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NUMERICAL OPTIMIZATION OF PITCH PROFILE FOR OVERALL EFFICIENCY ENHANCEMENT OF A SPACE TWT

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Abstract—Obtaining higher efficiency during the development of space Traveling Wave Tubes (TWTs) is always one of the most important goals for scientists. In this paper, a scheme of obtaining the maximum theoretical overall efficiency is explored by optimizing the helix pitch profile of a TWT based on the collectability of spent beam. The collectability of the spent beam was evaluated by the maximum collector efficiency, and this maximum collector efficiency was employed to calculate the maximum theoretical overall efficiency. The energy distribution of the spent beam and the output power of TWTs were calculated by the 3-D large signal Beam-Wave Interaction Simulator (BWIS) of MTSS. The detailed design of a Ku-band helix TWT is described according to three optimization goals (theoretical overall efficiency, theoretical collector efficiency and electronic efficiency). The simulation results indicate that the optimization for high interaction circuit efficiency or collector efficiency by itself is not adequate to obtain maximum overall efficiency. The maximum theoretical overall efficiency of 77% was achieved via the optimization of slow wave structure for theoretical overall efficiency.

1. INTRODUCTION

Space TWTs as the key component of final power amplifier have been widely used in satellites for communication, navigation, weather and science [1, 2]. High efficiency is an essential requirement for the development of modern space TWTs. A single percentage

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point increase in overall efficiency can be significantly translated into potential revenue increases for a space TWT [3]. In addition, any loss of efficiency leads to the waste of energy and worsens the thermal dissipation condition in space [4].

There are usually two strategies to increase the overall efficiency. One strategy is to increase the interaction circuit efficiency to minimize the power entering the collector. The other one is to increase the number of collector's stages to recover the spent beam energy as much as possible [3, 4]. The former may degrade the characteristics of output electromagnetic wave, such as bandwidth or phase distortion characteristics, whereas the latter may increase the complexity of power supply. With the increase of the number of stages, the improvement of collector efficiency is very little. If designers can perform global optimizations where they combine the optimization of the interaction circuit and the optimization of the collector together, this will mean much to the efficiency enhancement of a TWT, but the process of optimization is time-consuming.

Enhancing electronic efficiency of the slow wave circuit is a usual approach to improve overall efficiency for the designers [4–7]. When the maximum electronic efficiency is required, the RF signal extracts the maximum energy from the electron beam, which usually results in chaotic and relatively high energy spread of the spent beam. The spent beam will not be easy to recover if we focus only on the maximum electronic efficiency [8]. To achieve high collector efficiency, the number of stages of multistage depressed collector (MDC) is usually increased for space TWTs, which will make the design of MDC complicated. Therefore, the design of a TWT circuit must consider the energy distribution of spent beam. A more promising strategy to improve the overall efficiency has been proposed by Komm et al. [3]. If the electron beam comes out in several essentially mono-energetic groups even with relatively high energy spread, the relatively high energy can be recovered from the spent beam. The concept of *collectability* refers to the ability of the maximum amount of energy that can be recovered by a finite number of collector electrodes. For a spent beam with high *collectability*, its energy distribution function generally has a *stair-step* characteristic. Using this method, the overall efficiency of a Ku-band (11.2 GHz–11.7 GHz) space TWT in Boeing Electron Dynamic Devices Incorporation has been enhanced to higher than 70% [3]. However, Ref. [3] didn't describe how to improve the *collectability* characteristics of the spent-beam distribution function and this method may provide guidance for the designers who research on the high efficiency TWTs. In this work, based on the concept of collectability, a scheme of obtaining the maximum theoretical overall efficiency of a TWT is explored by optimizing the helix pitch profile. A *stair-step* shape and large spread of the spent-beam energy distribution was achieved simultaneously to obtain high collector efficiency and high electronic efficiency.

Optimization algorithm has great impact on the final result. A lot of algorithms such as simulated annealing algorithm [5, 6], modified steepest descent algorithm [9], Nelder-Mead method [10] and ε-MOEA [7] were implemented to optimize the circuit parameters for high electronic efficiency. Genetic Algorithm (GA) [11] and Simulated Annealing (SA) algorithm [12] have been applied in the design of multistage depressed collectors to obtain higher collector efficiency. The traditional optimization algorithm is more suitable for analytic functions' optimization but may be not suitable for the optimization of high power RF devices, because of their nonlinear interaction physics. The SA algorithm is a global search algorithm, and the feasibility of the optimization of helix pitch to enhance efficiency has been proved [5, 6], but the computational complexity of this algorithm increases greatly when the number of parameters to optimize increases a little. Genetic algorithm, which performs very well when the optimization landscape is non-convex, segmented, and non-continuous, is used more and more for optimization of electromagnetic problems [11, 13–15]. The optimization of circuit parameters with constraints to obtain better dispersion and coupling impedance using multi-objective genetic algorithm was first demonstrated by Xiao et al. [13]. The optimization of helix pitch profile to obtain high overall efficiency was seldom described by the researcher. In this paper, 3-D Beam-wave interaction simulator (BWIS) of MTSS which was developed by University of Electronic Science and Technology of China, Chengdu [16] was integrated with genetic algorithm to automate the optimization for overall efficiency enhancement. The other two optimizations for enhancing electronic efficiency and collector efficiency were also implemented to bring into comparison respectively.

2. GOAL FUNCTION

The largest fraction of waste heat is generated in the collector of a space TWT [8]. The multi-stage depressed collector (MDC) recovers as much of the remaining kinetic energy in the spent beam as possible so that each electron lands on the surface of collector with little kinetic energy. To design an MDC for a special spent beam, the following steps are usually implemented by designers. First, draw the energy spectrum of the spent beam (shown in Fig. 1) according to the distribution of the electron velocities at the output position. Second, choose the initial

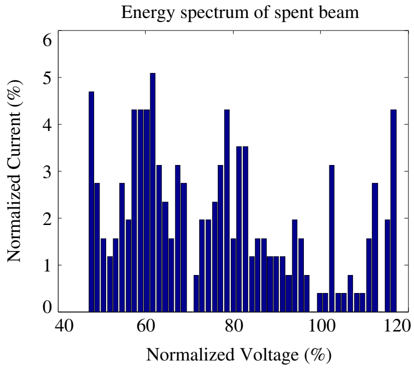

Figure 1. An example of spent beam's energy spectrum.

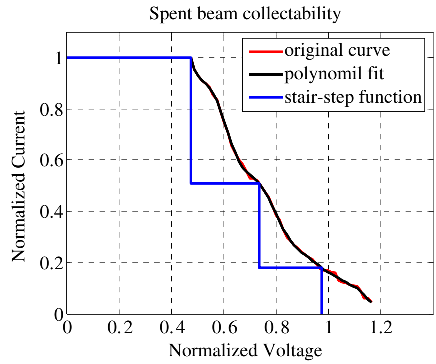

Figure 2. Spent beam collectability (original curve of distribution function, polynomial fit of original curve and stair-step function of the original cure).

value of electrodes' voltages according to the energy spectrum. The minimum energy (expressed in voltage) of the spent beam was chosen as the first electrode's voltage when the back-streaming electrons and the secondary electrons emission were ignored. The position of the peaks in the figure of energy spectrum was chosen as the voltages of the second, the third electrode and so on. Finally, design appropriate geometrical shape for the MDC and adjust the voltages of electrodes to obtain maximum collector efficiency.

More precision and convenient method to decide the collector's optimum voltages is to draw spent-beam energy distribution (collector voltage versus collector current) as Fig. 2.

The relationship of normalized collector voltage Eb and normalized collector current Ib in Fig. 2 is [3]

$$Ib = \int_{Eb}^{\infty} n_e(E)dE / \int_{0}^{\infty} n_e(E)dE \tag{1}$$

where, n_e is the probability density of the beam electrons which can be calculated by the spectrum of the spent beam, and $\int_0^\infty n_e(E)dE{=}1$. So, Equation (1) can be written as

$$Ib_j = 1 - \sum_{V_i < Eb_j} I_i (i, j = 1, 2, \ldots, n) \tag{2}$$

where, n is the number of bars in Fig. 1, and V_i, I_i is the normalized voltage and normalized current respectively in Fig. 1. Fig. 2 shows spent beam distribution function in the red line (part of which were covered by blue line). The area under the energy distribution function (The black line is the 15 order polynomial fit of red line) describes the total energy of the spent beam. The area under *stair-step* function (blue line) describes the maximum energy that can be recovered using three electrodes when the back-streaming electrons and the secondary electrons emission effect are ignored. The difference in these two areas is the dissipated power. If the difference between the energy distribution function and *stair-step* function is smaller, more energy can be recovered. The three optimal collector stage voltages can be calculated by minimizing the above difference.

To obtain a high overall efficiency, RF conversion efficiency by itself is not adequate, because too much RF conversion efficiency can lead to an overly chaotic spent beam which cannot be collected efficiently. Optimizing the TWT circuit by running the large-signal code to obtain a better *collectability* spent beam, is a much more promising method. The optimization algorithm varies helix pitch profile to maximize the overall efficiency as defined below. For each varying helix pitch profile, the maximum collector efficiency and electronic efficiency are calculated simultaneously. The maximum collector efficiency η_{coll} is defined as the ratio of the area under stair-step function $s(v)$ and the area under polynomial fit curve $p(x)$ when the back-streaming electrons and secondary electrons emission effect are ignored.

The stair-step function $s(v)$ is given by (In this paper, three-stage depressed collector was used except the Fig. 7(b))

$$s(v) = \begin{cases} 1 & (0 \leq v \leq v1) \\ c1 & (v1 \leq v \leq v2) \\ c2 & (v2 \leq v \leq v3) \end{cases} \tag{3}$$

The maximum collector efficiency η_{coll} is expressed in the form

$$\begin{aligned} \eta_{coll} &= \text{Maximize}\left[\frac{\int_0^{+\infty} s(v)dx}{\int_0^{+\infty} p(x)dx}\right] \\ &= \text{Maximize}\left[\frac{v1 + c1(v2 - v1) + c2(v3 - v2)}{\int_0^{+\infty} p(x)dx}\right] \end{aligned} \tag{4}$$

where $v1$, $v2$, $v3$ are the normalized optimum voltages of the three-depressed collector's electrodes calculated by the method described above, $c1 = p(v2)$, $c2 = p(v3)$, and x represent the various physical parameters that will be optimized.

The electronic efficiency $\eta_{ele}(x)$ which is defined as the difference in the RF output power (p_{out}) and the RF input power (p_{in}) divided by the beam power.

$$\eta_{ele}(x) = \frac{p_{out} - p_{in}}{I_b V_b} \tag{5}$$

where I_b and V_b are the beam current and beam voltage, respectively.

The theoretical overall efficiency $\eta_{overall}$ can be written as flowing if the heater power, interception loss, and the loss at the output circuit are ignored.

$$\eta_{overall} = \frac{\eta_{ele}}{1 - \eta_{coll}(1 - \eta_{ele} - \frac{p_{RF}}{I_b V_b})} \tag{6}$$

where p_{RF} is the power of harmonics and intermodulation.

The three optimization problems can be written as

1) the theoretical overall efficiency as the goal function

$$\text{Minimize } f(x) = 1 - \eta_{overall} \tag{7}$$

2) the theoretical collector efficiency as the goal function

$$\begin{array}{l}\text{Minimize } f(x) = 1 - \eta_{coll} \\ \text{Subject to } \eta_{ele} - 25\% \geq 0\end{array} \tag{8}$$

3) the electronic efficiency as the goal function

$$\text{Minimize } f(x) = 1 - \eta_{ele} \tag{9}$$

Electronic efficiency more than 25% as a constraint in Equation (8) is used to eliminate those individuals of high collector efficiency but with low electronic efficiency in the process of optimization for collector efficiency.

3. EXAMPLE OPTIMIZATION DESIGN OF A SPACE TWT

In order to achieve high output power, a helix pitch profile in Fig. 3 is appropriate, because the proportion of decelerated electrons increases and the proportion of accelerated electrons decreases in the output section of the tube [4]. For an easy manufacturing of the helix pitch in practice, the center of sever is set at point 2 and the input attenuator and output attenuation are symmetry arranged to sever. The input length was uniform (point 1-2) and the output divided into positive phase jump segment (point 2-3), negative phase jump segment (point 3-4) and last uniform segment (point 4-5). The position of points 2, 3, 4 and the pitch of section 1-2, sections 2-3, and section 4-5 were chosen as the parameters to be optimized.

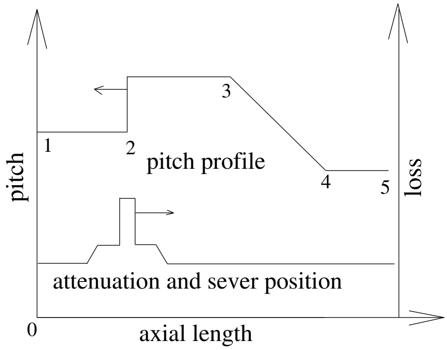

Figure 3. Diagrammatic sketch of the pitch and attenuation profile.

Using genetic algorithm and goal functions described in Section 2, the design of a Ku-band (13.2–13.8 GHz) helix TWT, which is developed at Institute of Electronics, Chinese Academy of Sciences, was explored. The three goals, theoretical overall efficiency, theoretical collector efficiency, and electronic efficiency at 13.4 GHz, were optimized respectively. The saturated output position of constant pitch helix was set as the output position in the process of optimization and this beam-wave interaction length kept unchanged. The input power for all optimizations is 5 mw.

The parameters of sever and attenuation were preset according to the experience. The cold-test parameters for series of pitches were simulated by Ansoft HFSS which can get a credible result [17, 18]. The optimization parameters were recorded in x and the initial variable was generated by randomly changing each parameter. The maximum and minimum of each parameter which limit the parameter to be changed were preset. The steps of the overall efficiency optimization are as follows.

Step 1: preset the species parameters, which involve the size of population M, the number of generation N, the probability of crossover and mutation, P_c and P_m.

Step 2: initialize the species and evaluate the population. The output power and energy distribution function of spent beam are calculated by BWIS. The theoretical overall efficiency and electronic efficiency are calculated by Equations (5), (6) respectively.

Steps 3: choose the elite individuals from population. The elite individuals are chosen according the overall efficiency by tournament algorithm. The individual of higher theoretical overall efficiency has higher probability to be chosen.

Step 4: Generate a new generation by the crossover the elite individual with the randomly selected individuals from the species. Then the new generation mutates. The crossover and mutation algorithm are implemented according to real polynomial algorithm [19].

Step 5: evaluate the new generation using the method described in step 2.

Step 6: repeat steps 3, 4, 5 until the user-specified number of iteration is reached or a converged solution is achieved.

4. THE RESULT AND DISCUSSION

The theoretical overall efficiency, theoretical collector efficiency and electronic efficiency were optimized using GA respectively. Compared with SA, GA takes up more memory and consumes more CPU time, because it finds the optimal solution over a population rather than point-by-point iteration of SA, however, given enough time, GA usually provides better solutions than SA [20, 21]. The maximum number of iterations was set 2000 times for all optimization process, and the results show that 2000 times can guarantee the obtained solution is near optimal solution. The process of the overall efficiency optimization was shown in Table 1. Little improvement in overall efficiency was achieved after iteration of 1000 times. For each iteration, the simulation time was nearly 30 seconds in a 2–1.99-GHz (Duo Core CPU) personal computer with a 2-GB random access memory (the time for running 3-D large-signal code BWIS is about 26 seconds). Compared with the initial constant pitch values (shown in Table 2), the overall efficiency and electronic efficiency both increased. The values of iterating 600, 800 and 1000 times have better overall efficiency and electronic efficiency than the values of iterating 400 times because the overall efficiency increases without degrading basic electronic efficiency. The optimum normalized voltages of the three electrodes for the spent beam after every 200 iterations were given in Table 1. The next step is the design of appropriate three-stage depressed collector to recover this high energy using the optimum voltages.

Figure 4 plots the helix pitch profiles for the constant pitch circuit and the theoretical overall efficiency, theoretical collector efficiency, and electronic efficiency optimized circuits. As expected, the electronic efficiency optimized pitch profile which features a strong dynamic velocity tapering at the end of the interaction region to better match the phase velocity of the axially propagating electromagnetic wave with the reduced electron velocity. To obtain maximum collector efficiency, the theoretical collector efficiency optimized pitch circuit has the smallest taper at the end of interaction region to decrease spent-beam energy spread. The theoretical overall efficiency optimized

Table 1. An example of overall efficiency optimization (Three-stage collector), Vo is the cathode voltage.

After iteration	Maximum Theoretical Overall efficiency (%)	Electronic efficiency (%)	Optimum Voltage (*Vo)		
			first electrode	second electrode	third electrode
200	66.6	22.99	0.4161	0.5611	0.9061
400	67.632	23.58	0.40669	0.55669	0.88669
600	74.1	26.9	0.37595	0.50595	0.90095
800	76.7	29.9	0.35262	0.42262	0.84762
1000	76.9	29.7	0.36184	0.44184	0.85684
1200	77	29.9	0.3588	0.4338	0.8538

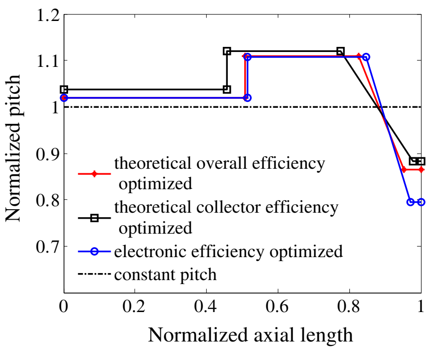

Figure 4. The result of three optimized helix pitch profiles together with constant pitch.

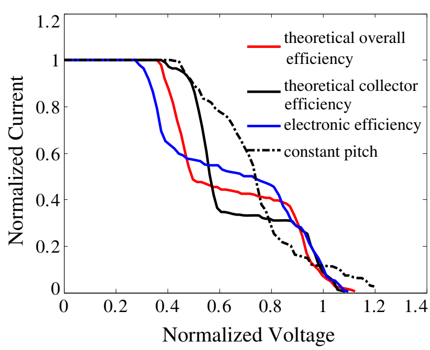

Figure 5. Collectability comparison of the three optimized circuits together with constant pitch circuit at center-band frequency.

circuit is a tradeoff between electronic efficiency optimized circuit and collector efficiency optimized circuit. This result agrees with Table 2. The theoretical overall efficiency optimized circuit has a little lower electronic efficiency and collector efficiency than the electronic efficiency and theoretical collector efficiency optimized circuit respectively. While compared with constant pitch circuit, the theoretical overall efficiency and electronic efficiency of the three optimized circuits have been greatly improved. Setting interaction circuit efficiency or theoretical collector efficiency as goal function

Table 2. Result comparison of the overall efficiency, electronic efficiency, collector efficiency optimized circuits and constant pitch circuit.

	Maximum theoretical overall efficiency (%)	Electronic efficiency (%)	Maximum theoretical collector efficiency (%)
Overall efficiency optimized circuit	77	29.9	88.4
collector efficiency optimized circuit	74.1	26.9	89.2
Electronic efficiency optimized circuit	71.4	30	83.9
Constant pitch circuit	64.7	22.9	84.3

via optimizing interaction circuit is an effective approach to enhance overall efficiency, but interaction circuit efficiency or collector efficiency by itself is not adequate to obtain maximum overall efficiency.

Figure 5 shows the spent beam *collectability* at the frequency of 13.4 GHz for the three optimized circuits and the constant pitch circuit. The spent beam of theoretical overall efficiency optimized circuit has a little greater spread in electron energies (from 35.88% of beam voltage to 112.4% of beam voltage) than constant pitch circuit (from 45.98% of beam voltage to 119.8% of beam voltage). At the end of output segment, a large portion of electrons were in accelerated phase resulting in the relative high energy spread and low electronic efficiency for constant pitch circuit. The less waste energy will be generated for overall efficiency optimized circuit than constant pitch circuit because of its *stair-step* characteristic even if it has a larger spread in electron energy. More energy of the former circuit was extracted from the electrons and more energy can be recovered from the spent beam, so that the theoretical overall efficiency has improved greatly (from 64.7% to 77%). The smallest energy spread and *stair-step* characteristic for the theoretical collector efficiency optimized circuit made the spent beam have largest *collectability*.

To obtain maximum collector efficiency, the characteristic of the electrons coming out of the interaction region in several mono-energetic groups was desired. This goal was achieved, as seen in Figs. 6(a)–(b). The spent electrons come out in two approximately mono energy groups if the three-stage depressed collector was used in the progress of the theoretical collector efficiency optimization. If the four-stage depressed collector was used, the energy spectrum of spent beam had the characteristic of three mono-energy groups. The electronic efficiency and collector efficiency of the theoretical collector efficiency optimized circuit by four electrodes were 27.8% and 90.3% respectively. It has greater energy spread because of its higher electronic efficiency, while the collector efficiency is larger because of one more additional electrode, compared with the collector efficiency optimized circuit by three-stage depressed collector.

Figure 7 shows the overall efficiency over the operation frequency band. Theoretical overall efficiency optimized circuit has the highest theoretical overall efficiency in the operation band whereas electronic

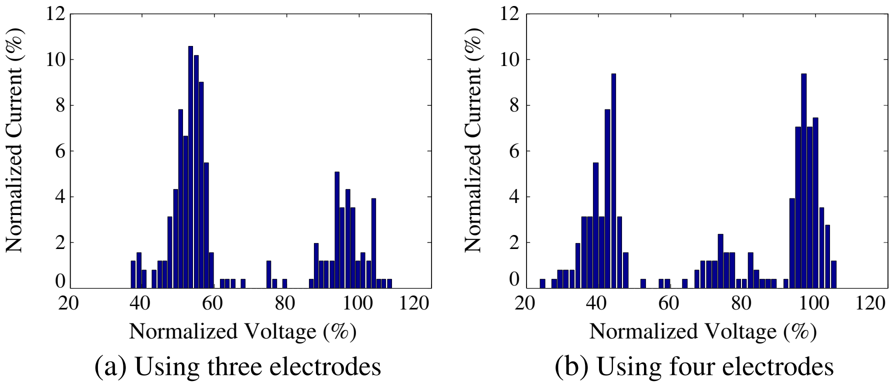

Figure 6. The energy spectrum of the collector efficiency optimized circuits using three electrodes and four electrodes respectively.

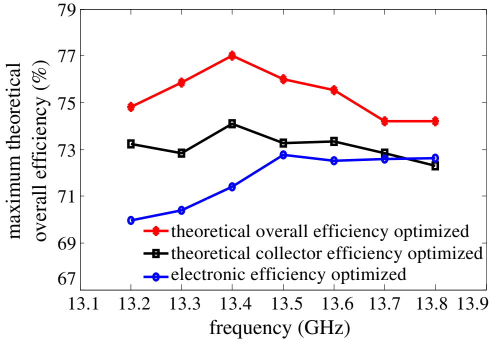

Figure 7. Comparison of maximum theoretical overall efficiency for the optimized circuits.

efficiency optimized circuit has the lowest maximum theoretical overall efficiency except at frequency 13.8 GHz. At lower frequency band, the maximum theoretical overall efficiency for electronic efficiency optimized circuit decreased fast because of bad collectability of spent beam at these frequencies. The optimization of pitch profile to obtain high theoretical overall efficiency has good potential to improve the efficiency of space TWT.

5. CONCLUSION

A scheme of obtaining the maximum overall efficiency is explored by optimizing the helix pitch profile of a TWT. 3-D large-signal code BWIS was integrated in the genetic algorithm to optimize helix interaction circuit. The energy distribution of *stair-step* characteristic of the optimized circuit was achieved even if it has relatively high energy spread. Compared with the optimization of helix pitch profile for electronic efficiency enhancement or theoretical collector efficiency enhancement, the optimization of helix pitch profile for theoretical overall efficiency enhancement is a more promising method. The scheme described in this paper provides useful guidance for the designers who research on the development of high efficiency space TWT.

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