Using Superformula to Miniaturize CPW Rat Race Coupler

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Abstract **─** This paper proposes a new CPW rat race coupler whose shape has been meandered using the superformula for size reduction. The coupler operates at a center frequency of 1.8 GHz. The size reduction in the proposed design is about 74% as compared to conventional ring rat race coupler. The bandwidth of the proposed coupler defined by |S11| < -15 dB is about 31.6%.

Index Terms **─** Coplanar waveguide, rat-race coupler, superformula.

I. INTRODUCTION

Rat race couplers have been attracting much attention lately for use in several applications such as in mixers, multipliers, amplifiers, beamformers, etc [1-5]. One of the disadvantages with these couplers is that their circumference is large (3λ/2), where λ is the wavelength at the operating frequency. This makes circuit miniaturization very important.

Several techniques have been used to miniaturize the size of the rat race coupler. This includes the use of phase inverters to reduce the length of the 3λ/2 arm [6]. It also includes the use of Microstrip-to-CPW Broadside-Coupled Structure with Stepped-Impedance Sections [2]. Miniaturization has also been achieved using six synthesized coplanar waveguide (CPW) cells, formed by meander line inductors, parallel-plate capacitors, and interdigital capacitors [7].

This paper attempts to miniaturize the rat race coupler using the superformula that was proposed by John Gielis in the year 2003 [8]. This formula is a generalization of the super ellipse formula. It is used to meander the circumference of the coupler so as to reduce its size. This works as follows; the circumference of the conventional circular coupler (3λ/2) remains almost the same when the ring CPW is meandered and bent. This has the effect of reducing the radius and hence the surface area of the meandered coupler as compared with the conventional coupler.

The superformula has six different parameters which when properly selected can produce many complex shapes and curves that are found in nature. It has been used by Simeone *et al*. [9] to produce dielectric resonator antennas of different shapes. It has also been used by Bia *et al*. to produce supershaped lens antennas for high frequency applications [10]. Paraforou [11] applied the superformula to get different patch antenna shapes. The same formula has also been used by Naser and Dib [12] to design a compact UWB microstrip-fed patch antenna. More recently, the superformula was used by Omar *et al* [13, 14] to design UWB CPW fed patch antenna that operates in the FCC band (3.1-10.6 GHz) where the proposed patch shape was circular with sawtooth-like circumference.

In this paper, the transmission line element used is coplanar waveguide which enjoys several advantages over microstrip in terms of easier integration with active and passive elements and with shunt and series elements in addition to the more versatility of controlling the characteristic impedance of CPW by controlling the slot-to-strip width ratio.

The basic rat race coupler has 4 ports each of which has 50 Ω impedance, while the CPW forming the ring has a 70 Ω impedance.

II. COUPLER DESIGN

The superfromula proposed by Gielis [8] is a polar formula which has the general form:

$$r = \left[\left|\frac{\cos\left(\frac{m\theta}{4}\right)}{a}\right|^{n_2} + \left|\frac{\sin\left(\frac{m\theta}{4}\right)}{b}\right|^{n3}\right]^{\frac{-1}{n1}}. \qquad (1)$$

The superformula consists of six parameters n_1, n_2, n_3, m, a, and b. Each of the parameters a and b must be chosen to be 1 to insure symmetry of the coupler geometry. The parameters n_1, n_2, and n_3 are positive real numbers. The number m determines the number of points, corners, sectors, or hollows fixed on the shape and their spacing, while n_2 and n_3 determine if the shape is inscribed

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or circumscribed in the unit circle. For $n_2=n_3$ <2, the shape is inscribed, while for $n_2=n_3$ >2, the shape will sumscribe the circle [8]. In this design, the chosen superformula parameters are $n_1=n_2=n_3=1$, $a=b=1$, $m=24$ (corresponding to 24 bends on the meandered ring). The general shape of the coupler is shown in Fig. 1.

The proposed coupler was designed for operation at 1.8 GHz using CPW on a 1.5 mm thick FR4 substrate (ε_r=4.4, loss tangent=0.02). The feeding CPW center conductor is 2.74 mm, and the slot is 0.3 mm resulting in 50 Ω feed line. Bond wires are used to connect the two grounds on either sides of the center conductor, as shown in Fig. 1, for elimination of the undesired coupled slotline mode. The performance of the coupler with and without bond wires is given in Section IV.

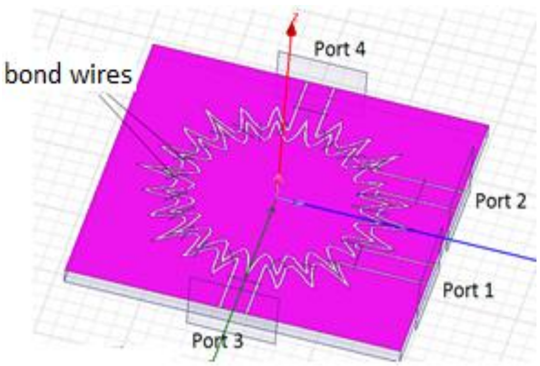


Fig. 1. 3-D view of the simulated rat race coupler.

A. Design procedure

The superformula (Eq. (1)) is programmed in MATLAB to get the data (points) of one of the meandered ring slots shown in Fig. 1, with $n_1=n_2=n_3=1$, $a=b=1$, $m=24$ in Eq. (1). Note that m=24 corresponds to the number of bends on the meandered slotted ring. These points are then entered in Excel to generate (x,y) pairs. These pairs are entered in Autocad to draw a polyline shape of the slot ring shown in Fig. 1. The shape generated in Autocad is imported in the simulator HFSS.

The initial dimension of the slot ring is scaled to $3\lambda/2$ at 1.8 GHz (including the meander lengths, with bends). The ring slot is then duplicated and reduced in size to form the other slotted ring and then the 4 ports are added as numbered in Fig. 1, with feeding CPW port center conductor = 2.74 mm, and slot = 0.3 mm resulting in 50 Ω feed lines. Note that the CPW circular ring has an impedance of about 70 Ω (with slot=0.3 mm and center conductor=0.68 mm). The overall dimension of the proposed coupler is 38.4 x 38.4 x 1.5 mm.

The conventional rat race coupler has circular slotted rings (no meander). The circumference of the outermost slotted circle is $3\lambda/2$ at 1.8 GHz (corresponding to a radius of a=24.5 mm) and a total surface area of πa^2=1885 mm^2. The area of the meandered coupler is obtained using the "measure surface area" option in HFSS.

III. MEASUREMENTS

The designed coupler was fabricated and built in our lab to measure the S-parameters. A photograph of the measured coupler is shown in Fig. 2 (without bond wires). A second photograph showing the coupler with bond wires and connectors is shown in Fig. 3. Figure 1 shows that ports 1 and 2 are close from each other. This prevented us from measuring the 4 port S-parameters and allowed only measuring 3 port S-parameters with port 2 matched to a 50 Ω load, as shown in Fig. 3.

The design is simulated using high-frequency structure simulation (HFSS). Moreover, the validity of the design is demonstrated by measuring the divider using an E5071C ENA Vector Network Analyzer using standard SMA connectors.

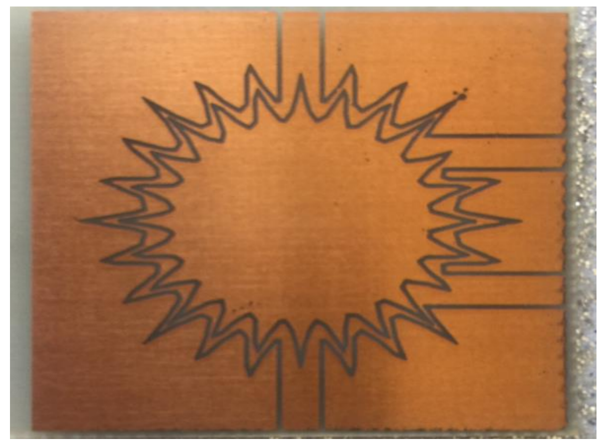
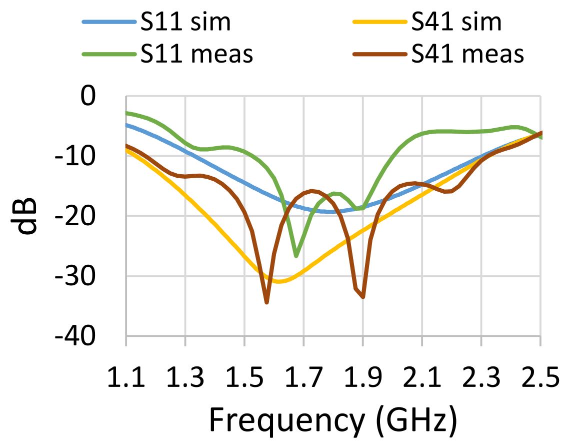


Fig. 2. A photograph of the measured coupler (no bond wires).

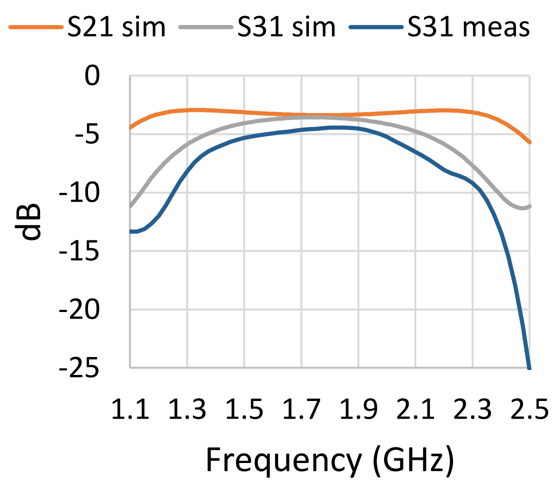
Fig. 3. A photograph of the measured coupler with bond wires and connectors (port 2 is match terminated).

IV. NUMERICAL AND MEASURED RESULTS

Figures 4 (a), (b) show comparison between the numerical results obtained using HFSS and the measured results with port 2 excluded from the measured data. This figure shows good agreement between the two over the operating frequency range. It also shows very good input port matching and very good isolation between ports 1 and 4 at the design frequency. Moreover, S_{21} and S_{31} are close to -3 dB at 1.8 GHz.



(a)



(b)

Fig. 4. (a) Comparison between measured and simulated S_{11} and S_{41} (with bond wires). (b) Comparison between measured and simulated S_{21} and S_{31} (with bond wires). S_{21} was not measured.

Figure 5 below shows the simulated angles of selected S-parameters. The angles of S_{21} and S_{31} are almost the same while the difference between the angles of S_{34} and S_{24} is about 180°.

The bond wires are important to suppress the undesired coupled slot line (even) mode and allow for the dominant CPW (odd) mode to propagate, hence reducing loss and improving performance. This is shown in Figs. 6 (a), (b) which provide a comparison between the performance of the coupler with and without bond wires. Clearly without bond wires, the return loss reduces to around 10 dB instead of 20 dB with bond wires. Also S_{21} and S_{31} are no longer equal at 1.8 GHz. The bond wire locations are shown in Fig. 1 and Fig. 3.

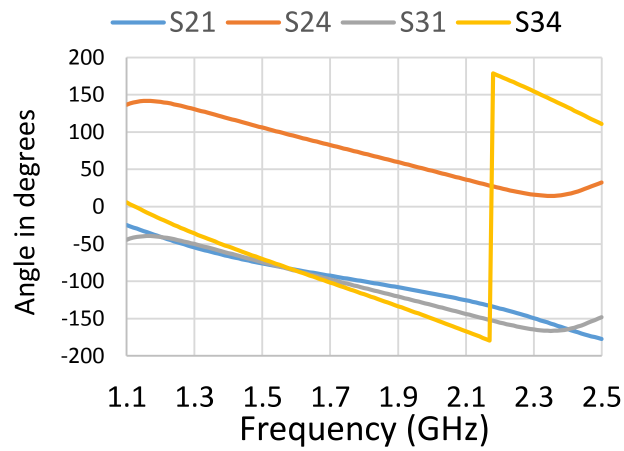
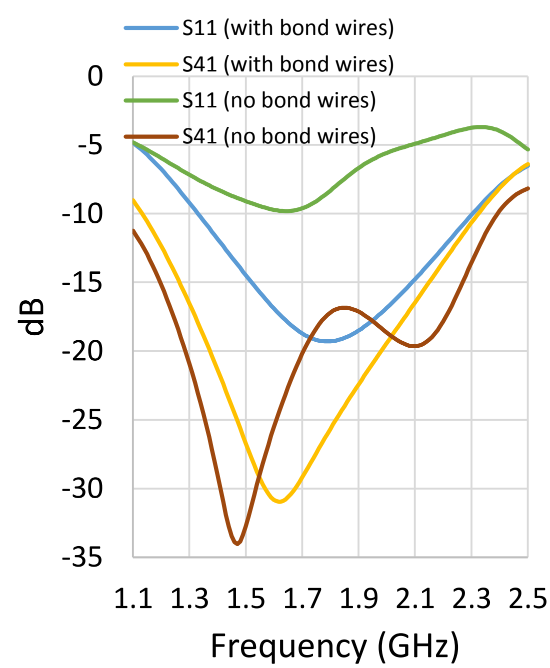
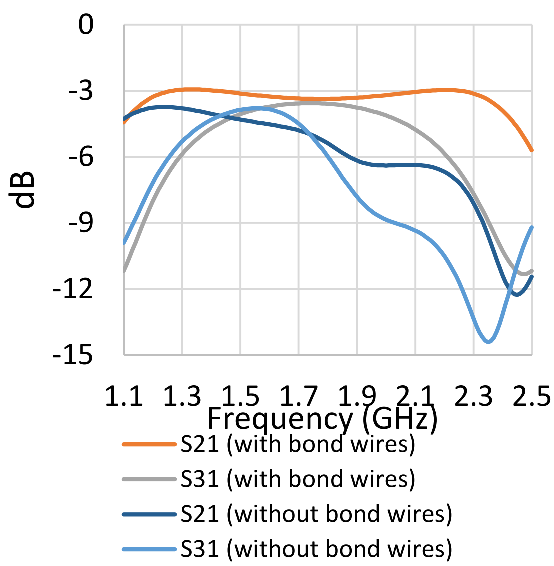


Fig. 5. Simulated angles of S-parameters versus frequency (with bond wires).



(a)



(b)

Fig. 6. (a) Comparison between simulated S11and S41 with and without bond wires. (b) Comparison between simulated S_{21} and S_{31} with and without bond wires.

V. SIZE REDUCTION

Table 1 shows a comparison between the size of the proposed rat-race coupler and other sizes presented in the literature.

Table 1: Comparison between the sizes of different couplers

Paper	ε_r	Operating Frequency	Proposed Coupler Area/ Conventional Coupler Area
This paper	4.4	1.8 GHz	26%
[1]	2.2	2.5 GHz	41.8%
[16]	2.94	3 GHz	77%
[17]	2.65	5 GHz	45%
[18]	2.5	5 GHz	55.2%

This table shows that the coupler proposed in this paper has more size reduction as compared to the other couplers investigated in Table 1. Note that the conventional coupler area is about 1885 mm^2.

VI. BANDWIDTH OF COUPLER

Table 2 shows the simulated bandwidth of the proposed coupler using 4 different definitions of bandwidth [1].

VII. CONCLUSION

This paper proposed a new design of coplanar waveguide rat race coupler operating at 1.8 GHz. The size of the coupler has been reduced using the superformula yielding about 74% size reduction as compared with conventional ring rat race coupler. The proposed coupler has a bandwidth of about 32%.

Table 2: Simulated bandwidth of the proposed coupler

Definition	|S11|<-15 dB (Input Matching)	|S41|<-20 dB (Isolation)	<S21-<S31= ±5°	<S24-<S34= 180±5°
Freq. Range (GHz)	1.52-2.09	1.37-1.98	1.17-1.7	1.48-1.72
% Bandwidth	31.6%	33.8%	29.4%	13.3%

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