results related to the magnitude and phase functions of the S_{21} are given, respectively, in Figs. 3(b) and (c). The integer-order and fractional-order model parameters are the optimum parameters given in Table II.

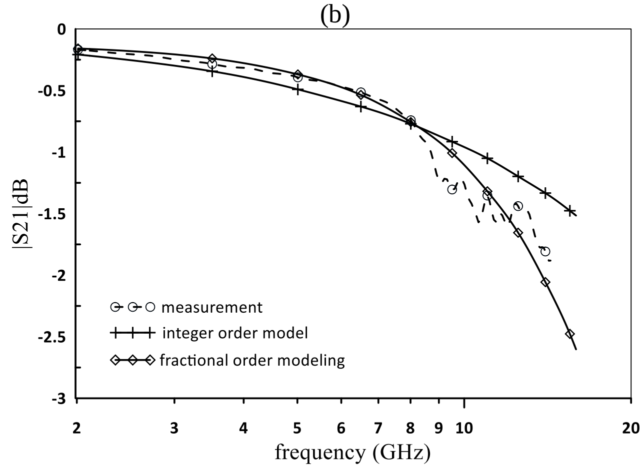
As can be seen from the results in Fig. 3(b), both integer and fractional-order models give similar results for the phase characteristic of S_{21}. However, the accuracies of the models differ significantly for the characteristic impedance, Z_0 (see Fig. 3a) and the magnitude of the s-parameter, S_{21} in Fig. 3c. Therefore, in Figs. 4(a) and (b), we have also provided the variations of the error function for the characteristic impedance, Z_0 and $|S_{21}|$, respectively.



(a)



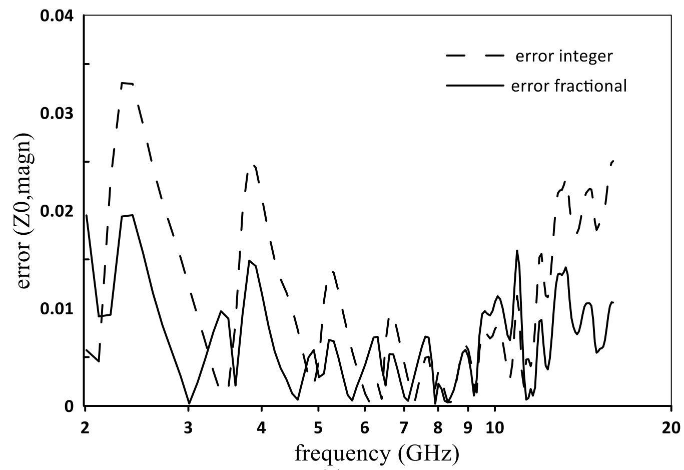
(b)



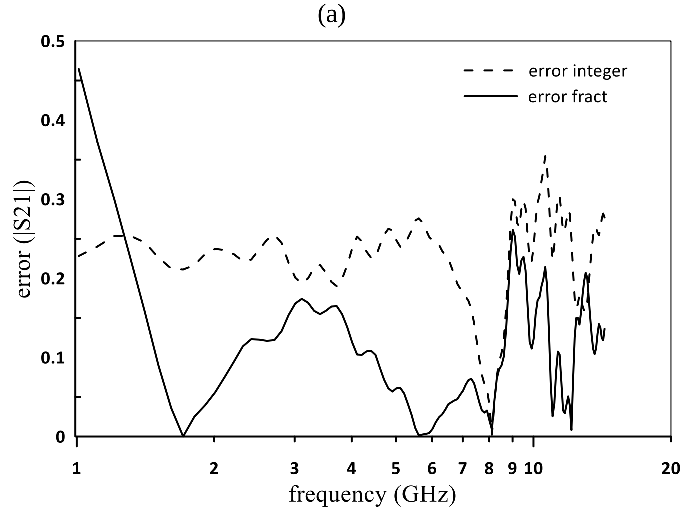
(c)

Fig. 3. Experimental results and RLGC model based approximations of the (a) Magnitude of the characteristic impedance, Z_0 (b) Phase of S_{21} in degrees, (c) Magnitude of S_{21} in dB.

From these characteristics, it is seen that fractional-order model approximates the experimental results more accurately in a wider-frequency range compared to the integer-order model. This advantage is more stiking when the errors in the magnitude of the S_{21} are considered.



(a)



(b)

Fig. 4. Error variations of both integer-order and fractional-order RLGC models, (a) for the characteristic impedance, Z_0 (b) for the magnitude of S_{21}.

IV. CONCLUSION

In this paper, the fractional-order model of the transmission line for the microstrip with FR-4 substrate is developed. This model is extracted via the measurements of the S-parameters. It is observed that fractional-order model allows more compact and accurate analytical model over wide-frequency band compared to the traditional integer order model. We have concluded that fractional-order characterization allows the derivation of an efficient model which incorporates the loss of the transmission line over a wide frequency range, thus is useful in applications requiring wide bandwidth. The results may be useful for those who design circuits for 5G technology built around high loss but low cost PCB materials.

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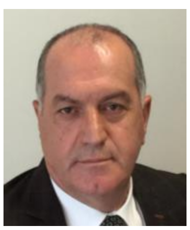
BIOGRAPHIES



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