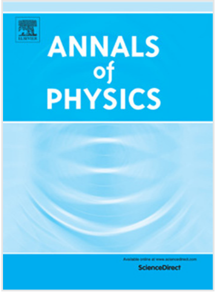

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Efficiency enhancement of slow-wave electron-cyclotron maser by a second-order shaping of the magnetic field in the low-gain limit

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Based on the anomalous Doppler effect, we put forward a proposal to enhance the conversion efficiency of the slow-wave electron cyclotron masers (ECM) under the resonance condition. Compared with previous studies, we add a second-order shaping term in the guild magnetic field. Theoretical analyses and numerical calculations show that it can enhance the conversion efficiency in the low-gain limit. The case of the initial velocity spread of electrons satisfying the Gaussian distribution is also analysed numerically.

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I. INTRODUCTION

Due to the wide applications in plasma heating, high resolution radars, advanced materials processing and high-power particle accelerators, electron cyclotron masers (ECM) becomes one of the most important sources for high power coherent radiations at millimeter and submillimeter wavelength regions [1–3]. The gyrotron and its invariants are the successful devices based on the fast-wave ECM in which the phase velocity of the wave is faster than the velocity of light in the vacuum [4, 5]. The amplification mechanism of the gyrotron and its invariants is that the high-speed electrons transfer their gyrating energy to the electromagnetic waves thus leading to the wave amplification.

Slow-wave ECM is a promising high-power and frequency-tunable radiation source. Different from the gyrotron and its invariants, the phase velocity of the wave in the slow-wave ECM is slower than the velocity of light in the vacuum. In this case, an electron beam with axial velocity interacts the electro-magnetic wave in a dielectric-loaded or periodically-loaded waveguide. Due to the anomalous Doppler effect, the axial velocity of electrons decreases and correspondingly the transverse velocity increases. It will resonant with electromagnetic waves provided the initial axial velocity of beam electrons slightly exceed the phase velocity [6]. This results in a net energy transfer from electrons to waves and consequently realize the amplification [7].

The resonance condition of ECM is $\omega - k_z v_z - s\Omega = 0$, with $\omega,\ k_z,\ \nu_z, s$ and Ω being the wave angular frequency, axial wave number, electron axial velocity, cyclotron harmonic numbers and the relativistic cyclotron frequency respectively. The resonance condition shows that the fast wave ECM happens at the positive cyclotron harmonics ($s > 0$) while the slow-wave ECM happens at the negative cyclotron harmonics ($s < 0$) [8, 9]. It has been shown that the slow-wave ECM has several superiorities which have great potentials in practical applications [10, 11]. Firstly, the low requirement for the properties of beam electrons, and thus the initial rectilinear beam can be easily gained by a Pierce electron gun with a high quality. Secondly, there is no need for a strong guiding magnetic field and the tolerance of beam velocity spread is better than gyro-devices. And another is the comparatively small mode competition, which can realize a easy mode or frequency selection in the wave generation [12–14].

Due to these superiorities, slow-wave ECM has been intensively investigated from both theoretical and experimental aspects. The self-consistent theory was constructed in Ref.[15]. In this paper, the author also estimated the conversion efficiency. Based on anomalous Doppler effect, the authors of Ref. [16] suggested a tapered waveguide amplifier, in which the self-consistent equations and the interaction efficiency were presented as a function of the waveguide length. The Effects of tapering structures on the characteristics of ECM were numerically demonstrated in Ref. [17]. Experiments on the slow-wave ECM for a partially dielectric-loaded waveguide, oversized corrugated waveguide, or a dielectric-loaded strip line structure were reported in Refs. [18–20] respectively.

As far as the conversion efficiency is concerned, the experimental data are very low. It is only about 4.5% [21] although it was predicted that the limit of the conversion efficiency would approach 100% in the ideal case [16]. In the same paper, the authors proposed a practical scheme. They analysed this scheme numerically and showed that the conversion efficiency may exceed 30%. Therefore, it is an interesting issue to enhance the conversion efficiency of

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