DESIGN AND IMPLEMENTATION OF RIDGE WAVEGUIDES FOR DUAL-MODE MICROWAVE STRUCTURE*

X.X. Huang†,[1], A. Grudiev[2], J.H. Tan[1], W.C. Fang[1]
[1]Shanghai Advanced Research Institute, Chinese Academy of Sciences, Shanghai, China
[2]European Organization for Nuclear Research, Geneva, Switzerland

Abstract

The dual-mode microwave structure is receiving increasing attention and research. In the application of dual-mode structures, it is necessary to solve the problem feeding microwave power at different frequencies. One method is to use complex waveguide components, such as first and second harmonic photocathode bimodal gun, which consists of the assembly of the directional coupler and the mode launcher. The structure combines the S-band and C-band power into a waveguide and feeds them into the dual-mode electronic gun. Another method is to use ridge waveguide to achieve selectable transmission or blocking of specific frequency. Currently, the ridge waveguide has been applied to dual-mode deflecting structure. This paper presents a X-band bandpass filter has been engineered to achieve a power reflection level of less than -30 dB at 12 GHz and a power transmission level of less than -40 dB at 24 GHz.

INTRODUCTION

In modern accelerator and radio frequency (RF) structures, dual-mode and dual-frequency operation has attracted considerable attention due to its ability to integrate multiple functions and improve beam performance. Examples include photoinjector operating with fundamental and second harmonics [1], variable-polarization deflection realized by a dual-mode transverse deflecting structure (TDS) [2], and bunch length manipulation based on a double-RF system [3]. All these schemes superimpose different frequencies or modes within a single cavity to achieve longitudinal bunch shaping, transverse deflection control, and suppression of emittance and energy spread. Such designs typically require simultaneous handling of multiple resonant modes, placing high demands on frequency isolation, power coupling, and higher-order mode (HOM) suppression.

To achieve frequency selection and directional power transmission, various waveguide structures have been introduced. A directional coupler, through its multi-branch design, shown in Fig. 1, enables dual-frequency combining and high-directivity transmission, ensuring that microwave power is delivered along a prescribed direction while providing bandpass/band-stop functionality. However, its structure including multiple branches and matching sections is relatively complex, making fabrication and tuning more difficult. In contrast, a ridge waveguide, shown in Fig. 1, owing to its simple structure and controllable bandwidth, can effectively realize transmission or band-stop or bandpass filtering at specific frequencies. It has been used, for example, as a bandpass filter in a dual-mode TDS to effectively isolate reverse leakage of high-frequency signals. Furthermore, in a dual-mode (TM_{010}/TM_{020}) harmonic cavity, a ridge waveguide is employed as an HOM extraction structure, and its band-stop property is utilized to precisely suppress the third-harmonic power. By adjusting the length of the short-circuited stub and the position of the tuning vane in the band-stop waveguide, an isolation bandwidth of approximately 15 MHz with –20 dB rejection can be achieved around 1.5 GHz, effectively blocking harmonic power leakage while introducing only minor loss to the operating modes.

In summary, ridge waveguides are increasingly used in dual-mode and dual-frequency RF structures, meeting diverse requirements such as compact filtering, suppression of reverse power transmission, and high-power harmonic rejection. It will provide important support for the integrated design of advanced accelerator and light source systems.

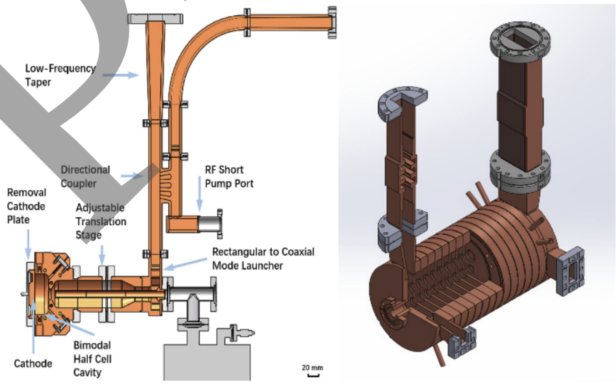

Figure 1: Engineering drawing of the first and second harmonic photocathode bimodal gun (left) and two-mode transverse deflecting structure (right).

SCHEME DESIGN FOR THE RIDGE WAVEGUIDE

The Compact Linear Collider (CLIC) is a proposed high-energy electron-positron collider based on normal-conducting accelerating structures operating at high frequencies, typically in the X-band (12 GHz) and above [4]. In such high-frequency accelerators, the feeding waveguide for the accelerating structure is conventionally a standard rectangular waveguide. However, a significant drawback of a conventional rectangular waveguide is that it supports not only the fundamental TE_{10} mode but also a large number of higher-order modes (HOMs) at the operating

---

* Work supported by the National Natural Science Foundation of China (No. 12505171).
† huangxx@sari.ac.cn

frequency and its harmonics. These spurious modes can propagate through the waveguide, interfere with the beam, cause parasitic power losses, and potentially damage the RF source.

In the CLIC project, to ensure clean power delivery and avoid HOM contamination, the waveguide feeding system must selectively transmit only the desired fundamental mode while effectively blocking higher-order modes. The most straightforward solution is to introduce a ridge waveguide section. By properly designing the ridge dimensions, the cutoff frequencies of the waveguide can be shifted such that only the fundamental mode (TE_{10}-like) propagates at the design frequency (e.g., 12 GHz), while all higher-order modes are cutoff or strongly attenuated. Moreover, the ridge waveguide can be engineered to provide band-stop characteristics at the second harmonic (24 GHz), preventing unwanted harmonic power from reaching the accelerating structure.

In the paper, an X-band bandpass filter based on a ridge waveguide structure has been designed and simulated. The filter aims to provide excellent frequency selectivity for dual-mode operation: it must allow the fundamental frequency (12 GHz) to pass with minimal reflection, while strongly rejecting the second harmonic (24 GHz) to prevent power leakage and mode interference. At the fundamental frequency of 12 GHz, the power reflection coefficient (S_{11}) is less than –30 dB, indicating very good impedance matching and efficient transmission of the desired signal. The –30 dB reflection bandwidth exceeds 500 MHz, ensuring stable operation over a wide frequency range. At 12 GHz, the adjustable range of the gap, shown in Fig. 2, is greater than 0.3 mm while maintaining $S_{11} < –30$ dB, providing sufficient tolerance for manufacturing errors. At the second harmonic frequency of 24 GHz, the power transmission coefficient (S_{21}) is less than –40 dB, demonstrating excellent suppression of the unwanted harmonic component.

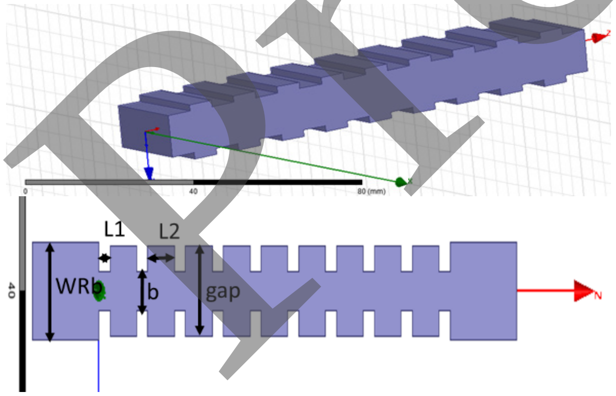

Figure 2: Free-angle (top) and cross-sectional (bottom) views of the ridge waveguide structure.

SIMULATION RESULT

The design of the ridge waveguide uses a standard WR90 waveguide as power feed port. Figure 3 shows the results calculated with HFSS [5], corresponding to the raised-ridge and recessed-ridge waveguide designs shown in Fig. 2, respectively. In the upper part of Fig. 3, the S_{11} curve contains a set of eight peaks and valleys, while in the lower part of Fig. 3, the S_{11} curve contains a set of nine peaks and valleys. It can be seen from the figure that each peak and valley is very sharp, and the bandwidth below –30 dB is very narrow.

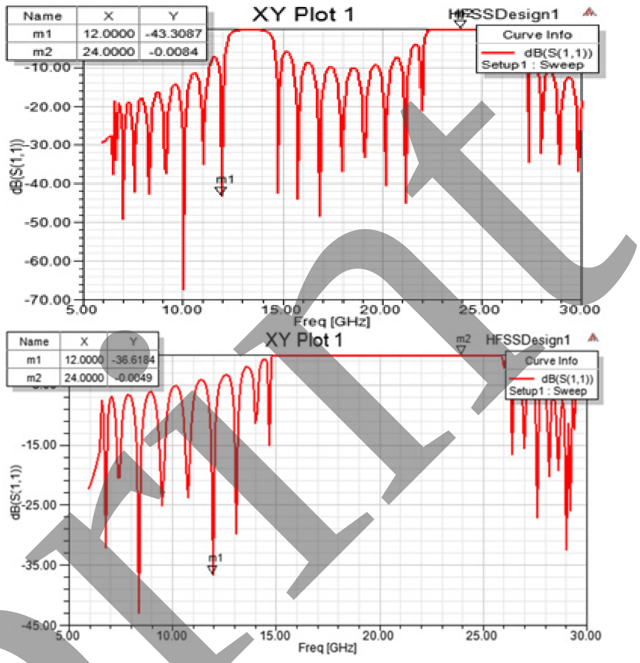

Figure 3: Simulated S_{11} results for the two types of ridge waveguide designs: raised-ridge (top) and recessed-ridge (bottom).

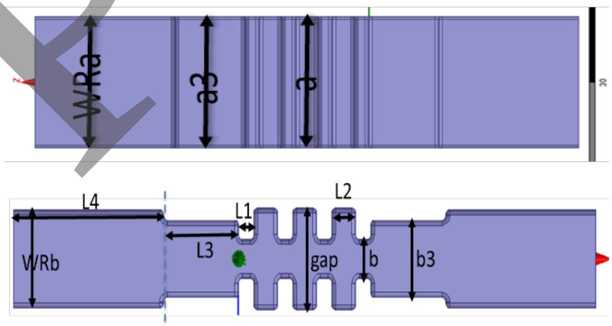

Figure 4: XZ plane view (top) and YZ plane view (bottom) of optimized ridge waveguide structure.

To meet the requirements for bandwidth and manufacturing tolerance margin, the number of ridges in the ridge waveguide is adjusted. When the number of ridges in the ridge waveguide is reduced to three, the bandwidth is 120 MHz, and the margin for the gap is only 0.07 mm. However, simply reducing the number of ridges cannot meet the design specifications. The design of the ridge waveguide mainly involves optimizing the length (e.g., L1, L2) and depth (e.g., b, gap) of the ridges, as shown in Fig. 4. Adding a step between the ridge and the standard waveguide to provide a transmission line transition for impedance matching can effectively broaden the bandwidth. Adjusting the dimension of L3 can increase the bandwidth to over 500 MHz and reduce the dependence on the precision of the gap size. Additionally, rounded fillets on the ridge waveguide also contribute to bandwidth broadening.

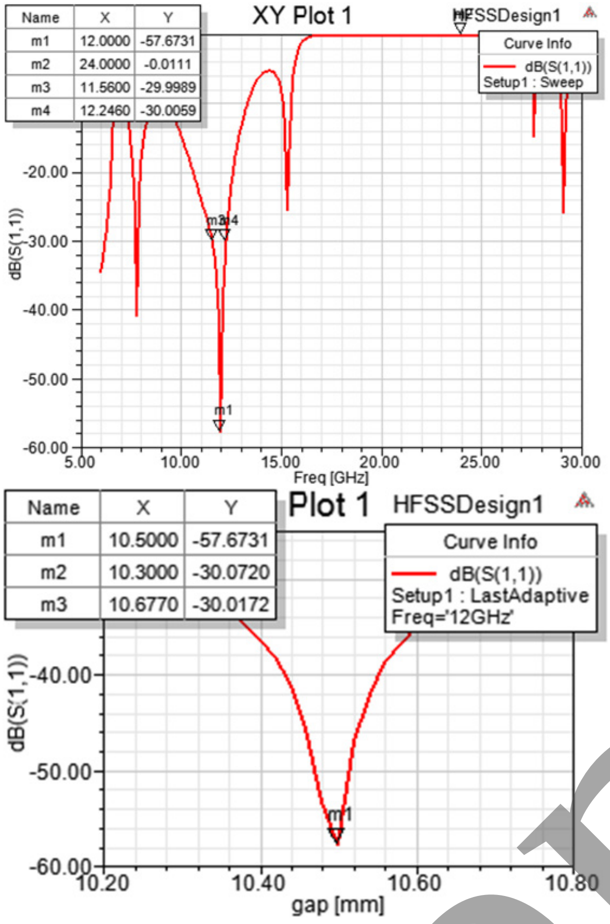

Figure 5: Simulated S_{11} of the optimized ridge waveguide: frequency (top) and gap (bottom).

Through parameter optimization, the final dimensions are determined as follows: a = 22.86 mm, b = 4 mm, a_3 = 22.86 mm, b_3 = 8 mm, L_1 = 2 mm, L_2 = 3.2 mm, L_3 = 10 mm, gap =10.5 mm, and a fillet radius of 0.5 mm. The corresponding S_{11} response is shown in Fig. 5. At the fundamental frequency of 12 GHz, $S_{11} = -57.67$ dB, while at the second harmonic of 24 GHz, $S_{11} = -0.01$ dB. The reflection coefficient remains below −30 dB over the frequency range from 11.56 GHz to 12.246 GHz. Furthermore, a parametric sweep of the gap value at 12 GHz indicates that $S_{11} < -30$ dB is maintained for gap lengths between 10.3 mm and 10.677 mm. Consequently, the –30 dB reflection bandwidth at the operating frequency reaches 686 MHz, and the gap tuning range is 0.377 mm, both of which satisfy the prescribed design requirements.

In addition to the fundamental mode, higher-order modes can also propagate in waveguides. Figure 6 presents the analysis of higher-order mode transmission in the optimized ridge waveguide. At the operating frequency of 12 GHz, the fundamental mode has an S_{11} of –55.5 dB, representing nearly lossless propagation. At 24 GHz, the S_{21} values of the first, second, and third higher-order modes are –75.4 dB, –42.3 dB, and –65.7 dB, respectively, indicating negligible transmission and thus total reflection. These simulation results demonstrate that the proposed ridge waveguide transmits only the fundamental mode while effectively suppressing higher-order modes.

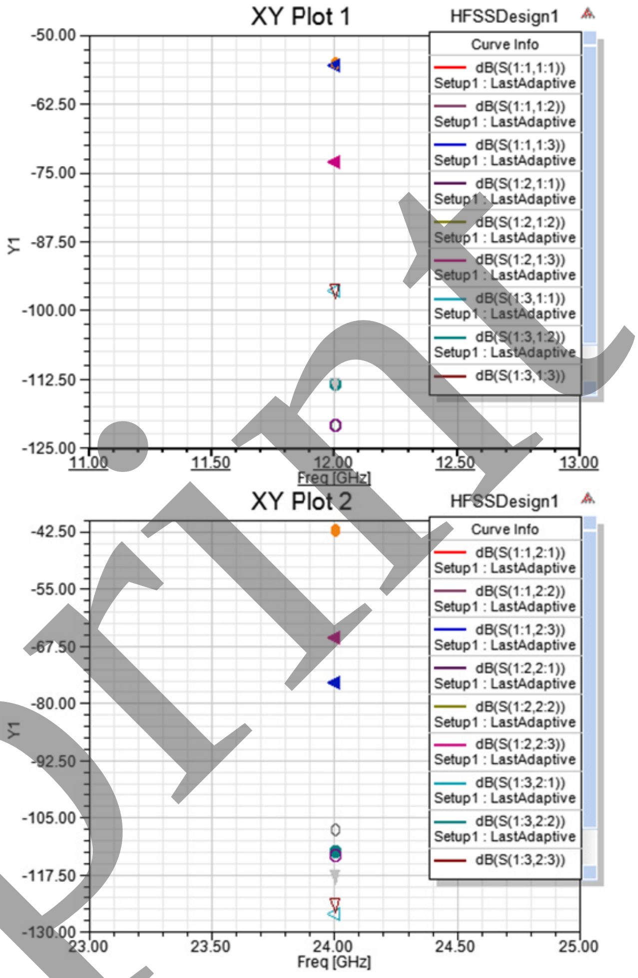

Figure 6: Simulated S_{11} results at 12 GHz (top) and simulated S_{21} results at 24 GHz (bottom).

CONCLUSION

These results confirm that the optimized ridge waveguide structure effectively serves as a frequency-selective component in dual-mode RF systems. It exhibits low insertion loss (S_{11} = -55.5 dB) at the fundamental frequency of 12 GHz and provides strong rejection of higher-order modes at the second harmonic (24 GHz), with the first three modes showing S_{21} values below -42 dB. The -30 dB reflection bandwidth reaches 686 MHz, and the gap tuning range is 0.377 mm, exceeding the design requirements. Consequently, the proposed ridge waveguide transmits only the fundamental mode while effectively blocking higher-order modes, making it a compact and reliable solution for dual-frequency isolation in advanced accelerator applications.

REFERENCES

[1] L. Wang *et al.*, “Simulation study of first and second harmonic photocathode bimodal gun”, *Phys. Rev. Accel. Beams*, vol. 24, no. 2, pp. 020401, 2021. doi:10.1103/PhysRevAccelBeams.24.020401

[2] H. Gong *et al*., “Design of a dual-mode transverse deflecting structure using neural network and multiobjective algorithms”, *Phys. Rev. Accel. Beams*, vol. 27, no. 4, pp. 042001, 2024. doi:10.1103/physrevaccelbeams.27.042001

[3] D. Su *et al*., “Novel rf design of bimodal normal-conducting active rf cavity for synchrotron radiation light sources”, *Phys. Rev. Accel. Beams*, vol. 29, no. 4, pp. 042001, 2026. doi:10.1103/m77b-mkm4

[4] P.N. Burrows *et al*., “Updated Baseline for a staged Compact Linear Collider”, *CERN Yellow Reports*, vol. 4, 2016. doi:10.5170/CERN-2016-004

[5] Ansys HFSS, http://www.ansys.com