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Design of a 3.8-GHz Microstrip Patch Antenna for Sub-6 GHz 5G Applications

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***Abstract*— This paper presents a design of a centre-fed Rectangular Microstrip Patch Antenna (RMSA) that resonates at exactly 3.8 GHz. The effect of the dielectric material's choice, substrate height, dielectric constant, and the substrate material is on the RMSA for a constant resonant frequency while maintaining signal integrity and reducing signal loss. The antenna's gain and input return loss are improved by adjusting the upper and lower bounds of the height of the dielectric substrate. Results show that a maximum bandwidth of 350 MHz, a gain of 7.77 dBi, and input return loss (S_{11}) of below –33 dB were obtained. Furthermore, a smaller dielectric constant below 2.5 and a Voltage Standing Wave Ratio (VSWR) below 2 dB will conveniently provide a wider bandwidth (BW) of over 250 MHz which is convenient to meet frequency range 1 (FR1) bandwidth expectation.**

Keywords— Rectangular Microstrip patch antenna, frequency range, S-parameter, antenna gain.

I. Introduction

Deployment of the fifth-generation (5G) network system has been evolving since late 2019 in most developed countries, which includes fixed wireless access (FWA) and mobile communication [1]. The 5G networks support both FWA and mobile communication networks. 5G NR support two types of frequency range which are FR1 (3.3-3.8,4.5-5,5.925-7.125 GHz) and FR2 (24.25-27.5,37.5-40.5,42.5-43.5,45.5-47,47.2-50.2,50.4-52.6,66-76,81-86GHz) respectively. In this paper, we will be focusing on the sub 6 GHz frequency bands, i.e., FR1 [2],[3].

Microstrip antenna (MSA) or Microstrip patch antennas are made from a metallic material (patch and ground), dielectric material (substrate) [4],[5]. The limitation can be optimized by carefully varying the dielectric layers, the height, shape, and size to keep the antenna resonating at the desired frequency.

MSA has different types, determined by their geometrical shapes, such as rectangular, triangular, circular, helix, H-shape, circular-ring, and square, as shown in [4]. The choice of selection is dependent on the trade-off between design simplicity and antenna performance, which were considered in this paper. Rectangular MSA (RMSA) will be discussed due to its simplicity, alluring radiation design features, and good impedance matching. There is also the need to choose a suitable substrate dependent on the frequency, power level, circuit design, and functionalities [6]. Most of the literature [7]–[14] focused on designing 2.4 GHz RMSA for wireless local area networks (WLAN) in the sub – 6GHz frequency band. In this paper, we shall be focusing on the 3.8 GHz frequency band, which falls within the FR1. This paper analyses and optimizes RMSA, a 3.8 GHz frequency band for 5G user equipment, using different dielectric substrates with the patch antenna's dimension. In [9], FR-4 substrate material with a dielectric constant of $\varepsilon_r = 4.8$ for a 4 GHz frequency band RMSA was employed. The thickness of the dielectric substrate is varied, which tends to change the resonant frequency (F_r) of the antenna. The S_{11} parameter for F_r at 3.77 GHz, 3.84 GHz, 4.01 GHz and 4.07 GHz were -19.13 dB, -20.56 dB,-49.67 dB and -32.54 dB respectively and (VSWR) for 3.77 GHz, 3.84 GHz, 4.01 GHz and 4.07 GHz were 1.27,1.34,1.28,1.18. A single-element 1x2 and 2x2 line-fed RMSA for a 3.8 GHz application has been designed [15]. The substrate utilized is Rogers Duriod RT-5880.

Substrates are dielectric materials that have properties of poor conductors of electricity but good storage for the electrostatic field. Dielectric materials are situated between the patch and the ground to reduce the loss of energy radiation. Dielectric substrate comes in diverse forms: glass epoxy-based (e.g. Flame Retardant four (FR4)), reinforced microfiber with Polytetrafluoroethylene (PTFE) or Teflon (e.g. RT/Duriod 5880) and ceramic filled PTFE (e.g. RO 3000 series). These dielectric materials meet mechanical, thermal, radiation loss, electrical and chemical properties. Further studies about dielectric material properties can be found in [17]–[18]. In this paper, the authors compare their simulation results with the measured, fabricated antenna responses.

II. Methodology

A. Design of a Rectangular MSA

When designing a Microstrip Antenna, the first consideration is reducing the fringing effect, one of the dominant factors in RMSA due to the patch antenna's finite dimension.

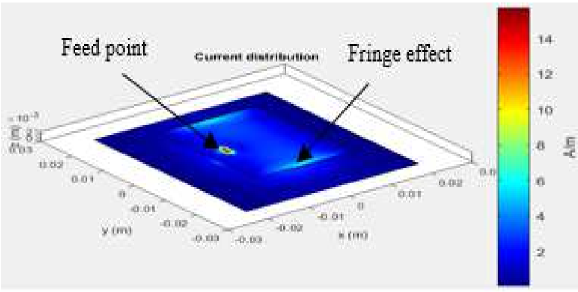

Fig. 1. The current distribution of an RMSA

The dimensions of the patch (length (L) and width (W)) and height of the dielectric substrate (h) must conform to certain principles such as L/h "1 **,** W/h "1 and ε_r"1, which reduces the fringing effect on the performance of the RMSA, as shown in Fig. 1 [4], [16]. The above statement can be achieved through (1) - (8), respectively, and the derived parameters are shown in Table I.

I. Determination of Frequency f,

This is the frequency of choice with which the antenna is going to resonate, i.e., the resonant frequency f,

$$\lambda = {}^{v}/_{f} \ or \ {}^{c}/_{f} \tag{1}$$

λ: Wavelength of the antenna; $v \ or \ c$: $3x10^8$ m/s

II. Choice of substrate

In [17]–[18], they showed the characteristics of dielectrics substrate of different materials. Each dielectric substrate is suitable for a specific purpose. If Rodger series materials are considered, they have a low loss when used for high frequencies and have a low dielectric constant. FR-4 is more suitable for less than 1 GHz frequencies, and TMM dielectric is similar to the Rodger series except for their materials, high dielectric constant, and low moisture absorption [17][18]. A thick substrate will increase radiation power, improve bandwidth impedance, increase dielectric loss, and increase surface loss and weight. Table I shows the dielectric substrates used in the simulation.

III. Dimension of Patch $\boldsymbol{L, W}$*,*

The design of the patch includes the length, width, and position of the centre-fed

$$W = \frac{c}{2f}\left(\sqrt{\frac{2}{\varepsilon_r+1}}\right) \tag{2}$$

where W is the width of the patch, and f is the frequency.

To calculate the length L we need to compute the effective length L_{eff}, effective dielectric constant ε_{reff}, the height of the substrate $h, \ and \ \Delta L$. The substrate's height or thickness must be carefully chosen because resonant frequency highly depends on its choice [4].

$$\varepsilon_{reff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left(1+12\left(\frac{h}{W}\right)\right)^{-1/2} \tag{3}$$

$$L_{eff} = \frac{c}{2f\sqrt{\varepsilon_{reff}}} \tag{4}$$

$$L = L_{eff} - 2\Delta L \tag{5}$$

IV. Dimensions of ground $\mathbf{L_g}$ **,** $\mathbf{W_g}$

$$W_g = W + 6h \tag{6}$$

$$L_g = L + 6h \tag{7}$$

V. Impedance $\boldsymbol{Z_{in}}$*,*

The feed-in of this type of MSA is at the centre of the patch y_o as shown in Fig. 2, the minimum value for the frequency resonance depends on the feed line; as the feed line moves from the edge to the centre, the frequency resonant [4]**.**

$$R_{in}(y = y_o) = Z_{in}\cos^2\left(\frac{\pi}{L}y_o\right) \tag{8}$$

y_o=feed point position, $R_{in} = R_{50\Omega}$: impedance at 50 Ω
Equations (1)-(8) are used in designing Fig. 2.

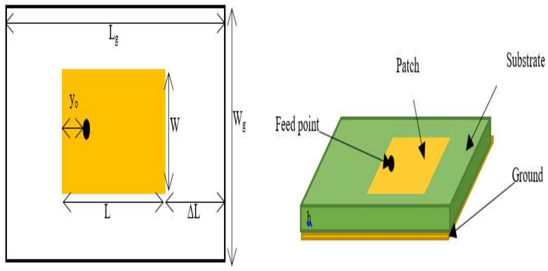

Fig. 2. Top view and side of Dimension of rectangular MSA

As shown in Fig. 2, MATLAB 2020b software is used to design the patch antenna and also the parameters such as S-parameter, VSWR, antenna gain, return loss and impedance

III. Result and Analysis

We considered five types of dielectric substrate (FR-4 at $\varepsilon_r = 4.4 \ and \ 4.8$, RO4730JXR at $\varepsilon_r = 3$, RT/Duriod 5870 at $\varepsilon_r = 2.3$ and RT/Duriod 5880 at $\varepsilon_r = 2.2$ for different h as shown in Table I. Another criterion that was considered for the stability of the antenna in the design was VSWR (0.5 ≤ VSWR ≤ 1.5), the S_{11} parameter and return loss must be reasonably low, i.e. below -10 dB [4],[7],[15]. When the dimension is considered, the RO4730JXR substrate has the largest dimension, followed by RT/Duriod 5880 and RT/Duriod 5870 because of the height of h. When the $h = 3mm$, RT /Duriod 5880 dimension was the largest. FR-4 at $\varepsilon_r = 4.8, h = 4 \ mm$ only resonated at the 3.8 GHz frequency band; that was why we have a single computation in Table I. When VSWR is considered, FR-4 has the highest value compared to others, as shown in Table I.

Table I. Summary of results on 3.8 GHz Microstrip Patch Antenna

	Dielectric substrate																
Material	FR4				RO4730JXR					RT5870				RT 5880			
Thickness (mm)	0.06				0.06					0.127				0.127			
δ	0.026				0.0023					0.0012				0.0009			
ε_r	4.4			4.8	2.3					2.3				2.2			
L (mm)	17.80	17.70	17.70	16.40	21.60	21.30	21.10	20.90	20.70	24.40	24.30	24	23.60	25.10	24.80	24.50	24.40
W (mm)	24	24	24	23.20	27.90	27.90	27.90	27.90	27.90	30.70	30.70	30.70	30.70	31.2	31.2	31.2	31.2
ε_{reff}	3.80	3.78	3.76	3.98	2.68	2.68	2.63	2.62	2.60	2.10	2.09	2.07	2.06	2.02	2.01	1.99	1.99
L_G (mm)	34.60	35.70	36.30	40.40	37.80	40.50	42.10	43.70	45.90	41.20	42.30	45	47.60	40.70	42.80	45.50	46
W_G(mm)	40.80	42	42.60	47.20	44.10	47.10	48.90	50.70	53.10	47.50	48.70	51.70	54.70	46.80	49.20	52.20	52.80
$R_{in}(\Omega)$	197.60	197.70	197.70	208.20	170	170.20	170.30	170.40	170.50	154.50	154.510	154.640	154.80	152.06	152.15	152.28	152.31
y_o (mm)	5.90	5.90	5.90	5.50	6.80	6.80	6.70	6.60	6.60	7.50	7.50	7.40	7.30	7.70	7.60	7.50	7.50
h (mm)	2.80	3	3.10	4	2.70	3	3.50	3.80	4.20	2.70	3	3.50	4	2.60	3	3.50	3.60
ΔL(mm)	1.20	1.30	1.30	1.70	1.30	1.50	1.60	1.80	1.90	1.40	1.50	1.70	20	1.30	1.50	1.80	1.80
Gain (dBi)	6.56	6.63	6.62	6.64	7.13	7.17	7.20	7.23	7.23	7.50	7.58	7.64	7.67	7.40	7.66	7.76	7.77
L_{eff} (mm)	20.30	20.30	20.30	19.80	24.10	24.30	24.3	24.40	24.50	27.20	27.30	27.40	20	27.70	27.90	28	28
S_{11} (dB)	-13	-13.90	-13.80	-10	-12.50	-20	-24.50	-20	-15.28	-14	-18.3	-31.28	-17.61	-12	-18.80	-33.87	-28.29
RL (dB)	12.98	13.90	13.83	10	12.50	20	24.48	20	15.28	14	18.30	31.28	17.61	12	18.80	33.87	28.29
VSWR (dB)	1.58	1.51	1.51	1.80	1.55	1.24	1.23	1.219	1.41	1.5	1.28	1.056	1.30	1.5	1.26	1.04	1.08
BW (MHz)	320	300	280	200	230	300	300	340	280	170	275	350	325	120	270	275	330

For example, during our simulation for FR-4 at $\varepsilon_r = 4.4$, we discovered that when the value keeps decreasing as the substrate's height is increased and when $h > 3.1mm$,the VSWR value spikes above 1.51, and the resonant frequency changes slightly from 3.8 GHz. In other types, VSWR showed a lesser value when compared to FR-4. This shows that provided the substrate dielectric is kept low at i.e $\varepsilon_r < 2.5$ and at a reasonable height, the VSWR will be below the threshold. When VSWR is one or less, there is no or minimal mismatch; likewise, when the value is 3, 75 % of the power is delivered, equivalent to 1.25 dB.

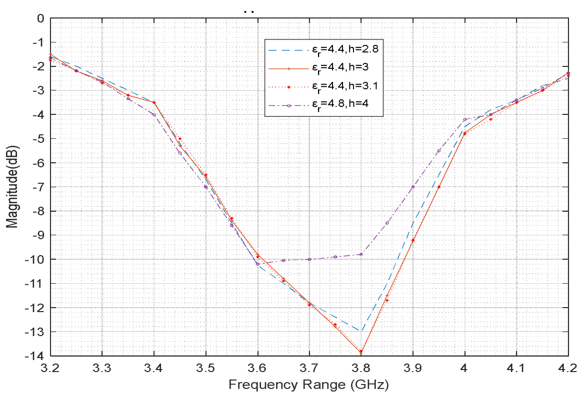

Fig. 3. S_{11} Parameter for FR4 Dielectric substrate

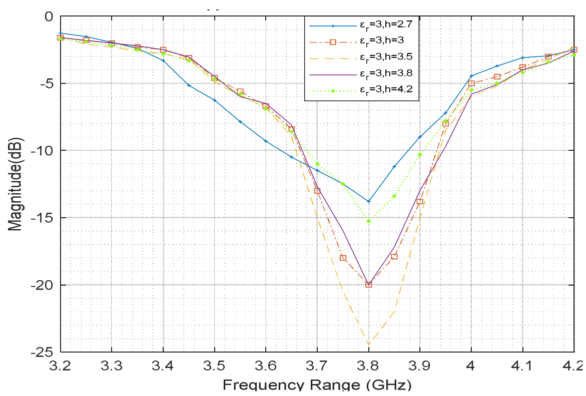

Fig. 4 S_{11} Parameter for RT/Duriod and RO Series Dielectric substrate

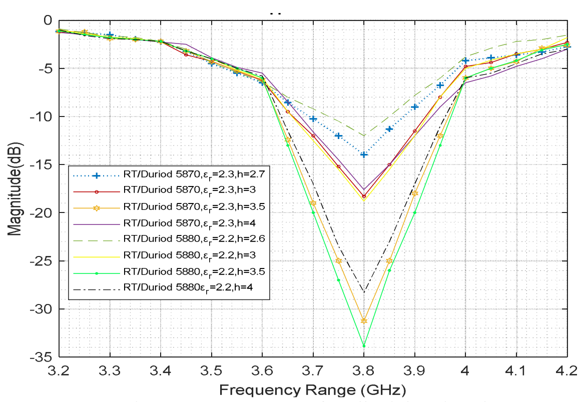

Fig. 5. S_{11} parameter for all Dielectric substrate

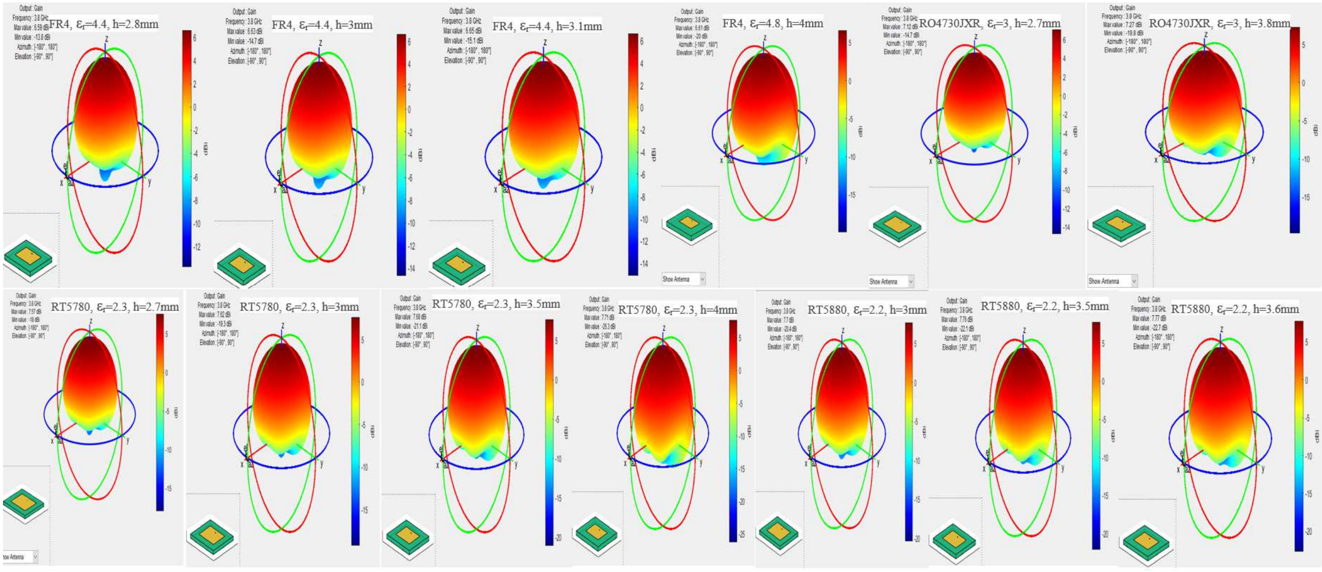

Fig. 6. Antenna pattern for all RMSA

The S_{11} parameter for all the simulation scenarios was shown in Table I and Figs. 1 to 5, respectively. When Figs. 3 to 5 are compared, the S_{11} parameter for RT/Duriod 5880 at $h = 3.5mm$ was the least, i.e. -33.87 dB, and FR-4 at $h = 4mm$ has the highest, i.e. -10 dB. When S_{11} The parameter of substrates in Figs. 4 and 5 are compared with FR 4 in Fig. 3, and they showed lower values. The values in S_{11}parameter is the same with return loss, which indicates that the return loss (RL) will also be low and makes the RMSA more stable. The loss calculation is dependent on the material being used for the dielectric substrate because they contribute to dielectric loss and conductor loss which tends to degrade the signal. In our design, we simulated to optimize the RMSA antenna gain such that the side lobe and mini lobes were small, and we arrived at a value which ranges between 6.63 -7.7 dB, as shown in Fig. 6.

It can be demonstrated that the RT/Duriod 5880 substrate had the highest gain and lowest side lobe. Also, we observed that when the S_{11} parameter has a low value, doesn't infer that the antenna's gain would be high. In our simulation, results showed a better value for antenna gain, bandwidth and S_{11} parameters, which were between 7.4-7.77 dBi, 120-330 MHz, and -12 dB to -28.28 dB when compared with [15], which was 7.02 dBi, 106.6 MHz, and between -14.22 dB to -18.2 dB RT/Duriod 5880, respectively.

IV. Conclusion

The RMSA being evaluated is intended to operate at the 3.8 GHz band of the FR1 band for 5G communication with a bandwidth capacity between 170-350 MHz. In the paper, the RMSA was fixed to resonant at 3.8 GHz. At the same time, findings showed that the chosen dimension of the RMSA and the dielectric material would significantly increase the return loss, antenna gain, and bandwidth. Also, the dimension of the RMSA is considered adequate to sit on a mobile phone perfectly. The paper showed that a quality dielectric substrate material would improve the antenna gain; however, its dimension will increase to maintain the desired resonant frequency. The RT/Duriod 5880 dielectric substrate's overall performance was observed to be the best when other antenna parameters are considered except the size of the dielectric, which tends to increase as the height of the dielectric substrate increases. Further works will be conducted in designing a multiple-band RMSA antenna for 5G user equipment and consider the effect of the roughness of the patch on the performance of the antenna.

References

[1] GSMA, "5G Global Launch," 2020. https://www.gsma.com/futurenetworks/ip_services/understanding-5g/5g-innovation (accessed May 24, 2020).

[2] Qualcomm Technologies Inc., "Spectrum for 4G and 5G," 2017. [Online]. Available: https://www.qualcomm.com/media/documents/files/spectrum-for-4g-and-5g.pdf.

[3] T. Wang, G. Li, Q. Miao, J. Li, and Y. Wang, "5G Spectrum : Is China Ready ?," *IEEE Communications Magazine*, no. July, pp. 59–65, 2015.

[4] C. A. Balanis, *Antenna Theory: Analysis and Design*, 3rd ed. New Jersey: John Wiley & Sons Inc., 2005.

[5] J. R. James, *Handbook of Microstrip Antennas*, vol. 36, no. 9. 1989.

[6] P. Hindle, J. Kimery, T. Mattingly, and J. Coonrod, "Selection of PCB Materials for 5G," *Microwave*, no. February, pp. 1–22, 2018.

[7] F. Wang, S. Li, Q. Zhou, and Y. B. Gong, "Compact wideband quad-element MIMO antenna with reversed S-Shaped walls," *Progress In Electromagnetics Research*, vol. 78, pp. 193–201, 2019, doi: 10.2528/PIERM19010201.

[8] A. B. Obot, G. A. Igwue, and K. M. Udofia, "Design and Simulation of Rectangular Microstrip Antenna Arrays for Improved Gain Performance," *International Journal of Networks and Communications*, vol. 2019, no. 2, pp. 73–81, 2019, doi: 10.5923/j.ijnc.20190902.02.

[9] R. Satyanarayana and Shankaraiah, "Bandwidth Enhancement of 4GHz Probe Fed Rectangle Microstrip Patch Antenna with Diagonal DGS Technique for Wi-Fi Applications," *International Journal of Applied Engineering Research*, vol. 14, no. 12, pp. 2925–2934, 2019.

[10] M. Khaliluzzaman, D. Kumar Chy, and M. R. H. Chowdhury, "Enhancing the Bandwidth of a Microstrip Patch Antenna at 4 GHz for WLAN using H-shaped Patch," *International Journal of Innovative Science, Engineering & Technology (IJISET)*, vol. 2, no. 2, pp. 231–237, 2015, [Online]. Available: https://www.researchgate.net/publication/272678977_Enhancing_the_Bandwidth_of_a_Microstrip_Patch_Antenna_at_4_GHz_for_WLAN_using_H-shaped_Patch/figures?lo=1.

[11] V. Bankey and N. A. Kumar, "Design and performance issues of Microstrip antennas," *International Journal of Scientific and*

Engineering Research, vol. 6, no. 3, pp. 1572–1580, 2015, doi: 10.14299/ijser.2015.03.008.

[12] M. S. Bhandari and S. C. Gupta, "Increasing Resonant Frequency of Microstrip Patch Antenna by Decreasing the Value of Dielectric Constant of Substrate," *International Journal of Advanced Research in Computer Engineering and Technology*, vol. 1, no. 5, pp. 164–166, 2012.

[13] M. I. Memon, "Microstrip Patch Antenna Design Calculator," *International Journal of Engineering Research & Technology (IJERT)*, vol. 2, no. 9, pp. 3080–3084, 2013.

[14] J. Vijayalakshmi, V. Dinesh, and S. Rubasri, "Design and analysis of high gain 2x1, 4x1, 8x1 and 8x8 circular patch antenna arrays for 2.4 GHz applications," *International Journal of Scientific and Technology Research*, vol. 9, no. 4, pp. 834–841, 2020.

[15] H. Sajjad, W. T. Sethi, K. Zeb, and A. Mairaj, "Microstrip patch antenna array at 3.8 GHz for WiMax and UAV applications," in *2014 International Workshop on Antenna Technology: Small Antennas, Novel EM Structures and Materials, and Applications (iWAT)*, 2014, pp. 107–110, doi: 10.1109/IWAT.2014.6958609.

[16] R. Garg, P. Bhartia, I. Bahl, and A. Ittipibon, *Microstrip Antenna Design Handbook*. Artech House, 2001.

[17] Rogers Corporation, "Data Sheet of RT/Duriod 5870/5880 High-Frequency Laminates," 2020. https://rogerscorp.com/advanced-connectivity-solutions/rt-duroid-laminates/rt-duroid-5880-laminates (accessed Dec. 30, 2020).

[18] Rogers Corporation, "Data Sheet of RO4730 AND RO4730G3 Antenna Grade Laminates." https://rogerscorp.com/-/media/project/rogerscorp/documents/advanced-connectivity-solutions/english/data-sheets/ro4725jxr-ro4730g3-antenna-grade-laminates-data-sheet.pdf (accessed Dec. 30, 2020).

[19] Rogers Corporation, "Data Sheet Thermoset Microwave Materials (TMM)."https://rogerscorp.com/-/media/project/rogerscorp/documents/advanced-connectivity-solutions/english/data-sheets/tmm-thermoset-laminate-data-sheet-tmm3----tmm4----tmm6----tmm10----tmm10i----tmm13i.pdf (accessed Dec. 30, 2020)