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RESEARCH PAPER

Ultra-wideband (UWB) eight-way ring-cavity power divider

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A novel compact ultra-wideband (UWB) eight-way ring-cavity power divider is presented in this paper. To broaden the bandwidth of the power divider/combiner, the stepped-impedance technology is used to realize the impedance match. The network of this eight-way ring-cavity power divider has been analyzed. The measured results reasonably agree with the simulated ones. The measured return loss is greater than 10 dB from 5.2 to 18.6 GHz. The average insertion loss, amplitude imbalance, and phase imbalance are around 9.4 dB (including the 9-dB power-dividing insertion loss), ±0.7 dB, ±6°, respectively, across the entire operating frequency range.

Keywords: Ultra-wideband (UWB), Coaxial taper, Power divider, Ring cavity, Stepped impedance

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I. INTRODUCTION

Multi-way broadband power dividers/combiners are an important part of many microwave systems such as power-combining amplifiers and antenna arrays. Recently, various multi-way power combiners/dividers have been presented at microwave and millimetre-wave frequencies [1–15], such as substrate integrated waveguide power dividers [2], rectangular waveguide power dividers [4–6], radial waveguide power dividers [7, 8], conical power dividers [9, 10], and coaxial waveguide power dividers [11–14]. In these designs, waveguide-based broadband power dividers have been widely investigated and used in microwave and millimetre-wave systems because of their low insertion loss, wide bandwidth, and high-power capability. However, the operating bandwidth of the rectangular waveguide is limited by the cutoff frequency and the rectangular waveguide environment is dispersive, which complicates broadband impedance matching over an extended frequency range [4–6]. In the previous studies, the authors presented the broadband ring-cavity power dividers/combiners using probe array that achieved low-loss waveguide-to-probe transition [1, 3, 15]. The designed and measured results indicated that this novel structure has wide bandwidth and low loss.

In this paper, an eight-way ring-cavity power divider using stepped-impedance matching technology has been presented. Compared to the previous work [1, 3, 15], this modified structure can achieve a wider bandwidth by combing the taper with the stepped impedance transformer. The proposed power-dividing structure can not only hold large numbers of power-dividing ports but also can have ultra-wideband (UWB) performance. The use of the stepped-impedance technology makes the modulation easily. A coaxial taper feeding port has been applied into the ring cavity to provide uniform excitation for the multiple-way ring-cavity power divider, and then, excellent amplitude and phase balance of the output ports has been obtained. The network of this eight-way ring-cavity power divider has also been analyzed. The measured results agree with the simulation closely. The design results indicate that this structure has several advantages, such as a wider bandwidth, large numbers of power-dividing ports, excellent input impedance matching, low insertion loss, and good balance of amplitude and phase at output ports.

II. STRUCTURE, ANALYSIS, AND DESIGN

Figure 1 shows the proposed ring-cavity eight-way power combiner/divider. A coaxial taper feeding port has been applied to provide axially symmetric electromagnetic-field excitation for the ring-cavity power divider and to implement good amplitude and phase balance for the power-combining ports, which can also obtain good impedance matching from the coaxial port to the oversized ring cavity. The coaxial taper can be designed according to [1]. The proposed ring-cavity power combiner/divider is terminated by the Sub-Miniature-A (SMA) connector (coaxial port). The power combiner/divider can be divided into three parts: the transition from input SMA connector to the oversized coaxial waveguide, the transition from the oversized waveguide to the ring cavity, and the transition from the ring cavity to the output SMA connector.

In general, the length of the coaxial probes is chosen to be normally about $\lambda g/4$ to implement impedance matching, where λg is the wavelength at central frequency. However, for the capacitance-loaded coaxial probe, its length is far less than $\lambda g/4$. As shown in Fig. 1, the length of L_o should be

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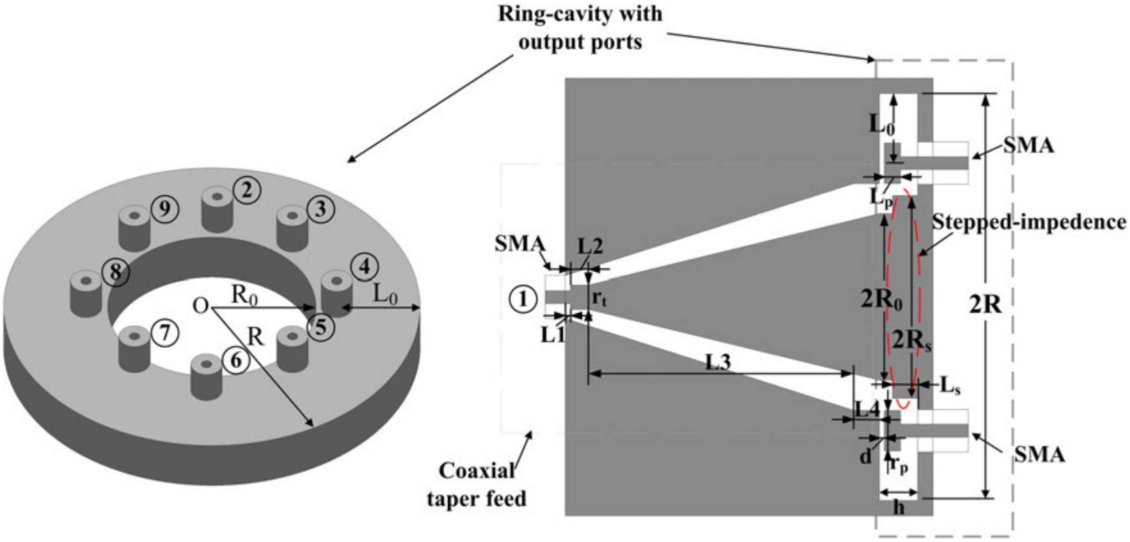


Fig. 1. Proposed ring-cavity eight-way power divider: (a) sketch of the ring cavities with output ports and (b) structure of the power divider.

maintained as about $\lambda g/4$ to make the outer side of the ring cavity be the short wall. So the width $(R - R_o)$ and height of the ring cavity are kept constant. That is to say, when the number of probes increases greatly, only the perimeter of the ring cavity increases, the section of the ring cavity keeps constant, and the higher-order modes cannot propagate in the ring cavity after an appropriate design. So, this type of power-combining structure is very suitable for large numbers of power-combining ports. The proposed ring power combiner/divider can be constructed and optimized in the three-dimensional electromagnetic simulation tools (such as Ansoft-HFSS), and the optimized structural dimensions of the proposed ring-cavity power combiner/divider can also be obtained.

When compared the proposed structure in Fig. 1(b) and the structure in [1], stepped-impedance technology is used between the coaxial taper feeding port and the ring cavity to improve the impedance matching which will broaden the bandwidth. The approximate equivalent circuit of the proposed eight-way ring-cavity power divider is shown in Fig. 2. The stepped discontinuity from the output port of the coaxial taper to the ring cavity is modeled as a capacitive reactance $-jX_S$, which is marked by the dashed line. In the structure of [1], the capacitive reactance X_S cannot be modulated when the size of the ring cavity is determined, while in the proposed structure of this paper, X_S, could be modulated easily (by modulating the size of L_2 and R_s), that means the impedance matching between the coaxial taper feeding port and the ring cavity would be improved.

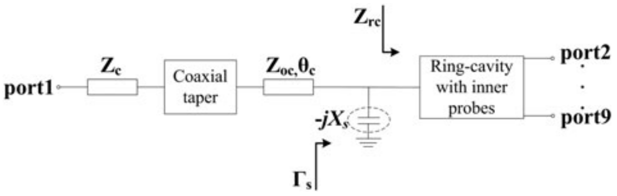


Fig. 2. The approximate equivalent circuit of the proposed power divider.

In the equivalent circuit above, Z_{rc} is the input impedance of the ring cavity with inner probes, Γ_s is the reflection coefficient of the stepped impedance and ring cavity including the planar probe array, and Z_{oc} is the impedance of the extended coaxial. Based on the transmission-line theory, the reflection coefficient Γ_s can be given by

$$\Gamma_s = \frac{((-jX_S Z_{rc})/(-jX_S + Z_{rc})) - Z_{oc}}{((-jX_S Z_{rc})/(-jX_S + Z_{rc})) + Z_{oc}}. \qquad (1)$$

It can be seen that the reflection coefficient Γ_s is determined by X_S, Z_{rc}, and Z_{oc}. So the adjustability of X_S will improve the impedance matching greatly. Figure 3 shows the simulated S_{11} at different structural parameters. It can be seen that the stepped-impedance part could improve the *impedance match effectively*.

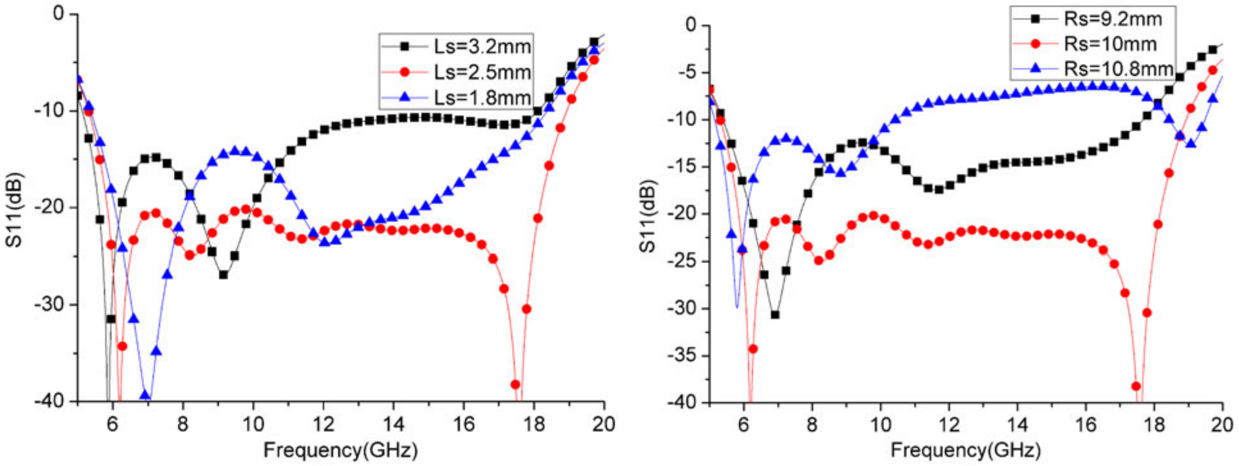
The characteristics of the proposed structure can be analyzed by the microwave network theory. As it is known, for the n-port lossless reciprocal network, there is

$$\sum_{k=1}^{N} S_{ki} S_{ki}^{*} = \delta_{ij}. \qquad (2)$$

If $i = j$, then $\delta_{ij} = 1$; if $i \neq j$, then $\delta_{ij} = 0$. That is

$$\begin{cases} \sum\limits_{k=1}^{N} S_{ki} S_{ki}^{*} = 1, \\ \sum\limits_{k=1}^{N} S_{ki} S_{kj}^{*} = 0, \quad i \neq j. \end{cases} \qquad (3)$$

For the proposed ring-cavity eight-way power combiner/divider in this paper, its structure is axially symmetric. Port 1 is set as the input port, and the last n ports are set as the output ports in turn (shown in Fig. 1(a)). Assuming that the input port is impedance matched, the S-parameter matrix of this kind of axially symmetric power combiner/divider could



(a) (b)

Fig. 3. The simulated S_{11} at different structural parameters: (a) L_s and (b) R_s.

be given as

$$S = \begin{pmatrix} 0 & S_{1n} & S_{1n} & \cdots & S_{1n} \\ S_{1n} & S_{22} & S_{23} & \cdots & S_{2n} \\ S_{1n} & S_{32} & S_{33} & \cdots & S_{3n} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ S_{1n} & S_{n2} & S_{n3} & \cdots & S_{nn} \end{pmatrix}. \tag{4}$$

This is an $(n+1)$-order square matrix [16]. If this structure is lossless, the above matrix would be the unitary matrix. So according to equation (3), there will be

$$|S_{1n}|^2 = \frac{1}{n}, \tag{5}$$

$$|S_{1n}|^2 + |S_{22}|^2 + \left|S_{32}\right|^2 + \cdots + |S_{n2}|^2 = 1, \tag{6}$$

$$S_{1n}\left(S^*_{22} + S^*_{32} + \cdots + S^*_{n2}\right) = 0. \tag{7}$$

Here, as the structure is axially symmetric, there is

$$\left|S_{i,j}\right| = \left|S_{i,n+4-j}\right|, \quad \left|S_{i,j}\right| = \left|S_{i+1,j+1}\right|. \tag{8}$$

According to equations (6) and (8), it could be concluded that the return loss of the output port is in correspondence with the isolation of the output port. In general, the isolation of the output port is not equal, but they are all around the average value. So the derivation of this average value can provide a certain reference. It can be given by

$$\left|S_{ij}\right|^2 = \frac{n-1}{n^2}, \quad i \neq 1,\ i \neq j. \tag{9}$$

As to the proposed ring-cavity eight-way power combiner/divider, n is equal to 8, so the average value of isolation and return loss of the output ports is

$$10\lg\left(\left|S_{ij}\right|^2\right) = -9.6\,\text{dB} \quad \left(n = 8,\ i \neq 1,\ i \neq j\right). \tag{10}$$

Table 1 shows some average values of several different n (n is the number of the output ports). From Table 1, it can be seen that the power divider/combiner designed by this structure (axially symmetric) is not suitable for the power divider/combiner with fewer output ports, as the isolation or the return loss of the output port could not reach the requirement of some systems. But, to the multi-way power divider's design, this issue will not exist.

III. RESULTS AND DISCUSSION

According to the above analysis, the proposed ring-cavity eight-way power combiner/divider is designed, simulated, and optimized using the electromagnetic simulation tool Ansoft-HFSS. The optimized dimensions of the proposed power combiner/divider are listed in Table 2 (as shown in Fig. 1). The ring-cavity eight-way power dividing structure

Table 1. Average value with different n.

n	3	8	10	32	64	100
$10\lg(\|S_{ij}\|^2)$ $(i\neq 1,\ i \neq j)$	−6.5 dB	−9.6 dB	−10.4 dB	−15.1 dB	−18.1 dB	−20 dB

Table 2. Optimized dimensions of the ring-cavity power divider (unit: millimetre).

Dimensions	r_t	r_p	R_0	R_s	R	h	d	L_1	L_2	L_3	L_4	L_s	L_p	L_0
Value	1.2	2	8.2	10	20.1	3.8	0.5	0.5	1.8	26.3	2.5	2.5	1.6	6.9

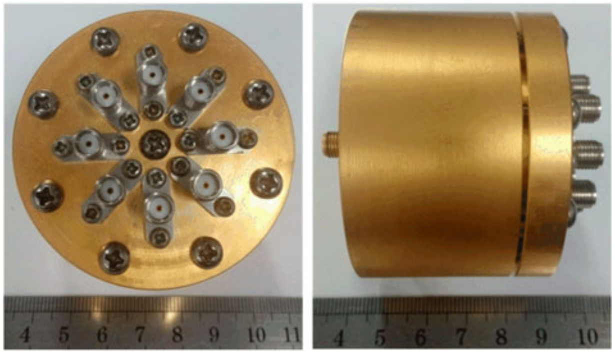


Fig. 4. Photograph of the fabricated power divider.

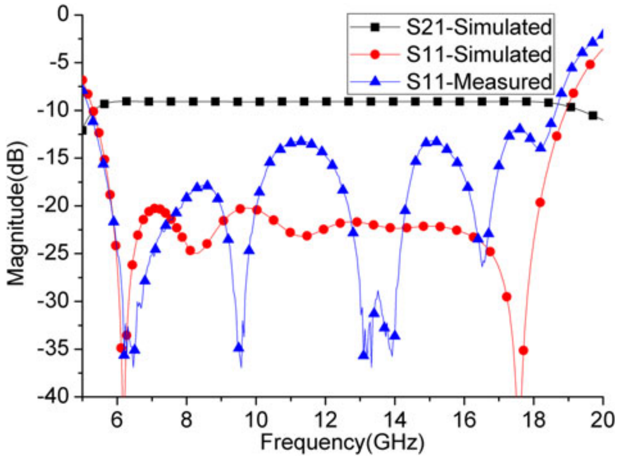


Fig. 5. Simulated and measured results of the proposed power divider.

has been fabricated by machining of a ring cavity and a coaxial taper. In addition, the coaxial probes are machined and inserted inside the ring cavity at the designed locations. The assembly and overview of the fabricated power divider is shown in Fig. 4.

The fabricated power divider has been measured by using an Agilent network analyzer. The simulated and measured reflection coefficients of the fabricated power divider are

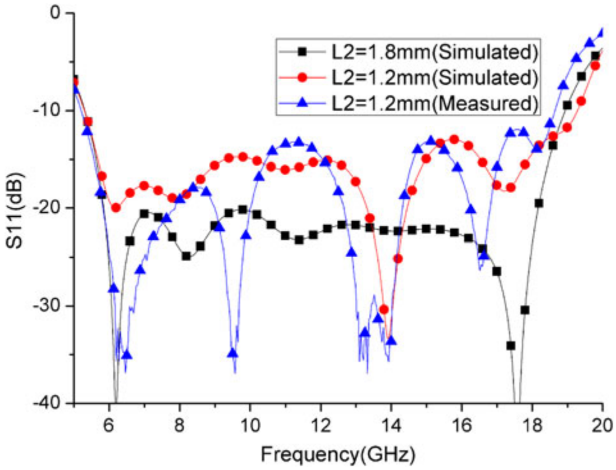


Fig. 6. Simulated and measured results of S_{11} with different values of L_2.

shown in Fig. 5, which also include the simulated transmission coefficient between the input port and one of the output ports (the measured transmission coefficients are shown in Fig. 7(a)). Only insertion loss S_{21} is plotted in Fig. 5 and the insertion losses between port 1 and the other ports are the same as S_{21} because of the *n*-fold symmetry with respect to the input port axis. It can be seen that the measured results agree with the simulated ones closely. The simulated and measured −10 dB return loss bandwidths are 13.6 GHz (from 5.3 to 18.9 GHz) and 13.4 GHz (from 5.2 to 18.6 GHz), respectively. The difference between the simulated and measured S_{11} is most likely attributed to the fabrication and assembly. We have found that there is a mistake for the length L_2 when the power divider was fabricated. In fact, L_2 should be equal to 1.8 mm for an optimized power divider. However, L_2 of the fabricated power divider was equal to 1.2 mm, which greatly affects S_{11}. As shown in Fig. 6, the measured S_{11} of the fabricated power divider is close to the simulated S_{11} for $L_2 = 1.2$ mm.

Figure 7 shows the measured transmission characteristics of the fabricated power divider. The average insertion loss is around 9.4 dB (including the 9-dB power-dividing insertion loss). A maximum amplitude imbalance of ±0.7 dB and a phase imbalance of ±6° are observed over the entire band.

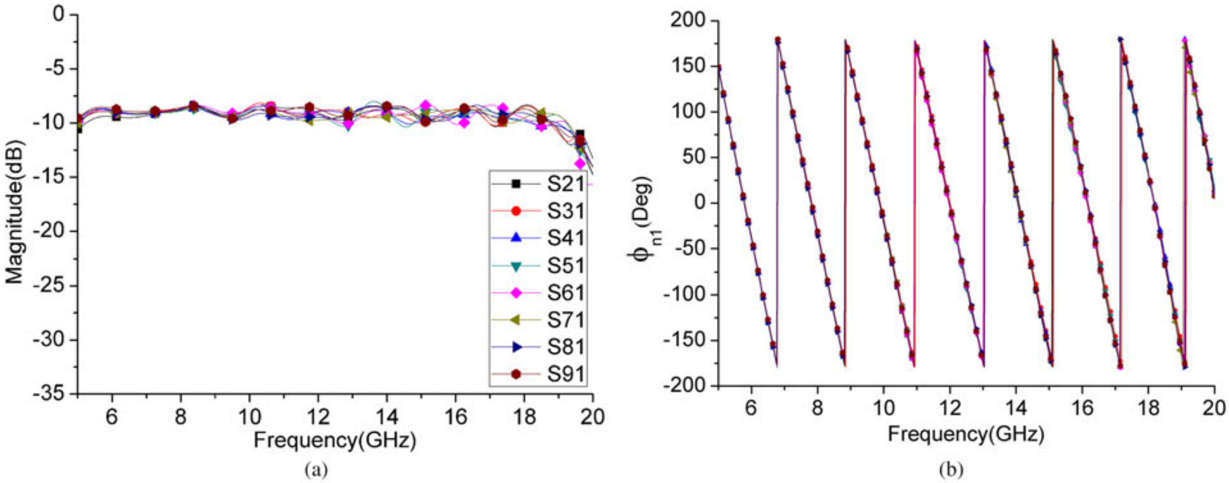


Fig. 7. Measured transmission coefficients of the fabricated coaxial power divider ($n = 2, 3, \ldots, 8$): (a) amplitude and (b) phase.

Table 3. Comparison with some prior power dividers.

	Frequency (GHz)	10 dB (S_{11}) RBW (%)	AIL (dB)	A/PI	Structure
[1]	3.1–10.6	109.5	0.4	±0.7 dB/ ± 5°	Ring cavity
[8]	7–15	72.7	0.5	–/–	Radial waveguide
[9]	6.2–14.2	78.4	0.5	±1.5 dB/ ± 10°	Conical line
[10]	7–12.7	57.8	0.28	±0.7 dB/ ± 5°	Conical line
[11]	11.6–16.6	35.5	0.8	±1 dB/ ± 5°	Coaxial waveguide
This work	5.2–18.6	112.6	0.4	±0.7 dB/ ± 6°	Ring cavity

RBW: relative bandwidth; AIL: average insertion loss; A/PI: amplitude/phase imbalance.

The amplitude and phase imbalance is due to the fabrication errors. Moreover, the comparison of the presented power combiner/divider with other designs is summarized in Table 3. It can be seen that the novel power combiner/divider presented in this paper has a wider bandwidth and low insertion loss, good amplitude, and phase balance.

IV. CONCLUSION

In this paper, a ring-cavity eight-way power divider with UWB performance has been presented. The proposed power-dividing structure can not only hold large numbers of power-dividing ports but also can have UWB performance. A coaxial taper feeding port has been applied into the ring cavity to provide uniform excitation for the multiple-way ring-cavity power divider, and then, excellent amplitude and phase balance of the output ports has been obtained. The network of this eight-way ring-cavity power divider has also been analyzed. It gives the limitation of this axially symmetric structure. The measured results reasonably agree with the simulated results, which also demonstrate UWB performance, good amplitude and phase balance, and very low losses. It is expected that such a power dividing/combining structure can be used easily in power-combining amplifier and array antenna feeding networks.

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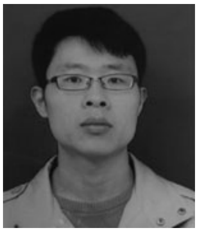

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