Thermal analysis of gyro-amplifiers with helically corrugated waveguides

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Introduction

Microwave sources find numerous application in modern physics and technology. In particular, development of wideband amplifiers with high continuous-wave/average output power operating in millimeter and sub-millimeter frequency ranges has drawn a considerable amount of interest in recent years in connection with emerging telecommunication and long-distance high-precision radiofrequency imaging systems [1].

For the mentioned classes of systems, traditional Cherenkov electron devices as well as solid-state devices at frequencies higher than 100 GHz become non-competitive when compared with vacuum electron devices based on electron cyclotron resonance effect. The most prominent class of amplifiers of such type are the gyrotron traveling wave amplifiers – wideband amplifiers in which the electron beam interacts with a non-resonant electromagnetic wave of the interaction circuit.

For a number of years, a variety of gyro-TWTs having the interaction circuit in the form of a waveguide with helical corrugation of its inner surface is being investigated at IAP RAS. A number of Ka-band second-harmonic operating gyro-TWTs of this type have been created during the last two decades and a record-high values of CW / average power have been achieved [2]. Presently, a great deal of effort is directed towards advancing theses devices to higher frequency bands [3, 4].

One of the factors preventing gyro-TWTs from reaching high CW or average output power is the overheating of the interaction circuit caused by Ohmic loss in its walls. The problem becomes increasingly serious for higher operating frequencies. In this work we investigate this problem for a *W*-band high-power gyro-TWT in the cascade of two gyro-TWTs being developed at IAP RAS [4].

Thermal problem statement

The inner surface of a typical interaction circuit (most commonly made of copper) has a form helical waveguide while the outer has a form of a circular cylinder (fig. 1). The inner surface is heated by the dissipation of operating wave's power due to finite conductivity of the circuit's walls.

The steady-state temperature distribution in the bulk of the interaction circuit of the gyro-TWT is governed by stationary heat transfer equation [5]:

$$\nabla(\kappa\nabla T) = 0 \qquad (1)$$

where κ – coefficient of thermal conductivity, T is the temperature distribution being sought.

The boundary conditions on the inner surface are that of Neumann type and correspond to setting the value of power being dissipated into the wall

$$-\kappa\nabla T\cdot\mathbf{n} = 0.5R_{surface}\cdot\left|\mathbf{j}_{surface}\right|^2 \qquad (2)$$

where $R_{surface} = \sqrt{\pi\cdot f\cdot\rho\cdot\mu_0}$ is reactive part of the surface impedance, f is frequency, ρ – resistivity of the interaction circuit's material, μ_0 – vacuum permeability.

The outer boundary of the interaction circuit is cooled by a stream of water. Mathematically this can be described by the so-called convective boundary condition:

$$-\kappa\nabla T\cdot\mathbf{n} = h_c(T - T_\infty) \qquad (3)$$

where T_∞ is the temperature of the water far away from the surface, h_c – convection coefficient. The convection coefficient depends on the properties of the coolant and the surface.

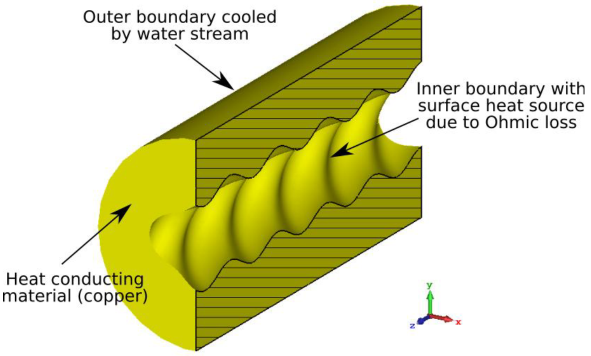


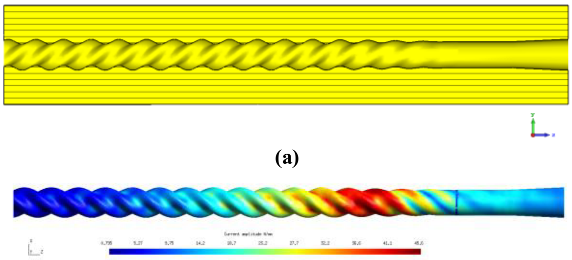
Fig. 1. Illustration to thermal problem

The thermal conductivity, κ, and the electric resistivity, ρ, are in general temperature-dependent, which renders the problem (1)-(3) non-linear. While for copper, the dependence of the thermal conductivity on the temperature for most practical cases may be neglected, the dependence of the ρ on temperature in the operating temperature range is quite strong and cannot be ignored.

Results of simulation

The simulation of thermal distributions in the interaction circuit of the high power gyro-TWT suggested in [4] has been carried out. Since the inner surface of the structure has a complex shape, no analytic method can be employed, instead a full 3D finite element analysis has been performed.

The heat source has been calculated based on the surface current distribution obtained from the particle-in-cell simulation of the gyro-TWT [4]. The current distribution corresponds to maximum output power of about 350 kW (fig. 2). The outer radius of the interaction circuit and the duty cycle were the parameters being investigated. The rest parameters were as follows: k = 0.37 W/ K · mm h_c = 3 W/ K·cm^2, T_∞ = 300 K, f = 95 GHz; the dependence $\rho(T)$ was taken to be linear with the resistivity thermal coefficient of $3.8\cdot10^{-3}$ K^{-1}, and the room temperature resistivity of $3.4\cdot10^{-8}$ Om·m (resistivity two times higher than that of pure copper). Since the boundary condition (2) non-linearly depends on the temperature, the solution of the problem was carried out in an iterative manner: the surface sources distribution on the current iteration was calculated using the solution from the previous iteration; this procedure was repeated until convergence with some predefined accuracy was achieved.



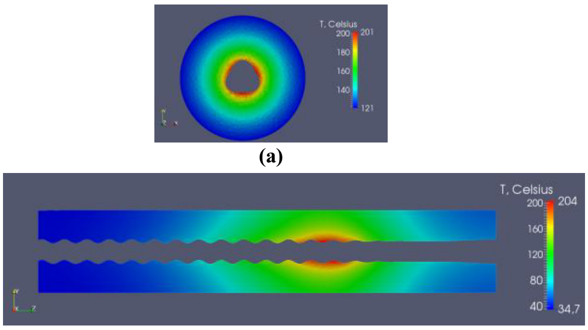
(a)

(b)

Fig. 2. (a) Part of the interaction circuit of the gyro-TWT being investigated; (b) distribution of the amplitude of the surface current on the inner surface of the interaction structure in case of maximum output power.

There are two major factor limiting the maximum possible duty cycle (or, alternatively, average power) of the device's interaction circuit: the temperature of the water on the outer surface of the structure should not exceed the boiling point (130 ºC for the water stream under pressure of 3 atm.) and the maximum temperature on the inner surface should not exceed some safe value (the value of 200 ºC was chosen) to ensure long operating time of the device.

With these limiting values set, the outer radius and the duty cycle could be determined. The simulation shows (fig. 3) that for r_{outer} > 5.5 mm and duty cycle ~ 14% (average power ~ 50 kW) safe operation of the device's interaction circuit is possible.



(a)

(b)

Fig. 3. Temperature distribution (results of 3D finite element simulation) in the interaction circuit: (a) z cross-section at the point of maximum temperature; (b) - longitudinal distribution.

Acknowledgements

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