IJICTR
International Journal of Information & Communication Technology Research

Volume 15- Number 4 – 2023 (1 -7)

Mathematical Formulation and Experimental Evaluation of Efficient 8-Way Microwave Radial Power Combiner for High Power Applications

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Received: 5 November 2022 – Revised: 14 February 2023 - Accepted: 3 April 2023

Abstract—**An 8 port narrowband Radial Power Combiner (RPC) with excellent combining efficiency is presented. A novel useful criteria for optimal design of the RPC is developed and the design is studied based on it. Also to provide a reliable, tolerant and cost effective mechanical design, the mechanical structure of the combiner is simplified for fabrication and assembly. The designed RPC has standard waveguide ports at inputs, so it can be used in standard high power applications without any adaptors. The physical structure simplicity guarantees the product reliability for industrial high power applications. The optimized RPC design is fabricated and the measurement results are presented. The back-to-back measurement setup using customized through lines and two identical combiners have helped to take into account other efficiency degrading phenomena like port junctions' discontinuity. It is shown that simulated power combining efficiency of 99% and measured power combining efficiency of 97.7 % is achieved.**

Keywords: Combining efficiency, Radial power combiner, High power amplifier, graceful degradation, rectangular waveguide.

Article type: Research Article

I. INTRODUCTION

High power solid-state amplifiers have been interesting subject among researchers for decades. Usually power generated by a single solid-state power transistor is not sufficient for most applications. So, power combining with high efficiency is among attractive solutions to reach higher powers in different bands. The combining loss as well as the other technical challenges like power handling capability have been limiting factors for designers. High power combiners such as radial [1-4], spatial [5-7] and traveling wave [8] power combiners are presented in the literature for different applications. In waveguide radial power combiners [1], the compromise between the bandwidth and combining efficiency is the main subject of the researches and the combining efficiency can be considered as the main advantage of them. In [10] to achieve the optimal isolation between the adjacent channels, Gycel technique have been invoked in the

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[DOI: 10.61186/itrc.15.4.1]

waveguide technology at the cost of the structure volume and weight consequently, given that the structure complexity is negligible.

With the advent of the modern technologies for wideband PAs [9], wideband combining techniques became necessary. The power handling characteristics and losses in microstrip radial power combiners [3] is a challenge that limits the combining efficiency of the wideband radial power combiners. The wideband techniques presented in literature as spatial power combiners [2,5-7] reach the ultra-wideband bandwidths at the cost of system complexity and also combining losses. RGW based radial combiners have tried to reduce the complexity of wideband radial combiner while preserving the bandwidth [11,12]. The main drawback of these type of combiners are the complexity of the common port to realize appropriate mode transducer. The electromagnetic (EM) field pattern of the exciting mode at the common port is selected to have azimuthal symmetry for proper power division. When the ultimate common port is a rectangular waveguide port, this dilemma is typically solved using intermediate mode converters to circular waveguide, working in modes with no angular variation as TE_{01} or TM_{01}.

The mechanical complexity and realization challenges of the reported wideband designs may degrade the system reliability for high reliability industrial or satellite applications. Also the combining loss in these products result in need to heat dissipation which can be challenging if not addressed well [15,17].

To eliminate the need to mode transducer in waveguide radial combiners, a compact pyramidal radial combiners based on parallel plate waveguide sections with constant wave impedance and with direct coaxial output ports in presented in [13]. The premise of this approach relies on taking advantage of the inherent symmetries in an N-way radial combiner circuit to reduce the complexity of the design from that of an (N + 1) port circuit to the simple design of an equivalent two-port circuit. Although this papers [13] present an improvement in structural complexity compared to other complicated power combiners, the coaxial input port can limit the application of this technique. So in this paper [14] this problem have been focused on to resolve this limitation and present a combiner with waveguide ports at the inputs.

Following this research trend, in this paper we focus on presenting a simple robust radial power combiner with standard waveguide ports and very high combining efficiency. The goal of this design is to reach a very high reliability and fabrication cost which can be achieved with straightforward and simple mechanical design. The proposed design is capable of combining eight power amplifiers through standard WR75 input ports. Schematic of the mechanical structure of the proposed design with complete EM design parameters are shown in Fig.1. The structure simplicity assures the reliability of the component which is of great importance in output section of the Power Amplifiers (PA) where any failure at the output section of the PAs will result in chips burn out and sometimes system failure consequently. On the other hand, increasing the number of inputs in this design requires larger combiner radius (R_{Radial}) which may require compromising the combining efficiency. The structure is designed and analyzed using HFSS and analysis results of the combiner will be presented. In section II the design procedure with required electromagnetic simulations are presented. The designed combiner is fabricated and measurements results are presented in section III. In section IV conclusions will be drawn from the design and measurement results will be presented.

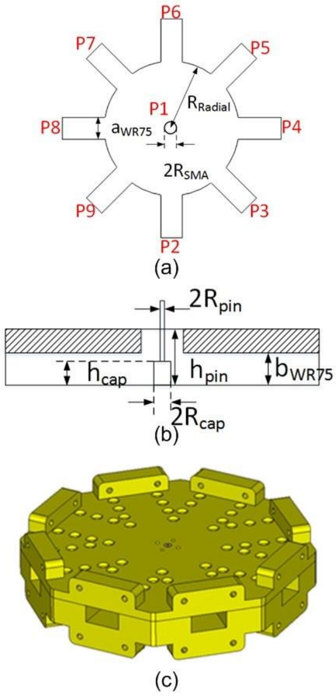

Figure 1. Top view (a), side view (b) and 3D view (c) of the proposed 8 port radial power combiner

II. DESIGN AND SIMULATION

Fig. 1 presents the mechanical structure of the proposed Radial Power Combiner (RPC). The RPC has eight input ports in standard rectangular waveguide structure with TE_{10} mode, a summation coaxial port with TEM mode and a circular waveguide with the TM_{01} mode as the combiner heart. For an eight-port microwave network with radial symmetrical structure, scattering matrix can be considered generally as follows

$$S=\begin{bmatrix} \alpha & \beta & \beta & \beta & \beta & \beta & \beta & \beta & \beta \\ \beta & \gamma & \lambda_1 & \lambda_2 & \lambda_3 & \lambda_4 & \lambda_3 & \lambda_2 & \lambda_1 \\ \beta & \lambda_1 & \gamma & \lambda_1 & \lambda_2 & \lambda_3 & \lambda_4 & \lambda_3 & \lambda_2 \\ \beta & \lambda_2 & \lambda_1 & \gamma & \lambda_1 & \lambda_2 & \lambda_3 & \lambda_4 & \lambda_3 \\ \beta & \lambda_3 & \lambda_2 & \lambda_1 & \gamma & \lambda_1 & \lambda_2 & \lambda_3 & \lambda_4 \\ \beta & \lambda_4 & \lambda_3 & \lambda_2 & \lambda_1 & \gamma & \lambda_1 & \lambda_2 & \lambda_3 \\ \beta & \lambda_3 & \lambda_4 & \lambda_3 & \lambda_2 & \lambda_1 & \gamma & \lambda_1 & \lambda_2 \\ \beta & \lambda_2 & \lambda_3 & \lambda_4 & \lambda_3 & \lambda_2 & \lambda_1 & \gamma & \lambda_1 \\ \beta & \lambda_1 & \lambda_2 & \lambda_3 & \lambda_4 & \lambda_3 & \lambda_2 & \lambda_1 & \gamma \end{bmatrix} \tag{1}$$

By applying unitary condition we have

$$|\alpha|^2 + 8|\beta|^2 = 1 \tag{2}$$

$$|\beta|^2 + |\gamma|^2 + 2|\lambda_1|^2 + 2|\lambda_2|^2 + 2|\lambda_3|^2 + |\lambda_4|^2 = 1 \tag{3}$$

$$\alpha\beta^* + \beta(\gamma^* + 2\lambda_1^* + 2\lambda_2^* + 2\lambda_3^* + \lambda_4^*) = 0 \tag{4}$$

Assuming perfect match in summation port ($\alpha = 0$) gives us

$$|\beta|^2 = \frac{1}{8} \quad (5)$$

$$|\gamma|^2 + 2|\lambda_1|^2 + 2|\lambda_2|^2 + 2|\lambda_3|^2 + |\lambda_4|^2 = 7/8 \quad (6)$$

$$\gamma + 2\lambda_1 + 2\lambda_2 + 2\lambda_3 + \lambda_4 = 0 \quad (7)$$

TABLE I. THE OPTIMIZED DIMENSION VALUES OF THE PROPOSED 8 PORT RADIAL POWER COMBINER

Parameter	Value(mm)
a*WR*75	19.050
b*WR*75	9.525
Rsma	2.05
Rpin	0.635
Rcap	3
Rradial	27
hcap	5.41
hpin	12.65

It is clear from (5) that the division ratio of 8, results in 9 dB intrinsic insertion loss. Also, it can be inferred from (6) that simultaneous perfect match and perfect isolation at input ports are impossible, i.e., it is not possible to simultaneously have γ=0 and λi=0. On the other hand (7) implies that if all ports except the summation port of the combiner are driven by signals with identical amplitude and phase and the summation port is terminated to its match load, no return signal is expected to appear at the input ports of the combiner. This implies that as long as the power amplifiers driving the combiner have enough amplitude and phase balance at their outputs, there is no need to use circulators for protection of them from reflection signals. In can also be inferred that when one or more PAs fail, other amplifiers will sense the associated effect(s) due to the limited isolation between the combiner ports.

In standard design of the combined power amplifiers, we prefer to have γ=0, i.e. perfect matching in dividing ports. The complete impedance match at the combiner input ports also guarantees the optimal power delivery of the PAs to the combiner and no degradation in PAs performance under normal conditions consequently. Using the above-mentioned criteria, the perfect isolation between ports or equal isolation between them is not possible under optimum impedance match in the input ports. Considering these limitations during the design of the combiner, we have optimized the design parameters of the radial combiner.

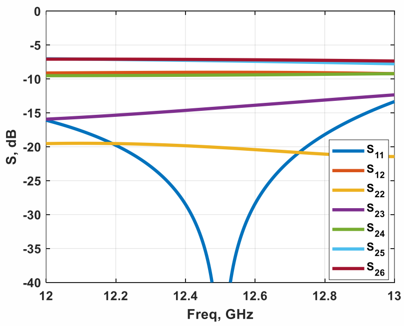

Figure 2. The simulated results of the proposed 8x1radial power combiner.

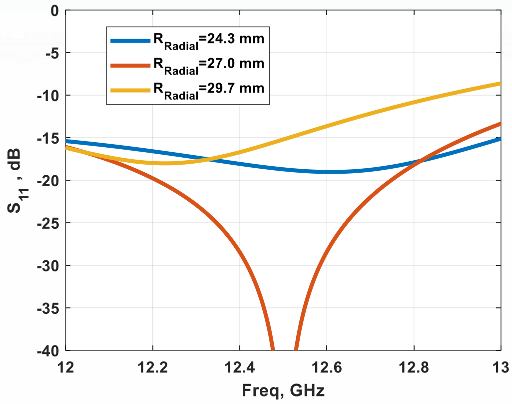

Figure 3. The effect of the RRadial parameter variation on the proposed 8x1radial power combiner.

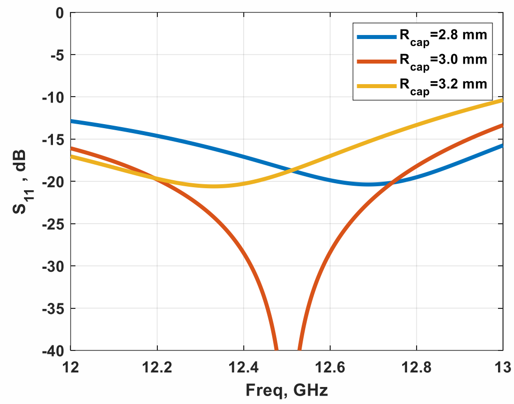

Figure 4. The effect of the Rcap parameter variation on the proposed 8x1radial power combiner.

For this design, the parameters are TM_{01} area radius (R_{radial}) and also physical structure paramours of the impedance transformer between TM_{01} region and TEM coaxial section (R_{cap}, h_{cap}). Table I shows the optimized dimensions of the RPC for operational frequency band of 12.2-12.7 GHz. The simulated results of the optimized combiner are presented in Fig. 2.

As it can be seen from the Fig. 2, ports matching (α or S11, γ or S22) of better than 20 dB can be achieved in common and input ports. The achieved isolation between the dividing ports (λ_i (S_{2j} , j=3, 4, 5, 6)) are in the range of -15 dB to -6 dB depending on the angle between the input ports normal axis.

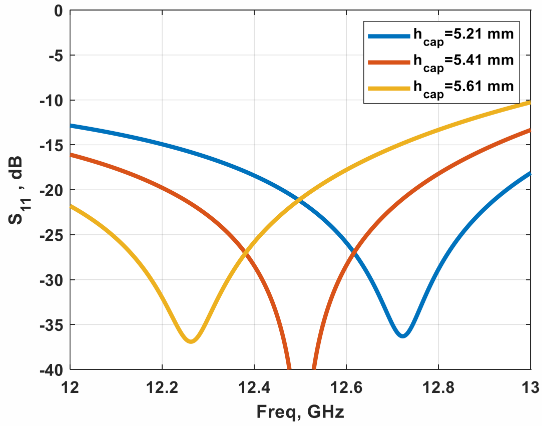

Figure 5. The effect of the hcap parameter variation on the proposed 8x1 radial power combiner.

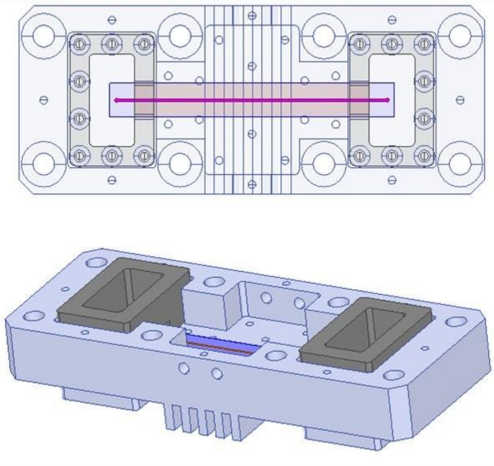

Figure 6. The proposed thru module.

For better evaluation of the combiner, it is common to simulate its performance in the back-to-back configuration. Figures 3-5 depicts the parametric studies of the design parameters on combining performance. As can be seen from the Figures 3 and 4, R_{Radial} and R_{cap} parameters control the matching frequency center and its associated value. Fig. 5 also shows that h_{cap} can help in adjusting the center frequency of the matching by tuning the associated capacitor formed between the ring and waveguide walls.

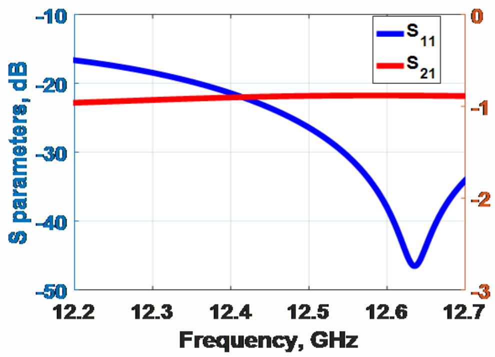

Figure 7. Simulated results of a thru module, insertion loss (right), return loss (left).

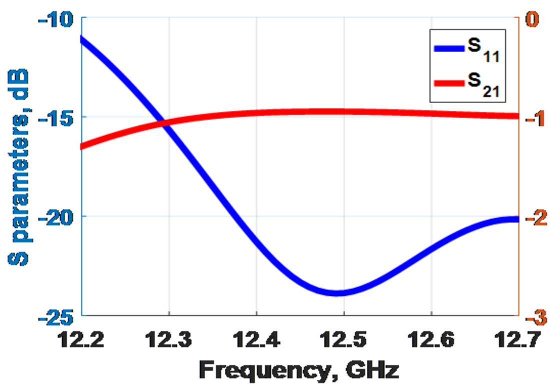

Figure 8. Simulated results of the radial power combiner in back to back configuration, insertion loss (right), return loss (left).

For this aim, two combiners are cascaded via eight custom fabricated thru modules (Fig. 6). The proposed thru modules are composed of a 50-ohm microstrip line and two microstrip to WR 75 transitions. Simulated frequency response of the thru module is depicted in Fig. 7. Return losses of better than 17 dB and insertion loss of about 0.9 dB is achieved for these components. In the mechanical design of the thru modules, the mechanical considerations like heat sink for potential use of them with operational PAs are included. The simulated results of the total back-to-back configuration of the RPC divider, through modules and RPC combiner are presented in Fig. 8. As is clear from this figure, impedance matching of better than -12 dB and insertion losses of less than 1dB is achieved. Since matching of the RPC ports and through modules are good enough, de-embedding of the thru module losses from the back-to-back measurements can be approximated by subtraction of the insertion losses. To reach the thru modules insertion loss, independent test with TRL calibration is performed with VNA to achieve exact results. So after subtraction of the through module loss, the insertion loss of about 0.1 dB is achieved as contribution of the two RPCs. Consequently, simulated combining efficiency of 99 percent is achieved. The thru modules use microstrip lines for power transmission in which PAs will be mounted later. Also two microstrip to WR75 transducers have been incorporated which combined with the microstrip transmission lines result in the transmission loss of the thru modules.

III. Power Handling Capability

Air-filled waveguide power handling capability is limited by to both average power (heat dissipation) and peak power (dielectric-breakdown). Electric field strength breakdown in air at room temperature and sea-level pressure is about 3×10^6 V/m. In an air-filled rectangular waveguide maximum power capacity before breakdown can be calculated as follows: [12]

$$P_{br} = \frac{a\times b\times E_{br}^{\ 2}}{4Z_w}$$
$$\rightarrow P_{br} \approx 6.63\times10^{-4}\times a\times b\times \frac{\lambda_0}{\lambda_g}\times E_{br}^{\ 2}, W \quad (8)$$

For example, at 12.5 GHz the maximum peak power capacity of WR75 waveguide is about 841 kW. According to the simulations the maximum magnitude of the electric filed of the power combiner at 12.5 GHz is 9459.5 V/m for 0.5W input power in the sum port. So the combiner power handling capacity is about 50.3 kW. As this power is much lower than capacity of WR75 waveguide, we reconsidered the combiner structure. Fig.9 shows the electric field in the combiner from top and side views. As can be seen from the figure the summation port of the combiner is a coaxial port. In an air-filled coaxial line with outer radius (b) and inner radius (a) the maximum power capacity before breakdown is [12]

$$P_{br} = \frac{(a\times E_{br})^2}{120}\ln\frac{b}{a}, W \quad (9)$$

[DOI: 10.61186/itrc.15.4.1]

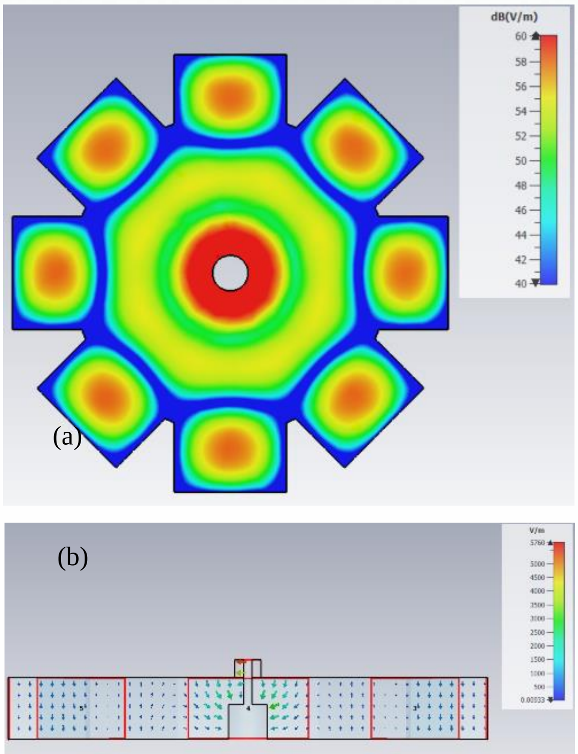

Figure 9. The simulated electric field of the proposed 8x1 radial power combiner in 12.5 GHz in top (a) and side (b) view planes.

For sum port, at 12.5 GHz the maximum peak power capacity of is about 51 kW. So, the limiting part of the combiner in very high-power applications is the coaxial port.

IV. Results and Discussions

Fig. 10 shows the fabricated radial power combiners in back to back configuration. As can be seen from the figure, eight WR75 ports from the top combiner are connected to the corresponding ports of the bottom combiner. Two coaxial ports of the combiners act as the input/output. Combiners are connected via amplifier modules which its active area is replaced by a microstrip lines called thru module. Measured results of the thru module is shown in the Fig. 11. Insertion losses of about 1.1 dB and matching better than 15 dB is in good agreement with the expected values from the simulations shown in Fig.7.

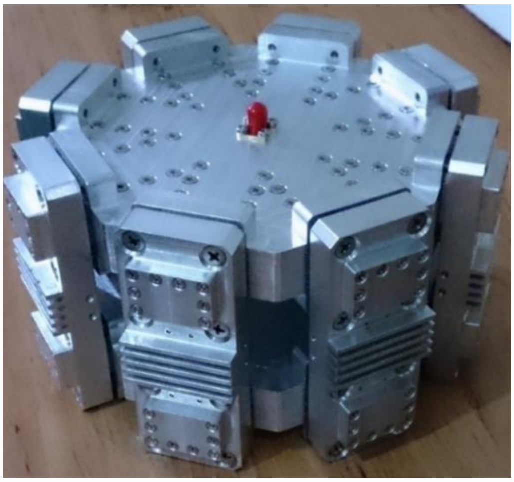

Figure 10. The fabricated radial power combiner in back to back configuration

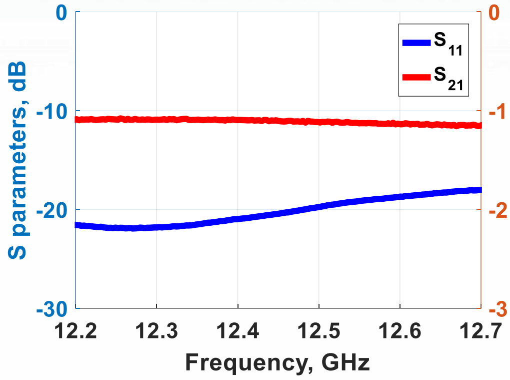

Figure 11. Measured results of a thru module, insertion loss (right), return loss (left).

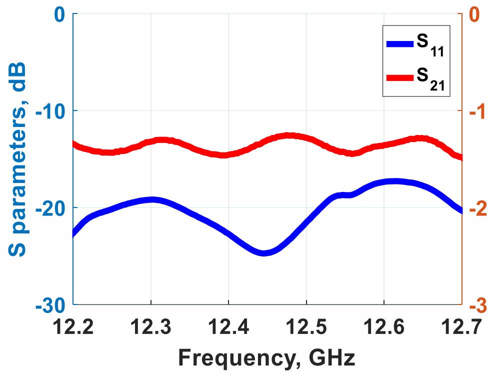

Figure 12. Measured results of the radial power combiner in back to back configuration, insertion loss (right), return loss (left).

Fig. 12 presents the measurement results of the back-to-back configuration. It is clear from this plot that good matching (better than 15 dB) in the input and output ports are achieved. The measured insertion loss of the structure is about 1.3 dB, which includes both combiners loss and also the thru module losses as well as the other system losses like junctions' discontinuity.

By eliminating the thru module loss of 1.1 dB derived from the standalone measurements (Fig.11), the dividing and combining loss of 0.2 dB is achieved for back-to-back structure. Consequently, combining efficiency of about 97.7 percent can be concluded based on the measurements. Table II compares the performance of three most recently reported waveguide radial power combiners in the similar frequency band.

Even though all RPCs have good combining efficiency, the presented RPC have slightly better combining efficiency. This slight outperformance in the combining efficiency is drawn from the back-to-back measurements which accounts all the potential degradations of the operational use of the combiner. Also, the measurement results of this paper are for the prototype product fabricated in Aluminum without silver coating which in conjunction with polishing can help in reaching the expected theoretical combining efficiency. The presented works in [16] [17] have compromised the combining efficiency of the product by adding an extra complicated mode transducer at the output section of the combiner to reach waveguide port at the output.

[DOI: 10.61186/itrc.15.4.1]

TABLE II. PERFORMANCE COMPARISON BETWEEN KU-BAND RPCS

REF.	FC (GHZ)	BW (GHZ)	NO. OF PORTS	EFFICIENCY (%)	BACK TO BACK EVALUATION
[11]	4	2	5	80	NO
[12]	7	5	5	90	NO
[13]	6	4	7-16	90	NO
[14]	10	2	3	90	NO
[15]	10	1	12		NA
[16]	12	2	16	95	NO
[17]	12	2	10	96.5	NO
THIS WORK	12.5	0.5	8	97.7	YES

V. CONCLUSION

Power combining with high efficiency in microwave and millimeter wave frequencies is one of the challenging interests among researchers. In this paper a radial power combiner with eight combining port is presented. The RPC is composed of two metallic parts that separately fabricated and easily can be assembled. For better evaluation of the combiner, two RPC and eight thru modules are designed and fabricated. Each thru module is composed of two waveguides to microstrip transitions and a microstrip line section. Measurement results of the back-to-back configuration show return losses better than 15 dB in input and output ports and insertion loss of better than 0.1 dB is achieved. Combining efficiency of better than 97.7 percent is measured for the back-to-back measurements. Compared to the similar recently reported works, the proposed design achieves the excellent combining efficiency by using a simpler impedance transformer at the output port.

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[DOI: 10.61186/itrc.15.4.1]

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[DOI: 10.61186/itrc.15.4.1]