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ANALYSIS ON THE EFFECT OF DIELECTRIC MATERIAL AND COPPER THICKNESS OF SUBSTRATE TOWARDS THE PERFORMANCE OF ULTRA WIDEBAND GROUND-SLOTTED T-SHAPED POWER DIVIDER

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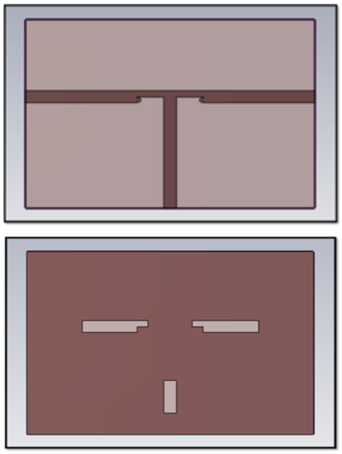
Graphical abstract



Abstract

Nowadays, the fifth generation (5G) wireless system is extensively studied to fulfill the continuously increasing demand for high data rate and mobility in wireless communication applications. Thus, to cope with this demand, various researches are required for front-end microwave components, which includes power divider. Therefore, in this article, the design and analysis of ultra wideband T-shaped power divider is presented. Two substrates are chosen in the design, which are Rogers RO4003C and TMM4 with copper thickness of 17 μm and 35 μm to analyze their effect towards ultra wideband performance of the designed power divider. The design and analysis are performed by using CST Microwave Studio. The optimal performance of the designed power divider is subjected to dielectric material and the copper thickness of the substrate. Where, the best design is obtained using TMM4 substrate that made of ceramic thermoset polymer with 35 μm copper thickness.

Keywords: Copper thickness, ground-slotted, power divider, T-shaped, substrate.

Abstrak

Pada masa kini, sistem tanpa wayar generasi kelima (5G) dikaji secara meluas untuk memenuhi permintaan yang terus meningkat bagi kadar data tinggi dan kemudahgerakan dalam aplikasi komunikasi tanpa wayar. Oleh itu, untuk memenuhi permintaan ini, pelbagai penyelidikan dilakukan pada komponen gelombang mikro bahagian-depan, termasuk pembahagi kuasa. Oleh yang demikian, dalam artikel ini, reka bentuk dan analisis bagi pembahagi kuasa berbentuk-T jalur lebar ultra dibentangkan. Dua substrat dipilih dalam reka bentuk, iaitu Rogers RO4003C dan TMM4 dengan ketebalan tembaga 17 mikron dan 35 mikron untuk menganalisis kesannya terhadap prestasi pembahagi kuasa jalur lebar ultra yang direka. Reka bentuk dan analisis dilakukan dengan menggunakan CST Microwave Studio. Prestasi optima pembahagi kuasa yang direka adalah tertakluk kepada bahan dielektrik dan ketebalan tembaga substrat. Di dalam analisis ini, reka bentuk yang terbaik diperolehi dengan menggunakan substrat TMM4 yang diperbuat daripada seramik polimer termoset dengan 35 mikron ketebalan tembaga.

Kata Kunci: Ketebalan tembaga, satah bumi berslot, pembahagi kuasa, bentuk-T, substrat.

1.0 INTRODUCTION

Nowadays, the wireless technologies penetrate into many aspects of human life globally. The technologies of wireless systems promise a world of networked and interconnected devices that provide relevant information, wherever the locations of the users. The innovative and effective use of information and communication technologies (ICT) is becoming increasingly important for economy development. Wireless communication networks are perhaps the most critical element in the global ICT strategy, underpinning many other industries. It is one of the fastest-growing and most dynamic sectors in the world. The developments of wireless technologies have greatly improved people's ability to communicate and live in both business operations and social functions. Consequently, these developments lead to an increasing of wireless traffic volume, which predicted to increase a thousand-fold over the next decade. The phenomenal success of wireless communications is mirrored by a rapid pace of technology innovation. Thus, due to that, the fifth-generation wireless system (5G), that expected to be deployed beyond 2020 is extensively studied.

A new 5G technologies' architecture has been proposed with separated indoor and outdoor applications using distributed antenna system (DAS) and massive MIMO technology [1], which can be seen as promising candidates to provide high-quality and high-data-rate services to indoor users while at the same time reducing the pressure on outdoor applications. In addition to support this requirement, various thorough research works are needed in front-end component designs, including alternative to a mixer as one of the important components. Commonly, the design of the mixer will involve active devices, which need a certain biasing voltage to be in an active state. In order to reduce the complexity of the design, the mixer-based approach can be replaced by using a six-port network, which is formed by only using passive devices such as coupler and power divider. By including these devices, it can reduce the complexity of the design and increase the performance of bandwidth. To date, there is no yet spectrum specified for 5G spectrum resulting numerous bands used in the research and testing that can be classified to two; below 6 GHz [2] and higher 6 GHz [3]. Hence, it is worth using ultra wideband as the designated spectrum, which expected to cover the concerned spectrum at microwave band.

In improving the bandwidth performance of microwave passive components forming the six-port network, which particularly in power divider design, a lot of works have been performed by using different design approaches [4-10]. Chui et. al in [4] proposed coupled-line approach in the power divider design, which leads to smaller circuit dimension of 4.3 cm x 2.8 cm. It offers good RF performance of return loss, insertion loss, and isolation at frequency range from 1.3 to 3.7 GHz. Unfortunately, this component has quite limited bandwidth and therefore, unsuitable to be used in the wider band applications.

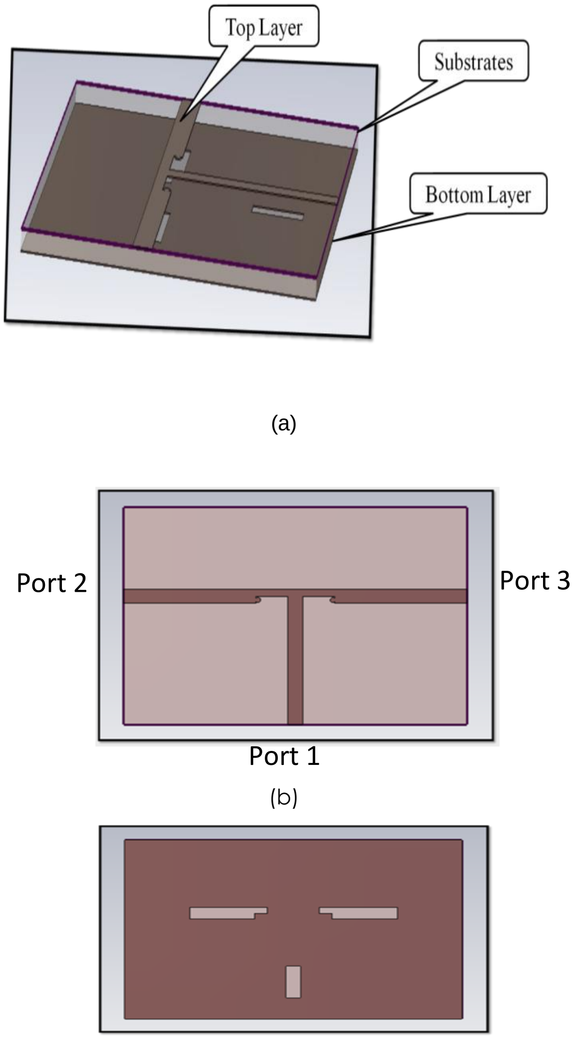
A method combining coarse-grained parallel micro-genetic algorithm (PMGA) with CST Microwave Studio has been reported in [5] to achieve UWB operating frequency. The combination between two software is to obtain an automated parallel design process. The good result of this design is achieved across 3.1-10.6 GHz. However, the PMGA cannot directly call the CST MWS via the VBA macro language. Another method to achieve UWB operational bandwidth is proposed in [6] by using multilayer microstrip-slot technology. This technique involved the use of two substrates with a common ground layer of slotline in between. This design technique is able to demonstrate well UWB performance. However, the implementation of two substrates without careful monitoring during the fabrication process might cause an air gap between those two substrates and misalignment [7]. To solve these limitations, design approaches with a single substrate are presented in [8-10] without affecting the UWB operating frequency.

In [10], a compact coplanar power divider is proposed by using microstrip-slot technique. In the proposed design, two in-phase signals over a wide frequency range are obtained by placing the two output branches in the same layer. Moreover, a half-wavelength slotline is employed to expand the working frequency range. The presented compact power divider shows a low insertion and good return loss performance at input port over the frequency range of 2.2-11 GHz. However, the isolation between output ports is no better than 10 dB, which commonly required in the divider design.

Beside design techniques, it is also essential to investigate the type of material (substrate) used in the design. Suitable substrate with optimal copper thickness will contribute to enhance the performance of the designed power divider. Here, T-shaped power divider is designed with simple structure using a single substrate with slots formed in the ground plane. The effect of the use of two substrates that made of different materials with different relative permittivity and copper thickness towards ultra wideband performance of the designed power divider is observed.

2.0 DESIGN

The configuration of the proposed T-shaped power divider is shown in Figure 1. This design consists of input port (port 1) and two output ports (port 2 and 3) at the top layer, and slots formed in the ground plane at the bottom layer. At the port 2 and 3, radial stubs are used as a matching circuit. In the design, the concept of step impedance is used at the transition between port 1 to port 2, and port 1 to port 3. Then, a slotline is placed underneath of each microstrip arm to improve the performance of frequency range and reduce the size of the circuit.



(a)

(b)

(c)

Figure 1 (a) The configuration of the proposed power divider: (b) Top layer of microstrip and (c) Bottom layer of slotted ground plane

In this design, two substrates are considered, which are Rogers RO4003C and TMM4 with the following specifications as listed in Table 1. Furthermore, two copper thicknesses of 17 μm and 35 μm are implemented in the investigation. These two substrates have different material composition, where RO4003C is composed of woven glass polytetrafluoroethylene (PTFE) and while, TMM4 is made of ceramic thermoset polymer. These substrates are suitable to operate in high frequency range and used in wideband applications.

Table 1 Specification of the used substrates

Substrate	Relative Permittivity (ε_r)	Thickness, h (mm)	Loss tangent (tan δ)
RO4003C	3.38	0.508	0.0027
TMM4	4.50	0.508	0.0020

Figure 2 shows the top view layout of the proposed T-shaped power divider with its dimensions. The value of characteristic impedance of this design, Z_m is assumed to be 50 Ω and the impedance of quarter wave is set to be 70.7 Ω. Meanwhile, the step impedance value of Z_i, (i = 1, 2, 3 and 4) are obtained using equation 1 and shown in Table 2. The overall dimension of the designed power divider is 17 mm x 26 mm.

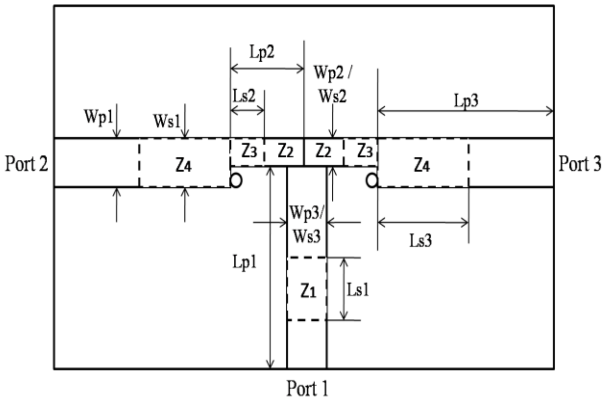


Figure 2 The top view of T-shaped power divider and its dimensions.

In this proposed design, a slotline is placed underneath of each microstrip arm. This line of microstrip with slot underneath is named as microstrip-slot line with the characteristic impedance of Z_{ms}. The relationship between microstrip-slot impedance (Z_{ms}) with the width of the slot (Ws) and microstrip line impedance (Z_m) can be expressed as in equation (1)[11-12]:

$$Z_{ms} = 18.22W_s^2 + Z_m \qquad (1)$$

This equation is derived by using completing square curve fitting method. However, the equation is only valid for microstrip-slot impedance, Z_{ms} in the range between 40 Ω and100 Ω, relative permittivity, ε_r between 2 and 5 and substrate thickness, h of 0.508 mm. This Z_{ms} corresponds to the step impedance value of Z_i, where, i = 1, 2, 3 and 4. In this case of proposed divider, step impedance values of Z_i for two substrates, which are RO4003C and TMM4 are shown in Table 2.

Table 2 The step impedance, Z_i of power divider depending on the substrate and thickness of copper (*t*)

Impedance, Z_i (Ω)	Substrate			
	RO 4003C		TMM4	
	t=35µm	*t*=17µm	*t*=35µm	*t*=17µm
Z_1	72.81	74.10	64.92	65.76
Z_2	70.70	70.70	70.70	70.70
Z_3	77.26	77.46	74.39	74.93
Z_4	72.81	74.10	64.92	65.76

According to these values of Z_i and Zm, the slot width, W_{s1} and W_{s2} of each arm can be computed using equation (1). Then, by using the obtained values of W_{s2} and W_{s3}, the impedances of slot can be determined by implementing equation (2) or (3) [13]:

$$Z_{si} = 73.6 - 2.15\varepsilon_r + (638.9 - 313.7\varepsilon_r)\left(\frac{W_{si}}{\lambda_0}\right)^{0.6} + \left(36.23\sqrt{\varepsilon_r^2 + 41} - 225\right)\frac{W_{si}/h}{\left(\frac{W_{si}}{h} + 0.876\varepsilon_r - 2\right)} + 0.51(\varepsilon_r + 2.12)\left(\frac{W_{si}}{h}\right)ln\left(\frac{100h}{\lambda_0}\right) - 0.753\frac{\varepsilon_r\left(\frac{h}{\lambda_0}\right)}{\sqrt{\frac{W_{si}}{\lambda_0}}} \qquad (2)$$

The formula in (2) is valid for the case of relative permittivity, ε_r range from 3.8 to 9.8, $0.0015 < W_{si}/\lambda_0 < 0.075$ and $W_{si}/h > 1.67$. Meanwhile, for the case of $0.0015 \leq W_{si}/\lambda_0 \leq 0.075$ and low dielectric constant substrate of $2.22 \leq \varepsilon_r \leq 3.8$, the impedance of slotline can be determined by implementing equation (3) [13]:

$$Z_{si} = 60 + 3.69\,sin\left[\frac{(\varepsilon_r - 2.22)\pi}{2.36}\right] + 133.5\,ln(10\,\varepsilon_r)\sqrt{\frac{W_{si}}{\lambda_0}} + 2.81[1 - 0.011\,\varepsilon_r(4.48 + \ln\varepsilon_r)]\left(\frac{W_{si}}{h}\right)ln\left(\frac{100h}{\lambda_0}\right) + 131.1(1.028 - \ln\varepsilon_r)\sqrt{\frac{h}{\lambda_0}} + 12.48(1 + 0.181\ln\varepsilon_r)\frac{\frac{W_{si}}{h}}{\sqrt{\varepsilon_r - 2.06 + 0.85(W_{si}/h)^2}} \qquad (3)$$

where, *h* and λ_0 are 0.508 mm and 46.15 mm, respectively. By applying equation (2) and (3), the slot impedance of each section is obtained, where it is depending on the substrate and thickness of copper (*t*) as shown in Table 3.

Table 3 The slot impedance of power divider depending on the substrate and thickness of copper (*t*)

Impedance, Zs_i (Ω)	Substrate			
	RO 4003C		TMM4	
	t=35µm	*t*=17µm	*t*=35µm	*t*=17µm
Zs_1	149.11	150.22	139.29	140.48
Zs_3	126.28	126.77	113.11	115.32
Zs_4	149.11	150.22	139.29	140.48

In addition, the width of microstrip-line at the top layer of proposed design, W_{p1}, W_{p2} and W_{p3} can be obtained using equation (4) [14]:

$$\frac{W_{pi}}{h} = \frac{2}{\pi}\left[B - 1 - ln(2B - 1) + \frac{\varepsilon_r - 1}{2\varepsilon_r}\left\{ln(B - 1) + 0.39 - \frac{0.61}{\varepsilon_r}\right\}\right] \qquad (4)$$

$$\text{where}, B = \frac{377\pi}{2Z_m\sqrt{\varepsilon_r}}, \quad \text{and} \quad i = 1,2,3$$

Once the initial dimensions of the proposed power divider have been obtained by using equation from (1) to (4), the optimization is performed. The final dimensions of the T-shaped power divider for each case of substrate and copper thickness (*t*) are shown in Table 4.

Table 4 The dimension (in mm) of power divider depending on the substrate and thickness of copper (*t*)

Dimension	Substrate			
	RO4003C		TMM4	
	t=35µm	*t*=17µm	*t*=35µm	*t*=17µm
Wp1&Ws1	1.119	1.150	0.905	0.930
Wp2&Ws2	0.600	0.609	0.450	0.482
Wp3&Ws3	1.119	1.150	0.905	0.930
Lp1	10	10	10	10
Lp2	3	3	3	3
Lp3	10	10	10	10
Ls1	3	3	3	3
Ls2	1	1	1	1
Ls3	5	5	5	5

From the Table 4, it can be noted that the width of microstrip line is decreased with larger value of permittivity and thicker conducting copper layer.

3.0 RESULTS AND DISCUSSION

Figure 3, 4 and 5 show the performance of the designed T-shaped power divider by using two types of substrates with two different thickness of copper. As observed in Figure 3, S21 and S31 of the power divider that is designed using RO4003C substrate with both copper thickness are -3 to -4 dB within the frequency range of 2 to 14 GHz. Whilst, for the case of TMM4 with thickness copper of 35 µm and 17 µm, better performance is achieved from 2 to 18 GHz.

In this design, the lowest return loss performance is set to be 10 dB. From Figure 4, it is seemed that the worst performance is shown by the design with TMM4 and copper thickness of 17 µm, which the return loss better than 10 dB only covers the frequency range of 3 to 12 GHz. Meanwhile, the design using substrate of RO4003C for both cases of copper thickness, good performances are depicted within the band of 3-13 GHz. The best performance is obtained with the use of TMM4 and 35 μm copper thickness. Where, the return loss of this power divider is greater than 10 dB from 3 to 18 GHz. Figure 5 shows phase characteristics of the designed T-shaped power divider. It can be observed that the performance of phase difference between port 2 and 3 is 0° ± 1° for both substrates even though with different copper thickness.

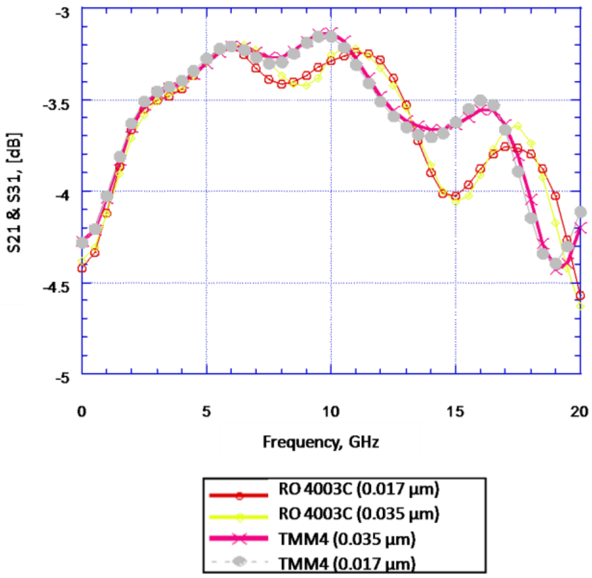


Figure 3 S21 and S31 performances of the proposed power divider by using two different substrates and two thickness of copper

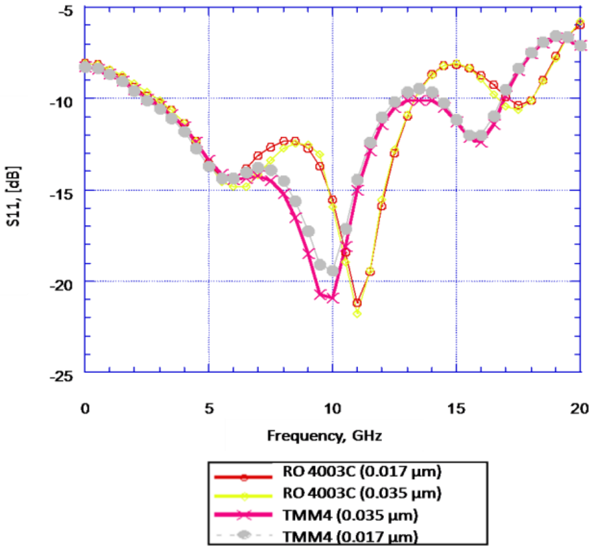


Figure 4 S11 performance of the proposed power divider by using different substrates and thickness of cooper.

The comparison performance between two different substrates of RO4003C and TMM4 is shown in Table 5. From the analysis, with the use of same thickness of substrates, which is 0.508 mm, Rogers TMM4 substrate with 35 μm thickness of conducting copper layer shows the best performance in the operating frequency from 3 to 17 GHz. This good performance can be due to the TMM4 substrate has lower loss tangent, temperature coefficient and better tolerance relative permittivity compared to RO4003C. This is contributed from the material of ceramic thermoset polymer used to form the TMM4 substrate.

Table 5 The performance comparison of the designed power divider using two substrates, RO4003C and TMM4 with 35 μm copper thickness.

Parameter	T-Shaped Power Divider	
	RO 4003C	**TMM4**
S11 [dB]	< -10	< -10
S21 and S31 [dB]	-3 ± 1	-3 ± 1
Phase Difference	0 ± 1°	0 ± 1°
Bandwidth (GHz)	3 - 13	3 - 17

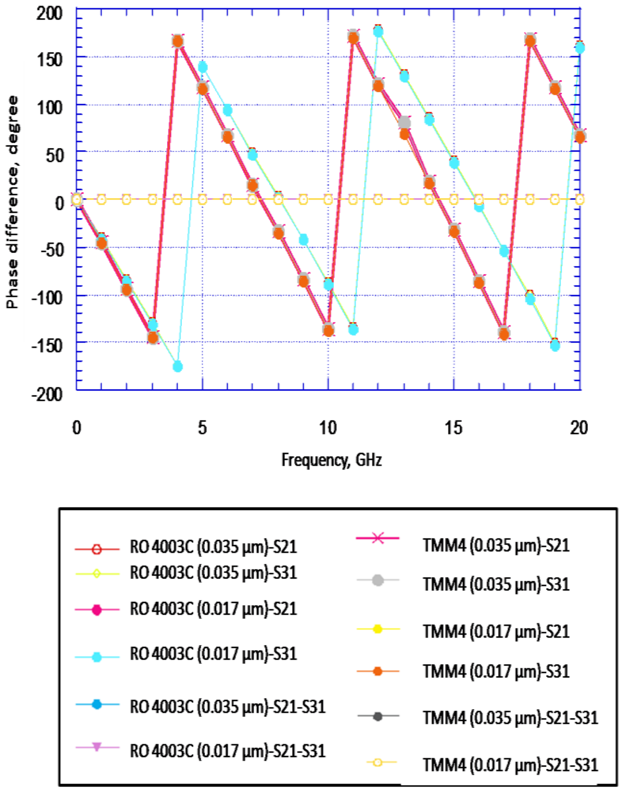


Figure 5 The performances of S21 and S31 phase and the phase difference for the designed power divider with two different substrates and two thickness of copper

4.0 CONCLUSION

The investigation of the T-shaped power divider design using ground-slotted technique has been performed with two substrates and two different thickness of copper up to 20 GHz. The performance is observed and analyzed in terms of the S-parameters and phase characteristics. Broader bandwidth performance can be obtained by using suitable substrate with optimum value of copper thickness. The best T-shaped power divider design has been demonstrated by using TMM4 substrate with 35 µm copper thickness.

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