Searching the start oscillation conditions of gyrotron backward wave oscillator using particle swarm optimization

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Abstract: Particle swarm optimization (PSO) is used to search the start oscillation conditions of gyrotron backward wave oscillator (gyro-BWO), the results are more accurate than the original algorithms.

Keywords: Gyro-BWO, Oscillation conditions, PSO

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1. Introduction

The high power capability of the gyro-BWO makes it an attractive source of coherent radiation in the millimeter and submillimeter wavelength ranges. Generally, we have searched the oscillation conditions by local equation, solving algorithm based on a certain boundary condition in a simulation. However, these gradient based algorithms are very sensitive to the initial value and easy to get into local optimization.

Particle Swarm Optimization (PSO) is an evolutionary computation technique developed by Eberheart and Kennedy in 1995 and is a simple and effective swarm-intelligence-based technique for optimization of wide range of functions. PSO is a meta-heuristic technique as it makes few or no assumptions about the problem being optimized and can search very large spaces of candidate solutions. Over the decade, PSO has been proved to be one of the most promising algorithms for many intricate problems in engineering and sciences [1]. Its simplicity and faster convergence make it an attractive algorithm to employ. The population is called "swarm" and the individuals are termed as particles. The word "swarm" is inspired from the jagged movement of particles in the problem region. The particles are assumed to be mass-less and volume-less.

2. Theory

In order to describe the beam-wave interaction in gyro-BWO, a self-consistent nonlinear theory is used. Some basic assumptions of the theory are introduced below. Assuming the existence of the electron beam does not affect the transverse field profiles, the right circularly polarized TE_{mn} mode can be expressed as

$$\vec{E}_t = \mathrm{Re}\left\{ \frac{i\omega\mu_0}{k_{mn}^2} f(z)\vec{b}(r,\theta)e^{i\omega t} \right\} \tag{1}$$

$$\vec{B}_t = \mathrm{Re}\left\{ \frac{\mu_0}{k_{mn}^2} f'(z)\vec{e}(r,\theta)e^{i\omega t} \right\} \tag{2}$$

$$B_z = \mathrm{Re}\left\{ \mu_0 f(z)\phi(r,\theta)e^{i\omega t} \right\} \tag{3}$$

where $k_{mn} = x_{mn}/r_w$, x_{mn} is the nth root of $J_m'(x)=0$ and $\phi(r,\theta) = J_m(k_{mn}r)e^{-im\theta}$, $\vec{e}(r,\theta) = \nabla_t\phi$, $\vec{b}(r,\theta) = \hat{z}\times\vec{e}$, which represent the transverse field profiles, and $f(z)$ is the complex amplitude of the field.

For the self-oscillation, we have a pure backward-wave at the left end given by the boundary conditions and (4) (5) [2]

$$f(z_1) = |f_-|e^{-ik_z z_1} \tag{4}$$

$$f'(z_1) = -ik_z|f_-|e^{-ik_z z_1} \tag{5}$$

where $|f_-|$ is the amplitude of the backward wave at the left end z_1. The phase of the wave is of no significance to the self-oscillation. The boundary condition at the right end is again given by

$$f'(z_2) = ik_z f(z_2) \tag{6}$$

and the undetermined quantities are $|f_-|$ and the oscillation frequency ω. Equation (6) can be written by

$$D(|f_-|,\omega) = f'(z_2) - ik_z f(z_2) = 0 \tag{7}$$

Generally, we can solve this complex equation by 2-dimension equation solving algorithm such as Newton or Powell. However, these gradient based algorithms are very sensitive to the initial value and easy to get into local optimization. Here, we use PSO algorithm to solve this problem. From (7), the fitness function of the problem can be written by

$$FitnessFunction = abs\left(f'(z_2) - ik_z f(z_2)\right) \tag{8}$$

3. Results and discussion

Applying the above equations to a TE_{01} mode gyro-BWO, with beam Voltage V_b=100 *kV*, velocity ratio $\alpha=1$, beam current I_b=1 *A*, waveguide radius r_w=0.57 *cm*, guiding center radius r_c=0.48 *rw*, external magnetic field B_0=1.3 B_g, where B_g is the grazing magnetic field of the operating mode, interaction region length L=14.5 *cm*., Figure 1 plots the $\omega - k_z$ diagram of the transverse electric TE_{01} waveguide modes.

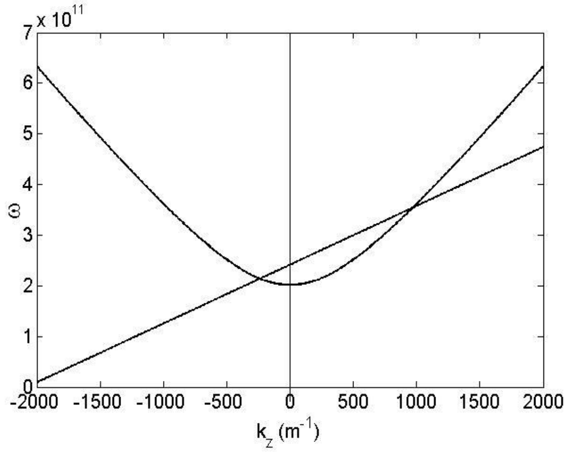

Fig. 1 $\omega - k_z$ diagram of the transverse electric TE01 waveguide modes.

Figure 1 shows the interaction frequency $f_0 = 34.03\,GHz$, as is known that the actual oscillation frequency of gyro-BWO is higher than f_0. The range of values considered for the parameters are shown in Table 1.

Tab. 1 The range of values considered for the parameters.

Name of the parameter	Range
Frequency (*GHz*)	[34,36]
Amplitude	[2e-6,10e-6]

In the design optimization process, PSO is executed with 40 particles for max 100 generations. The convergence graph and the swarming graph for the simulations are presented in Fig. 2 and Fig. 3.

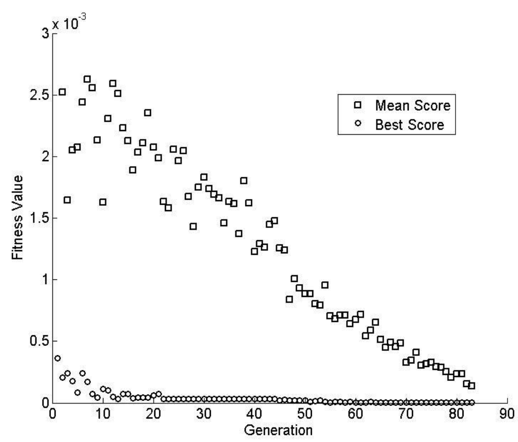

Fig. 2 The convergence graph for the simulations.

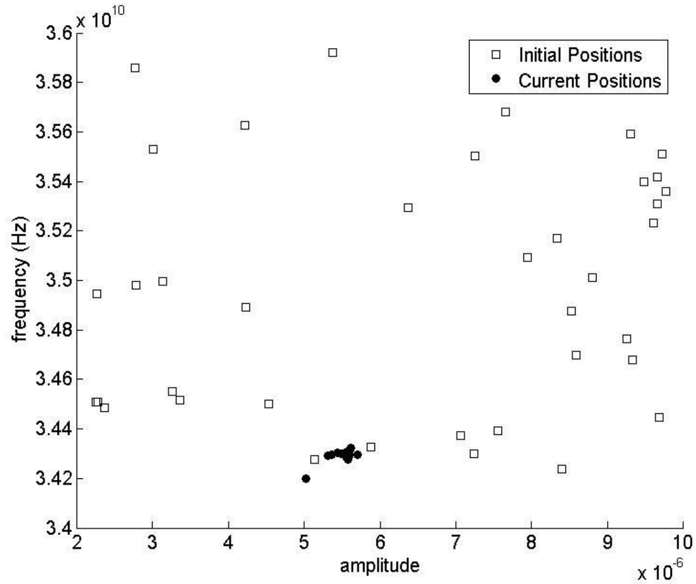

Fig. 3 The swarming graph for the simulations.

It is observed from the graphs that the particles swarm quickly together after a few generations, and the optimization process stops when the average cumulative change in value of the fitness function over 30 generations is less than 1e-06. The final optimized parameter values are frequency f=34.297 *GHz* and amplitude $|f_{-}|$ =5.555e-06 with best value of 1.109e-06.

Figure 4 shows the power flow along z-axis of the gyro-BWO, and it can be seen that the start oscillation conditions are found with great accuracy and the output power of gyro-BWO is more 5 *kW* at the left end of the interaction region.

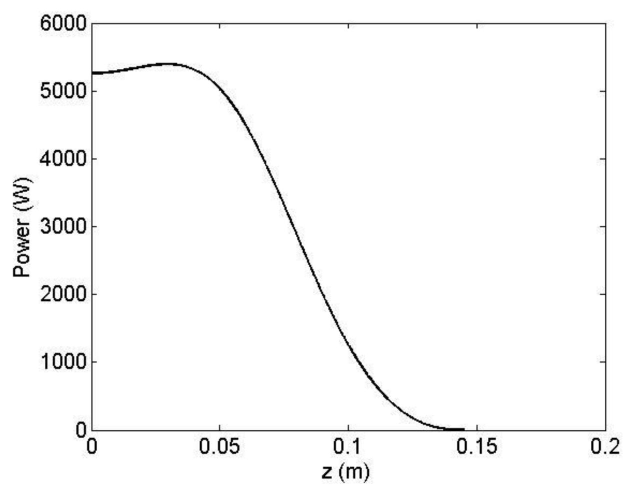

Fig. 4 Power flow along z-axis of the gyro-BWO.

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