Progress In Electromagnetics Research B, Vol. 77, 103–116, 2017

Frequency and Time Domain Design, Analysis and Implementation of a Multi-Gbps UWB Wilkinson Power Divider for 5G New Spectrum and CAR Applications

Gholamreza Askari* **and Mahmoud Kamarei**

Abstract—5G new spectrum radio access should support data rates exceeding 10 Gbps in most of its applications. An Ultra Wide Band (UWB) Ultra-high data rate Wilkinson power divider up to 6.9 Gbps for 5G new spectrum and CAR applications is presented in this paper. The step by step design procedure, optimization and implementation of this Wilkinson power divider in 20–30 GHz are completely done to achieve the optimum performance. The final fabrication results show the average of −14 dB of input matching, −20 dB of isolation of isolated Ports, −4.2 dB of coupling in output ports (considering 2 SMA connectors and transitions in each path), and linear phase variation of outputs in the whole bandwidth of 20–30 GHz. During the design procedure, a new and very useful coaxial to microstrip transition in K-band is designed, analyzed, developed and fabricated to achieve the best results. Also a complete study of time domain analysis with ultra-high data rate signal is presented to minimize the total reflection coefficient caused by the partial reflections from several discontinuities. To complete and validate the final fabricated Wilkinson power divider in ultra-high data rate application in 5G new spectrum, the extracted results of UWB-IR impulse radio with modulated ultra-high data rate signal up to 7 Gbps and in 20–30 GHz bandwidth is completely done. The measured results show that this fabricated Wilkinson power divider can handle a periodic modulated signal up to 7 Gbps, which are valuable results for many applications in 5G and CAR systems.

1. INTRODUCTION

Ultra-high speed connections in the range of multi-gigabit per second (up to 10 Gbps) could potentially be achieved through using ultra-wide carrier bandwidths in the order of up to several hundred MHz or multi-GHz. Many proposed applications in 5G need ultra-high speed links and data rates, such as UHD video (4 k, 8 k), Virtual Reality, Vehicular (cars, buses, trains, aerial stations, etc.), and collision avoidance Radar. There are significant studies underway in both industry and academia on characterization of frequencies below and above 30 GHz for 5G applications. Penetration loss, diffraction loss, etc., also increase with increasing frequency; so the bands between 6–30 GHz are important to consider due to propagation reasons [1, 2]. Also for automotive UWB short range radar systems, the FCC allocated the band 22–29 GHz. The new decision permits the use of radar frequencies in this band with a phase out for existing CAR lines until 2022 [3]. High bandwidth is also an important problem for these systems [4, 5]. So the spectrum requirements and the need for access to numerous spectrum ranges, the challenges and implications with different frequency ranges, various licensing aspects and potential technology enhancements to enable access to new spectrum are under investigations [2].

Also many microwave applications require the determination of a ratio of two complex voltages or two complex wave amplitudes over a specified frequency band [6]. In these contexts, a six-port receiver

Received 22 April 2017, Accepted 8 July 2017, Scheduled 28 July 2017

* Corresponding author: Gholamreza Askari (askarigh@ut.ac.ir).

The authors are with the School of Electrical and Computer Engineering, University College of Engineering, University of Tehran, North Kargar st., Tehran, Iran.

is a good alternative and is also good for low volume markets. A six-port vector voltmeter or six-port modulator/demodulator can be designed using three 3-dB quadrature couplers and one in-phase or out-of-phase power divider which are the essential components of the six-port. Several circuits as the rat-race, hybrid coupler, and T-junction are key components in the design of microwave devices, due to their planar integration, wide bandwidth in power dividing distribution, and high isolation factor between requested ports [6, 7]. However, many of them are not appropriate in near millimeter wave applications because of fabrication difficulty and other challenges. Moreover, applying the available designs of UWB couplers and dividers, from the open microwave literature, is also a challenge [6], and several ultra-wide band Wilkinson power dividers have been developed, such as UWB (3.1–10.6 GHz) Wilkinson power divider using tapered transmission lines [8], a K-band Wilkinson power divider composed of two step taper stubs based on empirical equations [9], theoretical Design of Broadband unequal multi-section Wilkinson Power Dividers With Arbitrary Power Split Ratio, using single-layer microstrip lines [10] and a novel ring power divider/combiner operating in the 60 GHz band [7]. Many technologies have been intensively used for the millimeter wave circuit design and in house prototype fabrication as coplanar, Substrate Integrated Waveguide (SIW), and microstrip technology. For further circuit miniaturization, easy integration of passive and active components and easy production, the microstrip technology on a suitable substrate is recommended [11, 12]. So choosing suitable laminates for the design and implementation of UWB short pulse signals is a challenge [12, 13].

One problem with microstrip circuits (and other planar circuits) is that the unavoidable discontinuities at bends, step changes in widths, and transitions in junctions can cause signal integrity problem and degradation in circuit performance. These discontinuities introduce parasitic reactances which can lead to impedance mismatching, possibly spurious coupling or radiation and finally phase and amplitude distortions [14, 15]. When the instantaneous bandwidth is increased in ultra-high data rate, these problems are important challenges and can decrease the data rate, and are topics of open researches in the literature for ultra-high data rate of collision avoidance radar (CAR) or 5G applications.

In this paper, design and implementation of a Multi-Gbps UWB Wilkinson Power Divider for 5G New Spectrum and CAR Applications up to 6.9 Gbps in 20–30 GHz with microstrip technology is presented. In Section 2 by choosing suitable laminates for design and implementation of UWB components, the complete design procedure, optimization and implementation of three different designs of UWB ultra-high data rate Wilkinson power divider in 20–30 GHz are completely discussed and done. In the design procedure of such dividers, minimizing the total reflection coefficient caused by the partial reflections from several discontinuities is discussed considering the theory of small reflections. Also during the design procedure, a new valuable coaxial to microstrip transition is analysed and developed to achieve the best results in final Wilkinson power divider. After that in Section 3, measured results are presented in frequency domain and time domain. The fabricated Wilkinson power divider shows valuable results of S-parameters and multi-Gbps modulated signal up to 6.9 Gbps in 20–30 GHz bandwidth. Finally, the paper is concluded in Section 4.

2. DESIGN PROCEDURE

As explained before, two essential components of a six-port are a 3-dB Wilkinson power divider and a 3-dB quadrature hybrid coupler. In this section, first a good method presented by the authors [12], to choose the suitable laminate for UWB applications to minimize distortion along microstrip lines is briefly presented. Then, step by step design, optimization and implementation process of the UWB Wilkinson power divider in 20–30 GHz, which is in the new spectrum of 5G and CAR, are completely discussed in frequency and time domains, to achieve the optimum performance.

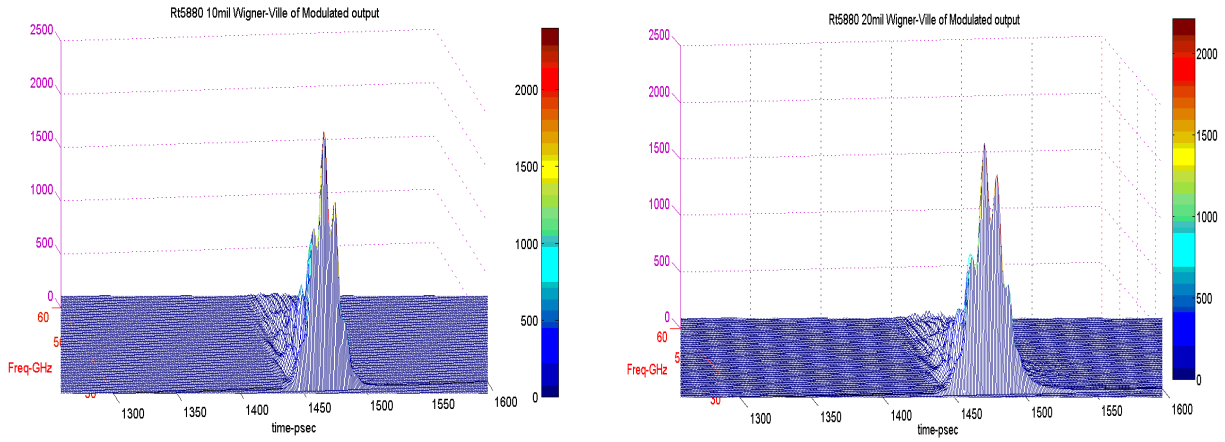
2.1. Suitable Laminates to Design and Implementation of Ultra Wideband Components

To have a great performance in UWB short pulse signals, all distortions in time and frequency domains must be negligible or removed. So the choices of the appropriate laminates for transmit/receive UWB waveforms and their propagation and minimum distortion in time and frequency domains across the circuit are very important. In this section based on the authors' analysis [12] and other design limitations such as transition between coaxial to microstrip lines and realization of the microstrip components,

three different transmission lines of RT/duroid 5880 with the relative permittivity about 2.2, copper thickness of 17 µm, roughness of 1.8 µm and dielectric loss tangent about 0.0023 with different substrate thicknesses of 5, 10 and 20 mil are briefly studied. The 10 cm lines of each laminate with different thickness and wave ports in the input and output are optimized by the ADS and CST softwares full wave analysis. Wave ports are considered because in this section the focus is on dispersion behaviors of different laminates. All analysis steps in time and frequency domains introduced in [12] applied to these laminates and for abstracting the final two-dimensional analysis based on the Wigner-Ville distribution are presented here, which can be expressed by the following equation [16].

$$\rho_z(tf) = W_z(tf) = \int_{-\infty}^{\infty} z\left(t + \frac{\tau}{2}\right) z^*(t - \frac{\tau}{2}) e^{-j2\pi f\tau} d\tau \tag{1}$$

After discretization of the Wigner-Ville distribution and precise selection of suitable windowing for time and frequency variables, which is done in this paper, the output signals of the input signals of modulated Gaussian ultra-short pulse (50 psec) are considered to be analyzed with WVD. Figure 1 shows the WVD of the propagated modulated UWB Gaussian pulses across the optimized 10 cm lines with 10 mil and 20 mil thicknesses. As can be seen from this figure, the output results of the 10 mil laminate are more concentrated in frequency and time; also some multi dominant components in the results of the 20 mil laminate are outspread and insufficient.



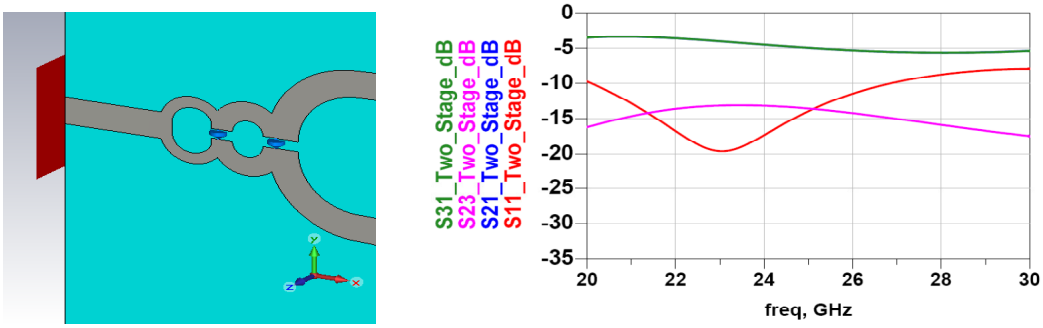
(a) (b)

Figure 1. WVD of the propagated UWB modulated Gaussian pulses across the (a) 10 mil and (b) 20 mil laminates.

Furthermore, other limitations such as realization design and input-output transitions, which are considered in this paper, must be perceived. Considering all these facts, the 10 mil laminate of RT/duroid 5880 with the relative permittivity about 2.2, copper thickness of 17 µm, roughness of 1.8 µm and dielectric loss tangent about 0.0023 is selected in this paper to design and fabricate.

2.2. First UWB Wilkinson Power Divider Design

Many designs and modifications have been proposed to increase the bandwidth of the conventional Wilkinson power divider. The bandwidth of Wilkinson power divider can be increased using multisections [8, 10]. In this paper for the primary step, a two-section Wilkinson power divider is designed and optimized in 20–30 GHz as shown in Figure 2. As can be seen from this figure, each section needs an isolated resistor which is 98 ohm and 248 ohm in the first and second sections, respectively. A multi-section Wilkinson power divider has many discontinuities, and as will be seen in the next section, more partial discontinuities lead to multi-dominant spurious response caused by multi-reflections in high data rate application. So this design is not considered as the final structure to cover our goals.



(a) (b)

Figure 2. (a) The layout of the two sections Wilkinson power divider in CST, and (b) the simulation results of S-parameters of the two section power divider.

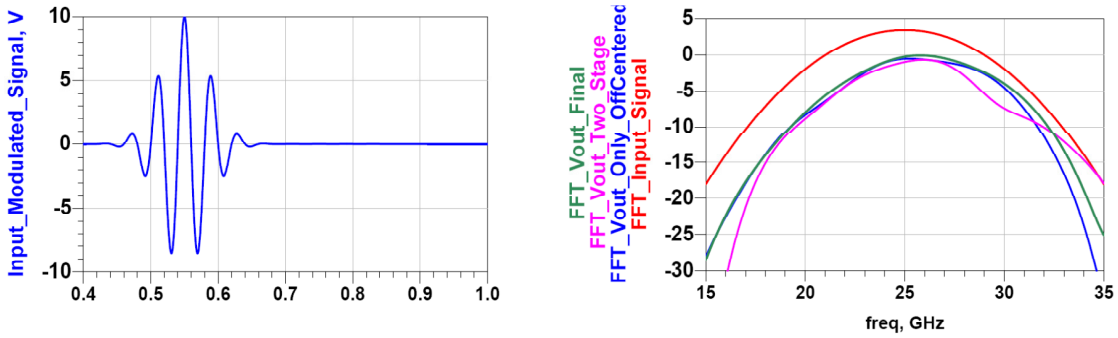
2.3. Time Domain Analysis Approach

As introduced, one problem with a Wilkinson power divider in microstrip technology is that the unavoidable discontinuities at bends, step changes in widths, and transitions in junctions and lumped elements can cause signal integrity problem and degradation in circuit performance. Especially in ultra-high data rate of, for example, CAR and 5G applications. In a microstrip power divider, some discontinuities are an unavoidable result of mechanical or electrical transitions from one medium to another (e.g., a transition between coax-to-microstrip or a junction between microstrip and the lumped isolation resistor), and some other discontinuities are introduced into the circuit to perform a certain electrical function (e.g., steps in microstrip lines or T-junctions). These discontinuities are significant enough to warrant circuit characterizations. In any way, a discontinuity can be represented as an equivalent circuit at some point on the transmission lines and introduce parasitic reactances that can lead to phase and amplitude errors, input and output mismatch, and possibly spurious coupling or radiation.

One approach for eliminating these effects is to construct some equivalent circuits for discontinuities, including them in the design of the circuit and compensating for their effect by adjusting other circuit parameters (such as line lengths and widths). This approach can be useful in narrow-band circuits or near wide-band circuits. Another approach is to minimize the effects of every discontinuity by compensating the discontinuity directly by itself, so the total reflection coefficient caused by the partial reflections from several small discontinuities can be minimized using this approach that is generally referred to as the theory of small reflection [15].

In this paper, the bandwidth is about 10 GHz, and the main goal is to design and implement a UWB Wilkinson power divider to support ultra-high data rate up to 7 Gbps. So in the design process, combination of the two discussed approaches is considered to reach the best performance. For better understanding, let study the time domain response of all different designed power dividers by injecting ultra-high data rate signals to them. For this purpose, a transient analysis is run in ADS software using S3P model of the frequency domain results of the UWB Wilkinson power divider, and a Gaussian modulated signal is applied to it. The (10 to 90%) step rise time points are inversely proportional to the span of desired frequency bandwidth. The Gaussian modulated short pulses with 10 GHz (-6 dB) bandwidth of double-side band and a 25 GHz carrier, as shown in Figure 3, is applied to all different designed Wilkinson power dividers.

The time domain input reflection and output results of the first design (two stages) of Wilkinson power divider are shown in Figure 4. As can be seen from this figure, there are multi-dominant reflections in input reflected signal, and so it yields multi-dominant response in output signal, and thus ultra-high data rate is limited. In the next section, a new design will be presented to minimize not only the total reflection in frequency domain but also the partial reflections of each circuit discontinuity and yield higher data rate.



(a) (b)

Figure 3. (a) The Gaussian modulated input signal, and (b) FFT of the input signal and output signals of different designed Wilkinson power dividers.

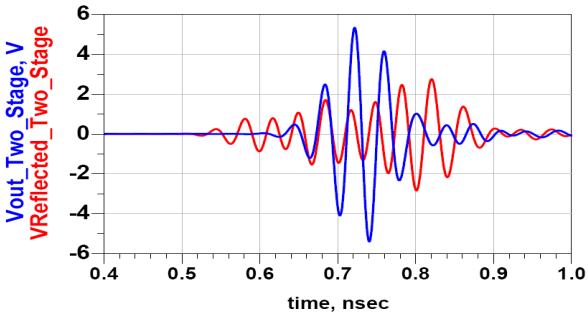


Figure 4. The time domain input reflection and output results of the first design (two stages) of Wilkinson power divider.

2.4. Second UWB Wilkinson Power Divider and New Transition Design

The second structure is considered based on the Wilkinson power divider introduced in [7, 16]. The authors in [16] presented the design, development and construction of a new Ultra High Data Rate Six-port Receiver for 5 G New Spectrum Radio Access and CAR applications. Because of large amount of design process and considerations and existent of many design procedures and results, the final results were presented in [16]. In this paper, to reach our main goals in [16] (Ultra High Data Rate Six-port Receiver) and also to reach main goals together with new design approach, the design and development of many circuits must introduce, discuss and improve new designs, new analysis (time domain ultra data rate analysis) and new valuable transition design and implementations. In a previous paper, the authors used the same results of the final designed and implemented Wilkinson power divider of this paper, and consequently, the final simulated and experimental results of the final Wilkinson power divider of this paper are the same as those of the authors' previous paper [16], such as Figure 8(b), Figures 7(a), (b), Figure 8(b), Figure 15, and Figure 16.

At near millimeter wave frequencies, the two output arms of the conventional Wilkinson circuit must be placed very close to each other, to be connected to the 100 Ω resistor. This layout raises undesirable mutual coupling between the output lines. To design a Wilkinson power divider for millimeter wave and near millimeter wave applications, it is necessary to modify the traditional Wilkinson power divider to connect the integrated resistor. So the additional transmission lines can be a good candidate to create the ideal layout for this isolation resistor. These additional symmetry lines create an ideal structure for this isolation resistor, reducing undesirable mutual coupling between the transformer arms. Also this structure needs only one section to realize, so less discontinuity effects against the two section Wilkinson power divider. The layout of this power divider is depicted in Figure 6. The symmetry of this circuit allows for the analysis through the even- and odd-mode half circuits. As shown in Figure 5, the line

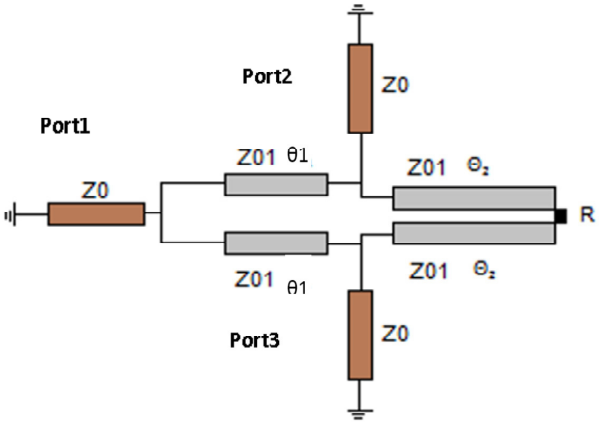


Figure 5. The schematic of the proposed modified Wilkinson power divider.

of symmetry bisects the resistor in two series resistors of $R/2$, doubling the effective impedance of the input port 1. All impedances are normalized to Z_o. As formulated in [7, 16], there are five unknown parameters; the characteristic impedances Z_{01}, Z_{02}, the electrical lengths θ_1 and θ_2, and the resistor R which should be determined for the desired frequency bandwidth. To minimize the discontinuity in each arm, Z_{01} and Z_{02} can be considered equal.

Several equations can be obtained by using even- and odd-mode analysis method [7, 15, 16]. In this analysis, it is possible to depict the Wilkinson power divider circuit in a normalized and symmetric form. For even-mode excitation, there are no current flows through resistors, or the even-mode analysis gives a virtual open circuit along the symmetry line, eliminating the resistor R. So it can be considered as a two-port circuit for even-mode analysis with the normalized ABCD matrix of Equation (2),

$$\begin{bmatrix} A_e & B_e \\ C_e & D_e \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ \dfrac{j\tan\theta_2}{Z_{01}} & 1 \end{bmatrix} \begin{bmatrix} \cos\theta_1 & jZ_{01}\sin\theta_1 \\ \dfrac{j\sin\theta_1}{Z_{01}} & \cos\theta_1 \end{bmatrix} \tag{2}$$

Also it is noted that matching and isolation conditions related to ports 2 and 3 yield $S_{22e} = S_{22o} = 0$. So imposing the real and imaginary parts of the even return loss (S_{22e}), equal to zero, yields Equation (3).

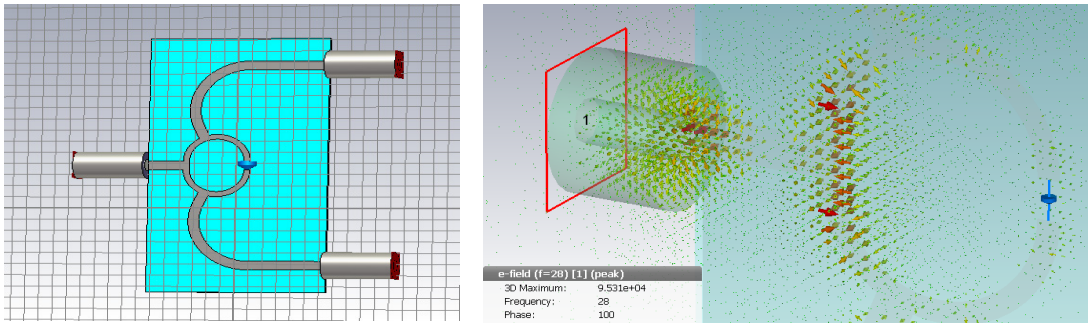
$$\tan\theta_1 = -\frac{1}{\tan\theta_2}, \quad 1 - \frac{z_{01}^2}{2} = \frac{1}{(\tan\theta_1)^2}, \quad \text{where} \quad z_{01} = \frac{Z_{01}}{Z_0}, \tag{3}$$

In the odd-mode analysis, the symmetry line corresponds to a virtual short circuit, eliminating port 1. Therefore, the odd return loss is calculated using the impedance of the resulting mono-port. So Equation (4) is obtained by making the real and imaginary parts of S_{22o} equal to zero

$$1 - \frac{r}{2} = \frac{1}{(\tan\theta_1)^2}, \quad r = z_{01}^2. \tag{4}$$

where, r is the normalized resistor. According to Equation (3), θ_1 and θ_2 must be orthogonal phases. r is selected equal to 2 which is a particular solution of Equations (3) and (4). The corresponding electrical lengths θ_1 and θ_2 are $\pi/2$ and π, respectively, and the normalized ring characteristic impedance z_{01} is found to be $\sqrt{2}$. According to above process, the Wilkinson power divider is designed at center frequency of 25 GHz, and by using ADS and CST softwares, the design is optimized. In this optimization, the coaxial connectors are a little off-centered to improve the results. The magnitudes of S-parameters of this design are presented in Figure 8(a) and compared with the third design in Figure 8(b), which are discussed as follows.

As can be seen from Figure 6, the electrical fields are not concentrated enough in coaxial to microstrip contact and in the input microstrip line, so a new coaxial-to-microstrip transition is required to improve the performance of the proposed Wilkinson power divider. The coaxial-to-microstrip transition must support only a single propagating mode over a broad frequency, and it is important

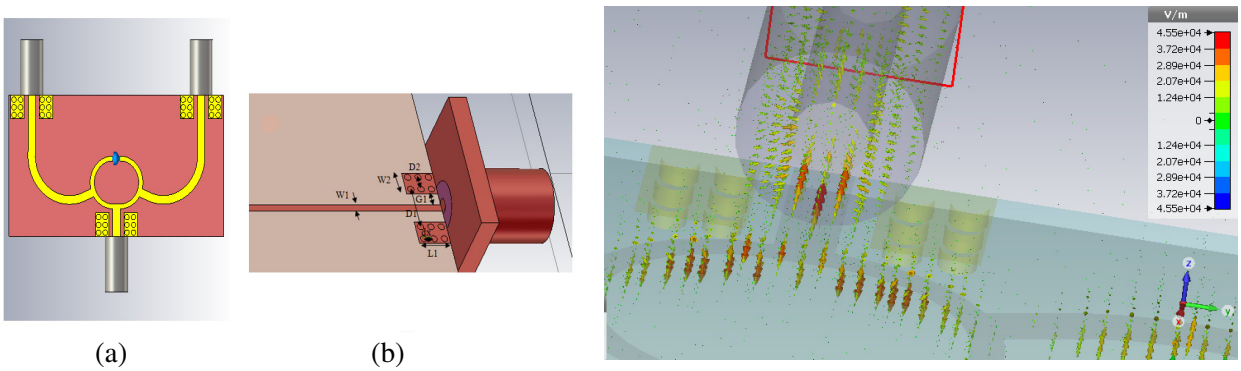


(a) (b)

Figure 6. (a) The layout of the proposed Wilkinson power divider without CB-CPW pre transition section in CST, and (b) the electrical fields of the proposed Wilkinson divider without CB-CPW pre transition section.

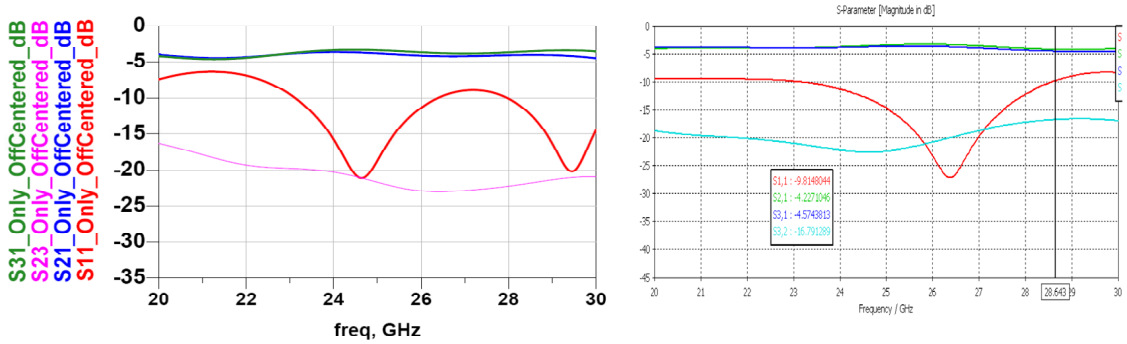
to be simple, low cost and wideband. The authors presented a useful wideband coaxial-to-microstrip pre-transition in [17]. The first consideration in the design of transition is impedance matching, so the coaxial and microstrip lines are designed to be 50 Ω. But having the same characteristic impedance does not always guarantee a good transition between two transmission lines, and the field distributions of the transmission line must also be matched.

After reviewing all suitable coaxial connectors, the 2.4 mm JACK PCB MOUNT from the "Precision Connector, Inc." company is selected for this work, which is shown in Figure 10. Center conductor of this SMA connector is wider than microstrip line, and therefore direct soldering of them causes an impedance mismatch. The diameter of the inner rod of the connector is such that it needs some off-centre alignment to avoid direct contact to microstrip ground plane. Then a conductor backed CPW (CB-CPW) pre-transition section is used to ensure a proper field match between coaxial and microstrip lines. This pre-transition and total geometry are shown in Figure 7. The parameters of the transition are $W1 = 0.78$; $W2 = 1.4137$; $D1 = 1.572$; $D2 = 0.7$; $G1 = 0.396$; $L1 = 2.154$ and $dx = 0.7$ (all in millimeter). In the CB-CPW section, the values of $W1$ and $G1$ are chosen in order to yield a characteristic impedance of 50 ohm along the transition within the desired frequency band. The value of $W1$ is chosen nearly equal to the width of microstrip line to avoid any abrupt discontinuity and to minimize the reflection along the transition. In this transition, the number of vias and placement of them are optimized to suppress parallel plate mode and radiation loss and to obtain maximum bandwidth.



(a) (b) (c)

Figure 7. (a) The CST model of second proposed modified Wilkinson power divider, (b) the proposed transition dimensions, (c) the electrical fields of the second proposed Wilkinson power divider with CB-CPW pre transition section.



(a) (b)

Figure 8. (a) The magnitudes of S-parameters of second Wilkinson power divider design without pre-transition and only with off-centred coaxial connectors and (b) the magnitude of S-parameters of the third design with Coaxial off-centred from microstrip line and CB-CPW pre transition.

Considering this pre-transition, the third design of Wilkinson power divider is done and optimized to meet our goals. The electrical fields of the third design are depicted in Figure 7(c). As can be seen from this figure and compared with the electrical fields of the second design in Figure 6, the electrical fields are more concentrated in the third design. The magnitudes of S-parameters of this design are presented in Figure 8(b) and compared with the second design 8(a).

The only off-centered coaxial connectors from the input-output microstrip lines in the second design yield good simulation results of Figure 8(a). But as can be seen in this figure, the input reflection and transmission coefficient are not acceptable. Adding GCPW pre-transition, which was explained before, and new off-center optimization of the coaxial connector inner rod, the new results are extracted in the third design, shown in Figure 8(b). Compared with Figure 8(a), these new results are much better, but the input reflection is not so good in some frequencies, and the transmission coefficients need more flatness in total bandwidth of 20–30 GHz. Hence a new transition is designed to improve the scattering parameters results.

The time domain input reflection and output results of the second design (without pre-transition and only with off-centred coaxial connector) of the Wilkinson power divider is shown in Figure 9. As can be seen from this figure, the multi-dominant reflections in input reflected signal and the multi-dominant response in output signal are better than the first design, but can still be improved. In the next section, the final new design with optimizing the transition is presented to minimize the total reflection more in frequency domain and so yield more data rate.

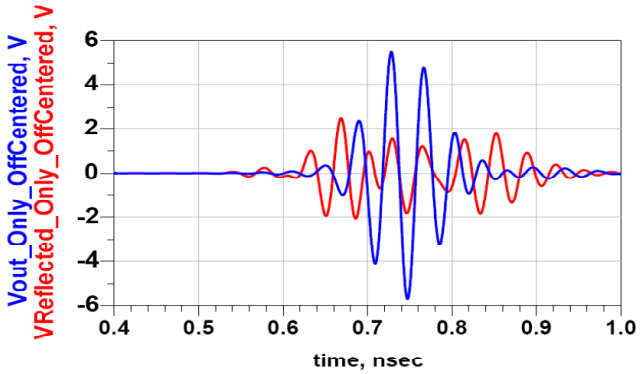
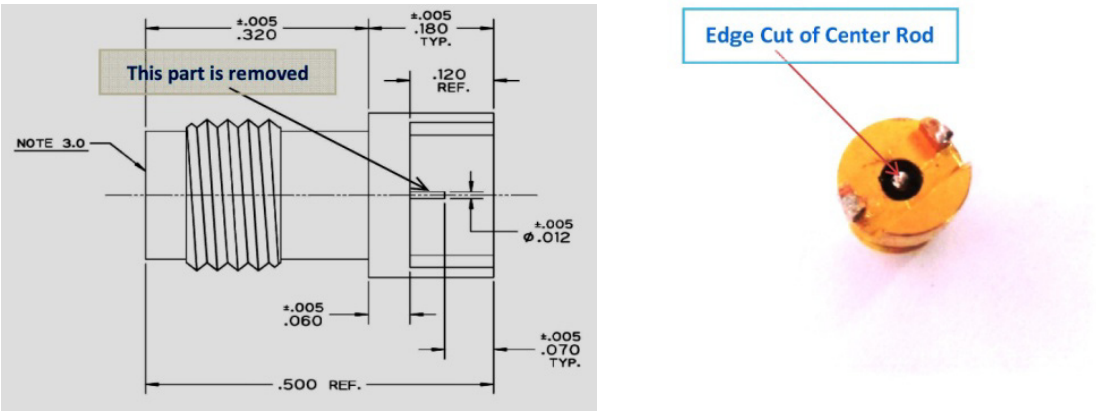


Figure 9. The time domain input reflection and output results of the second design (without pre-transition and only with off-centerd coaxial connector) Wilkinson power divider.

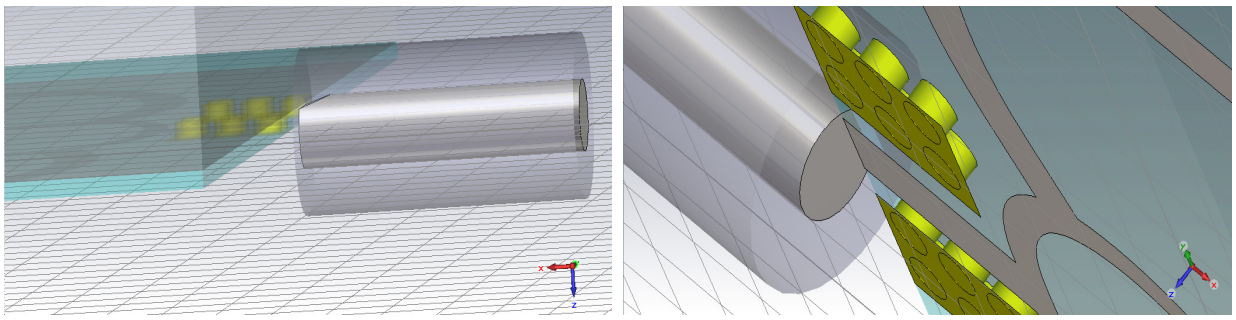
2.5. Final UWB Wilkinson Power Divider and Final Transition Design

As explained before, the coaxial connector used in this work is 2.4 mm JACK PCB MOUNT, shown in Figure 10. Also the inner rod diameter of this connector is larger than the width of the input-output microstrip lines, and as discussed before, the field match is very important in coaxial to microstrip transitions. To solve this problem, the coaxial connector must be off-centred to avoid direct contact to microstrip ground and must be optimized. Because the microstrip thickness is only 10 mil, it needs much off-centering of the coaxial connector in front of the microstrip lines, and tip limitation causes field mismatch and thus bad input reflection. Now as can be seen from Figure 10 and Figure 11, if one removes some parts of the inner rod of the connector, then there are two parameters to help the fields matching and impedance matching in coaxial to microstrip transition; the edge cut of the center-rod and the off-centering of the coaxial connector. So the final design is optimized. Many different conditions of transitions with these two parameters are designed and then optimized using CST software, and the best results are extracted.



(a) (b)

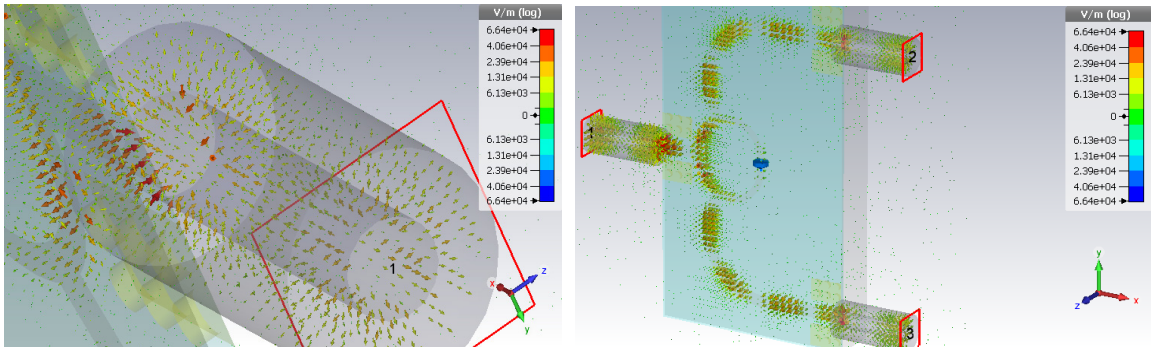
Figure 10. (a) Dimensions of the "Precision Connector, Inc." 2.4 mm JACK PCB MOUNT, and (b) the photo of the connector with removing outer part of center rod and edge cut of remind center rod.



(a) (b)

Figure 11. The structure view of the new proposed coaxial to microstrip transition. (a) The simulation graph of the edge cut of the center rod of the 2.4 mm connector in CST Software, (b) Coaxial Off center from microstrip line and CB-CPW to optimize the S-parameters results in CST software.

The electrical fields of the final proposed Wilkinson power divider with CB-CPW pre-transition, coaxial off-center from microstrip line and the edge cut of the center rod of the 2.4 mm connector are shown in Figure 12. As can be seen from this figure, the electrical fields matching and their concentration in coaxial to microstrip contacts and in the whole structure are much better that the second and third designs.



(a) (b)

Figure 12. The electrical fields of the final proposed Wilkinson power divider with CB-CPW pre transition, Coaxial Off center from microstrip line and the edge cut of the center rod of the 2.4 mm connector. (a) The electrical field distribution in coaxial to microstrip line, and (b) electrical field distribution in the whole final Wilkinson power divider structure.

The final simulation S-parameters of the final modified Wilkinson power divider with the final proposed transition are shown in Figure 13. The bandwidth of the power divider is more than 20–30 GHz with less than 0.2 dB ripples of the transmission coefficients. Comparing Figure 13 and Figures 8(a), (b), it is clear that all s-parameters of the final Wilkinson power divider with proposed transition are much better than the previous.

The time domain input reflection and output results of the final design (with CB-CPW pre transition, coaxial off-center from microstrip line and the edge cut of the center rod of the coaxial connector) of the Wilkinson power divider are shown in Figure 14. As can be seen from this figure, the multi-dominant reflections in input reflected signal and the multi-dominant response in output signal are good enough to support ultra-high data rate up to 7 GHz, as it is proved with the measurement results in the next section.

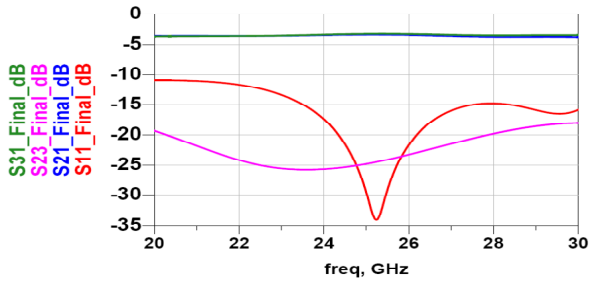


Figure 13. The final simulation results of magnitudes of S parameters of new Wilkinson power divider with transition.

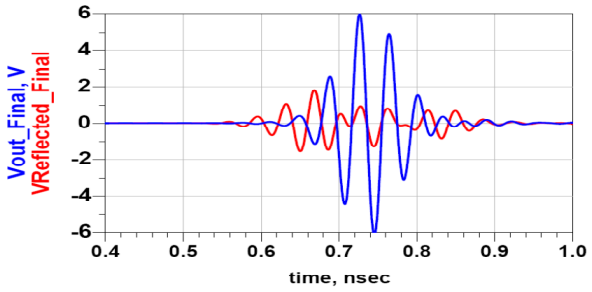


Figure 14. The time domain input reflection and output results of the final design (with CB-CPW pre transition, Coaxial Off center from Microstrip line and the edge cut of the center rod of the coaxial connector) Wilkinson power divider.

3. EXPERIMENTAL RESULTS

The final designed Wilkinson power divider with the proposed transition is implemented on an RT/Duroid 5880 Rogers laminate using the proposed two 2.4 mm SMA air coaxial connectors as depicted in Figure 15. The 100 ohm isolation resistor is RC3-0402PW-1000J from International Manufacturing Services, INC.

Figure 15. A photo of the final proposed modified Wilkinson power divider.

3.1. Frequency Domain Experimental Results

The measured results are extracted using the Network Analyzer model *hp* 8510C which are shown in Figure 16. As shown in this figure, the average of −14 dB of input matching and −20 dB of isolation of output ports and the average of −4.2 dB of coupling between input and output ports (considering 2 SMA connectors and transitions) in the bandwidth of 20–30 GHz are achieved with the final proposed Wilkinson power divider. The differences between simulated and fabricated results are due to practical measurements and assembly issues such as spurious coupling, higher order modes, junction discontinuities, and thermal effects.

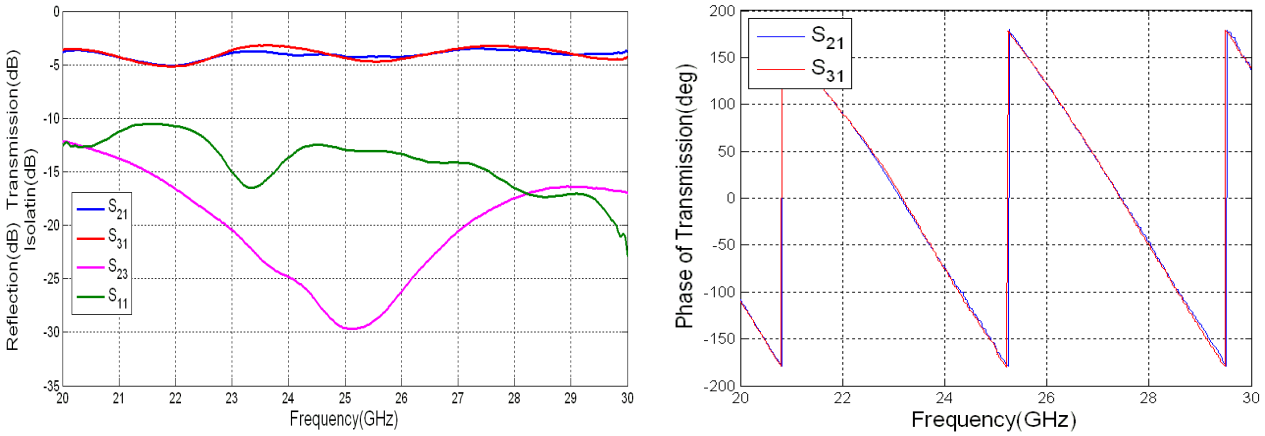
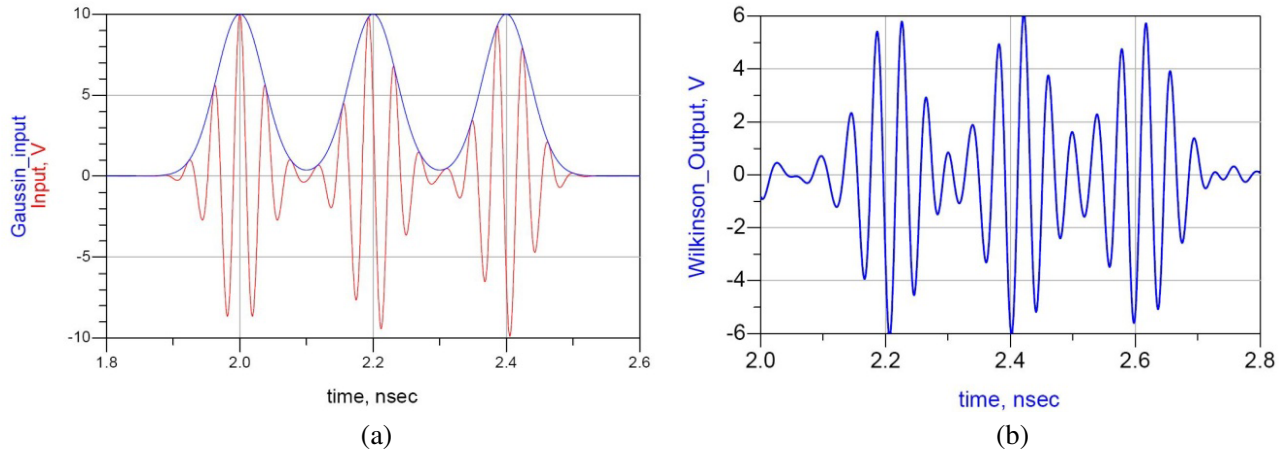


Figure 16. The measured S parameters results of the final proposed Wilkinson power divider; (a) Amplitude of the input reflection (S_{11}), transmissions (S_{21}, S_{31}), and isolation (S_{23}), and (b) phase of the transmission coefficients.

3.2. Gaussian Modulated Ultra Short Pulse Experimental Results

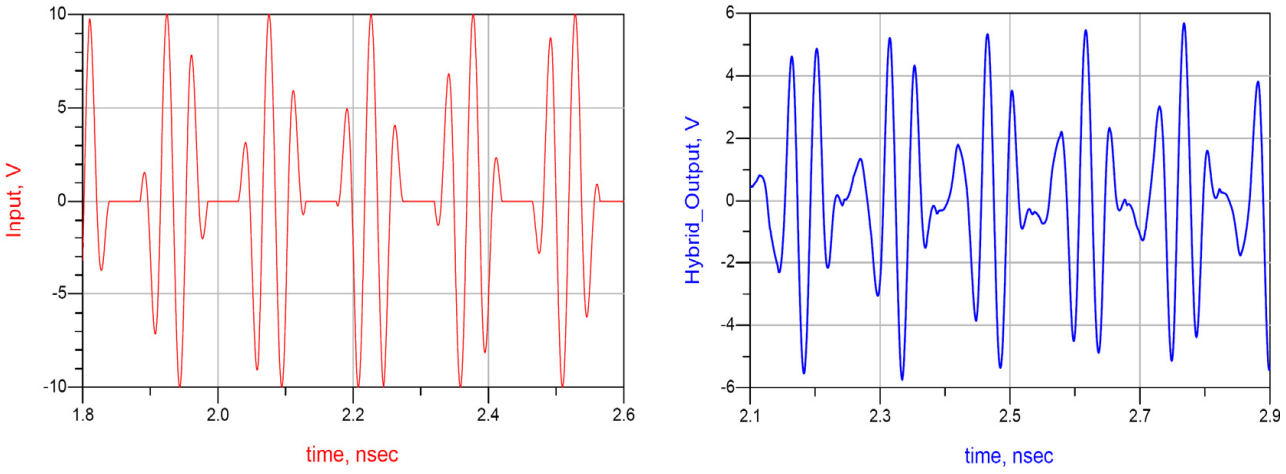
As introduced before, many applications of new 5G spectrum and CAR need ultra-high speed connections in the range of multi-gigabit per second which can be achieved through using ultra-wide carrier bandwidths in the order of up to several hundred MHz or multi-GHz. It means that UWB-IR impulse radio works with very short signals, typically less than 0.5 ns. Therefore, a UWB-IR system working with ultra-short pulse duration will be able to distinguish multipath components that are separated with $\sim$ 15 cm or less. It is why UWB-IR systems are superior over narrow-band or UWB-

OFDM systems. So for more study of this work, let's inject modulated Gaussian short pulses which are shown in Figure 17 to the final Wilkinson power divider using their extracted scattering parameters in ADS transient analysis. The (10 to 90%) step rise time points are inversely proportional to the span of measured frequency. A stream of modulated Gaussian and rectangular short pulses with 10–14 GHz (−6 dB) bandwidth of double-side band, a 25 GHz carrier and with the pulse spaces of 0.145–0.2 nsec which mean a data rate of 5–6.9 GHz are applied to the final Wilkinson. The output experimental results of the proposed Wilkinson power divider with Gaussian modulated input signal is shown in Figure 17. As can be seen in this figure, the 5 Gbps Gaussian modulated signal can be applied to these final fabricated Wilkinson power dividers, and the output signals remain safe and the output results are with acceptable distortions. There are some aliasing reminded signals in output results, which are the convergence problem in ADS transient analysis software. Also if streams of rectangular modulated pulses, Figure 18(a), are applied to the fabricated components, data rate can improved. It can be seen in Figure 18(b) that the fabricated Wilkinson power divider can handle a periodic rectangular modulated signal with data rate up to 6.9 GHz.



(a) (b)

Figure 17. (a) 5 Gbps gaussian modulated input signal, and (b) 5 Gbps Gaussian modulated pulse output results of the measured final Wilkinson power divider.



(a) (b)

Figure 18. (a) The 6.9 Gbps rectangular modulated input signal, and (b) the measured results of the fabricated Wilkinson power divider with 6.9 Gbps rectangular modulated pulse input signal.

4. CONCLUSIONS

Complete design procedure, analysis and implementation of an Ultra Wide Band (UWB), ultra-high data rate Wilkinson power divider up to 6.7 Gbps in 20–30 GHz in microstrip technology is presented in this paper. Also, considering the theory of small reflections and optimization, a new approach in time domain analysis with ultra-high data rate signal is presented in design procedure of the UWB Wilkinson power divider to minimize the total reflection coefficient caused by the partial reflections from several discontinuities of the circuit. The final fabrication show very good results, and the average of -14 dB, -20 dB and -4.2 dB of input matching, isolation of the isolated Ports, and coupling in output ports are achieved (considering 2 SMA connectors and transitions in each path) in the whole instantaneous bandwidth of 20–30 GHz. Compared with other works [7, 9], the measured results of this work are considered with input-output coaxial connectors and coaxial to microstrip transitions, but other works removed these two essential effects and then reported their results, but yet this work has comparable results with them. Also in this work, the experimental time domain results with an instantaneous bandwidth of about 10 GHz or 7 Gbps are reported which are valuable results for using this Wilkinson power divider in many applications in 5G and CAR systems in 20–30 GHz. Also, a new valuable coaxial to microstrip transition is designed, analysed and developed for the final fabrication to achieve the best results in the final Wilkinson power divider. A complete study of time domain analysis and the theory of small reflections considerations are under development by the authors and will be presented in the future works. As we know, high frequency UWB transitions (coaxial to microstrip junction discontinuities) can affect the overall performance of the circuits, because for example they can produce other spurious coupling and higher order modes, leading to excess power loss, phase dispersion and possibly undesired coupling between adjacent microstrip ports and elements, which must be removed or neglected. So all performances of the proposed dividers can be improved to reach higher data rate in the Wilkinson power divider alone, and as a result, in the final constructing six-port. The authors are developing a new Wilkinson power divider to reach higher data rates, by considering important new challenges with instantaneous ultra-wide Bandwidth more than 10 GHz, and new ultra-wide bandwidth transitions.

ACKNOWLEDGMENT

The authors would like to thank from "Information and Communication Technology Institute" of Isfahan University Technology for their support of fabrication and measurements in this work.

REFERENCES

1. Ericsson White paper, "5G radio access," Uen 284 23-3204 Rev C, Apr. 2016.
2. 4G Americas White paper, "5G spectrum recommendations," Aug. 2016.
3. *European Commission — Press release, Commission facilitates deployment of car radar systems to boost road safety*, Reference: IP/11/937, Date: 29/07/2011, http://europa.eu/rapid/press-release_IP-11-937_ en.htm? Locale=en.
4. Koelpin, A., G. Vinci, B. Laemmle, D. Kissinger, and R. Weigel, "The six-port in modern society," *IEEE Microwave Magazine*, S35–S43, Dec. 2010.
5. Nedil, M., T. A. Denidni, and H. Boutayeb, "Ultra-wideband CPW six-port circuits based on multilayer technology," *Electronics Letters*, Vol. 43, No. 23, Nov. 2007.
6. Bialkowski, M. E., A. M. Abbosh, and N. Seman, "Compact microwave six-port vector voltmeters for ultra-wideband applications," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 55, No. 10, 2216–2223, Oct. 2007.
7. Hammou, D., E. Moldovan, and S. O. Tatu, "Novel MHMIC millimeter wave power divider/combiner," *24th Canadian Conference on Electrical and Computer Engineering (CCECE)*, 000280–000283, Niagara Falls, ON, 2011.
8. Razzaz Hamood Kasim, F., M. A. S. Alkanhal, and A.-F. A. Sheta, "UWB Wilkinson power divider using tapered transmission lines," *PIERS Proceedings*, 882–884, Aug. 19–23, Moscow, Russia. 2012.

9. Huang, S., X. Xie, and B. Yan, "K-band Wilkinson power divider based on a taper equation," *Progress In Electromagnetics Research Letters*, Vol. 27, 75–83, 2011.
10. Honari, M. M., L. Mirzavand, R, Mirzavand, and P. Mousavi, "Theoretical design of broadband multisection Wilkinson power dividers with arbitrary power split ratio," *IEEE Transactions on Components, Packaging and Manufacturing Technology*, Vol. 6, No. 4, 605–612, Apr. 2016.
11. Hannachi, C., D. Hammou, Z. Ouardirhi, and S. O. Tatu, "Complete characterization of novel MHMICs for V-band communication systems," *Journal of Electrical and Computer Engineering*, Vol. 2013, 1–9, 2013.
12. Askari, G. and M. Kamarei, "Distortion analysis of UWB short pulses using time-frequency distribution," *17th International Conference on Transparent Optical Networks (ICTON)*, 1–4, Budapest, Hungary, Jul. 2015.
13. Sadler, B. M., D. Goeckel, M. L. Honig, A. J. Van der veen, and Z. Xu, "Introduction to the issue on performance limits of ultra-wideband systems," *IEEE Journal of Selected Topics in Signal Processing*, Vol. 1, No. 3, 337–339, Oct. 2007.
14. Qiao, Q., Y. Dai, and Z. Chen, "Signal integrity analysis on discontinuous microstrip line," *7th International Conference on Applied Electrostatics, Journal of Physics: Conference Series 418*, 1–5, 2013.
15. Pozar, D. M., *Microwave Engineering*, 4th Edition, John Wiley & Sons, Inc., 2012.
16. Askari, G. and M. Kamarei, "Design, analysis and implementation of ultra high data rate UWB six-port receiver up to 7 Gbps for 5 G new spectrum radio access and CAR," *Progress in Electromagnetics Research B*, Vol. 73, 31–48, 2017.
17. Askari, G., M. Kamarei, M. Shahabadi, and H. Mirmohammad Sadeghi, "Analysis, design and implementation of a broadband coaxial-to-micro strip for UWB radar," *PIERS Proceedings*, 972–977, Guangzhou, Aug. 25–28, 2014.