

Numerical Modeling Analysis of Planar Low-Pass Filter with Variable Impedance[†]

Delia Veres, Claudia Pacurar , Claudia Constantinescu , Oana Luca and Adina Giurgiuman * 

Department of Electrotechnics and Measurements, Technical University of Cluj-Napoca, 400027 Cluj-Napoca, Romania; delia.veres@campus.utcluj.ro (D.V.); claudia.pacurar@ethm.utcluj.ro (C.P.); claudia.constantinescu@ethm.utcluj.ro (C.C.); oana.lazar@campus.utcluj.ro (O.L.)

* Correspondence: adina.giurgiuman@ethm.utcluj.ro

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Abstract

Low-pass filters play an essential role in facilitating the passage of low frequencies and eliminating high-frequency noise, thus contributing to ensuring the stable and high-performance operation of modern communication systems. Their performance depends on the dielectric material used, which influences losses and stability. This paper investigates the influence of dielectric material on the performance of planar low-pass filters with variable impedance, with the analysis performed for a third-order low-pass filter. The obtained results highlight the significant effects of dielectric material choice and its thickness on frequency response, impedance matching, and losses, thus providing recommendations for optimal design of these filters used in various radio frequency applications.

Keywords: planar technology; low-pass filter; variable impedance; Rogers; FR4 Epoxy

1. Introduction

The accelerated evolution of modern electronic systems has determined the need for developing high-performance components capable of operating efficiently at high frequencies. In this context, planar electromagnetic technology has become an innovative solution for realizing various planar devices, such as planar coils, filters for electromagnetic interference suppression, planar antennas, and microstrip filters, which are reliable and easy to integrate into modern substrate circuits [1–6]. In Ref. [1], the conventional filter using stepped impedance techniques for third and fifth orders with Chebyshev response was studied. In Ref. [7], a stepped-impedance low-pass microstrip filter composed of graphene-based film (GBF) microstrip is proposed. The GBF filter achieves a good performance, which is comparable to that of a traditional copper filter. Overall, these studies illustrate the evolution of planar low-pass filter design from conventional stepped-impedance structures.

Compared to traditional solutions, planar magnetic structures offer reduced electromagnetic losses due to the diminution of skin and proximity effects present at high frequencies. The goal of planar magnetic technology is miniaturization, increased energy efficiency, improved thermal dissipation, and integration of planar components into modern electronic circuits [6].

Low-pass filters realized in planar technology have wide applicability due to their reduced dimensions and ease of integration into circuits with active components, as can be observed in the example presented in Figure 1 [8].



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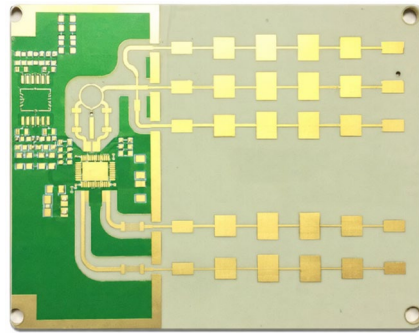


Figure 1. Example of a filter used in radar applications [8].

Figure 2 presents the general configuration of a low-pass filter with variable impedance, which consists of a succession of segments with high characteristic impedance (Z_H) and, respectively, low impedance (Z_L). The narrow thickness line segment can be considered equivalent to an inductor, corresponding to impedance Z_H , while the wide thickness line segment is equivalent to a capacitor, with impedance Z_L . The characteristic impedance of the system is denoted by Z_0 .

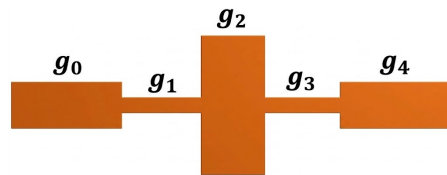


Figure 2. General configuration of a low-pass filter with variable impedance.

Filter dimensioning is performed in two stages involving both analytical and numerical calculations. The first stage consists of defining design parameters specific to the application and identifying normalized coefficients from specialized literature [1,9,10].

The electrical length, βl , is proportional to the respective inductance and capacitance and is calculated as follows [11–13]. For capacitors:

$$\beta l = \frac{g_k Z_L}{Z_0} \text{ [rad/m]} \quad (1)$$

For inductors:

$$\beta l = \frac{g_k Z_0}{Z_H} \text{ [rad/m]} \quad (2)$$

For determining segment thickness, the following relations are applied [1,9,14]:

✓ if $\frac{W}{h} \leq 2$:

$$Z_0 = \frac{60}{\sqrt{\epsilon_{\text{eff}}}} \ln \left(\frac{8h}{W} + \frac{W}{4h} \right) \text{ } [\Omega] \quad (3)$$

✓ if $\frac{W}{h} \geq 2$:

$$Z_0 = \frac{120\pi}{\sqrt{\epsilon_{\text{eff}}}(W/h + 1.393 + 0.667 \ln(W/h + 1.444))} \text{ } [\Omega] \quad (4)$$

After identifying dimensions based on calculations, the analysis stage follows, performed through successive numerical modeling using Ansys HFSS software 2023/R2 because parasitic effects affect the output response.

2. Analysis of Planar Filter as a Function of Different Dielectric Materials

To analyze how the dielectric material used for realizing the low-pass filter influences its performance, three low-pass filter configurations were designed and analyzed through numerical modeling using FR4, RO3003, and RO5880.

The configuration from specialized literature presented in Ref. [1] Figure 1a, realized on FR4 dielectric ($\epsilon_r = 4.3$), was chosen to validate the correctness of model implementation in HFSS and the use of this program.

Based on the specifications taken from [1], the formulas presented in Section 1 were applied and the lengths for the microstrip segments presented in Figure 3a were obtained. It is noted that the widths of the microstrip segments are identical. This configuration was implemented and run, and the obtained results are presented in Figure 3b. It is observed that the filter's performance is limited and the condition for the cutoff frequency of 1.9 GHz is not fulfilled.

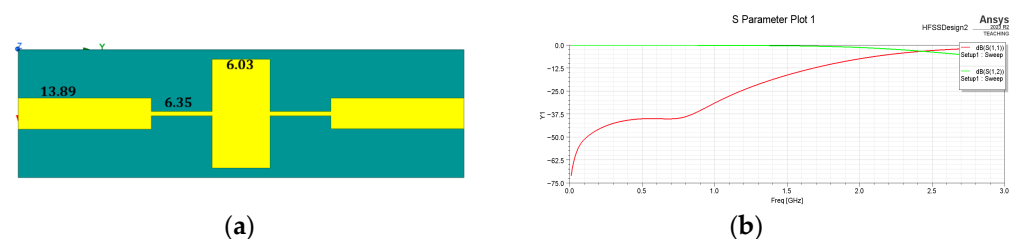


Figure 3. Low-pass filter with variable impedance: (a) geometry based on calculated dimensions; (b) S-parameters.

Thus, adjustment of the microstrip section lengths is necessary, as also specified by the authors of article [1]. Therefore, a new run was performed taking into account the same lengths as in the article. Figure 4 presents the model realized in HFSS based on dimensions taken from the article together with the obtained result.

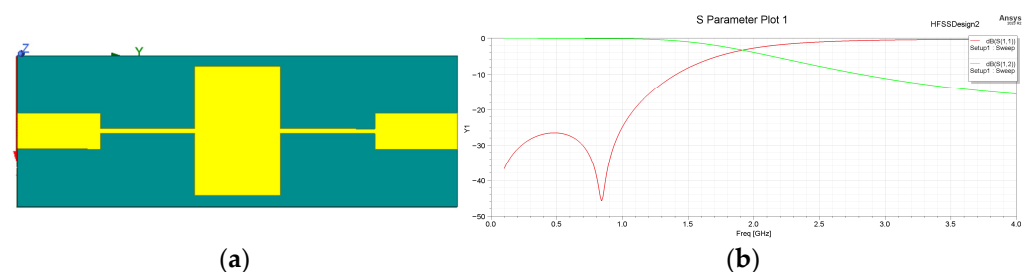


Figure 4. Low-pass filter with variable impedance: (a) optimized geometry; (b) S-parameters.

For conducting the proposed research, a low-pass filter was designed and analyzed on Rogers RO3030 substrate (Rogers Corporation, Chandler, AZ, USA) ($\epsilon_r = 3$) with $g = 1.52$ mm and Rogers RO 5880 (Rogers Corporation, Chandler, AZ, USA) ($\epsilon_r = 2.2$) with $g = 1.57$ mm, respectively. Rogers is a composite laminate characterized by very low dielectric losses, very good thermal stability, and constant permittivity [15].

Because the new substrates have different electrical permittivity and thickness, calculations are redone based on the steps presented previously, for each individual case, and then the structure is implemented in HFSS software to determine the analysis of the proposed filter. To reach the imposed frequency, it was necessary to complete eight projects with different geometric dimensions for each case. The optimal geometric dimensions determined to obtain the imposed cutoff frequency for the planar filter geometry are presented in Table 1.

Table 1. Optimal dimensions of the two filter configurations.

Dimensions		Filter RO3003				Filter RO5880		
l (mm)	0.63	13.14	0.63	3.85	0.91	16.12	0.91	4.87
L (mm)	7.31	7.09	7.31	16.16	10.39	10.31	10.39	20

The results obtained from numerical simulations for all three analyzed dielectric substrates are presented in Figures 5–7.

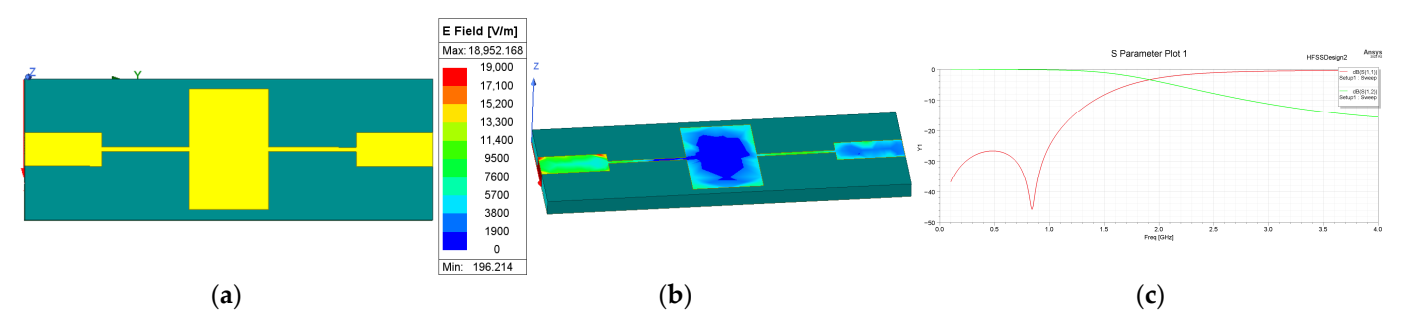


Figure 5. Third-order low-pass filter with FR4 dielectric: (a) model geometry; (b) electric field distribution; (c) S-parameters.

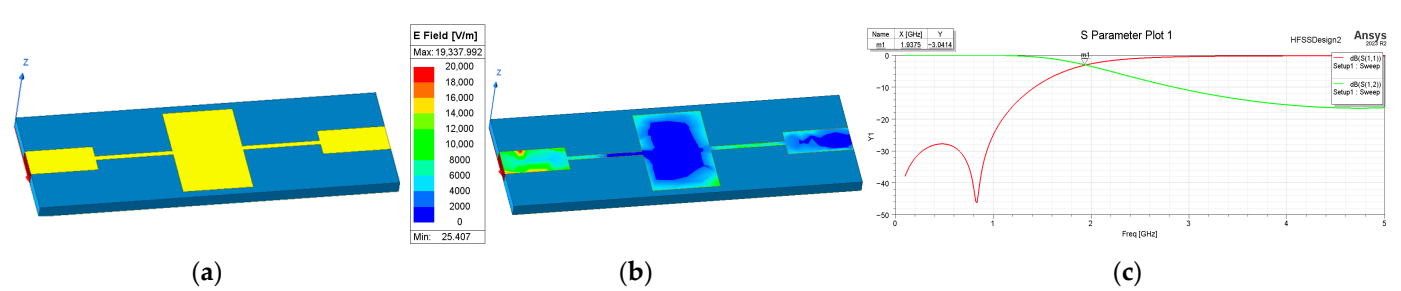


Figure 6. Third-order low-pass filter with RO3003 dielectric: (a) model geometry; (b) electric field distribution; (c) S-parameters.

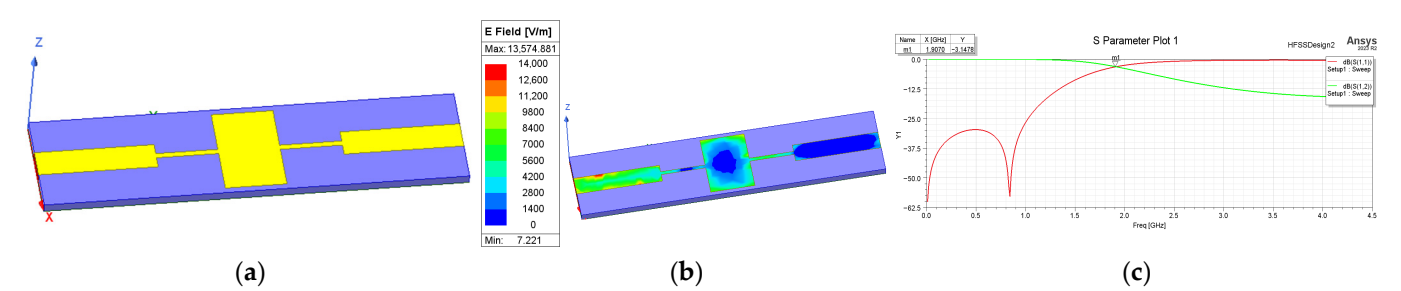


Figure 7. Third-order low-pass filter with RO5880 dielectric: (a) model geometry; (b) electric field distribution; (c) S-parameters.

The electric field distribution highlights the influence of the dielectric substrate on filter performance. In the case of FR4, the field is more dispersed, indicating high dielectric losses. For RO3003, better field concentration is observed, alongside reduced losses and improved performance. The RO5880 substrate presents the best electric field localization (with minimal losses). Thus, filter performance increases with the reduction in dielectric losses and improvement in electromagnetic field distribution.

3. Analysis of Dielectric Layer Thickness Influence on Analyzed Planar Filter Parameters

Subsequently, the influence of dielectric substrate thickness on the performance of the third-order planar filter is analyzed using the same substrate for all analyses, namely Rogers RO3003 dielectric, but using three different thicknesses that are frequently used in practical applications. Thus, starting from the filter geometry [1], its geometric dimensions were redesigned for the standard thicknesses of RO3003 ($\epsilon_r = 3$) 1.52 mm, 0.76 mm, and 0.51 mm. For each case, the design steps are mentioned and the cutoff frequency is 1.9 GHz.

3.1. Low-Pass Filter with $f_c = 1.9$ GHz

In this case, the geometry presented in Figure 3a was considered, in which the dielectric material was replaced in turn with RO3003 of different thicknesses.

3.1.1. RO3003 Dielectric $g = 1.52$ mm

In this project, a RO3003 type dielectric with thickness 1.52 mm was used. The new project was run in HFSS to determine the cutoff frequency, and then the geometric dimensions of the filter were successively modified until the imposed cutoff frequency was obtained. The determined optimal dimensions are: $l_{ZH} = 7.31$ mm, $w_{ZH} = 0.63$ mm, $l_{ZL} = 7.09$ mm; $w_{ZL} = 13.14$ mm; $l_{Z0} = 16.16$ mm; $w_{Z0} = 3.85$ mm. Figure 8 presents the optimal filter geometry together with the graphical representation of S-parameters.

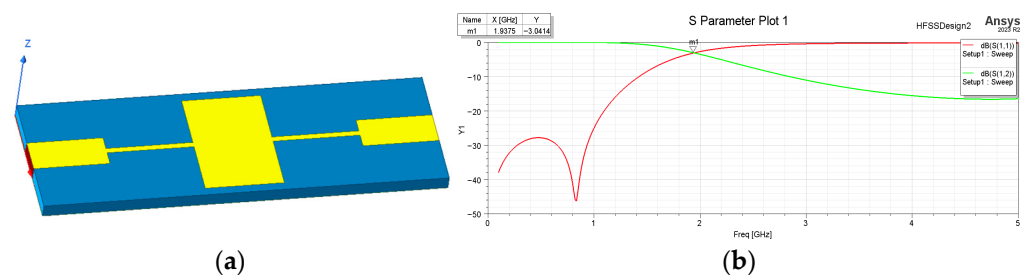


Figure 8. Third-order low-pass filter with RO3003 dielectric, 1.52 mm, 1.9 GHz: (a) model geometry; (b) S-parameters.

3.1.2. RO3003 Dielectric $g = 0.76$ mm

A similar procedure was followed to determine the optimal filter geometry with RO3003 dielectric thickness 0.76 mm to obtain a cutoff frequency of 1.9 GHz. The geometric dimensions obtained have the following values: $l_{ZH} = 9.73$ mm, $w_{ZH} = 0.32$ mm, $l_{ZL} = 9.39$ mm, $w_{ZL} = 6.55$ mm, $l_{Z0} = 9.05$ mm, and $w_{Z0} = 1.92$ mm. Figure 9 presents the optimal filter geometry together with a graphical representation of the S-parameters.

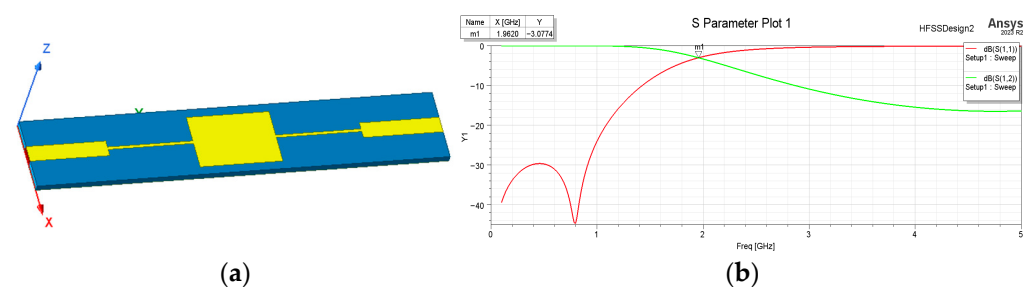


Figure 9. Third-order low-pass filter with RO3003 dielectric, 0.76 mm, 1.9 GHz: (a) model geometry; (b) S-parameters.

3.1.3. RO3003 Dielectric $g = 0.51$ mm

For the low-pass filter configuration with RO3003 dielectric of thickness 0.51 mm, the following optimal geometric dimensions were obtained: $l_{ZH} = 10.25$ mm, $w_{ZH} = 0.21$ mm, $l_{ZL} = 9.89$ mm, $w_{ZL} = 4.41$ mm, $l_{Z0} = 9.53$ mm and $w_{Z0} = 1.29$ mm. Figure 10 presents the optimal filter geometry together with a graphical representation of the S-parameters.

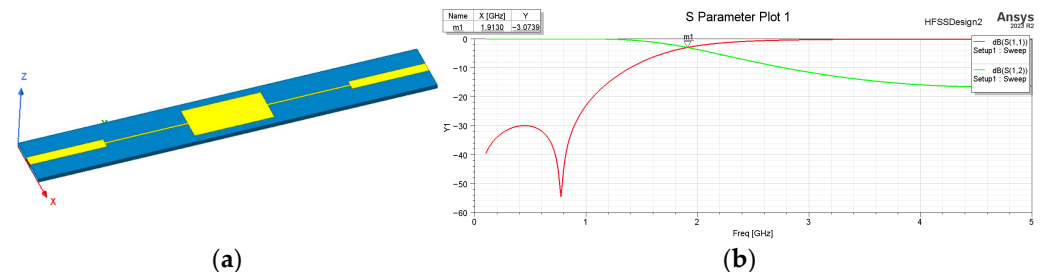


Figure 10. Third-order low-pass filter with RO3003 dielectric, 0.51 mm, 1.9 GHz: (a) model geometry; (b) S-parameters.

Based on the analyses performed, it was concluded that the filter realized on RO3003 substrate with thickness 0.76 mm offers the best compromise between electromagnetic performance and technological feasibility, while the 0.51 mm variant presents the best theoretical performance but also higher manufacturing costs.

4. Conclusions

In this article, the analysis of third-order low-pass filter performance was proposed both as a function of the dielectric material used in its design and as a function of dielectric thickness. Following the analyses performed, it was found that low-pass filter performance is influenced by both the type of dielectric and substrate thickness; specifically, materials with reduced losses ensure better transmission and superior matching, and reducing substrate thickness increases selectivity and impedance ratio but introduces greater sensitivity to technological variations and requires precise optimization. Thus, in practice, the optimal choice represents a compromise between electromagnetic performance, stability, and manufacturing cost. The best-performing filter configuration described in this paper will be practically implemented, tested, and validated for concrete industrial applications.

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References

1. Ghanem, S.; Allam, A.M.M.A.; Shubair, R.M. Equivalent Circuit for Implemented LowPass Filter with SRR Metamaterial. In Proceedings of the International Conference on Electrical and Computing Technologies and Applications (ICECTA), Ras Al Khaimah, United Arab Emirates, 21–23 November 2017.
2. Mitra, S.; Kumuda, D.K. Stepped Impedance Microstrip Low-Pass Filter Implementation for S-band Application. *Int. J. Latest Trends Eng. Technol. (ILJTET)* **2015**, *5*, 248–255. [\[CrossRef\]](#)
3. Racasan, A.; Munteanu, C.; Topa, V.; Pacurar, C.; Hebedean, C. Filter geometry optimization for the conduction electromagnetic interferences suppression. In Proceedings of the 2014 International Conference on Optimization of Electrical and Electronic Equipment (OPTIM), Bran, Romania, 22–24 May 2014; pp. 46–51. [\[CrossRef\]](#)
4. Hebedean, C.; Munteanu, C.; Racasan, A.; Pacurar, C. Application of Windings Shifting for the Optimization of Planar Structures. *Environ. Eng. Manag. J. (EEMJ)* **2013**, *12*, 1153. [\[CrossRef\]](#)
5. Racasan, A.; Munteanu, C.; Topa, V.; Pacurar, C.; Hebedean, C. Electromagnetic interferences suppression in planar integrated devices. In Proceedings of the 2014 International Symposium on Electromagnetic Compatibility, Gothenburg, Sweden, 1–4 September 2014; pp. 940–945. [\[CrossRef\]](#)
6. Cretu, M.; Micu, D.D. Improved coil design for repetitive magnetic stimulation of the spinal cord. *COMPEL* **2015**, *34*, 1043–1053. [\[CrossRef\]](#)
7. Zhou, W.; Xia, W.; Zhang, J.; He, D.; Liu, C.; Wu, Z. Flexible Graphene Based Films for Stepped Impedance Lowpass Microstrip Filter. In Proceedings of the 2018 IEEE International Conference on Computational Electromagnetics (ICCEM), Chengdu, China, 26–28 March 2018.
8. PCB Printed Circuit Board and PCBA Manufacturing. Available online: www.ipcb.com (accessed on 25 March 2026).
9. Pozar, D.M. *Microwave Engineering*; Wiley: Hoboken, NJ, USA, 2012.
10. Hong, J.-S.; Lancaster, M.J. *Microstrip Filters for RF/Microwave Applications*; Wiley: Hoboken, NJ, USA, 2001.
11. Matthaei, G.L.; Young, L.; Jones, E.M. *Design of Microwave Filters Impedance-Matching Networks and Coupling Structures*; McGraw-Hill Book Company: Columbus, OH, USA, 1964.
12. Majidifar, S.; Makki, S.V.A.L.-D.; Ahmadi, A.; Alirezaee, S. Compact Microstrip Lowpass Filter Using Stepped Impedance Spiral Resonator. In Proceedings of the Fourth International Conference on Computational Intelligence and Communication Networks, Al-Khobar, Saudi Arabia, 4–6 December 2022. [\[CrossRef\]](#)
13. Zhu, W.-g.; Wang, P.-z.; Liu, H. A Low-Pass Filter Design Based on Split-Ring Resonator with Defected Ground Structure. In Proceedings of the 2018 10th International Conference on Communications, Circuits and Systems (ICCCAS), Chengdu, China, 22–24 December 2018.
14. Das, A.; Roy, A.; Roy, K.; Bhattacharyya, A.; Chowdhury, D.; Paul, S. Design and Analysis of Microwave Stepped Impedance Low Pass Filter for Bluetooth Application. In Proceedings of the 2015 IEEE International Conference on Electrical, Computer and Communication Technologies (ICECCT), Coimbatore, India, 5–7 March 2015.
15. Rogers Corporation. Available online: www.rogerscorp.com (accessed on 25 March 2026).

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