Terahertz harmonic gyrotron based on spoof surface plasmon

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***Abstract*—Gyrotron is based on the principle of relativistic electron cyclotron maser. With the working frequency increasing to terahertz band, the mode competition problem is caused by the interaction between harmonic cyclotron electrons and high order electromagnetic modes. In order to solve this problem, the interaction cavity of harmonic gyrotron based on spoof surface plasmon (SSP) is proposed in this paper, and its eigenmode frequency is studied, the concept of *Band Gap* is proposed. If the competition frequency is in the stopband, the competition mode will not be generated. Finally, the Particle-in-cell (PIC) simulation is carried out, which proves that the structure can make the terahertz gyrotron work in the single mode in state of high harmonics.**

Index Terms—Terahertz, gyrotron, higher harmonic, spoof surface plasmon, mode competition

I. INTRODUCTION

Gyrotron, based on the principle of relativistic electron cyclotron maser, can generate high-stability coherent electromagnetic radiation in millimeter wave and terahertz frequency band. It can be used in plasma heating, imaging of dynamic nuclear polarization nuclear magnetic resonance, and high-speed wireless communication [1][2].

When the frequency of gyrotron reaches terahertz band, the interaction cavity of gyrotron generally adopts high-order electromagnetic mode. In order to reduce the intensity of magnetic field, the terahertz gyrotron usually works in the state of high harmonics. Therefore, it leads to the problem of mode competition. The same cyclotron harmonic may excite multiple modes with similar working frequency; at the same time, different cyclotron harmonics may excite different modes, and the frequency of the competing mode is approximately the frequency doubling relationship [3]. The excited competition mode will reduce the working efficiency of the gyrotron, seriously affect the working stability, and generate incoherent electromagnetic radiation.

In order to suppress the mode competition, the interaction cavity of harmonic gyrotron based on spoof surface plasmon is proposed in this paper. The characteristic of its eigenfrequency distribution is studied, and the possibility of the gyrotron working in the single mode in state of high harmonics is explored.

II. BAND-GAP OF SPOOF SURFACE PLASMON RESONATE CAVITY

Spoof surface plasmon (SSP) was first proposed by a team led by J. Pendry of Imperial College London. They found that the structure of one-dimensional metal groove can reduce the metal plasma frequency ω_p to microwave band, so that this spoof structure can produce surface plasmon polaritons similar to the light wave band [4].

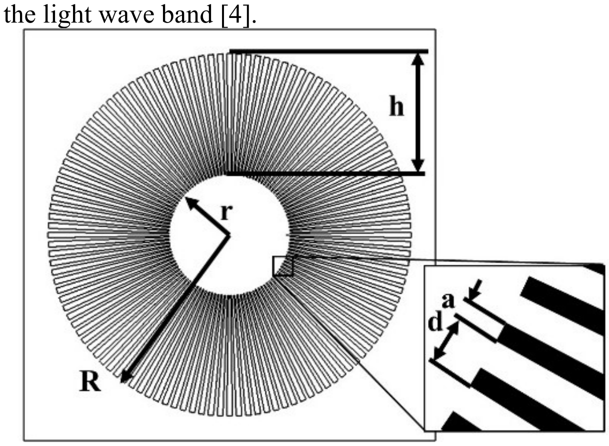

Fig. 1 The structure of the spoof surface plasmon resonator.

A resonate cavity based on spoof surface plasmon has been proposed (Fig. 1), which is a kind of closed textured cavity. The material of the outer wall of the resonant cavity is perfect electric conductor (PEC), and the groove with the depth of h=R-r along the radial direction of the circumference is made, R is the radius of the outer wall of the resonator, r is the radius of the air cavity, and the material of the giant groove is perfect electric conductor (PEC). The grating constant is d, the duty cycle of grating is a/d, and the number of grating is N, which satisfies the quantitative relationship $Nd = 2\pi r$. According to the approximate condition proposed by Pendry [4], the grating constant satisfies the subwavelength limit $d \ll \lambda_0$, and λ_0 is the wavelength corresponding to the eigen frequency of the resonator. The specific parameters are as follows: $N = 120$, $a / d = 0.6$, $r = 3R$, $r = 0.5mm$. In the analysis of eigenmodes, only the plane structure is considered, and the number of axial modes is not considered, or the electromagnetic wave is considered to be uniformly distributed along the axial direction.

The analytical solution of the eigenmode of the section of spoof surface plasmon resonator is obtained from [5]. Because this structure is circular symmetric, it is convenient to use polar coordinates.

$$\frac{a}{d}\sin c^2\left(\frac{ma}{2r}\right)\frac{J_m(k_0 r)}{J'_m(k_0 r)}\frac{f}{g} = n_g \qquad (1)$$

Where $f = Y_1(k_0 n_g r)J_1(k_0 n_g R) - Y_1(k_0 n_g R)J_1(k_0 n_g r)$, $g = Y_1(k_0 n_g R)J_0(k_0 n_g r) - Y_0(k_0 n_g r)J_1(k_0 n_g R)$ .This is a transcendental equation. J_0 and J_1 are the zero order and the first order forms of the first kind of Bessel function respectively. Y_0 and Y_1 are the zero order and the first order forms of the second kind of Bessel function, respectively. Different N represents different modes. Through observation, we can find that the eigen equation contains the frequency of resonance.

Because the principle of gyrotron is the interaction between the gyrotron electron beam and the transverse electric field to exchange energy, we mainly consider TE mode here. The eigen frequencies of $TE_{n,1}$、$TE_{n,2}$、$TE_{n,3}$ mode are solved and plotted on a two-dimensional coordinate graph. (Fig. 2.)

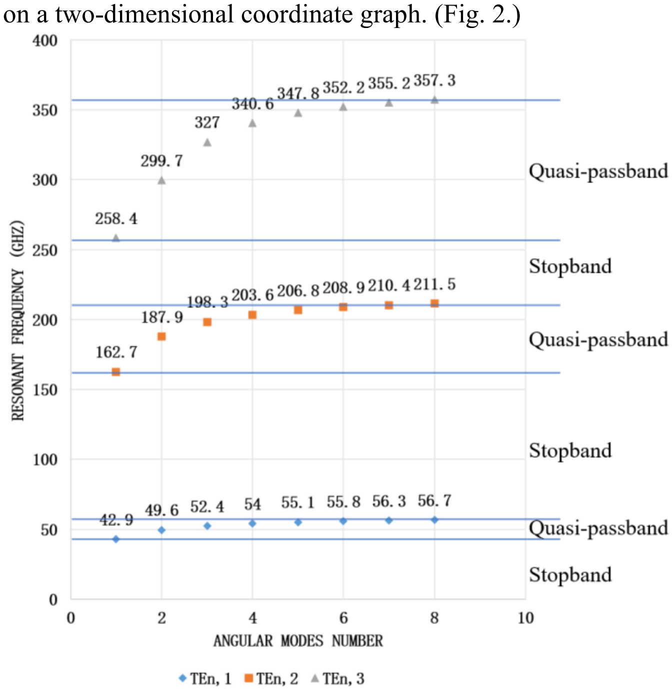

Fig. 2 The resonant frequency of $TE_{n,1}$, $TE_{n,2}$, $TE_{n,3}$

It can be seen that for the same radial mode, the larger the number of angular modes is, the higher the resonance frequency is, the smaller the resonance frequency gap between adjacent modes is, and finally converges to a frequency value [6]. For different radial modes, the larger the number of radial modes is, the higher the resonance frequency is. There is no resonance frequency between 0-42.885 GHz, so 0-42.885 GHz can be called "first stopband". The resonant frequency of $TE_{1,1}$, $TE_{2,1}$, $TE_{3,1}$, $TE_{4,1}$……$TE_{n,1}$ mode is only between 42.885-60 GHz, so we can call 42.885-60 GHz as "first quasi-passband". There is no resonance frequency between 60-162.662 GHz, so 60-162.662 GHz can be called "second stopband". The resonant frequency of $TE_{1,2}$, $TE_{2,2}$, $TE_{3,2}$, $TE_{4,2}$……$TE_{n,2}$ mode is only between 162.662-220 GHz, so we can call 162.662-220 GHz as "second quasi-passband". There is no resonance frequency between 220-258.386 GHz, so 220-258.386 GHz can be called "third stopband". The resonant frequency of $TE_{1,3}$, $TE_{2,3}$, $TE_{3,3}$, $TE_{4,3}$……$TE_{n,3}$ mode is only between 258.386-370 GHz, so we can call 258.386-370 GHz as "third quasi-passband". We can call this phenomenon as Spoof Surface Plasmon "Band Gap". The "quasi-passband" and "stopband" are shown in Figure 2.

Compared with a traditional circular waveguide resonator, the spoof surface plasmon resonator has two advantages. First, there is "stopband". Because the resonant frequency of each mode of the section of the spoof surface plasmon resonator is the cut-off frequency of each mode of the spoof surface plasmon resonator, and the gyrotron works in the near cut-off area, so the working frequency of the gyrotron is similar to which of the section of the spoof surface plasmon resonator. If the competition frequency of the gyrotron is in the "stop band" of the resonance frequency, the mode competition can be eliminated fundamentally. However, there is no "stopband" in the circular waveguide. The distribution of the eigenfrequency is related to Bessel function. There are eigenmodes near any frequency point. Second, for the same radial number, when the angular number n is small, the interval between adjacent eigenfrequencies is large, so the mode competition problem can be reduced by setting the operating frequency at the frequency point of the angular number n is small.

III. TERAHERTZ HARMONIC GYROTRON BASED ON SPOOF SURFACE PLASMON

Next, we design a terahertz harmonic gyrotron based on spoof surface plasmon. The working mode of the gyrotron is $TE_{2,3}$, the operating frequency is 299.749GHz and the electron cyclotron frequency is 74.94GHz. Therefore, it works in the fourth harmonic state, which is unprecedented in all previous studies. There are two advantages of this design. First, the fundamental frequency of electron cyclotron radiation is 74.94GHz, the second harmonic frequency is 149.87GHz, and the third harmonic frequency is 224.81GHz. These three frequencies are competitive frequencies, but they are all in the "stopband" frequency. There is no corresponding eigenmode in the spoof surface plasmon resonator, and each of competitive lower-order harmonics cannot find an available mode in the stopbands and accordingly, cannot start oscillate. Second, the operating frequency is 299.749GHz, and the competition modes near this frequency are 258.386GHz $TE_{1,3}$ mode and 327.017GHz $TE_{3,3}$ mode, but the frequency interval is far, so it is difficult to compete with the operating frequency. The specific design parameters are shown in Table 1.

TABLE 1 Design parameters of terahertz harmonic gyrotron

Parameters	value
Emitting voltage	1kV
Emitting current	50mA
Operating frequency	299.749GHz
Electron cyclotron frequency	74.94GHz
Harmonic number	4
Guiding radius	0.35mm
Ratio of transverse to longitudinal speed	2
Operating mode	$TE_{2,3}$
Cavity length	5mm
Internal radius	0.5mm
External diameter	1.5mm
Applied magnetic field	2.78T

By using the Particle-in-cell (PIC) module of CST particle studio, the interaction process of electron beam and electromagnetic field in the harmonic gyrotron resonator based on spoof surface plasmon is simulated. Figure 3 shows the frequency spectrum of the field in the cavity. It shows that there is only one frequency in the spoof surface plasmon resonator, and there is no competition frequency. Because of the fourth harmonic working state, the efficiency is inevitably low. The electron emission power is 50 W, the output power is 2.8 mW, and the efficiency is 0.0056%.

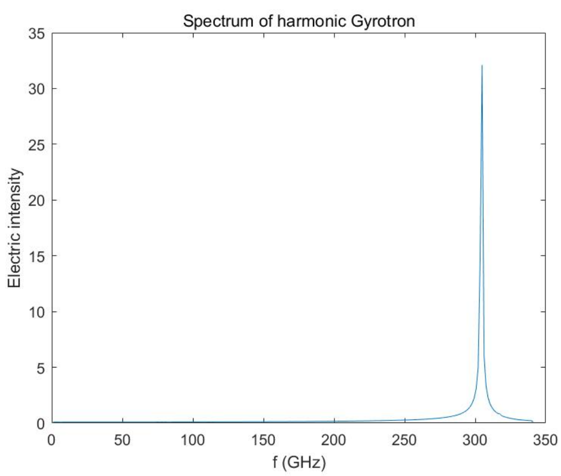

Fig. 3 Frequency spectrum of field in resonator

IV. Conclusion

The results show that the eigenfrequencies of the section of the spoof surface plasmon resonator have “quasi-passband” and “stopband”, which provides a way to reduce the mode competition of the harmonic gyrotron. Finally, the simulation results show that the terahertz gyrotron can work in the single mode in the state of high harmonics by using the spoof surface plasmon resonator, which greatly reduces the requirement of magnetic field.

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