RESEARCH ON DIODE TM_{00}-COAXIAL TEM MODE CONVERTER

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In order to analyze the radiation mode of electromagnetic wave vacuum planar in diode, Borgnis function is used to solve the field equation of the radial line in the cylindrical coordinates. Sequentially, the electric field of TM_{00} mode is obtained. According to the analysis of TM_{00} mode, it shows that the electric field has no directionality under TM_{00} mode. Thus, design of the mode converter is necessary in order to realize the directional radiation of microwave, and then a diode TM_{00}–coaxial TEM mode converter is presented. Through analysis and calculation, initial size of the mode converter is obtained, and the conversion efficiency is 90.9%. In order to increase the conversion efficiency, size of the mode converter is adjusted by optimization design. The calculation results show that the conversion efficiency via optimization arrives at 98.4%. In addition, when the frequency of converter is 2-4GHz, the relative bandwidth of efficiency more than 90% is 10%-15% and the lowest efficiency is 65.2%.

Keywords: Mode converter; Microwave; Radial transmission line; Coaxial Waveguide

1. Introduction

Intense-current electron-beam vacuum planar diode is applied to fields of high intensity accelerator and high power microwave for its advantages of simple and compact structure, high power, adjustable frequency and easy realization of repetition frequency[1]-[4].

Generally, vacuum planar diode with triggered electrode has been studied on its switch characteristics [5]-[7]. However, seldom study reports about radiation characteristics of triggered vacuum diode. In this paper, radiation mode of

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electromagnetic wave of intense-current electron-beam vacuum planar diode is researched.

2. Radiation Electromagnetic Wave Process

Structure of vacuum planar diode with triggered electrode is shown in Fig. 1. Generation of electromagnetic wave process is as follows, ①trigger device generates triggered pulsed high voltage to form initial plasma near cathode and triggered electrode, as shown in Fig. 2-a; ②Under the effect of electric field, electrons are extracted from initial plasma to move towards anode, and then the bombard anode to form plasma anode, as shown in Fig. 2-b. Subsequent electrons move towards the anode and interact with the plasma near the anode. At this stage, microwave is generated; ③simultaneously, under the effect of electric field, ions move from cathode to bombard cathode, and then form arc plasma. Subsequently, plasma near the cathode and anode diffuse rapidly in the inter-electrode gap. Finally, it causes conduction of inter-electrode gap, and then microwave radiation terminates [8][9]. The stage is shown in Fig. 2-c.

Through the analysis on the structure diagram of diode, it can be founded thatthe microwave radiation propagates in the radial direction [9]. Because the structure of diode is cylindrical symmetry, microwave radiation propagation also has the characteristic of cylindrical symmetry. However, the characteristic goes against the directional radiation of microwave. Thereby, in order to realize the directional radiation of microwave, radiation mode of cylindrical symmetry should be converted into TE_{11} mode, which has the characteristic of axial radiation maximum. The converter has been studied by many researchers. Reference [10] presented the converter of circular waveguide TM_{01} - coaxial TEM - circular waveguide TE_{11} mode. Reference [11][12] designed a coaxial fin-inserted mode converter of coaxial TEM - circular waveguide TE_{11}.

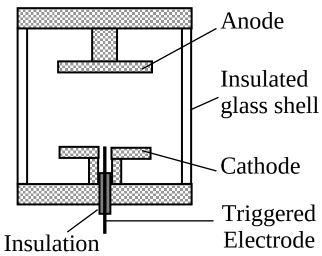


Fig. 1. Structure diagram of diode

However, seldom study reports about the converter of cylindrical symmetry TM_{00} - circular waveguide TE_{11} mode. In this paper, the converter of TM_{00} - coaxial TEM - circular waveguide TE_{11} mode is studied. Considering the research on the converter of coaxial TEM - TE_{11} mode is mature, only cylindrical symmetry TM_{00} - coaxial TEM is studied in this paper. In addition, the frequency range of radiation microwave of the diode is from 2GHz to 4.2GHz. Ultra-wideband characteristic of the converter is also researched in this paper.

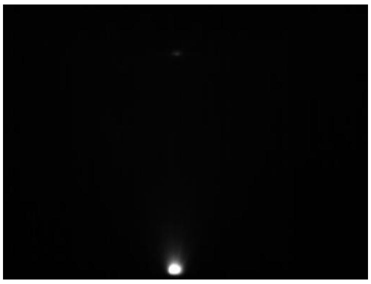


Fig. 2-a. Initial Plasma formed

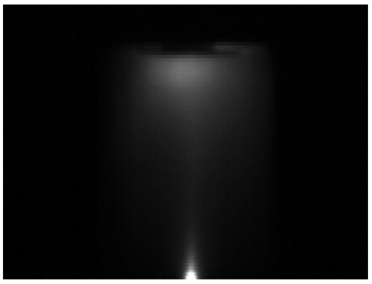


Fig. 2-b. Plasma formed near anode

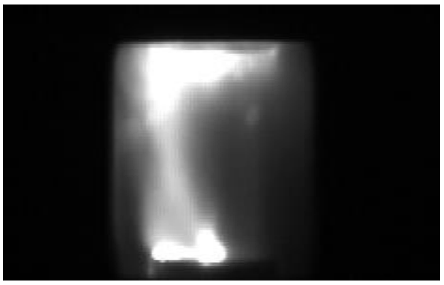


Fig. 2-c. Discharge channel formed

3. Analysis of Propagation Mode of Diode

In order to receive the propagation mode of microwave in the parallel plate electrode, Borgnis function is used to solve field equation of radial line in the cylindrical coordinates. Radial propagation line is shown in Fig. 3. Because the radial propagation line is inhomogeneous waveguide, longitudinal and transverse field could not be separated to solve. Therefore, z direction is used as longitudinal, U and V functions are used to solve field components in the cylindrical coordinates.

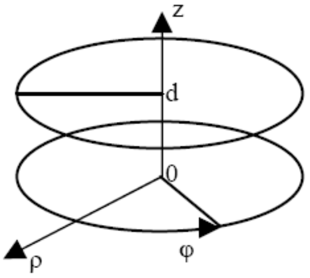


Fig. 3. Schematic diagram of the radial transmission line

$$\frac{1}{\rho}\frac{\partial}{\partial\rho}\left(\rho\frac{\partial U}{\partial\rho}\right)+\frac{1}{\rho^2}\frac{\partial^2 U}{\partial\varphi^2}+\frac{\partial^2 U}{\partial z^2}+k^2U=0 \tag{1}$$

$$\frac{1}{\rho}\frac{\partial}{\partial\rho}\left(\rho\frac{\partial V}{\partial\rho}\right)+\frac{1}{\rho^2}\frac{\partial^2 V}{\partial\varphi^2}+\frac{\partial^2 V}{\partial z^2}+k^2V=0 \tag{2}$$

where, $k^2=\omega^2\mu\varepsilon$

The continuity boundary condition of the circle is as follows.

$$v(\varphi+2\pi)-v\varphi=n2\pi \qquad (n=0,1,2\ \Lambda) \tag{3}$$

It can be obtained,

$$v=n \qquad (n=0,1,2\ \Lambda) \tag{4}$$

The boundary condition of the parallel plate electrode is as follows.

$$\frac{\partial U}{\partial z}\Big|_{z=0}=\frac{\partial U}{\partial z}\Big|_{z=d}=0 \tag{5}$$

$$V\big|_{z=0}=V\big|_{z=d}=0 \tag{6}$$

It can be obtained,

$$\beta=\frac{p\pi}{d} \qquad (p=0,1,2\ \Lambda) \tag{7}$$

So general solutions of U and V can be derived as,

$$U(\rho,\varphi,z)=[A_1J_n(T\rho)+B_1N_n(T\rho)]\cos n(\varphi-\phi_1)\cos\beta z \tag{8}$$

$$V(\rho,\varphi,z)=[A_2J_n(T\rho)+B_2N_n(T\rho)]\cos n(\varphi-\phi_2)\sin\beta z \tag{9}$$

The relationship between field components and U V functions is shown as,

$$E_\rho=\frac{\partial^2 U}{\partial\rho\partial z}-j\frac{\omega\mu}{\rho}\frac{\partial V}{\partial\varphi} \tag{10}$$

$$E_\varphi=\frac{1}{\rho}\frac{\partial^2 U}{\partial\varphi\partial z}+j\omega\mu\frac{\partial V}{\partial\rho} \tag{11}$$

$$E_z=T^2U \tag{12}$$

$$H_\rho=\frac{\partial^2 V}{\partial\rho\partial z}+j\frac{\omega\varepsilon}{\rho}\frac{\partial U}{\partial\varphi} \tag{13}$$

$$H_\varphi=\frac{1}{\rho}\frac{\partial^2 V}{\partial\varphi\partial z}-j\omega\varepsilon\frac{\partial U}{\partial\rho} \tag{14}$$

$$H_z=T^2V \tag{15}$$

where $T^2=k^2-\beta^2$.

By substitution of U and V expressions into above equations, field components can be obtained. TM_{np} and TE_{np} represent transverse magnetic wave and transverse electric wave mode respectively.

Obviously, the lowest order mode is TM_{00}. In this case, U and V are respectively:

$$U(\rho,\varphi,z) = A_1 J_n(T\rho) + B_1 N_n(T\rho) \tag{16}$$

$$V(\rho,\varphi,z) = 0 \tag{17}$$

So the field components of TM_{00} can be achieved:

$$E_z = T^2 U \tag{18}$$

$$H_\varphi = -j\omega\varepsilon \frac{\partial U}{\partial \rho} \tag{19}$$

$$E_\rho = E_\varphi = H_\rho = H_Z = 0 \tag{20}$$

Through the analysis of equations (18)-(20), it can be seen that,the electric field components only relate to ρ and have characteristics of rotational symmetry under the TM_{00} mode. Additionally, with the increase of ρ, the electric field intensity in z direction varies periodically with positive-negative alternation. The schematic diagram of E-plane electric field is shown in Fig. 4. Obviously, the above shows that the electric field of TM_{00} mode has no directionality in the structure. That is, TM_{00} mode goes against the directional radiation of microwave. Thus, TM_{00} mode of the diode should be converted into TE_{11} mode, which has characteristic of directionality. Method of TM_{00}-coaxial TEM-circular waveguide TE_{11} mode is adopted in this paper. Considering the research on the converter of coaxial TEM-TE_{11} mode is mature, only the converter of cylindrical symmetry TM_{00}-coaxial TEM is designed as follows.

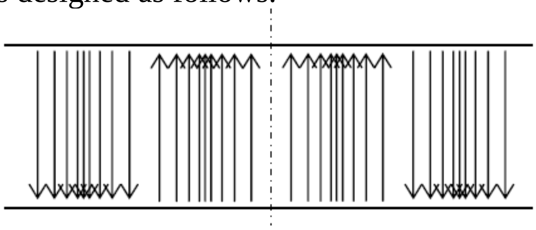


Fig. 4. Schematic diagram of E-plane electric field

4. Design of Mode Converter

Considering the microwave of TM_{00} mode can only transmit along the radial direction in the diode, the radiation direction of the microwave should be changed to transmit along the axial direction firstly. Thus, as shown in Fig. 5, the mode converter is designed specially. The converter is composed of upper part, middle part and lower part. The lower part is a reflection surface connecting with the bottom edge of the diode. The middle part is a coaxial waveguide of the fixed radius connecting the lower part with the upper part of mode converter. The upper part is the coaxial waveguide of the radius tapered.

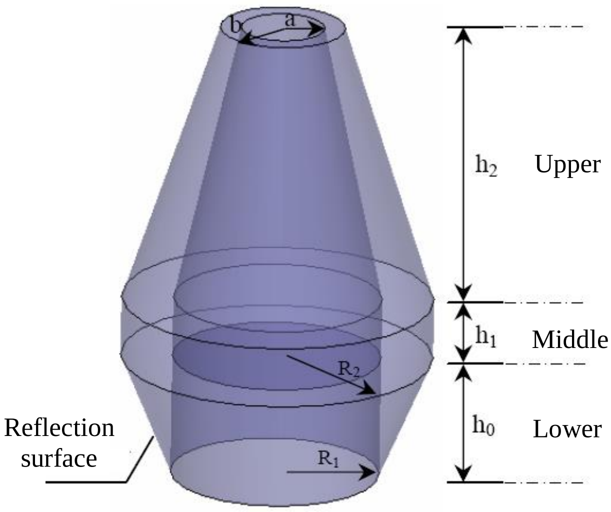


Fig. 5. Structure of the novel mode converter

Through the effect of reflection surface on the lower part, the radiation microwave from the diode changes propagation direction. TM_{00} mode, which transmits along the radial direction, is converted into coaxial TEM mode transmitting along z direction.

In the lower part of the converter, R_1 is the radius of diode and the reflection surface bottom; R_2 is the radius of the reflection surface top. R_1 = 5cm and R_2 = 7.485cm. Mode cut-off frequency of coaxial waveguide is calculated as follows.

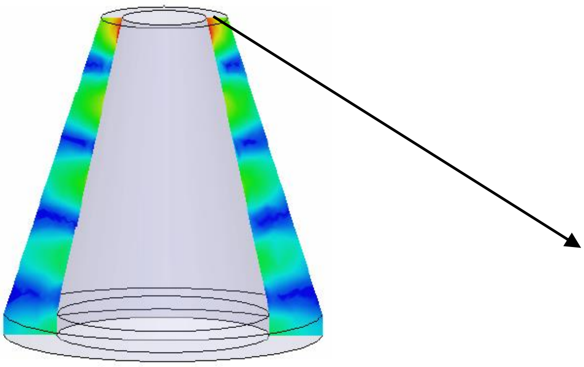
$$f_{cTE21} \approx \frac{2c}{\pi(R_1 + R_2)} \tag{21}$$

$$f_{cTE01} = f_{cTM01} \approx \frac{c}{2(R_2 - R_1)} \tag{22}$$

It can be calculated that the cut-off frequency of TE_{21}, TE_{01} and TM_{01} are respectively 1.53GHz, 6GHz and 6GHz. Due to the cut-off frequency of TE_{21} mode is less than 2GHz, TE_{21} mode can be excited in the coaxial waveguide. In order to avoid the generation of TE_{21} mode, the waveguide size should be reduced. Therefore, the upper part is designed as the coaxial waveguide of radius tapered. The lower part and the upper part are connected by middle part that is the coaxial waveguide of the fixed inner and outer radius.

R_1 and R_2 is the inner and outer radius of the middle part respectively. A and b are the inner and outer radius of the upper part top respectively. H_0, h_1 and h_2 are the height of the lower, middle and upper part.

Initial design parameters of the mode converter are as follows, h_0 = 6cm, h_1 = 1cm, h_2 = 14cm, a = 2cm and b = 3cm. Using HFSS simulation software, the electric field in the mode converter is received as shown in Fig. 6. The electric vector graph on the top is shown in Fig. 7. When f = 4GHz, the conversion efficiency is 90.9%.



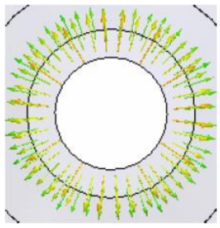


Fig. 6. Electric field in the mode converter   Fig. 7. Electric vector graph on the top

5. Optimization Design

In order to improve the conversion efficiency, initial design parameters of the mode converter should be optimized. Program based on finite element method is used to optimize these parameters. For the reason that h_0, R_1 and R_2, which are limited to the structure of diode, are fixed, only h_1, h_2, a and b can be optimized.

It is assumed that the frequency of the converter is 4GHz. The relation of h_1, h_2, a, b and the conversion efficiency is calculated as shown in Fig. 8-11. In Fig. 8, the conversion efficiency is the highest when h_1 is 4.25cm. When h_1 is 0.6cm, the efficiency is close to the highest. In order to reduce the size of the converter, h_1 = 0.6cm is adopted. In Fig. 9, when h_2 is 17.25cm, the conversion efficiency is the highest. When h_2 is 13.5cm, the efficiency is close to the highest. Simultaneously, in order to reduce the size of the converter, h_2 =13.5cm is adopted. In Fig. 10, when a is 1.75cm, the efficiency is the highest as 93.4%. In Fig. 11, when b is 3.35cm, the efficiency is highest as 95%.

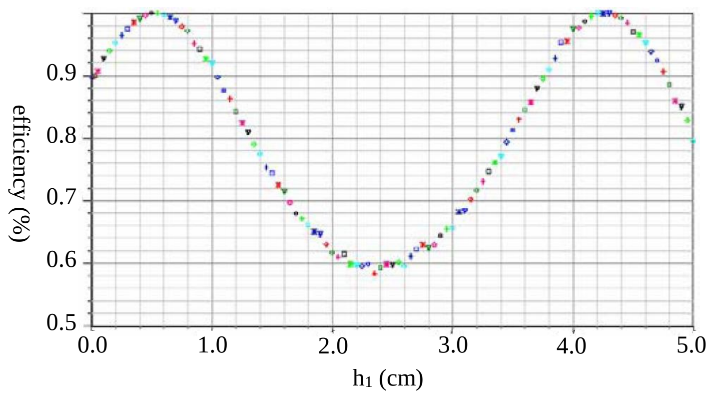


Fig. 8. Relation of h_1 and the conversion efficiency with other fixed parameters

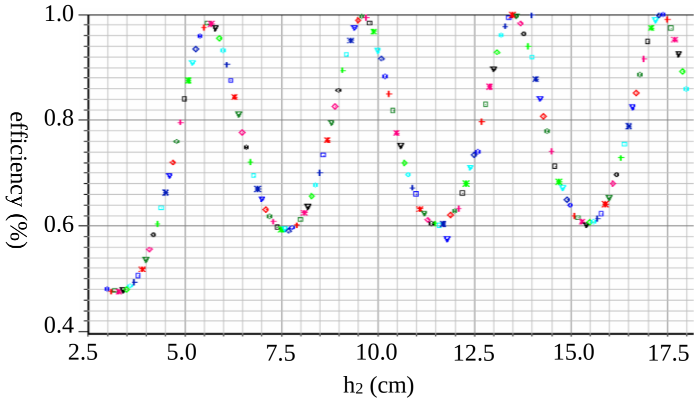


Fig. 9. Relation of h_2 and the conversion efficiency with other fixed parameters

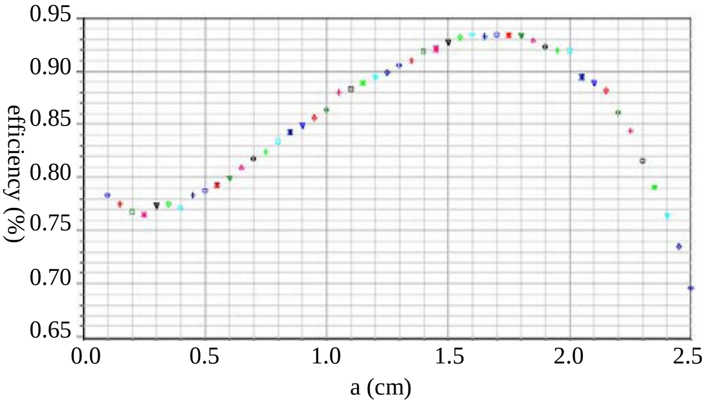


Fig. 10. Relation of a and the conversion efficiency with other fixed parameters

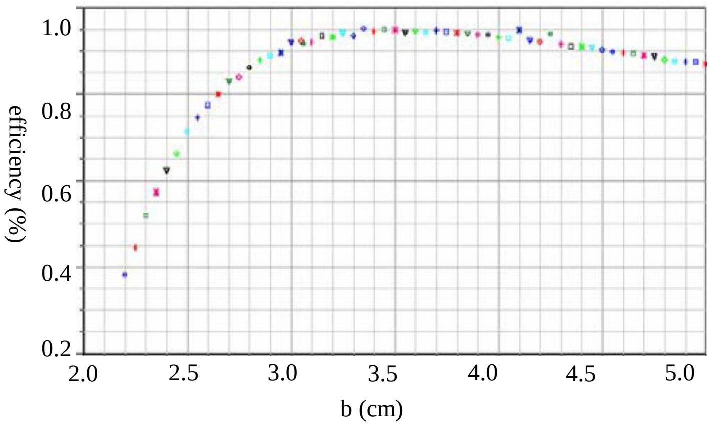


Fig. 11. Relation of b and the conversion efficiency with other fixed parameters

According to the relation between the conversion efficiency and parameters of the converter, the higher conversion efficiency can be obtained when h_1 = 0.6cm, h_2 = 13.5cm, a = 1.75cm and b = 3.35cm. Through the recalculation, the whole conversion efficiency reaches 93.1%. And then, through the comprehensive test on the above parameters when h_1 = 1cm, h_2 = 13.5cm, a = 1.9cm and b = 3.1cm, the whole conversion efficiency reaches 98.4%.

When the frequency of the converter is 2GHz, the whole conversion efficiency of the above parameters is 97.8%. The efficiency of 3GHz is 98.2%. In addition, when the frequency of the converter is 2-4GHz, the relative bandwidth of efficiency more than 90% is 10%-15%, and the lowest efficiency is 65.2%.

6. Conclusion

In order to convert TM_{00} mode into the coaxial TEM mode, TM_{00}-coaxial TEM mode converter is designed in this paper. The converter has characteristics of small size, easy realization and high efficiency. It consists of three parts, namely the lower part, the middle part and the upper part. The lower part is a reflection surface changing the direction of wave propagation. The middle part is a coaxial waveguide of fixed radius connecting the lower part with the upper part of the mode converter. The upper part is the coaxial waveguide of the radius tapered converting TM_{00} mode into TEM mode. Through the assumption of 4GHz operation frequency, the optimization parameters with h_1 = 1 cm, h_2 = 13.5 cm, a = 1.9 cm and b = 3.1 cm are calculated. The conversion efficiency reaches 98.4%. Meanwhile, under the above conditions of optimization parameters, the conversion efficiency of 2GHz and 3GHz is 97.8% and 98.2% respectively. The relative bandwidth of efficiency more than 90% is 10% -15%.

Acknowledgements

The authors would like to thank the National Natural Science Foundation of China under Grant No.51641708 and No.51207171 for financially supporting this research.

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