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Properties of the RF transmission line of a C-shaped waveguide

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A R T I C L E I N F O

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A B S T R A C T

A new type of waveguide, named the C-shaped waveguide (CSWG), has a structure similar to that of a coaxial line but with a plate connecting the inner conductor to the outer conductor. The CSWG has unique characteristics, such as a cutoff frequency and easy cooling of the inner conductor, that are absent in the coaxial line. The results of calculations using 3-dimensional simulation software and measurement with the CSWG model are in good agreement with the analytical solution. The CSWG can be applied to a pickup port with a high-pass filter that can attenuate the higher-order modes over the cutoff frequency without attenuating the accelerating mode.

1. Introduction

Waveguides are used to transmit RF power. There are many types of waveguides, which can be classified based on their structure, e.g., rectangular, circular, coaxial, elliptical, radial, or conical. In certain waveguides, such as the rectangular waveguide (RWG) and the circular waveguide (CWG), only an outside conductor is present. Other waveguides, such as the coaxial waveguide, have both an outer conductor and an inner conductor. The RWG is used for high-power RF transmission because it is straightforward to cool this waveguide by adding a cooling path outside of the structure. Since the RWG and the CWG have a cutoff frequency, they can be used as high-pass filters. The size of the RWG is up to half of the cutoff wavelength. Many types of RF sources have a coaxial type output line requiring a converter from the coaxial to the RWG. The coaxial waveguide is also used to transmit a large amount of RF power. The coaxial waveguides have no cutoff frequency. Since the inner conductor is isolated or weakly connected through a support dielectric substance, such as Teflon, a complex system is required to cool the inner conductor. Poor cooling of the inner conductor can cause a severe problem in the case of the superconducting accelerator. The superconducting cavity has a large quality factor, giving rise to low loss of the RF power. This low loss is beneficial for the accelerating mode yet harmful for the other modes. The high Q-values of the higher-order modes (HOMs) cause beam breakup (BBU) and limit the maximum beam current [1]. Therefore, HOM damping equipment such as an HOM coupler is installed in the superconducting cavity. For high-power HOM, the inner conductor of the RF connector for HOM power extraction can lead to a temperature rise due to the weaker heat transmission from the inner conductor to the outer conductor. In the worst case scenario, an increase in the temperature of the connector leads to the quenching of superconductivity. Thus, the cooling of the inner conductor is one of the most important issues for the superconducting accelerator in continuous-wave (CW)-mode operation, such as an energy-recovery linac (ERL) [2–4].

Here, we propose a new type of waveguide. Even though the structure of this waveguide is similar to the coaxial line, it features a cutoff frequency, easy cooling, and easy connection to the coaxial waveguide. This waveguide is named the C-shaped waveguide (CSWG) because the shape of the cross-section view is similar to that of the letter C. In this paper, we describe the fundamental RF properties, the calculation and measurement results and the application of the CSWG transmission line.

2. C-shaped waveguide

2.1. Principal characteristics

To propagate RF power from/to a coaxial line to/from an RWG, a coaxial-waveguide converter is used, as shown in Fig. 1 (top left). The CSWG can be produced by transforming the coaxial-waveguide converter topologically. Shortening the narrow side of the RWG does not change the field pattern. We round the RWG so that the wide side connected with the inner conductor of the coaxial line becomes the

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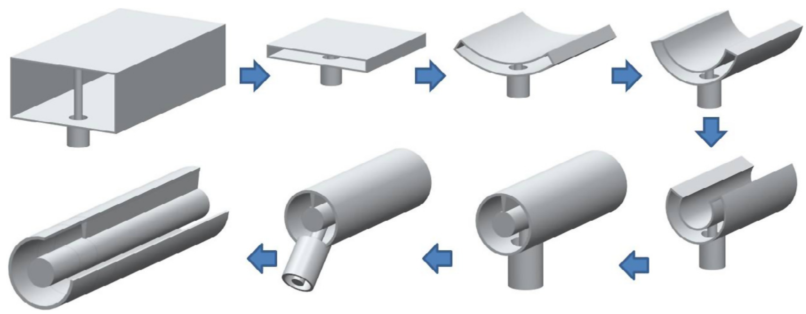

Fig. 1. Transformation from a coaxial-waveguide converter (top left) to a CSWG (bottom left).

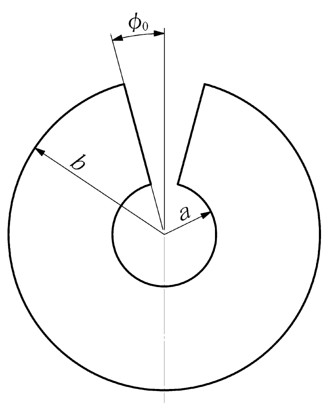

Fig. 2. Schematic CSWG cross sections with the radial connection plate (left) and the parallel connection plate (right).

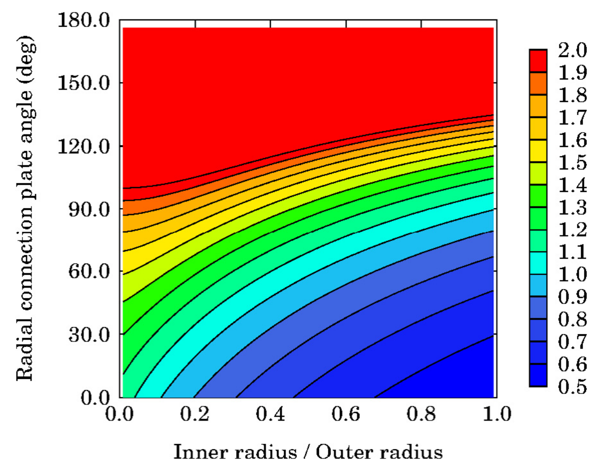

Fig. 3. Numerical solution of normalized eigenvalues for the radial connection plate.

inside, as shown in Fig. 1 (top right). This transformation changes the narrow sidewalls into a plate that connects the inner conductor to the outer conductor. Moving the coaxial line to the end of the waveguide makes the coaxial-waveguide converter to the coaxial-like line for which the inner and outer conductors are partially connected to the connection plate, as shown in Fig. 1 (bottom left). Since the part with the connection plate is originally the RWG, the properties of this part are similar to those of the RWG.

The CSWG consists of the inner conductor, the outer conductor, and the connection plate. Two types of connection plates can be considered. The first is a parallel plate, and the second is a radial plate, as shown in Fig. 2. Although the parallel plate features a simple design, its shape cannot be described using cylindrical coordinates. The radial plate enables the description of the CSWG shape using the cylindrical coordinate, enabling straightforward analysis of the electromagnetic field in the CSWG.

Here, a uniform CSWG carrying a traveling wave is considered. Field patterns inside the waveguide can be analytically investigated using Maxwell's equations when the waveguide structure is expressed in the cylindrical coordinate system. Let us consider the CSWG with an inner radius a, an outer radius b and a connection plate angle ϕ_0 that lies along the z-axis and is carrying a traveling wave in the positive z-direction, as shown in Fig. 2. The waveguide has the wall of a perfect conductor and the hollow region of a perfect dielectric.

The general solutions for the transverse electric (TE) mode can be expressed by

$$E_r(r,\phi) = \frac{\nu}{k_c r}\left[A_1 J_\nu(k_c r) + A_2 Y_\nu(k_c r)\right]\sin(\nu\phi - \phi_c), \tag{1}$$

$$E_\phi(r,\phi) = \left[A_1 J'_\nu(k_c r) + A_2 Y'_\nu(k_c r)\right]\cos(\nu\phi - \phi_c), \tag{2}$$

where J_ν and Y_ν are the Bessel functions of the first and the second kind, respectively, and k_c is the eigenvalue of this field. These general solutions involve arbitrary constants A_1, A_2, ν and ϕ_c, which can be fixed with the help of the boundary conditions. Applying the boundary conditions $E_r = 0$ at $\phi = \phi_0$, $2\pi{-}\phi_0$ gives

$$\nu = \frac{n\pi}{2(\pi - \phi_0)}, \tag{3}$$

where n is an integer (called the mode number and representing the mode order). In this paper, we consider the fundamental mode so that the mode number n is set to unity. Applying the boundary conditions $E_\phi = 0$ at $r = a, b$ gives

$$J'_\nu(k_c a)Y'_\nu(k_c b) - J'_\nu(k_c b)Y'_\nu(k_c a) = 0, \tag{4}$$

$$J'_\nu(k_c b\cdot\frac{a}{b})Y'_\nu(k_c b) - J'_\nu(k_c b)Y'_\nu(k_c b\cdot\frac{a}{b}) = 0. \tag{4$'$}$$

CSWGs with similar cross-sectional shapes, corresponding to the same values of a/b and ν (ϕ_0), have the same values of $k_c b$. Therefore, the eigenvalue multiplied by the outer radius, $k_c b$, is defined as the normalized eigenvalue. This equation cannot be solved analytically; Fig. 3 shows the numerical solution of the normalized eigenvalue as a function of a/b and ϕ_0.

The normalized eigenvalue can be approximately expressed [5] as

$$k_c b \approx \frac{2\nu}{a+b}b = \frac{2\nu}{\frac{a}{b}+1}. \tag{5}$$

When the electromagnetic field has an eigenvalue, a cutoff frequency exists for the propagation through the waveguide, and the cutoff wavelength can be expressed as

$$\lambda_c = \frac{2\pi}{k_c} = \frac{2\pi}{k_c b}b \approx \frac{\pi(a+b)}{\nu} = 2\times\frac{\pi - \phi_0}{\pi}\times\pi(a+b). \tag{6}$$