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Dispersive characteristics and longitudinal resonance properties of trapezoidal corrugation coaxial slow-wave structure*

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Abstract: The method for calculating the expression of the trapezoidal corrugation slow-wave structure (SWS) is studied in detail, which uses Fourier series expandedness. The dispersion curves of the two lowest symmetry TM_{0n} waves are obtained with numerical calculation. Moreover, longitudinal resonance properties of the finite-length coaxial SWS are investigated with the S-parameter method. It is proposed that the introduction of a well designed coaxial extractor to slow-wave devices can reduce the period-number of the SWS, which not only can make the devices more compact, but also can avoid destructive competition between various longitudinal modes. Based on the theoretical study, a compact L-band coaxial relativistic backward wave oscillator is designed using the 2.5 D particle simulation code. Simulation results show that for an electron beam of 700 keV and 11.5 kA, the high-power microwave of coaxial TEM mode is generated with an average power of 2.60 GW after saturation and a frequency of 1.6 GHz, and a power conversion efficiency of 32.3% in the duration of 30 to 60 ns.

Key words: high-power microwave; coaxial slow-wave structure; relativistic backward wave oscillator; dispersive characteristics; longitudinal mode

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In recent decades, a considerable amount of research has been reported on high-power relativistic backward wave oscillators (RBWOs) utilizing intense relativistic electron beams. The operating principle of the RBWOs is the Cherenkov effect between microwaves and an electron beam passing through a metal tube slow-wave structure (SWS)[1-6].

As is known, the SWSs are the most important parts of high power microwave devices of Cerenkov-type[7-8]. During the design of the RBWO, the main goal is to find a SWS profile capable of 1) supporting slow waves with phase velocity below that of the electron beam with a certain voltage value, and 2) ensuring strong coupling impedance over the frequency range of interest for a beam located relatively far from the structure's surface[9]. In order to meet these requirements, various periodic SWSs have been analyzed, and among them coaxial SWSs are widely used due to the potential of increasing the beam-to-microwave conversion efficiency.

In this work, the trapezoidal corrugation SWS is chosen, because its power capacity is higher than that of the rectangular SWS. Compared with the sinusoidal corrugated SWS, it can be fabricated more easily in practical applications. For the trapezoidal corrugation cannot be described by a continuous function, it is difficult to obtain accurate dispersion. Note that, arbitrary geometry structures can be expanded using Fourier series expansion. Thus, this method is introduced to deduce the dispersion relation in the trapezoidal corrugation coaxial SWS. In addition, the length of the SWS is finite, which leads to the neighboring longitudinal modes competition. This brings on the cross-excitation instability in the interaction region and decreases the

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power conversion efficiency. Therefore, it is necessary to investigate the longitudinal resonance properties in the coaxial SWS.

1 Dispersive characteristics

The physical model of the coaxial SWS is illustrated in Fig. 1. The coaxial SWS consists of a coaxial cylindrical waveguide with inner conductor, and the outer wall radius $R(z)$ varying according to Floquet's theorem

$$R(z) = R(z + z_0) \tag{1}$$

Using Fourier series expansion, $R(z)$ can be expressed as

$$R(z) = \frac{a_0}{2} + \sum_{n=1}^{\infty}(a_n \cos nh_0 z + b_n \sin nh_0 z) \tag{2}$$

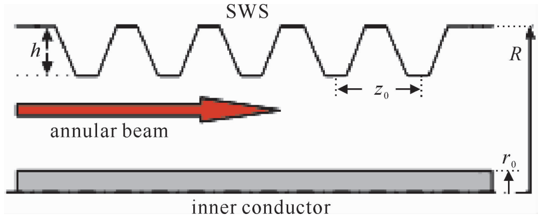


Fig. 1 Schematic of trapezoidal corrugation coaxial slow-wave structure

where a_n and b_n are the cosinoidal coefficient and sinusoidal coefficient of the nth order Fourier series, respectively; z_0 and $h_0 = 2\pi/z_0$ are corrugation period and longitudinal wave number, respectively.

$$\begin{aligned} a_n &= \frac{2}{z_0}\int_{-z_0/2}^{z_0/2} R(z)\cos nh_0 z\,\mathrm{d}z, \qquad (n = 0,1,2,\cdots) \\ b_n &= \frac{2}{z_0}\int_{-z_0/2}^{z_0/2} R(z)\sin nh_0 z\,\mathrm{d}z, \qquad (n = 0,1,2,\cdots) \end{aligned} \tag{3}$$

The numerical calculation results are plotted in Fig. 2. The solid line stands for the original structure. The dot line and the dash line stand for the SWS profiles obtained through one-step and ten-step numerical calculations, respectively. There is an obvious difference between the profile obtained by one-step calculation and the original structure. In addition, it is found that the difference decreases with the step increasing. Furthermore, there is almost no difference when the step number is ten. Therefore, we choose the ten-step results to resolve the dispersion curves.

For simplicity, we consider the normal modes of the coaxial SWS without the beam. Dispersion curves of the trapezoidal corrugation coaxial SWSs can be obtained according to the dispersion relations derived in Ref. [10], as shown in Fig. 3. In Fig. 3, Dispersion curves are plotted along with the beam line with energy of 700 keV, which is a typical value of our accelerator. The beam line corresponding to a beam voltage of 700 kV intersects with the −1st space harmonic of the quasi-TEM mode. The intersection point is in the backward wave region near the mode at about 1.7 GHz, which is slightly higher than the simulation results without nonlinear effects of the electron beam. From Fig. 3, it is clear that the quasi-TEM mode has no cutoff frequency in the waveguide, which is similar to the coaxial TEM mode[11-14]. Thus, the radius of the coaxial SWS can be obviously smaller than that of the non-coaxial SWS. Therefore, the coaxial RBWO of low operation band can be very compact and convenient for practical applications.

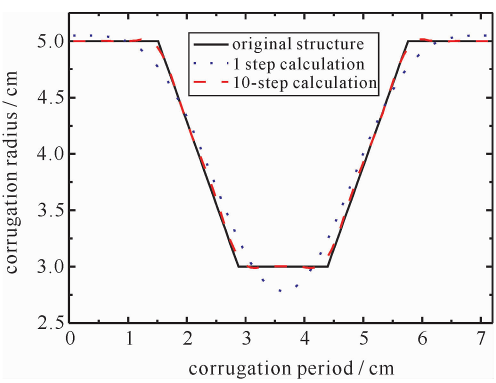


Fig. 2 Linear fitting chart of trapezoidal corrugation

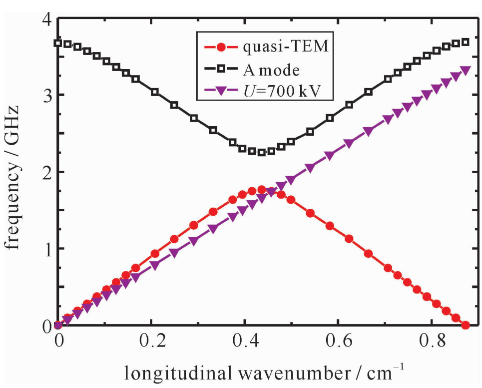


Fig. 3 Dispersion curves of the two lowest-frequency TEM modes and beam Doppler line with diode voltage of 700 kV. Here $z_0 = 7.2$ cm, $r_0 = 1.0$ cm, $h = 2.0$ cm and $R = 6.0$ cm

2 Longitudinal resonance characteristic

2.1 Longitudinal transmission characteristic of finite-length SWS

To illustrate the concept of longitudinal resonance characteristic in coaxial RBWO, we have conducted a comparative investigation on the structure of five-period SWSs with and without coaxial extractor (see Fig. 4). The parameters of both SWSs are the same. Let us excite the structure by a smooth wall waveguide coaxial TEM mode that runs from the left end to the right, as shown in Fig. 4. It is convenient to characterize their resonance properties by transmission coefficient T, which is defined as[15-16]

$$T(f) = S_{\text{out}}^{+} / S_{\text{in}}^{+} \tag{4}$$

where S_{out}^{+} and S_{in}^{+} are the electromagnetic power fluxes for direct waves through the input and the output cross-sections of a structure, respectively.

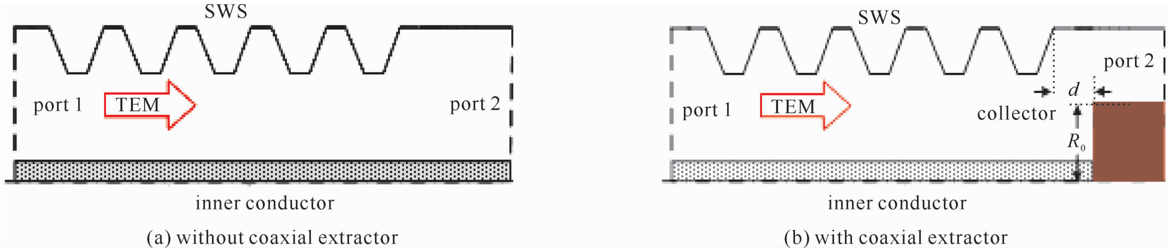


Fig. 4 Five-period SWSs with and without coaxial extractor

Fig. 5 shows the transmission coefficient as a function of frequency. The curve marked by empty squares and the curve marked by solid triangles stand for the resonance properties of the five-period SWSs without and with a coaxial extractor, respectively. Each peak in Fig. 5 represents a longitudinal mode of coaxial TEM mode. It is found that, the general transmission coefficient of the conventional structure is higher than that of the coaxial extractor structure. However, the peak of each longitudinal mode of the coaxial extractor structure is sharper than that of the conventional structure. The peak of π-like mode (point "P") is the sharpest in all longitudinal modes, which means that it has the biggest Q-factor and can be excited firstly. Therefore, a stable single-frequency oscillation can be excited effectively by choosing resonance point "P" as the longitudinal operation mode[16]. It must be noted that the dimension of the collector should be optimized numerically so that the value of the transmission coefficient at point "P" is suitable for both the beam-wave interaction and the extraction of microwave energy.

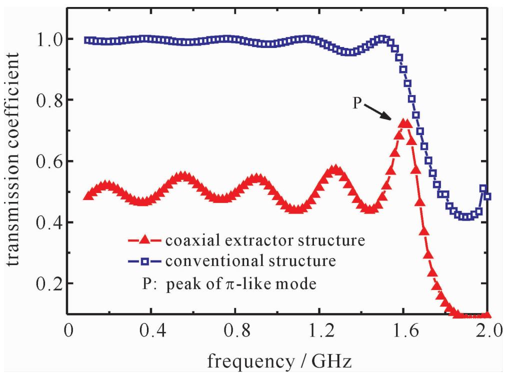


Fig. 5 Power transmission coefficient *vs* frequency for two structures

2.2 Effects of collector parameters

To further explain the effects of coaxial extractor structure, we have studied resonance properties of five-period SWS with different parameter collectors by transmission coefficient, as shown in Fig. 6 and Fig. 7.

The transmission coefficient as a function of frequency in three cases is shown in Fig. 6, where the radius of collectors is constant, and the distance between the right end of the SWS and the collector is 0, 2 or 4 cm. It is found that, the peak of each longitudinal mode decreases as the distance increases, and the frequency of resonance point decreases, too. In Fig. 7, the distance is constant and the radius is 3.8, 4.0 or 4.2 cm, the peak of each longitudinal mode decreases slightly with the radius increasing, while the frequency of each resonance point stays the same. According to the above simulation, the resonance properties are sensitive to the distance, but not to the radius.

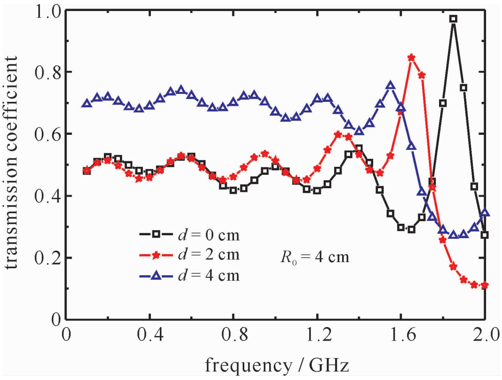


Fig. 6 Transmission coefficient *vs* frequency with different distances

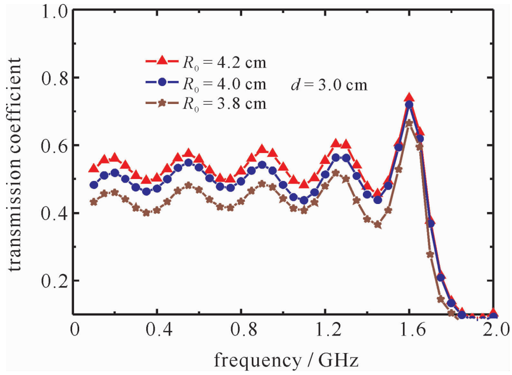


Fig. 7 Transmission coefficient *vs* frequency with different collector radii

3 Particle simulation

Based on the theory of dispersive characteristics and longitudinal resonance properties in the trapezoidal corrugation coaxial slow-wave structure, we have configured and investigated a compact L-band coaxial RBWO using the KARAT code, whose model is illustrated in Fig. 8. Its basic structure is similar to that of the conventional RBWO. However, the length of the SWS section is reduced from over ten periods to five periods, and there is a coaxial extractor structure at the end of the SWS section.

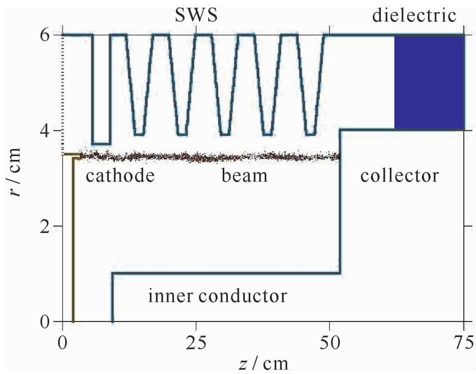
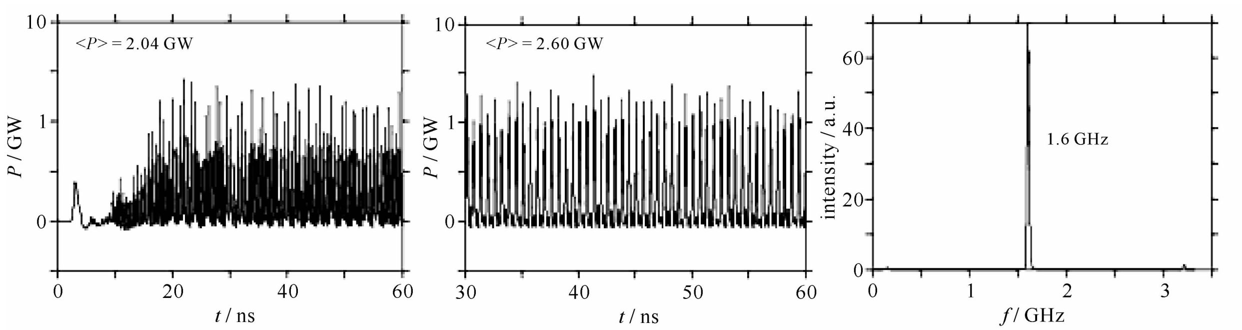


Fig. 8 Model for PIC simulation

The mechanism of generating HPM by the device is investigated numerically in detail with a 2.5-dimensional PIC code, with related physical pictures presented in Figs. 9(a) to (c). Under the optimized configuration, the L-band coaxial RBWO, driven by a 700 kV, 11.5 kA electron beam, comes to a nonlinear steady state at 18 ns [Fig. 9(a)]. A microwave of longitudinal TEM mode is generated with an average power of 2.60 GW [Fig. 9(b)] after saturation, a frequency of 1.6 GHz [Fig. 9(c)], and a power conversion efficiency of 32.3% in the duration of 30 to 60 ns. It should be noted that the length and the maximum diameter of the SWS region are only 40 cm and 12 cm, respectively, thus the coaxial RBWO is much smaller in overall size than the L-band non-coaxial RBWO. Therefore, the simulation results verify the theoretical analysis and demonstrate that the device can generate microwave with high efficiency.



(a) output power *vs* time (b) saturated output power *vs* time (c) spectrum of saturated output power at 30 ns

Fig. 9 Simulation results at output window

4 Conclusion

In this paper, we present theoretical analysis and particle simulation of the dispersive characteristics and longitudinal resonance properties in trapezoidal corrugation coaxial RBWO. With the Fourier series expandedness, the expression of the trapezoidal corrugation SWS is obtained. Based on the expression through 10 step linear fitting, the dispersion curves of the two lowest symmetry TM_{0n} waves are obtained with the numerical calculation. In particular, when the coaxial SWS parameters are matched with the annular beam voltage and radius, the system can operate in single coaxial TEM mode. In addition, through the S-parameter method, the longitudinal resonance properties of the finite-length coaxial SWS are investigated in detail. Furthermore, a compact L-band coaxial RBWO is designed with the KARAT code. In simulation, the L-band coaxial RBWO, driven by a 700 kV, 11.5 kA electron beam, generates the HPM with a power of 2.60 GW and a frequency of 1.6 GHz, and a power conversion efficiency of 32.3% in durations of 30 to 60 ns. The limitation of the device is that the guiding-magnetic system is so large that it is difficult to manipulate in experiments. Therefore, we should investigate the performance of the coaxial RBWO operating at the low guiding magnetic field.

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梯形波纹同轴慢波结构色散特性及其纵向谐振特性

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摘　要： 利用傅里叶级数展开，给出了一种求解梯形慢波结构表达式的方法。通过数值模拟，研究了级数展开次数对求解精度的影响。当级数为10阶时，线型拟合而成的结构与原结构吻合较好。利用此表达式数值求解了色散方程，得到两个最低阶模quasi-TEM模和A模。分析了为实现电子束与quasi-TEM模的－1次空间谐波相互作用慢波结构参数所需满足的条件，并指出利用此条件下纵向电场具有表面波的特点可实现横向模式选择。采用S参数理论研究有限长慢波结构的纵向谐振特性，提出在同轴慢波器件中加入同轴引出结构可减少所需慢波结构周期数，这不但使器件结构更为紧凑，还可避免纵模竞争从而提高器件效率、稳定产生微波频率。在此基础上设计了一种L波段同轴相对论返波振荡器，采用KARAT 2.5维全电磁粒子模拟程序研究了器件内束-波作用的物理过程。模拟结果表明，该器件具有径向尺寸小、束-波作用效率高的特点。在电子束能量700 keV、电子束流11.5 kA的条件下，器件在频率1.6 GHz处获得较高的微波输出，饱和后微波的平均功率达2.60 GW，平均效率约为32.3％。

关键词： 高功率微波；　同轴慢波结构；　相对论返波振荡器；　色散特性；　纵向模式