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RESEARCH ARTICLE

Design of wideband microstrip power divider/combiner with input and output impedance matching for RF energy harvesting applications

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Abstract
Lately, it has been seen that wireless communication systems have been more developed and there has been a huge demand for multi-spectral transactions. Using circuits for more than one function is a serious requirement in communication technology. Especially, it expected from RF output stages to show the same performance on more than one frequency. To that end, it is required to produce a solution with wideband designs. In this study, a novel power divider/combiner design with a layered conic line has been investigated for the RF energy harvesting applications. The center frequency was set at 2 GHz and concluded with three different designs. In each design, bandwidth and *S* parameter characteristics were compared according to the number of layers of the transmission, and it was observed that as the number of layers increases, the bandwidth also increases. According to the design result, triple layer Wilkinson power divider was selected to connect to Villard voltage doubler circuit. The Wilkinson power combiner circuit inputs were given between −10 dBm and 5 dBm input power. As a result, when low input power was given, efficiency was observed about 70%.

KEYWORDS
impedance matching, RF energy harvesting, Villard voltage Doubler, Wilkinson power divider/combiner

1 | INTRODUCTION

The RF energy harvesting method has received the most attention in the last decades. This might be because of the increasing capacity of wireless broadcasting systems in urban areas. For examples; wireless sensor networks, mobile communication systems, Wi-Fi base stations, and wireless portable devices. The basic building blocks for the harvester for RF ranges are consist of three segments: (1) RF receiving antenna; (2) rectifying and booster circuits; and (3) impedance matching circuits. RF power divider/combiner structures designing is the important part of the harvesting circuit.[1]

It is significant to understand the various RF and microwave power divider/combiner structures as they determine the path to be followed for a good RF integrated circuit design. Optimization of the power divider/integrator's design process can save time and unnecessary expenditure and reduce design iterations, improving the quality of the product to the designer.

The design process involves many processes ranging from exploration of divider/combiner requirements to documentation of the final product, balancing of factors such as electrical performance, size and cost, and clearing.[2–4]

Power divider/combiners are used in attenuators, phase shifters, mixers, amplifiers, modulators, high power transmitter antenna arrays in base stations, wireless communication systems, signal processing applications, and RF and microwave integrated circuits. A reversible divider can

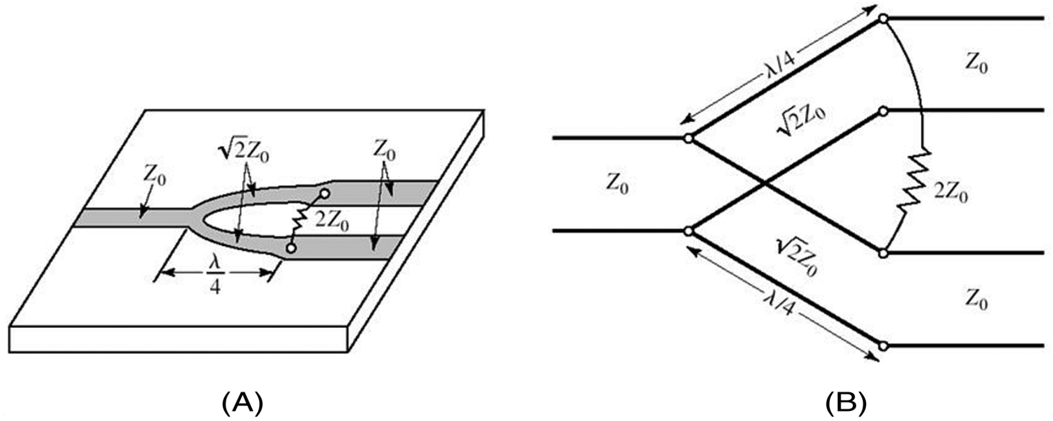

FIGURE 1 A, An equal-split power divider in microstrip form. B, Equivalent transmission line circuit

divide evenly or unevenly between two or more outputs, and thanks to this reversibility feature, these circuits can be used to assemble the oscillator and amplifier into a single port. The merge operation has a few exceptions so that the input signs for the lossless join must be harmonious and equal in amplitude.[5–7]

Wideband is a high-speed and high-capacity data transmission medium that allows multiple signals to be transmitted by dividing the total line capacity into multiple channels. It can also be referred to as a signaling method that allows data particles to be sent consecutively over this medium, thereby increasing the effective transmission rate.[8,9]

The essential and most important features of wideband services are the fact that the line is always upright, even if it is not symmetrical, it has to work in both directions and allow many applications to operate in parallel. The features that many services can work within an ideal network structure are as follows:

- High speed and capacity
- Multi-services, multi-media
- Universal coverage
- Open access
- Convenient and cost-effective
- High data security
- User and business friendly
- Resource efficient
- High social value as well as economic value

These features have become indispensable to the development of technology. Due to these reasons wideband has an important place nowadays.[5]

The main variables of RF and microwave power divider/combiners are bandwidth, power divider, phase balance, amplitude balance, insertion loss, compatibility, return loss, isolation, power capacity, integration level, and cost. Of course, these variables have barter relationships, and the selection is made by the designer depending on the application requirements.[10]

The insertion loss in dB is the ratio of the input power to the output power when nonreflective terminations are connected to the divider/coupler ports. Bandwidth is the frequency range at which the desired characteristics are provided. The power section is the number of outputs through which the input power is divided. The phase balance describes the phase difference between the power divider outputs, and this difference can be zero, ninety, or one hundred eighty degrees. The amplitude balance is the same magnitude of the power divider outputs. Insertion loss, loss of conductors, dielectric loss, loss of insulation, and loss of incompatibility. The voltage standing wave ratio (VSWR) is defined by the maximum standing wave amplitude versus the minimum standing wave amplitude. Return loss is the measurement of the amount of back reflection from the outputs of the signal given to the entry.

Insulation is the ability of the power divider outputs to not interfere. The power limit, or in other words the power limit, is the greatest power that can be used by the power divider. Good isolation between the power divider outputs has high isolation, good VSWR and near-loss dissipation.[10]

1.1 | Wilkinson power divider

In this section, the Wilkinson power divider (WPD) is versatile and multi-layered and multichannel structures are examined in the advanced design system simulation environment. The WPD power divider is invertible because it is a passive circuit, so if the power divider's outputs give power to the

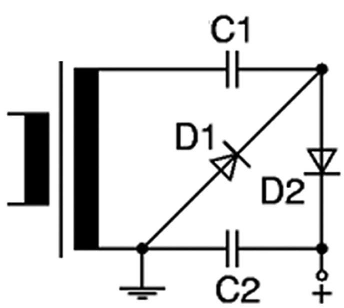

FIGURE 2 Schematic view of the Villard voltage doubler circuit

TABLE 1 Spice parameters

Parameters	Units	SMS7630
Is	A	5E–06
Rs	Ω	20
Cjo	pF	0.14
IBV	A	1E–04
Vj	V	0.34
M	No units	0.4
EG	eV	0.69
Bv	V	2

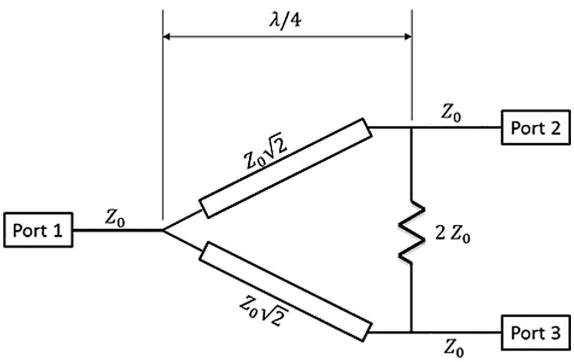

FIGURE 3 Schematic diagram of Wilkinson power divider

port we call it, the port we call the power divider's entrance will be the output in this case and the power will be connected at this port. In this section, explanations will be made through the power divider. It should be kept in mind that the power divider must comply with the signs given in the use of terrestrial use as a power combiner, and the combined strength of the isolation port must be calculated.[11–14]

A power divider must have the following characteristics:

- The power supplied to the inlet must be divided into n output port, in the desired position.

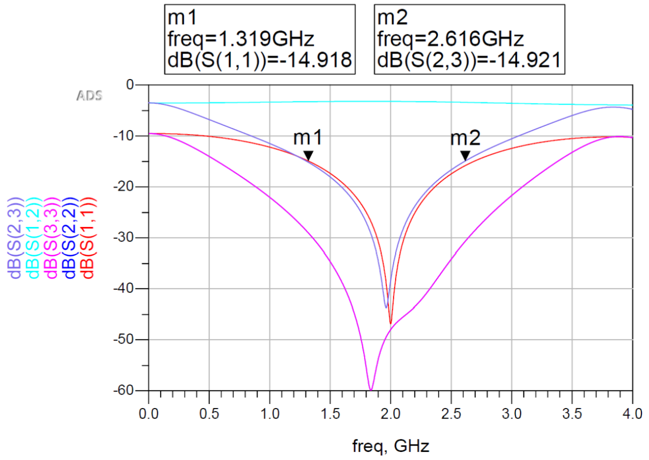

FIGURE 5 Single, two-way power equal division Wilkinson power divider S parameter results

- Input port impedance to source impedance; the impedance of the output ports must be matched to the load impedances.
- When one of the output ports is powered, there should be no power output at the other output ports.
- A power divider type that provides these features is the WPD. The equivalent circuit of this circuit is shown in Figure 1.

The WPD is a lossless switch with compatible output ports. Thus, only the power reflected from the output ports is consumed.[15] This circuit can be realized for an arbitrary power section, but firstly the equal division (3 dB) will be considered. This divider is usually made of microstrip or strip lines. Microstrip devices are widely used in modern microwave techniques.[16,17] This circuit is reduced to two simple circuits fed on symmetrical and nonsymmetrical sources on the output ports. This analysis is called the double-single mode analysis technique.

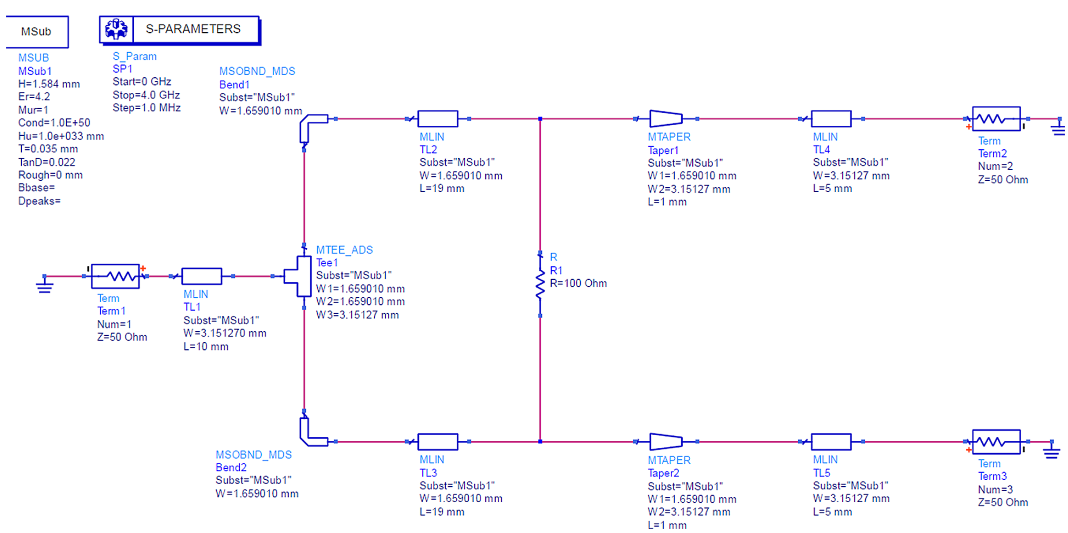

FIGURE 4 Single, two-way power equally dividing Wilkinson power divider circuit schematic

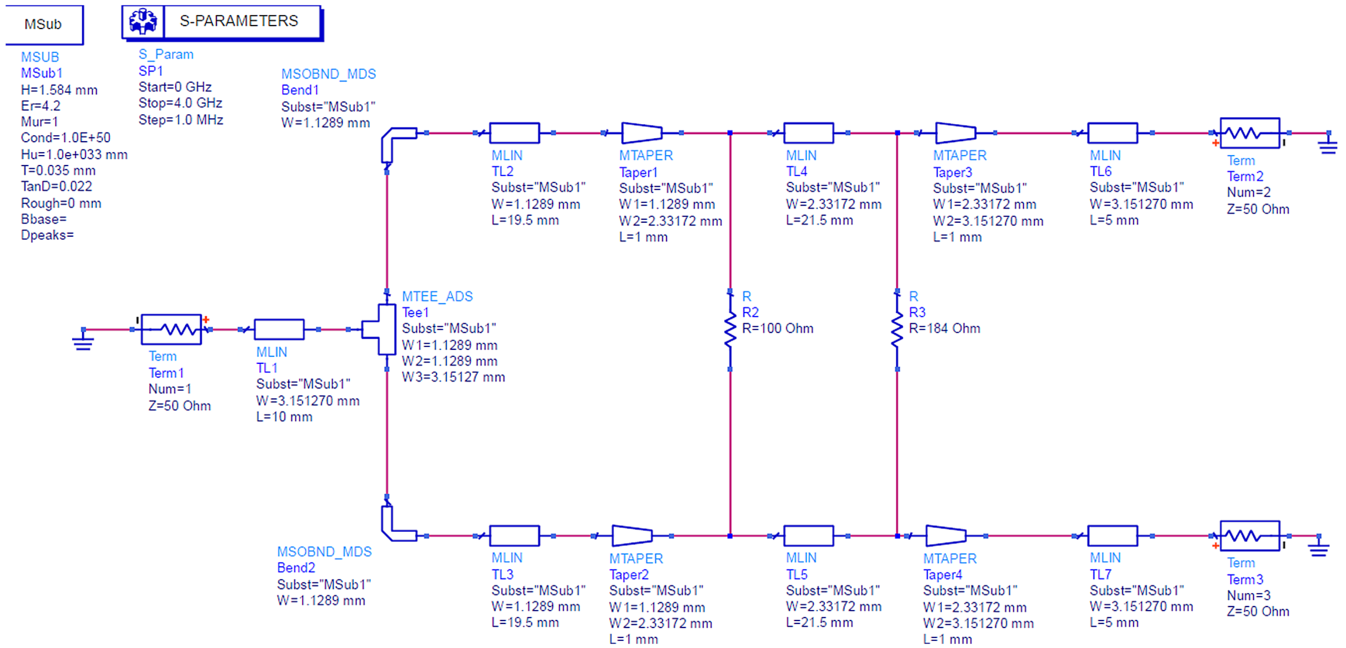

FIGURE 6 Twofold, two-way power equally dividing Wilkinson power divider circuit schematic

1.2 | Villard voltage Doubler

There are a lot of voltage doubler circuit topologies. In this work Villard voltage doubler circuit was used. Because Villard voltage doubler circuit consists simply of capacitor and diode. Besides, this is a great benefit of simplicity, its output is very poor surge characteristics. Villard voltage doubler circuit can be cascaded to from a voltage multiplier with an optional output voltage. The schematic view of the Villard voltage doubler circuit is shown in Figure 2.[12]

1.3 | Diode modeling

The voltage doubler circuit in this design uses zero bias silicon schottky detector diode SMS7630 from Skyworks. This schottky diode very low barrier height. The low barrier height results in good detector sensitivity without the need for external bias current. The associated spice model parameters were given in Table 1.[13]

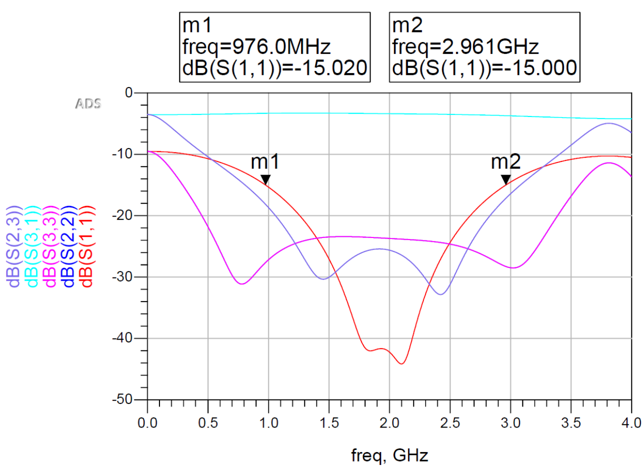

FIGURE 7 Twofold, two-way power equally dividing Wilkinson power divider *S* parameter results

2 | SYSTEM DESIGN AND ANALYSIS

2.1 | Design of single layer

In this designed circuit, the FR4 material was selected as substrate. The relative permeability coefficient of this material is 4.2, the loss tangent was 0.0022 and the height H was 1.584. The circuit design was shown in Figure 3 and the S parameters obtained from the design were shown in Figures 4 and 5.

The impedance of the quarter wave transducer in the power divider in Figure 3 is $Z = \sqrt{2}Z_0$ and the parallel resistance value $R = 2Z_0$. Transmission lines were $\lambda/4$ long. Using a computer-aided design tool capable of microwave circuit analysis, the amplitudes and phases of scattering parameters could be calculated.

2.2 | Design of double layer

In this designed circuit, the FR4 material was selected as substrate. The relative permeability coefficient of this material was 4.2, the loss tangent was 0.0022 and the height H was 1.584. The circuit design as shown in Figure 6 and the S parameters obtained from the design was shown in Figure 7.

2.3 | Design of triple layer

In this designed circuit, the FR4 material was selected as substrate. The relative permeability coefficient of this material was 4.2, the loss tangent was 0.0022 and the height

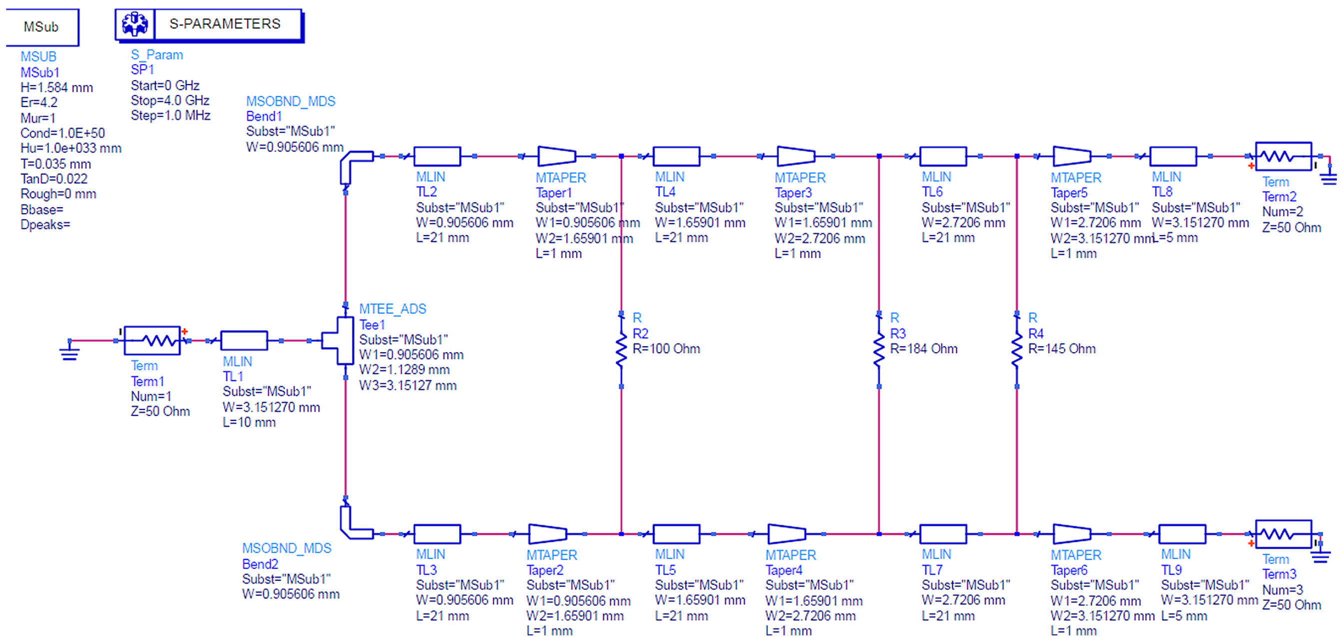

FIGURE 8 Threefold, two-way power equally dividing Wilkinson power divider circuit schematic

H was 1.584. The circuit design as shown in Figure 8 and the *S* parameters obtained in the design result was shown in Figure 9.

2.4 | Implementation with the Villard voltage Doubler circuit

The originality of the recommended design of the Wilkinson power combiner (WPC) circuit was integrated with RF powers as a consequence of the contrary operation of WPD circuit. After, the Villard voltage doubler circuit was connected to the output of the triple layer WPD circuit. Because of triple layer WPD bandwidth better than other applications. Thus, it was intended to collect the RF power by a rectifier circuit. The advantage of this design is that it can convert a lot of RF input power into direct current and voltage using a rectifier circuit using Wilkinson power combiner. The circuit design as shown in Figure 10.

It was benefited from the impedance matching feature of the Wilkinson power combiner circuit to bandwidth and to achieve higher efficiency.

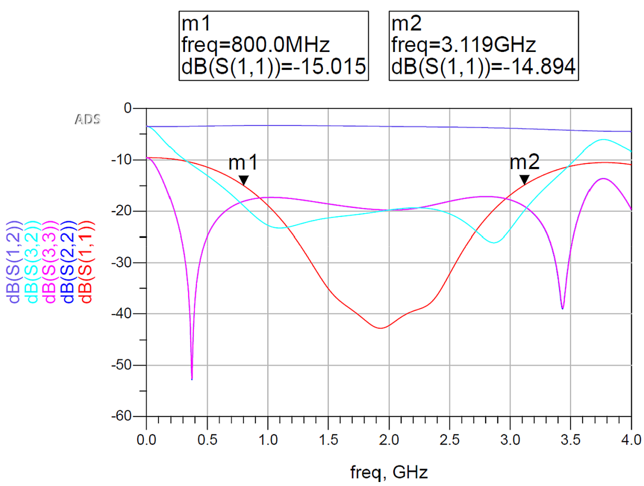

FIGURE 9 Threefold, two-way power equally dividing Wilkinson power divider *S* parameter results

3 | RESULTS

The center frequency of the design was 2 GHz. For center frequency performance, 10 log (1/2) −3.01 dB insertion loss of $S_{21} = S_{31}$ was expected. It was desired that the signs returning to the entrance port S_{11}, the projections $S_{22} = S_{33}$ on the output ports and the insulation S_{32} between the isolations are low. Bandwidth was measured with reference to −15 dB. Three different circuit designs were made, and the observed results were given in Table 2.

When the above table is examined, the following results are obtained:

- The main benefit of increasing the number of floors was the increase in bandwidth.
- Insulation between isolation (S_{32}) has been increased.
- Reductions were observed in outputs ($S_{22} = S_{33}$).

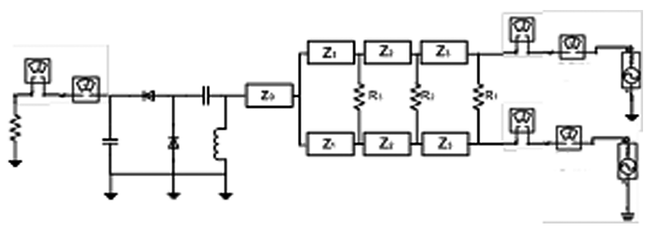

FIGURE 10 Schematic view of the Wilkinson power divider with the Villard voltage doubler circuit

TABLE 2 Simulation results based on the number of Wilkinson power divider layers

	S_{11} (dB)	S_{22} (dB)	S_{33} (dB)	$S_{21} = S_{31}$ (dB)	$S_{23} = S_{23}$ (dB)	Band width
Single layer	−46.8	−48	−48	−3.2	−38.3	70%
Double layer	−42.2	−23.7	−23.7	−3.3	−25.6	99.25%
Three layer	−44.7	−19.8	−19.8	−3.5	−19.8	115.9%

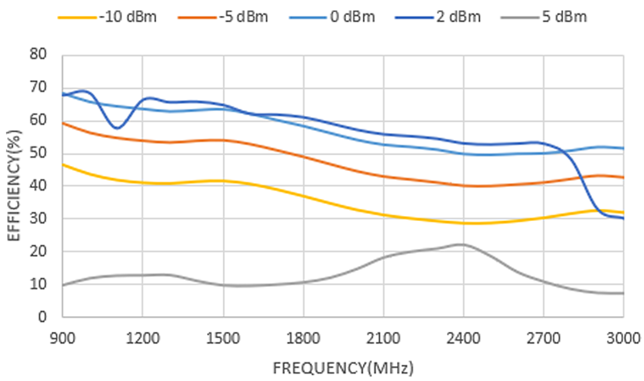

FIGURE 11 Schematic view of efficiency-frequency result

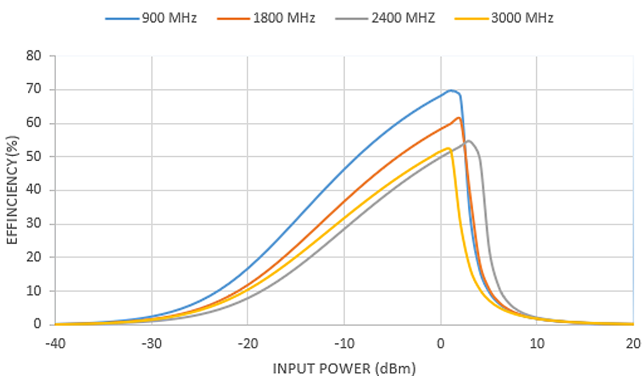

FIGURE 12 Schematic view of input power-frequency result

- The imbalance ($S_{21} = S_{31}$) was increased when the signal was divided into two.
- Projection reflections (S_{11}) were generally an increased character.
- Growing as the number of circuits have been increased both cost and difficulties in terms of implementation.

The WPC circuit inputs were given −10 dBm, −5 dBm, 0 dBm, 2 dBm, and 5 dBm input power. The efficiency graph according to the frequency is shown in Figure 11.

According to the graph highest efficiency was seen between 2 dBm and − 5 dBm.

The WPC circuit inputs were given between −40 dBm input power and 20 dBm input power. The efficiency graph according to the input power is shown in Figure 12. According to the graph highest efficiency was seen between 2 dBm and −5 dBm.

In the application, firstly it was commissioned triple layer circuit was created to provide high bandwidth. Then, the Villard voltage doubler circuit was designed to analyze the efficiency for input power. After, the Villard voltage doubler circuit was connected to the output of the triple layer WPD circuit. As a result, the highest efficiency was seen between 2 dBm and −5 dBm input power at 2 GHz center frequency and 115.6% bandwidth. The efficiency observed results were given in Table 3.

When the above table is examined the highest efficiency was seen at 900 MHz and 1800 MHz frequency. The efficiency at low input RF power was seen over 50% as 0 dBm. According to the application highest efficiency was seen 0 dBm input power at 900 MHz frequency. As a result, the efficiency was observed about 70% at low input power.

TABLE 3 As a result of efficiency according to frequency and input power

	−10 dBm	−5 dBm	0 dBm	2 dBm
900 MHz	46.5%	59.1%	68%	67.9%
1800 MHz	36.9%	49.1%	58.4%	61.2%
2400 MHz	28.7%	40.3%	50%	53.2%
3000 MHz	31.9%	42.8%	51.7%	30.1%

4 | CONCLUSION

Today, wireless communication systems have become a necessity and the need for wideband and multi-band processing has increased. For this reason, in order to provide more than one frequency filtering, amplification, and adaptation, either the bandwidth of the circuits must be wide or the frequency of the operation must be different.

In this work, a novel power divider/combiner design with a layered conic line has been examined for the RF energy harvesting applications. Conical lines were used to increase the frequency response. The center frequency was set at 2 GHz and concluded with three different designs. In each design, bandwidth and S parameter characteristics were compared according to the number of layers of the transmission, and it was showed that as the number of layers increases, the bandwidth also increases. According to the design result, the Villard voltage doubler was connected Wilkinson power combiner. The Wilkinson power combiner circuits were given low input power. When low input power was given to the Wilkinson power combiner efficiency was seen about 70%.

As a result, various improvements have been made to the circuit elements used to obtain high efficiency from RF energy harvesting systems. Power losses have been minimized thanks to the impedance matching methods used in the system. The power divider/converter selection is restricted because of bandwidth and power surges; the power divider/converter to choose must have a wide bandwidth. In WPD designing the number of layers increases, the bandwidth also increased was observed. This ensures high efficient collection of signals with high power density.

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REFERENCES

1. Kasar O, Kahriman M, Gozel MA. Wide-band Wilkinson power combiner with DVB-T, GSM-900, RF energy harvesting applications in GSM-1800 and ISM band. URSI-TÜRKİYE'2018 IX. Scientific Congress, 2018; KTO Karatay University, Konya.
2. Song K, Xue Q. Planar probe coaxial-waveguide power combiner/divider. *IEEE Trans Microwave Theory Techn*. 2009;1:2761-2767.
3. Zhou J, Morris KA, Lancaster MJ. General design of multiway multi-section power dividers by interconnecting two-way dividers. *IEEE Trans Microwave Theory Techn*. 2007;55(10).
4. Hong YP, Kimbal DF, Asbeck PM, Yook JG, Larson LE. Single-ended and differential radial power combiners theory implemented with a compact broadband probe. *IEEE Trans Microwave Theory Techn*. 2010;58:1565-1572.
5. Pozar DM. *Microwave Engineering*. New York: John Wiley & Sons, Inc.; 1998:363.
6. Konishi Y. *Microwave Electronic Circuit Technology*. Vol 273-284. New York: *Marcel Dekker, Inc.*; 1998:397-399.
7. Jain A, Sharma DK, Gupta AK, Hannurkar PR. High-power, low-loss, radial RF power dividers/combiners. *APAC*. 2007;520-522.
8. Kasar O, Kahriman M, Gozel MA. A new multi-layer real impedance adaptation technique and transmission line application with Euler polynomials. *J Eng Sci Des*. 2017;5:547-552.
9. Kasar O, Kahriman M, Gozel MA. 5.8 GHz ISM band microstrip patch antenna design and its impedance matching with Euler method. The International Workshop on Mathematical Methods in Engineering, 2017; Ankara.
10. Maloratsky LG. Setting strategies for planar dividers/combiners. *Microw J*. 2010;62-84.
11. Wilkinson EJ. An n-way hybrid power divider. *IRE Trans Microwave Theory Techn*. 1960;8:116-118.
12. Jabbar H, Song S, Jeong TT. RF energy harvesting system and circuits for charging of mobile devices. *IEEE Trans Consum Electron*. 2010;56:247-253.
13. SMS-7630, Surface mount, 0201 Zero Bias Silicon Schottky Detector Diode http://www.skyworksinc.com/uploads/documents/SMS7630_061_201295H.pdf.
14. Li J. Novel design of Wilkinson power dividers with arbitrary power division ratios. *IEEE Trans Ind Electron*. 2011;58:2541-2546.
15. Moulay A, Djerafi T. Wilkinson power divider with fixed width substrate integrated waveguide line and a distributed isolation resistance. *IEEE Microwave Wirel Compon Lett*. 2018;28:114-116.
16. Pomarnacki R, Krukonis A, Urbanavicius V. Acceleration techniques for analysis of microstrip structures. *Elektronika ir Elektrotechnika*. 2014;(5):108-111.
17. Parad LI, Moynihan RL. Split-tee power divider. *IEEE Trans Microwave Theory Techn*. 1968:110-116.

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