

DESIGN OF 166 MHz AND 500 MHz BIMODAL RF CAVITIES BASED ON COAXIAL COUPLING

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Abstract

Ultra-low emittance is one of the primary directions for the development of synchrotron radiation facilities. To mitigate coupled-bunch instabilities and meet beam-lifetime requirements, higher-harmonic cavities are commonly required in diffraction-limited storage rings. Bimodal cavities are considered multifunctional and compact accelerating structures capable of integrating the functions of a fundamental RF cavity and a higher-harmonic cavity. To support the application of active bimodal RF cavities in low-energy storage-ring light sources, this paper investigates a coaxial coupling and mode-isolation scheme for bimodal cavity operation at 166 and 500 MHz.

INTRODUCTION

Advanced storage rings are core platforms for delivering high-brightness synchrotron radiation. Driven by the concept of diffraction-limited storage rings, fourth-generation light sources are evolving from high-flux facilities toward radiation sources with higher brightness and enhanced transverse coherence [1]. Today, approximately five fourth-generation storage rings worldwide are in operation or user operation, while more than ten others are under construction, being upgraded, or in the design stage. Among these facilities, MAX IV, ESRF-EBS, Diamond-II, Elettra 2.0, and other advanced light sources have adopted or plan to adopt a double-RF system consisting of a normal-conducting fundamental RF cavity and a higher-harmonic cavity. Considering operational reliability, construction cost, and maintenance cost, normal-conducting RF cavities remain a practical and preferred option for many storage-ring light sources. This indicates that the advantages of normal-conducting RF systems are receiving increasing attention in the development of next-generation storage rings.

The bimodal normal-conducting RF cavity is a recently proposed concept for storage-ring applications. By supporting two electromagnetic eigenmodes within a single cavity, this structure can simultaneously provide accelerating voltage and higher-harmonic voltage for bunch lengthening, thereby offering a potential alternative to conventional double-RF systems based on separate fundamental and harmonic cavities. In addition, the compact configuration of the bimodal cavity can reduce the overall footprint of the storage-ring RF system and alleviate the limited space available in the straight sections. Therefore, this concept is of practi-

cal significance for compact lattice design and miniaturized storage-ring light-source applications [2].

In the design of a bimodal cavity, a suitable pair of operating modes must first be selected, and their resonant frequencies must be tuned to satisfy the required harmonic relationship. Employing the TM_{010} mode as the fundamental accelerating mode and the TM_{020} mode as the third-harmonic mode can provide favorable RF characteristics for bimodal operation [3]. To optimize the performance of the TM_{020} mode, its field should be confined within the cavity volume. Therefore, suppressing the leakage of the TM_{020} mode through the fundamental power coupler is a key issue in bimodal cavity design. In this work, a coaxial fundamental-power-coupler scheme for a bimodal cavity is investigated, enabling efficient fundamental-mode power coupling while providing effective isolation of the TM_{020} mode.

MAIN CAVITY DESIGN

The cavity adopts a nose-cone-loaded pillbox-type cylindrical geometry, which is commonly used in normal-conducting RF cavities. The electromagnetic performance of the bimodal cavity was analyzed using the frequency-domain solver in CST Studio Suite, and the corresponding simulation model is shown in Fig. 1. To achieve frequency matching between the two operating modes, the nose-cone gap and the main cavity dimensions were carefully optimized. The cavity radius is $r = 502.38$ mm, and the nose-cone gap is $g = 620.19$ mm.

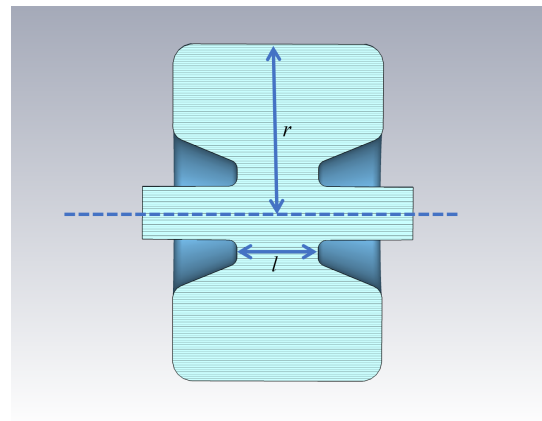


Figure 1: Cavity model.

The optimized design parameters of the bimodal cavity are summarized in Table 1. The shunt impedances of the TM_{010} and TM_{020} modes are 11.82 M Ω and 0.98 M Ω , re-

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spectively. To investigate the coupling behavior of the two operating modes, two loop-type coaxial couplers were introduced in the simulation as the corresponding power-coupling ports. The electric-field distributions near the couplers indicate that the TM_{010} mode is coupled to the TM_{020} -mode port, and thus significant leakage of the fundamental mode occurs through this port. Similarly, the TM_{020} mode has a non-negligible field component near the TM_{010} -mode port, which can result in harmonic-mode leakage through the fundamental power coupler. The corresponding experimentally measured S -parameter are shown in Fig. 2.

Table 1: Electrical Parameter Fitting Results

Parameter	TM_{010}	TM_{020}	Unit
f	166.831	500.254	MHz
R/Q	206.13	18.13	Ω
R_s	11.82	0.98	$M\Omega$
Q	45423	54063.88	-

The two coaxial couplers can effectively feed the two operating modes. The corresponding reflection coefficients are $S_{11} = -26.93$ dB and $S_{22} = -17.85$ dB, respectively. The transmission coefficients between the two mode couplers are $S_{21} = -6.06$ dB and $S_{12} = -1.27$ dB, respectively. These results indicate that the leakage between the two mode-coupling ports is significant.

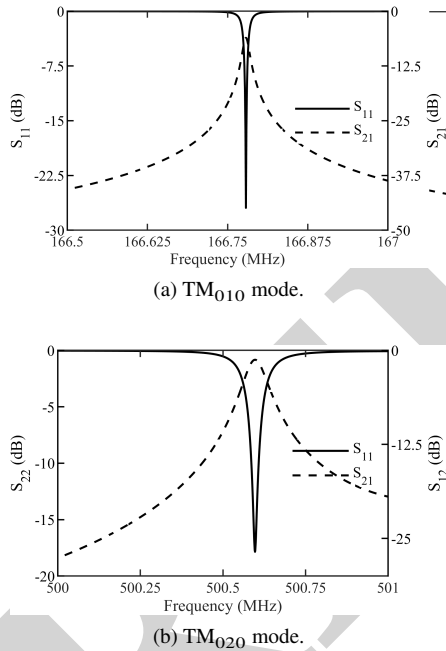


Figure 2: S parameters of coaxial coupler without isolator.

To suppress the power cross coupling between the two modes, effective mode-isolation measures are required [4,5]. For the coaxial coupling scheme, an effective method is to use a coaxial quarter-wavelength stub band-stop filter. The coaxial filter structure used for the preliminary verification is shown in Fig. 3. It is equivalent to a stub with an effective electrical length of one quarter wavelength, with an electric boundary at the end of the stub.

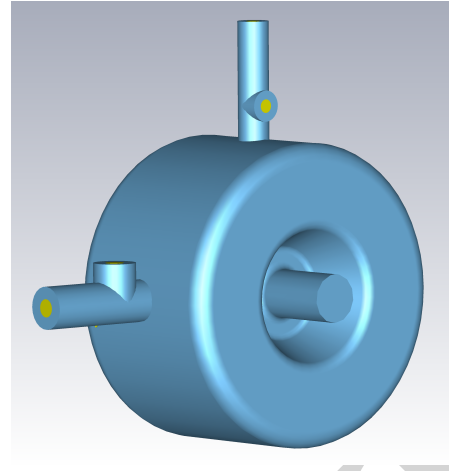


Figure 3: Coaxial coupler for bimodal cavity.

After introducing this structure into the coaxial coupler, the simulated S -parameters are shown in Fig. 4, the transmission coefficients between the two mode couplers are $S_{21} = -33.62$ dB and $S_{12} = -36.11$ dB, respectively. This indicates that the TM_{010} mode is not transmitted through the TM_{020} -mode coupler port, and vice versa. Therefore, the power coupling between the two mode couplers is effectively suppressed.

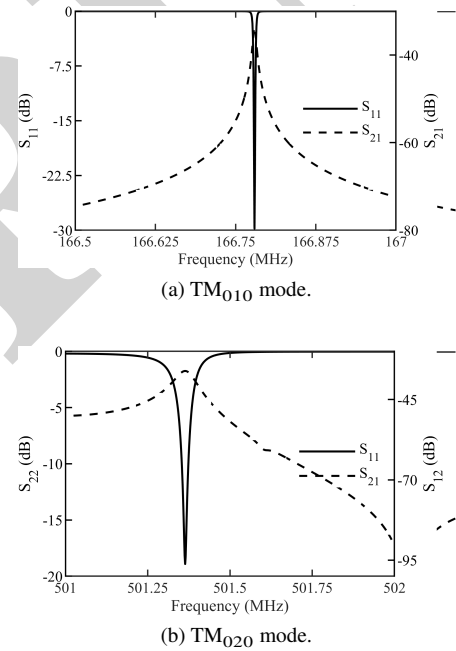


Figure 4: RF cavity bimodal operation.

EQUIVALENT-CIRCUIT ANALYSIS OF COUPLING EFFECTS IN THE BIMODAL CAVITY

In the bimodal cavity, the combined use of coaxial couplers and isolators can effectively suppress the mutual interference between the operating modes. Nevertheless, a portion of the electromagnetic field still leaks into the isolator structures, which influences the operational performance of

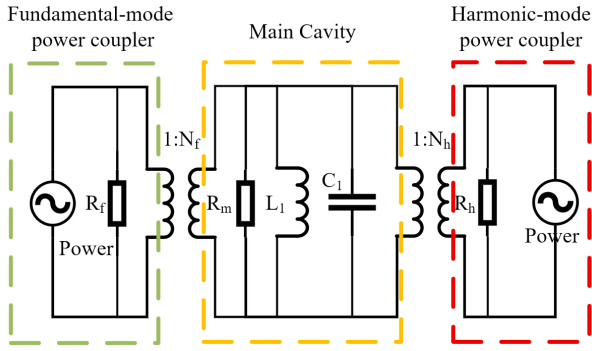


Figure 5: Equivalent circuit of two coaxial couplers.

the bimodal cavity, particularly in terms of impedance characteristics. This effect can be qualitatively analyzed using an equivalent-circuit model. The equivalent circuit model of the bimodal RF cavity is illustrated in Fig. 5. Following the standard mapping procedure that relates the microwave characteristics of an RF cavity to an equivalent resonant circuit. Accordingly, the equivalent circuit is divided into three parts: the fundamental-mode power couplers, the main cavity body and the harmonic-mode power couplers, two couplers connected to the responding RF source, and the HOM damper, each part is represented by the parallel RLC circuit.

The introduction of these couplers perturbs the field distributions and equivalent parameters of the TM₀₁₀ and TM₀₂₀ modes. To quantify these effects, the impedance Z_i and admittance Y_i of a parallel RLC circuit are introduced and denoted as

$$\begin{cases} Z_i(\omega) = R_i + jX_i(\omega), & X_i(\omega) = \omega L_i - \frac{1}{\omega C_i}, \\ Y_i(\omega) = G_i + jB_i(\omega), & B_i(\omega) = \omega C_i - \frac{1}{\omega L_i}. \end{cases} \quad (1)$$

For the target modes, the total admittance of the bimodal cavity, as seen from the power coupler ports, is given by the parallel combination of the cavity admittance and the external circuits enclosed by the green and yellow boxes, and can be written as

$$\begin{aligned} G_{\text{eq}} &= \frac{1}{R_m} + \frac{1}{N_f^2 R_f} + \frac{1}{N_h^2 R_h}, \\ B_{\text{eq}}(\omega) &= \omega C_1 - \frac{1}{\omega L_1}. \end{aligned} \quad (2)$$

Here, G_{eq} and B_{eq} denote the real and imaginary parts of the total admittance as seen from main cavity. It follows that only when the resonant frequencies of the cavity body, the power couplers, and the HOM damping structure coincide does the imaginary part B_{eq} approach zero, such that the equivalent circuit exhibits a purely resistive behavior at both ports.

In the equivalent circuit, the coupling between the cavity and the power couplers is described by transformer ratios. The harmonic-mode power coupler and the fundamental-mode power coupler correspond to transformer ratios of $N_h : 1$ and $N_f : 1$, respectively. The magnitudes of N_f and N_h characterize the power coupling strength, and the coupling coefficient β is proportional to N^2 . The cavity shunt impedance is therefore an effective quantity formed on the basis of the intrinsic cavity impedance R_1 , after being jointly loaded by the two power couplers and the HOM damper.

Consequently, enhancing the isolation between the TM₀₂₀ mode and the TM₀₁₀ power coupler not only helps prevent power leakage of the TM₀₂₀ mode but also enables a higher achievable shunt impedance under bimodal operation.

CONCLUSION

This work discusses the performance of the coaxial coupling scheme in a bimodal cavity. Since coaxial couplers theoretically have no cutoff frequency, frequency leakage may occur. It then discusses the mode isolation provided by coaxial quarter-wavelength isolation stubs between couplers. The results show that this scheme can effectively avoid intermodal crosstalk in the design of coaxial couplers. Finally, the paper analyzes, using an equivalent-circuit model, the factors affecting bimodal performance in the design of dual-feed couplers and isolators. Controlling the coupling strength and enhancing the intrinsic impedance are important measures for optimizing bimodal performance.

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