Invited Paper

A Method for non-destructive testing of resonant frequency in the W-band second harmonic gyrotron complex cavity

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Abstract: In this study, the HFSS is utilized to obtain the field distribution and resonant frequency of the gyrotron complex cavity. The resonant frequency of the complex cavity is experimentally tested with mode converters, and the correctness of the measurement method of the resonance cavity frequency is validated through practical tube fabrication testing.

Keywords: Gyrotron, Complex Cavity, Oscillation Frequency Testing, Mode Converter, Spectrum

Doi:

1. Introduction

The high-frequency gyrotron faces a critical issue related to magnetic fields. Utilizing the interaction between high-order harmonics and the electron beam can exponentially decrease the operating magnetic field in gyrotrons. However, as the harmonic number increases, the issue of mode competition becomes more severe. Recent research has shown that employing a complex cavity with gradual transition [1-5], which has a transmission mode of TEmn/TEmn can effectively suppress mode competition and enhance the efficiency of gyrotron operation.

Due to manufacturing errors, discrepancies may arise between the designed resonant frequency and the actual resonant frequency after the assembly of the complex cavity. If these discrepancies are significant, they may severely impact the output parameters of the gyrotron, leading to substantial inefficiencies. In this study, the TE02-TE03 mode is employed for the complex cavity, and a mode converter of rectangular waveguide mode TE10 to circular waveguide mode TE01 is designed, along with TE01-TE02, and TE02-TE03 mode converters. These mode converters are utilized to inject the TE03 mode into the complex cavity, enabling resonant frequency testings without damaging the resonance cavity.

2. Theoretical analysis

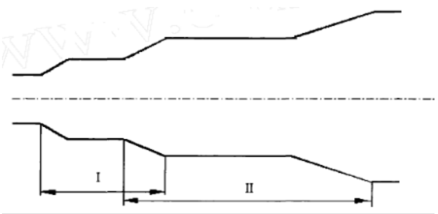

Fig. 1 Structure of complex cavity

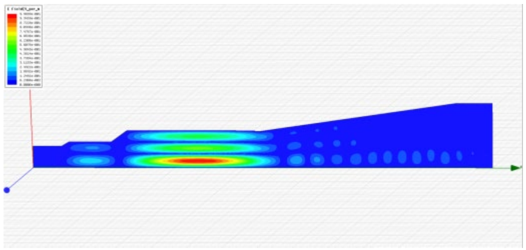

Fig. 2 HFSS simulation of the field distribution in the complex cavity

The complex cavity used in the experiment, as shown in Figure 1, is evolved from a waveguide open resonator with axisymmetric, radially gradual varying characteristics. The first resonator, labeled as "I," operates at TE02 mode, while the second one, labeled as "II" operates at TE03 mode. The connection between the first and second cavities is established through a gradual transition section, forming the complex cavity. Within the complex cavity, a TE02-TE03 working mode pair is generated, which is advantageous in overcoming mode competition and thus enhancing the interaction efficiency of the entire device.

In the first resonator, the gyrotron electron beam interacts with the resonant TE02 mode, exchanging energy and causing modulation of the electron beam by the high-frequency field, leading to the pre-bunching of electrons. In the second resonator, appropriate cavity dimensions are optimized to preferentially excite the TE03 mode, enabling an energy exchange with the gyrotron electron beam and resulting in high-frequency oscillations that amplify the high-frequency field. Ultimately, this configuration outputs microwave oscillation signals, meeting the power requirements.

Figure 2 displays the field distribution of the complex cavity after HFSS involved-optimization. It is evident that a mode pair TE02-TE03 is formed in the first and second resonators, with a resonant frequency point at 93.9849 *GHz*.

3. Testing process

The testing diagram is shown in Figure 3. It begins with the output of the rectangular waveguide mode TE10 from the W-band vector network analyzer. Subsequently, the TE10 mode is sequentially fed into theTE10-TE01, TE01-TE02, and TE02-TE03 mode converters. Finally, the TE03 mode is input into the complex cavity. Figure 4 illustrates the test setup in the actual testing environment.

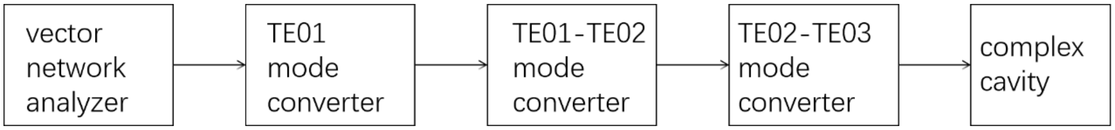

Fig. 3 Testing workflow diagram

The TE03 mode is introduced into the complex cavity through the mode converter, and the resonant frequency is determined by searching for the minimum value of the S11 parameter. As seen in Figure 5, the reflection is minimized at a frequency point of 94.0009 *GHz*, indicating that resonance occurs at this frequency within the cavity. A frequency offset of 16 *MHz* can be observed when comparing the test and simulated values, between which the alignment demonstrates the accuracy and reliability of this testing method.

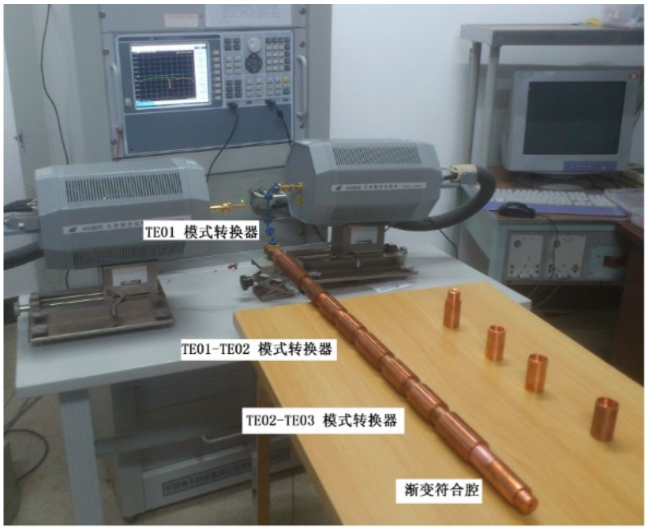

Fig. 4 Testing site

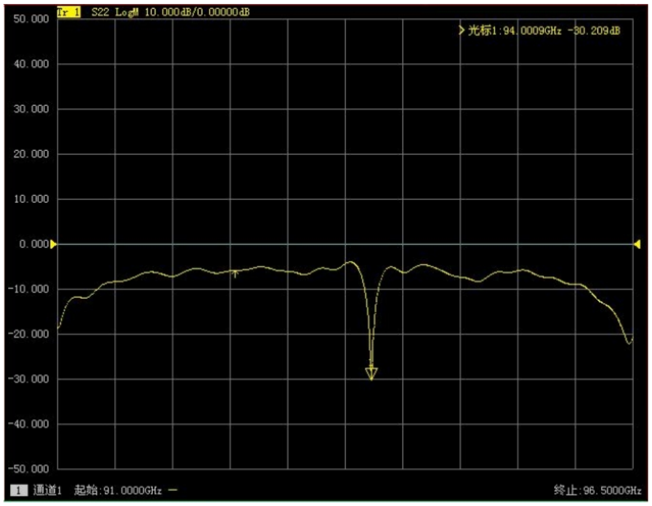

Fig. 5 Testing the resonance point of the compound cavity

4. Tube fabrication testing

Particle simulation software is used to perform beam-wave interaction calculations for the resonator model. The resulting field distribution pattern, as shown in Figure 6, reveals the formation of a pair of mode TE02-TE03 in the first and second resonators. Figure 7 displays the simulated spectrum, which indicates a frequency of 93.956 *GHz*. This result aligns with the HFSS simulation results in Figure 2 and the testing results. The interaction simulation yields an output power of 110 *kW*, where the electron beam velocity spread is not considered.

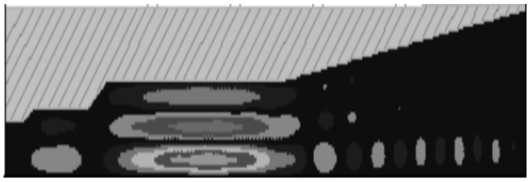

Fig. 6 PIC software simulation of the complex cavity field distribution diagram

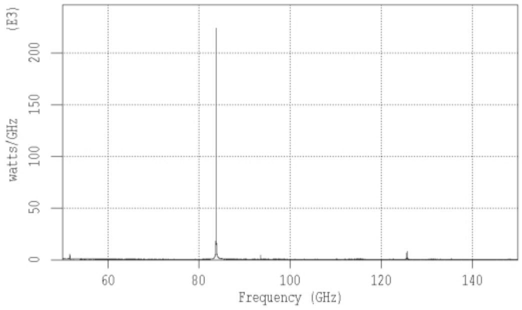

Fig. 7 PIC (Particle-in-Cell) software simulation of the gyrotron output spectrum diagram

The complex cavity is utilized as the high-frequency structure for developing a gyrotron, as depicted in Figure 8, and a dual-anode magnetron injection gun is employed. Under the conditions of 63 *kV* voltage, 15 *A* current, and a magnetic field of 1.8 *T*, an output power of 85 *kW* can be achieved at an oscillation frequency of 93.87 *GHz*. Figure 9 illustrates the spectrum obtained during the testing process. The testing of the spectrum in the W-band frequency range is performed using an external mixer. The high-frequency segment of the two spectral lines represents the actual spectrum at 93.87 *GHz* and the low-frequency segment is the mirror image spectrum.

Fig. 8 Gyrotron's external appearance

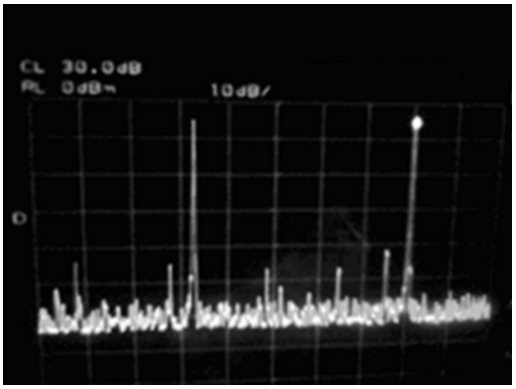

Fig. 9 Test spectrum graph

5. Conclusion

In this paper, HFSS is utilized to calculate the resonant frequency of the TE02-TE03 complex cavity with gradual transition for the W-band gyrotron. By employing mode converters, the frequency of this resonance cavity is experimentally tested, and the results match well, thus presenting a method for testing the resonant frequency of the cavity. Finally, the complex cavity is tested in actual gyrotron fabrication, resulting in an output power of 85 *kW* at an oscillation frequency of 93.87 *GHz*, thereby confirming the accuracy of this testing method.

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