Influence of SWS Size on Mode Purification in an Overmoded Ka-Band Cerenkov Oscillator

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ABSTRACT Overmoded slow-wave structure (SWS) plays an important role in developing the performance of Cerenkov oscillators at the millimeter-wave range. To investigate the effect of SWS size on power capacity as well as the problem of mode competition, the properties of the resonance modes in an overmoded SWS are focused on. Based on the mode selection method of enhancing the field of TM_{01} and keeping the field of TM_{02} mode steady, the output results for SWSs with various sizes are studied. Consequently, the size of SWS is reasonably determined, which can provide an effective beam-wave interaction process and the purified output mode. Moreover, the study on electron's movement in the diode area under the magnetic field of 0.8 T is conducted and then the value of the overmoded ratio α is finally confirmed as 2.5 to guarantee a lossless transportation of the electron beam. Verified by the particle-in-cell (PIC) simulations, the optimized structure shows a good capability of improving the output power and purifying the output mode.

INDEX TERMS Cerenkov oscillator, millimeter wave, mode competition, PIC simulation, power capacity.

I. INTRODUCTION

As one of the most promising high power microwave (HPM) generators, Cerenkov oscillator has shown great advantages in providing high output power, good tunability and compact structure [1]–[4]. A great deal of effort has been made on the development of Cerenkov devices in the last decades to achieve higher output power, longer pulse duration and higher conversion efficiency for various applications, especially in the C-band and X-band [5]–[8].

Cerenkov oscillator is also believed potential in the millimeter wave range [9], [10]. By enlarging the device's transverse section area, the power capacity is much improved, which is quite meaningful and essential in advancing the performance of millimeter-wave generators [11]–[15]. J. Zhu has developed a Cerenkov oscillator with an overmoded ratio (α) as high as 4.5 [16]. With the magnetic field of 0.85 T, the device provides the output power of 320 MW in experiment and the output microwave mode is quasi-TM_{01} mode. After that, the device has been moved forward by D. P. Wu to achieve the output power of nearly 500 MW with the magnetic field of 1.05 T [17]. Recently, V. V. Rostov has put forward a novel two-section structure for the Ka-band oscillator, whose α is designed as 2.6 [18]. The device is operating stably

and efficiently with the magnetic field of 2.5 T. The mode in the output waveguide is mainly TM_{02} and the device's efficiency is obtained as high as 42%. Obviously, the overmoded structure is helpful in improving the output power, especially for the devices operating over the millimeter-wave ranges.

However, the problem regarding mode competition appears due to the enlarged structure in the Cerenkov devices. As a competitor, the high order mode can also interact with the electron beam, which is harmful to the device's efficiency and stability [19]–[21]. Worse more, the enlarged size of the device leads to an immense increase of the system's weight, especially the mass of the magnet. A too large device is impossible to be built compact and light as the permanent magnet's mass is strongly related with its transverse section size [22], [23]. Therefore, it is rather crucial to select a proper size for an overmoded SWS.

In an overmoded SWS with a moderate size of $\alpha = 1.8$ to 2.7, only TM_{01} and TM_{02} are considered in the structure. In order to improve the mode purity and minimize the influence of the competitive mode, the characteristics of the modes including the field distribution and the resonance property are firstly studied in this paper. Based on the results in the structures with different sizes, the effect of α on the performance is investigated.

Accordingly, the proper values for α are primarily advised. Next, along with the study of electron's movement
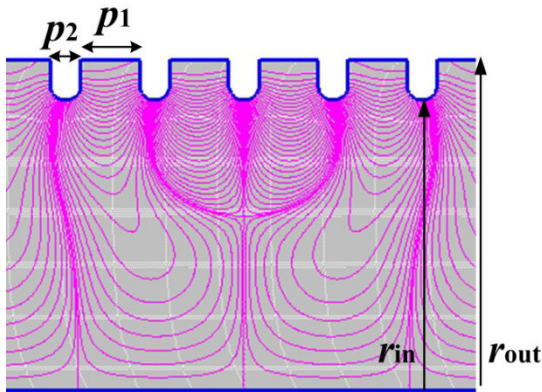
FIGURE 1. The diagram of an overmoded SWS.

FIGURE 2. Dispersions of the SWSs with different overmoded ratios.

under the condition of a low magnetic field, the optimal value of α for a Ka-band oscillator is finally confirmed. In the optimized overmoded SWS, the output power is improved and the issue of mode competition is effectively solved.

The paper is organized as follows. In Section II, the dispersion and the electric field for the modes in an overmoded SWS are theoretically studied. The resonance properties for all the modes in various sizes of SWSs are also researched in detail. Next, combined with the analysis of electrons movements under the low magnetic field, the suitable value of α is determined in Section III. Lastly, the performance of the optimum configuration is tested by the particle-in-cell (PIC) simulations.

II. PERFORMANCE OF THE MODES IN THE OVER-MODED SWSS WITH VARIOUS SIZES

As shown in Fig.1, the profile of SWS that contains a rectangular ripple and a semicircular head is preferred here because of its high power handling capacity [10]. The periodic length of SWS is marked as $l = p_1 + p_2$. The inner and outer radius for SWS is labeled as r_{in} and r_{out} respectively and the average radius is defined as $r_{ave} = (r_{in} + r_{out})/2$.

A. THE DISPERSIONS FOR THE SWSS WITH DIFFERENT RADII

According to the contributions of J. A. Swegle on the analytical theory regarding to the electromagnetic field in SWS, it is convenient to analyze the dispersion and the field distribution in a certain SWS [24]. Here, only the azimuthal symmetrical modes are considered. The components of the electric field E_r and E_z can be expressed as the superposition of a series of the spatial harmonics according to the Floquet's theorem

$$
\begin{cases}
E_r = j \sum_{n=-\infty}^{+\infty} T_n \beta_n A_n \mathrm{J}_1 (T_n r) e^{-j\beta_n z} \\
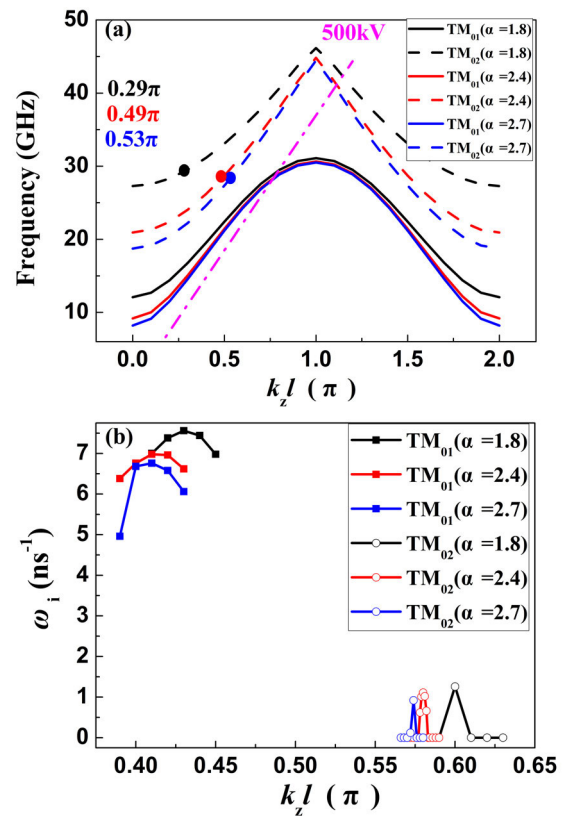E_z = \sum_{n=-\infty}^{+\infty} T_n^2 A_n \mathrm{J}_0 (T_n r) e^{-j\beta_n z},
\end{cases}
\tag{1}
$$

where A_n is the coefficient of the n th spatial harmonic, and $\beta_n = \beta_0 + \frac{2n\pi}{p}$ and $T_n = \sqrt{(\frac{\omega}{c})^2 - \beta_n^2}$ are the longitudinal and transversal wave numbers of the n th spatial harmonic, respectively. By substituting equation (1) into the perfect conducting boundary condition on the surface of the chosen SWS, the characteristic equation of the SWS can be derived as

$$
\det [D] = 0. \tag{2}
$$

The elements of the matrix D_m are

$$
D_{mn} = \int_0^p e^{j(\beta_m - \beta_n)z} \left(T_n^2 - j\beta_n \frac{d}{dz} \right) [\mathrm{J}_0 (T_n R_w)] \, dz, \tag{3}
$$

where m and n are the index numbers of the spatial harmonics.

From the equations (1) to (3), the details of E_r and E_z and their corresponding dispersion can be obtained. The following Fig.2 (a) accordingly shows the dispersion curves for the SWSs with $\alpha = 1.8$, 2.4 and 2.7 individually.

It is clear that the beam line of 500 kV interacts with the fundamental harmonic of the TM_{01} modes. The operation points on TM_{01} for the three structures are close and they are all near the π-points of TM_{01}. Under this condition, the fundamental wave of TM_{01} is shaped as the surface wave with the group velocity close to zero. The quality factor for the operation point of TM_{01} is effectively enhanced and then the start current for TM_{01} is lowered, which leads to an effective interaction process between the electron beam and

the fundamental wave of TM_{01}. From the results of growth rate in Fig.2 (b), it is also clear that the growth rate for TM_{02} is far lower than that for TM_{01}. So, the TM_{02} mode is comparatively weak during the synchronical interaction process with the beam line of 500kV. However, in an overmoded structure, the high-order mode naturally exists, especially in such a structure with rippled boundaries. The discontinuous boundary promotes the mixture of modes, which seriously affects the efficiency and stability of device. So purifying the mode in an overmoded device is tough but rather essential.

In our opinion, it is impossible to absolutely exclude the high order mode in an overmoded SWS. A possible way to improve the mode purity is promoting the strength of the designed mode as high as possible. Here the mode in operation is designed as TM_{01}. By deeply enhancing the electric field of TM_{01} and keeping the field of TM_{02} steady in SWS, the field distributions of TM_{01} and TM_{02} are differentiated. Then TM_{01} holds the predominant position in the beam-wave interaction and the influence of TM_{02} is minimized. Accordingly, the mixed output mode is effectively purified.

In Fig.2 (a), the colored solid-spots on TM_{02} represent the non-synchronous points that have the same frequencies with the synchronous operating points on TM_{01}. These points on TM_{02} are mainly caused by the discontinuous waveguide and the size of waveguide has an obvious influence on the non-synchronous points on TM_{02}. When the overmoded ratio is enlarged from 1.8 to 2.7, the phase shifts of the corresponding points on TM_{02} are growing form $0.29\,\pi$ to $0.53\,\pi$. Because of this shift, the status of the corresponding TM_{02} mode, including the resonance property and the field distribution, would be changed. And this is exactly the basis of carrying out our proposed mode selection method. In the subsequent sections, the distributions of E_z and the resonance results for TM_{01} and TM_{02} in different SWSs will be discussed in detail.

B. RADIAL DISTRIBUTIONS OF E_z IN VARIOUS SIZES OF SWSs

The field strength of E_z along the radial direction is obtained under the same injected power condition. The detailed results acquired in different sizes of SWSs are compared in Fig.3. Moreover, for each mode, the results regarding various phase shift constants are also involved in Fig.3.

In Fig.3 (a), the circles on the curves indicate the positions where the amplitude of E_z is reduced to the half of its top value. Clearly, as the value of α is increased from 1.8 to 2.7, the positions of the circular points under the same phase shift are approaching to the SWS surface. At the same time, the amplitude of electric field is slightly decreasing with increase of the overmoded size. Besides that, in the same structure, the choice of synchronous phase shift affects the performance of electric field as well. When the synchronous phase shift on TM_{01} is approaching to the π point, the electric field is obviously improved.

The distribution of E_z along the radius for the TM_{02} mode is shown in Fig.3 (b). Similar to the performance in Fig.3 (a), in each SWS, the field strength is growing with the increase of
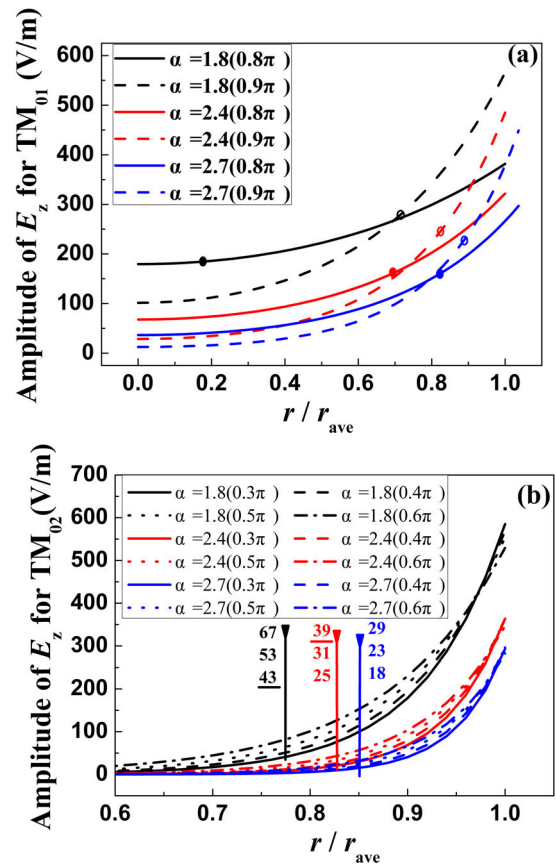

FIGURE 3. Distribution of the electric field along radial directions for (a) the TM_{01} mode and (b) the TM_{02} mode.

phase shift constant. Taking the position which is 2 mm away to the surface of SWS into consideration [14], [25], the field strengths at this position for all the harmonic waves are lined out by the dash lines in Fig.3 (b). According to the analysis in Fig.2, the non-synchronic points on TM_{02} have the phase shift values from $0.29\,\pi$ to $0.53\,\pi$ when the overmoded ratio of SWS is increased from 1.8 to 2.7. Then the corresponding field strength of TM_{02} is varied from 43V/m to 36V/m.

Generally, in the condition of the same injected power, the field strengths for both TM_{01} and TM_{02} are slightly decreased with the increase of SWS's transverse area. So the enlarged SWS cavity is contributive to reduce the strong electric field near the SWS's surface. Alternatively, the enlarged cavity is also competent in improving the power capacity.

C. RESULTS OF S_{11} FOR THE MODES IN SWSs WITH VARIOUS SIZES

In this paper, the mode selection method is proposed as enhancing the field strength of TM_{01} in SWS and simultaneously keeping the field of TM_{02} propagating smoothly in SWS. Through discriminating the field strengths of TM_{01} and TM_{02} in SWS, the problem of mode competition is then solved. So, for the resonance modes, the characteristics including both the reflection coefficients and the longitudinal distributions of E_z are focused on. Here, a periodic system
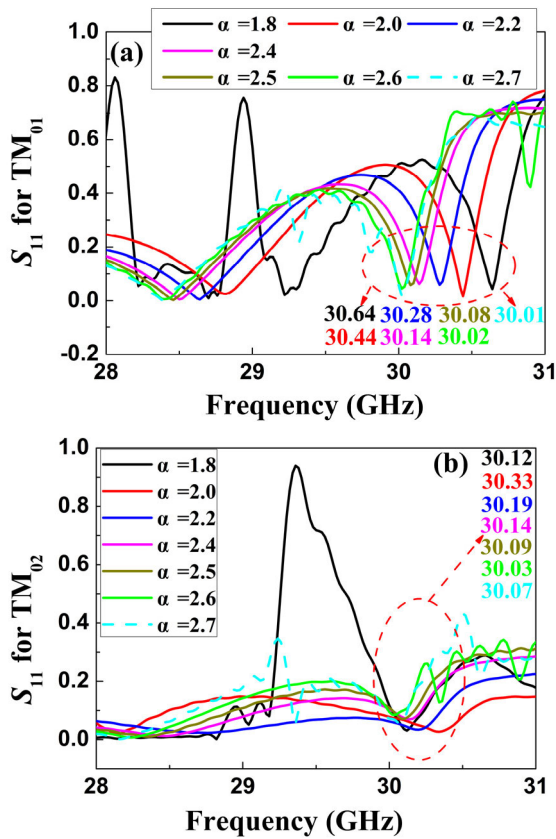
FIGURE 4. Reflection results for the modes in various sizes of overmoded SWSs. (a) the TM_{01} mode; (b) the TM_{02} mode.

FIGURE 5. Distributions of E_z amplitude along the longitudinal direction in various sizes of SWSs. (a) TM_{01} mode; (b)TM_{02} mode.

consisting of nine ripples is established to research the performances of SWSs with different values of α. The reflection results for both TM_{01} and TM_{02} are shown in Fig.4.

Taking the resonance points around 30 GHz into consideration, the resonance frequency is decreasing with increasing the SWS size, as shown and labeled in Fig.4. In the structure with the size of $\alpha = 1.8$, the frequency gap between the resonance frequencies on TM_{01} and TM_{02} are as wide as 0.5 GHz. In such a situation, the reflection in SWS grows, which affects the interaction efficiency and the purity of the output mode. Nevertheless, as presented in Fig.4 (a) and (b), increasing the transverse size of SWS is helpful to reduce the frequency gap between the resonance frequencies of TM_{01} and TM_{02}. In the structures whose overmoded ratios are higher than 2.4, it is clear that the two resonance points are almost the same. Then the injected waves of TM_{01} and TM_{02} are scarcely reflected and they enter directly into SWS. However, when α is higher than 2.6, the frequency gap begins to expand again. Therefore, in the range of 1.8 to 2.7 for the value of α, choosing a moderate value as 2.4 to 2.6 is necessary.

D. LONGITUDINAL DISTRIBUTIONS OF E_Z FOR THE MODES IN SWSs WITH VARIOUS SIZES

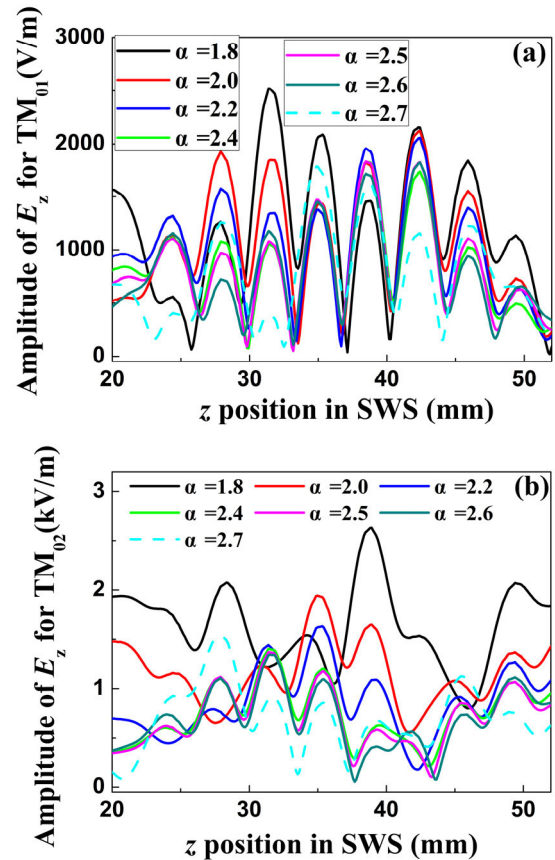Besides the study on the reflection results, the distributions of E_z along the axial direction are also researched. The field results in various structures are presented in Fig.5. The fields are all observed at the radial positions which are 2 mm away from the surfaces of SWSs [14], [25]. And the focused frequencies are located at the resonance frequencies of TM_{01} in each structure.

It is clear in Fig.5 (a) that a series of resonance peaks appear along the longitudinal direction which correspond to the positions of the ripples in SWS. Moreover, in the structures where the TM_{01} mode has a low reflection coefficient, the strength of E_z in SWS is strongly enhanced. This is significant in improving the device's efficiency and accomplishing the mode selection.

The situation for the field of TM_{02} in the periodic system is not the same. In the structure with $\alpha = 1.8$, the phase shift of the field over each ripple approximately coincides with the result of 0.3π in Fig.2. With the increase of α, the phase shifts for the E_z fields are increasing. Especially when the value of α is higher than 2.4, the state of E_z in SWS tends to be the same, including the phase shift and the field strength. It can also be found in Fig.5 (b) that the peak value of E_z for TM_{02} mode in the structure with a high value of α is much lower than that in the structure with a small value of α. This is quite important for purifying the dominate mode in the interaction process, because lowering the field of TM_{02} in SWS is exactly required by the proposed mode selection

method. Consequently, the proper value of α is advised again to be 2.4 to 2.6 for the overmoded SWS in this study.

III. ELECTRON MOVEMENTS IN THE DIODE AREA

Besides the characteristics of the modes in the overmoded SWS, the statement of the electron beam is also responsible in deciding the size of SWS, especially in the condition of a low guiding magnetic field. In the practicable millimeter-wave devices, the density of the permanent magnet can't be very high since the consideration of the system's weight and size [26], [27]. Under the condition of a low guiding magnetic field, such as 0.8 T, the transverse movement of the electrons can't be ignored and the movement plays a crucial role in determining the transportation of beam as well as the efficiency of interaction. Based on the study on the movement of the electrons in the diode region, the electron's radial shift d_0 can be estimated from [25]

$$
B = \frac{2(r_c + d_0)}{(r_c + d_0)^2 - r_c^2} \left(\frac{2m_0 U_d \ln\left(1 + \frac{d_0}{r_c}\right)}{e \ln \frac{r_a}{r_c}} \right)^{\frac{1}{2}}
$$
$$
\times \left(1 + \frac{e U_d \ln\left(1 + \frac{d_0}{r_c}\right)}{2m_0 c^2 \ln \frac{r_a}{r_c}} \right)^{\frac{1}{2}} \quad (4)
$$

where r_a and r_c are the radii of the anode and the cathode respectively. d_0 denotes the radial expansion of electron as shown in Fig. 6(a). U_d is the electron's voltage and B is the density for the guiding magnetic field. The results of d_0 in different sizes of SWS are shown in Fig. 6(b). The applied values of U_d are all 500 kV.

Clearly, the electrons' radial movement is serious in the condition of a low magnetic field. When the value of d_0 is too large, it means lots of the electrons strike on the anode directly, which is harmful to the device's efficiency and stability. With the increase of the SWS's transverse scale, the values of d_0 are reducing under the same magnetic field. That's to say, enlarging the transverse size of SWS is helpful to ease the difficulty of beam transportation under a low magnetic field. However, when the value of α is beyond 2.7, this effect is no longer that remarkable. The values of d_0 are approaching a constant. Thus the overmoded structure with $\alpha = 2.5$ is appropriate by considering the performance of the resonance modes, the movement of the electrons and the mass of the whole system. Guiding by the magnetic field of 0.8 T, the theoretically predicted d_0 is about 1.3 mm. In this condition, perfectly controlling and transporting the electron beam is practicable in our laboratory.

IV. PIC VERIFICATIONS

Based on the analytical study, the overmoded size for a Ka-band Cerenkov oscillator operating with the magnetic field of 0.8 T is determined as $\alpha = 2.5$, in which the electric field of TM_{01} is intensive and the influence of TM_{02} is restricted. Combined with the successfully transportation of the relativistic electron beam, the interaction process
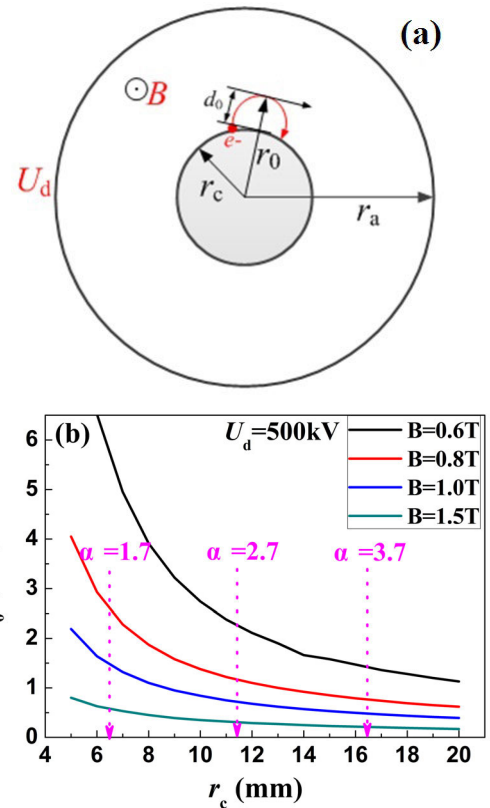

FIGURE 6. Instruction for d_0 in (a) and estimation of d_0 in different guiding magnetic fields in (b).

would be effective. Now the PIC method of UNIPIC and the self-developed scan code are introduced to test the above conclusion [28]–[30]. In the PIC models, only the SWSs with various average radii connected with the diode and the straight waveguide are researched. The output results are summarized in Fig.7.

Based on the efforts to optimize the structural parameters for each model, the models are tuned to reach a stable state. Then all the models are tested with different voltages and the performance in regard of the output power and the mode component are compared in Fig.7. It is obvious in Fig.7 (a) that enlarging the transverse area of the device is capable in improving the output power in general. When α is higher than 2.5, the advantage of providing a high output power is conspicuous. As to the ratio of TM_{01} in the mixed output modes, the results are researched in Fig.7 (b). Clearly, in the devices with a small value of α, the proportion of TM_{01} in the output modes is quite low, demonstrating the mode competition is not well solved. It can also be found that when the value of α is 2.5, the proportion of TM_{01}, which is over 95%, is remarkably high compared with the other devices. In the range of 1.8 to 2.7 for α, the proportion of TM_{01} reaches the peak value when α is 2.5, showing its advanced ability in solving the problem of mode competition. And this consequence is in good coincidence with the analytical study on the resonance characteristics of such structures above. Thus the device with
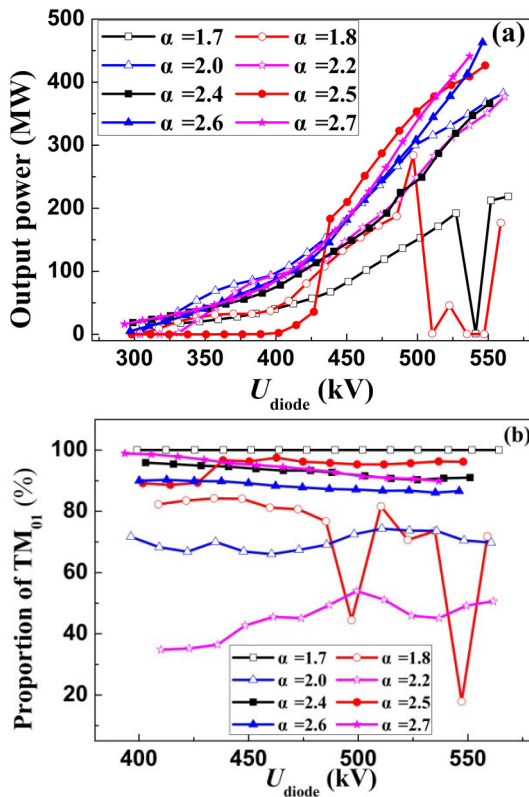
FIGURE 7. Performance of the devices with different α. (a) output power ; (b) proportion of TM_{01}.

FIGURE 8. (a) Diagram of the whole device and (b) the size of the dual-reflector.

FIGURE 9. Comparison of the output performance for the optimized structures with and without reflectors. (a) output power and frequency; (b) E_z field.

the overmoded ratio of 2.5 shows the significant quality in enhancing the power capability and solving the problem of mode competition in this study. Besides, the device with this moderate size is potential in reducing the whole device's weight. Consequently, the value of α is reasonably determined as 2.5 in this study for developing a compact and stable Ka-band Cerenkov oscillator.

According to the above studies, the electro-dynamic structure of SWS for an overmoded Ka-band oscillator with the purified output mode is proposed. In order to further improve the efficiency, a dual-reflector whose central frequency is in coincidence with the operating frequency is set ahead of the SWS. The diagram of the whole structure is shown in Fig. 8. Through the method of PIC simulations, the performance of the whole structure is tested and the results are presented in Fig. 9. The density of guiding magnetic field is also set as high as 0.8T. The applied beam voltage is 515kV and the beam current is 3.7kA.

It can be seen from Fig.9 (a) that the device with a reflector has a deep improvement on the output power, comparing to the one without reflectors. In the optimized device, the output power reaches 560 MW. In order to diagnose the mode component in the output modes, a series of observing planes are setting in the output waveguide. The electric field on each plane is repeatedly monitored at the time interval of $T/4$, where T is the period of the generated millimeter-wave.
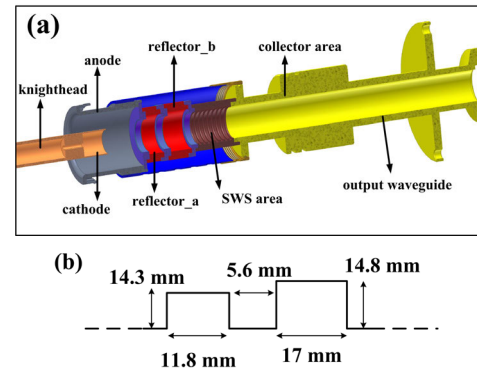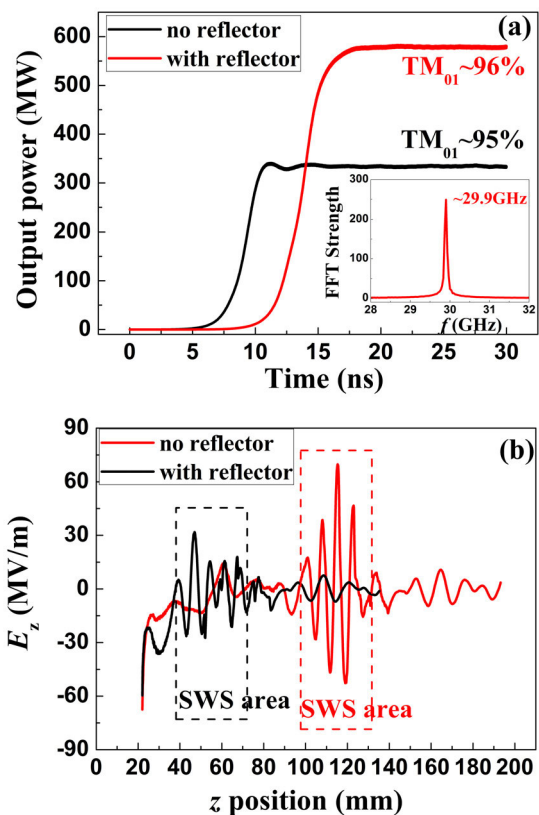
This method to analyze the mode component has been used and verified in [19], [31], [32]. As can be seen in Fig. 9 (a), the ratios of TM_{01} at the output positions are close in the two cases, which are both over 95%, demonstrating the validity of the overmoded SWS in achieving the mode purification. With the reflection of the negatively going waves, the electric field in the SWS area is accordingly enhanced. As shown in Fig.9 (b), the strength of E_z in SWS from the device with a reflector is almost twice over that in the device without reflectors. The enhanced electric field in SWS is

helpful in promoting the interaction efficiency. Consequently, the designed SWS is capable in enhancing the electric field in cavity and purifying the mode component. Accompanied with the workable reflector, the whole structure can operate stably with a high performance.

V. CONCLUSION

Reasonably choosing the size of SWS is the basis of designing an overmoded Ka-band Cerenkov oscillator. Based on the mode selection method of enhancing the field strength of TM_{01} and simultaneously propagating the field of TM_{02} smoothly in SWS, the influence of SWS size on the issues of output power and mode purification is studied. And the moderate value of 2.4~2.6 for α is suggested. What's more, along with the investigation of the electron's radial movement under a low magnetic field, the proper size of SWS is further advised to be $\alpha = 2.5$ and this proposal is verified by the PIC simulations. In which, the proportion of TM_{01} in the output modes is purified to be over 95% and the output power is also in advance. All the results demonstrate the validity of the proposed method in designing the overmoded SWS. Next, the approaches such as employing an abstractor and the non-uniform SWS will be conducted to further improve the device's efficiency. The potential of breakdown caused by the strong electric field in device is also focused on.

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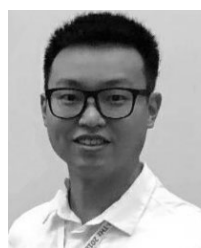
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