Balanced-to-Balanced Rat-Race Coupler with Bandpass Response

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Abstract – **This paper presents a balanced-to-balanced rat-race coupler with bandpass response. In the differential mode, good frequency selectivity is obtained with the integration of second-order Chebyshev bandpass filters. Common-mode signals are rejected within a wide frequency range. The proposed design has been supported by measurement and simulation. To the best of our knowledge, this is the first balanced-to-balanced filtering rat-race coupler in literature.**

***Index Terms*—Bandpass filter, common-mode rejection, differential circuit, rat-race coupler.**

1. Introduction

180° hybrids and microwave filters are important components in communication systems. Single-band [1] and dual-band [2] single-ended dual-function circuits integrating 180° hybrids with filters have been developed in recent years. In order to resist environment noise, many circuits adopt differential architecture. Fully differential circuits get rid of the use of baluns. Insertion loss caused by baluns is thus eliminated. In [3], a differential rat-race coupler was realized by a pair of single-ended rat-race couplers with swapped interconnection for size reduction. However, common-mode rejection and frequency selectivity are poor.

Recently, balanced filtering Gysel power dividers with good common-mode rejection were presented [4]. Based on [4], a balanced-to-balanced rat-race coupler with bandpass response is developed in this work.

2. Analysis And Design Method

(1) Schematic of the Proposed Circuit

According to the coupling scheme of a bandpass rat-race coupler [1], schematic of a balanced-to-balanced rat-race coupler with bandpass response is depicted in Fig. 1. In Fig. 1, single-ended ports A^+ (B^+, C^+, D^+) and A^- (B^-, C^-, D^-) represent respectively the positive and negative terminals of differential port A (B, C, D). A and D are the sum and difference ports of the coupler, respectively. Port impedance of each terminal is Z_0. Each resonator is realized by short-circuited one-wavelength (λ) transmission line of characteristic impedance Z_a. The λ/2 transmission line between each pair of the positive and negative terminals is used to reject common-mode signals. The λ/4 transformer of impedance Z_b is required at each single-ended terminal to obtain the specified external quality factor Q_e. The open and shorted stubs of line impedance $Z_a/2$ between resonators are served as K inverter of –90° and +90° phase shifts, respectively. θ_o and θ_s are, respectively, the electrical lengths of the open and shorted stubs. θ_x is the electrical length of the transmission line sections between Port C^+ and D^+. The other transmission line segments have electrical length of θ_a.

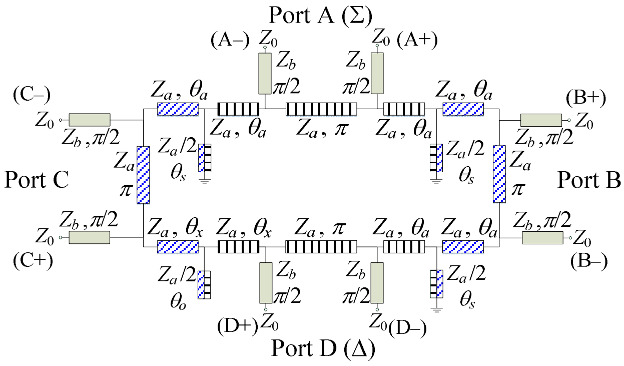

Fig. 1. Schematic of balanced-to-balanced rat-race coupler with bandpass response.

(2) Design Procedure

Following the analysis presented in [4], design procedure for the proposed circuit of specific center frequency f_0 and fractional bandwidth Δ is as follows.

Step 1. Obtain Q_e and coupling coefficient M from the specified frequency response of a second-order filter with the fractional bandwidth Δ [5].

Step 2. With arbitrarily selected Z_a, use (1) and (2) to calculate Z_b and the impedance of K inverter, respectively [4].

$$Z_b = \sqrt{\frac{2 Z_a Z_0 Q_e}{\pi}} \quad (1)$$

$$K = M Z_a \pi \quad (2)$$

Step 3. Use shunt open/shorted stub to serve as the K inverter of –90°/+90° phase shift [5]. The shunt stub is equivalent to a K inverter with two resident transmission lines. The value of K inverter can be used to find the shunt reactance X, from which electrical lengths θ_o and θ_s of the stubs with line impedance $Z_a/2$ could be then determined. The electric length of each resident line section of the open/shorted stub could also be found and is denoted θ_{ro}/θ_{rs}. It is noticed that X and θ_{ro} are negative for the open stub.

Step 4. The value of θ_a and θ_x at f_0 can be calculated by $\theta_a = 90° - \theta_{rs}$ and $\theta_x = 90° + |\theta_{ro}|$, respectively.

3. Simulation and Measurement

The central frequency of f_0 = 2.45 GHz and fractional bandwidth of Δ = 8% are specified. From the specifications of a second-order Chebyshev bandpass filter of 0.043-dB in-band ripple, Q_e = 8.299 and M = 0.133 can be obtained. The impedances of shunt stubs and $\lambda/4$ transformers, respectively, determine the lower and upper bounds of Z_a. With port impedance Z_0 = 50 Ω, Z_a = 60 Ω is selected so that $Z_a/2$ = 30 Ω and Z_b = 126 Ω could be realized by microstrip lines. Following the design procedure, θ_s = 33.8°, θ_a = 73.1°, θ_x = 106.9°, and θ_o = 56.2° are obtained.

Layout of the proposed coupler is shown in Fig. 2. The values of layout parameters in Fig. 2 are (unit: mm): g_1 = 1.25, g_2 = 0.17, g_3 = 1.4, g_4 = 0.92, g_5 = 0.89, t_1 = 0.81, t_2 = 2.1, t_3 = 5.91, t_4 = 36.78, t_5 = 20.55, t_6 = 21.39, t_7 = 2.36, t_8 = 10.72, t_9 = 8.19, t_{10} = 0.93, t_{11} = 8.48, t_{12} = 7.35, t_{13} = 18.56, t_{14} = 4.0, t_{15} = 14.07, and t_{16} = 13.2. The circuit was fabricated on a Roger RO4003C substrate which has dielectric constant of ε_r = 3.55, loss tangent of tanδ = 0.0028, and thickness of h = 20 mil.

Fig. 3 shows the differential-mode S parameters when signal is fed into Port A. The measured S_{ddBA} and S_{ddCA} at the central frequency are –4.2 dB and –3.5 dB, respectively, the simulated values of which are, respectively, –3.8 dB and –3.7 dB. The measured fractional bandwidth of ±1-dB amplitude imbalance is 41.8%. In the frequency range of 1 – 4 GHz, the measured isolation ($1/S_{ddDA}$) is better than 23 dB. The measured phase difference between S_{ddBA} and S_{ddCA} (S_{ddBD} and S_{ddCD}) is 1.5° (184.2°), which is not shown here for simplicity. Some discrepancy between the simulated and measured results can be observed and may be caused by fabrication deviation, especially for the high-impedance $\lambda/4$ transformers.

The common-mode S parameters are depicted in Fig. 4. The measured bandwidth of return loss ($1/S_{ccAA}$) in 0.5-dB is 57.1%. The bandwidth of 30-dB rejection for S_{ccBA}, S_{ccCA}, and S_{ccDA} is 46.5%. A wideband common-mode rejection is achieved. In addition, the bandwidth of 20-dB cross-mode rejection is 61.7%, which is not shown for simplicity.

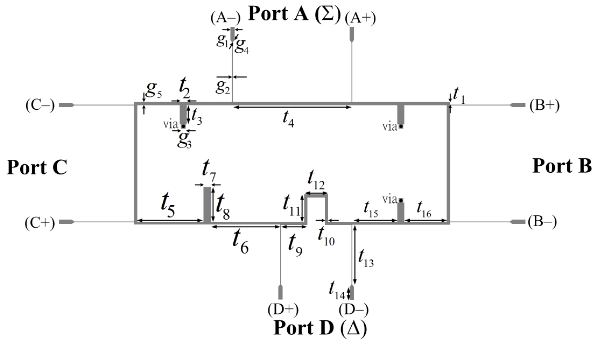

Fig. 2. Layout of the balanced-to-balanced rat-race coupler with bandpass response.

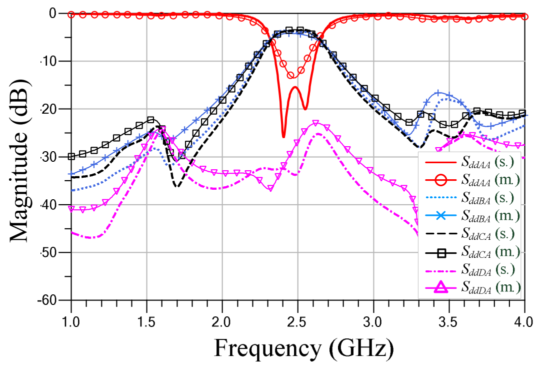

Fig. 3. Simulation (s.) and measurement (m.) of differential-mode S parameters.

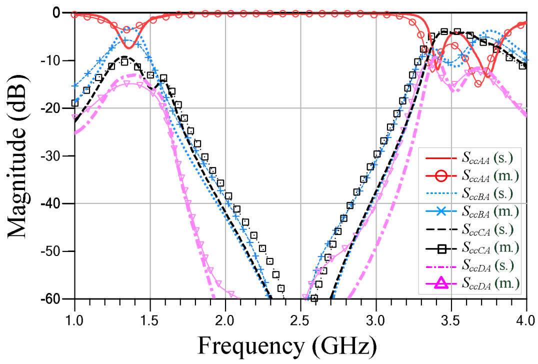

Fig. 4. Simulation (s.) and measurement (m.) of common-mode S parameters.

4. Conclusion

Design of a balanced-to-balanced rat-race coupler with bandpass response using coupled resonator theory is presented for the first time and experimentally verified. Measured results show that the circuit exhibits wideband differential-mode isolation and common-mode rejection.

Acknowledgment

This work was supported in part by Ministry of Science and Technology, Taiwan, R.O.C., under Grant MOST 104-2221-E-390-008-. The authors thank National Chip Implementation Center (CIC), National Applied Research Laboratories, Taiwan, R.O.C. for their support in simulation software.

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