Design of Wideband Filtering Power Divider with High Port Isolation Performance for RF Energy Harvesting

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Abstract – This paper presents a novel wideband filtering power divider with designable bandwidth and high port isolation, developed for RF energy harvesting applications. Two classes of structures integrate different shared networks with impedance transformers in their filtering branches to realize Chebyshev transformer functions. This synthesis approach allows for precise control over the bandwidth and return loss (*RL*). Furthermore, high isolation is achieved by incorporating two resistors between the two output ports. Measured results demonstrate a wide operating band 103.7%, and high isolation level better than 25 dB of the bandwidth.

Index Terms – Filtering power divider, high isolation, RF energy harvesting, wideband power divider

I. INTRODUCTION

Power dividers play a vital role in radio frequency (RF) energy harvesting by enabling efficient signal distribution [1]. In RF energy harvesting setups, power dividers are used to aggregate the collected energy from multiple antennas. Their low voltage standing wave ratio and high isolation between ports are critical for minimizing energy loss and preventing detrimental interactions between the harvesting channels, thereby maximizing the overall power collection efficiency and stability [2, 3]. Figure 1 depicts the block diagram of the system, where RF signals generated by multiple RF sources are captured by antenna. A broadband antenna is used to capture ambient RF energy across ISM/WiFi/5G bands. The power divider is designed to cover the corresponding wide operating bandwidth. The rectifier

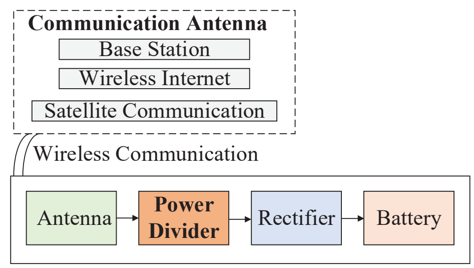

Fig. 1. Wireless system architecture of proposed wideband filtering power divider for RF energy harvesting.

is optimized for large power conversion efficiency and the generated DC power is used to recharge its battery. Among these components, the power divider is essential for realizing the system's overall functionality.

In RF energy harvesting systems, the received ambient RF signals are distributed across multiple frequency bands (e.g., GSM, WiFi, 5G). A multi-pole filtering response is employed to realize a wide passband with good in-band flatness and high out-of-band rejection. This ensures that only useful RF energy within the target frequency range is collected and transmitted to the rectifier, while out-of-band interference and noise are suppressed. This improves the stability and power conversion efficiency of the entire harvesting system. As for port isolation, high isolation between output ports is critical to avoid channel interactions. When port isolation is poor, the harvested RF power from one channel will leak into the other channel, causing unexpected signal reflection, power loss, and phase mismatch. Therefore, it is imperative to improve the bandwidth and isolation performance of power dividers.

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The conventional wideband Wilkinson power dividers are designed for the broadband RF energy harvesting system [4–6]. For example, in [4], a multisection Wilkinson wideband power divider is applied to the ultra-wideband energy harvesting circuit, but the isolation is only −10 dB.

Recent research has focused on integrating filtering functions into power dividers to improve overall performance. The resistive isolation technique, which introduces resistors between the output ports to absorb reflections, is demonstrated in designs with improved isolation [7, 8]. Multimode resonator structures utilize multiple transmission poles to improve bandwidth and isolation by adjusting coupling; however, achieving both wide bandwidth and high isolation simultaneously remains challenging. Although power dividers based on substrate-integrated waveguide (SIW) or self-packaged air-filled SIW can achieve good in-band isolation, these designs tend to be complicated and operate over relatively narrow bandwidths [9–11]. Advanced techniques employing composite isolation impedances and surface wave suppression can achieve high isolation of −36 dB, but usually at the expense of operating bandwidth [12]. Recent works in filtering power dividers focus on achieving wideband performance, utilizing approaches such as multilayer slotline structures, direct synthesis techniques, and multilayer stacked stripline designs [13–15]. In conclusion, most approaches suffer from inherent limitations in achieving both wide bandwidth and high isolation. Generally, even though the isolation component is appropriately selected, the crosstalk between output ports will also limit the isolation level of filtering power dividers. For most microstrip wideband filtering power dividers, crosstalk cannot be avoided, and the isolation level is usually below 25 dB [16–20]. Achieving over 25 dB of isolation remains challenging, particularly across a wide and designable bandwidth and, to our knowledge, no existing design has simultaneously met both of these requirements.

In this paper, we propose a novel wideband filtering power divider design featuring designable bandwidth and high port isolation. A novel integrated scheme of shared resonant network and Chebyshev impedance transformer is proposed to realize designable four-pole and five-pole wideband filtering responses. The shared resonant structure broadens matching bandwidth and miniaturizes circuit size, eliminating bulky multi-section cascaded configurations. Different from traditional single-resistor schemes, the design adopts dual isolation resistors cooperating with resonant branches, achieving high wideband isolation without degradation of bandwidth and filtering performance. The synergistic design of the filtering transformer and shared resonant structure enables precise control over the fractional bandwidth (FBW).

II. THEORETICAL ANALYSIS

To realize wideband responses, two classes of power dividers based on $\lambda/4$ resonators, as shown in Fig. 2, are presented herein. First, two different shared networks before the power dividing junction are designed to enlarge *RL* bandwidth. Designs I and II realize four-pole and five-pole Chebyshev function, respectively. As Fig. 3 shows, both designs achieve a 20-dB *RL* bandwidth of 100%, demonstrating that both topologies manifest good bandpass responses in

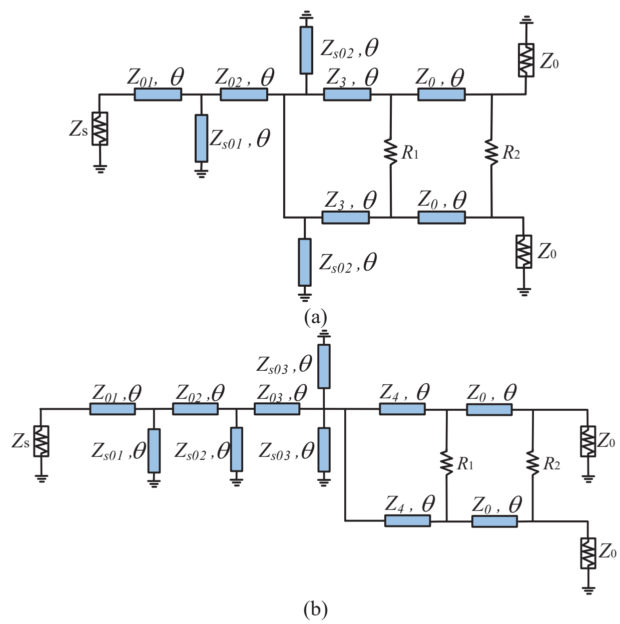

Fig. 2. Proposed wideband filtering power divider with different shared networks. (a) Design I and (b) Design II.

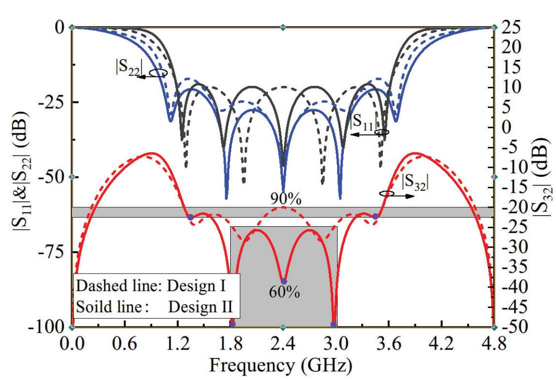

Fig. 3. Theoretical results of proposed Designs I and II with same *RL* bandwidth of 100% and different isolation bandwidth of 90% (−20 dB) and 60% (−25 dB).

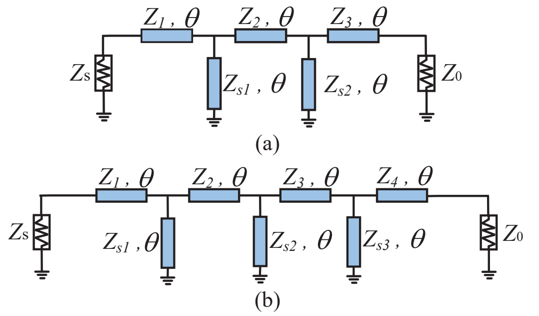

Fig. 4. Proposed wideband filtering transformer I and II. (a) With four-pole Chebyshev response and (b) with five-pole Chebyshev response.

the passband range. Design I features a simple structure and achieves an isolation of −20 dB. In contrast, Design II incorporates increased complexity to achieve an enhanced isolation level of up to −25 dB. Second, all the impedance parameters of the two designs can be determined by the synthesis theory. Third, only two isolation resistors are used to ensure good isolation and port matching.

The working principle for the realization of the wideband power dividers is detailed as follows. To achieve wide matching bandwidth, two classes of filtering transformers shown in Fig. 4 as branches are synthesized. As an example, the filtering transformer I shown in Fig. 4 (a) is discussed in detail. The proposed wideband filtering transformer is designed with impedance transformer ratio $r = Z_S/Z_0 (Z_0 = 50\ \Omega)$. To implement the four-pole equal-ripple response, the Chebyshev polynomial function is adopted in [21–23]. The theoretical S-parameters of the wideband filtering transformer can be expressed by

$$|S_{21}| = \sqrt{\frac{1}{1+\varepsilon^2\cos^2(3\phi+\xi)}}, \tag{1}$$

where

$$\begin{aligned}\varepsilon\cos(3\phi+\xi) = {}& \left(4\varepsilon\alpha^3(\alpha+\sqrt{\alpha^2-1})\right)\frac{\cos^4\theta}{\sin\theta} \\ &+ \left(-\varepsilon\alpha(5\alpha+3\sqrt{\alpha^2-1})\right)\frac{\cos^2\theta}{\sin\theta} \\ &+ \frac{\varepsilon}{\sin\theta}.\end{aligned} \tag{2}$$

All the impedance parameters are normalized by the load impedance Z_0. Then, the theoretical S-parameters can be transformed as

$$|S_{21}| = \sqrt{\frac{1}{1+|F|^2}} = \sqrt{\frac{1}{1+\left|\frac{2\sqrt{r}}{A_1+B_1+C_1r+D_1r}\right|^2}}. \tag{3}$$

The A_1, B_1, C_1, and D_1 of the entire filtering transformer can be obtained by multiplying the ABCD matrices of each transmission line segment. Through the formula derivation, the function F of the filtering transformer I shown in Fig. 4 (a) can be derived as

$$\begin{aligned}F = {}& \frac{j}{2\sqrt{r}z_1z_2z_3\sin\theta}[k_1\cos^4\theta + k_2\cos^2\theta + k_3] \\ &+ k_4\cos^3\theta + k_5\cos\theta,\end{aligned} \tag{4}$$

where

$$\begin{aligned}k_1 = {}& (r-z_1z_3)(z_1+z_2+y_{s1}z_1z_2)(z_2+z_3 \\ &+ y_{s2}z_2z_3),\end{aligned} \tag{5a}$$

$$\begin{aligned}k_2 = {}& 2z_1^2z_3^2 - 2rz_2^2 + z_1z_2z_3(z_1+z_2+z_3) \\ &+ z_1z_2z_3(y_{s1}z_1z_3 + y_{s1}z_1z_2 + y_{s2}z_2z_3 + y_{s2}z_1z_3 \\ &+ y_{s1}y_{s2}z_1z_2z_3) - ry_{s1}z_1z_2^2 - ry_{s2}z_2^2z_3 \\ &- r(z_1z_2 + z_1z_3 + z_2z_3),\end{aligned} \tag{5b}$$

$$k_3 = -(z_1^2z_3^2 - rz_2^2), \tag{5c}$$

$$\begin{aligned}k_4 = {}& -((z_2-rz_0)(z_0+z_1)(z_1+z_2+y_{s1}z_1z_2 \\ &+ y_{s2}z_1z_2),\end{aligned} \tag{5d}$$

$$\begin{aligned}k_5 = {}& z_0z_2^2 + z_1z_2^2 + z_1^2z_2 - r(z_0z_1^2 + z_0^2z_1 + z_0^2z_2) \\ &+ z_1^2z_2^2(y_{s1}+y_{s2}).\end{aligned} \tag{5e}$$

By solving equations (1) and (3), the five normalized impedance parameters z_1, z_2, z_3, y_{s1}, and y_{s2} are all determined by the specified FBW, *RL*, and r. To achieve equal power divider, the filtering transformers with impedance transformer ratio $r = 2$ are designed and simulated. The impedance parameters meet the condition of $Z_{01} = Z_1/2, Z_{02} = Z_2/2$, and $Z_{s01} = Z_{S1}/2$. The shared network reduces the size of the circuit and enlarges the available *RL* bandwidth of power divider. For enhancing isolation performance, two $\lambda/4$ resonators with impedance of Z_0 and two resistors are added as shown in Fig. 2 (a). Design II as shown in Fig. 2 (b) can be devised using a similar approach. By trading off the output port matching and isolation performance, the values of the isolation resistors can be finally decided. Figure 5 illustrates the simulated results of the proposed wideband filtering power dividers I and II with different numbers of isolation resistors. The wideband filtering power divider I exhibits a narrow isolation bandwidth with one resistor (R_1) and fails to achieve isolation below −25 dB with two resistors (R_1 and R_2). In contrast, the wideband filtering power divider II delivers both good port matching and a wide isolation bandwidth when two resistors are incorporated.

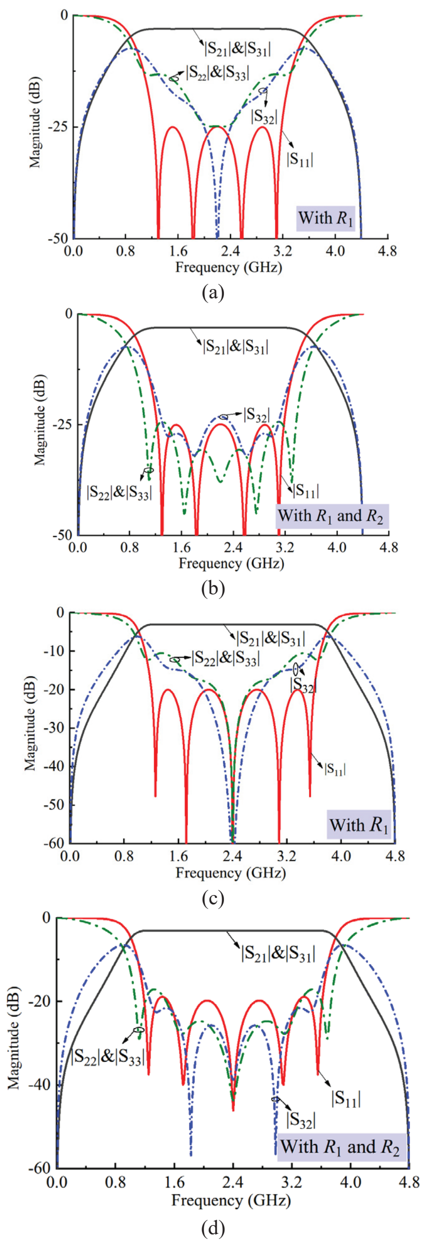

Fig. 5. Simulated results of proposed wideband filtering power dividers. (a) Design I with isolation resistor R_1, (b) Design I with isolation resistors R_1 and R_2, (c) Design II with isolation resistor R_1, and (d) Design II with isolation resistors R_1 and R_2.

The design method of the proposed wideband filtering power divider is summarized as follows:

(1) Specify the design goals: center frequency, fractional bandwidth, return loss level, and port isolation requirement;
(2) Determine the characteristic impedances of the filtering transformer using the proposed Chebyshev synthesis method;
(3) Synthesize the shared resonant network to extend the matching bandwidth;
(4) Calculate the initial circuit parameters of all transmission-line segments;
(5) Introduce two isolation resistors between the output ports and optimize their values for high port isolation;
(6) Perform fine-tuning in circuit simulation to satisfy specifications;
(7) Fabricate and measure the prototype for experimental verification.

III. SIMULATION AND EXPERIMENT

For verification, two wideband filtering power dividers are designed, simulated, and fabricated on an RO4003C substrate ($\varepsilon_r = 3.55$, thickness = 0.508 mm). The first design, shown in Fig. 2 (a) with center frequency of 2.2 GHz, FBW = 90%, and $RL = 25$ dB is designed, simulated, and fabricated. Prior to simulation and fabrication, detailed theoretical calculations were conducted to determine the key characteristic impedance parameters of the divider's transmission lines, which are critical to its filtering and power division performance. Its theoretical parameters are calculated as: $Z_{01} = 36.5\ \Omega$, $Z_{02} = 19.9\ \Omega$, $Z_3 = 36.5\ \Omega$, $Z_{s01} = 148.8\ \Omega$, $Z_{s2} = 31.4\ \Omega$. The second wideband filtering power divider shown in Fig. 2 (b) with center frequency of 2.4 GHz, FBW = 100%, and $RL = 15$ dB is designed. Theoretical parameters are calculated as: $Z_{01} = 33.5\ \Omega$, $Z_{02} = 20.2\ \Omega$, $Z_{03} = 14.3\ \Omega$, $Z_4 = 33.5\ \Omega$, $Z_{s01} = 57.7\ \Omega$, $Z_{s02} = 34.8\ \Omega$, $Z_{s03} = 31.4\ \Omega$, $Z_{s04} = 31.4\ \Omega$. After global tuning, the dimensions displayed in Figs. 6 (a) and 7 (a) are listed. The chip resistors in Fig. 6 (b) are selected as $R_1 = 68\ \Omega$ and $R_2 = 270\ \Omega$. The chip resistors in Fig. 7 (b) are selected as $R_1 = 56\ \Omega$ and $R_2 = 270\ \Omega$. The fabricated prototypes are measured by a Keysight N9918A vector network analyzer before measurement, two-port calibration are performed via electronic calibration module to eliminate the effects of test cables and connectors. For the 2.2 GHz design in Fig. 6 (b), the measured FBW is 108.6% with RL better than 10.6 dB and in-band isolation over 18.6 dB (90% isolation bandwidth). The 2.4 GHz design in Fig. 7 (b) achieves 103.7% FBW, RL better than 12.8 dB, and in-band isolation over 25 dB (60% isolation bandwidth). As observed in Figs. 6 (b) and 7 (b), slight discrepancy between simulated and measured S_{11}/S_{22} can be reasonably attributed to several inevitable practical factors. First, fabrication tolerance of microstrip line width and etching deviation introduces impedance variation. Second, SMA connector soldering parasitic effect and assembly misalignment bring extra stray inductance and capacitance. These non-ideal practical factors are common in microstrip circuit implementation and lead to

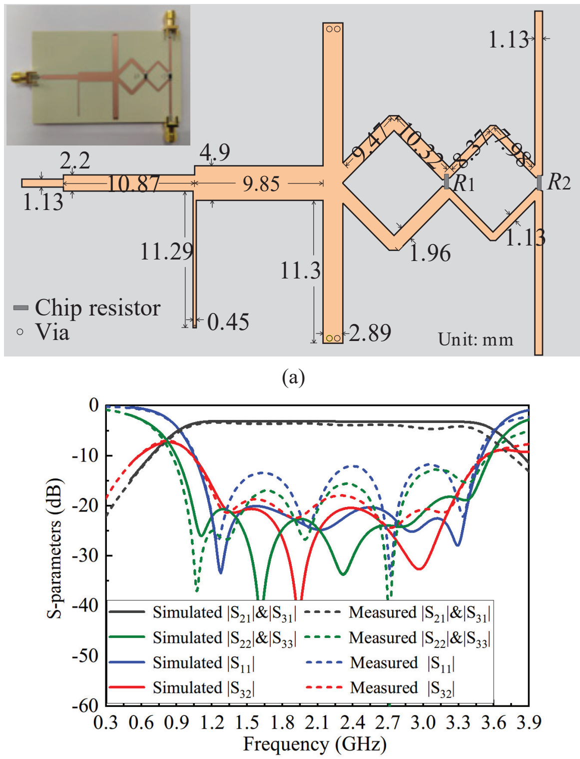

Fig. 6. (a) Physical layout and photograph of Design I and (b) simulated and measured results of Design I.

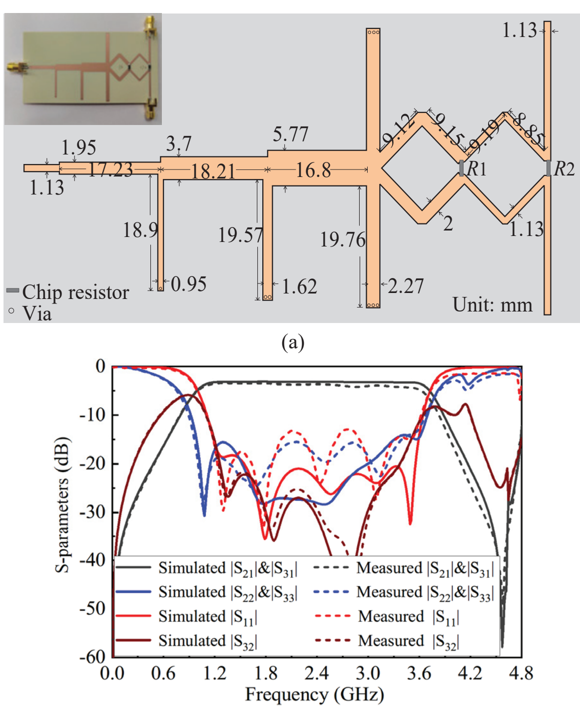

Fig. 7. (a) Physical layout and photograph of Design II and (b) simulated and measured results of Design II.

Table 1: Comparison with recently published power dividers

Ref.	Freq. (GHz)	FBW (%)	Isolation (dB)	RL (dB)
[12]	1.28	12.5	−36	−20
[8]	2	33	−10.1	−15.1
[20]	30	46.67	−12	14.1
[18]	2.35	55.32	−17	−14
[16]	1.8	73	−18.5	−10
[15]	3	84	−19.5	−15
[6]	6.5	138.5	−10	−10
This	2.2	108.6	−18.6	−10.6
Work	2.4	103.7	−25	−12.8

the observable minor mismatch between simulation and measurement.

Table 1 summarizes the key performance parameters of the two proposed wideband filtering power dividers, along with a comparison with other state-of-the-art designs reported in the literature. The comparison clearly demonstrates that the proposed designs exhibit superior performance, including ultra-wide bandwidth, embedded filtering functionality (eliminating the need for additional filtering components), and high-level in-band isolation.

IV. CONCLUSION

In this paper, two novel wideband filtering power dividers with improved isolation level have been proposed. The designs achieve Chebyshev transformer functions, enabling wideband impedance matching and equal power division. The two resistors further enhance port isolation without compromising insertion loss. The proposed wideband filtering power dividers demonstrate designable bandwidth and high isolation, thereby offering an efficient solution for broadband RF energy harvesting systems.

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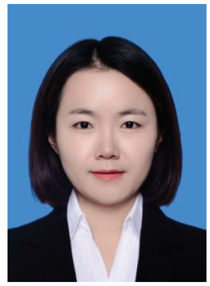

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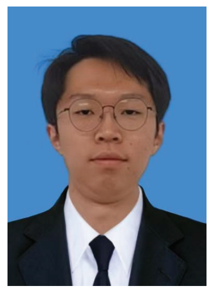

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