A novel eight-way power combiner on suspended substrate stripline for Ku-band applications

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ABSTRACT

This work proposes a novel 8-way power combiner implemented using suspended substrate stripline technology for Ku-band applications. The equivalent circuit of the design is analyzed to obtain parameters for the physical realization of the structure. The combiner is well matched at both input and output ports with VSWR better than 1.6:1, achieves low insertion loss of less than 1 dB and isolation of more than 16.8 dB over the range from 12 GHz to 18 GHz. The structure is also able to handle high thermal dissipated power due to its housing, hence, suitable to find application in high power-amplifier subsystems.

Keywords: Power combiner; Wideband; Suspended substrate stripline.

1. INTRODUCTION

Power combiners are passive devices, which are either used to split the input power into multiple output ports or to combine the power from multiple input ports to a single output port. These devices generally find application in microwave systems, power amplifiers, feeding networks of antenna arrays, etc. The Wilkinson power combiners (WPCs) gained their popularity due to their simplicity of design and ability for unequal power division. However, such structures suffer from limited operating bandwidth. In essence, dividers and combiners have the same structure, so the summaries of the papers below are completely valuable for comparison in designing combiners.

Several designs and modifications have been proposed to expand the working bandwidth of the traditional WPCs. Utilizing multiple sections that broaden the bandwidth by increasing the cascaded sections [1], using tapered transmission lines (TTLs) [2], or by adding open-circuited stubs [3] are among bandwidth extending techniques that are worth mentioning. The multi-wafer packaging technique can also be employed to design ultra-wideband (UWB) power combiners [4]. The application of TTLs in microwave components reduces the overall size of components and broadens the bandwidth [5, 6]. In [7], a Wilkinson power combiner with ultra-wideband performance using open-circuited stubs added to each branch was proposed. Furthermore, open-circuited radial stubs were also used in the design of the ultra-wideband Wilkinson power combiner [8, 9]. Moreover, an ultra-wideband Wilkinson power combiner with an open-circuited delta stub was proposed in [10]. Additionally, the designs with UWB performance using TTLs on their sections were also proposed in [11-14].

Wilkinson power combiners with multilayer substrates were introduced in [15] for wideband applications, however, this typically led to a large-size circuit. Another wideband Wilkinson power combiner using non-uniform transmission lines was presented in [16] which obtained an operational bandwidth extending from 3.1 GHz to 10.6 GHz. In [17], the authors presented a wideband Wilkinson power combiner with two cascaded sections of different electrical lengths and the same impedance was presented. Additionally, an UWB power combiner using a square ring multiple-mode resonator proposed in [18] also attained a bandwidth extending from 3.1 GHz to 10.6 GHz.

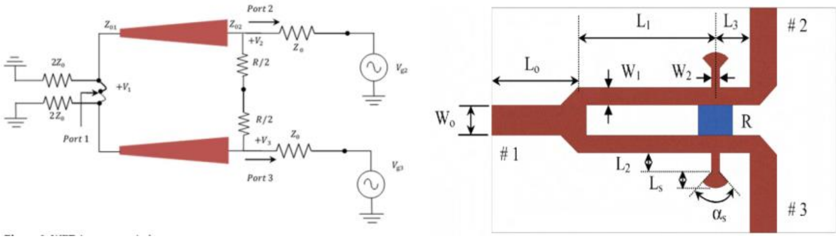


Figure 1. *Tapered transmission lines (TTLs) [2] and adding open-circuited stubs [3].*

In this work, an 8-way 3-section power combiner is proposed for Ku-band applications. The design is implemented using suspended substrate stripline (SSSL) technology, thus, it possesses low-loss nature over a wide bandwidth. Furthermore, thanks to the housing structure, the proposed combiner can be integrated into the heat sink with ease, resulting in a capability of regulating low operating temperature while handling high thermal dissipated power.

2. DESIGN METHOD OF MULTI-SECTION POWER COMBINER

Fig. 1 describes the equivalent circuit of a multi-section three-port hybrid with N pairs of equal length transmission lines and N bridging resistors distributed from port 1 to ports 2 and 3 [19]. This class of symmetrical circuit is easily analyzed by the method of even- and odd-mode excitations in which electromagnetic waves are excited at ports 2 and 3 while port 1 is terminated with Z_0.

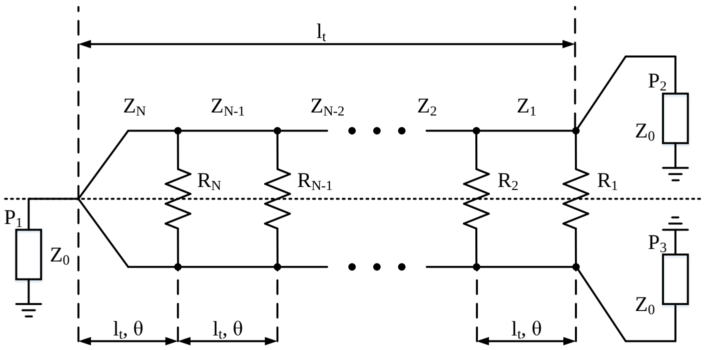


Figure 2. *General circuit of the multi-section three-port hybrid.*

When even mode is excited, waves propagate from ports 2 and 3 are of equal amplitude and in-phase. The voltage difference between the corresponding points of the upper and lower transmission lines is then zero, and no power is dissipated in the resistors. Hence, the circuit in Fig. 1 can be bisected symmetrically by a non-conducting wall, resulting in the equivalent circuit in Fig. 2 (a). It should be noted that the load at P1 is replaced by $2Z_0$ as a result of the bisection.

When an odd mode is excited, waves propagate from ports 2 and 3 are of equal amplitude but out-of-phase. As a result, the resistors are impressed with substantial voltages across them. The mid points of the resistors and the junction of the lines at port 1 are at ground potential due to the circuit's symmetry. Therefore, the circuit in Fig. 1 can be bisected as shown in Fig. 2 (b). It should be noted that port 1 is short-circuited.

For convenience, circuits depicted in Fig. 2 (c) and Fig. 2 (d) which are equivalent to those in Fig. 2 (a) and Fig. 2 (b) respectively would be used for analysis. The conductance, admittance, impedance, and resistance represented in the circuits have the following relationship

$$\begin{array}{lll} Y_1 = 1/Z_1, & Y_2 = 1/Z_2, \ldots & Y_N = 1/Z_N, \\ G_1 = 1/R_1, & G_2 = 1/R_2, \ldots & G_N = 1/R_N, \\ Y_0 = 1/Z_0 = 1, & G_L = 1/2Z_0 = 0.5 & \end{array} \quad (1)$$

It is assumed that the admittance values of the transmission lines are the same for both even- and odd-mode.

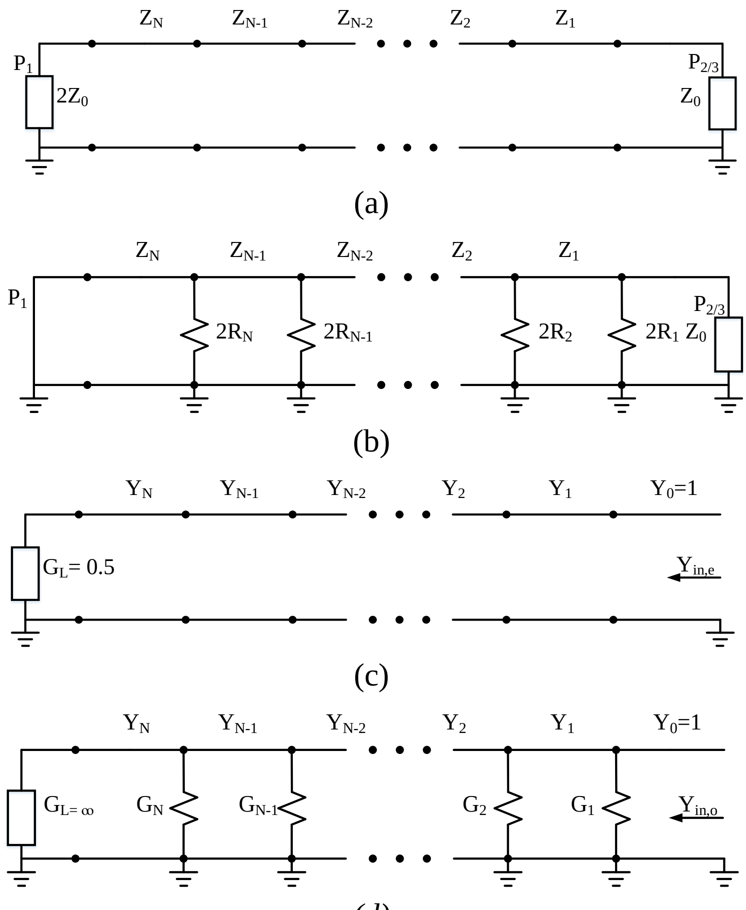


Figure 3. *Bisected circuit of (a) even mode, (b) odd mode, (c) even mode with conductance, and (d) odd mode with conductance.*

In the even mode, the input waves propagate through a network of multiple sections of transmission lines with different characteristic impedances to the load of $2Z_0$. For optimum reflection, the multiple sections should be selected as a multi-section quarter wavelength transformer.

In the odd mode, the conductance values are chosen by the equations (2) – (4) as follows

$$G_1 = 1 - Y_1, \tag{2}$$

$$G_k = \frac{Y_k - Y_{k-1}}{Y_k T_1 T_2 \ldots T_k} \quad ; k = 2 \text{ to } N - 1 \text{ where} \tag{3}$$

$$T_k = \frac{4Y_{k-1}Y_k}{(Y_{k-1} + Y_k + 2G_k)^2} \quad ; k = 1 \text{ to } N$$

$$G_N = \cfrac{0.5Y_{N-1}^2}{-2G_{N-1} + \cfrac{Y_{N-2}^2}{-2G_{N-1} + \cfrac{Y_{N-3}^2}{\ddots \cfrac{}{-2G_2 + \cfrac{Y_1^2}{-2G_1 + 1 + 0.7(S - 1)}}}}} \tag{4}$$

where

$$S = \begin{cases} 1, N\ odd \\ S_e, N\ even \end{cases}$$

The admittance of N^{th} section is determined by equation (4) while satisfies the condition that the VSWR of the input and output ports must meet the requirements given by the following equations (5) – (7)

$$S_1 = S_e, \tag{5}$$

$$S_2 = S_3 \approx 1 + 0.2(S_e - 1), \tag{6}$$

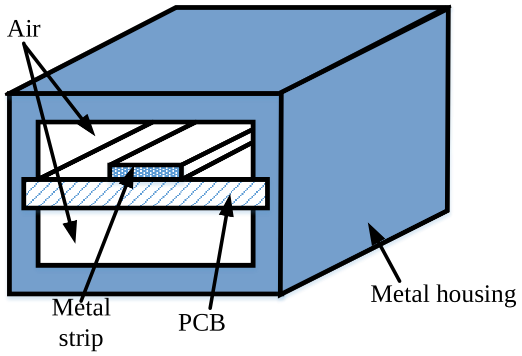
$$I \approx 20log_{10}\left(\frac{2.35}{S_e - 1}\right) dB, \tag{7}$$

However, the results from above calculation should be used as initial values for the design because the calculated resistance might not be commercially available. Hence, the closest values should be selected for the optimization process. It should also be noted that the TTLs are worth employing in the structure to obtain optimum performance.

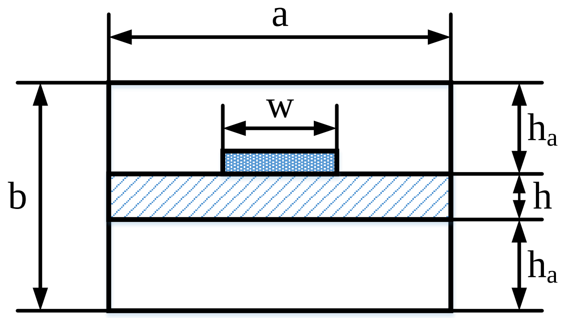
3. PHYSICAL IMPLEMENTATION OF SSL 8-WAY POWER COMBINER

3.1. Suspended substrate stripline design

The suspended substrate stripline is a type of transmission line which utilizes a thin printed circuit board (PCB) hanging between two parallel plates of ground plane. The space between the PCB and the ground planes is filled with air instead of a solid material. This configuration allows the SSSL to have a high quality factor, low loss as the electromagnetic waves propagate mainly in the air rather than dielectrics. In practice, a rectangular waveguide is employed as a host for the PCB, as depicted in Fig. 3 (a). The SSSL can be utilized in microwave applications from 0.5 GHz to 50 GHz.



(a)



(b)

Figure 4. *(a) Physical implementation of SSSL in which a PCB is loaded into a rectangular waveguide, and (b) cross section of the hosted waveguide.*

SSSL supports quasi-TEM (Transverse Electromagnetic) mode, which is not supported by the host rectangular. In order to excite the appropriate mode to propagate along the transmission line, the operating frequencies should be within the cut-off region of the hosting rectangular waveguide. Provided that the dimensions of the rectangular waveguide are provided (length a, width b) as depicted in Fig. 3 (b), the cut-off frequency of the waveguide is calculated below [20].

$$f_c = \frac{1}{2a\sqrt{\mu\varepsilon}}, \quad (8)$$

where μ, ε are the permeability and permittivity of air, respectively.

SSSL parameters such as characteristic impedance (Z_0), effective permittivity, electrical length, etc. can be calculated by empirical formulas in [21]. However, these calculated values should be used as initial values for the design process only, the optimum ones must be obtained by full-wave simulation and characterization.

3.2. Design of 2-way power combiner on SSL

The designed 2-way power combiner with 3 sections is presented. The SSSL structure was realized on a Rogers RT/duroid 5880 substrate with ε_r = 2.2, thickness of h = 10 mil, and loaded into a metal housing with a height of h_a = 1 mm, and with of a = 5 mm. The bridging resistors are selected based on equations (1) to (7) as follows R_1 = 250 Ω, R_2 = 150 Ω, R_3 = 100 Ω, and separated from each other by a gap of l_s = 2.8 mm as shown in Fig.4.

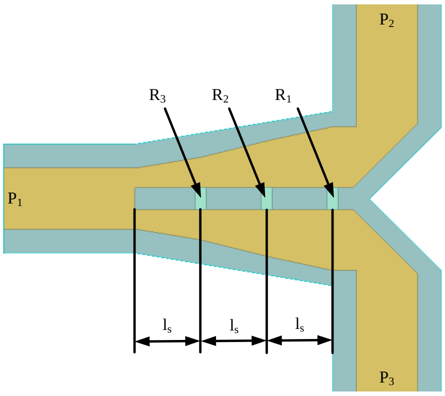
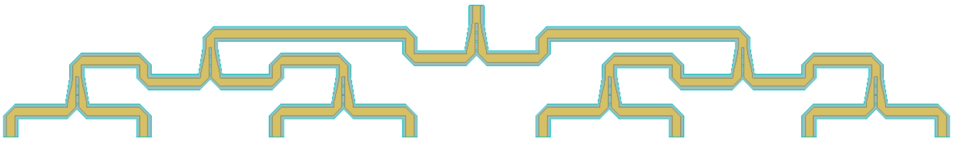


Figure 5. *PCB layout of the 2-way power combiner.*

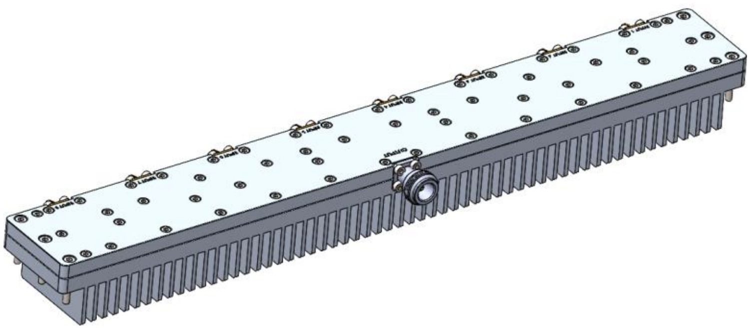
3.3. Design of 8-way power combiner on SSL

The design of 8-way power combiner is implemented by cascading the seven 2-way power combiners in three levels as shown in Fig. 5 (a). The design of all 2-way power combiners that compose the final structure are identical. The transmission lines and mitered bends, which connect 2-way combiners, are carefully designed to achieve optimized performance.

The structure depicted in Fig. 5 (b) is the complete design with metal housing and heat-sink. The heat sink is designed to regulate an operating temperature of less than 50 degrees Celsius while dissipating thermal power of 30 Watts.



(a)

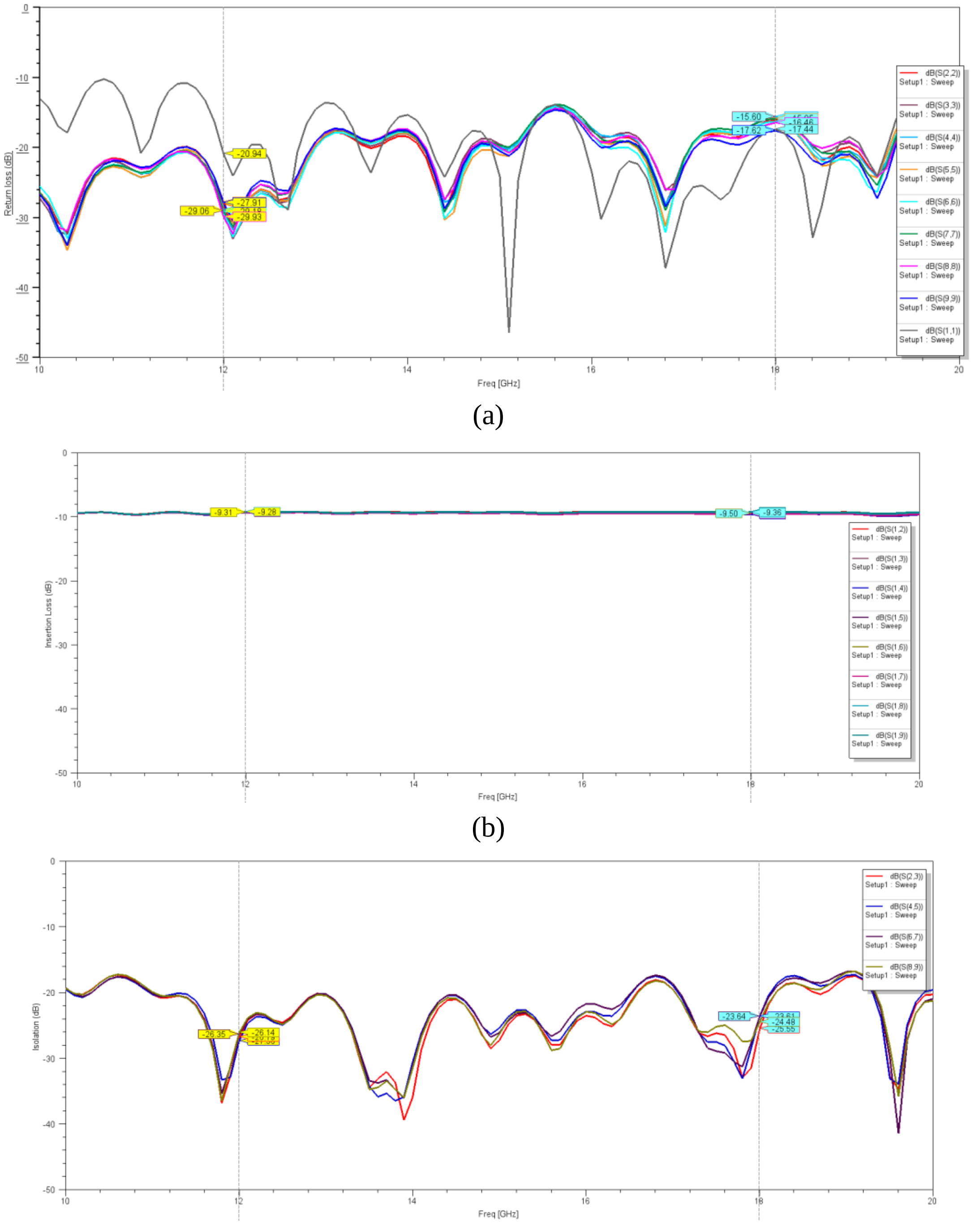


(b)

Figure 6. *Design of the 8-way power combiner (a) inside the metal housing, (b) viewed from outside.*

4. RESULTS AND DISCUSSIONS

The simulations are performed to evaluate the scattering parameters and thermal performance of the proposed 8-way power combiners.



(a)

(b)

(c)

Figure 7. *Simulated scattering parameters of the designed power combiner include (a) return loss, (b) insertion loss, (c) isolation.*

In Fig. 6 (a) – (c), it is observed that the design has less than 1 dB insertion loss, better than 13 dB return loss (better than 1.6:1 VSWR), and over 16.8 dB isolation in the operating band of 12 GHz to 18 GHz.

The combiner has a loss of around 1 dB, corresponding to 20 percent of the total power fed into the structure. This amount of power turns into heat dissipated on the combiner. As shown in Fig. 7, the hottest areas are at the center of the combiner and the temperature decreases at the edge of the structure. However, the heat distribution is quite uniform on the combiner as the difference between the maximum and minimum temperature values on the metal housing is less than 3 degrees Celsius. This proves the design is efficient enough to dissipate a great deal of thermal power.

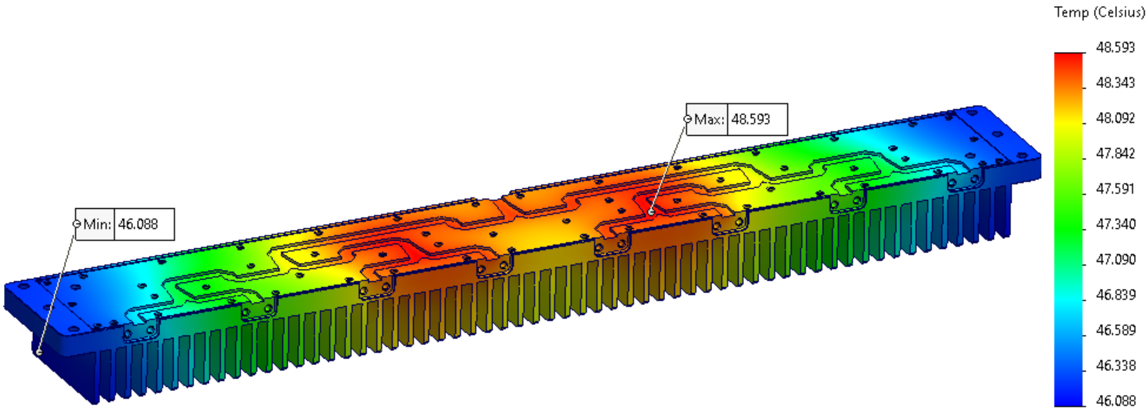


Figure 8. *Temperature distribution over the combiner.*

5. CONCLUSIONS

A proposal for an ultra-wideband multi-section power combiner implemented on suspended substrate stripline technology is presented. As a demonstration of the design method, an 8-way 3-section power combiner was designed, showing input/output VSWR of 1.6:1, isolation of over 16.8 dB, and a low insertion loss of 1 dB. Along with the low loss, the well-designed heat sink allows the structure to combine high power over 100 Watts over broad operating frequencies from 12 GHz to 18 GHz.

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TÓM TẮT

Giải pháp mới cho bộ cộng công suất tám đầu vào sử dụng công nghệ đường truyền dải treo cho các ứng dụng băng Ku

Bài báo này đề xuất giải pháp thiết kế bộ cộng công suất 8 đầu vào mới sử dụng công nghệ đường truyền mạch dải treo cho các ứng dụng băng Ku. Việc thiết kế được bắt đầu bằng việc phân tích mạch nguyên lý tương đương của cấu trúc nhằm tìm ra các giá trị tối ưu cho việc thiết kế vật lý. Nhờ đó, cấu trúc được phối hợp trở kháng tốt ở các đầu vào và đầu ra, đạt được tỷ lệ VSWR tốt hơn 1.6:1 trên toàn dải tần từ 12 GHz đến 18 GHz. Ngoài ra, công nghệ đường truyền mạch dải treo cho phép cấu trúc đạt được tổn hao thấp (dưới 1 dB), trong khi vẫn đảm bảo khả năng cách ly giữa các cổng tốt hơn 16.8 dB. Ngoài ra, ưu điểm của cấu trúc sử dụng đường truyền mạch dải treo là dễ dàng tối ưu hiệu suất của tản nhiệt trên vỏ cơ khí của cấu trúc, khiến bộ cộng có thể đảm bảo nhiệt độ làm việc trong khi vẫn đang hoạt động ở mức công suất cao.

Từ khoá: Bộ cộng công suất; Băng rộng; Đường truyền mạch dải treo.