2D-FEM Electromagnetic Characterization Of Quasi-TEM Coupled Elliptical Microstrip Line For Microwave Applications

Yamina Bekri, Nasreddine Benahmed

Abstract: In this paper, we present analysis and study of quasi-transverse electromagnetic (quasi-TEM) coupled elliptical microstrip line (CEML), convenient for microwave and RF applications, by using finite element method (FEM) in two dimensions (2D) under FreeFEM environment. Firstly, we have rigorously determined the quasi-TEM electromagnetic parameters (EM) of the CEML line. For this type of structure, there are no analytical or numerical results found in the scientific literature. Accordingly, to validate our results, we have adapted our 2D-FEM program to study the general configuration of the coupled cylindrical microstrip line (CCML), and excellent agreement is found between our FEM results and those obtained with other techniques of the scientific literature. Later, to show the practicality and the usefulness of our 2D-FEM results, we have successfully used the found quasi-TEM parameters to design a new microwave directional 20-dB, 50-Ω elliptical microstrip coupler (EMC) operating at 2-GHz, with high-performances in terms of isolation (53 dB), directivity (34 dB) and reflection (46 dB), realized in Matlab environment, convenient for microwave measurement telecommunication systems and radar applications. Finally, to reinforce our work, the directional EMC coupler's coupling response obtained under Matlab environment was validated by our results obtained under CST Microwave Studio Software.

Index Terms: 2D-FEM electromagnetic characterization, Quasi-TEM coupled elliptical microstrip line, Elliptical microstrip directional coupler.

1 INTRODUCTION

Recently, elliptical and cylindrical microstrip lines have found widespread applications in both engineering communities and telecommunication systems. The main advantage of these types of lines over the conventional planar microstrip lines is the excitation of conformal antennas and arrays mounted on elliptical and cylindrical objects. Furthermore, these lines have been widely used in the design of directional couplers, filters, transition adaptors, impedance transformers, and medical applications. This has brought about the need for developing computer-aided design (CAD) programs for determining the quasi-TEM parameters of such structures. However, the analysis of passive components on the elliptical and cylindrical substrate with non-homogeneous media is not an easy task [1].

Several investigations for the electromagnetic characteristics of quasi-transverse electromagnetic elliptical and cylindrical microstrip lines have been reported in the literature. Until now, the finite difference time method [1]-[4] and method of moments [4]-[8] have been the most frequently used methods to study non-planar elliptical and cylindrical microstrip lines.

In all the previous works, the capacitance (C) and the inductance (L), per unit length, of the elliptical microstrip lines have not been investigated, and the available expressions for characteristic impedance and effective permittivity existed in the scientific literature [7] contain many intermediate parameters and are so lengthy and cumbersome. The FEM method is well known to deliver optimal results for a wide range of structure parameters and over a very large band [9]-[14]. In the previous works, based on the FEM in 2D, we have successfully analyzed and delivered exact formulas for different types of TEM and quasi-TEM, planar and non-planar structures, and we have well explicated this method in references [9]-[14]. It is founded on solving Laplace's equation in a TEM or a quasi-TEM approximation. The primary objective of this paper is the electromagnetic characterization of the open inhomogeneous quasi-TEM coupled elliptical microstrip line basing on the 2D-FEM technique under FreeFEM [15] environment, and to use the found 2D-FEM results to design a new conformal quasi-TEM elliptical microstrip directional coupler of high-performance in terms of directivity, isolation, and with minimum losses, widely requested in high-frequency telecommunication measurement systems, and microwave and radar applications. In this work, firstly, we have focused on studying the effect of the geometrical parameters on the quasi-TEM parameters, such as the strip-angle (θ) and the inner-conductor semi-major axis to the strip-conductor semi-major axis ratio (a_1/a_2), on the variation of the even- and the odd-mode characteristic impedances (Z_{0e}, Z_{0o}), the even- and the odd-mode effective dielectric constants (ε_{effe}, ε_{effo}), the coupling coefficient (K), and the [L] and [C] matrices of the CEML line where:

$$[L]=\begin{bmatrix} L_{11} & L_{12} \\ L_{12} & L_{11} \end{bmatrix};\ [C]=\begin{bmatrix} C_{11} & C_{12} \\ C_{12} & C_{11} \end{bmatrix} \quad (1)$$

We can calculate the elements of the [C] matrix by using:

$$C_{11}=C_{22}=\frac{C_e+C_o}{2} \quad (2)$$

$$C_{12}=C_{21}=\frac{C_e-C_o}{2} \quad (3)$$

Where C_e and C_o are the capacitance per unit length of the structure, for the even and the odd modes respectively.

The elements of the matrix [L] are calculated from the matrix [C] when the quasi-TEM structure is empty, i.e. for (ε_r)=1.

The [L] matrix can be calculated as:

$$[L]=\mu_0\varepsilon_0[C]^{-1} \quad (4)$$

- *Yamina Bekri is an Associate Professor at the Institute of Sciences and Technology, University center of Maghnia, Telecommunications Laboratory-LTT, Algeria. E-mail: mina_souf1@yahoo.fr*
- *Nasreddine Benahmed is a Full Professor at University of Abou Bekr Belkaid-Tlemcen, Telecommunications Laboratory-LTT, Algeria, E-mail: n_benahmed@yahoo.fr*

In order to show the value and the practicability of our study, we have used the identified 2D-FEM results to design a new 50-Ω, 20-dB, 2-GHz elliptical microstrip directional coupler with high performances in terms of isolation and directivity. To reach this goal, we have successfully established a program under Matlab [16] environment to obtain the response of the directional EMC coupler. Furthermore, to reinforce our work, we have validated the coupler's coupling response by using CST Microwave Studio software [17].

2 2D-FEM RESULTS

2.1 Presentation of the Quasi-TEM Coupled Elliptical Microstrip Line

In Fig. 1, we present the schematic representation of the quasi-TEM coupled elliptical microstrip line. The CEML line consists of two outer infinitely elliptical conducting arc-strips, with major and minor axes of (a_2,b_2) and a conduction angle of (θ), and an inner central grounded elliptical conductor of dimensions (a_1,b_1). The dimensional relationship between the two ellipses is $a_1 / a_2 = b_1 / b_2$ $a_1/a_2 = b_1/b_2$. The substrate fills the inside of the CEML line and has a relative dielectric constant (ε_r) of 9.6. The ratio $R = a_1 / a_2 = b_1 / b_2$ and the conduction strip-angle (θ) are used to define and determine the EM-parameters of the CEML line. In Fig. 2, we present the equipotential lines of the structure for the even- and the odd-modes. For the even mode: the potential V = 1 V on the two elliptical strips and V = 0 on the central elliptical ground conductor. For the odd mode: V = 1 V on one of the two elliptical conducting arc strips, V = −1 V on each other, and V =0 on the central elliptical ground conductor.

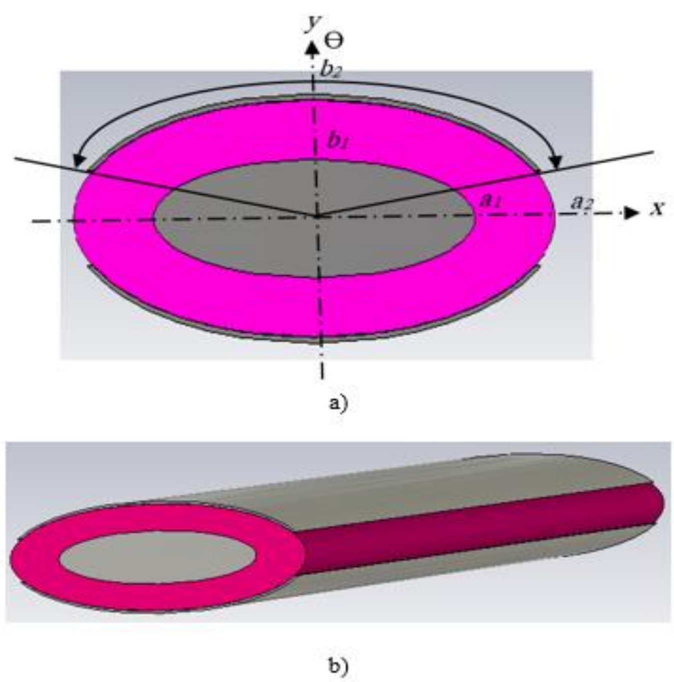

Fig. 1. *This figure illustrates (a) a cross-sectional view of the coupled elliptical microstrip line with its (b) 3D representation.*

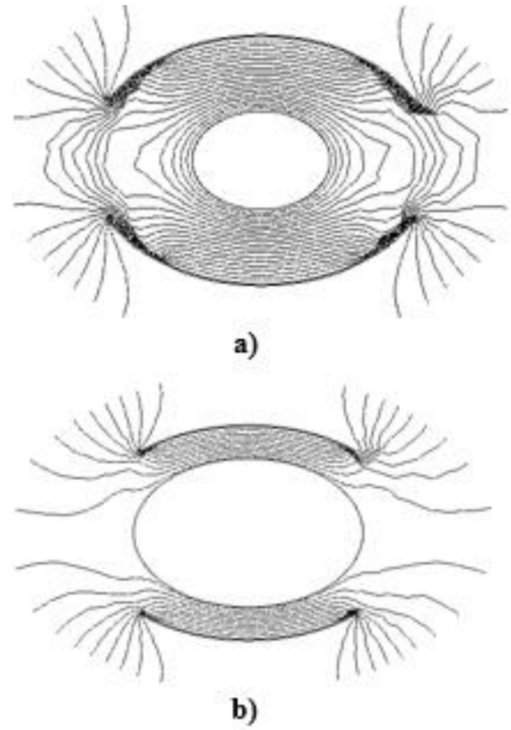

Fig. 2. *Potential distribution for the CEML (a) even-mode with V_1=V_2=1 V on the two conducting strips, with θ=120° and R=a_1/a_2=0.4 (b) odd-mode with V_1=1 V on one of the two elliptical strips and V_2=-1 V on the other one, with θ=80° and R=a_1/a_2=0.7.*

2.2 2D-FEM Quasi-TEM Electromagnetic Parameters Results

For our studied structure, there are not analytical or numerical results existing in the scientific literature except the numerical results of the general configuration of the open coupled cylindrical microstrip line (CCML) presented in Fig. 3 studied before in reference 4. Accordingly, to validate our FEM results, we have first adapted our program to study the CCML structure with a_1/a_2=0.9 and ε_r=9.6 studied previously with other techniques. We show in Tables 1 and 2 the numerical 2D-FEM results for the CCML line compared against existing results found in the literature [4]. The results are very satisfactory and excellent agreement is found, which confirms the exactitude and the correctness of our 2D-FEM program.

Table 1. *Odd-mode characteristic impedance and effective permittivity of the cylindrical coupled microstrip line, compared with other techniques.*

θ	FEM	Quasi-static results [4]	Full wave analysis [4]
178.854°	31.62	31.65	31.67
	5.518	5.485	5.486
174.268°	43.68	43.72	43.76
	5.823	5.722	5.722
122.675°	50.71	50.9	51.01
	6.382	6.369	6.372

Table 2. *Even-mode characteristic impedance and effective permittivity of the cylindrical coupled microstrip line, compared with other techniques.*

θ	FEM	Quasi-static results [4]	Full-wave analysis [4]
122.675°	66.39 6.922	66.46 6.921	66.55 6.926

Then, we have studied the influence of the geometrical parameters such as the conduction strip-angle (θ) and the (R) ratios on all the EM-parameters of the quasi-TEM CEML line with taking (ε_r) of 9.6 and (a_2/b_2) of 3. This study is applicable in a wide variety of (θ) and (R) values, varying respectively between 10-180° and 0.1-0.9.

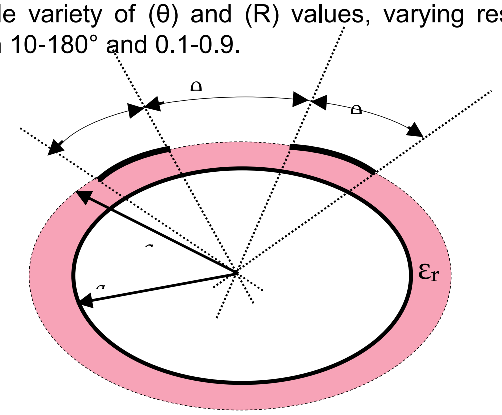

Fig. 3. *Cross-sectional view of the general configuration of the coupled cylindrical microstrip line (CCML). $w = \theta_w r_2$, $s = \theta_s r_2$ and h=r2-r1.*

Our interesting results for even- and odd-mode characteristic impedances, even- and odd-mode effective dielectric constants, coupling coefficient, and [L] and [C] matrices of the CEML, as functions of the strip conduction angle (θ), with taking R as a parameter, are illustrated in Figs. 4-12. The graphs are realized under Origin 50 [18]. It is observed that all the calculated quasi-TEM parameters depend strongly on the variation of strip conduction-angle (θ) and the (R) ratio. These curves allow the design of the CEML lines having a characteristic impedance ($Z_c = \sqrt{Z_{0e} Z_{0o}}$) varying between 2.97 and 88 Ω, and a coupling coefficient from 2.58 to 150 dB or more. For these dimensions, a very tight coupling was reached, of (-2.59 dB) at (R=0.1) and (θ) of 179°, which is a very interesting result. Another interesting result is, when the even- and the odd-mode effective permittivities are equal, the even- and odd-mode phase velocities became also equal, this structure will allow very high-performances in terms of low-losses, high-directivity, and good isolation. Thus, from these design-curves, we can find the geometrical parameters of any high-performance circuit, with equal even- and odd-mode phase velocities, using our quasi-TEM CEML line.

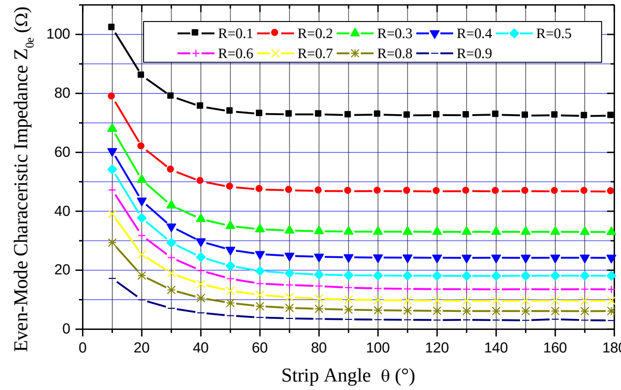

Fig. 4*. Even-mode characteristic impedance of coupled elliptical microstrip line as a function of (θ), with taking the (R) ratio as a parameter.*

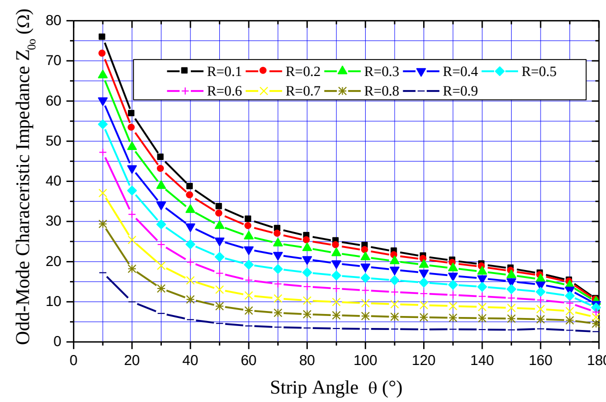

Fig. 5*. Odd-mode characteristic impedance of coupled elliptical microstrip line as a function of (θ), with taking the (R) ratio as a parameter.*

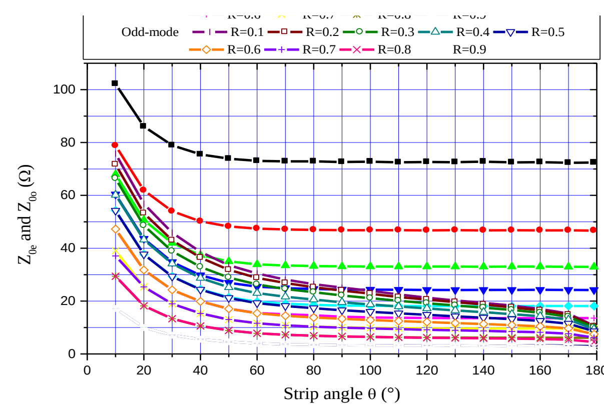

Fig. 6*. Even- and odd-mode characteristic impedances of coupled elliptical microstrip line as a function of (θ), with taking the (R) ratio as a parameter.*

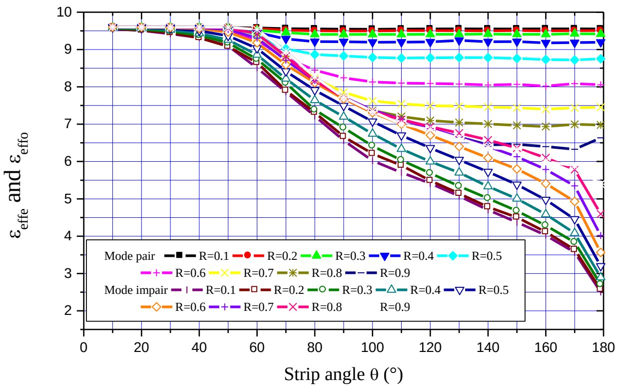

Fig. 7. *Even- and odd-mode effective dielectric constants of coupled elliptical microstrip line as a function of (θ), with taking the (R) ratio as a parameter.*

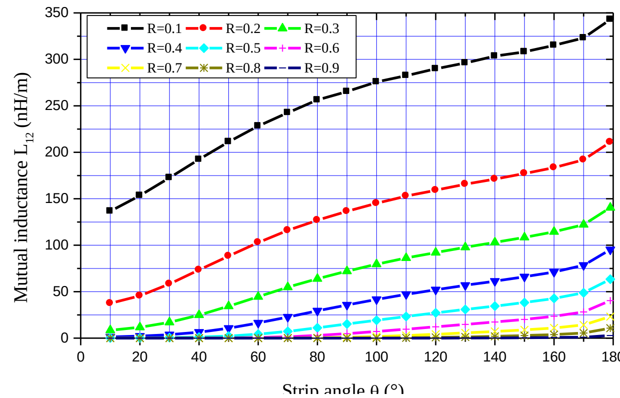

Fig. 10. *Mutual inductance of coupled elliptical microstrip line as a function of (θ), with taking the (R) ratio as a parameter.*

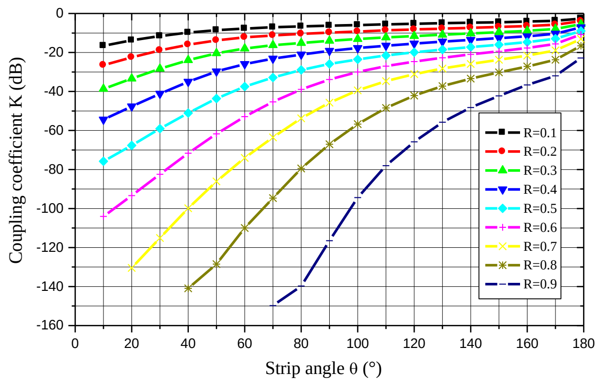

Fig. 8. *Coupling coefficient of coupled elliptical microstrip line as a function of (θ), with taking the (R) ratio as a parameter.*

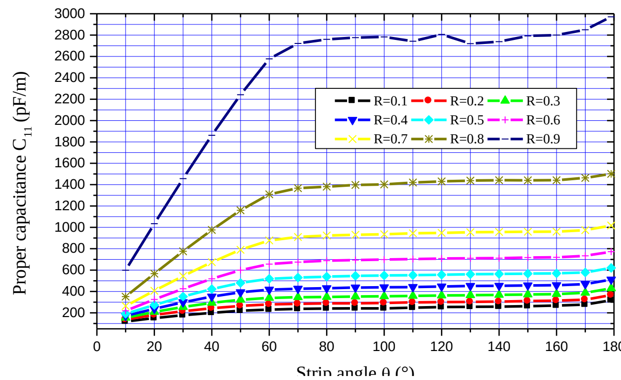

Fig. 11. *Proper capacitance of coupled elliptical microstrip line as a function of (θ), with taking the (R) ratio as a parameter.*

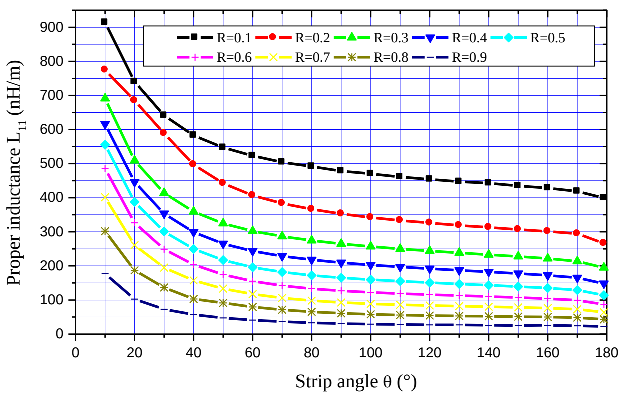

Fig. 9. *Proper inductance of coupled elliptical microstrip line as a function of (θ), with taking the (R) ratio as a parameter.*

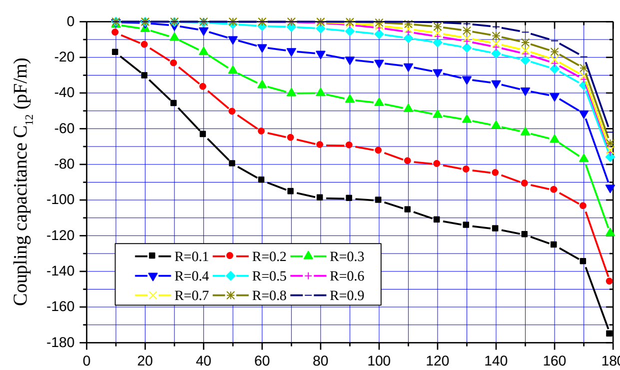

Fig. 12. *Coupling capacitance of coupled elliptical microstrip line as a function of (θ), with taking the (R) ratio as a parameter.*

3 50 Ω MICROWAVE ELLIPTICAL MICROSTRIP DIRECTIONAL COUPLER DESIGN

In order to show practicability and the usefulness of our analysis, the found results were used to design a new (20-dB) quasi-TEM directional EMC coupler, with equal even- and odd-mode phase velocities, adapted to (50 Ω) and operating at (2 GHz), convenient for microwave measurement systems and telecommunication applications.

$$v_{\varphi e} = c_0 / \sqrt{\varepsilon_{effe}} = v_{\varphi o} = c_0 / \sqrt{\varepsilon_{effo}} \quad (5)$$

$$\sqrt{Z_{0e} Z_{0o}} = 50\Omega \quad (6)$$

To reach this objective, we have proposed an EMC directional coupler having (b_2=1mm, a_2/b_2=3, a_1/a_2=0.2, a_1/b_1=3, b_1/b_2=0.2, θ = 30°). The features of the coupler obtained from the FEM-analysis results include a dielectric constant (ε_r) of 9.6, a length $l = \lambda/4 = c/(4f\sqrt{(\varepsilon_{effe}+\varepsilon_{effo})/2}) = 12.145mm$, even- and odd- mode characteristic impedances Z_{0e} and Z_{0o}, of 55.42Ω and 45.41Ω, respectively, coupler's characteristic impedance $Z_c = \sqrt{Z_{0e} Z_{0o}} = 50.16\Omega$, even and odd-mode effective dielectric constants ε_{effe} and ε_{effo} of 9.596 and 9.47, coupling coefficient of $k = 20\log_{10}\left(\frac{Z_{0e}-Z_{0o}}{Z_{0e}+Z_{0o}}\right) = -20.06dB$, and [L] and [C] matrices calculated are as follows:

$$[L] = \begin{bmatrix} 516.6 & 52.96 \\ 52.96 & 516.6 \end{bmatrix} (nH/m) \quad (6)$$

$$[C] = \begin{bmatrix} 206.12 & -19.78 \\ -19.78 & 206.12 \end{bmatrix} (pF/m) \quad (6)$$

For a quarter wavelength (l) of 12.145 mm of the directional coupler, we present in Fig. 13 the coupler's response realized in Matlab environment. The obtained Scattering (S) parameters results show that the quasi-TEM EMC coupler has excellent performances, directivity (S_{13}-S_{14}) is of (34 dB), isolation (S_{14}) is of (53 dB), and reflection is of (46 dB). Accordingly, this type of coupler has very good characteristics in terms of isolation, directivity, and provide minimum losses. Furthermore, to reinforce our work, we have designed this structure (Fig. 14) in CST Microwave Studio as shown in Fig.15, and we have found very good agreement between the two coupling responses (S_{13}) of the designed EMC directional coupler of interest.

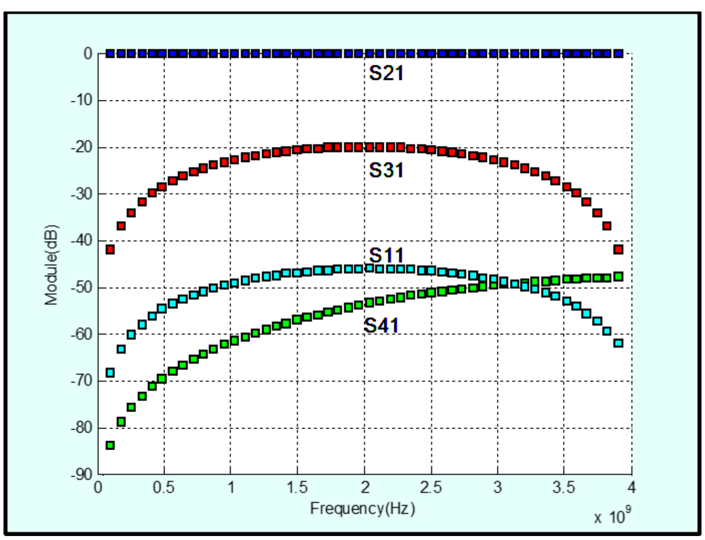

Fig. 13*. EMC coupler's response obtained in Matlab environment.*

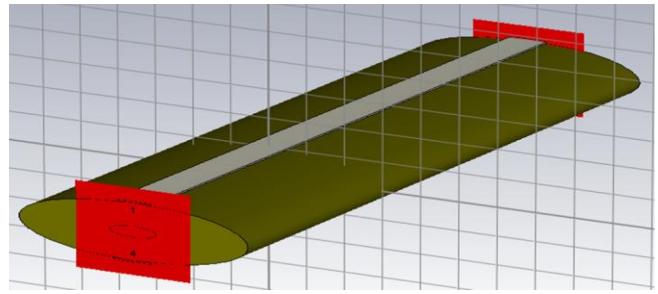

Fig. 14*. EMC coupler designed under CST Microwave Studio environment.*

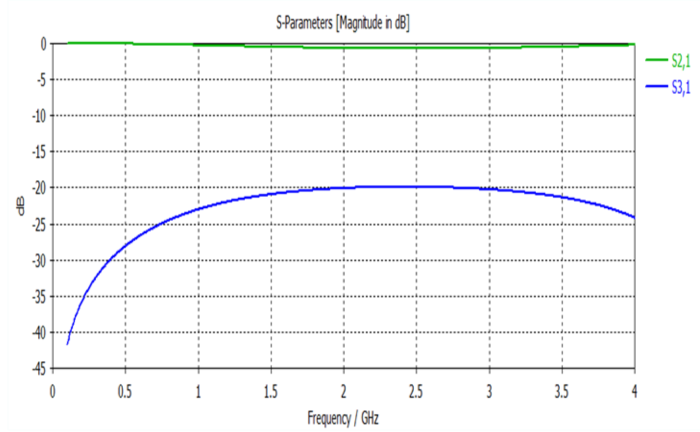

Fig. 15*. EMC coupler's response obtained in CST Microwave Studio environment.*

4 CONCLUSION

The most important focus of the present work is the 2D-FEM characterization of the inhomogeneous open quasi-TEM coupled elliptical microstrip line, and to use the found EM-parameters to design a new high-performance microwave elliptical microstrip directional coupler of good directivity and high isolation. Our results were validated by using the found results in the literature, and by using Matlab and CST Microwave Studio Softwares. The found 2D-FEM characterization results represent a considerable improvement in the coupled elliptical microstrip line designs, and are completely compatible with the trends and requirements of microwave non-planar components mounted on non-planar shaped substrates. Our perspective is to develop new accurate closed-form formulas for all the EM-parameters of the CEML line, which are very required and well-suited in the design of non-planar microwave and RF circuits, convenient for high-frequency and telecommunication applications.

REFERENCES

[1] N. Dib, T. Weller, M. Scardelletti., and M. Imparato, "Analysis of cylindrical transmission lines with the finite difference time domain method," IEEE Transactions on Microwave Theory and Techniques, vol. 47, no. 4, pp. 509-512, 1999.

[2] T. Kitamura, T. Koshimae, K. Hira, and S. Kurazono, "Analysis of cylindrical microstrip lines utilizing the finite

difference time-domain method," IEEE Transactions on Microwave Theory Techniques, vol. 42, no. 7, pp. 1279-1282, 1994.
[3] N. Dib and T. Weller, "Two-dimensional finite difference time domain analysis of cylindrical transmission lines," International journal of electronics, vol. 87, no. 9, pp. 1065-1081, 2000.
[4] A. Nakatani and N. Alexopoulos, "Coupled microstrip lines on a cylindrical substrate," IEEE Transactions on Microwave Theory and Techniques, vol. 35, no. 12, pp. 1392–1398, 1987.
[5] A. Nakatani, "Microstrip circuits and antennas on cylindrical substrates", PhD thesis, University of California, Los Angeles, 1988.
[6] F. Silva, S. Fonseca, A. Soares, and A. Giarola, "Effect of dielectric overlay in a microstrip line on circular cylindrical surface," IEEE Transactions on Microwave Theory and Techniques, vol. 2, no. 9, pp. 359-360, 1992.
[7] H. Chen and K. Wong, "Characterization of coupled cylindrical microstrip lines mounted inside a ground cylinder," Microwave and Optical Technology Letters, vol. 10, no. 6, pp. 330-333, 1995.
[8] H. Chen and K. Wong, "A Study of the transverse current contribution on the characteristics of a wide cylindrical microstrip line," Microwave and Optical Technology Letters, vol. 11, no. 6, pp. 339-342, 1996.
[9] D. Lachachi, Y. Bekri, N. Benabdallah, M. Chetioui, A. Boudkhil, and N. Benahmed, "Accurate closed-form formulas for the electromagnetic parameters of a new low-loss high performance quasi-TEM sliced coaxial coupler," International Journal of Microwave and Optical Technology, vol. 15, no. 2, pp. 122-131, 2020.
[10] Y. Bekri, N. Benabdallah, D. Lachachi and N. Benahmed, "Expressions for the TEM-parameters deduced from FEM-analyses for shielded and coupled cylindrical striplines," International Journal of Electronics and Communications (AEÜ) , vol. 70, no. 3, pp. 241-249, 2016.
[11] Y. Bekri and N. Benahmed, "Simple CAD Models for Novel 50 Ω and 75 Ω Cylindrical Stripline Couplers," 2019 International Conference on Wireless Technologies, Embedded and Intelligent Systems (WITS), Fez, Morocco, 2019, pp. 1-6, doi: 10.1109/WITS.2019.8723813.
[12] Y. Bekri and N. Benahmed, "FEM Analysis of a New Type of Cylindrical Stripline Couplers for High-Power Applications," 2019 International Conference on Advanced Electrical Engineering (ICAEE), Algiers, Algeria, 2019, pp. 1-6, doi: 10.1109/ICAEE47123.2019.9015141.
[13] Y. Bekri, N. Benabdallah, D. Lachachi, and N. Benahmed, "Novel analytical expressions for the electromagnetic parameters of cylindrical striplines," Journal of Science & Technology, vol. 16, no. 01, pp. 01-11, 2016.
[14] Y. Bekri, N. Benahmed, N. Benabdallah, and D. Lachachi, "2D-FEM Characterization and Design of Inhomogeneous Coupled Cylindrical Microstrip Line for Microwave Applications," 020 1st International Conference on Communications, Control Systems and Signal Processing (CCSSP), EL OUED, Algeria, 2020, pp. 545-551, doi: 10.1109/CCSSP49278.2020.9151645.
[15] www.freefem.org
[16] www.mathworks.com
[17] http://www.cst.com.
[18] http://www.microcal.com.