Development of a Symmetric Waveguide T-Junction Power Divider with Equal-Phase Characteristic

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Abstract ─ An efficient method is proposed to design a versatile rectangular waveguide T-junction power divider without changing the length of either of the output branches for phase compensation. Instead, the phase balance is controlled by the widths of the output branches, which, in turn, help to achieve the same time-of-arrival of waves propagating to the two output ports. This method does not sacrifice the T-junction's symmetric characteristic physically. Numerical analysis has been utilized to design several T-junction power dividers operating in Ku-Band with different power ratios, and results are compared with the measured ones to verify the design feasibility.

Index Terms ─ Microwave power divider, rectangular waveguide, symmetric T-junction, wideband.

I. INTRODUCTION

In advanced microwave systems, especially in radar and satellite communication systems, high performance power dividers are wanted to achieve particular functions such as low sidelobe radiation patterns on antenna aperture, which is important for avoiding the interference from jamming environments. A proper power distribution feed-network, constructed by multiple power dividers in the rear, is always required to excite the radiation elements with correct amplitudes and phases [1-3]. Waveguide-based power dividers are the preferred candidate due to their unique advantages like robust structure, low loss, high-power handling capability and wide operational bandwidth. Lots of published literatures have focused on the impedance matching design of *H*-plane waveguide T-junction power dividers; and most of them adopted either a central splitter or an inductive post to minimize the reflection [4-9]. Analytical methods have also been reported [10-13], as well as their practical application in constructing array feed-networks [14,15]. Some metamaterial-inspired resonators or dielectric slab insertion have been recently used to design waveguide power dividers [16]. Although low input reflection and required power-split can be obtained in these power dividers, in most of the cases, the only way to achieve phase-balance between two output ports is to modify the length of one output branch compared to the other one's in order to compensate the phase difference. Some typical design examples can be viewed in [7,10]. These designs apparently destroy the symmetry of the T-junction power dividers and result in even larger feed-network in application eventually. Besides, most of their operational bandwidths are limited.

In this paper, an efficient method is proposed to design an equal-phase and unequal-power-division T-junction power divider without changing the length of either of the output branches for phase compensation. Instead, the phase balance is controlled by the widths of the output branches, which, in turn, help to achieve the same time-of-arrival of waves propagating to the two output ports. This method does not sacrifice the T-junction's symmetric characteristic physically.

II. DESIGN METHODOLOGY

The proposed equal-phase and unequal-power-division waveguide T-junction power divider with equal-branch-length is shown in Fig. 1. Here the physical symmetry of the T-junction power divider is illustrated as follows: when the central line of the input port (Port 1) is taken as reference, the physical lengths from this line to the two output ports (Port 2 and Port 3) are equal, i.e., $l_1=l_2+d_1=l_3-d_1$. The waveguide port dimensions (a and b) are the same as those of a standard WR-62 Ku-Band waveguide adapter, which will ease the setup in measurement. Fillets are incorporated to avoid sharp corners in order to take the practical fabrication process (machining method) into consideration. Different power-split ratios can be efficiently obtained by offsetting a

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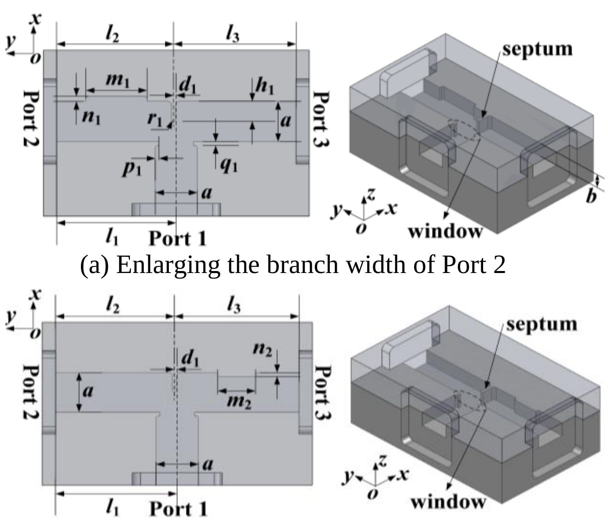
septum from the center (d_1). Different d_1 corresponds to different output power ratios. To ease the explanation and discussion in this work, the offset value (d_1) is fixed at several values instead of fixing the power ratio. d_1 is set to 1 mm in the models shown in Fig. 1. Impedance matching can be controlled by the dimensions of the septum (h_1 and r_1), and adding a window (p_1) would help to further reduce the input reflections. However, the phase difference between the two output ports is affected significantly while shifting the septum's position to produce the required power ratio. This is mainly due to the unequal propagating distances of electromagnetic (EM) waves from the input port to the two output ports, i.e., $l_2 \neq l_3$. To solve this problem, traditional ways usually extend or shorten one of the output branches in order to compensate the phase difference [5-10]. However, this destroys the physical symmetry of the T-junction power divider.



(a) Enlarging the branch width of Port 2

(b) Shrinking the branch width of Port 3

Fig. 1. Symmetric T-junction power divider #1 mm.

Instead of adopting the above-mentioned asymmetric structure, one can consider increasing or slowing down the EM waves inside the T-junction so as to force the propagating waves to arrive at the two output ports simultaneously. The wave velocities can be controlled by tuning the widths of the output branches, i.e., n_1 in Fig. 1 (a) and n_2 in Fig. 1 (b). It can be understood that a waveguide with varying width introduces different propagating velocities and, in effect, produces the required phase compensation so that the physical symmetry of the power divider is retained. More theoretical explanation is as follows.

According to waveguide theory, the guide wavelength (λ_g) can be expressed as:

$$\lambda_g = \lambda_0 / \sqrt{1-(\lambda_0/\lambda_c)^2}\ , \tag{1}$$

where λ_c is the cut-off wavelength and λ_0 is the wavelength in free-space [17]. The phase velocity inside the waveguide (v_p) is expressed as:

$$v_p = \lambda_g f = v_0 / \sqrt{1-(\lambda_0/\lambda_c)^2}\ , \tag{2}$$

where v_0 is the phase velocity in free-space and $v_0 = \lambda_0 f$. For the dominant TE_{10} mode, $\lambda_c = 2a$, where a is the width of the waveguide port. Then (2) can be rewritten as;

$$v_p = v_0 / \sqrt{1-(\lambda_0/2a)^2}\ . \tag{3}$$

Let the physical distance from input port (Port 1) to the two output ports (Port2, Port 3) be l_2 and l_3, respectively (Fig. 1) where,

$$l_2 = l_1 - d_1,\ l_3 = l_1 + d_1\,. \tag{4}$$

The corresponding wave propagation time from the septum to the two output ports are denoted by τ_2 and τ_3, respectively. The waveguide phase velocities in the two output branches are denoted by v_{p2} and v_{p3} respectively. Therefore, τ_2 and τ_3 can be obtained as follows:

$$\begin{aligned} \tau_2 &= l_2 / v_{p2} = l_2\sqrt{1-(\lambda_0/2a_2)^2}\,/\,v_0, \\ \tau_3 &= l_3 / v_{p3} = l_3\sqrt{1-(\lambda_0/2a_3)^2}\,/\,v_0, \end{aligned} \tag{5}$$

where a_2 and a_3 indicate the branch widths of the Port 2 and Port 3, respectively. The objective is to achieve unequal power division from Port 1 to Port 2 & Port 3 while maintaining the equal-phase. In other words, the time for the wave propagating from the input port to the two output ports should be equal, namely, $\tau_2 = \tau_3$,

$$l_2\sqrt{1-(\lambda_0/2a_2)^2}\,/\,v_0 = l_3\sqrt{1-(\lambda_0/2a_3)^2}\,/\,v_0\,. \tag{6}$$

Thus,

$$l_2 / l_3 = \sqrt{1-(\lambda_0/2a_3)^2}\,/\,\sqrt{1-(\lambda_0/2a_2)^2}\,. \tag{7}$$

One should note that, in order to make (7) valid under the condition $l_2 < l_3$ as shown in Fig. 1, a_2 should be larger than a_3. Hence, there are three feasible ways to achieve this requirement: ① enlarging the branch width of Port 2 alone, i.e., $a_2 = a + n_1$ in Fig. 1 (a); ② shrinking the branch width of Port 3 alone, i.e., $a_3 = a - n_2$ in Fig. 1 (b); ③ enlarging and shrinking the branch width of Port 2 and Port 3, respectively. To simplify the analysis, case ① is taken into account below and other cases can be analyzed in the same way. In the case shown in Fig. 1 (a), a_2 is enlarged from a to ($a+n_1$) in order to reduce the waveguide phase velocity while a_3 is unchanged. The value of n_1 can be obtained by solving (4) and (7):

$$\begin{aligned} n_1 &= \frac{\lambda_0}{2\sqrt{1-(l_3/l_2)^2(1+\lambda_0/2a_3)(1-\lambda_0/2a_3)}} - a \\ &= \frac{\lambda_0}{2\sqrt{1-(\frac{l_1+d_1}{l_1-d_1})^2(1+\frac{\lambda_0}{2a})(1-\frac{\lambda_0}{2a})}} - a \end{aligned}\ . \tag{8}$$

According to (5) and (8), once the branch width of an output port (e.g., a_3) is fixed, the time difference of the wave arriving at the two output ports is determined by the wave propagating velocity via adjusting the other output port's width (a_2). Hence, the unequal-power-division can be realized in this symmetric structure while maintaining phase-balance from the input to the output ports. Nevertheless, one should note that the above analysis is not rigorous. The main reason of being an approximation is that the formulas, e.g., (8) are frequency dependent. Therefore, there exists no analytical formula which is valid in a frequency band. Higher order modes will occur when enlarging the width of the waveguide to some extent. But (8) can provide a convenient way to get an initial trial value for the parameter n_1 in numerical analysis and save time for the design of an equal-phase performance.

III. RESULTS AND ANALYSIS

Based on the above analysis, the phase-balance in the symmetric T-junction power divider can be realized by adjusting the widths of the output branches. Although enlarging or shrinking the waveguide branch from its narrow wall (changing n_1 or n_2) will cause the magnetic field (H-field) in that region to be expanded or squeezed, equivalent to add a shunt reactance in the waveguide circuit [17], the mismatching can be alleviated by adjusting the length of the enlarging or shrinking part (m_1 or m_2). Therefore, further numerical analysis has found that the phase-balance and impedance matching can be improved by optimizing the enlarging parameters (m_1, n_1) or the shrinking parameters (m_2, n_2). Three configurations of the T-junction power divider with septum's offset value d_1 fixed at 1 mm have been designed and fabricated: one without the equal-phase design, two with the equal-phase design (same as shown in Figs. 1 (a) and (b)). The three models are optimized by the commercial EM simulation software HFSS®. Dimensions of the latter two configurations are obtained from the numerical analysis and listed in Table 1. One of the prototypes is shown in Fig. 2 with and without WG-62 waveguide adapters. Figure 3 shows the internal view of the two prototypes before assembly, which are corresponding to those in Fig. 1. All the prototypes are fabricated in aluminum by the milling technique and assembled by screws. It is a standard machining fabrication process and the typical manufacturing accuracy is better than 30 μm, which is much less than a wavelength in Ku-Band and would not affect the power dividers' performance a lot. Some screw holes are opened around the waveguide channels for assembly alignment and tight electrical contact. Each port is connected to a WR-62 waveguide adapter during the measurement. It is worth mentioning that some microwave chokes are incorporated into the prototypes for preventing energy leakage via gaps (if any) after the assembly. All of the prototypes are measured by a two-port Vector Network Analyzer (VNA) while the third port is terminated by a matching load. A measurement setup is shown in Fig. 4.

Experimental results compared with the analytical ones obtained from HFSS® simulation are plotted in Fig. 5 and Fig. 6. It can be seen from Fig. 5 that the measured unequal-power-division level ($|S_{21}/S_{31}|$) remains stably in both designs (Fig. 1 (a) & case ①) and (Fig. 1 (b) & case ②). The reflections of the input port, represented by the voltage standing wave ratios (VSWRs), are less than 1.3 over the major part of a wide bandwidth of 13.0 GHz~17.0 GHz. Figure 6 shows that the phase difference is improved significantly from the original 20º to less than ±6º after adopting the phase-equalization technique. The value of n_1 in the enlarging design is 2 mm, which is close to the estimated initial value (n_1 = 1.6 mm) based on (8) of case ①. Additionally, the phase-balance improvement can also be verified by observing the electric-field (E-field) distribution plotted in Figs. 7 (a)~(c). Compared with the T-junction divider without phase-equalization design in Fig. 7 (a), EM waves propagating inside the two output branches almost reach the two output ports simultaneously after applying the equal-phase design, as shown in Fig. 7 (b) and Fig. 7 (c).

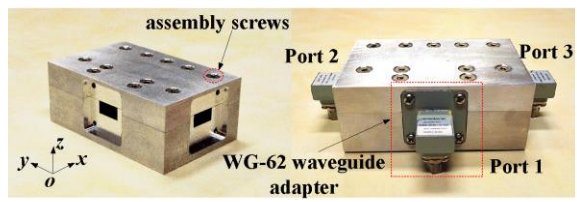


Fig. 2. Prototypes of T-junction power divider.

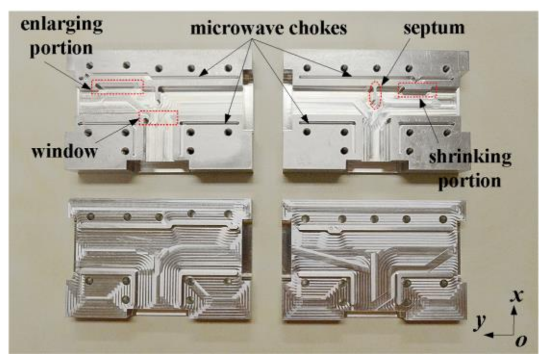


Fig. 3. Parts of the proposed T-junction before assembly.

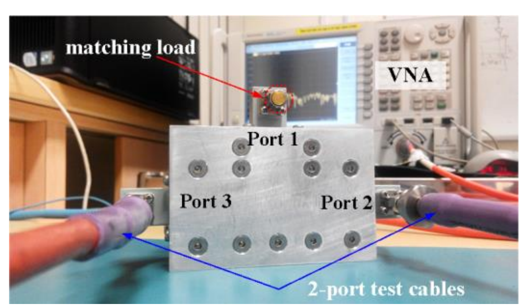


Fig. 4. Power divider measurement setup.

Table 1: Dimensions of T-junction #1 mm (unit: mm)

a	b	l_1	l_2	l_3	d_1	h_1
15.8	7.9	45.0	44.0	46.0	1.0	7.75
r_1	p_1	q_1	m_1	n_1	m_2	n_2
0.75	1.4	1.5	23.0	2.0	14.0	1.6

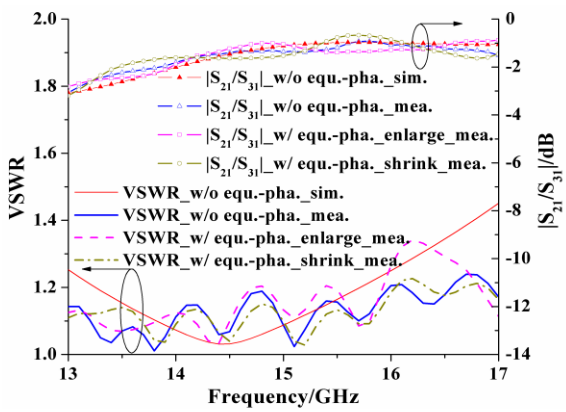


Fig. 5. T-junction amplitude comparison #1 mm.

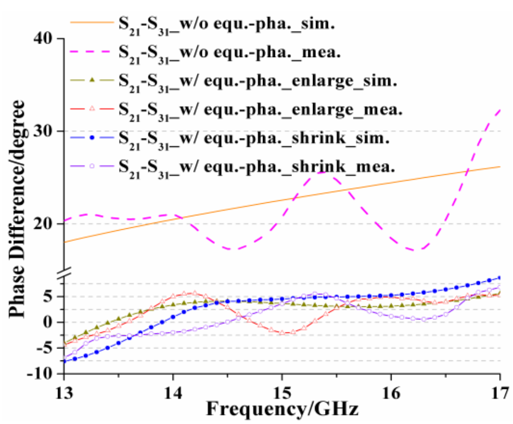


Fig. 6. T-junction phase comparison #1 mm.

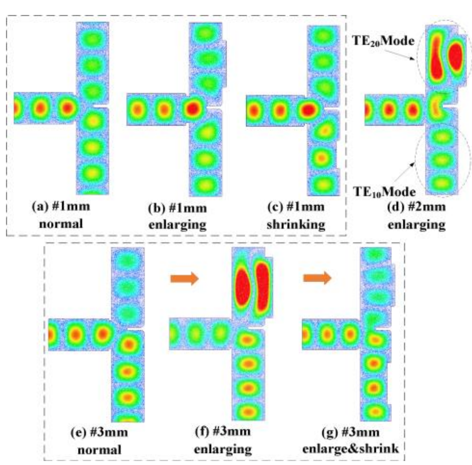


Fig. 7. *E*-field distribution for models of different power-ratios: (a)~(d) at 16.0 GHz, (e)~(g) at 15.8 GHz.

IV. FURTHER INVESTIGATION

The last section verifies the phase-balance of the symmetric T-junction power divider can be greatly improved by using the proposed design method. However, when a larger power ratio is to be realized with a larger septum offset, one cannot monotonically enlarge one branch width to compensate the phase difference without considering the possibility of occurrence of high-order-modes. Figure 8 shows the structure of T-junction power divider with d_3 fixed at 2 mm. Here only the branch width of Port 2 is enlarged to balance the phase difference. Dimensions of the power divider are listed in Table 2. Measured results are compared to the simulated ones before and after enlarging the branch's width, as shown in Fig. 9 and Fig. 10. VSWRs of less than 1.2 and consistent trends of power-division between measurement and simulation, as well as good phase-balance improvement can be achieved in a wide bandwidth. Nevertheless, there is an anomaly at 16.0 GHz for both the amplitude and phase results (highlighted as the shadow areas). Further investigation shows that it is due to a higher-order-mode generated at 16.0 GHz when the waveguide width is enlarged to a certain value. It can also be verified by a close looking at the *E*-field distribution in Fig. 7 (d), where a TE_{20} mode is observed in the enlarging portion.

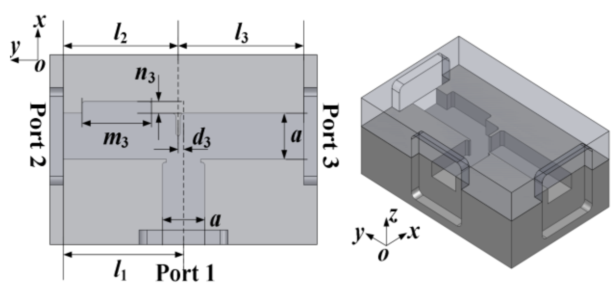


Fig. 8. Symmetric T-junction power divider #2 mm.

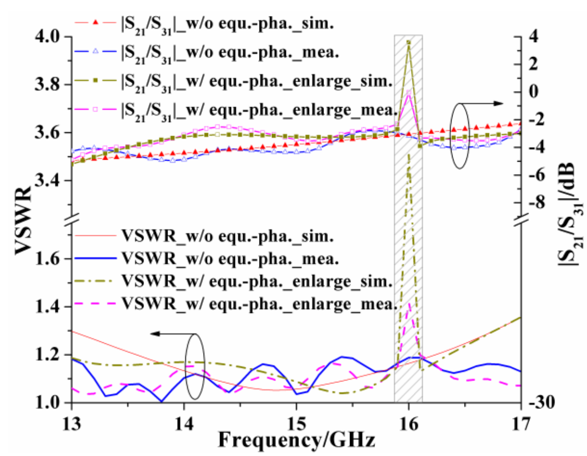


Fig. 9. T-junction amplitude comparison #2 mm.

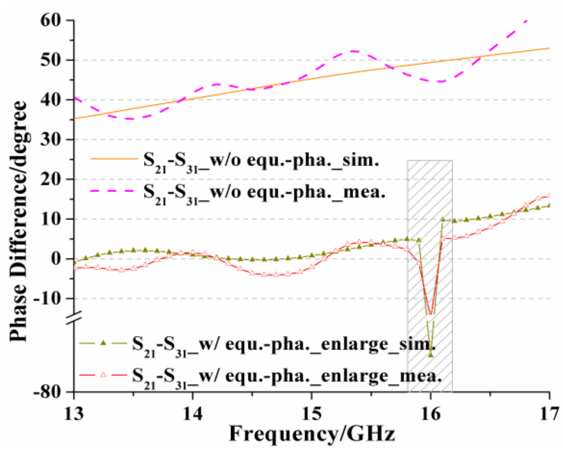


Fig. 10. T-junction phase comparison #2mm.

Table 2: Dimensions of T-junction # 2mm (unit: mm)

a	***b***	***l_1***	***l_2***	***l_3***	***d_3***	***m_3***	***n_3***
15.8	7.9	45.0	43.0	47.0	2.0	26.0	4.0

(Other parameters are the same as in Fig. 1 and Table 1)

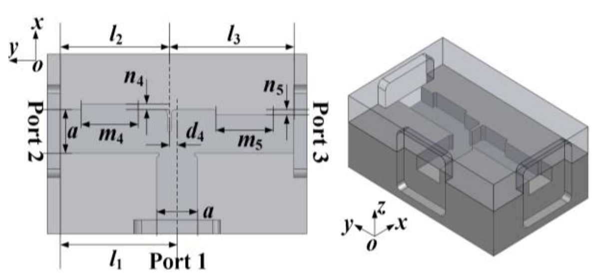


Fig. 11. Symmetric T-junction power divider #3 mm.

Table 3: Dimensions of T-junction #3 mm (unit: mm)

a	***b***	***l_1***	***l_2***	***l_3***
15.8	7.9	45.0	42.0	48.0
d_4	***m_4***	***n_4***	***m_5***	***n_5***
3.0	22.0	2.0	22.0	2.0

(Other parameters are the same as in Fig. 1 and Table 3)

Apparently, the occurrence of high-order-modes would limit the operational bandwidth of the power divider. In this work, an effcient approach is devised to solve this problem without monotonically adjusting one branch width alone. When an even larger power ratio is required, e.g., d_4 = V3 mm in Fig. 11, the branch width of Port 2 (n_4) can be enlarged and that of Port 3 (n_5) can be shrunk at the same time in order to avoid high-order-modes. The selection criteria of values is similar to the case ③ of (7). Detailed dimensions of the T-junction power divider are listed in Table 3.

For comparison, results of the T-junction power divider with only one branch width modification (similar to the structure in Fig. 8) are shown in Fig. 12 first. A much wider branch width is required to compensate the larger phase difference caused by the larger power-division. There is obviously a high-order mode occurring at around 15.8 GHz, as shown in the shadow area in Fig. 12. The results of the proposed method of adjusting widths for the two output branches are shown in Fig. 13 and Fig. 14. Compared with Fig. 12, it can be seen that the anomaly at around 15.8 GHz has been removed, which can also be observed in the *E*-field distribution in Figs. 7 (e)~(g). There is a relatively good agreement between measurement and simulation. Phase difference between the two output ports can be improved from around 65º of the original design to less than ±10º of the equal-phase design from 13.0 GHz~15.3 GHz.

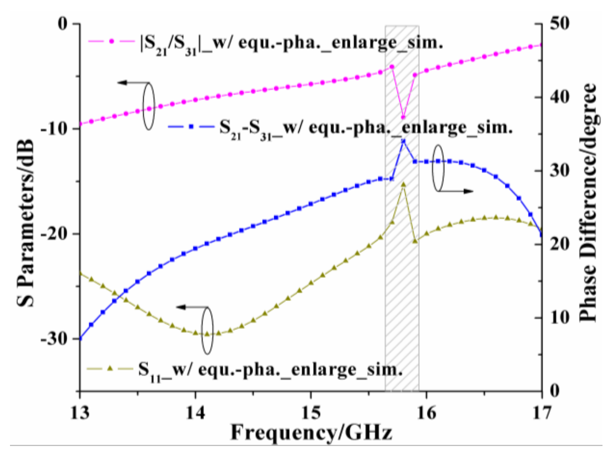


Fig. 12. Results of modifying single branch #3 mm.

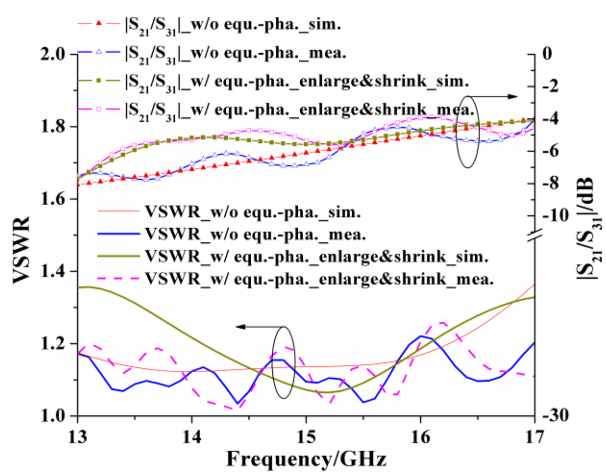


Fig. 13. Amplitudes of modifying two branches #3 mm.

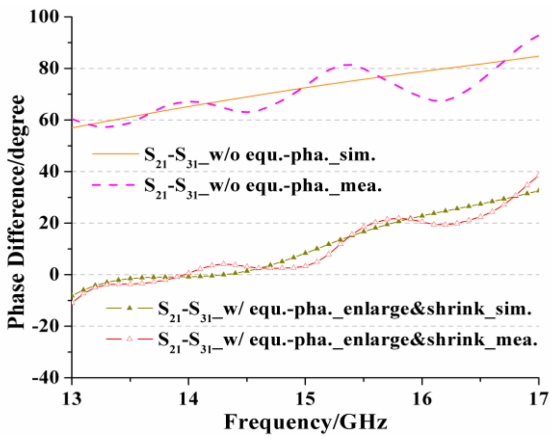


Fig. 14. Phases of modifying two branches #3 mm.

V. CONCLUSION

An efficient method has been proposed for developing a symmetric waveguide T-junction power divider with equal-branch lengths. The phase-balance improvement has been demonstrated via both numerical analysis and practical measurements. High-order-mode phenomenon is also taken into account. Results reveal that the proposed T-junction power divider can achieve good amplitude and phase performance over a wide bandwidth. This device has a potential merit in high-power feed-network designs where equal-phase and unequal-power-division are to be achieved by equal-length feeding lines.

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