

Numerical modeling of a high-power coaxial-waveguide transition for microwave energy input into a cylindrical resonator cavity

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Abstract. The results of numerical modeling of the transition from a rectangular waveguide to a circular coaxial line of large cross-section, designed to transmit microwave power in units of kilowatts at a frequency of 2.45 GHz, are presented. The design feature of the transition is access from the outside to the inside of the hollow tube of the inner conductor of the coaxial line to supply coolant to the target load of the coaxial line. In this case, the centre electrode of the coaxial crosses the wide wall of the waveguide. Three transition options are considered: stepwise reduction of the narrow waveguide wall, smooth transition with inductive loading, and feeding the coaxial with two waveguides. In addition to matching, attention is paid to the uniformity of mode excitation in the coaxial line, and ways to reduce field inhomogeneity are proposed.

Keywords: coaxial-waveguide junction, waveguide load, rectangular waveguide modes, microwave radiation.

1. Introduction

Modern applications of plasma technologies are shifting towards non-contact creation of plasma initiated by a powerful microwave discharge in low-pressure chambers. In the design of technological installations it is necessary to solve the problem of microwave radiation input into the working cavity of a cylindrical resonator to excite the TM_{021} mode. This mode is symmetric, has a maximum electric field strength near the excitation element in the form of a disc fed by a coaxial transmission line. The cylindrical resonator with TM_{021} mode [1, 2] has a wide region with uniform distribution of plasma formation. To prevent heating of the disc material and contamination of the vacuum volume with metal ions, as well as overheating of samples on the surface of the disc, a cooling liquid is circulated in its inner cavity. The only way to get the coolant inside the disc is through the hole in the centre electrode of the coaxial line.

The waveguide path of a microwave installation usually includes standard parts such as a microwave generator head with rectangular waveguide output, a circulator and a stub tuner. The radiation input device in the resonator chamber is a non-standard component that is dependent upon the design of the vacuum chamber and the selected operation mode. The distinguishing feature of the waveguide-coaxial transition under consideration is that the inner electrode of the coaxial must be connected to the outer side of the wide wall of the rectangular waveguide in order to facilitate the supply of coolant within it.

Microwave energy is used to heat materials, create plasma assisted chemical reactions and excite gaseous media in resonator cavities. Magnetron tubes are inexpensive and similar to household microwave ovens, which ensures their widespread use. They use two main authorized oscillation frequencies 915 MHz and 2.45 GHz. A frequency of $2450 \pm 2.0\%$, i.e., the frequency band 2.4–2.5 GHz, is allocated for industrial, scientific, medical, and household devices. Experiments were conducted on ordinary magnetrons of household microwave ovens with an input power rating of 700–800 W and magnetrons of increased power (2 and 3 kW), which showed that at a single-half-period scheme, with voltage doubling, almost all magnetrons produced a frequency of 2.437–2.452 GHz for the radiation of output. These results were consistent with those previously observed in other studies. It is possible to obtain a power generation of 1.8–2 kW when switching on magnetrons of household microwave ovens in quasi-continuous mode from a three-phase network and increasing the average cathode current by 2.5 times relative to the passport values. The centre frequency in the emission spectrum has a spread of up to 2.42–2.47 GHz at such a supply of

magnetron. This determines the frequency range in which good matching of the waveguide-coaxial junction should be achieved.

At a frequency of 2.45 GHz and microwave oscillation power up to 5 kW, a waveguide with a cross-section of $90 \times 45 \text{ mm}^2$ or its analogue WR340 with a cross-section of $86.36 \times 43.18 \text{ mm}^2$ is typically used. To reduce the probability of electrical breakdown, the coaxial line filled with air should have a certain gap between the electrodes, not less than 10 mm. Based on the assortment of rolled pipes, the optimum variant of the coaxial path is the use of an outer pipe with a diameter of 57 mm (inner diameter 51 mm) and an inner pipe with a diameter of 28 mm. The air gap is 12.5 mm and the wave impedance of the coaxial is 36 Ohm. Three variants of transition from a $90 \times 45 \text{ mm}^2$ waveguide to such a coaxial line are shown below.

2. Waveguide-coaxial transition with staggered reduction of the narrow waveguide wall

A model of the waveguide-coaxial transition is shown in Fig. 1. A cross section of the structure along the wide waveguide wall in the xz plane is shown. The rectangular waveguide 1 has a shorted wall and is connected to the output by a coaxial waveguide 2. The inner electrode of the coaxial line 3 is hollow with access to the inner cavity from below. A stepwise reduction in the height of the rectangular waveguide is applied to match the wave impedance. The front part of the stepped part 4 is inclined, the length of this part and the angle of inclination were found as a result of optimization by numerical simulation in the software product CST Studio Suite.

The distribution of electric field strength near the metal surface is shown in Fig. 2. The root-mean-square (RMS) value of the field modulus at the effective power value of 0.5 W at the input is shown. The figure illustrates the region of localized field enlargement over the stepped part, which limits the maximum transmitted power. At an incident power of 10 kW, the peak electric field strength does not exceed 6 kV/cm. However, in the presence of a reflected wave, this calculated value can double, but does not exceed the breakdown voltage for dry air.

The primary issue with using a waveguide-coaxial junction with a large diameter tube is the non-uniformity of the field in the coaxial transmission line, as shown in Fig. 2. The wave propagating in the rectangular waveguide excites currents on the front and back surfaces of the inner electrode of the coaxial line with different phases. This leads to non-uniform excitation in the coaxial line in the xy plane and subsequently non-uniform excitation of the load. One potential solution to reduce the phase difference is to reduce the diameter of the inner electrode of the coaxial line to a fraction of the wavelength in a rectangular waveguide. However, reducing the diameter of this electrode is undesirable because of a reduction in the cross-sectional area of the internal cavity required to supply coolant to the coaxial line load. A second possibility is to reduce the width of the rectangular waveguide a . The wavelength λ_w of the main mode H_{01} in the rectangular waveguide increases as the critical wavelength $\lambda_c = 2a$ is approached according to the expression:

$$\lambda_w = \lambda / \sqrt{1 - (\lambda / \lambda_c)^2},$$

where $\lambda = c/f$, and f is a microwave frequency, c – velocity of light. Consequently, reducing the width of the waveguide a will result in a shift λ_w to the cut-off wavelength at a frequency of 2.45 GHz. At a distance equal to the diameter of the inner electrode and at large λ_w , the oscillation phase change will become less significant.

The result of the calculation of the absolute value of reflection coefficient $|S_{11}|$ is shown in Fig. 7 (curve 1). The matching bandwidth was 2.42–2.52 GHz at –10 dB level. The presented model has constructive simplicity and is suitable for manufacturing, but the value of $|S_{11}|$ should be reduced in order to have a margin for deviation of the dimensions of the manufactured sample from the model.

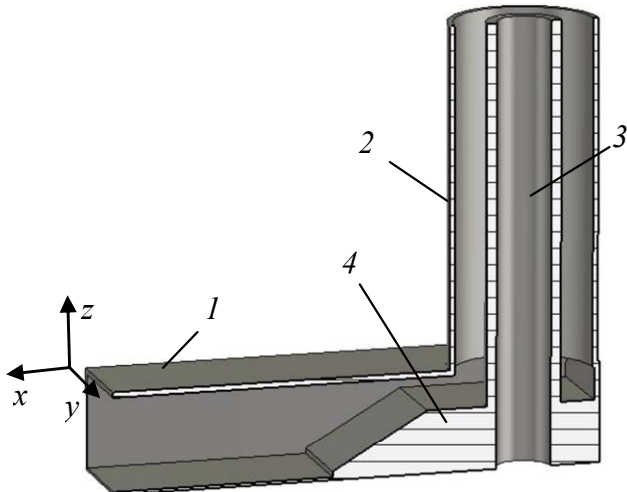


Fig. 1. Schematic representation of the waveguide-coaxial junction design.

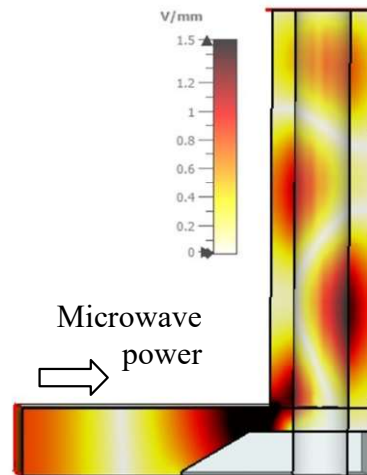


Fig. 2. Electric field strength distribution near the electrode surface.

3. Waveguide-coaxial junction with inductive loading and smooth change of the coaxial line cross section

The design of the waveguide-coaxial transition with an extended matching bandwidth is illustrated in Fig. 3, which depicts the section along the centre of the wide wall. The rectangular waveguide 1 is equipped with a short-circuited wall 2 at a distance of approximately $\lambda_w/3$ the centre electrode of the coaxial line 3 is located. The outer electrode of the coaxial line has a tapered section 4 which allows for a gradual change in the cross-sectional area of the line [3–4]. The matching bandwidth can be expanded by using of an inductive element, formed by the short-circuited section of the coaxial line. Additional control of the reflection coefficient is possible with the help of aperture 6. The frequency dependence $|S_{11}|$ is shown in Fig. 7 (curve 2). The matching bandwidth according to the simulation and optimisation results was 2.41–2.52 GHz.

The distribution of electric field strength (effective value for the period of microwave oscillations) is shown in Fig. 4. The field non-uniformity in the section of the coaxial line has decreased compared to the previous example. However, the effect of excitation of coaxial line sections with different phases remains.

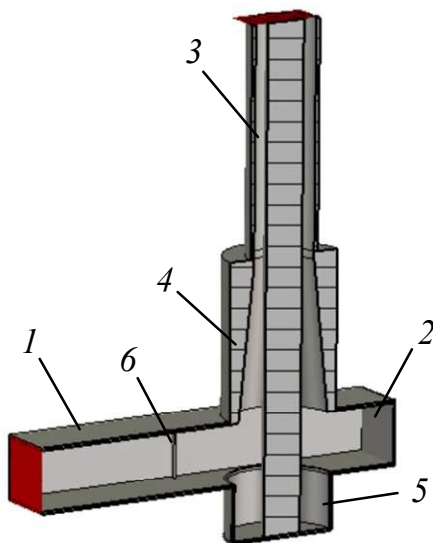


Fig. 3. Model of waveguide-coaxial transition with inductive element.

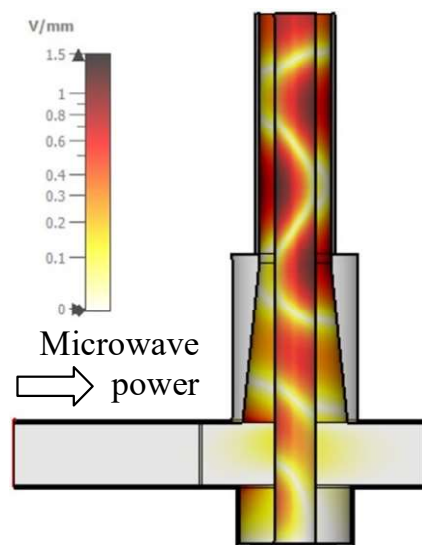


Fig. 4. Electric field strength (RMS) distribution in the proposed model.

4. Waveguide-coaxial junction with two rectangular waveguides feeding the coaxial line

In order to enhance the field uniformity in the cross section of the coaxial line, the following transition design was proposed, a section of which is shown in Fig. 5. The rectangular waveguide 1 is divided into two sections coiled in a ring. These sections in-phase feed the coaxial line 3. A short-circuited coaxial line segment 4 and an aperture 5 are used for matching. Their dimensions are found as a result of the carried out optimization procedure of the parameterized model. The frequency dependence of the reflection coefficient is shown in Fig. 7 (curve 3). The matching bandwidth was 2.38–2.6 GHz at –10 dB level. The distribution of electric field strength near the metal electrodes of the transition model is shown in Figure 6. The field in the cross section of the coaxial line is almost uniform with inhomogeneity not more than 20%. Despite the complexity of fabrication of the proposed model, the possibility to obtain uniform excitation of the coaxial line leaves this design promising. The absence of areas of significant local field enlargement allows for the use of this transition at high microwave power.

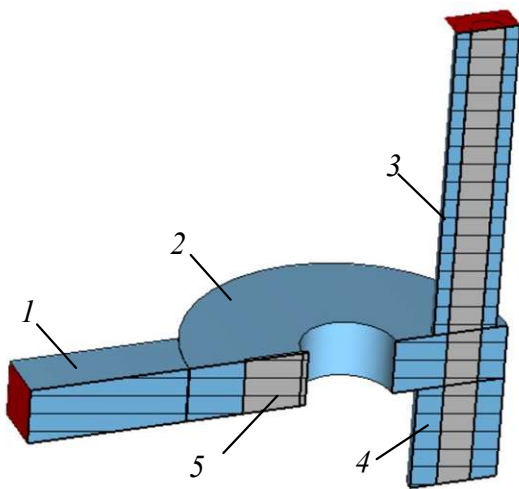


Fig. 5. Transition model with a coaxial line fed by two sections of a rectangular waveguide.

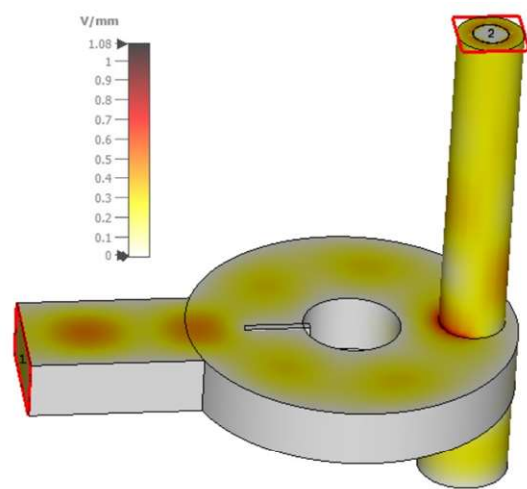


Fig. 6. Distribution of electric field strength (RMS) in the transition model.

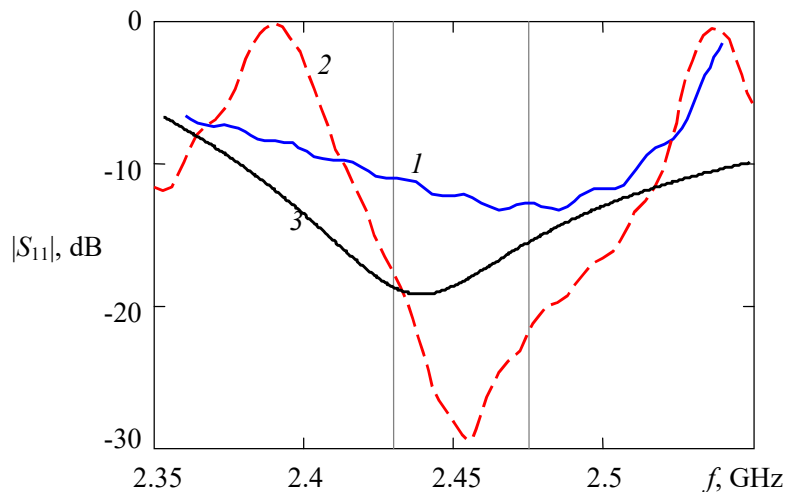


Fig. 7. Reflection coefficient from the rectangular waveguide input.

5. Conclusion

The results of numerical modeling of three variants of the design of the transition from a rectangular waveguide to a round coaxial line of large cross-section designed to transmit microwave

power in units of kilowatts at a frequency of 2.45 GHz are presented. These models allow the execution of the centre electrode as a hollow tube to supply coolant to the coaxial line load. It is shown that field uniformity in the cross section of the coaxial line can be achieved by in-phase feeding it with two sections of rectangular waveguide. The matching bandwidth of all considered variants of waveguide-coaxial transitions allows to use at excitation by magnetron generators of industrial frequency 2.45 GHz.

Acknowledgements

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6. References

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