Research on a Ka-band large-orbit gyro-TWT with periodic dielectric-loaded structure

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Abstract

This paper presents a design of a gyro-TWT operating in the large-orbit electron beam mode, with the aim of reducing the working magnetic field while ensuring operational efficiency. The periodic dielectric-loaded structure is adopted as the high-frequency interaction circuit, which has not been reported in the application of large-orbit gyro-TWT in literature, while this structure has been successfully applied in the development of small-orbit devices. This paper conducts a comprehensive study and analysis of this structure and achieves stable operation in the Ka-band after the optimization of the tube. This tube works at second harmonic of electron frequency in the mode of large-orbit electron beam. The required magnetic field is only 5100 Gauss, which can be generated using electromagnetic coils instead of superconducting magnets. The operational parameters include voltage of 75 kV, current of 9A, and velocity spread of 3.5%. Under these conditions, the device presents stable operation, with -3 dB bandwidth of 4.3 GHz, and maximum output power of 165 kW. This result meets the expected requirements for magnetic field and operational efficiency, thus validating the feasibility of practical fabrication of large-orbit gyro-TWT with periodic dielectric-loaded structure.

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This paper presents a design of a gyro-TWT operating in the large-orbit electron beam mode, with the aim of reducing the working magnetic field while ensuring operational efficiency. The periodic dielectric-loaded structure is adopted as the high-frequency interaction circuit, which has not been reported in the application of large-orbit gyro-TWT in literature, while this structure has been successfully applied in the development of small-orbit devices. This paper conducts a comprehensive study and analysis of this structure and achieves stable operation in the Ka-band after the optimization of the tube. This tube works at second harmonic of electron frequency in the mode of large-orbit electron beam. The required magnetic field is only 5100 Gauss, which can be generated using electromagnetic coils instead of superconducting magnets. The operational parameters include voltage of 75 kV, current of 9A, and velocity spread of 3.5%. Under these conditions, the device presents stable operation, with -3 dB bandwidth of 4.3 GHz, and maximum output power of 165 kW. This result meets the expected requirements for magnetic field and operational efficiency, thus validating the feasibility of practical fabrication of large-orbit gyro-TWT with periodic dielectric-loaded structure.

Introduction: The gyrotron traveling wave tube (gyro-TWT) is capable of generating high-power, wide-band coherent radiation in the millimeter and submillimeter wavebands. It has significant applications in millimeter-wave radar, communication, electronic warfare, deep space exploration, and other fields [1-2].

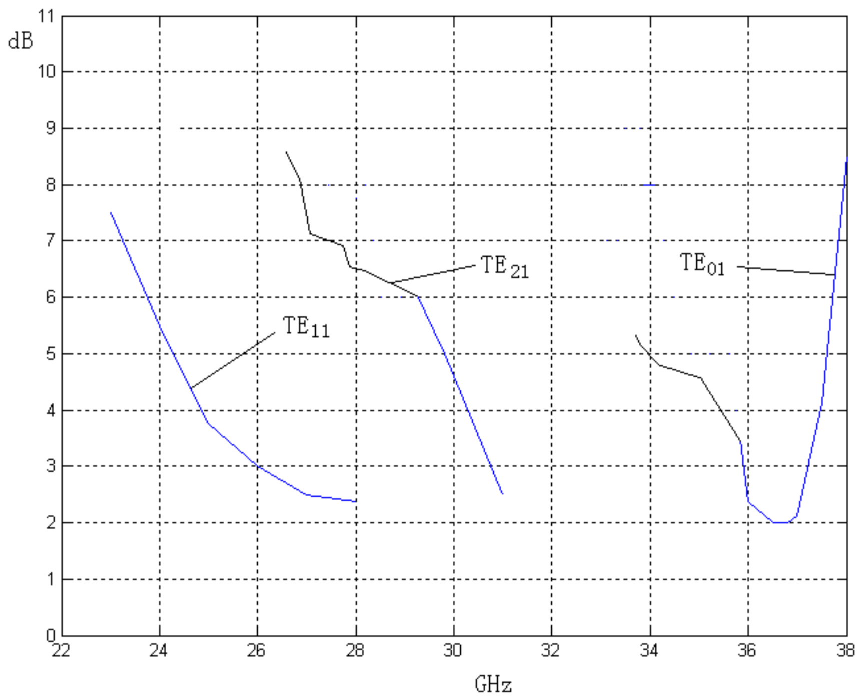
The high-intensity magnetic field in gyro-TWT is used to guide the electron beam. In the Ka-band gyro-TWT, the working magnetic field is around 1.2 Tesla. Due to issues related to heat dissipation and power consumption, the maximum magnetic field achievable with electromagnetic coils is currently around 7000 Gauss, which falls short of the 1.2 Tesla magnetic field that only superconducting magnets can offer. However, superconducting magnets bring limitations in terms of flexibility, maneuverability, and quick startup, significantly impacting the practical applications of gyro-TWTs.

To overcome the mentioned drawbacks, it is necessary to reduce the working magnetic field, which can be achieved by using higher harmonic number. However, higher harmonic number leads to a sharp decrease in output power, efficiency, and bandwidth. The large-orbit electron beam working mode offer a promising solution to this problem. Compared to the small-orbit mode, the large-orbit mode has the following characteristic: (1) High interaction efficiency: Even when reducing the working magnetic field, the interaction efficiency remains nearly on par with that of the fundamental harmonic. It has been reported that the interaction efficiency can still reach 22% when a 94 GHz large-orbit gyrotron operates in the 6th harmonic mode [3]. (2) good mode selectivity: In the large-orbit mode, the electron beam only interacts with modes where s equals m, where s represents the harmonic number, and m represents the azimuthal mode index.

The Institute of Applied Physics in Russia (IAP) has successfully developed a prototype of a Ka-band large-orbit gyro-TWT. This tube operates at second harmonic with working magnetic field of 0.6 Tesla, which can be achieved using conventional electromagnetic coils. Under the conditions of 70 kV voltage and 10A current, it achieves a maximum peak output power of 160 kW with -3 dB bandwidth of 2.1 GHz and gain of 20-30 dB [4]. The tube employs a three-fold helically corrugated waveguide as the high-frequency interaction structure. This structure ensures that the waveguide's dispersion curve is nearly linear in the region where the axial wave number is zero. This characteristic is advantageous for bandwidth extension, and the structure exhibits lower sensitivity to velocity spread. In addition to IAP, the University of Strathclyde in the United Kingdom has also been dedicated to research on helically corrugated waveguides [5]. Up to this point, reports on large-orbit gyro-TWTs have only mentioned the helically corrugated waveguides used as their high-frequency interaction circuit.

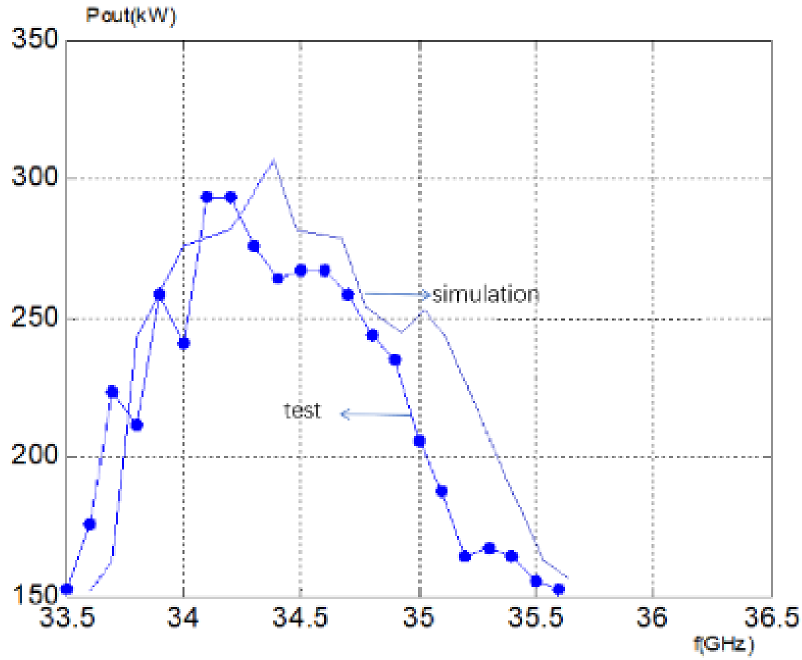
The Beijing vacuum electronic research institute(BVERI) has developed a series of gyro-TWTs utilizing periodic dielectric-loaded structures as high-frequency interaction circuits, employing small-orbit electron beams, and has achieved good results in the Ka, Q, and W bands [6-8]. The lossy material of the periodic dielectric-loaded structure is made of high thermal conductivity AlN-SiC ceramics. This structure is simple, well-established in terms of manufacturing, and provides easy control of loss with good thermal conductivity. Building on the research of Ka-band gyro-TWTs with periodic dielectric-loaded interaction structures in the laboratory, this paper has shifted to using a large-orbit electron beam while retaining the periodic dielectric-loaded interaction structure. The tube in this paper operates in TE_{21} mode, designed at the second harmonic to reduce magnetic field.

Model design: For the Ka-band, the interaction structures adopted by the existing small-orbit gyro-TWTs in the laboratory are periodic dielectric-loaded structures, as shown in Figure 1a. In this structure, conductor rings and dielectric rings are alternately placed. The lossy material used for dielectric rings is the high thermal conductivity AlN-SiC ceramic series. By adjusting the axial spacing ratio and radial thickness of the rings, effective suppression of non-working modes can be achieved. In the Ka-band, the lossy characteristics of the ceramic material for various modes are depicted in Figure 1b. The complete tube with periodic dielectric-loaded structure is depicted in Figure 2a. During testing, it operates with magnetic field of 1.24 Tesla, working voltage of 66 kV, and working current of 13A, achieving a maximum peak power of 293 kW [9]. Figure 2b illustrates the relationship between output power and frequency. Additionally, the test results and PIC simulation results are presented on the same graph. The -3 dB bandwidth is calculated as 2.1 GHz. The maximum efficiency is 34.2%, and the maximum gain reaches 56 dB. It is evident from the graph that the simulation results closely match the test results. The high-frequency interaction circuit of the Ka-band large-orbit TWT studied in this paper adopts the above-mentioned periodic dielectric-loaded structure.



(b)

Fig 1 *The dielectric-loaded structure and its lossy test. (a) The dielectric-loaded structure, (b) loss test.*



(b)

Fig 2 *The complete tube with periodic dielectric-loaded structure and its output power. (a)the complete tube, (b) simulation and test.*

The analysis of mode competition is an important part of the study of the performance of high-frequency interaction structures. Figure 3 shows the dispersion curves of different waveguide modes and electron cyclotron resonant curves, the dispersion curve of the working mode TE_{21} and the electron cyclotron resonant curve when s=2 are tangent to point C, where the tangent magnetic field B_g=5190 Gauss; At the same time, there are intersections between the dispersion curves of the TE_{31} and TE_{41} modes and the electron cyclotron resonant curves in the region of negative axis (k_z<0), that are the two points A and B in the figure, which may cause return oscillation, and the corresponding starting frequency points are 36.56 GHz and 46.56 GHz, respectively. Therefore, the suppression of the main competitive mode TE_{31} and TE_{41} mode is the key to designing second harmonic TE_{21} gyro-TWTs.

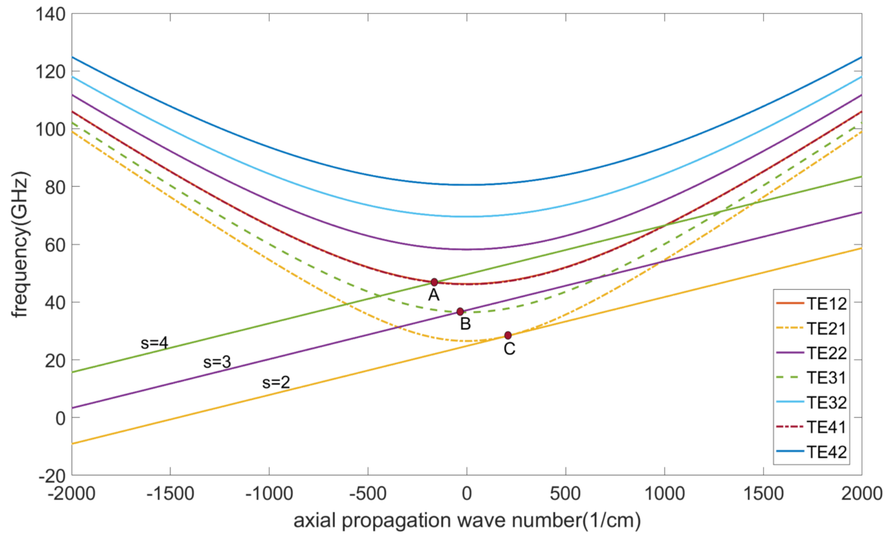


Fig 3 *dispersion curves of different waveguide modes and electron cyclotron resonant curves* .

The interaction structure of this tube is shown in Figure 4. The L_1 section is a metal waveguide. In the L_2 section, the dielectric rings and the metal rings are alternately placed. The L_3 section is a metal waveguide at the input end.

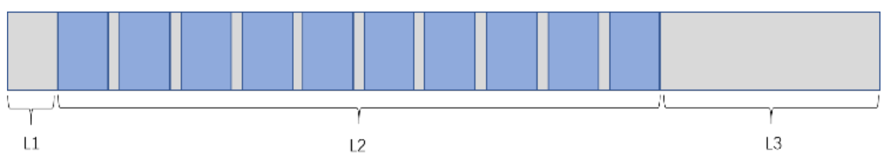


Fig 4 *The interaction structure of the designed tube* .

The start oscillation length of the competition mode is a consideration in the design of the L_1 and L_2 sections. Under the condition that the working voltage is 75kV, the radius of the guide center is R_c=0, and the radius of the waveguide is R_w=5.5mm, the variation of the starting length of each mode in the lossless waveguide with the current is shown in Figure 5. When the working current I=9A, the corresponding start length of TE_{31} and TE_{41} are 50.2mm and 101.3mm, respectively, so the length of the lossless section L_1should be less than 50.2mm. Under the same conditions, the start oscillation length and oscillation frequency of the TE_{31}mode, which has smaller oscillation length than TE_{41}mode, vary with the logarithm of the ratio between the resistivity of the dielectric and of copper, ???10(?/???????) (???????= 1.72e-8 S/m), as shown in Figure 6. According to the resistivity of the dielectric rings in the laboratory, the length of dielectric-loaded section L_2, should be less than 271 mm.

The dielectric ring in the interaction structure is made of AlN-SiC ceramics, as shown in Figure 7a. The ceramics has high thermal conductivity of 60 W/m. K and a certain mechanical strength. The loss amount is easy to control by the period number. Its relative permittivity is ε_r=12, the loss tangent tanϑ=0.16, and the effect of beam-wave interaction is the best in simulation when the thickness d=1.8mm. Figure 7b shows the loss of ceramics to microwaves in the operating frequency band of working mode TE_{21}, and it can be seen that the actual measured values are close to the simulation values according to the comparison. Figure 8a and 8b only show the simulation results of the loss of the ceramic ring near the start frequency of the competition modes TE_{31} and TE_{41}, which are also relatively close to the real situation. (TE_{31} and TE_{41} mode converters are not prepared).

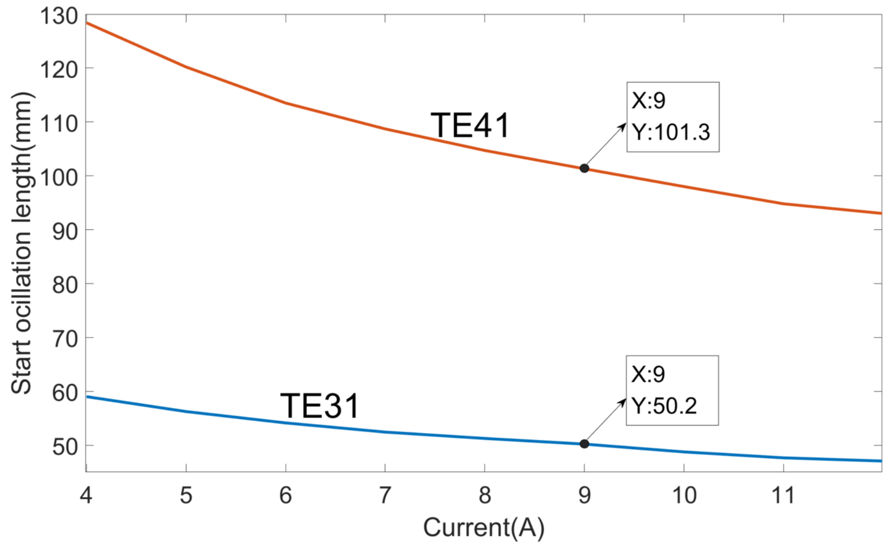


Fig 5 *Start ocillation length changes with working current* .

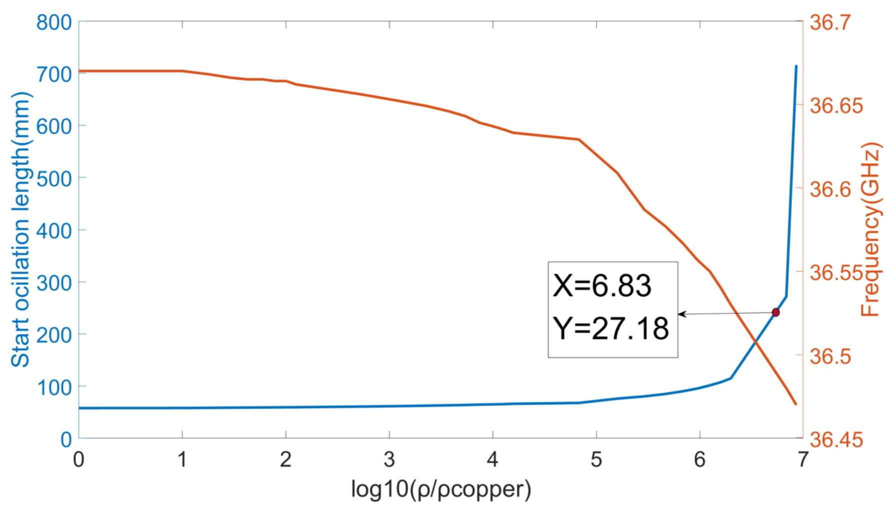
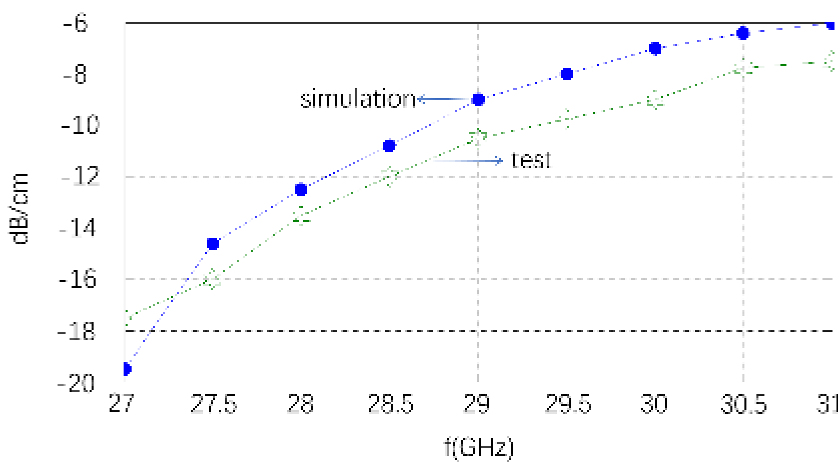
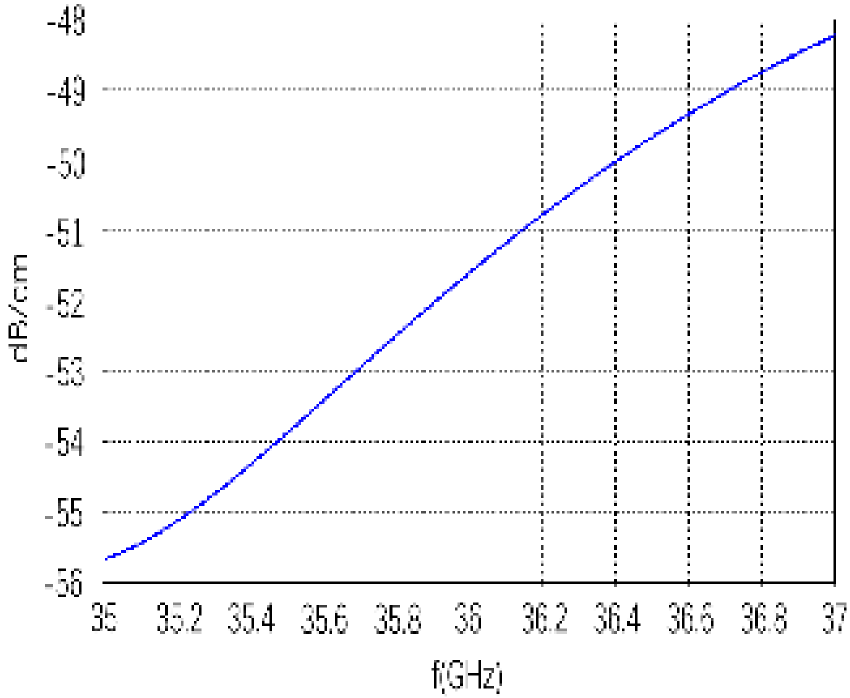


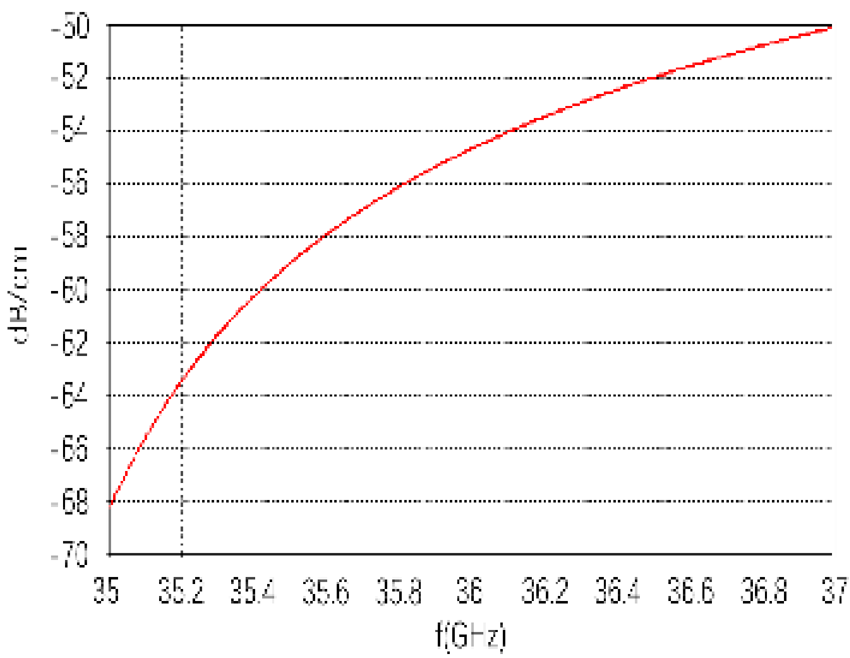
Fig 6 *Σταρτ οςιλλατιον λενγτη ςηανγες ωιτη λογ10*$(\rho/\rho_{\varsigma o\pi\pi\epsilon\rho})$.



(b)

Fig 7 *AlN-SiC ceramics and its loss to mode* TE_{21}. *(a) AlN-SiC ceramics, (b)loss simulation and test .*





(b)

Fig 8 *Loss simulation of competition mode. (a)simulation of TE_{31}, (b)simulation of TE_{41} .*

Simulation: Table 1 shows the parameters of electron beam and high-frequency interaction circuit.

Table 1 Parameters of high-frequency structure and electron .

parameters
working mode waveguide radius length of L_2 length of L_3 the relative permittivity of the dielectric ring the number of perio

The simulation has been conducted using CST-PIC to study the beam-wave interaction in the designed model of large-orbit gyro-TWT. When the electron beam velocity spread is 3.5%, by varying the power of the input signal, the output saturation power corresponding to each frequency can be obtained, and the result is shown in Figure 9, with -3dB bandwidth of 4.3 GHz, from 27 GHz to 31.3 GHz. Figure 10 shows the gain and efficiency curves, with saturation gains ranging from 37 dB to 48 dB, and efficiency between 12 and 25 percent.

Under the same working conditions, the change of output power with the electron beam velocity spread at the working frequency f=29GHz is shown in Figure 11, it can be seen that when the spread is higher than 5%, the output power begins to decrease significantly, so the velocity spread of the electron gun is best controlled within 5%. This result is close to that of the small-orbit gyro-TWTs, which means dielectric-loaded structure is more sensitive to velocity spread than the helically corrugated waveguide structure.

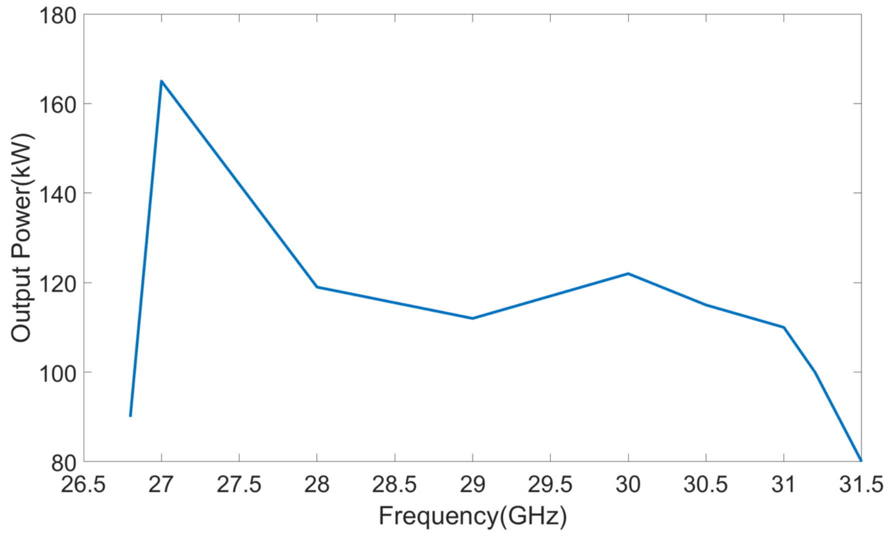


Fig 9 *Output saturation power changes with frequency .*

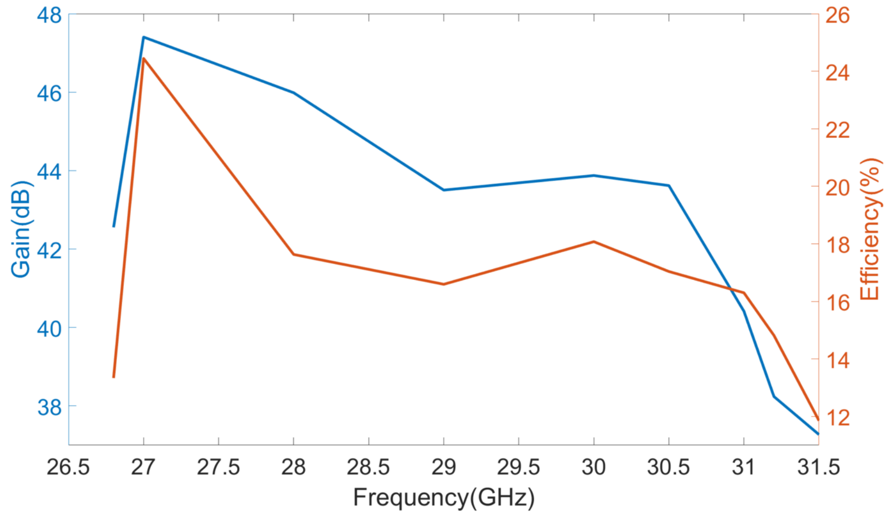


Fig 10 *Gain and efficiency changes with frequency* .

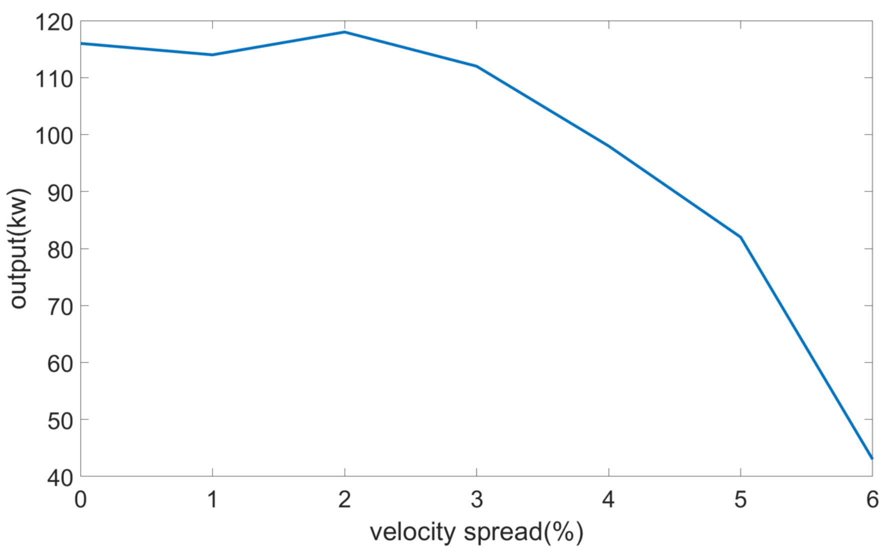


Fig 11 *Output power changes with velocity spread when frequency is 29GHz* .

Conclusion: This paper designs a Ka band large-orbit gyro-TWT employing large-orbit electron beam and dielectric-loaded structure, which has achieved good effect on small-orbit gyro-TWTs. According to the PIC simulation results, the model performs well in terms of peak output power and bandwidth, with a magnetic field of only 5100 gauss, which can be provided by conventional electromagnetic coils. Compared with the large-orbit gyro-TWT with helically corrugated waveguide, the large-orbit gyro-TWT with periodic dielectric-loaded structure has mature process and high gain. This study provides a basis for the development of the upcoming Ka-band large-orbit TWT.

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