Thermal analysis of TWT delay line by combined theoretical and numerical approach.

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Abstract: Simulation of thermal flow through complicated structures is usually a challenge. An example of such problem is heat generation and transfer through microwave delay structure in the travelling wave tube (TWT). A high level of microwave power and considerable energy of electrons intercepted by the delay line leads to the increase of local temperature of the microwave structure. Determination of the heat transfer from the hot spots is essential for the proper design of the delay line and assisting cooling system. This problem has been investigated by means of a combined, analytical and computer simulation method. Such methodology does not require expensive equipment and is much faster than the pure experimental analysis. Presented analytical model is focused on evaluation of the electron beam power dissipation and microwave losses along the delay line, which is not uniform and most of the power is accumulated at terminal part of the delay line. The analytically evaluated power dissipation is then used in numerical simulation of temperature distribution in the working TWT. As the result it was concluded that the temperature distribution is nonuniform, with high temperatures at the delay line output, which can influence reliability parameters.

1. Introduction

Simulation of thermal flow through complicated structures is usually a challenge. An example of such problem is heat generation and transfer through microwave delay structure in the travelling wave tube (TWT). These tubes are very often used as a power amplifiers in the microwave telecommunication. In this applications the reliability and MTBF are of major concern. A high level of microwave power and considerable energy of electrons intercepted by the delay line lead to the increase of local temperature of the microwave structure. Determination of the heat transfer from the hot spots is essential for the proper design of delay line and cooling system and finally to manufacture high reliability microwave tubes.

2. Description of the fundamental problems

In a project of C-band, continuous wave TWT for troposphere communication which is goal of the current project, this problem was investigated by means of a hybrid, analytical and computer simulation method. The assumed parameters of electron beam designed tube are: cathode voltage - U_0= 8500 V, beam current - J_0 =300 mA, summary helix delay line current- J_a=10 mA and max. microwave output power –Pout =500W. For this difficult conditions density of electron beam power achieve 1400 W/mm^2 and dissipation of power in delay line can easily lead to increased temperature of structure above the admissible value.

The above paper describes the thermal analysis of the TWTs helix delay line by combined analytical and numerical approach. Analytical model is focused on evaluation of the beam current power dissipation and microwave losses along the delay line, which is not uniform and most of the power is accumulated at terminal part of the delay line. This results in non-uniform temperature distribution, with very high temperatures at the delay line output. The analytically evaluated power dissipation is then used in numerical simulation of temperature distribution in the working TWT.

The operation principle of TWT is based on interaction of electromagnetic wave guided by the delay line (e.g. helix) with the electron beam injected along the its axis. A simplified structure of TWT is illustrated in Figure 1. The axial electric field e-m wave components accelerate same electrons and decelerate others. This results in electron beam density modulation and the energy extracted from decelerating bunches of electrons is then transferred to the circuit. Microwave power generated in delay line exponentially growths along the travelling zone direction of the wave [1].

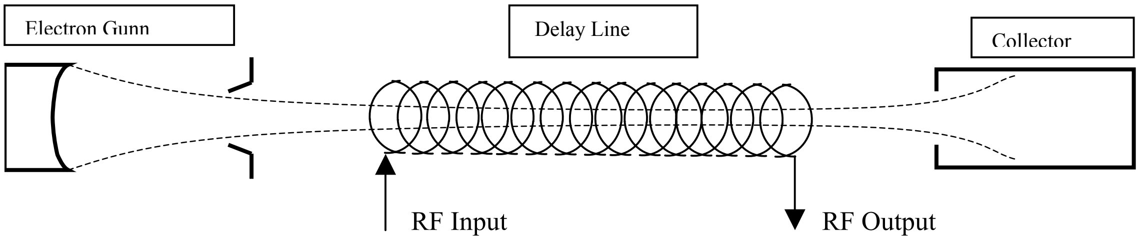


Figure 1. Simplified structure of TWT.

3. Analysis of temperature distributions

The analysis of temperature distribution was done using at first analytical analysis, which lead to description of the linear power density dissipated in the delay line and then numerical modeling based on FEM in order to find out the temperature distribution due to the analytically evaluated power dissipation.

3.1. Analytical description

The relationship between microwave power in the point *z* of delay line, along axis *z* - $P_{rf}(z)$, and beam power dissipated in the helix – $P_{db}(z)$, was evaluated under the following assumptions:

1. All beam electrons in a point *z* inside an incremental length layer - ***dz***, have the same energy.
2. Initial power of electron beam coming in the interaction zone equals to $P_b(0)= U_0J_0$.
3. Electrons intercepted by helix in point *z* result in interaction with an e-m wave experience energy decrease by value of energy transfer to the wave on the way from ***0*** to *z*; and all its energy is converted into heat.
4. Due to the experimental results it seems to be justified to take an assumption that linear density of beam current intercepted by helix - $j(z)$, can be described by linear relationship of microwave power in point *z*, while an overall helix current equals to J_a.

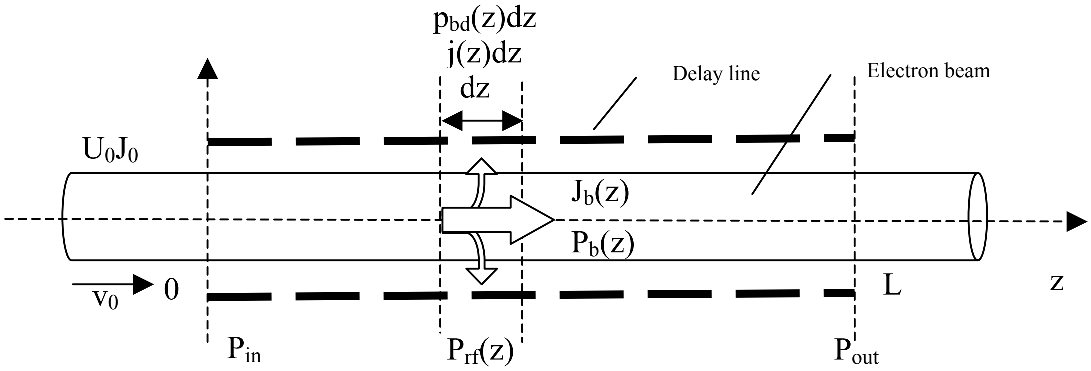


Figure 2. Scheme of interaction space of TWT.

Basing on the TWT's Pierce's theorem it is possible to assume that P_{rf} change along *z* axis equals to:

$$P_{rf}(z) = P_{in}e^{\frac{(g-a)ln10}{10}z}, \quad (1)$$

where ***g*** is a gain constant, ***a*** is a attenuation constant ([***g***]=dB/m, [**a**]=dB/m) and P_{in} is an input helix power. The assumption No.3 allows to write the formula on linear power dissipation of electron beam in the helix in a form of:

$$p_{bd}(z) = \frac{j(z)}{J_b(z)}P_b(z), \quad (2)$$

where:

$$j(z) = J_a\frac{Be^{Bz}}{e^{BL}-1}; \; B = \frac{(g-a)ln10}{10}, \quad (3)$$

$$J_b(z) = J_0 - \frac{J_a(e^{Bz}-1)}{e^{BL}-1}. \quad (4)$$

Distribution of the beam current power along axis *z* - $P_b(z)$, could be evaluated from the principle of energy conservation:

$$\frac{d}{dz}P_b(z) = -\frac{d}{dz}P_{rf}(z) - p_{bd}(z) \quad , \tag{5}$$

witch leads to the following differential equation:

$$\frac{d}{dz}P_b(z) = -P_{in}J_0Be^{Bz} - J_aB\frac{e^{Bz}}{J_0(e^{BL}-1) - J_a(e^{Bz}-1)}P_b(z) \quad . \tag{6}$$

Analytical solution of the above formula for the initial condition in point $z=0$: $P_{rf}(0) = P_{in}$ and $P_b(0) = U_0J_0 - P_{in}$ while using the denotation $J_a/J_0 = \chi$, results in the following function:

$$P_b(z) = (U_0J_0 - P_{in})\left(1-\chi\frac{e^{Bz}-1}{e^{BL}-1}\right) + \frac{P_{in}(e^{BL}-1)\ln\left(1-\chi\frac{e^{Bz}-1}{e^{BL}-1}\right)}{\chi\left(1-\chi\frac{e^{Bz}-1}{e^{BL}-1}\right)} \quad . \tag{7}$$

It should be noted that $U_0J_0 << P_{in}$, $e^{Bz} \gg 1$ and $P_{in} = P_{out}e^{-BL}$. Thus, formula for electron beam linear power density dissipated on helix (3-3) while taking into account relations (3), (4) and (7) may be rewritten as:

$$p_{bd}(z) = U_0J_0Be^{-B(L-z)}\left\{\chi + \frac{P_{out}}{U_0J_0}\ln\left(1-\chi\frac{e^{Bz}-1}{e^{BL}}\right)\right\} \quad . \tag{8}$$

The another part of total dissipation power in a helix are RF losses described by attenuation constant a, where α is a part of the propagation constant Γ:

$$p_{fd}(z) = \frac{\ln(10)a}{10}P_{rf}(z) \quad . \tag{9}$$

So, the final formula for linear power density dissipated in helix TWT can be described by the following formula:

$$p(z) = U_0J_0Be^{-B(L-z)}\left\{\chi + \frac{P_{out}}{U_0J_0}\ln\left(1-\chi\frac{e^{Bz}-1}{e^{BL}}\right)\right\} + \frac{a}{10}ln10e^{B(z-L)} \tag{10}$$

Figure 3 shown result of calculation for designed C band TWT which then was assumed as the reference curve in the followed up computer simulation of temperature distribution.

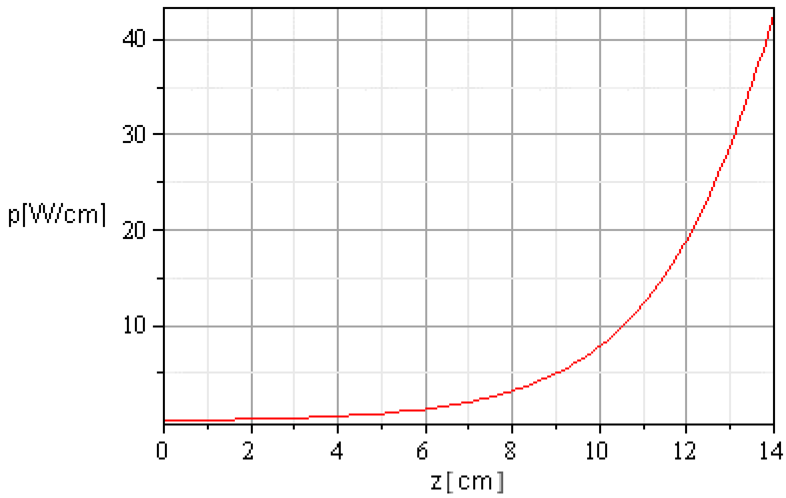
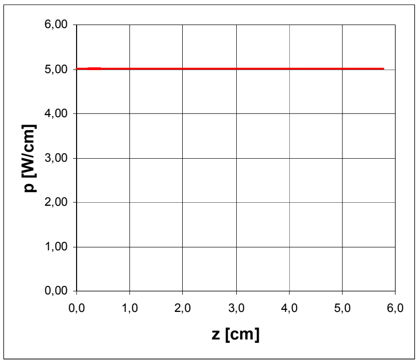


Figure 3. Linear power density dissipated in the delay line of designed TWT.

3.2. Numerical modeling

The main goal of numerical analysis was to asses whether the assumption on uniform or non-uniform electron beam power dissipation and RF losses leads to meaningful difference between temperature distribution in the delay line. For that purpose numerical modelling technique based on finite element method with ANSYS package was used. The figure 4 and 5 show the results of numerical analysis for uniform and non-uniform power dissipation. The non-uniform power dissipation was assumed in accordance to analytically evaluated linear power density dissipated in the delay line and given by formula (10). The assumed total power dissipated in the delay line was equal in both cases 30W.

a. 

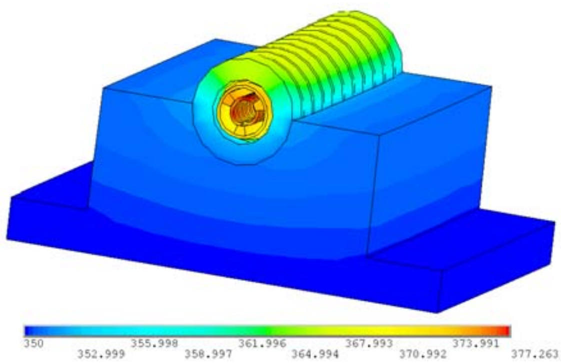
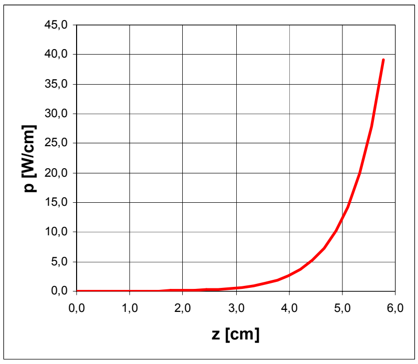
b. 

Figure 4. The results for uniform power dissipation (a) and the corresponding temperature distribution (b).

a. 

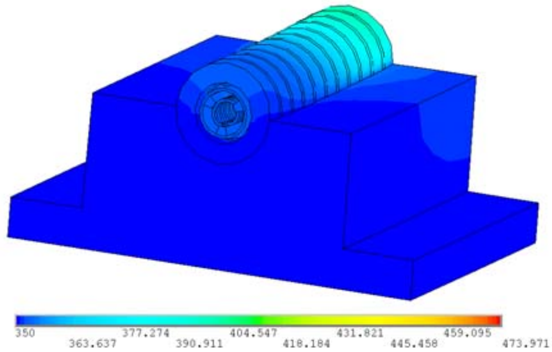
b. 

Figure 5. The results for non-uniform power dissipation (a) and corresponding temperature distribution (b).

According to the achieved results the difference between maximal temperature in the delay line for uniform and non-uniform power dissipation reached almost 100 K. In case of non-uniform power dissipation, as expected, almost all power is dissipated at the delay line output which results with high temperatures. It is worthy to mention, that the presented analysis and corresponding results were based on a couple of simplifications. For example, it was assumed that the power dissipation in the delay line is mainly due to thermal conductivity phenomenon with the boundary conditions at the bottom of the support, which was equal to 350K. The heat dissipation due to convection and radiation phenomena was neglected and additionally the thermal contact resistance between the tube parts was not included. Nevertheless, according to the achieved results it can be concluded that application of non-uniform power dissipation is a prerequisite for appropriate numerical prototyping of TWT delay line.

4. Conclusions

The goal of the presented paper was to present the preliminary results of the project, which aims towards improved design of the TWT delay line. The presented results focused on the problem of temperature distribution assessment based on analytical analysis and followed up numerical simulation. In fact the working TWT is exposed to high temperatures, which can influence its reliability. Therefore the presented methodology would be implemented at the design stage and would hopefully lead to better design, which mainly means improved thermal properties and corresponding reliability parameters.

Acknowledgments

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References

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