Design of Dual-Band Rat-Race Combiner

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Abstract
In this we paper present the design of a dual-band rat-race combiner. The desired dual-band operation is realised by adding tapped open stub to the branches of the conventional rat-race coupler. The proposed design demonstrates low and high ratios between two operating bands and provides an enhanced design flexibility. The even-odd mode analysis is used to develop the necessary design formula. The combiner is designed and manufactured on a Rogers 5870 substrate and operates at 2.45/5.8 GHz frequency bands. The measurement results revealed good performances and validated the design approach.
Keywords:
Flexibility,dual-band, rat-race, combiner.

1. Introduction

Rat-race combiner is an important passive component, generally used in RF front ends of modern microwave communication systems. It provides equal power splitting with in- and anti-phase responses at different output ports. The rat-race combiners can be used in balanced mixers for spurious signal rejection and phase shifters differentially fed antenna etc [1]. Previous works in this area were mainly focused on size reduction [2 – 3] and bandwidth enhancement [4 –5], which had resulted in great improvements in these two aspects.In fact, the basic principle to augment the bandwidth of a combiner is to use multiple sections as described in [6].The dual-band combiner can be used in a variety of applications, including wireless base stations, distributed antenna systems, and small cell networks. Recently, several types of rat-race combiners and other microwave passive components featuring dual-band operations were developed [7-8-9]. The merit of this type of dual-band circuits lies in its ability to reduce both the size and cost of the overall system.

In this paper, a dual-band rat-race combiner has been developed. The proposed combineruses a stub with open circuit termination tapped at the centres of the branches of a conventional rat-race combiner to satisfy the dual-band operation conditions. The use of open-circuit terminated stubs enables the elimination of via holes, which are required for short terminated stubs.

The paper has been organized as follows: Section 2, outlines the analysis of the proposed combiner.A numerical validation is given in section 3. The experimental validation of the concept, structure and practical implementations of the proposed dual band rat race combiner, and subsequent discussions are included in section 4.Finally, conclusions will be presented in section 5.

2. Theoretical analysis of the rat-race combiner

The topology of the proposed rat-race combiner is shown in Fig. 1. The even–odd mode analysis is applied here to study the combiner's properties. The ABCD matrices are then used to find the transmission (T_e, T_o) and reflection (R_e, R_o) coefficients of each mode.

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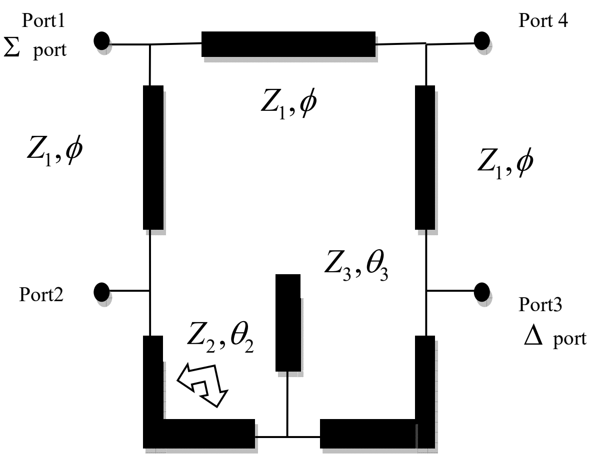


Fig. 1. General Topology of the proposed combiner

As shown in Fig. 1, the signal input at port 1 (Σ_{port}) will be equally split with in-phase responses and the signal input at port 3 $\left(\Delta_{port}\right)$ will be equally split with anti-phase responses. Besides, under the assumption that the combiner is lossless, it is found that the sufficient and necessary conditions for ideal rat-race combiner are defined as follows:

$$R_e = T_e \tag{1}$$

$$R_o = -T_o \tag{2}$$

where R_e and R_o are the even- and the odd-mode reflection coefficients, while T_e and T_o are the even- and the odd-mode transmission coefficients respectively.

The overall S-parameters of the rat race combiner can be calculated utilizing the following expressions:

$$S_{11} = \frac{1}{2}\left(R_e + R_o\right) \tag{3}$$

$$S_{21} = \frac{1}{2}\left(R_e - R_o\right) \tag{4}$$

$$S_{41} = \frac{1}{2}\left(T_e + T_o\right) \tag{5}$$

$$S_{32} = \frac{1}{2}\left(T_e - T_o\right) \tag{6}$$

$$R_e = \frac{A_e + \left(B_e/Z_0\right) - C_e Z_0 - D_e}{A_e + \left(B_e/Z_0\right) + C_e Z_0 + D_e} \tag{7}$$

$$T_e = \frac{2}{A_e + (B_e/Z_0) + C_e Z_0 + D_e} \tag{8}$$

$$R_o = \frac{A_o + \left(B_o/Z_0\right) - C_o Z_0 - D_o}{A_o + \left(B_o/Z_0\right) + C_o Z_0 + D_o} \tag{9}$$

$$T_o = \frac{2}{A_o + (B_o/Z_0) + C_o Z_0 + D_o} \tag{10}$$

$$A_o = \cos\phi + \frac{Z_1 \sin\phi}{Z_2 \tan\theta_2} \tag{11}$$

$$B_o = jZ_1 \sin\phi \tag{12}$$

$$C_o = j\frac{\sin\phi}{Z_1} - j\frac{\cos\phi}{Z_1 \tan(\phi/2)} - j\frac{\cos\phi}{Z_2 \tan\theta_2} - j\frac{\sin\phi}{Z_2 \tan(\phi/2)\tan\theta_1} \tag{13}$$

$$D_o = \cos\phi + \frac{\sin\phi}{\tan(\phi/2)}$$

$$A_e = \cos\phi - \frac{Z_1 Z_2 \sin\phi \tan\theta_3 + 2Z_1 Z_3 \tan\theta_2 \sin\phi}{2Z_2 Z_3 - Z_2^{\,2} \tan\theta_2 \tan\theta_3} \tag{14}$$

$$B_e = jZ_1 \sin\phi \tag{15}$$

$$C_e = j\frac{\tan(\phi/2)\cos\phi}{Z_1} + j\frac{\sin\phi}{Z_1} + jZ_2\cos\phi\tan\theta_3 - Z_2\sin\phi\tan(\phi/2) + \frac{2Z_3\cos\phi\tan\theta_2 - 2Z_3\sin\phi\tan(\phi/2)\tan\theta_2}{2Z_2Z_3 - Z_2^2\tan\theta_2\tan\theta_3} \quad (16)$$

$$D_e = \cos\phi - \sin\phi\tan\frac{\phi}{2} \quad (17)$$

The transmission (T_e, T_o) and reflection (R_e, R_o) coefficients could be represented in terms of ϕ , θ_1 and θ_2 by applying the equations (3)-(17). When these expressions are inserted into equations (1) and (2) the design parameters are determined.

As for the dual-band operation (1) and (2) must be satisfied at assigned lower and upper frequencies, f_1 and f_2 respectively. To facilitate the analysis at these two frequencies, we define

$$\phi = \frac{\pi}{2} - \varepsilon \quad \text{at} \quad f_1$$

$$\phi = \frac{3\pi}{2} + \varepsilon \quad \text{at} \quad f_2 \quad (18)$$

Furthermore

$$\theta_2 = \frac{\pi}{2} - \delta \quad \text{at} \quad f_1$$

$$\theta_2 = n_1\pi - \frac{\pi}{2} + \delta \quad \text{at} \quad f_2 \quad (19)$$

$$\theta_3 = \frac{\pi}{2} + \psi \quad \text{at} \quad f_1$$

$$\theta_3 = n_2\pi - \frac{\pi}{2} - \psi \quad \text{at} \quad f_2 \quad (20)$$

Where n_1 and n_2 are integers. As depicted in Fig. 1, ϕ , θ_2 and θ_3 represent the electrical lengths corresponding to the main branches and the tapped stubs. Additionally, three variables (ε , δ , ψ) each with real number values are employed to parameterize ϕ , θ_2 and θ_3 at the two operating frequencies f_1 and f_2 .

Thus, the design equations of the dual-band Rat-Race combiner turn out to be:

$$\beta = \frac{f_2}{f_1} \quad (21)$$

$$\varepsilon = \frac{\pi}{2} - \frac{2\pi}{1+\beta} \quad (22)$$

$$\delta = \frac{\pi}{2} - \frac{n_1\pi}{1+\beta} \quad (23)$$

$$\psi = \frac{n_2\pi}{1+\beta} - \frac{\pi}{2} \quad (24)$$

The characteristic impedances are determined by the following equation:

$$Z_1 = \frac{\sqrt{2\cos 2\varepsilon}}{\cos\varepsilon} Z_0 \quad (25)$$

$$Z_2 = \frac{\sqrt{2\cos 2\varepsilon}}{(\sin\varepsilon - 1)\cot\delta} Z_0 \quad (26)$$

$$Z_3 = \frac{\sqrt{2\cos 2\varepsilon}\cot\psi}{(1-\sin\varepsilon)\left[\cot^2\delta(\sin\varepsilon - 1) + \sin\varepsilon + 1\right]} Z_0 \quad (27)$$

From (21) – (27), the characteristic impedances of the branch lines and the tapped stubs (Z_1 , Z_2 , Z_3) are determined as a function of the frequency ratio β . In practice, the realisable impedance values are constrained. Therefore the realisable frequency ratio using the proposed combiner is also limited. However, with the changing of the stub lengths which corresponds to changing the values of n_1 and n_2 in (23) and (24), a wide range of frequency ratios can be realised. A simple numerical searching program has been developed to find these values. In our case, we have limited the values of n_1 and n_2 between 1 and 9.

3. Numerical validation

For the values of $n_1 = 3$ and $n_2 = 3$ to get a realisable characteristic impedance and referring to (18) – (27), the characteristic impedances and electrical lengths of the three branches are mentioned in Table 1.

Table 1: Impedances and electrical lengths at 2.45 GHz

Characteristic impedance (Ω)	Electrical length (°)
Z_1=67.3	$\phi = 107°$
Z_2=140.0	$\theta_2 = 160.4°$
Z_3=32.7	$\theta_3 = 160.4°$

Where Z_1, Z_2, Z_3, ϕ, θ_2 et θ_3 are labelled in *Fig. 1.*

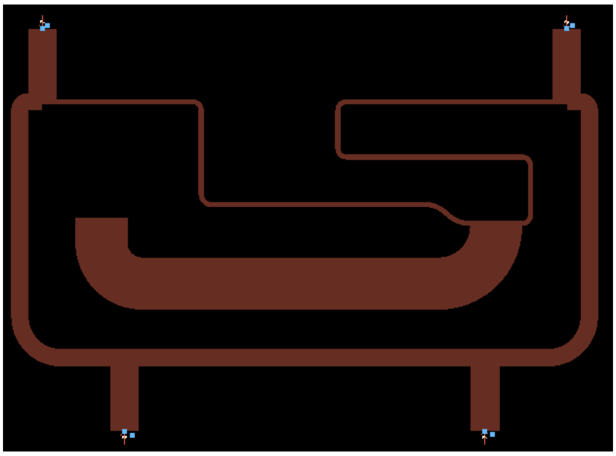


Fig. 2. Layout of the proposed dual-band rat race combiner

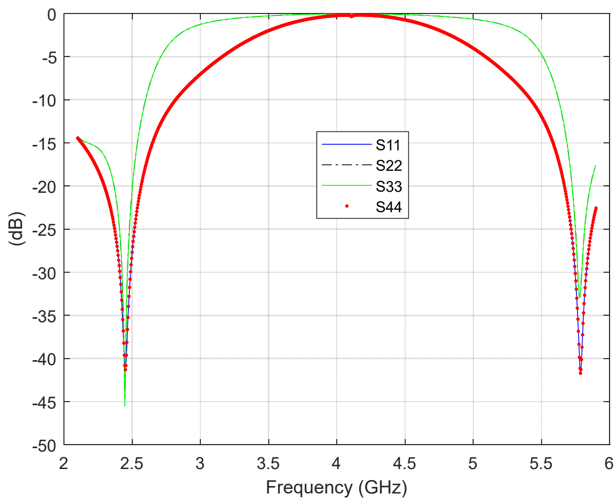
To validate the presented analysis, the combiner has been built using the microstrip technology on a Rogers 5870 substrate with a dielectric constant ε_r =2.33 and a thickness H=0.79 mm. The selection of the Rogers substrate was based on his low loss with a tgδ as low as 0.0013 at 10GHz. This helps to minimize the insertion loss of the combiner.Using the beforementioned substrate, the impedances Z_1, Z_2 and $Z_3$and the electrical lengths ϕ, θ_1 and θ_2 have led to the microstrip widths and lengths given in table 2.

Table 2: microstrip transmission lines widths and lengths

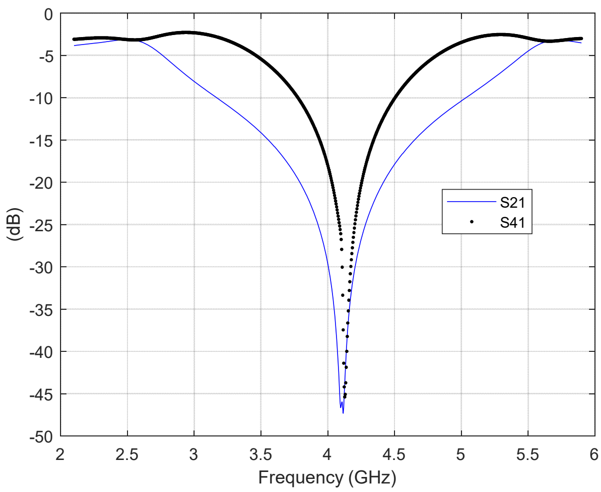
Line width (mm)	***Line length (mm)***
W_1=1.3	l_1=25
W_2=0.4	l_2=40
W_3=4.0	l_3=36

Converting the ideal transmission lines of Fig. 1 to microstrip transmission lines and stubs and optimising the shape of the resulting combiner for size reduction, the layout of Fig, 2 has been obtained. The combiner measures 46 mm in length and 33 mm in width.

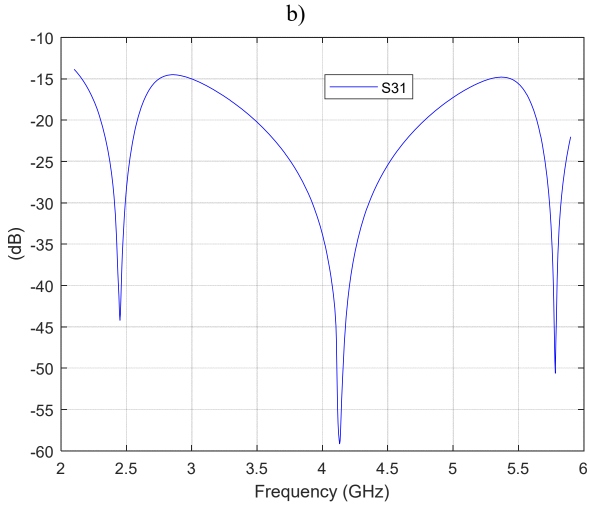
As a passive, linear microwave circuit, the RF combiner is best characterized by itsscattering (S) parameters. The (S) parameters describe the self and mutual ratios between the incident andreflected waves at each port of the combiner, thus making it possible to evaluate its behavior in termsof reflection and transmission between ports. At this stage, an electromagnetic simulation can be performed using the Momentum tool of ADS for a frequency range between 2GHz and 6GHz.For comparison purposes, an electrical simulation has been performed on the ideal structure of Fig. 1.



a)



b)



c)

Fig. 3.*Electrical simulation of the ideal combiner*
(a) Port matching, (b) insertion loss, (c) isolation

The simulated S-parameters are presented in Fig.3.Figure 3.a shows the matching of the four ports.We notice a good matching with reflexion coefficients below -14 dB in the 2.45 GHz and 5.8 GHz frequency bands.Besides, the insertion losses between port 1 &2 and port 1 & 4range from 3 to 3.1dB.Besides figure 3.c shows a good isolation between port 1&3.

4. Experimal validation

To experimentally validate the proposed design, the dual-band rat-race combiner of figure 2has been fabricated as shown in figure 4 and measured. using the S5085 network analyzer of Copper Mountain Technologies over the frequency range of 2 to 6 GHz.

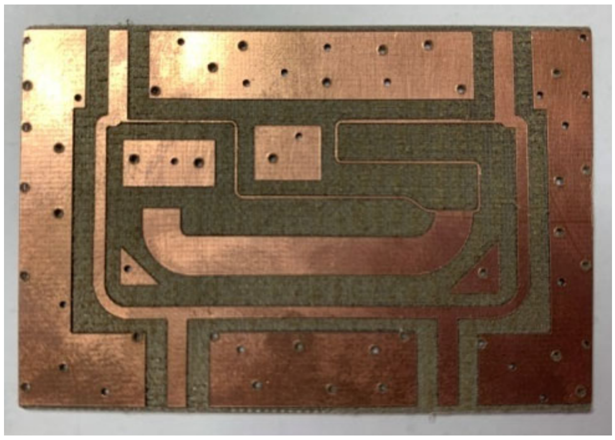


Fig. 4. Photo of the fabricated dual-band rat-race combiner

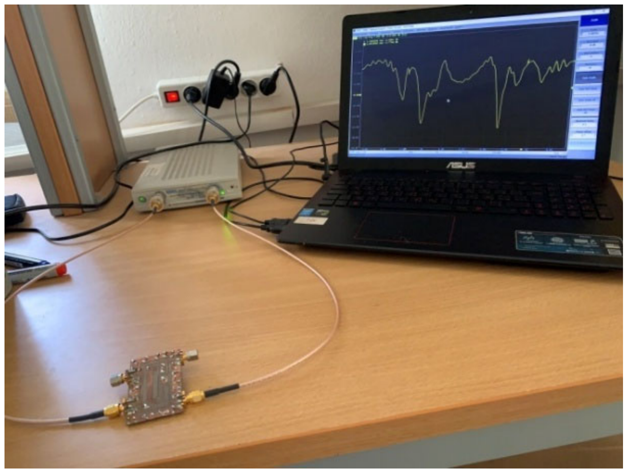
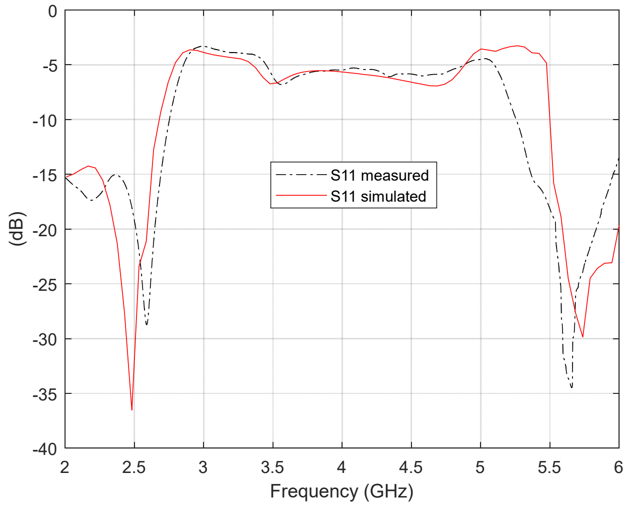
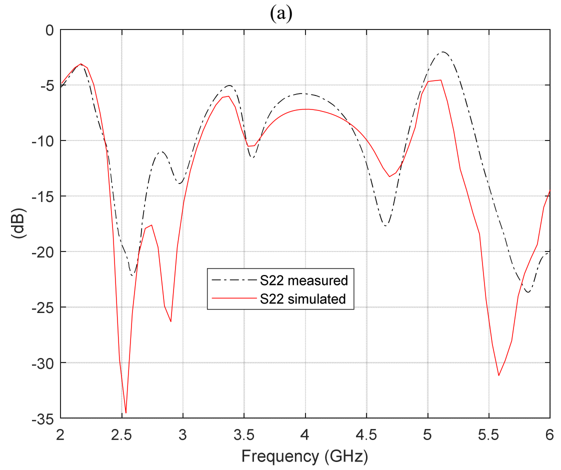


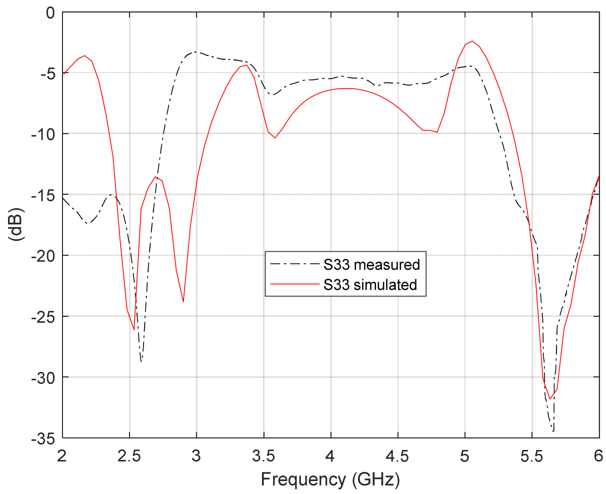
Fig. 5. Measurement of the proposed combiner


S11 measured
S11 simulated
(dB)
Frequency (GHz)

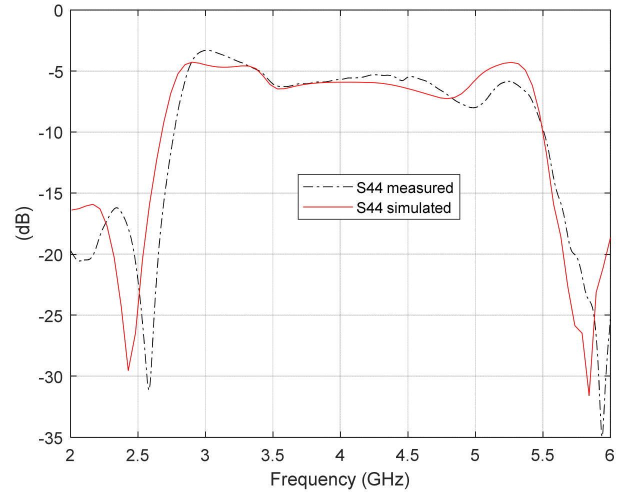
(a)


S22 measured
S22 simulated
(dB)
Frequency (GHz)

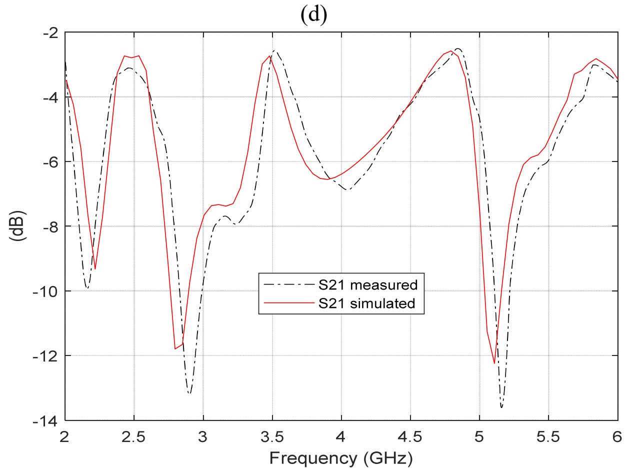
(b)


S33 measured
S33 simulated
(dB)
Frequency (GHz)

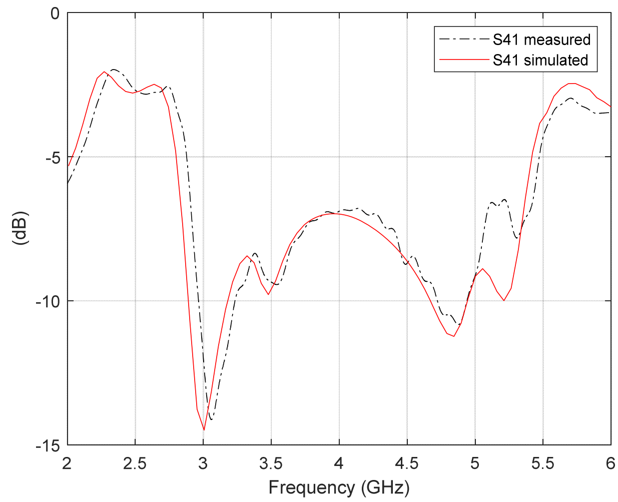
(c)


S44 measured
S44 simulated
(dB)
Frequency (GHz)

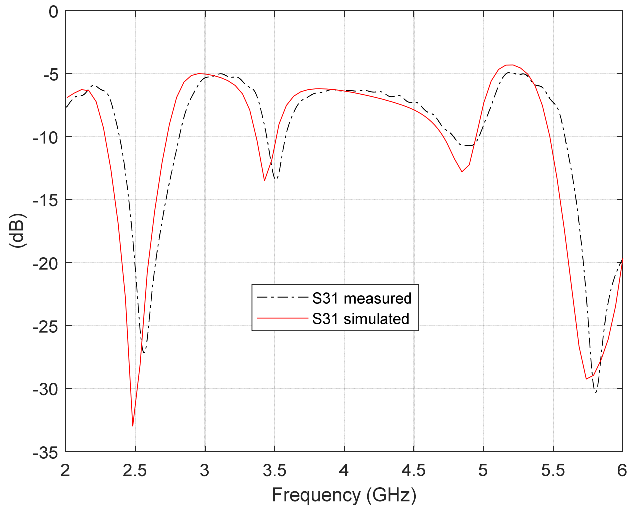
(d)


S21 measured
S21 simulated
(dB)
Frequency (GHz)

(e)


S41 measured
S41 simulated
(dB)
Frequency (GHz)

(f)



(g)

Fig. 6. ADS Simulation and measurement results of the proposed rat-race combiner.
(a),(b),(c),(d)port matching, (e),(f) insertion loss(g)port isolation

Fig.6 present the performances obtained in practice from theproposed Rat-Race combiner. Figures 6.a, 6.b, 6.c and 6.d) show the reflections coefficients at the four ports of the combiner., Figures 6.e and 6.f show the insertion losses and figure 6.g shows the isolation coefficient. Figures 6 reveal a good match between the simulated and measured S-parameters. The measured insertion losses between port 1&2 and between port 1&4 vary between 2.4 - 3.2 dB while the isolation between port 1 & 3 is below -14 dB. The obtained results outperform those presented in [6] like shown in Table 3.

Table 3: comparative study

Obtained results / ***Works***	***S11(dB)***	***S21(dB)***
Previous work [6]	-24	-3.4
Proposed work	-34	-3.2

5. Conclusions

The proposed rat-race combiner has been studied in this paper. It is based on tapped open stub. Theoretical design equations of this combiner are derived with the even –odd mode analysis. For the purpose of verification, an experimental prototype is fabricated and tested. The measurement results have shown good agreement with the theoretical predictions.

References

[1] POZAR D.M.: 'Microwave engineering' (New York, John Wiley Sons, 4th edn. 2012)

[2] HIROTA T., MINAKAWA A., MURAGUCHI M.: 'Reduced-size branch-line and rat-race hybrids or uniplanar MMICs', IEEE Trans. Microw. Theory Tech., 1990, 38, (3), pp. 270– 275.

[3] CHUANG M.-L.: 'Miniaturized ring coupler of arbitrary reduced size', IEEE Microw. Wirel. Compon. Lett., 2005, 15, (1), pp. 16– 18.

[4] HO C.-H., FAN L., CHANG K.: 'Broad-band uniplanar hybridring and branch-line couplers', IEEE Trans. Microw. Theory Tech., 1993, 41, (12), pp. 2116– 2125

[5] ANG K.S., LEONG Y.C., LEE C.H.: 'A new class of multisection 1808 hybrids based on cascadable hybrid-ring couplers', IEEE Trans. Microw. Theory Tech., 2002, 50, (9), pp. 2147– 2152.

[6] Anuj Kumar Sahoo, Karun Rawat: 'A wideband rat-race coupler using stepped impedance resonator'.Proc. Int. Conf.International Wireless Symposium (IWS),Chengdu, China,May, 2018.

[7] H. Zhang,K.J. Chen. 'Design of dual-band rat-race couplers', IETMAP., 2009, 3,(3), pp.514– 521.

[8] CHENG K.-K.M., WONG F.-L.: 'A novel rat race coupler design for dual-band applications', IEEE Microw. Wirel. Compon. Lett., 2005, 15, (8), pp. 521– 523.

[9] PARK M.-J., LEE B.: 'Dual-band, cross coupled branch line coupler', IEEE Microw. Wirel. Compon. Lett., 2005, 15, (10), pp. 655– 657.