Review article

Design of 5.0-GHz KSTAR lower-hybrid coupler

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Abstract

The Korean Superconducting Tokamak Advanced Research (KSTAR) tokamak is being constructed to perform long-pulse, high-β, advanced tokamak fusion physics experiments by Korean Basic Science Institute (KBSI). The KSTAR tokamak will use the non-inductive plasma current drive system, lower-hybrid current drive (LHCD) system for lone-pulse operation. A 5.0-GHz microwave coupler is designed for KSTAR LHCD experiments. Four high-power klystrons feed 128 guidelets at front coupler using hundred and twenty 3-dB power dividers including 3-dB power splitters in the coupler. The guidelet has a height of 5.5 cm and the width of 0.55 cm in order for the power flux density not to exceed 4.0 kW/cm² at the guidelet. The coupler is constructed by laminating a stack of metal plates milled to waveguide patterns. This paper describes detailed design for the 3-dB power splitter, the fixed-phase shifter, and the taper section composing the coupler. Using the High Frequency Structure Simulator (HFSS) program, we achieved a phase difference of ±0.5° and a relative power difference less than 0.2% between two vertical guidelets.

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1. Introduction

One of the research objectives of Korean Superconducting Tokamak Advanced Research (KSTAR) tokamak [1] is to perform advanced tokamak research in high-performance regime and to explore methods for achieving a steady-state operation for a tokamak fusion reactor. The device will be distinguished by having the capability to study advanced tokamak plasmas for long-pulse lengths of up to 300 s. The heating and current drive systems are based on multiple technologies such as neutral beam injection, ion cyclotron range of frequencies, lower-hybrid current drive (LHCD) and electron cyclotron heating. They will provide heating and current drive capabilities as well as the profile control of current density and pressure to meet the mission and research objectives of the machine.

We are developing a LHCD system for KSTAR. The non-inductive plasma current drive can be generated using the LHCD system so that steady-state operation will be possible. The LHCD system
will use four 500 kW 5.0-GHz klystrons. The RF power will be delivered through long transmission lines composed of waveguides and 3-dB dividers from the klystrons to the coupler. Due to the insertion losses in the transmission lines, the power transmitted to the KSTAR plasma will be reduced from 2 to 1.5 MW. The coupler will be composed of two modules that are assembled at upper and lower positions. Each module has a waveguide antenna of 2 rows of 32 guidelets near the plasma. Therefore, the KSTAR front coupler is composed of 4 rows of 32 guidelets, and each klystron feeds 8 columns of guidelets of the waveguide antenna. Fig. 1 shows the transmission lines and the phase shifters of the KSTAR LHCD system. The short dimension of the standard WR187 waveguide is reduced to 0.55 cm (E-plane taper) before the input of the upper and lower modules.

Each input with the same phase is further divided vertically into two branches using a 3-dB power splitter. The two vertical outputs will be in the same phase via a fixed-phase shifter. Water pipes in the matching waveguide of the splitter serve both as a dummy load and for heat removal. The waveguide in long dimension, 4.75 cm in each module, is tapered up to a larger width, 5.5 cm in order to reduce the RF power flux density at the guidelets while maintaining the short dimension of 0.55 cm. With this waveguide dimension, the KSTAR LH coupler will be operated below the weak conditioning limit based on the empirical data of power flux density [6] in the waveguide as shown in Fig. 2. Fig. 2 shows the weak conditioning region and the breakdown region as a function of \( f^2b \), where \( b \) is the short dimension in centimeter, and \( f \) is the frequency in gigahertz. The hexagonal symbol in Fig. 2 corresponds to the KSTAR LH coupler and \( f^2b = 13.75 \text{ GHz}^2 \text{ cm} \) and the power flux density is 3.8 kW/cm². Fig. 3 shows that each module has a 3-dB power splitter, a fixed-phase shifter, a taper section, and a matching waveguide with a water load.

The coupler is fabricated by stacking 32 metal plates with the waveguide patterns milled on. The design of 3-dB power splitter, fixed-phase shifter, and taper section has been optimized for the 5.0-GHz frequency using the High Frequency Structure Simulator (HFSS) program [2]. The detailed results are presented in the following sections.

### 2. 3-dB power splitter

Fig. 4 shows a schematic drawing of the 3-dB power splitter. An ideal 3-dB power splitter is designed to have a zero reflection power, i.e., \( S_{11}^2 = P_r/P_0 \approx 0.0 \) and an exact half power (3.0 dB) of the input power at each splitting arms. Where, the \( P_r \) is the reflected power, and \( P_0 \) is the input power. Our modeling has determined that the reflection power ratio is less than \(-40 \text{ dB} \) and that the relative power difference between transmitted powers is \( \delta P = (S_{12}^2 - S_{14}^2)/(S_{12}^2 + S_{14}^2) < \pm 0.5\% \). In order to have an equal power split from the output ports to the input port, the phase difference between the even TE\(_{10}\) mode and the odd TE\(_{20}\) mode in the coupling region of a 3-dB splitter must be 90° [3].

\[
\frac{2\pi d}{\lambda_{Ge}} = \frac{2\pi d}{\lambda_{Go}} + \phi_r = \frac{\pi}{2},
\]

where \( \lambda_{Ge} \) is the guided wavelength of even TE\(_{10}\) mode, \( \lambda_{Go} \) is the guided wavelength of odd TE\(_{20}\) mode in the coupling region, \( d \) is the coupling length, and \( \phi_r \) is the phase shift due to the reflection from the coupling iris wall.

Fig. 5 shows the plot of Eq. (1) for the width of coupling region as a function of the coupling length when \( \phi_r \) is neglected. The 8.0 cm width of the coupling region is chosen for TE\(_{30}\) mode not to be excited in the coupling region. From Eq. (1), the coupling length is 5.65 cm for 8.0 cm width of the coupling region. A capacitive button is required in the coupling iris wall of 0.5 cm as shown in Fig. 4. From HFSS simulations, the diameter and depth of the capacitive buttons are determined for the design goal. Figs. 6 and 7 show the results of HFSS simulation. The coupling, \( C = 10 \log(P_r/P_0) = 20 \log|S_{14}| = 3.06 \text{ dB} \), the directivity, \( D = 10 \log(P_d/P_0) = 20 \log(|S_{14}/|S_{13}|) = 40.00 \text{ dB} \), the isolation, \( I = 10 \log(P_r/P_3) = 20 \log|S_{13}| = 43.07 \text{ dB} \). The phase difference between two outputs is 89.97° that is 0.03° smaller than 90°. The final design values are found in Fig. 4. The coupling
length is 5.65 cm, the width of the coupling region is 8.0 cm, the height of the coupling iris wall is 0.5 cm, and the diameter and the penetration depth of the buttons are 2.1 and 0.13 cm, respectively.

3. Taper section

The taper section is tapered up to 5.5 cm linearly. The taper length is determined to have
minimum reflection. Mode conversion is not considered since the cut-off frequency of the higher mode is above 5.0 GHz for up to 5.5 cm. Therefore, the coupled equations for impedance matching in the taper section is calculated numerically. The coupled equations are given by Eqs. (2) and (3) [4].

\[
\frac{I^{(+)}(z)}{dz} = -j\beta(z)I^{(+)}(z) + c(z)I^{(-)}
\]

Fig. 2. The power flux density as a function of \(f^2b\). This data is based on empirical experimental data. The hexagonal symbol corresponds to the KSTAR LH coupler with the waveguide dimensions: 5.5 cm height and 0.55 cm width of the guidelet at the front coupler.

Fig. 3. Schematics of one metal plate milled with two 3-dB power splitters; two capacitive buttons, two fixed-phase shifters, four taper sections, and six Teflon pipes in the matching waveguide of the 3-dB splitter.
\[
\frac{I^-(z)}{dz} = j\beta(z)I^-(z) + c(z)I^+(z),
\]

where \(I^+(z)\) is the amplitude of forward wave, \(I^-(z)\) is the amplitude of reflected wave. \(\beta(z)\) is the propagation constant, and \(c(z)\) is the coupling coefficient between forward wave and reflected wave.

\[
\beta(z) = k_0 \sqrt{1 \left( \frac{\lambda_0}{2a(z)} \right)^2}
\]

\[
c(z) = -\frac{1}{2Z} \frac{dZ}{dz}
\]

where \(k_0\) is the free space propagation constant; \(\lambda_0\) is the free space wavelength, 6.0 cm; \(a(z)\) is the broad wall dimension as a function of \(z\) (it is tapered from 4.75 to 5.5 cm), and \(Z\) is the characteristic impedance of TE\(_{10}\) mode,

\[
Z = \eta_0 \left(1 - \left(\frac{\lambda_0}{2a(z)}\right)^2\right)^{-1/2}.
\]

Fig. 8 shows the return losses as a function of taper length for three taper types from the numerical calculations. The exponential taper is the best, but the linear taper is chosen for easy fabrication. The minimum in the return loss is at a taper length near \(n\lambda_G/2\) (\(n\) is integer). Fig. 9 shows the HFSS simulation results for linear taper and the taper lengths of \(\lambda_G/2\), \(\lambda_G\), \(3\lambda_G/2\), \(1.4\lambda_G\), and 11.35 cm. Since the bandwidth decreases as the taper length increases, the taper length of 11.35 cm is enough and it gives very low reflection (\(<-50\) dB) at 5.0 GHz.

4. Fixed-phase shifter

The fixed-phase shifter is designed for maintaining the two vertical outputs in the same phase. When the RF is split from the 3-dB power splitter, the RF phase of the secondary arm is delayed by 90°. Then, the location of the fixed-phase shifter is in the secondary arm. But, we have to consider the additional electrical path length results from the difference in length of the rows facing the plasma boundary surface. It is easily seen that the location of the fixed-phase shifter depends on the value of this additional electrical path length. Since the KSTAR coupler structure shall be designed to have the longer primary arm than the secondary arm as shown in Eq. (3), and if the electrical path
length is larger than 90°, the fixed-phase shifter must be located at the primary arm. Otherwise, the fixed-phase shifter is located at the secondary arm. The fixed-phase shifter is made by cutting with two steps. The next step is one quarter wavelength away from the previous step in order to cancel out each wave reflected from the cut walls. Thus, the fixed-phase shifter is designed to satisfy Eq. (7).

$$\frac{2\pi}{\lambda_1}(2y) + \frac{2\pi}{\lambda_2}(2x) = \frac{2\pi}{\lambda_G}(2y + x) - \left( \frac{\pi}{2} - \phi \right)$$  \hspace{1cm} (7)$$

where $\lambda_1$, $\lambda_2$, $\lambda_G$ are guided wavelengths of the fundamental mode at the first step region, at the second step region, and the flat region with a waveguide width of 4.75 cm, respectively. The $y = \lambda_1/4$, and $x$ is the distance going after the second step. The free space wavelength, $\lambda_0 = 6.0$ cm, for the 5.0 GHz and therefore, $\lambda_G = 7.74$ cm. The additional electrical path length, $\phi$, is positive because the primary arm is longer than the secondary arm, and it is given by $(2\pi/\lambda_G)p$. The dimension $p$ is the longitudinal length difference of the waveguide center between two rows above or below the coupler center, and it is given by 0.81 cm from the KSTAR plasma boundary surface data [5]. The $\lambda_G$ is the guided wavelength in the waveguide whose width is 5.5 cm. Thus, the electrical path length becomes 40.7°. This value is smaller than 90°, so that the fixed-phase shifter is located at the secondary arm. In case of the C-MOD LH coupler for Alcator C-MOD tokamak, the coupler has the longer primary arm than the secondary arm, and $\phi = 100°$ greater than 90° [6]. Therefore, the C-MOD has a fixed-phase shifter at the primary arm. The Fig. 7 shows that the large cut depth gives the shorter length $x$ as shown in Fig. 10. However, a too narrow waveguide could cause arcing in the fixed-phase shifter region. When the cut depth is 0.3 cm, $y = 2.03$ cm (one quarter of wavelength) and from the Eq. (7), $x = 7.89$ cm. But, the HFSS simulation gives a shorter length of $x = 7.29$ cm for the phase difference less than 1.0° between two output ports. The phases
fronts propagating in the two arms (the secondary arm has a fixed-phase shifter) are shown in Fig. 11. It shows that the split wave fronts are arrive at the end at the same time.

5. Summary

The KSTAR 5.0-GHz lower-hybrid coupler is designed to use the HFSS program. Mechanical
Tolerances can result in a phase difference between two guidelets in row. But, the phase difference is less than $\pm 0.5^\circ$ even if the tolerance is given $\pm 1.0$ mm. This is acceptable in the LH coupler operation. Since the total length of the KSTAR LH coupler going into the port is very long, the insertion loss must be considered in practice. The water load in the matching waveguide will be designed in near future. Since the coupler is fabricated by stacking 32 metal plates with waveguide patterns milled on, there is no enough space for installing the water loads to each matching waveguide independently. Therefore, the water load in the matching waveguide shall be designed to have a simple structure.

Fig. 10. The fixed-phase shifter lengths as a function of cut depth. For the cut depth of 0.3 cm, $x = 7.29$ cm.

Fig. 11. A contour plot of magnitude of electric field in the fixed-phase shifter. The cut depth is 0.3 cm, $y = 2.03$ cm, and $x = 7.29$ cm.

References

[6] Private communication with Dr S. Bernabei.