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# Study on the high frequency structure of FEM amplifier

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**Abstract**

The compact free electron maser (FEM), with the advantages of small size and low cost, is important for realistic applications in medicine and industry. In order to utilize the planar wiggler to the best advantage and simultaneously to reduce the necessary electron beam voltage and the size of FEM device, we propose to utilize an elliptical waveguide as the high frequency structure of planar wiggler FEM. A set of universal operating equations suitable for elliptical waveguide and rectangular waveguide FEMs is derived by using the nonlinear theory. The characteristics of the FEMs are numerically analyzed, comparatively.


*Keywords:* FEM amplifier; Elliptical waveguide; Rectangular waveguide; Planar wiggler; Nonlinear analysis; Numerical computation

## 1. Introduction

The free electron maser (FEM) is an important high power radiation source with broad bandwidth and continuous tunability in frequency. It has potential applications in industrial, agricultural, military and medical areas. FEM experimental systems have been constructed in many labs in America, Netherlands, Israel, and important results have been obtained [1–4].

Compact FEMs operating in the spectrum from microwave to the far infrared have recently been a subject of much attention because of their many realistic applications [5,6]. Those FEM devices employ low current electron beams to reduce the size and cost of the required electron source, and hence their output power is only modest. To increase the output power, many gain and efficiency enhancement techniques have been suggested, for instance the employment of prebunched electron beams, the waveguide optical klystron arrangement, and the energy recovery technique [7,8].

In addition to reducing the size of these compact FEM systems, another goal is to minimise the electron beam voltage required to generate a strong radiation at a given frequency. For this purpose, many schemes of wiggler have been proposed, but typi-

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cally a planar wiggler with parabolically tapered pole pieces is used to transverse focus the beam. Thus in order to utilize the planar wiggler to the best advantage, the choice of waveguide suitable for this kind of wiggler is rather important. Compared with rectangular waveguide used conventionality, the elliptical waveguide is well suited to the planar wiggler in terms of structure. In this Letter, we propose to use elliptical waveguide as the high frequency structure of planar wiggler FEM. A set of universal operating equations suitable for elliptical waveguide and rectangular waveguide FEM is derived by using the nonlinear theory. Based on these equations, we develop a computer numerical simulation program and comparatively analyze the characteristics of FEMs with these two different types of waveguides.

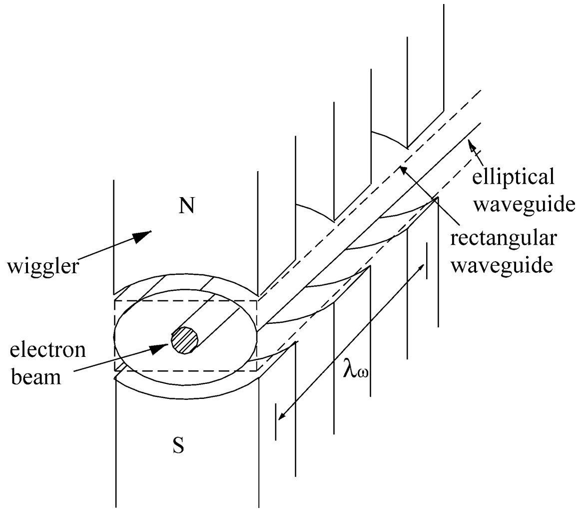


Fig. 1. High frequency configuration of FEM.

## 2. FEM amplifier general operating equations

The physical configuration shown in Fig. 1 includes interactive rectangular or elliptical waveguide, a planar wiggler with parabolic pole pieces, and electron beam. The wiggler field generated in this way provides for electron beam focusing in the plane of the principal wiggler motion, it is assumed to be the form [9]

$$\vec{B}_z(\vec{x}) = B_\omega(z)\left\{\cos(k_\omega z)\left[\sinh\left(\frac{k_\omega y}{\sqrt{2}}\right)\vec{e}_x + \cosh\left(\frac{k_\omega x}{\sqrt{2}}\right)\vec{e}_y\right] - \sqrt{2}\cosh\left(\frac{k_\omega x}{\sqrt{2}}\right)\sinh\left(\frac{k_\omega y}{\sqrt{2}}\right)\sin(k_\omega z)\vec{e}_z\right\}, \tag{1}$$

where $B_\omega$ denotes the wiggler amplitude and $k_\omega$ ($\equiv 2\pi/\lambda_\omega$) is the wiggler wave number. In addition, the beam injected into the wiggler is modeled by an adiabatic increase in the wiggler amplitude from zero to a constant over $N_\omega$ wiggler periods. We choose the $B_\omega(z)$ form as follows

$$B_\omega(z) = \begin{cases} B_\omega \sin^2(k_\omega z/4N_\omega), & 0 \leqslant z \leqslant N_\omega\lambda_\omega, \\ B_\omega, & z > N_\omega\lambda_\omega. \end{cases} \tag{2}$$

The interaction between the electron beam and the radiation field, space charge effect neglected, is described by the wave equation with current source in terms of vector potential $\delta\vec{A}(r,t)$ as follows

$$\nabla^2\delta\vec{A} - \frac{1}{c^2}\frac{\partial^2\delta\vec{A}}{\partial t^2} = -\frac{4\pi}{c}\delta\vec{J}, \tag{3}$$

where $\delta\vec{A}(r,t)$ can be expressed by the orthogonal basis functions of the vacuum waveguide, and we write the vector potential of the radiation field in the form [10]

$$\delta\vec{A} = \sum_{m,n}^{\infty}\delta A(z)\vec{e}_{mn}^{\,\mathrm{TE}}(x,y)\cos\alpha_{mn}, \tag{4}$$

where frequency $\omega$ and wave number $k_{mn}(z)$

$$\alpha_{mn} = \int_0^z k_{mn}(z')\,dz' - \omega t. \tag{5}$$

It is implicitly assumed that both the mode amplitude $\delta A(z)$ and the wave number $k_{mn}(z)$ vary slowly over a wave period. The notation $\vec{e}_{mn}^{\,\mathrm{TE}}(x,y)$ is TE mode function, defined as follows.

For rectangular waveguide

$$\vec{e}_{mn}^{\,\mathrm{TE}}(x,y) = \frac{n\pi}{k_c b}\cos\left(\frac{m\pi}{a}x\right)\sin\left(\frac{n\pi}{b}y\right)\vec{e}_x - \frac{m\pi}{k_c a}\sin\left(\frac{m\pi}{a}x\right)\cos\left(\frac{n\pi}{b}y\right)\vec{e}_y, \tag{6}$$

where $\vec{e}_x$, $\vec{e}_y$ are the unit vector in the direction of $x$ and $y$, and cutoff wave number $k_c = \pi[\frac{m^2}{a^2} + \frac{n^2}{b^2}]^{1/2}$.