

Radio-frequency design of a new C-band variable power splitter

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Abstract A novel variable C-band radio-frequency (RF) power splitter was designed at Shanghai Institute of Applied Physics, Chinese Academy of Sciences. Using three RF impedance combiners, an H-bend, and an RF polarizer, this new power splitter is much more compact than a traditionally designed splitter, which comprises three 3-dB hybrids. The parameters were optimized to achieve good matching and minimize reflection. Here, the RF design of the new C-band variable power splitter is presented.

Keywords Power splitter · Variable · Polarizer · Compact

1 Introduction

A radio-frequency (RF) power splitter is a common and useful multiport passive structure in RF technology. It can divide input power into several parts with various outputs or combine several input powers into one for different uses.

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For example, for a simple T-type three-port power splitter, the input power comes from one port and is divided into two parts equally. Finally, the power goes out from two output ports with the same amplitudes and phases. Ideally, there is no power reflected to the input port.

A variable RF power splitter that can provide an alterable and variable output power on its output port(s) is necessary in some cases [1–5]. A typical traditional variable power splitter comprises three 3-dB hybrids, which work as a power divider, a phase shifter, and a power combiner. Moving the position of the short-circuited plane of the phase shifter enables the output power to be arbitrary.

The principle of a 3-dB hybrid-based power splitter is concise. Because the device is cascaded by three 3-dB hybrids, the power-splitting performance is mainly determined by the 3-dB hybrid, which simplifies the design. However, three hybrids also make this splitter relatively large in size. Considering the volume of this splitter, a novel scheme was proposed at the European Organization for Nuclear Research (CERN) [6]. This X-band variable power splitter contains three RF impedance combiners, one H-bend, and an RF polarizer. The RF polarizer combines the two traditional short-circuited ports into one, which makes the system more compact in size and more precise when tuning.

A similar design of a C-band variable power splitter was advanced at the Shanghai Institute of Applied Physics, Chinese Academy of Sciences (SINAP, CAS), for the Shanghai Soft X-ray FEL (SXFEL). With geometric parameters properly chosen, this power splitter can output a variable power ratio from two ports by mechanically moving the position of the short-circuited piston with minimized power reflected to the input port. The

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fundamental concept and theory were described in detail previously [6]. Therefore, only the RF design and some machining considerations of the C-band one are presented here, in Sect. 2. Conclusions are given in Sect. 3.

2 RF design of the new C-band variable RF power splitter

The four kinds of component—H-bend, RF impedance combiner, RF polarizer, and reflector—were designed separately using ANSYS HFSS and then combined.

2.1 H-bend

The H-bend in Fig. 1a changes the direction of the connection between two rectangular waveguide ports. The simulation results are shown in Fig. 1b. The reflection is less than -60 dB, which means the structure is well matched.

2.2 Impedance combiner

The impedance combiner is utilized to reassign the impedances. It is a three-port RF structure. The three ports are identical. Each port sees the combined RF impedance of the other two. Figure 2a, b shows the design and its S-parameters. S_{11} is approximately 0.33 while both S_{21} and S_{31} are 0.67, which agrees with the goals well. It is a broadbandwidth structure.

The width and height of the protuberance mainly determine the performance of this impedance combiner. For the width, the machining error must be controlled within \pm 70 µm and the height within \pm 10 µm according to the simulation results in Fig. 2c, d.

2.3 Polarizer

A five-port RF structure was created by cascading three impedance combiners, as shown in Fig. 3a, b. In this structure, if Port 4 and Port 5 are short-circuited, as illustrated in Fig. 3a, the output power on Port 2 and Port 3 would be changed by moving the position of the shortcircuited plane.

To simplify the system in Fig. 3, an RF polarizer [7-11]was introduced, as shown in Fig. 4a, b. The polarizer combines the two rectangular waveguide ports into one, converting the rectangular waveguide TE mode, TE_{10}^{\sqcup} , into the circular waveguide mode TE_{11}^{\bigcirc} to the circular waveguide with no power leaking to the other rectangular waveguide port, as shown in Fig. 4b. The polarizer is a perfect symmetrical structure, which means that, for the power that comes from the other rectangular waveguide port, Port 2, all the converted power is transmitted to the circular waveguide port. The two rectangular waveguide ports are isolated; therefore, if power comes from its two rectangular waveguide ports, the converted power becomes two degenerated TE_{11}^{\bigcirc} modes in the circular waveguide with orthogonal polarization. Compared with the CERN X-band polarizer, this design removes the cylinder on the opposite side of the piston to simplify the machining. Consequently, there must be some disturbance to reduce the reflection, such as some protuberances. Simulation results of the polarizer are shown in Fig. 4c. Both the reflection S_{11} and transmission to the other rectangular waveguide port S_{21} are less than -40 dB. The transmission of one TE₁₁ mode on the circular waveguide, $S_{3(2)1(1)}$, is less than -50 dB, whereas for the other TE₁₁ mode, the transmission $S_{3(1)1(1)}$ is -0.04 dB.

The size and position of the protuberances affect the performance of this polarizer. Figure 5 shows these influences. According to the simulation results, the machining error of the protuberances' size should be controlled



Fig. 1 a H-bend and b simulation results: transmission is -0.01 dB and reflection is -64.47 dB



Fig. 2 a Impedance combiner; b simulation results and machining-error analysis—c for width and d for height of protuberance: through (c) and (d), the machining error should be controlled within $\pm 10 \ \mu m$



Fig. 3 Illustration of the five-port structure (a), and its RF design (b)

within \pm 20 µm, and the position error should be no more than \pm 10 µm, which are not so strict for our machine.

2.4 RF contact-free movable reflector

The polarizer combines two rectangular short-circuited ports into a circular one, which is connected to a movable piston. The piston is expected to reflect all the input power. However, a coaxial waveguide formed by the piston and the circular waveguide results in considerable power leaking, even though the distance between the piston and circular waveguide is minimized to the limitation of machining and assembling (approximately 0.1 mm). To reflect the two TE₁₁ modes equally and efficiently, a new RF contact-free reflector was designed, as shown in Fig. 6a [12]. Instead of a regular flat short-circuit plane, a choke is introduced on the reflector, collecting the vast majority of input power. The radius of the circular waveguide is expanded to 21 mm; thus, the two TE₁₁ modes are not cut off in the choke. With this choke, the power in the circular waveguide carried by two TE₁₁ modes is totally reflected to the input port, and the power leaking is minimized. The simulation results for different positions of the reflector are shown in Fig. 6b. When the reflector moves in a relatively long range (45 mm), the transmission to the coaxial waveguide port is smaller than - 60 dB all the time.



Fig. 4 (Color online) **a** Design, **b** power flow of polarizer, and **c** the simulation results: S_{11} and S_{21} are lower than -40 dB, $S_{3(2)1(1)}$ is lower than -50 dB, and $S_{3(1)1(1)}$ is -0.04 dB

The depth of the choke is not so strict. The simulation results indicate that the reflector works well when the machining error can be relaxed to 0.5 mm, which is easy to implement with our machine.

2.5 Final design

The final design combined the three components as shown in Fig. 7a. To suppress high-order modes in the waveguide, one rectangular waveguide dimension *a* is reduced to 42 mm instead of 47.55 mm. However, a smaller waveguide can also cause a higher surface electrical field. In a standard C-band rectangular waveguide, the surface E-field is approximately 1.33 kV/m for 1-W input power. Therefore, the other dimension *b* is set to 25 mm instead of 22.15 mm to keep the same surface E-field, which is approximately 1.37 kV/m. The total size of the entire modal is approximately $250 \times 250 \text{ mm}^2$. The parameters are optimized to minimize the reflection. Finally, the maximum reflection is approximately - 36 dB.

This variable power splitter will be placed between the pulse compressor and the accelerators on SXFEL. According to operating experience with a C-band RF unit [13, 14], the accelerators can work at 47 MV/m, corresponding to a peak E-field of 122.2 MV/m. For the RF unit of SXFEL, the output power of the klystron is 50 MW, and the average power gain of the pulse compressor is 3.2 for the SLED (SLAC Energy Doubler) [15] and 3.8 for the new spherical pulse compressor [16]. If the new spherical pulse compressor is utilized, the input power of the variable power splitter is 190 MW. As shown in Fig. 7b, the maximum surface E-field is approximately 3.4 kV for 1-W input power. If the input power is 190 MW, the maximum surface electric field is 46.9 MV/m, which is smaller than the peak E-field of the accelerator, 122.2 MV/m. Therefore, the power splitter can work at the SXFEL facility.

Figure 8 shows the S-parameters of this system versus piston positions. The reflection to Port 1 is less than -35 dB all the time. As the piston moves from z = 0 to 17.9 mm, the power emitted from Port 2 changes from 1 to



Fig. 5 (Color online) Machining-error analyses of polarizer: analysis of **a** width of protuberances, **b** height of protuberances, **c** different positions of protuberances when the four protuberances are symmetric, and **d** when four protuberances are not symmetric—the machining

error of the protuberances' sizes should be controlled within \pm 20 $\mu m,$ and the position error should be lower than \pm 10 μm



Fig. 6 a RF contact-free movable reflector and b its simulation results: the transmission to the coaxial waveguide port is smaller than -60 dB



Fig. 7 a Design of C-band variable RF power splitter and b its E-field: the maximum surface E-field is approximately 3.4 kV for 1-W input power



0 and that from Port 3 changes from 0 to 1, indicating variable power splitting.

3 Conclusion

A new type of C-band variable RF power splitter was designed at SINAP that can provide a variable output RF power ratio on its two output ports with minimized reflection to the power source. Moreover, the use of an RF polarizer, as well as an RF impedance combiner, significantly reduced the size of the power splitter's structure. A similar X-band design was proposed for the X-band deflecting structure [17, 18] and accelerator [19].

Deringer

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