Three New Rat-Race Couplers with Defected Microstrip and Ground Structure (DMGS)

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Abstract **─** In this paper, three new types of rat-race ring couplers with defected microstrip and ground structure (DMGS) are presented and one type is fabricated to validate the simulation results. The proposed structures have the advantages of size reduction as well as 3rd harmonic suppression. Embedding the DMGS section increases the slow-wave factor (SWF) and as a result the resonant frequency of the coupler decreases, which sets the stage for size reduction. In addition, insertion losses of the 3rd harmonic of the proposed couplers are reduced to 35 dB. After optimizing with genetic algorithm (GA), one type is fabricated. Good agreement between the simulation and measurement results is observed. Simulations are carried out using HFSS 13 and the designed coupler is validated by measurement.

Index Terms – Defect on microstrip, defect on ground, DMGS, and hybrid ring rat-race coupler.

I. INTRODUCTION

Microstrip rat-race ring couplers are important structures in microwave engineering. Among all couplers, rat-race couplers are widely used due to their simplicity and wide bandwidth in dividing power. They are used in power amplifiers, mixers, and antenna systems [1]. Hybrid ring couplers are also used in isolated power dividers where high level of isolation between the ports is required. However, this isolation is generally limited in bandwidth by the phase balance performance of the hybrid. The conventional 180º hybrid ring coupler has several shortcomings. It is inherently narrow band, large in size, and it requires impractically high impedance line sections for large power-split ratios. Therefore, many techniques have been proposed to improve the frequency characteristic of rat-race couplers and attempts are continually made to reduce their size, suppress their spurious harmonics, increase their bandwidth, and make a dual band coupler [2, 3].

Wireless communication systems usually require smaller device size in order to meet circuit miniaturization and cost reduction. Thus, size reduction is becoming a major design consideration for practical applications. However, in the low microwave frequency range, even a small size conventional hybrid coupler is still too large for some applications. Therefore, reduced size couplers are continually proposed for MMIC (Monolithic Microwave Integrated Circuit) applications [3-7].

Recently, there has been an increasing interest in microwave and millimeter-wave applications of the PBG (photonic band gap) [5, 6] and the DGS (defected ground structure) [2, 7-9]. In the case of 2-dimensional PBG structure [5], a lot of PBG cells increase the circuit size, which leads to feedline losses. Also, the slow-wave effect in [5] is sensitive to the location and direction of the line with respect to the principal axes of the periodic defected holes on the ground. In [7] a rat-race coupler with DGS sections has been proposed that is not optimum neither in size nor in shape. In

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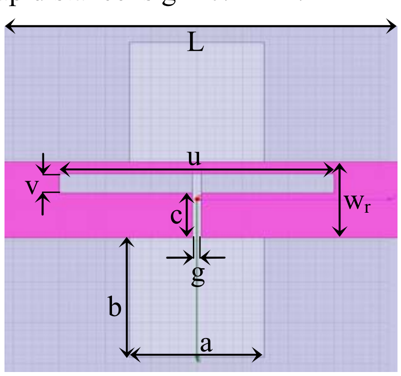
addition, several defected microstrip structures (DMS) have been proposed for suppression of spurious responses in the microstrip filters [10-12]. In this paper, we apply the novel idea of embedding defects on the strip and ground plane of a rat-race coupler, simultaneously. As a result we achieve the goal of very small size coupler as well as deep suppression of third harmonic signal that are very important in the MMIC applications. For all proposed structures, the used substrate is of relative dielectric constant equal to 3.55 and thickness of 31 mil.

II. MICROSTRIP LINE WITH DMGS SECTION

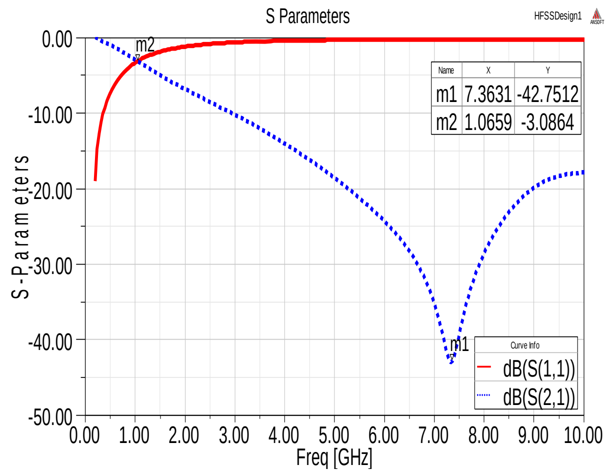
Figure 1 shows a microstrip line with DMGS section and S-parameters of the line. The width and length of the microstrip line are 3 mm and 16.65 mm, respectively. As shown in Fig. 1 (b), these lines with DMGS section acts as a lowpass filter [10]. Therefore, the DMGS can be modeled with an RLC circuit and the circuit parameters are achieved according to equation (1).

$$L=\frac{1}{4\pi^2 f_0^2 C}mH, C=\frac{f_c}{2Z_0}\cdot\frac{1}{2\pi(f_0^2-f_c^2)}nf$$
$$R=\frac{2Z_0}{\sqrt{\frac{1}{|S_{11}(\omega)|^2}-(2Z_0(\omega C-\frac{1}{\omega L}))^2-1}}, \quad (1)$$

in which f_0 and f_c are the attenuation pole and cut-off frequencies, respectively. From Fig. 1 (b) it is seen that the microstrip line with DMGS has a cut-off frequency at 1.07 GHz and an attenuation pole at 7.4 GHz. The parameters of defects on the microstrip and ground plane are: u = 8 mm, v = 1.2 mm, c = 1.5 mm, a = 5 mm, b = 5 mm and the narrow gap distance is g = 0.2 mm.



(a)



(b)

Fig. 1. Configuration of the microstrip line with DMGS: (a) parameters of microstrip line with DMGS and (b) the return loss (solid line) and insertion loss (dotted line) of the microstrip line with the DMGS section.

To compare the effect of three types of defects on the phase response of a microstrip line, we simulate four different types of microstrip lines: the conventional microstrip line, microstrip line with DGS section, line with DMS section and line with DMGS section in Fig. 2. As shown by Fig. 2, the frequency at which the phase of S21 becomes -90° is different for each type of defect. Fig. 2 illustrates that the line with the DMGS sections has the most effect on the phase of a microstrip line and reduces the resonant frequency from 2.1 GHz to 1.12 GHz. This decrease in the resonant frequency of the microatrip line with DMGS is due to the slow-wave effect. In fact, embedding a defect on a microstrip line changes the inductance and capacitance of the line and subsequently the resonant frequency of the line. The effect of embedding a DMGS section on the inductance of the line is much more than other types of defects. Furthermore, according to (1), the increase in the inductance of the microstrip line results in decrease in the resonant frequency of the line. Note that we use this property of the DMGS, which affects the phase of microstrip line, to reduce the size of rat-race coupler, as well as to suppress the 3rd harmonic signal.

III. THREE TYPES OF RAT-RACE COUPLERS WITH DMGS SECTIONS

The shapes of the proposed couplers have been illustrated in Figs. 3, 6, and 8. For each proposed coupler, six DMGS sections are used and the DGS sections are exactly under the DMS sections.

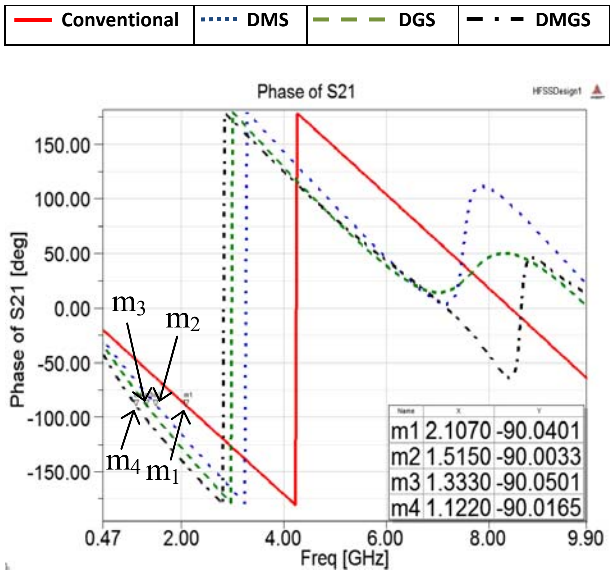


Fig. 2. Phase of the S21 for the conventional microstrip line (red solid line), microstrip line with DMS (blue dotted line), microstrip line with DGS (green dashed line), and microstrip line with DMGS (black dotted-dashed line).

A. Rat-race coupler α

The coupler α is shown in Fig. 3. We use GA as the optimization method [13, 14]. The properties of the substrate as well as the coupler dimensions remain unchanged during the optimization. Dimensions of the defects and the width of the strip line are optimized using GA. The optimum parameters of this type of coupler are obtained as u = 7 mm, v = 1.7 mm, c = 1.5 mm, g = 0.2 mm, a = 4 mm, b = 7.5 mm, and W_r = 4 mm. The simulated S-parameters of the proposed coupler α have been depicted in Fig. 4. For comparison, we simulated a conventional coupler and the simulated results have been shown in Fig. 5.

As shown in Figs. 4 and 5, the central frequency of coupler α has been lowered from 2.7 GHz to 1.35 GHz. The central frequency of the proposed coupler is half that of the conventional coupler (1.35/2.7). Therefore, the wavelength in coupler α is twice the wavelength in the conventional coupler. Due to direct relation between wavelength and the perimeter of the ring (P = 6λ/4), the perimeter and radius of the ring of coupler α are twice the perimeter and radius of the conventional coupler, respectively. Hence, the occupation area of coupler α is 0.25 that of the conventional one. In other words, the proposed coupler with central frequency 1.35 GHz acts as the conventional coupler with central frequency 1.35 GHz, but the proposed coupler α is 75 % smaller than the other one (note that the conventional rat-race coupler with central frequency 1.35 GHz is four times larger in size than the conventional coupler with central frequency 2.7 GHz). Additionally, Fig. 4 shows that the 3rd harmonic of the conventional rat-race coupler has been suppressed to more than 35 dB.

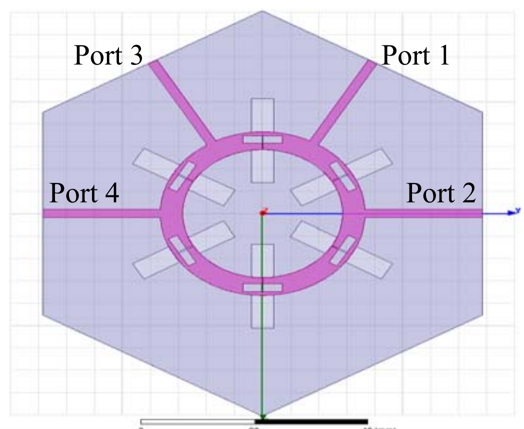


Fig. 3. Configuration of the proposed rat-race ring couplers α.

The S-parameters of the conventional rat-race coupler in Fig. 5 show strong passband near the 3rd harmonic frequencies, which has a bad effect on the overall performance of the RF systems. Therefore, a lowpass or bandpass filter is required to lessen the effect of the spurious signal, which leads to an increase in the insertion loss and RF front-end size. In the proposed coupler, there is no need to insert any filter because it rejects harmonics intrinsically, and as a result the performance of the overall system will be improved.

The bandwidth of the conventional rat-race coupler is 15.9 % at 2.7 GHz. For the proposed coupler, the bandwidth is 13.7 % at 1.35 GHz. Therefore, the new coupler has just 2 % narrower bandwidth than the conventional rat-race coupler. Return loss and isolation between input and output ports of the proposed coupler α, in the bandwidth, are less than -20 dB and the insertion losses are better than -3.4 dB. In addition, phase and amplitude imbalance of the coupler α are better than 1 dB and 5^0, respectively.

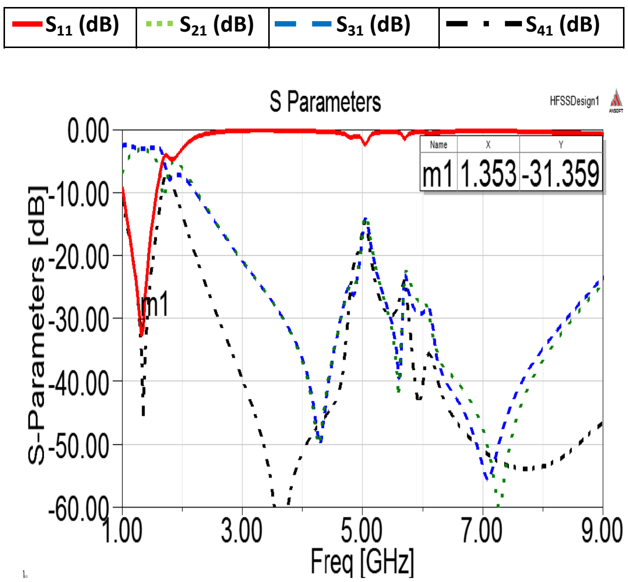


Fig. 4. Simulated S-parameters of the proposed rat-race coupler α.

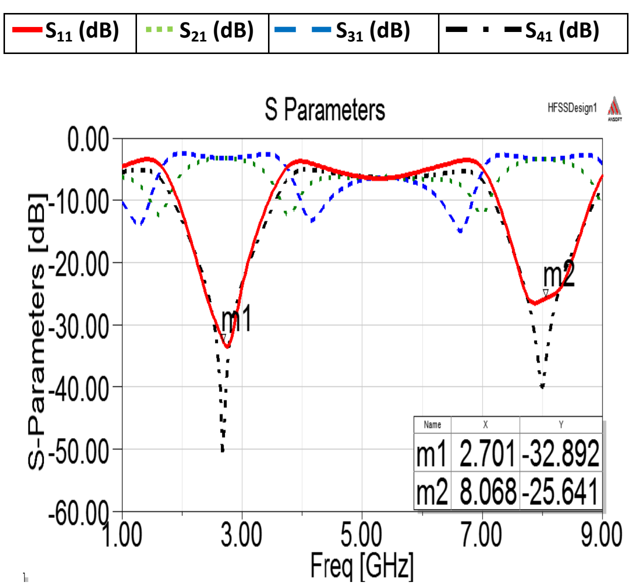
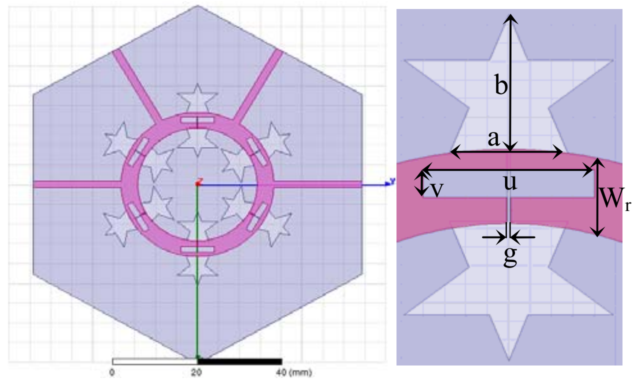


Fig. 5. Simulated S-parameters of the conventional rat-race coupler.

B. Rat-race coupler β

The schematic view of the proposed coupler β has been shown in Fig. 6. We used fractal DGS and T-shape DMS sections in this type of coupler. After optimization with GA, we obtained the optimum values as u = 8 mm, v = 1.5 mm, c = 1.5 mm, g = 0.2 mm, a = 5.5 mm, b = 7.5 mm, and W_r = 4 mm.



(a) (b)

Fig. 6. The proposed rat-race ring coupler β. (a) Configuration of the coupler β and (b) the parameters of the coupler β.

Figure 7 shows the S-parameters of coupler β. Central frequency has been reduced to 1.32 GHz, hence the size of the proposed coupler β is 0.239 that of conventional coupler (note to the procedure followed in section III A for coupler α). In one hand, the occupation area of coupler β is 4.6 % less than that of coupler α and it has wider bandwidth as well. On the other hand, coupler β has more return loss and less suppression of the 3^{rd} harmonic in comparison to coupler α.

C. Rat-race coupler γ

The coupler γ has been shown in Fig. 8. In [12] a spiral defected microstrip structure is proposed to make a dual band microstrip antenna. We use this type of defect on the microstrip ring line of a rat-race coupler with dumbell-shape DGS. The width of the ring is chosen to be W_r = 4 mm. The optimum parameters of the coupler γ are w1 = 0.5 mm, L1 = 10.5 mm, w2 = 0.8 mm, L2 = 11 mm, w3 = 0.4 mm, L3 = 1.1 mm, a = 5 mm, b = 8.5 mm, and g = 0.2 mm.

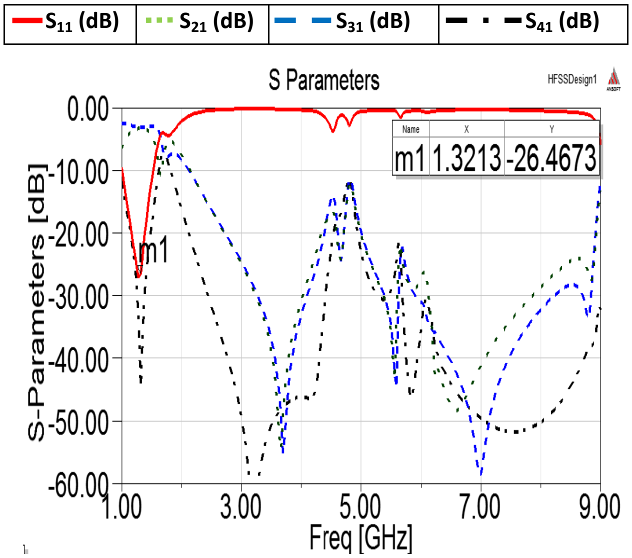
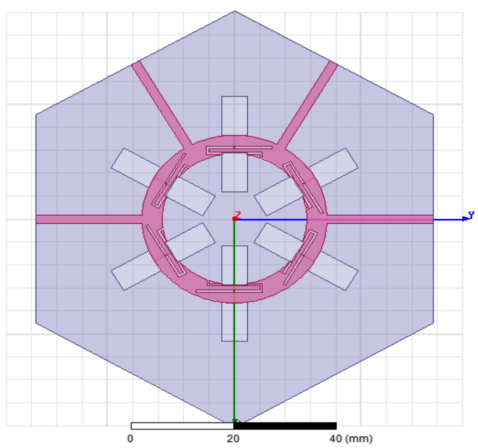
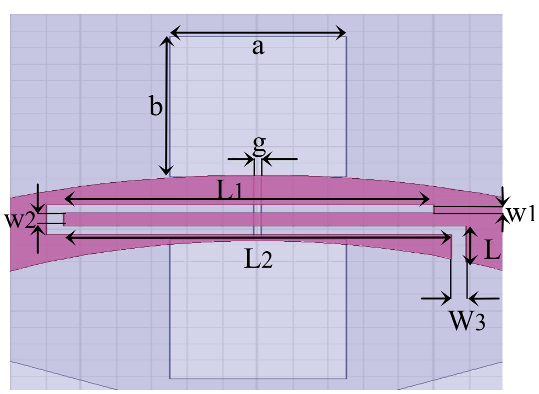


Fig. 7. Simulated S-parameters of the proposed rat-race coupler β.



(a)



(b)

Fig. 8. The proposed rat-race ring coupler **γ**. (a) Configuration of coupler **γ** and b) parameters of coupler **γ**.

The S-parameters of coupler γ are depicted in Fig. 9. It is evident that the central frequency of coupler γ has been reduced to 1.29 GHz. Therefore, coupler γ decreases the occupation area by 77.1 % in comparoison to the conventional rat-race coupler. Coupler γ has smaller size, but it has weak response in suppressing the 3rd harmonic. In other words, unlike the two previous couplers, coupler γ can not suppress spurios harmonics.

Table 1 shows the advantages and disadvantages of the three new proposed couplers relative to the conventional coupler. Size, bandwidth, and the ability of coupler to suppress the third harmonic are compared in Table 1.

Table 1: Properties of the three proposed couplers.

Type of coupler	Size	Suppression of 3rd harmonic	Bandwidth
Conventional coupler	1	No	15.9%
Coupler α	0.25	35dB	13.7%
Coupler β	0.239	25dB	14.3%
Coupler γ	0.228	5dB	15%

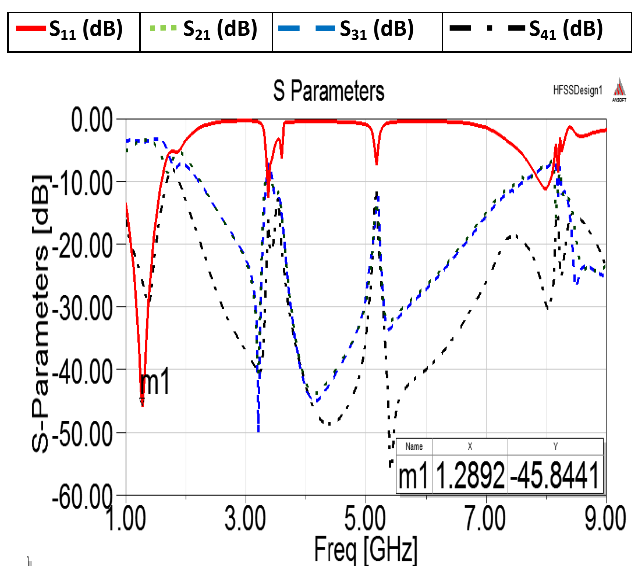
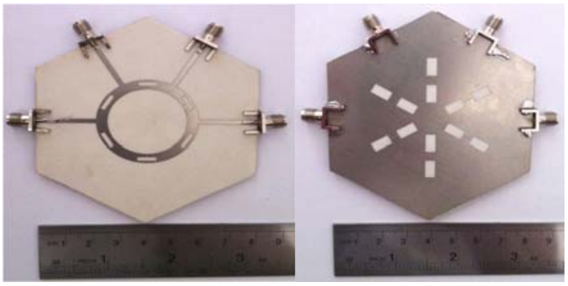


Fig. 9. Simulated S-parameters of the proposed rat-race coupler γ.

IV. EXPERIMENTAL RESULTS

To validate our novel idea, a rat-race coupler with DMGS sections has been fabricated and measured based on the optimum values we obtained from the simulations. Figure 10 shows the top and bottom view of the fabricated new coupler. Measurement of the fabricated coupler has been carried out with R&S ZVB vector network analyzer.

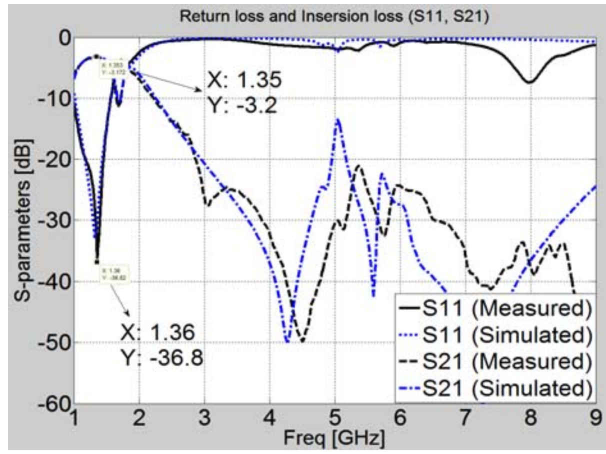


(a) (b)

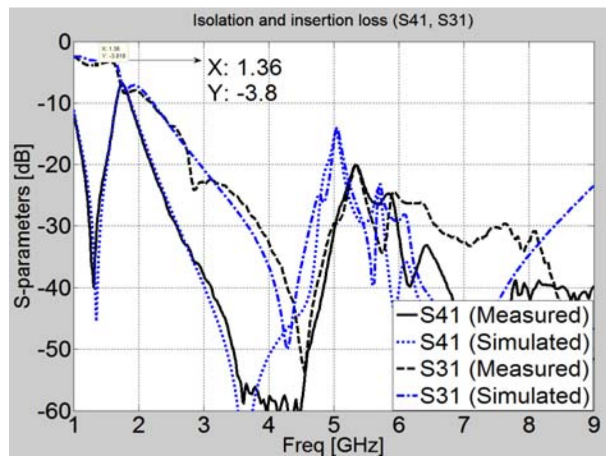
Fig. 10. Fabricated rat-race coupler with DMGS sections, (a) top view and (b) bottom view.

The measured S-parameters of the fabricated coupler have been shown in Figs. 11 and 12. Simulated and measured return loss and insertion loss between ports 1 and 2 are depicted in Fig. 11 (a), simultaneously. Simulated and measured isolation between ports 1 and 4 as well as insertion loss between ports 1 and 3 are shown in Fig. 11 (b). First, the insertion loss of the proposed coupler (S_{21}, S_{31}) is -3.8 dB around central frequency. There is always 0.3 dB to 0.5 dB loss due to the connectors. Without considering connector losses, the insertion loss of coupler is almost -3.4 dB around the central frequency that concedes the simulation results. Additionally, as shown by Fig. 11, insertion losses are less than -30 dB around the 3rd harmonic frequencies. Deep insertion loss ensures us about suppressing the 3rd harmonic signal. Finally, in Fig. 11 (a), it is obvious that the central frequency of the new coupler has been lowered to 1.35 GHz. Based on very good agreement between simulations and measurements of coupler α, it is evident that all simulation results for all the three proposed couplers are completely reliable.

To ensure the phase balance of the output signals, the phase difference between output ports (phase of S_{21} minus phase of S_{31}) has been depicted in Fig. 12. Good agreement between simulation and measurement, especially in the bandwidth, is obtained and this will again validate the simulated results. It is seen that around the central frequency of the proposed coupler, phase difference between the output ports is less than 5 degrees.



(a)



(b)

Fig. 11. Measured S-Parameters of the fabricated coupler, (a) simulated and measured S_{11} and S_{21} and (b) simulated and measured S_{41} and S_{31}.

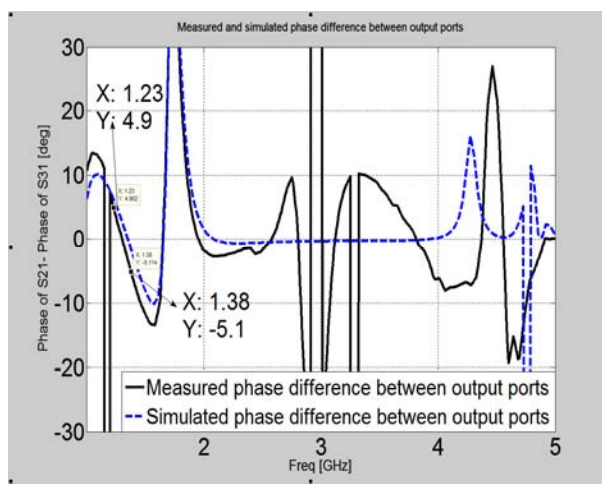


Fig. 12. Simulated and measured phase difference between output ports of the fabricated coupler.

V. CONCLUSION

In this paper, three new miniaturized rat-race couplers having harmonic suppression have been expressed. First, a microstrip line with DMGS section was examined, and then new couplers with DMGS sections were simulated. Finally, one type of the proposed couplers was fabricated and measured. The optimum parameters for all three couplers have been obtained using GA. In the proposed couplers, the central frequency has been lowered significantly and the 3rd harmonic has been suppressed to more than 30 dB. Due to compactness, low cost, and harmonic suppression, rat-race couplers with DMGS sections may be used widely in microwave and millimeter-wave integrated circuits.

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