Design of rf components for the Advanced Ring at KEK

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Abstract

We developed a three-way rf power divider in order to drive three rf cavities by one klystron. It consists of a new type magic-tee, which can divide the rf power into two ports by a power ratio of 1:2. It is possible to prove theoretically that such a magic-tee can be realized. The structure of the new magic-tee was designed by using the computer code HFSS. It was found that the ratio of the divided power of the magic-tee depends on the position of the E arm port and that of one post, and the impedance of all ports can be matched by adding two or three posts inside the magic-tee.

1. INTRODUCTION

A project to improve the Advanced Ring (AR) for pulsed X-rays is now in progress at KEK [1]. The final beam current of this project is 200 mA for single bunch operation at 6 GeV. To achieve stable operation, a total of six superconducting cavities which were developed for the KEKB project are needed. There are two straight sections in the AR. It is the best design to insert three cavities in each straight sections because of other ring components. We want to drive three rf cavities by one high power klystron that was used at TRISTAN AR. The three-way rf power divider is needed for the design of the rf system. Once the rf power is divided to two ports by a power ratio of 1:2, then the 2/3 power is divided into two equal amounts by a normal magic-tee as shown in figure 1. The magic-tee is a very good power divider because all ports of the magic-tee can be matched perfectly. The new type magic-tee that can divide rf power to two ports by a power ratio of 1:2 is a simple and small component. There is another requirement for the three way power divider, because the number of operating cavities may change due to the ring performance, independent of the klystron power. The new type magic-tee is realized by a small change of the normal magic-tee.

2. S-PARAMETER MATRIX

Figure 2 shows a wave guide hybrid junction which is known as a magic-tee. Normally the coupling between ports 1 and 2, and 1 and 3, is the same, as may be seen from the symmetry involved [2]. If all the ports are
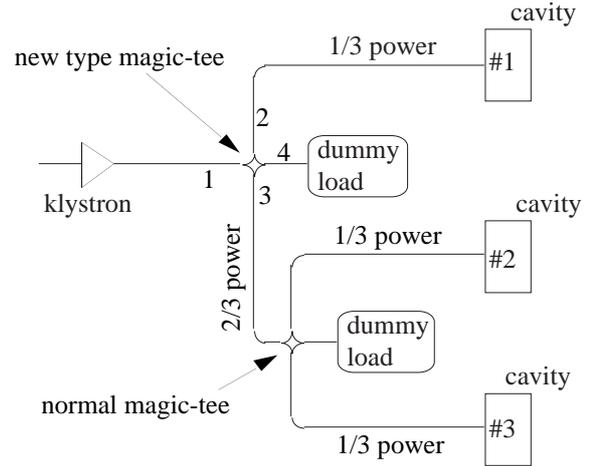
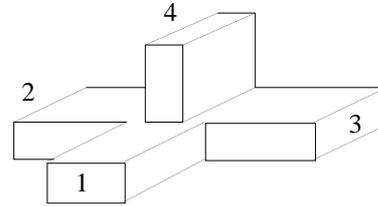

Figure 1. Block diagram of the RF power-source system

Figure 2. The magic-tee

matched perfectly, a TE$_{10}$ mode is incident in port 1 and goes out half power from port 2 and port 3. Then the S-parameter matrix is [2]:

$$S = \frac{1}{\sqrt{2}} \begin{bmatrix} 0 & 1 & 1 & 0 \\ 1 & 0 & 0 & 1 \\ 1 & 0 & 0 & -1 \\ 0 & 1 & -1 & 0 \end{bmatrix} \quad (1)$$

We want a magic-tee that divides the rf power into two ports by a power ratio of 1:2. We assume 1/3 of input power goes out from port 2, and 2/3 of input power goes out from port 3. If all ports are matched perfectly, $S_{11} = S_{22} = S_{33} = S_{44} = 0$. We assume that there is no coupling between ports 1 and 4 and ports 2 and 3. The reciprocity theorem shows that the S-matrix of a magic-tee is symmetric. $S_{14} = S_{41} = S_{23} = S_{32} = 0$, $S_{21} = \sqrt{1/3}$, $S_{31} = \sqrt{2/3}$ so that the S-matrix is given by:

$$S = \begin{bmatrix} 0 & S_{12} & S_{13} & 0 \\ \sqrt{1/3} & 0 & 0 & S_{24} \\ \sqrt{2/3} & 0 & 0 & S_{34} \\ 0 & S_{42} & S_{43} & 0 \end{bmatrix} \quad (2)$$

Further it is required for physical reasons:
$$[S]\dagger \, [S] = [1] \quad (3)$$

Then

$$1/3 + 2/3 = 1$$

$$\sqrt{1/3}\, S_{24} + \sqrt{2/3}\, S_{34} = 0$$

$$S_{12}*S_{12} + S_{42}*S_{42} = 1$$

$$S_{12}*S_{13} + S_{43}*S_{42} = 0$$

$$S_{13}*S_{12} + S_{43}*S_{42} = 0 \quad (4)$$

$$S_{13}*S_{13} + S_{43}*S_{43} = 1$$

$$S_{24}*\sqrt{1/3} + S_{34}*\sqrt{2/3} = 0$$

$$S_{24}*S_{24} + S_{34}*S_{34} = 1$$

from equations (4), $S_{12} = \sqrt{1/3}$, $S_{13} = \sqrt{2/3}$, $S_{24} = S_{42} = \sqrt{2/3}$, $S_{34} = S_{34} = -\sqrt{1/3}$ so that the S-matrix is given by

$$S = \begin{bmatrix} 0 & \sqrt{1/3} & \sqrt{2/3} & 0 \\ \sqrt{1/3} & 0 & 0 & \sqrt{2/3} \\ \sqrt{2/3} & 0 & 0 & -\sqrt{1/3} \\ 0 & \sqrt{2/3} & -\sqrt{1/3} & 0 \end{bmatrix} \quad (5)$$

S-matrix (5) fulfills equation (3). The minus signs of S_{34} and S_{43} indicate that the rf phase is shifted by 180 degrees. There is no coupling between ports 1 and 4, and 2 and 3. When we use a magic-tee for a rf power-divider, port 1 is connected to the klystron, port 2 is connected to the first cavity, port 3 is connected to the second cavity and port 4 is connected to the dummy load as shown in figure 1 and figure 2. If the reflected power comes from the first cavity, it goes into port 2, and goes out from ports 1 and 4. So one cavity's behavior has no influence to the other cavities. The S-matrix (5) suggest that it is possible to realize the new type magic-tee.

3. DESIGN OF THE MAGIC-TEE

Figure 3 shows a normal type magic-tee which is used in AR for a rf frequency of 508 MHz. This type of magic-tee was used at TRISTAN main ring too. There are two posts inside the magic-tee to reduce the reflection. The positions and lengths of posts 1 and 2 are adjusted to minimize the reflections of ports 1 and 4 respectively. This normal type magic-tee has a shape with even symmetry about the midplane and divides the power into two equal parts.
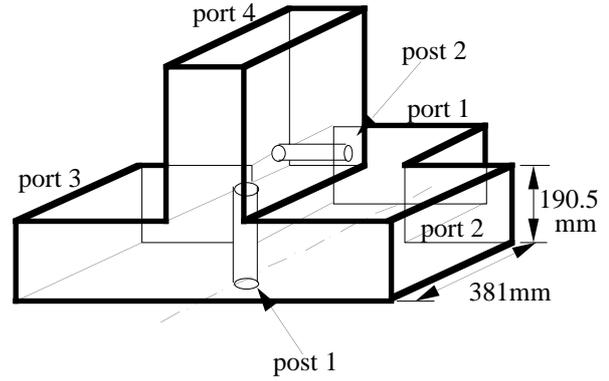

Figure 3 Normal type magic-tee in AR

3.1 Simple design of the new type magic-tee

Figure 4 shows a new type magic-tee for a rf frequency of 508 MHz. It was designed by using the computer code HFSS. In the new type magic-tee, port 4 and two posts are placed at asymmetric positions about the midplane. The wave guide sizes are the same as for the normal type magic-tee in figure 3. The midplane of port 4 is attached between port 1 and port 2, 50mm apart from the midplane of port 1. Post 1 has 40mm diameter and 333mm length. Post 1 is located 20mm apart from the midplane of port 4. Post 2 has 51mm diameter, and is located 93.5mm up from the down side of port 4, 63mm inside from the side wall of port 4 as shown in figure 3. The positions of port 4 and post 1 are important for the new type magic-tee. Post 1 has the only function to reduce the reflection in the normal magic-tee, but post 1 influences the power ratio in new type magic-tee. There is no coupling between ports 1 and 4 in the normal magic-tee, because the electric field has even symmetry about the midplane and hence cannot excite the TE10 mode in port 4, since this mode has an electric field with odd symmetry. The electric field has not even symmetry about the midplane of port 4 in the new type magic-tee. The position
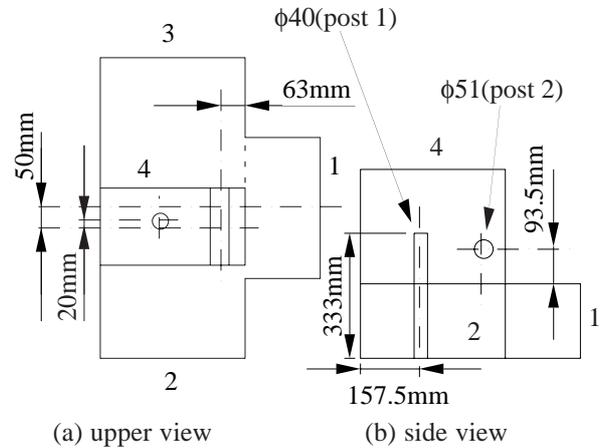
(a) upper view   (b) side view
Figure 4 design of new type magic-tee

of post 1 influences the coupling between ports 1 and 4 too. Post 1 has to be located to meet all these requirements. The absolute values of the S-parameters of the new type magic-tee in figure 4 are as follows:

$$S = \begin{bmatrix} 0.063 & 0.575 & 0.810 & 0.099 \\ 0.575 & 0.088 & 0.059 & 0.812 \\ 0.810 & 0.059 & 0.107 & 0.574 \\ 0.099 & 0.812 & 0.574 & 0.052 \end{bmatrix} \quad (6)$$

These S-parameters were calculated by using HFSS. The input power is divided into ports 2 and 3 by a ratio of almost 1:2. The reflected powers of port 1 and 4 are lower than 0.4%, this is sufficiently low. But the power traveling from port 1 to port 4 is about 1%. This means that, if 200kW power is incident in port 1 from the klystron, 2kW powers travels to port 4 and dissipates in the dummy load. This is a large amount of useless power. The reflected power of port 3 is rather high too. We couldn't find a better design than this, which equipped only two posts.

3.2   Reduction of the wasted power

The coupling between ports 1 and 4 can be reduced by adding one more post. Figure 5 shows another application of the new type magic-tee. The additional post 3 is attached at the connected plane of port 4, as shown in figure 5. A plate which covers a part of port 4 can be used instead of post 3. The absolute value of the S-parameters of the new type magic-tee in figure 5 is as follows:

$$S = \begin{bmatrix} 0.043 & 0.574 & 0.817 & 0.021 \\ 0.574 & 0.026 & 0.026 & 0.817 \\ 0.817 & 0.026 & 0.032 & 0.574 \\ 0.021 & 0.817 & 0.574 & 0.018 \end{bmatrix} \quad (7)$$

These S-parameters were calculated by using HFSS. The input power is divided into ports 2 and 3 by a ratio of 1:2 completely. The reflections of all ports are sufficiently
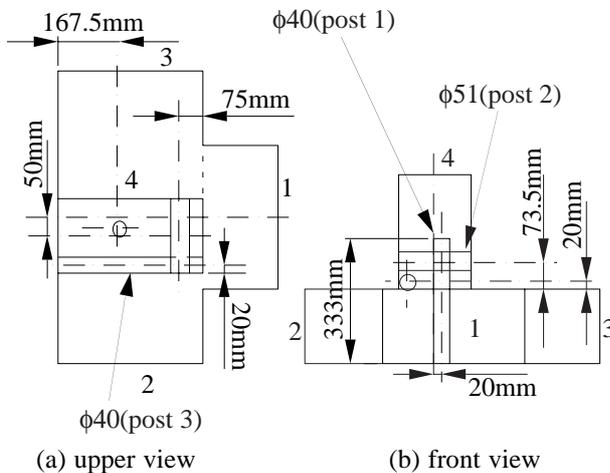
reduced. The coupling between ports 1 and 4 is sufficiently low too. The new type magic-tee that is illustrated in figure 5 is the optimal design at the moment. We are planning to experiment with some prototypes of these designs.

3.3 Other applications of the new type magic-tee

We discussed only the use of the new type magic-tee for a rf frequency of 508MHz that is used in AR. But the new type magic-tee can be applied for all rf frequency by a change of size. The power ratio can be changed too. It is possible to design a magic-tee that divides the rf power into two ports by a power ratio of q:1-q (q<1). We assume all ports are matched perfectly, so that the S-matrix is given by:

$$S = \begin{bmatrix} 0 & \sqrt{q} & \sqrt{1-q} & 0 \\ \sqrt{q} & 0 & 0 & \sqrt{1-q} \\ \sqrt{1-q} & 0 & 0 & -\sqrt{q} \\ 0 & \sqrt{1-q} & -\sqrt{q} & 0 \end{bmatrix} \quad (8)$$

This magic-tee can be realized as follows: The position of port 4 must be chosen according to the desired power ratio as shown in figure 4. Then the position of post 1 must be adjusted to minimize the coupling between ports 1 and 4, and to reduce the reflection of the ports. When the coupling between ports 1 and 4 can not be reduced enough, the additional post 3 should be attached at the connected plane of port 4 as shown in figure 5. The position of post 2 should be adjusted to minimize the reflection of port 4 at last.

4. CONCLUSION

We designed the new type magic-tee, which can divide the rf power into two ports by a power ratio of 1:2. The new type magic-tee can be realized by a change of positions of port 4 and two posts. The position of port 4 is chosen to adjust the power ratio. The positions of two posts are adjusted to minimize the reflected power mainly. If all ports cannot be matched perfectly by a use of only two posts, a third post can be introduced.

5. ACKNOWLEDGMENTS

6. REFERENCES

[1] "Design Report on Advanced Ring for Pulse X-rays (PF-AR)" in Japanese, KEK Report 97-2 May 1997.

[2] Peter A.Rizzi, "Microwave Engineering (Passive Circuits)", PRENTICE HALL.

(a) upper view   (b) front view
Figure 5 Optimal design of the new type magic-tee