

A Compact Uniplanar Rat-race Coupler with Arbitrary Power Division Ratio and Harmonics Suppression

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Abstract—In this paper, a miniaturized planar rat-race coupler is proposed to achieve arbitrary power division ratio and harmonic suppression performance simultaneously. It consists of six enhanced T-shaped line sections. The T-shaped lines can be equivalent to arbitrary electrical length lines rather than the conventional $\lambda/4$ lines. The explicit design formulas are derived and the characteristic impedances variations with the freedom variable are discussed. Simulated and experimental results show the harmonic suppression to be over -35 dB, while maintaining the conventional performance at the fundamental frequency. The circuit area of the prototype is only 30.8% of the conventional coupler.

1. INTRODUCTION

The rat-race hybrid is one of the fundamental components in microwave circuits [1, 2]. The perfect matching, ideal isolation, power-splitting capability and ease of implementation have led to its popularity. However, the conventional coupler has two main drawbacks which might be impractical. Initially, the traditional rat-race hybrid can work at its odd harmonics, which results in undesired interference introduced. With the growth of wireless communication systems, the rat-race couplers with harmonic suppression are in increasing demand. Nowadays there have been some kinds of harmonic suppression methods applied in the 3 dB rat-race hybrids [3–6]. It's regret that the characteristic of arbitrary power division ratio isn't considered in these designs.

On the other hand, the traditional coupler is composed of six quarter-wavelength transmission-line sections, which results in a large occupying area, especially at low frequencies [7, 8]. Accordingly, many attempts are continually being contributed to the miniaturization of rat-race couplers, as reported in [9–14].

In this paper, a compact planar unequal rat-race coupler with harmonic suppression is proposed by using the enhanced T-shaped transmission lines. Although there are some rat-race couplers with T-shaped transmission lines for harmonic suppression [15, 16], they can't achieve arbitrary power division ratio, which limits their applications. For miniaturization, these T-shaped lines should substitute for the arbitrary electrical length transmission lines rather than the conventional $\lambda/4$ transmission lines as [15–19]. In this paper, we take the model in [11] for example though this method can be applied in any other microstrip unequal design. The design equations of T-shaped lines are derived. For experimental verification, a model operating at 1 GHz with the third harmonic suppression is designed, simulated and measured. Due to its fully planar and no-via, the proposed coupler can be easily implemented by using the standard printed-circuit-board processes. Compared to the conventional unequal coupler, the measured results show compact size and well out-of-band harmonic rejection with the same performance at the operating frequency.

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2. THEORY AND DESIGN EQUATIONS

Figure 1 illustrates the topology diagram of the proposed unequal rat-race coupler based on the arbitrary power division design in [11]. This structure can be divided into four sections S1–S4 by the four ports. For harmonic suppression, the enhanced T-shaped transmission line is used to replace the general transmission line in the rat-race coupler. A shunted stub is tapped to the center of the uniform section, which is shown in Figure 2. For the realizable impedances, the section S3 employs three series T-shaped lines as Figure 1. In Figure 2, Z_a , Z_b , Z_c , θ_a , θ_b and θ_c represent the characteristic impedances and the electrical lengths of the series, shunted sections and the uniform section, respectively. For arbitrary power division ratio G , the design equations of Z_c and θ_c of every section have been derived in [11] as follows, where R_0 is the port impedance.

$$\begin{cases} Z_{cS1} = Z_{cS3} = \frac{\sqrt{(G^2 + 1) - (G \cos \theta_{cS2} + \cos 2\theta_{cS1})^2}}{\sin 2\theta_{cS1}} R_0 \\ Z_{cS2} = Z_{cS4} = \frac{\sqrt{(G^2 + 1) - (G \cos \theta_{cS2} + \cos 2\theta_{cS1})^2}}{G \sin \theta_{cS2}} R_0 \\ \theta_{cS3} = \theta_{cS1} + \frac{\pi}{2} \\ (G \cos \theta_{cS2} + \cos 2\theta_{cS1})^2 < G^2 + 1 \end{cases} \quad (1)$$

For the identical performance at the operation frequency f_0 , the $ABCD$ matrix of the enhanced T-shaped lines should be equivalent to that of the general transmission lines, which is expressed as the Equation (2).

$$\begin{bmatrix} \cos \theta_c & jZ_c \sin \theta_c \\ j \sin \theta_c / Z_c & \cos \theta_c \end{bmatrix} = \begin{bmatrix} \cos \theta_a & jZ_a \sin \theta_a \\ j \sin \theta_a / Z_a & \cos \theta_a \end{bmatrix} \times \begin{bmatrix} 1 & 0 \\ j \tan \theta_b / Z_b & 1 \end{bmatrix} \begin{bmatrix} \cos \theta_a & jZ_a \sin \theta_a \\ j \sin \theta_a / Z_a & \cos \theta_a \end{bmatrix}. \quad (2)$$

After some straightforward manipulation, the characteristic impedance of T-shaped line can be calculated as follows:

$$Z_a = \frac{1 - \cos \theta_c}{\tan \theta_a \sin \theta_c} Z_c, \quad (3)$$

$$Z_b = \frac{(1 - \cos \theta_c) \cos^2 \theta_a \tan \theta_b}{(\cos 2\theta_a - \cos \theta_c) \sin \theta_c} Z_c. \quad (4)$$

And for harmonic suppression, the electrical length of the shunt stub θ_b can be determined by the suppression frequency f_s ($f_s > f_0$) with the following formula [17]:

$$\theta_b = \frac{\pi f_0}{2 f_s}. \quad (5)$$

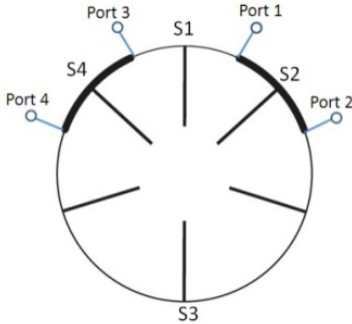


Figure 1. The proposed unequal rat-race coupler.

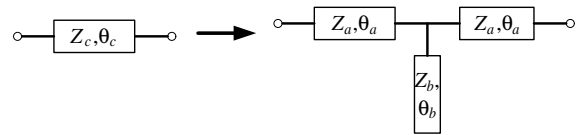


Figure 2. Substitution of a uniform section by the T-shaped line.

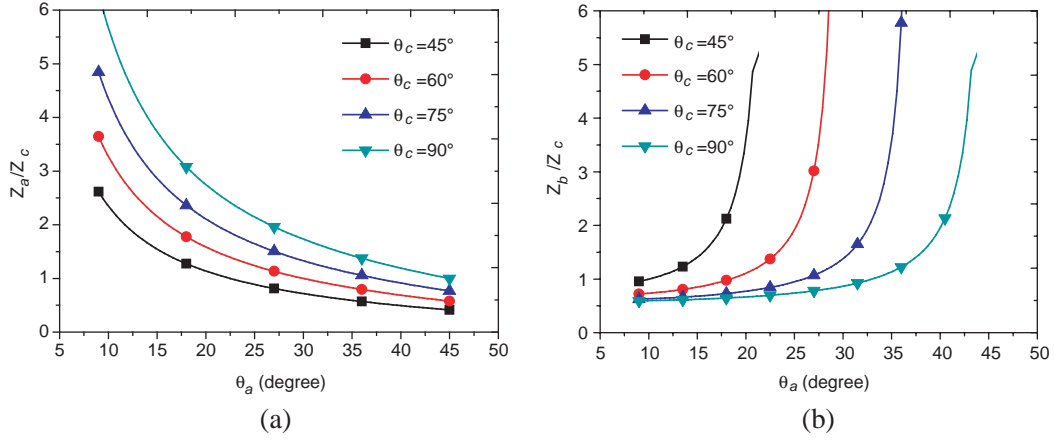


Figure 3. The variations of Z_a/Z_c and Z_b/Z_c with θ_a for difference θ_c at the third harmonic suppression: (a) Z_a/Z_c and (b) Z_b/Z_c .

The remaining parameter θ_a not only affects the performance of the T-shaped line, but also can be regarded as one degree of freedom in the circuit design. By optimizing the parameter θ_a , the characteristic impedances of T-shaped lines can be limited in the realizable range and the miniaturization can be achieved. For example, when the suppressed-frequency f_s is chosen as $3f_0$, the normalized characteristic impedances Z_a/Z_c and Z_b/Z_c are illustrated as a function of θ_a for different θ_c in Figure 3. From Figure 3, it can be found that the curve of Z_a/Z_c declines with the increase of θ_a and rises as θ_c is increased, while the variation of Z_b/Z_c is the opposite. Since the function $\tan \theta_b$ is increasing monotonically in the range of θ_b , the characteristic impedance of Z_b would be reduced as the rise of the suppressed-frequency f_s according to the Equations (4) and (5).

3. SIMULATION

In previous section, the design method of the proposed rat-race hybrid has been analyzed. For illustration, two different numerical cases are considered and simulated in this section. Both cases are simulated by using the circuit simulator ADS 2008. For simplification, the fundamental frequency is set at 1 GHz in these two examples.

3.1. The First Example

In the first example, the proposed rat-race coupler is expected to obtain equal power division outputs and reject the spurious signal at 2.25 GHz. The shunt stub of every section can be calculated to be $\theta_b = 40^\circ$ according to the Equation (5). For comparison, the Z_c and θ_c of every section are designed as the conventional rat-race hybrid. After optimizing, the θ_a of every section is set to be 25° . Then all of the parameters can be derived and listed in Table 1. The simulation results are illustrated in the Figure 4.

Table 1. The design parameters of the first case.

	S1	S2	S3	S4
Z_a (Ω)	151.6	151.6	151.6	151.6
θ_a ($^\circ$)	25	25	25	25
Z_b (Ω)	75.8	75.8	75.8	75.8
θ_b ($^\circ$)	40	40	40	40
Z_c (Ω)	70.7	70.7	70.7	70.7
θ_c ($^\circ$)	90	90	90	90

From the Figure 4, it can be found that the proposed model has a similar performance with the conventional rat-race coupler at the operating frequency, while it has a wide rejection band around 2.25 GHz. The circuit circumference of this case is only $5\lambda/6$, which is 55.5% of the conventional rat-race coupler.

3.2. The Second Example

In the second example, the proposed rat-race coupler is designed to achieve 6.02 dB power division ratio. And the suppressed frequency is set at 4.5 GHz, which means $\theta_b = 20^\circ$. For miniaturization and power division ratio optimum, the θ_c of every section is designed as different electrical length rather

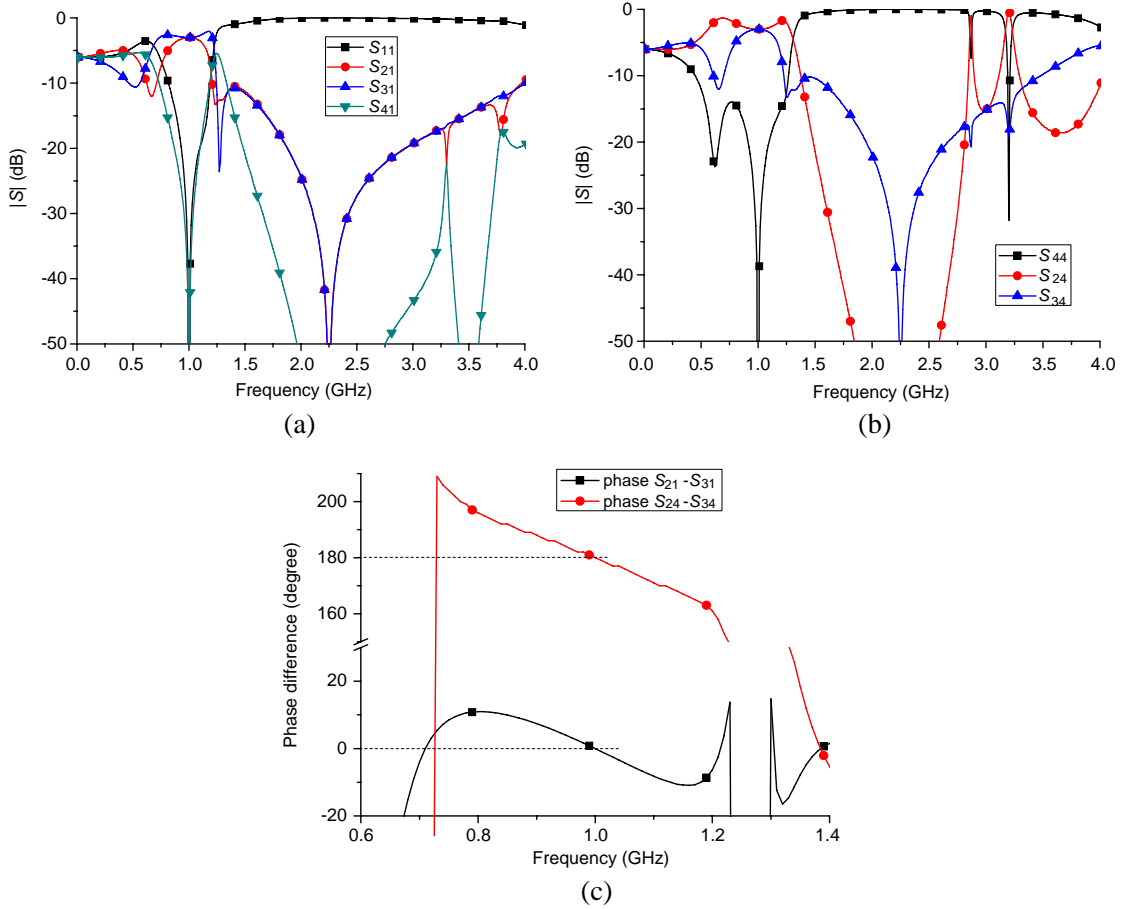


Figure 4. The simulated S -parameters of the first case: (a) the amplitude responses for in-phase, (b) the amplitude responses for anti-phase, and (c) the phase responses.

Table 2. The design parameters of the second case.

	S1	S2	S3	S4
Z_a (Ω)	137.3	78.5	174.5	78.5
θ_a ($^\circ$)	30	30	30	30
Z_b (Ω)	136.9	37.9	71.6	37.9
θ_b ($^\circ$)	20	20	20	20
Z_c (Ω)	113.2	54	113.2	54
θ_c ($^\circ$)	70	80	83.3	80

than quarter wavelength. Then the T-shaped lines replace general electrical length transmission lines in this case. The design parameters are derived and listed in Table 2. The simulation results are showed in the Figure 5.

As it is expected, its power division ratio is 6.02 dB at 1 GHz with perfect matching and isolation responses. Meanwhile, the design has a wider rejection band than 1.5 GHz around 4.5 GHz. Compared with the first case, the phase difference response of this case is more flat. The circuit circumference of this case is λ , which is $2/3$ of the conventional rat-race coupler.

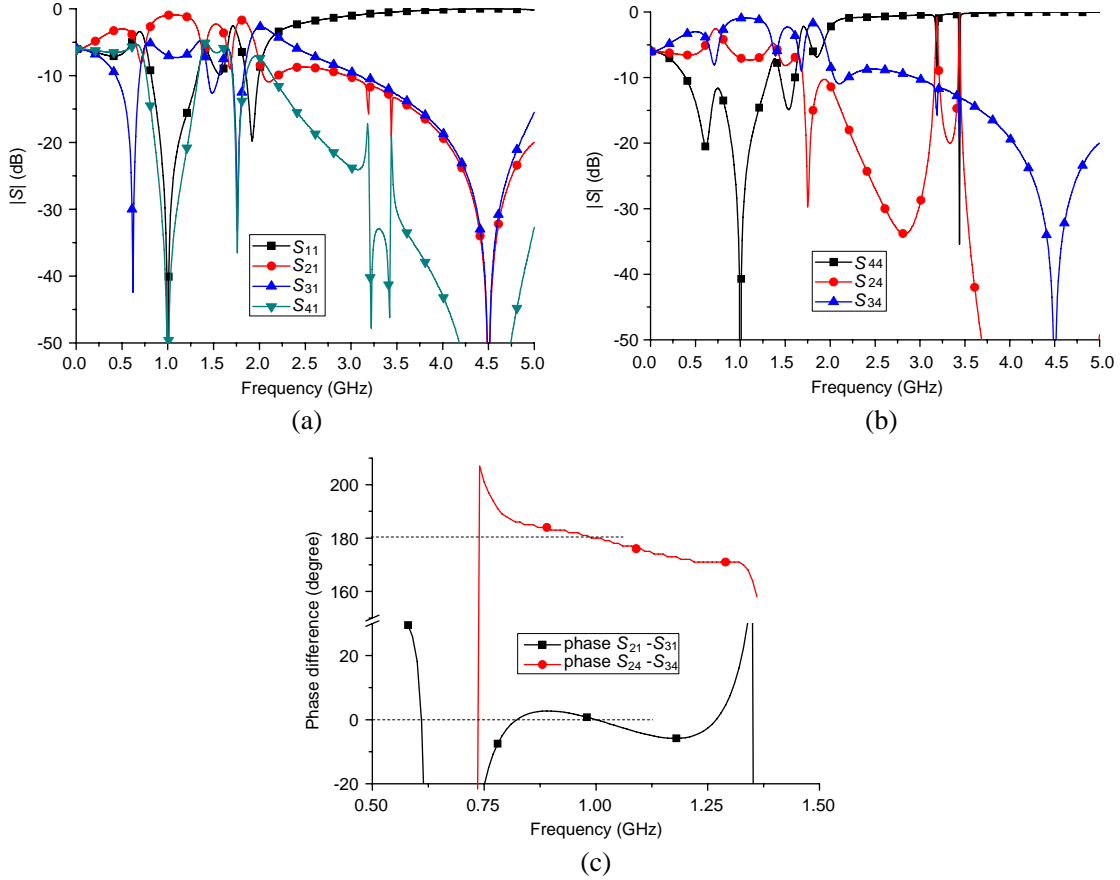


Figure 5. The simulated S -parameters of the second case: (a) the amplitude responses for in-phase, (b) the amplitude responses for anti-phase, and (c) the phase responses.

Table 3. The design parameters of this prototype.

	S1	S2	S3	S4
Z_a (Ω)	123.3	56.3	112.9	56.3
θ_a ($^\circ$)	20	20	30	20
Z_b (Ω)	86	84.7	86.5	84.7
θ_b ($^\circ$)	30	30	30	30
Z_c (Ω)	77.7	43.9	77.7	43.9
θ_c ($^\circ$)	60	50	80	50

4. MEASUREMENT

To validate our proposed method experimentally, a rat-race coupler operating at 1 GHz is designed to suppress third-order harmonic. The power division ratio is designated as 2, that is 6.02 dB. Based on the above method, the design parameters can be obtained and labelled in the Table 3. The prototype has been fabricated on a 0.762 mm-thick Rogers 4350B substrate, with relative permittivity of $\epsilon_r = 3.48$ and loss tangent of 0.003.

Figure 6 shows the comparison between the simulated and measured S -parameters of the prototype

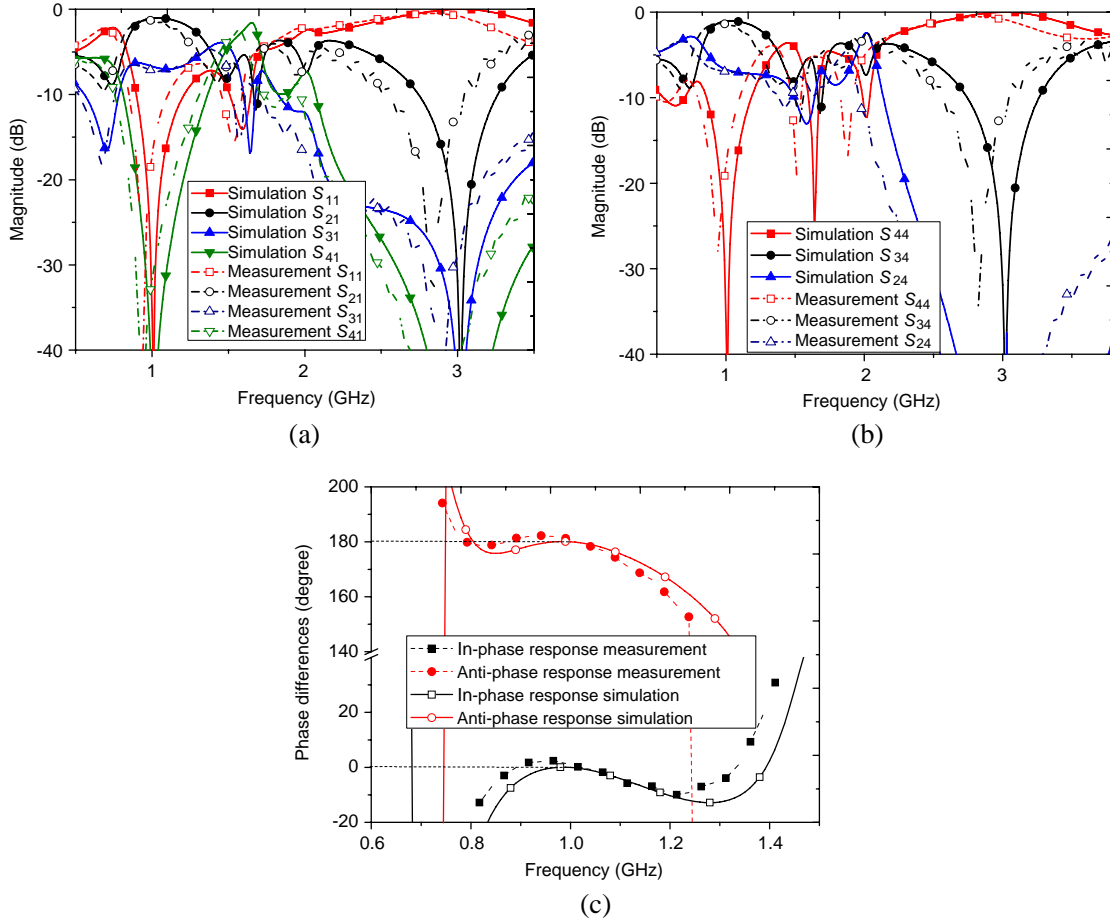


Figure 6. The S -parameters of the prototype: (a) the amplitude responses for in-phase, (b) the amplitude responses for anti-phase, and (c) the phase responses.

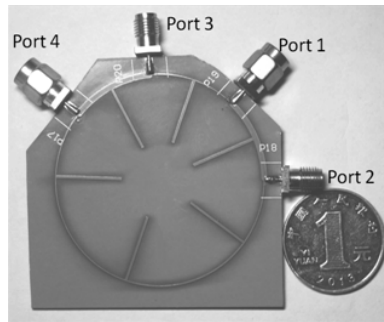


Figure 7. The photograph of the prototype.

Table 4. The performance comparison between the proposed coupler and the existing designs.

coupler type	relative size	harmonic suppression	power division
conventional coupler [7]	100%	no	1 : 1
[3]	45%	fixed	1 : 1
[4]	31%	arbitrary	1 : 1
[6]	21.5%	fixed	1 : 1
[11]	57.6%	no	arbitrary
[13]	60%	no	1 : 1
[14]	29%	no	12 dB
the proposed	30.8%	arbitrary	arbitrary

using ADS software and HP 8720D vector network analyzer. It indicates that the actual centre frequency is 0.94 GHz and the third harmonic is 2.84 GHz, which means a slight frequency shift due to the fabrication tolerance. At the operating frequency, the measured return losses and isolation parameters are all better than -28 dB. The power division ratios are 5.82 dB with the insertion loss of $|S_{21}| -1.49$ dB and $|S_{31}| -7.31$ dB, and the phase differences of in-phase and anti-phase are 1.4° and 181.3° , respectively. At the rejection frequency, the return losses are -0.48 dB, while harmonic output responses are rejected to more than -35 dB. It means that the prototype fulfills the third harmonic suppression with the excellent performance at the operating frequency. The photograph of this prototype is shown at Figure 7. The circuit circumference is only $5\lambda/6$. The performance comparison between the proposed and the existing designs is shown in Table 4.

5. CONCLUSION

A compact unequal rat-race coupler with harmonic suppression has been proposed. It can be constructed using enhanced T-shaped lines which are equivalent to arbitrary electrical length transmission lines. The closed-form formulas have been derived using $ABCD$ -matrix. For verification, two numerical cases are simulated in ADS 2008 software successfully. Then a prototype with power division ratio 6.02 dB is designed for the third harmonic suppression. It works well as a conventional unequal rat-race coupler at the operating frequency, while excellent rejecting the third-order harmonic component. The size of the prototype is only 30.8% of the conventional rat-race coupler without the folded lines.

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