

Design of a high power combiner in HF band

Trinh Xuan Thang*, Tran Trong Hanh, Nguyen The Duy

Technical Center 80, Department of Electronic Warfare, 15 Hoang Sam, Cau Giay, Ha Noi, Vietnam.

*Corresponding author: vstandup1981@gmail.com

Received 26 Jun. 2024; Revised 16 Aug. 2024; Accepted 21 Aug. 2024; Published 25 Oct. 2024.

DOI: <https://doi.org/10.54939/1859-1043.j.mst.98.2024.32-41>

ABSTRACT

Power combiners are commonly used in power amplifiers to achieve high power, especially in long-range and medium-range wireless communication device transmission systems. This paper proposes designing and implementing a high-power two-way power combiner operating in the HF (High Frequency) band, aiming to achieve an output power of over 1 kW. The power combiner is designed, implemented, and tested in the laboratory with the following achieved parameters: insertion loss between output and input better than 3.4 dB and isolation between inputs better than 26 dB. The experimental results showed that the proposed power combiner had better performance than existing combiners on the market. Mainly, power combining efficiency is over 88%, the standing wave ratio at ports is less than 1.25, and the operating temperature of the power combiner is less than 50 °C, meeting the set requirements.

Keywords: Power combiner; Insertion loss; Isolation.

1. INTRODUCTION

Power combiners are a primary component in power amplifiers and high-power transmitters. The circuit combines power from smaller power amplifier circuits to create a higher output power level. Their function is to ensure the achievement of the required power and minimize insertion loss over the operating frequency range. The power combiner has input ports where lower power amplifiers are connected and an output port that sums power from the amplifiers. The input ports of the combiner have to be isolated, meaning that if one input amplifier does not work correctly, the other inputs are unaffected and continue to operate as usual. In this case, a part of the input power is dissipated within the combiner circuit, and another part goes to the combiner's output port. The Wilkinson power combiner is commonly used [1]. It is a passive device with impedance matching at all ports and isolated input ports. The Wilkinson combiner is often used in narrow frequency bands, but the drawback is that it only operates within a relatively narrow frequency range. When used in the HF band, the Wilkinson combiner size becomes large, and achieving high power is challenging. An extension of the N-way Wilkinson power combiner was introduced in [2] and later called the Gysel power combiner. Several N-way lossless power combiners are presented in [3]. However, these combiners have the drawback of poor input isolation. They are unsuitable for high-power applications, particularly, if one of the input amplifiers fails, affecting the performance of the other amplifiers. In addition to the combiners discussed above, many different power combiners are suitable for specific frequency ranges. Depending on their power-handling capabilities, they can be used for some high-power applications. The development of power combiners and power combining techniques is introduced in [4]. Using transmission lines is another common solution for manufacturing power combiners; this type of power combiner originates from transmission line transformers [5]. The key point in design of an transmission line power combiner is the series or parallel connection of multiple transmission lines to combine voltage or current at the combiner's output port. However, the drawback of this technique is that at low frequencies, the size of a $\frac{1}{4}$ wavelength is considerable. As a result, for applications at low frequencies, ferrite transformers (autotransformers) are used to reduce the number of windings and the size of the combiner without affecting the desired objectives.

While many types of power combiners based on coaxial cables are implemented and put into practical use, there is a significant gap in our understanding of the methods for constructing and aligning the circuits. Based on the basic theory of transmission line transformers and selecting appropriate ferrite cores, the paper [6] has successfully simulated a two-way power combiner with a frequency range of $30 \div 512$ MHz. The simulation results showed that in this frequency range, the return loss of the output port is greater than 25 dB, the insertion loss is less than 0.6 dB. However, that is only the simulation result, in the process of manufacturing a power combiner in practice it is very difficult and requires strict requirements. The performance of transmission line power combiners is critically dependent on the implementation method. Incompatibility and unevenness in coaxial cable segments and component layout of the circuit can lead to a reduction in electrical properties. The development of accurate methods for analyzing and designing these power combiners is therefore of paramount importance, as current methods are limited and scarce.

In this paper, a high-power combiner in the frequency range of 1.5 to 30 MHz to withstand continuously signal power over 1 kW is designed and manufactured. The power combiner consists of a transmission line power combiner with an impedance of 50Ω at the input ports and an impedance of 25Ω at the output port, and a 1:2 transmission line transformer to convert 25Ω impedance to 50Ω . The proposed combiner has low loss, high isolation between the input ports, very low implementing cost; and for high power purposes, it is designed with winding transformers. Section 2 presents the design of the power combiner, section 3 shows the implementation of the two-way power combiner for the HF band, and conclusions are drawn in section 4.

2. DESIGN OF A POWER COMBINER

2.1. Two-way power combiner

The two-way power combiner, a fundamental component in the construction of N-way combiners for the proposed high-power combiners. This power combiner is illustrated in figure 1, comprises four coaxial cable segments with characteristic impedance Z_0 and two high-power isolation loads [8]. The characteristic impedance of the input ports is twice that of the output port. Ferrite cores play a critical role in inducing odd-mode current in the inner coaxial cables and canceling even-mode currents. In transmission mode, the current in the inner conductor and the cable sheath are equal in magnitude and opposite in direction. If the transmission line is impedance-matched, the waves will propagate without reflection, and their magnitude will remain constant along the cable. Under these conditions, the ratio of voltage to current in the cable remains unchanged and equals the characteristic impedance of the transmission line.

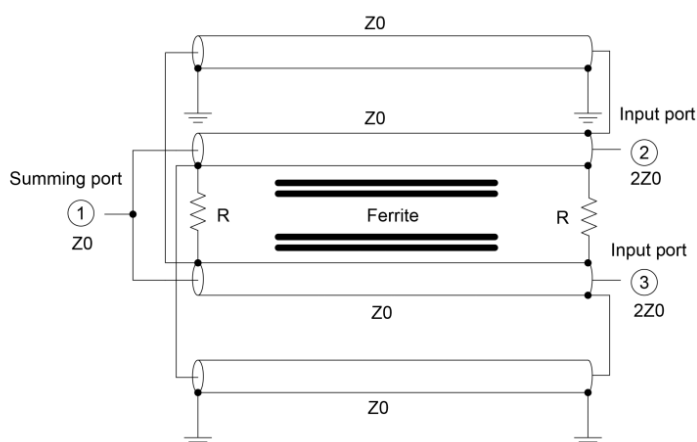


Figure 1. Schematic of the two-way power combiner.

The odd-mode current in the cable is not affected by the ferrite core, as the magnetic flux created by these currents is opposite and cancels each other out in the core. For the power combiner in figure 1 to operate normally, two conditions must simultaneously exist. All currents must be in transmission mode, and all reflections must be eliminated by connecting the cable with the appropriate impedance value. Under these conditions, the currents in each cable will be equal in magnitude and opposite in direction. On the other hand, the voltage at the input and output ports of the cable will be equal in magnitude.

To further understand the power combiner's operation, even-mode and odd-mode analysis can be performed as in [9]. For even-mode analysis, two sources with equal magnitude and phase are connected to the input ports. This is the normal operating mode of the power combiner, as the power combiner is typically used in a transmitter to combine the power of two in-phase power amplifiers. This concept is used to increase output power in most RF semiconductor transmitters. The schematic of the power combiner for even-mode analysis is shown in figure 2.

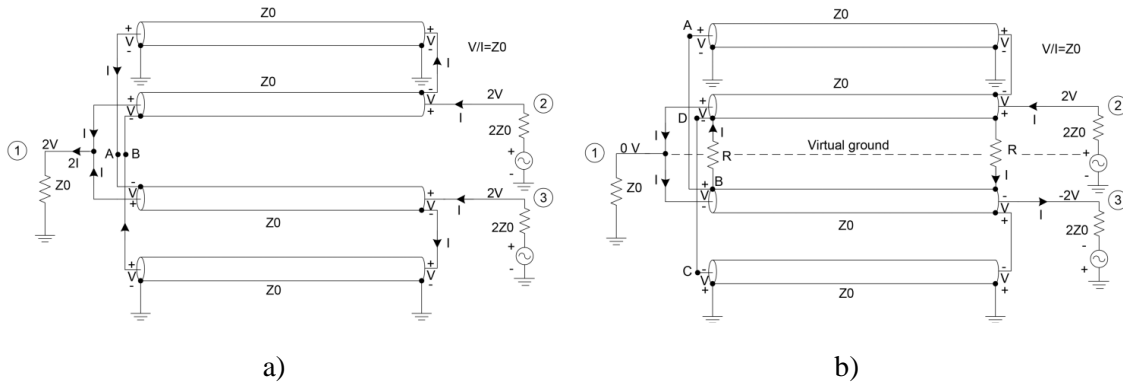


Figure 2. Schematic of the power combiner in: a) Even-mode, b) Odd-mode.

In-phase excitation creates the voltage and current, as shown in figure 2. For regular operation, the ratio of voltage to current in each coaxial cable must equal the cable's characteristic impedance. No current flows in the isolation resistors in even-mode, so these resistors are omitted in even-mode analysis. In the schematic of the power combiner for even-mode analysis, points A and B have the same electric potential. They can be interchanged without affecting the voltage and current in the circuit. If the connections at points A and B are swapped, the schematic of the power combiner can be divided into separate circuits. The impedance at the output port must be doubled to separate the circuit.

The two-port impedance matrix of the combiner, consisting of two series-connected cables with characteristic impedance Z_0 and electrical length θ , is given by:

$$\begin{bmatrix} -j2Z_0 \cot \theta & -j2Z_0 \csc \theta \\ -j2Z_0 \csc \theta & -j2 \cot \theta \end{bmatrix} \quad (1)$$

This two-port impedance matrix is equivalent to the impedance matrix of a cable with a characteristic impedance of $2Z_0$. Returning to the circuit in figure 2a, if the input ports are 50Ω , the coaxial cable must be 25Ω , and the output port impedance must be 25Ω to ensure matching conditions at all ports and low-reflection operation of the coaxial cable. The power flowing at each input port of the combiner is VI , and the power at the output port is $2VI$. Even-mode analysis shows that under in-phase excitation of the power combiner, the resistors do not dissipate power, which is crucial for the efficiency of the combiner and its power handling capability.

The schematic of the power combiner for odd-mode analysis is shown in figure 2b. In this mode, two sources with equal amplitude but 180° phase shift are connected to the input ports of the combiner. Under these conditions, the current in the connection between points A and B will be zero. The current in the connection between points C and D will also be zero. As a result, the circuit can be simplified for further analysis. If the outer terminals at the input and output ports of the circuit in figure 2b are ignored, the remaining two-port network has the following impedance matrix:

$$\begin{bmatrix} -jZ_0 \cot \theta + R / 2 & -j2Z_0 \csc \theta \\ -jZ_0 \csc \theta & -jZ_0 \cot \theta + R / 2 \end{bmatrix} \quad (2)$$

In the two-port network, where port one is grounded, the input impedance at port two is given by:

$$Z_{in} = Z_{22} - \frac{Z_{12}Z_{21}}{Z_{11}} \quad (3)$$

Where Z_{11} , Z_{12} , Z_{21} và Z_{22} are the components of the two-port impedance matrix of the network. The input impedance at port two of the circuit with port one grounded can be calculated using (2) and (3) and is given by:

$$Z_{in} = \frac{(-jZ_0 \cot \theta + R / 2)^2 - (-jZ_0 \csc \theta)^2}{R / 2 - jZ_0 \cot \theta} = \frac{(R^2 / 4) - jRZ_0 \cot \theta + Z_0^2}{R / 2 - jZ_0 \cot \theta} \quad (4)$$

The input impedance Z_{in} will not depend on the cable length if the resistor R equals $2Z_0$. Under this condition, the input impedance becomes $2Z_0$, and the circuit matches the source impedance. Odd-mode analysis shows that the 50 Ω resistor in the circuit ensures matching under odd-mode excitation. If the circuit is matched under both even and odd-mode excitation, it will be matched at all ports under single-source excitation [10]. The resistors in the combiner obtained through even-mode and odd-mode analysis ensure matching at all ports and simultaneously isolate the two input ports. Suppose one of the power amplifiers connected to the combiner is not operating. In that case, the matching at the remaining port will not be affected due to the existing isolation between the input ports. It can be shown that under this condition, half of the power connected to the input port will be transferred to the combining port, and the 50 Ω resistors will dissipate the remaining power. The power dissipated under this condition is equal for the two resistors. In applications with a system impedance of 50 Ω, a 2:1 transmission line impedance transformer can be used to increase the impedance of the combining port.

2.2. Ferrite for high power applications in HF band

The ferrite material used to suppress unwanted common-mode currents in the transmission line is material 61, a nickel-zinc (NiZn) ferrite developed for high-power broadband applications from HF through UHF frequencies. The initial permeability of material 61 is 125. The complex permeability dependent on the frequency of this material is presented in figure 3. A wire wound N turns around a ferrite with complex permeability $\mu' + j\mu''$ results in a complex impedance given in equation 5.

$$Z = \frac{\omega \mu' N^2 A}{l} + \frac{j \omega \mu'' N^2 A}{l} \quad (5)$$

Where, A is the cross-sectional area, and l is the length of the ferrite core. The real part of this complex impedance causes energy loss and heat generation. The factor $\mu' A / l$ is the inductance factor of the core and is equivalent to the inductance of a single-turn coil.

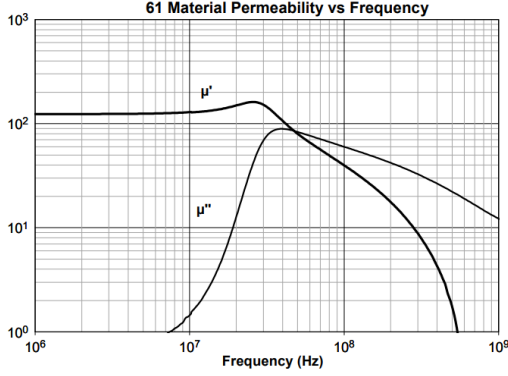


Figure 3. The complex permeability of material 61 [12].

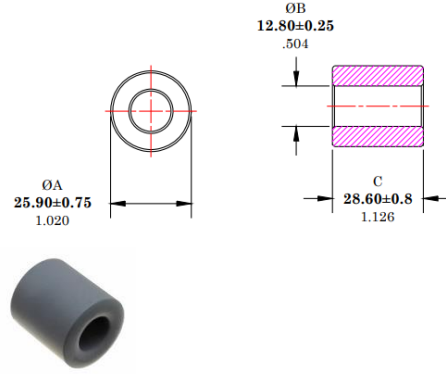


Figure 4. The cylindrical ferrite used in the power combiner.

The series impedance can be transformed into an equivalent parallel reactance through the following relationships.

$$R_p = \frac{\omega \mu'' N^2 A}{l} \left(1 + \left(\frac{\mu'}{\mu''} \right)^2 \right)$$

$$X_p = \frac{\omega \mu' N^2 A}{l} \left(\frac{1 + \left(\frac{\mu'}{\mu''} \right)^2}{\left(\frac{\mu'}{\mu''} \right)^2} \right), \quad (6)$$

Where, R_p and X_p are the equivalent parallel resistance and reactance, respectively.

If there is a voltage V across the ferrite core, the power dissipated on the equivalent parallel resistance is:

$$P_{diss} = \frac{V^2 l}{2 \omega \mu'' N^2 A \left(1 + \left(\frac{\mu'}{\mu''} \right)^2 \right)} \quad (7)$$

Another critical threshold parameter in ferrite is the energy loss density. The energy loss density is the total energy loss in the ferrite due to the equivalent parallel resistance divided by the total volume of the core. The energy loss density of material 61 is 350 mW/cm³, and this value should not be exceeded to ensure regular operation. There is a balance between permeability, core size, and the allowable energy dissipation in ferrite material. Material 61 is recommended for high-power broadband applications in the HF to UHF frequency range for this property.

According to Equation (7), power loss for the equivalent parallel resistance of ferrite depends on the core dimension. Using larger-sized ferrites enhances the energy conversion capability of the ferrite core. The length of the coaxial cable must be long enough to be wound in the core yet shorter than half a wavelength for the highest operating frequency. In high-power combiners above 1 kW, the cable length must be long enough to make a loop in two serially connected ferrite cores. On the other hand, the cable must be shorter than half a wavelength for the maximum operating frequency.

3. IMPLEMENTATION OF TWO-WAY POWER COMBINER IN THE HF BAND

3.1. Two-way power combiner

The schematic of the two-way power combiner is presented in figure 5.

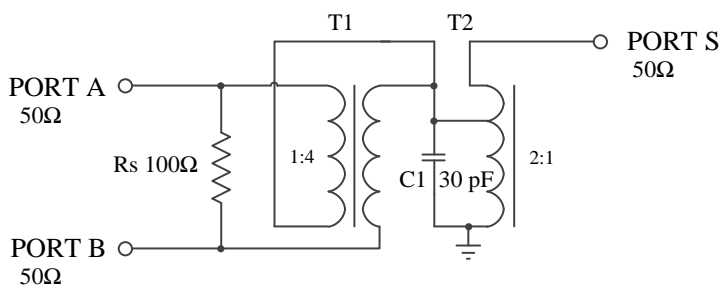


Figure 5. The schematic of the two-way power combiner 1 kW.

Transformers T1 and T2 ensure uniform efficiency of the combiner over the wide frequency range, we used ferrite transformers (Auto-transformers). The selected ferrite has uniform permeability in the range 1.5 to 30 MHz, an operating temperature range of up to 300 °C, and a large size (figure 4). We use the cylindrical ferrite of Fair-Rite [11] with permeability according to the frequency shown in figure 3. Figure 4 shows the cylindrical ferrite used in the power combiner and its permeability according to temperature.

Combiner transformer T1 designed as a ferrite transformer with a ratio of 4:1, using RG141 cable (impedance 50 Ω, voltage 1900 V, operating temperature up to 250 °C), described in figure 6.

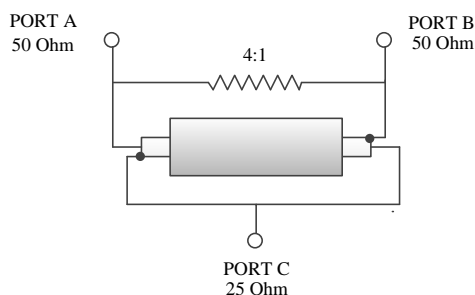


Figure 6. Power combiner transformer T1.

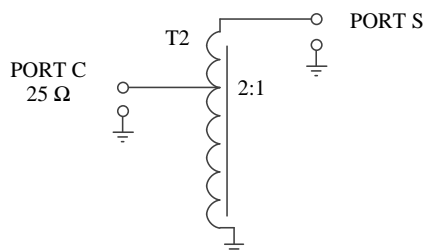


Figure 7. Power matching transformer T2.

Matching transformer T2 converts impedance from 25 Ω to 50 Ω, with an impedance ratio of 2:1, corresponding to a $\sqrt{2}$:1 turns ratio, approximately 1.4 with a turns ratio of 7:5. Transformer T2 has the structure shown in figure 7, using ferrite transformers and RG141 high-frequency cable.

When the signals at input ports A and B have the same amplitude and phase, the combiner circuit is balanced and the current through resistor R_s is 0. When there is an imbalance, the current through R_s is non-zero, or if one input signal port loses power, the power dissipated on R_s is half the input power of the remaining port. If the input power is 500 W, then the power dissipated on R_s is 250 W. Therefore, R_s is selected as a power resistor with a heat sink attached to the heat sink plate, and in this design, we chose a 100 Ω resistor with a 250 W power and an operating temperature of up to 150 °C.

Capacitor C1 used to compensate for the leakage inductance in the winding, with a minimal value from 20 pF to 33 pF and able to withstand high voltages. In this combiner, C1 has a value of 30 pF, a size of 1206, and a voltage of 500 V. For the design of the power combiner PCB in the HF band, we chose an FR4 PCB (used for frequencies below 2 GHz), with a thickness of 1.6 mm

and a copper layer thickness of 2 oz = 0.203 mm. The designed PCB dimensions are 95 mm x 165 mm.

3.2. Implementation and Testing

The fabricated power combiner is illustrated in figure 8 and the testing equipment block diagram is shown in figure 9. The 25 Ω coaxial cable is wound around two adjacent ferrite toroids, with a cable length of 13 cm.



Figure 8. Fabricated power combiner.

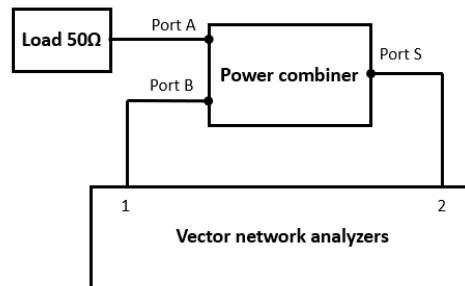


Figure 9. Block diagram of the experimental test of the fabricated combiner.

The power combiner parameters measured include insertion loss; isolation between the two input ports; efficiency of the combiner when combining two signals in the range in the working frequency range 1.5 ÷ 30 MHz with power from 400 W to 600 W, with in-phase signals; and operating temperature of transformers T1 and T2 when the combiner's output power is 1 kW.

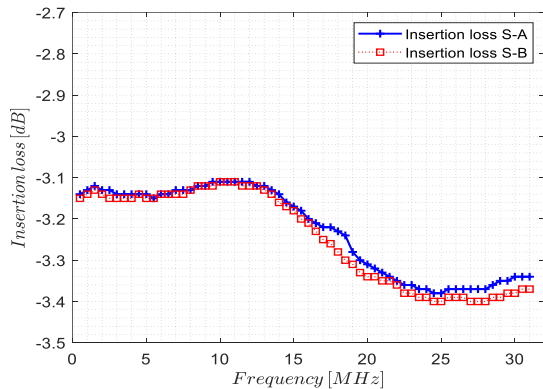


Figure 10. Insertion loss S-A and S-B of the fabricated power combiner.

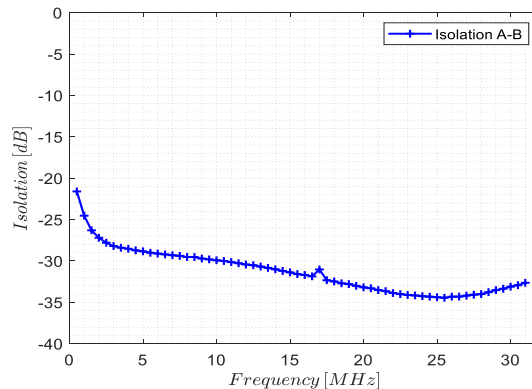


Figure 11. Isolation between ports A and B.

Figure 10 shows that the insertion loss comparison between the two ports is relatively balanced, which is an important factor in evaluating the quality of a two-way combiner. The maximum insertion loss difference between the two ports is 0.06 dB, so it can be concluded that the two input ports of the combiner are highly symmetrical.

The measurements reveal that the combiner operates with a low power loss. Compared to the ideal loss of -3 dB, the insertion loss is at most 0.37 dB for port A and 0.39 dB for port B. This efficiency is further demonstrated by the insertion loss uniformity parameter, which is 0.26 dB for port A and 0.29 dB for port B across the entire working frequency range of 1.5 ÷ 30 MHz.

Isolation between the two ports is an essential parameter of the power combiner. It is necessary to ensure high isolation between the two signal sources without significantly leaking from one port

to another, thereby changing the signal source. The measured isolation values across the entire frequency range have a maximum value of -26.3 dB at 1.5 MHz and a minimum value of -34.45 dB at 25.5 MHz, which is considered good (compared to the usual requirement of less than -20 dB). With an isolation of -26.3 dB, it means that if a 1.5 MHz signal with 500 W power is at port A, the power leakage to port B is 1.17 W, which is a small power level that does not significantly affect the signal source (or power amplifier) at port A.

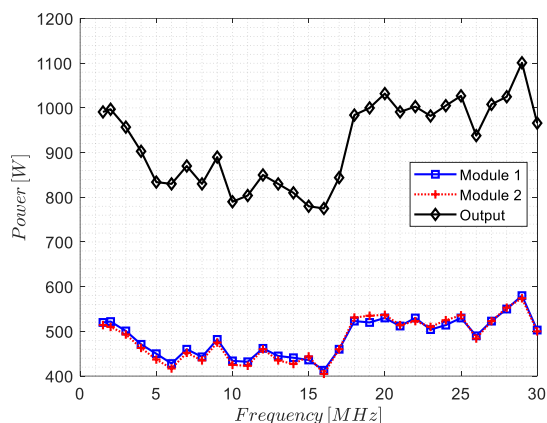


Figure 12. Output of the power combiner 1 kW.

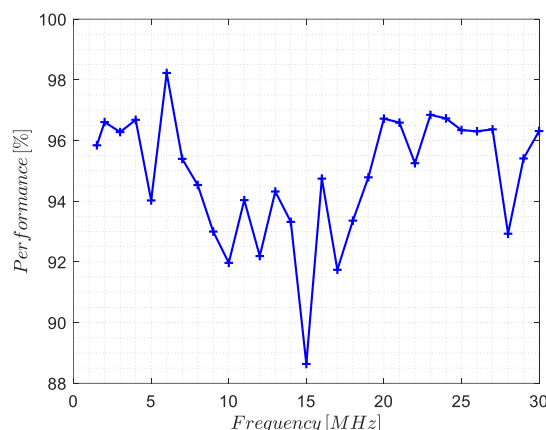


Figure 13. The performance of the power combiner 1 kW.

This measurement's two power amplifier modules have similar output signal phases, with negligible phase deviation, and power from 400 to 600 W in the range 1.5 ÷ 30 MHz. The power of the modules is measured sequentially at frequency points, then the output power of the two modules is combined. The output power of the combiner is shown in figure 12.

Figure 13 shows the power combiner's performance in the range 1.5 ÷ 30 MHz compared to the ideal value (no loss). In order to compute the performance of the power combiner, a calculation of from the following formula was used:

$$H = \frac{P_{S_m}}{P_A + P_B} \cdot 100\% \quad (8)$$

Where, P_{S_m} is measured output power, P_A and P_B are the input power at ports A and B, respectively. With the surveyed points, the power combiner's efficiency ranges from 88.6% to 96.7%, indicating that the combiner has good efficiency. This contributes to the overall efficiency of the implemented 1 kW power amplifier unit, which ranges from 40-50%.

Figure 14 presents the experimental results of the VSWR (Voltage Standing Wave Ratio) at the combiner's ports. The highest VSWR value at the combiner's output port is 1.25, and all values are less than 1.5, meeting the requirements. In high-power combiners, there is a loss of ferrite core, causing heat generation. When the operating temperature of the ferrite is outside the working range, the ferrite parameters will change, leading to changes in the combiner parameters. Therefore, the operating temperature of the combiner during operation is an important parameter. In this test, the actual temperature of the ferrite when the combiner's output is 1020 W at a frequency of 15 MHz, with a 5-minute transmission time, is measured. The result shows that the temperature of the sensor attached to the ferrite core increased from 28 °C to 36.3 °C, with the temperature change of the ferrite remaining within the allowable working range of the ferrite material without affecting its parameters.

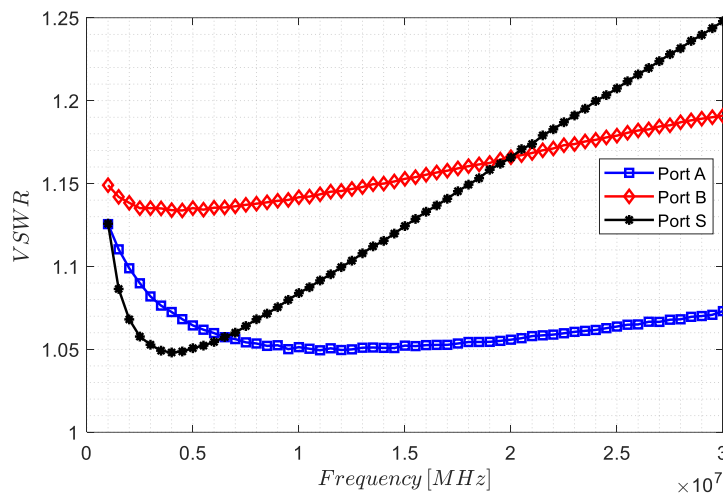


Figure 14. VSWR at the ports of the power combiner.

4. CONCLUSIONS

The article presented the results of designing a power combiner operating in the HF band (1.5 ÷ 30 MHz) with an output power of 1 kW in the transmitter system for long-range and medium-range radio communication devices. We used an experimental research method based on the theory of power combining circuits to design the power combiner. The measurements of critical parameters in the power combiner show that the circuit has an adequate insertion loss of less than -3.39 dB across the operating band, an isolation loss between ports of better than -26.3 dB, and the standing wave ratio on all ports is under 1.5. Compared to some imported two-way power combining circuits used in other communication devices, the designed circuit has advantages such as lower insertion loss, uniform parameters, and comparable efficiency and operating temperature.

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TÓM TẮT

Nghiên cứu thiết kế, chế tạo bộ cộng công suất cao ở dải sóng ngắn

Trong các bộ khuếch đại công suất nhằm đạt được công suất cao thì bộ cộng công suất được sử dụng rất phổ biến, tiêu biểu như trong các hệ thống phát của các thiết bị thông tin liên vô tuyến lạc tầm xa và tầm trung. Thông qua nghiên cứu phân tích bộ cộng công suất 2 cổng, bài báo đề xuất thiết kế chế tạo bộ cộng công suất cao 2 cổng làm việc ở dải tần từ 1.5 ÷ 30 MHz, nhằm đạt được công suất đầu ra trên 1 kW. Bộ cộng công suất được thiết kế, chế tạo và được đo kiểm tra trong phòng thí nghiệm với các tham số đạt được như sau: Suy hao chèn giữa đầu ra và đầu vào tốt hơn 3.4 dB, độ cách ly giữa các cổng đầu vào tốt hơn 26 dB. Kết quả ứng dụng bộ cộng công suất được đề xuất đạt được các tham số tốt hơn các bộ cộng hiện có trên thị trường như: hiệu suất cộng công suất trên 88%, hệ số sóng đứng tại các cổng nhỏ hơn 1.25, nhiệt độ làm việc của bộ cộng công suất nhỏ hơn 50 °C đáp ứng được với yêu cầu đề ra.

Từ khóa: Bộ cộng công suất; Suy hao chèn; Hệ số cách ly.