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SIZE REDUCTION AND HARMONIC SUPPRESSION OF RAT-RACE HYBRID COUPLER USING DEFECTED MICROSTRIP STRUCTURE

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Abstract—In this paper, defected microstrip structure (DMS) is applied to design a compact microstrip rat-race hybrid coupler. The proposed structure introduces both harmonic signal suppression and a significant reduction of size because half of the ring is embedded in upper section. By embedding the DMS, it is observed that the third harmonic signal is suppressed to -25 dB with respect to a conventional rat-race hybrid coupler. Besides, this structure also effectively reduces the occupied area to 25% of the conventional case. Finally, using even and odd modes analysis the ABCD matrix of the proposed rat-race coupler was extracted. It is observed that the results are in good agreement with the full wave analysis and measurement.

1. INTRODUCTION

Rat-race hybrid couplers are key components in the design of microwave devices such as power amplifiers, mixers, and antenna systems due to their simplicity, wide bandwidth in power dividing distribution, and a high isolation between the ports [1, 2]. Wireless communication systems usually require smaller device size in order to meet circuit miniaturization and cost reduction. Thus, size reduction is becoming major design considerations for practical applications. However, in low microwave frequency range, even the physically small size of a conventional hybrid coupler is still too large for some applications. Therefore, attempts are continually made to reduce its size [3–5].

At the fundamental operating frequency (f_0), the total electrical length of a conventional rat-race coupler is 540° [5]. Therefore, it

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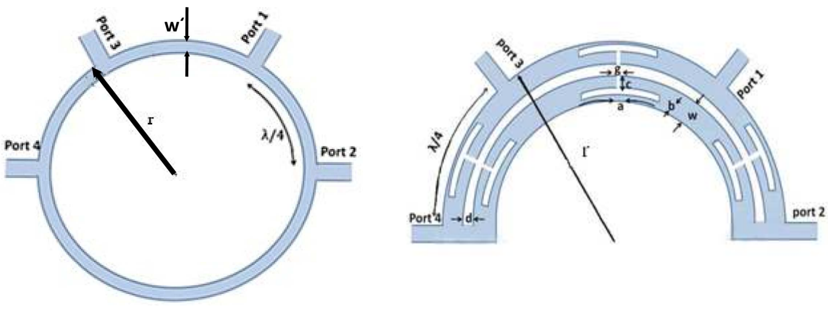


Figure 1. (a) Lay-out of the conventional rat-race hybrid ring and (b) Layout of small size ring coupler for symmetrical feeding ports with DMS ($a = 13.68$ mm, $b = 0.9$, $c = 1.5$ mm, $g = 0.4$ mm, $d = 0.4$ mm, $r = 21$ mm, $w = 3$ mm and $w' = 1.2$ mm).

occupy a large circuit area. On the other hand, nonlinear devices produce higher-order harmonics. Conventional couplers are unable to suppress these harmonics because of their periodic frequency responses. One way to suppress these harmonics is the integration of a low-pass filter with the coupler. This will further increase circuit area and front-end RF section as well as insertion loss.

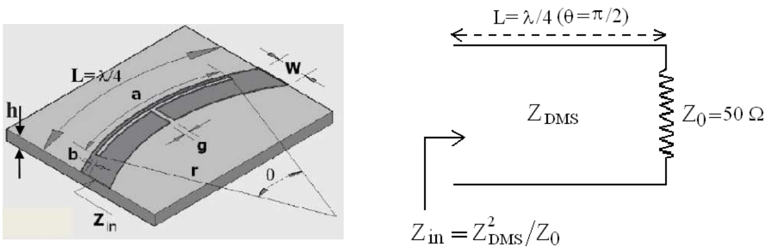
Another way to suppress the harmonics is defected ground structure (DGS). The rat-race coupler should be suspended from circuit ground for proper functioning of the slot. Also due to the slots on ground plane the structure is associated with considerable radiation loss at higher frequencies.

Here we offer a substitute to DGS sections using DMS ones. After studying different schemes for the implementations of the proposed DMS, resulted circuits have been designed as shown in Figure 1 using curved DMS.

Using the DMS version, the harmful radiation can be decreased effectively. Also, the DMS increases the electric length of microstrip and disturbs the current distribution. The effective capacitance and inductance of the microstrip line increase. Accordingly, a microstrip with a unit DMS has a stop band and slow-wave characteristics [6–15].

2. MICROSTRIP LINE WITH THE DMS SECTION

The curved DMS Pattern is etched on the microstrip line as shown in Figure 2.



(a) (b)

Figure 2. (a) Curved DMS Section ($a = 13.68\,\text{mm}$, $b = 0.9\,\text{mm}$, $c = 1.5\,\text{mm}$ and $g = 0.4\,\text{mm}$) and (b) simplified model for the microstrip line with the DMS.

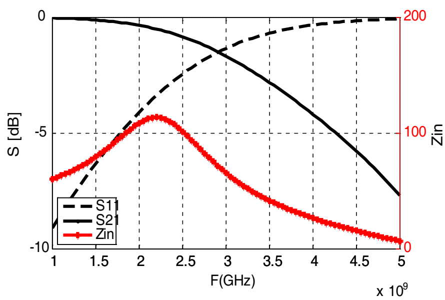


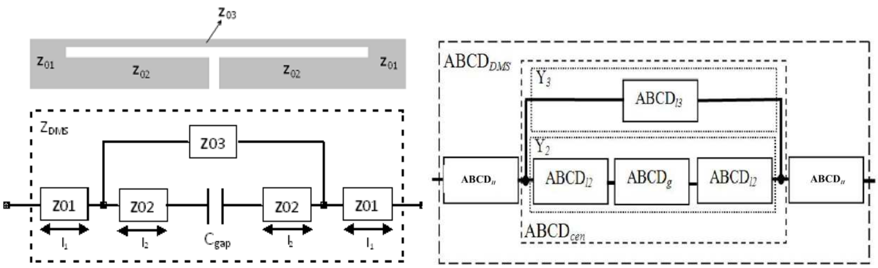
Figure 3. Matlab results of the microstrip line with the DMS section.

Using the substrate with 2.55 and $h = 0.762\,\text{mm}$, the length of the microstrip line $L = 20\,\text{mm}$, because it has to be $\lambda/4$ at the design frequency and its impedance must be $70.7\,\Omega$. Using the DMS pattern, we can get a $W = 3\,\text{mm}$ (this is a $25\,\Omega$ line without DMS etching). Using (1), the impedance Z_{in} can be calculated easily at the center frequency (2.5 GHz) that is $99.97 \approx 100\Omega$. Results of this calculation are shown in Figure 3.

Now, let's consider the simple model of the DMS section shown in Figure 4. Z_{01}, Z_{02} and Z_{03} are microstrip lines with different widths. As a result, the impedance of DMS (Z_{DMS}) can be calculated using formulas of the ABCDs matrices in [5]. So:

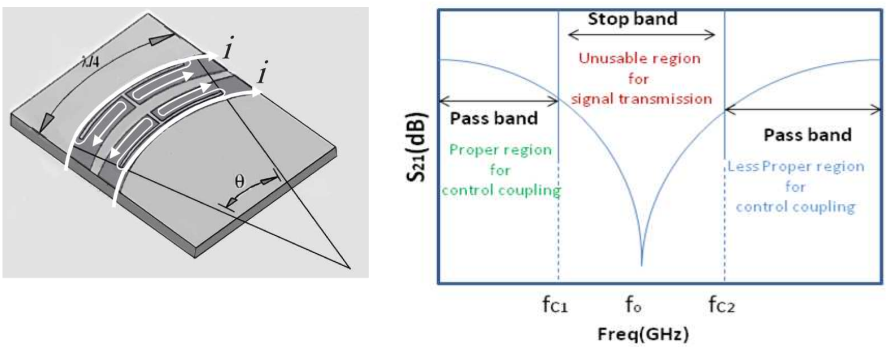
$$z_{in} = \frac{z_{DMS}^2}{z_0} \tag{1}$$

The ring lines of coupler due to size reduction are very close together which may increase the coupling between transmission microstrip lines. So, it is clear that here DMS can be helpful in reducing the coupling as shown in Figure 5(a). In this case, the distance between maximum current paths is increased physically.



(a) (b)

Figure 4. (a) A simple DMS circuit model with $l_1 = 3.16\,\text{mm}$, $l_2 = 6.64\,\text{mm}$, and $C_{gap} = 0.03\,\text{pF}$ and (b) ABCD configuration of a DMS Section model.



(a) (b)

Figure 5. (a) A part of transmission line of proposed rat-race and relationship between maximum current paths and (b) investigation of different region of DMS transmission line frequency response.

Figure 5(b) shows three regions which a signal encounters. There are two pass bands which can be used for signal transmission and a stop band which stops signal transmission. The first pass band has preference over the second one, because inductive coupling increases with frequency, so the lower pass band is more suitable for signaling design in couplers. It can be seen from Figures 3 and 6(a) that the cut-off frequency f_c and attenuation pole frequency f_0 are 2.8 GHz and 5.8 GHz, respectively. So, the selection of center frequency lower than cut-off frequency (f_{c1}) is proper. Figure 6(b) shows the phase of the transmission coefficient for a conventional line without DMS and the DMS etched one. It is obvious that the DMS creates slow wave effect and increases electrical length.

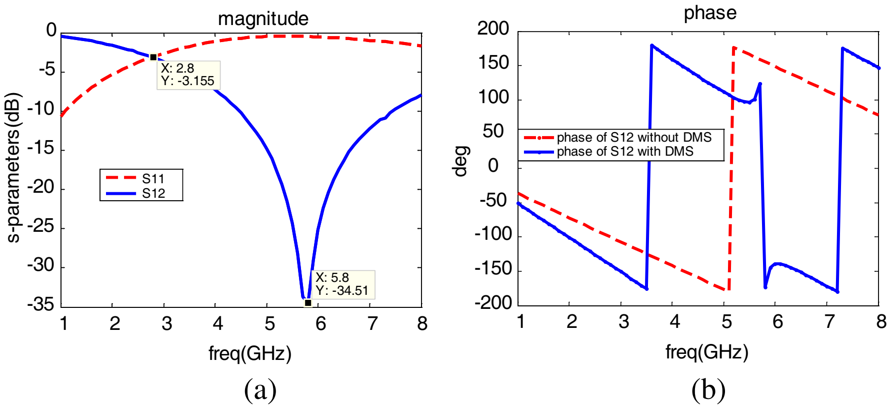


Figure 6. Simulation result of the microstrip line with the DMS section (a) S-parameters and (b) S_{12} phase.

3. EVEN AND ODD MODE RAT-RACE ANALYSIS

Figure 7 shows the even and odd circuits. By superposition, the ABCD matrices of these circuits are used to find their transmission (T_e, T_o) and reflection coefficients (Γ_e, Γ_o) [5]:

$$S_{11} = 1/2(\Gamma_e + \Gamma_o) \tag{2a}$$
$$S_{21} = 1/2(T_e + T_o) \tag{2b}$$
$$S_{31} = 1/2(\Gamma_e - \Gamma_o) \tag{2c}$$
$$S_{41} = 1/2(T_e - T_o) \tag{2d}$$

where

$$\Gamma_e = (A_e + B_e/Z_0 - C_e/Z_0 - D_e)/(A_e + B_e/Z_0 + C_e/Z_0 + D_e) \tag{3a}$$
$$T_e = 2/(A_e + B_e/Z_0 + C_e/Z_0 + D_e) \tag{3b}$$
$$\Gamma_o = (A_e + B_e/Z_0 - C_e/Z_0 - D_e)/(A_e + B_e/Z_0 + C_e/Z_0 + D_o) \tag{3c}$$
$$T_o = 2/(A_o + B_o/Z_0 + C_o/Z_0 + D_o) \tag{3d}$$

According to Figure 4, the ABCD matrix will be

$$\mathrm{ABCD}_{DMS} = \mathrm{ABCD}_{l1} \cdot \mathrm{ABCD}_{(Y2+Y3)} \cdot \mathrm{ABCD}_{l1} \tag{4}$$

According to Figure 7, Y_1 is a length of microstrip that includes bend as shown in Figure 8 [5].

Also, according to Figures 4 and 7, Y_2 is the admittance matrix of the resulted ABCD_2, and

$$\mathrm{ABCD}_2 = \mathrm{ABCD}_{l2} \cdot \mathrm{ABCD}_g \cdot \mathrm{ABCD}_{l2} \tag{5}$$

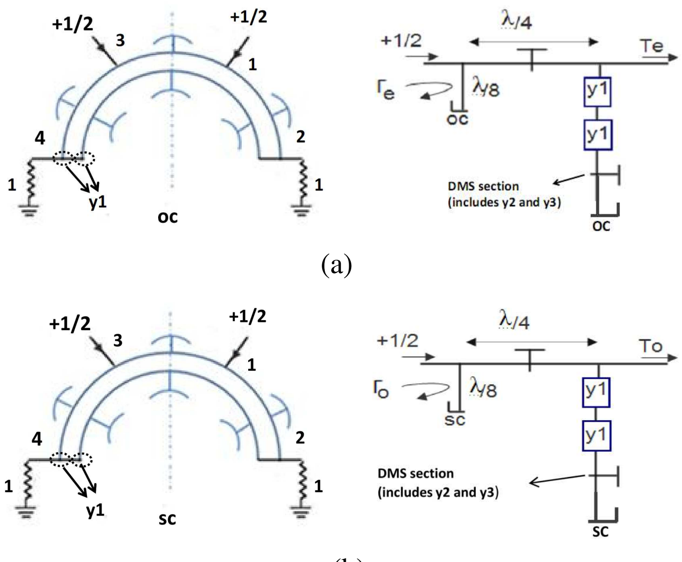


Figure 7. Equivalent topologies of the proposed rat-race coupler for (a) even and (b) odd excitations.

Figure 8. Equivalent topologies of microstrip that include bend.

and Y_3 is the admittance matrix of the ABCD_{l3}. Based on Figure 7(a), its ABCD matrix as shown in, so

$$\mathrm{ABCD}_{even} = \mathrm{ABCD}_{b1} \cdot \mathrm{ABCD}_{DMS} \cdot \mathrm{ABCD}_{b2} \tag{6}$$

ABCD_{b1} and ABCD_{b2} can be obtained from Figures 9(a) and 9(b).

The same thing can be done to the odd mode configuration in Figure 7(b) using Figure 9(c) to get its ABCD_{odd}. Finally, the S-parameters can be calculated based on Equations (2) and (3). The model simulation with even and odd modes and electromagnetic (EM) simulation with HFFS v.12 results are shown in Figures 10(a) and 10(b).

In the case of the conventional rat-race hybrid coupler without the DMS section, the width of ring line is 1.2 mm, which corresponds to the characteristic impedance of 70.7 Ω. The simulated S-parameters of the conventional rat-race coupler without the DMS sections are shown in Figure 11.

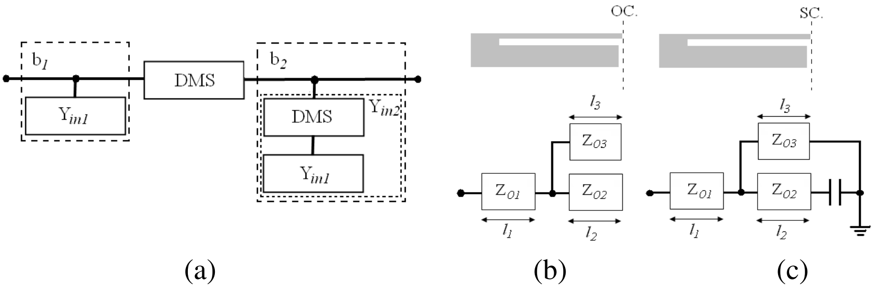


Figure 9. (a) ABCD configuration of the equivalent topologies of the proposed rat-race coupler, Branch line model Y_{in1} equivalent for (b) even and (c) odd excitations.

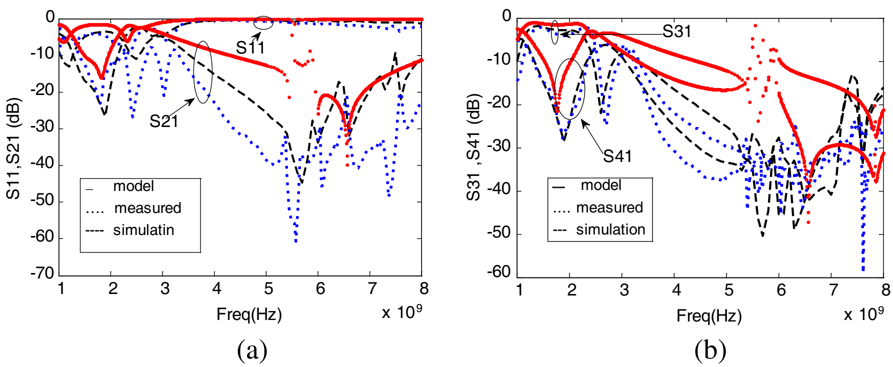


Figure 10. Performance of the rat-race coupler designed at f = 1.7 GHz. (a) S_{11} and S_{21} and (b) S_{31} and S_{41}.

The conventional rat-race coupler presents spurious passbands at harmonic frequencies, which tend to degrade the performance of the overall RF systems. It is usually necessary to add either the lowpass or bandstop filter that can reject the spurious signals. But, this approach increases a RF front-end size and yields an additional insertion loss. The advantages of the DMS section can be applied to construct a compact rat-race coupler with intrinsic spurious rejection. To validate the proposed design, a rat-race hybrid with six DMS sections is designed and fabricated. The measured results are shown in Figures 10(a) and 10(b).

It can be seen that the resonance frequency due to increasing the electrical length of transmission line using DMS has been shifted to 1.7 GHz with a coupling loss of about −3.4 dB. At frequency 7.5 GHz S_{21} falls to −19 dB. Also, the measured S_{11}, S_{21}, S_{31} and S_{41} at this

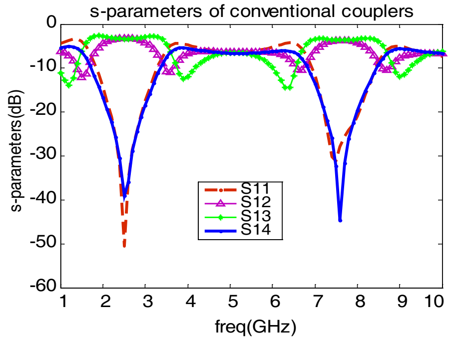
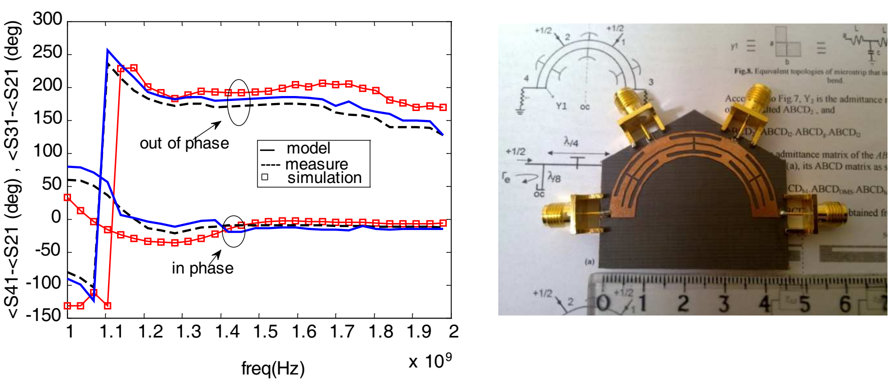


Figure 11. Simulation result of the conventional rat-race ring coupler with 70.7 ring impedance.



(a) (b)

Figure 12. Performance and layout of the rat-race coupler designed at $f = 1.7\,\text{GHz}$. (a) Responses of $< S_{31} - < S_{21}$ and $< S_{41} - < S_{21}$ and (b) fabricated DMS rat-race coupler.

frequency are $-25\,\text{dB}$, $-3.35\,\text{dB}$, $-3.2\,\text{dB}$ and $-28\,\text{dB}$, respectively.

Figure 12(a) plots the responses of $< S_{31} - < S_{21}$ and $< S_{41} - < S_{21}$. At the design frequency, the measured $< S_{31} - < S_{21}$ and $< S_{41} - < S_{21}$ are 3.2° and 183°, respectively. Figure 12(b) shows the layouts of the fabricated circuit.

4. CONCLUSION

In this paper, the compact rat-race hybrid coupler having harmonic suppression has been presented, which is based on a stop band characteristic of the DMS sections. The $70.7\,\Omega$ microstrip line with the DMS has a much wider conductor width than that of the conventional one by 400%. It has been demonstrated that high harmonic suppression ($< -25\,\mathrm{dB}$), as well as very good performance at the designed frequency, has been achieved in this type of rat-race coupler. Also, the proposed structure is significantly smaller in size than conventional rat-race couplers. It is well suited for compact low-cost active circuit applications for microwave and millimeter-wave integrated circuits.

The proposed circuit occupies only 25% of the area of a conventional rat-race. Larger impedance ratio is required for more area reduction, but fine trimming can be inevitable for compensating the parasitic resulted from the strong step discontinuities. The measured results show that the miniaturized coupler presents no spurious passband up to the sixth harmonic of the design frequency.

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