A method for designing a variable-channel high-power cavity combiner *

Yong-Tao Liu(刘勇涛)[1)] Gui-Rong Huang(黄贵荣)[2)] Lei Shang(尚雷)
Hong-Xiang Lin(林宏翔) Bai-Ting Du(杜百廷)

National Synchrotron Radiation Laboratory, University of Science and Technology of China, Hefei 230029, China

Abstract: Cavity combiners have been put forward for high power combining due to their advantages of larger combining ability, variable input channels and less power loss. For a high power cavity combiner, it is better to keep the power loss ratio in a reasonable range, because large power loss would lead to strict requirements on the cooling system. A combiner with variable input channels is convenient for outputting different power levels according to practical demands. In this paper, a method for designing a variable-channel high-power cavity combiner is proposed, based on the relation between input and output coupling coefficients obtained by analyzing the equivalent circuit of the cavity combiner. This method can put the designed cavity combiner in a matching state and keep its power loss rate in a reasonable range as the number of input channels changes. As an example, a cavity combiner with 500 MHz and variable input channels from 16 to 64 is designed, and the simulation results show that our proposed method is feasible.

Keywords: cavity combiner, variable channels, equivalent circuit, coupling coefficient

PACS: 29.20.-c, 07.57.-c **DOI:** 10.1088/1674-1137/40/8/087002

1 Introduction

The high power Radio Frequency (RF) Solid State Amplifier (SSA) has been widely employed as the power supply in accelerators in the past ten years and more [1, 2]. At present the SSA commonly adopts a multi-stage coaxial or waveguide combining structure, whose capability in accommodating input ports per stage is poor. The number of inputs is not normally more than 12 in the coaxial or 4 in the waveguide structure. In the case with high output power of 100 kW or even more, the SSA's combining tree will be very complicated, and therefore it is inefficient and expensive.

To resolve this problem, a cavity combining technique that can accommodate dozens or even hundreds of input ports was proposed by the ESRF, and has been developed in recent years [3–5]. The condition of an ideal lossless combiner $N_{\text{loop}} * \beta_{\text{loop}} = \beta_{\text{output}}$ is obtained in the design and calculation of the cavity combiner [6]. But in our opinion this approximation ignoring the cavity dissipation is, in fact, probably unsuitable. The cavity loss should be considered at first when designing a cavity combiner, since it determines the combining efficiency and the necessity to use the cooling system for outputting high power. In the paper we will analyze the characteristics of a cavity combiner with power loss, derive the relationship between the input and output coupling coefficients and then propose a method for designing a cavity combiner to achieve proper combining efficiency and coupling coefficient range. In order to demonstrate the method, a numerical study of a cavity combiner as an example of the application of the proposed method is done using the Computer Simulation Technology Microwave Studio (CST MWS) [7].

2 Equivalent circuit of a cavity combiner

The cavity combiner can be considered as a cavity, coupled with n identical input ports and one output port [8, 9]. The simple way to analyze such a RF network is to take the output port as the source end, and the equivalent circuit in this case is shown in Fig. 1, where I is the driving current, R_0 is the impedance of output port, R_S is the cavity shunt impedance, R_i is the impedance of input port, and n_1, n_2 are the transformer ratios of the cavity to input, output coupler, respectively. The coupling coefficients of input and output couplers are defined as

Received 23 January 2016, Revised 1 March 2016

∗ Supported by National Natural Science Foundation of China (11079034)

1) E-mail: lytao09@mail.ustc.edu.cn

2) E-mail: grhuang@ustc.edu.cn

$$\beta_i=\frac{R_{\rm S}}{n_2^2R_i},\beta_0=\frac{R_{\rm S}}{n_1^2R_0}. \tag{1}$$

We can simplify the equivalent circuit by normalizing R_i, and the normalized equivalent circuit is shown in Fig. 2, where the input, output impedances and the shunt impedance of the cavity are represented by 1, β_i/β_0 and β_i, respectively. Referring to the normalized circuit in Fig. 2, the impedance of the load end is

$$Z_{\rm L0}=\frac{\frac{1}{n}\beta_i}{\frac{1}{n}+\beta_i}=\frac{\beta_i}{n\beta_i+1}, \tag{2}$$

and the reflection coefficient of the output port is

$$\Gamma_0=\frac{Z_{\rm L0}-\frac{\beta_i}{\beta_0}}{Z_{\rm L0}+\frac{\beta_i}{\beta_0}}=\frac{\beta_0-n\beta_i-1}{\beta_0+n\beta_i+1}. \tag{3}$$

Similarly, specifying an arbitrary input port i as the source end, the load impedance is

$$Z_{{\rm L}i}=\frac{1}{n-1+\frac{1}{\beta_i}+\frac{\beta_0}{\beta_i}}=\frac{\beta_i}{\beta_0+(n-1)\beta_i+1}, \tag{4}$$

and the reflection coefficient of the input port is

$$\Gamma_i=\frac{Z_{{\rm L}i}-1}{Z_{{\rm L}i}+1}=-\frac{\beta_0+(n-2)\beta_i+1}{\beta_0+n\beta_i+1}. \tag{5}$$

In general, the output port of the combiner must be matched to the transmission line, which means

$$\Gamma_0=0. \tag{6}$$

This is the fundamental characteristic of the perfect multi-channel combiner or splitter.

The following derivations are based on the precondition of matching. Therefore, we have

$$\beta_0=n\beta_i+1, \tag{7}$$

$$\Gamma_i=-\frac{(n-1)\beta_i+1}{n\beta_i+1}. \tag{8}$$

According to the equivalent network theory, the transmission coefficients are derived as

$$S_{i0}=\sqrt{\frac{\beta_i}{n\beta_i+1}}, \tag{9}$$

$$S_{ij}=\frac{\beta_i}{n\beta_i+1}(i\neq j), \tag{10}$$

where i and j ports are different input ports. It can be proved that the relation between the output power P_0 and the power dissipated in the cavity $P_{\rm c}$ is

$$\beta_0=\frac{P_0}{P_{\rm c}}. \tag{11}$$

Then we can define the power loss ratio η_l and combining efficiency $\eta_{\rm c}$ of the combiner as

$$\eta_l=\frac{P_{\rm c}}{P_0}=\frac{1}{\beta_0}, \tag{12}$$

$$\eta_{\rm c}=1-\frac{1}{\beta_0}. \tag{13}$$

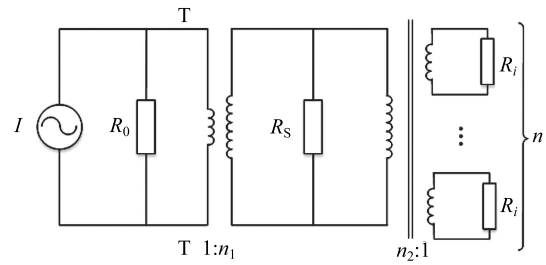

Fig. 1. Equivalent circuit of the n-channel cavity combiner.

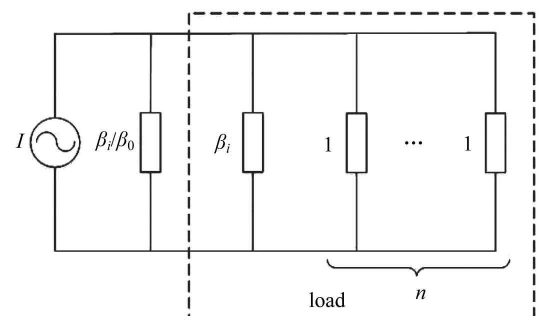

Fig. 2. Normalized circuit of the n-channel cavity combiner.

3 Design method

A significant advantage of the cavity combiner is that the input couplers can be designed and manufactured in a removable way. So according to the actual output power requirement, we can adjust the number of input channels, and meanwhile maintain the RF amplifier modules that are connected to the input channels operating in an efficient state. Even in the case that the SSA's output power and the number of the input channels of the cavity combiner are determined, the removable input coupler is still suggested. The reason is that in the design and test stages of the combiner, a prototype usually needs to be manufactured. It will be convenient for carrying out the RF measurement and the power testing of the prototype, which is coupled by partial input couplers.

We redefine the input and output coupling coefficients as $\beta_i(n)$ and $\beta_0(n)$, respectively. Their relation is

$$\beta_0(n)=n\beta_i(n)+1, \tag{14}$$

where n is the number of inputs. If the maximum number of input channels is set to N, we have

$$\beta_0(N)=n\beta_i(N)+1. \tag{15}$$

When outputting high power, the combining efficiency is important for the cavity combiner. For example, in the case of 100 kW output, it is better to set the loss rate η_l to be less than 1%, because in this case the air conditioning can meet the cavity cooling requirements. Otherwise, a water-cooling system probably has to be used.

According to Eq. (12), η_l is inversely proportion to β_0. The larger β_0 is, the higher the combining efficiency η_c becomes. But if the β_0 is larger than 200, it is difficult to achieve due to a strong perturbation of the electromagnetic field caused by the output coupler. Therefore, $\beta_0(N)$ is suggested to be in the range of 100 to 200, which corresponds to η_l in the range of 0.5%–1% for a cavity combiner with 100 kW or more output power. In addition, $\beta_i(N)<1$ (under-coupling state) is also unsuitable. In this case the geometrical dimensions of the input coupler are small, so it is hard to keep the coupling coefficient stable, due to the coupling coefficient being easily changed by even a small mechanical deviation or deformation in the coupler. Therefore, when designing an N-channel cavity combiner with maximum output power of 100 kW or more, the range of the parameters are suggested as

$$\begin{cases} 100\leqslant\beta_0(N)\leqslant 200 \\ \beta_i(N)\geqslant 1 \end{cases}. \tag{16}$$

The upper limit of N is

$$N=\frac{\beta_0(N)-1}{\beta_i(N)}\leqslant\frac{200-1}{1}=199. \tag{17}$$

If the number of input channels decreases from N to n, there are two methods to maintain the cavity combiner under the matching condition.

The first method is to keep $\beta_0(n)=\beta_0(N)$. This method has the advantage of maintaining a stable combining efficiency of the cavity combiner. But the input coupling coefficient will increase as the number of inputs n decreases,

$$\beta_i(n)=\frac{N}{n}\beta_i(N). \tag{18}$$

Due to a large number of inputs being mounted on the cavity, it will take a lot of work to tune the input couplers when the input number decreases. Besides, it will increase the electromagnetic field perturbation, because the geometrical dimensions of loops are very large if n is small.

The second method is to keep $\beta_i(n)=\beta_i(N)$, and the output coefficient is changed as

$$\beta_0(n)=n\beta_i(N)+1. \tag{19}$$

The advantage of this method is that we can only tune the output coupler to maintain the cavity combiner matching. With this approach, it will change the combining efficiency of the cavity combiner since it is determined by $\beta_0(n)$. The loss power can be maintained in the acceptable range, however, by choosing a proper input coupling coefficient. The number of inputs n may vary from one to dozens, and thus the output coupler must be tunable in a large range. So the waveguide coupler should be taken into consideration [10, 11].

On the basis of the above analysis, compared with the first method, the second method is more convenient when the number of input couplers changes. Therefore, the second method is adopted for designing the high power cavity combiner.

The relation between the input and output coupler coupling coefficients that are calculated with different values of power loss ratio η_l varying from 1%–5% is presented in Fig. 3. From this figure, it can be clearly seen that for a given constant β_i, we can obtain the ranges of combining number and power loss ratio, which are convenient for designing the cavity combiner.

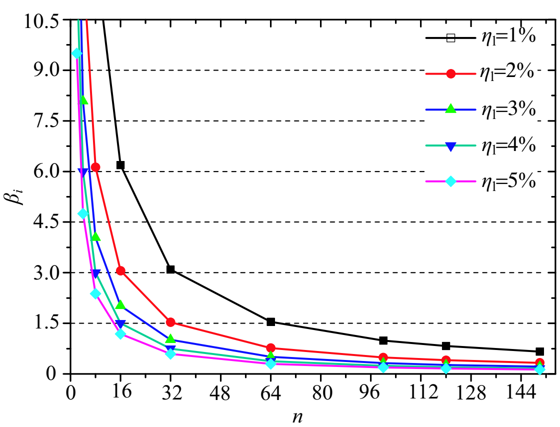

Fig. 3. (color online) The change of β_i with input channels n at different power loss ratios η_l.

4 Application

To demonstrate the method, we carried out a numerical study on a 500 MHz cavity combiner prototype design using CST MWS. The coefficient β_i was set to 1.5, referring to Fig. 3, which corresponds to the ranges of n and β_0 being 16-64 and 20-100, respectively. The specific parameters of the cavity combiner prototype are listed in Table 1.

Table 1. The parameters of the cavity combiner prototype.

frequency/MHz	500
max. output power/kW	80
input power per channel/kW	1.5
range of the input channels n	16, 32, 48, 64
input coupling coefficient β_i	1.5
output coupling coefficient β_0	20–100

4.1 Resonant cavity and couplers design

The layout of our designed cavity combiner operating at 500 MHz is shown in Fig. 4. The cavity is made of aluminium and the cross-section of the cavity is a regular hexadecagon. The sixteen side walls of the cavity are assembled and disassembled, eight of which will totally employ 64 input couplers. The TE_{010} mode is chosen as the operating mode and the radius of the hexadecagon incircle is $R_0=2.405*\lambda_0/(2*\pi)$ [12]. To make sure that there is enough bandwidth between TE_{010} and other modes, the height of the cavity must be set to a proper value.

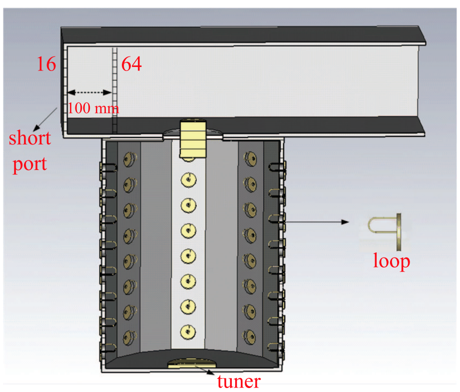

Fig. 4. The layout of the cavity combiner.

Magnetic-coupling loops mounted on the cavity, also shown in Fig. 4, are used to feed energy into the cavity. The coupling coefficient can be adjusted by attaching a rotatable flange on the coupler. The dimensions of the loop can be estimated by the analytical equation in reference [13] and then the coupling coefficient of the input couplers is optimized to 1.5.

A WR 1800 waveguide transition to 6 1/8 inch coaxial used as the output coupler is shown in Fig. 4. The short port of the waveguide is shiftable, which has a large effect on tuning the coupling coefficient β_0. To guarantee that the coupling coefficient can be varied between 15 and 110, which needs some allowance, the length of probe and the shiftable short port of the waveguide are calculated and chosen by CST MWS.

4.2 Simulation results

The numerical study on the cavity combiner was carried out from 16 to 64 input channels, increasing in step of 16.

There are 16 identical input couplers and an output coupler optimized as above that are symmetrically mounted on the cavity by columns, each side wall with 8 couplers. Before simulation, we define the output waveguide as port 1, and the input couplers as ports 2–17 by columns. Due to the perturbation caused by the couplers, the resonant frequency of the cavity may deviate from the design value, so a tuner is needed, which is inserted into the bottom of the cavity as shown in Fig. 4. The calculated results of the S parameter of the 16-channel cavity combiner are given in Fig. 5. We can see that the scattering coefficient S_{11} is better than −30 dB at 500 MHz, which indicates the combiner is matched by tuning the short port of the waveguide and the tuner.

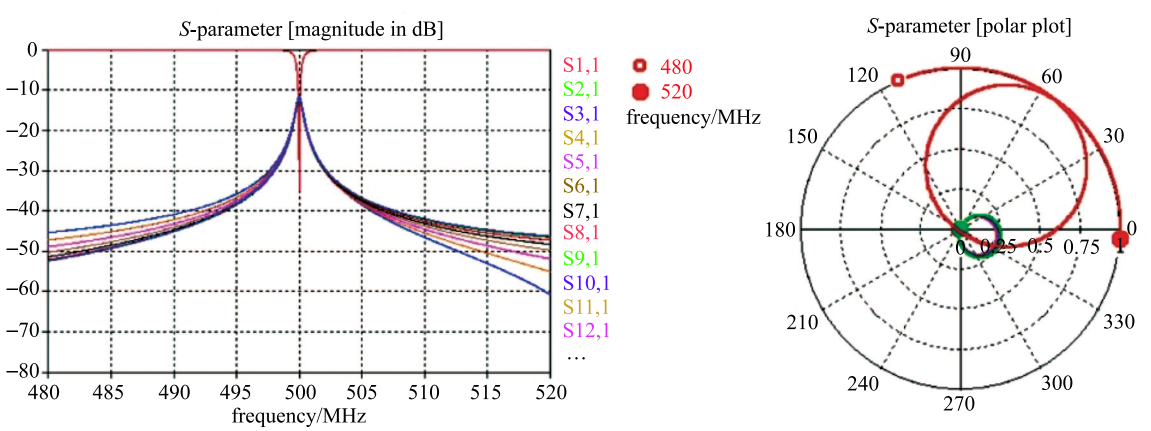

Fig. 5. (color online) The S parameters of 16-channel matching cavity combiner.

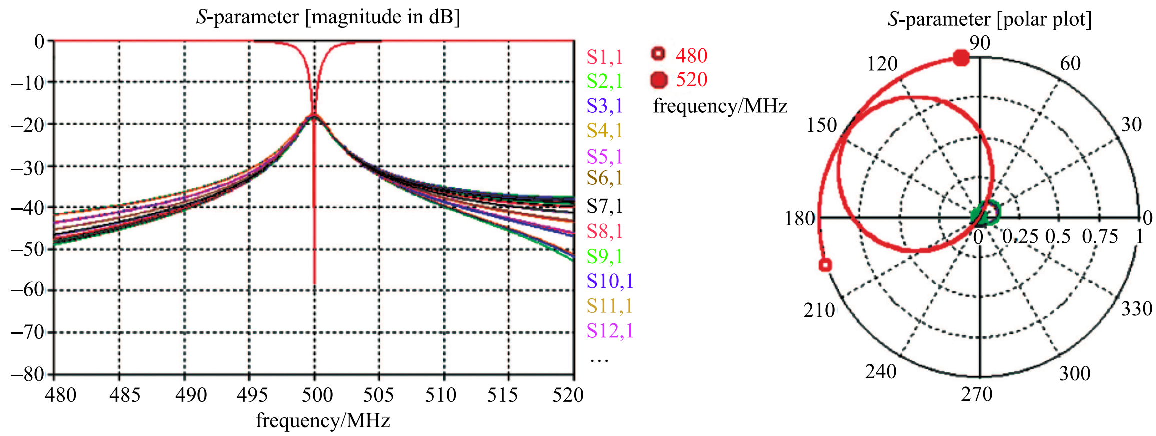

Fig. 6. (color online) The S parameters of 64-channel matching cavity combiner.

The cases of 32, 48 and 64 input couplers symmetrically mounted on the cavity are studied in the same way as in the case of 16 input couplers above. By adjusting the short port of the waveguide and the tuner, the S_{11} of the 32, 48 and 64 channel cavity combiners are tuned to less than −30 dB at resonant frequency 500 MHz, which means that the combiner achieves the matching condition. Compared with 16 channels, in the case of 64 channels the short port of the waveguide is shifted 100 mm along the waveguide transmission direction under the matching condition. The matching scattering coefficients of the 64 channels cavity combiner are given in Fig. 6. Figure 7 shows the change of the maximum and minimum input reflectance coefficients in the simulation and the theoretical reflectance coefficients, which are calculated by Eq. (8), with the number of input channels. The variation of transmission coefficient S_{15} and its theoretical values calculated by Eq. (9) in the simulation with the number of input channels is shown in Fig. 8.

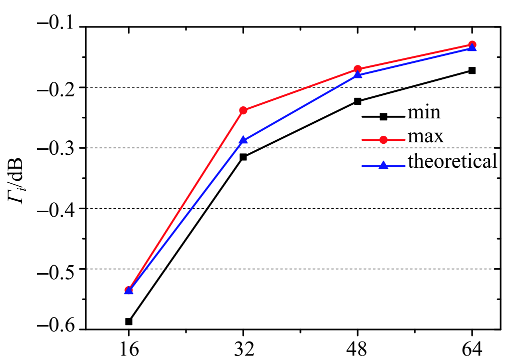

Fig. 7. (color online) The change of Γ_i with number of input channels.

It can be seen from Fig. 7 that the difference between the simulated maximum and minimum Γ_i is less than 0.1 dB. This is because the TE_{010} field strengths at different coupling loops are slightly different. We can also see that the theoretical Γ_i always stays in the range between the simulated maximum and minimum Γ_i, which illustrates that all the input channels have good RF coherence and the simulation results are consistent with the theoretical results. We can see from Fig. 8 that the simulated transmission coefficient S_{15} is also consistent with the theoretical values.

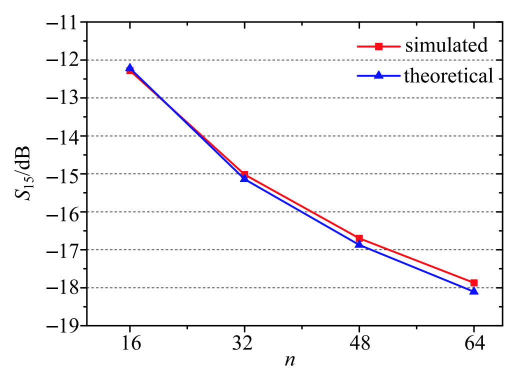

Fig. 8. (color online) The change of S_{15} with number of input channels.

All the simulation results above demonstrate that the cavity designed using the proposed method is capable of combining 16-64 identical input channels, just needing to tune the short port of the waveguide and tuner when the number of input channels changes. The results are in good agreement with the proposed method, which means that this method of cavity combining is feasible.

5 Conclusion

In this paper, we first analyzed the equivalent circuit of the cavity combiner, and derived the relation between the input and output coupling coefficients, as well as the scattering parameters under the matching condition. Based on the obtained relation and practical application, it is suggested that the range of power loss rate for the maximum output power is 0.5%–1% and the number of input channels of the high power cavity combiner is less than 200. Then we proposed a method for designing the variable-channel high-power cavity combiner, in which the input coupling coefficient is constant and the output coupling coefficient is tunable. The method was applied to the design of a cavity combiner with 500 MHz and variable input channels from 16 to 64, and the simulation results agree well with the theoretical RF parameters, thus demonstrating the reliability of the proposed method. In addition, to experimentally test and verify the simulation results, a prototype is being designed and will be manufactured.

References

1 P. Marchand, T. Ruan, F. Ribeiro et al, Phys. Rev. ST Accel. Beams, **10**: 112001 (2007)

2 P. Marchand, M. Louvet, K. Tavakoli et al, Successful RF and Cryogenic Tests of the SOLEIL Cryomodule, in *Proceedings of the 21st Particle Accelerator Conference* (Tennessee: PAC'05 ORNL/SNS, 2010), p. 3438

3 J. Jacob, J.-M. Mercier, M. Langlois et al, 352.2 MHz-150 KW Solid State Amplifiers at The ESRF, in *Proceedings of the 2nd International Particle Accelerator Conference* (San Sebastian: IPAC'11 EPS-AG, 2011), p. 71

4 Bravo, B, Mares, F and Perez et al, CACO: A CAVITY COMBINER FOR IOT AMPLIFIERS, in *Proceedings of the 2nd International Particle Accelerator Conference* (San Sebastian: IPAC'11 EPS-AG, 2011), p. 181

5 J. Jacob, L. Farvacque, G. Gautier et al, Commissioning of First 352.2 MHz-150 kW Solid State Amplifiers at the ESRF and Status of R&D, in *Proceedings of the 4th International Particle Accelerator Conference* (Shanghai: IPAC'13 OC/SPC, 2013), p. 2708

6 CST Microwave Studio manual, 2011, http://www.cst.com

7 Status of RF Solid State Amplifier Project, http://www.crisp-fp7.eu/fileadmin/_migrated/content_uploads/CRISP_AM_2012_WP7_Jacob.pdf, (2012) 1-13

8 Thomas P. Wangler, *RF linear accelerators* (2nd edition, John Wiley & Sons, Inc., 2008), p. 145

9 David M. Pozar, *Microwave engineering* (Fourth edition, John Wiley & Sons, Inc., 2009)

10 Rajesh Kumar, P. Singh, Divya Unnikrishnan et al, Nucl. Instrum. Methods A, **481**: 203-213 (2012)

11 J. Gao, Nucl. Instrum. Methods A, **664**: 36-42 (2002)

12 V. Khoruzhiy, arXiv:1305.3770, (2013)

13 J. Corlett, Derun Li, and A. Mitra, A 35 MHz re-buncher RF cavity for ISAC at Triumf, in *Proceedings of the 6th European Particle Accelerator Conference* (Stockholm: EPAC'98 IOP/Ltd, 1998), p. 1790