Study of the waveguide elements for mm-wave traveling wave tube

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Abstract. The use of a millimeter waves for future mobile networks demands a creation of broadband transceivers with output power more than 10 W. Only vacuum electron devices, in particularly, traveling wave tubes can provide those parameters. Because of the short wavelength, the reference dimension of the interaction system becomes close to 100 microns and skin layer depth reaches 0.4 micron. Its fabrication comes across with low surface roughness challenge. In this paper, we evaluate interaction system elements fabricated by electrical discharge machining. The surface roughness of the microdimensional slot in a brass plate is determined experimentally. Based on the experimental roughness value, a computer simulation of a folded waveguide, a perspective type of an interactive system for a millimeter band traveling wave tube has been carried out. It is found that the loss value on the 40-period waveguide due to the roughness increases by 80% in comparison with the ideal surface of the waveguide walls.

1. Introduction
Transition to the next generation of mobile communications (5G) includes a development and implementation of several key technical directions. One of them is a use of a millimeter wave frequency band providing peak data rate up to 20 Gbps [1]. Taking into account an availability of a low atmospheric attenuation window for 92–95 GHz frequencies, this W-range opens a new prospective for mobile networks in the future.

The use of a millimeter wave band for mobile networks demands a creation of broadband transceivers with output power more than 10 W. In this frequency band it can be provided only by vacuum electron devices. More and more attention is being given to a development of traveling wave tubes (TWT) [2–8], which fully meet the requirements of wide frequency bandwidth and output power.

Numerous publications on simulation results of separate TWTs blocks have determined their optimum design features. First, it is a use of folded waveguide [2, 4] as interaction structure between travelling wave and sheet electron beam. The wavelength about 3 mm results in decrease of TWT reference dimensions, particularly the minimum size of waveguide cross section, which can make only 100 microns, and a skin layer depth – 0.4 microns (for brass). The losses in interaction structures produced by the roughness of conducting surfaces significantly influence TWT gain. These factors determine way of fabrication for folded waveguides.

The minimum roughness of conducting surface is reached at milling [9] of the waveguides, however this way of processing demands the use of unique microdimensional milling cutters and is applicable for waveguides with cross sectional dimensions of more than 500 microns.
discharge machining (EDM) [10–11], widely applied in electronic devices parts manufacturing, succumbs in surface finish fineness, but allow to produce more complex shapes of parts.

The work purpose is an estimation of a surface roughness and finding ways of its decrease in microdimensional slots formed by EDM in a brass plate.

2. Experimental data
For surface roughness estimation experimental model was made as a brass plate with a 350 microns width through slot (figure 1) using EDM. Thickness of dark layer on the inner side of a slot gives one an opportunity to visually evaluate maximum depth of surface layer as a half difference of measured width of a slot (PL2-PL1)/2=28 a micron.

![Figure 1](image1.png)

**Figure 1.** Microphotographs (a) of a through slot (dark horizontal band in centre) in a brass plate before polishing PL1=354 microns, PL2=410 microns; side slot surface, magnification x420 (b).

Later the experimental model was electrochemically polished to decrease roughness (figure 2). As a result, width of a slot increased at 43 microns.

![Figure 2](image2.png)

**Figure 2.** Microphotographs (a) of a through slot (dark horizontal band in centre) in a brass plate after polishing PL1=397 microns; side slot surface, magnification x420 (b).

For visualization of the objects, geometrical measurement and relief depth definition high-resolution microscope Hirox KH-7700 with a set of lenses for wide range of magnifications was used as well as for contactless geometrical measurements of experimental model. The software and hardware complex HIROX KH-7700 synthesize three-dimensional model of object using a series of captured frames at different levels of a focusing (up to 100 slices).

Resolution of focusing (altitude of irregularities) reaches 0,25 microns. In cases, if the depth of a relief does not exceed microns, the model is synthesized under in a semiautomatic mode with a preliminary manual measurement of depth of a relief. The three-dimensional models of objects allow to thoroughly studying a relief of a surface.

The map of three-dimensional model of a surface before polishing is shown in figure 3. It is found that an average profile of a surface has maximum depth of 20 microns. The map of three-dimensional model of a surface after polishing is shown in figure 4. It is found that an average profile of a surface has maximum depth of 7 microns.
Figure 3. Map of three-dimensional model of a surface before polishing (a); an average profile of a surface with maximum depth of 20 microns (between horizontal lines) (b).

Figure 4. Map of three-dimensional model of a surface after polishing (a); an average profile of a surface with maximum depth of 7 microns (between horizontal lines) (b).

3. Simulation
Simulation of an ohmic loss in the 40-periods folded waveguide, a four period segment of which is shown in figure 5, has been carried out in CST Studio Suite with surface roughness of metal taken into consideration. The gradient model of surface losses [12] was used, making possible a correct description of an ohmic loss in case of a considerable surface roughness, when the depth of a skin layer appears to be comparable and even less than typical metal roughness. Single-parametric description of a roughness by means of route mean square deviation of a profile parameter Rq is used. Its value can be determined experimentally.

Figure 5. Geometry of four periods of folded waveguide with channel for sheet electron beam [5].

4. Simulation results
The simulation results as relations of s-parameters across a surface roughness of the 40-periodic folded brass waveguide are represented in figure 6. In case of folded waveguide, fabricating by milling the increase of losses on the 40-periodic waveguide at the expense of a roughness does not exceed on an order of magnitude maximum value of a factor of increase of losses, which one can be obtained using conventional approaches [13–14]. At increase of a roughness, more than 1 micron losses in the waveguide essentially increase.
Figure 6. Relation of S-parameters to a surface roughness of the brass folded waveguide (40 periods): (a) – S11; (b) – S12.

5. Conclusions
The standard electrical discharge machining for the multiperiodic brass folded waveguides create a surface with a roughness producing increase of losses up to 80 % in comparison with ideal surface. The electrochemical polishing allow reducing a roughness almost three times, however loss value remain very high.

References
[1] Rappaport T S, Sun S, Mayzus R, Zhao H, Azar Y, Wang K, Wong G N, Schulz J K, Samimi M and Gutierrez F 2013 IEEE Access 1 335
[2] Cai J, Feng J, Li B and Liao F 2005 IEEE International Symposium on Microwave, Antenna, Propagation and EMC Technologies for Wireless Communications DOI: 10.1109/MAPE.2005.1618016
[3] Ryskin N M, Rozhnev A G, Karetnikova T A, Torgashov G V, Sinitsyn N I, Shalaev P D and Bourtsev A A 2013 IEEE International Vacuum Electronics Conference DOI: 10.1109/IVEC.2013.6571022
[4] Sharma R K, Grede A and Chaudhary S 2014 IEEE Transactions on Plasma Science 10 343
[5] Grigoriev A D, Ivanov A S, Ilyin V V, Luchinin V V and Titov V N 2015 Electron Engineering, ser. 1, HF Engineering 4 26–32
[6] Ryskin N M, Karetnikova T A, Rozhnev A G, Torgashov G V, Bushuev N A and Shalaev P D 2015 IEEE International Vacuum Electronics Conference DOI: 10.1109/IVEC.2015.7223784
[7] Paoloni C, Letizia R, André F, Kohler S, Magné F, Rocchi M, Marilier M, Zimmerman R, Krozer V, Ulisse G, Ramirez A and Vilar R 2016 IEEE International Vacuum Electronics Conference DOI: 10.1109/IVEC.2016.7561865
[8] Gamzina D, Li H, Himes L, Barchfeld R, Popovic B, Pan Pan, Letizia R, Mineo M, Feng J, Paoloni C and Luhmann Jr. N C 2016 IEEE Transactions on Nanotechnology 1 85
[9] Stil I, Fontana A L, Lefranc B, Navarrini A, Serres P and Schuster K F 2012 22nd International Symposium on Space Terahertz Technology Proceedings pp 151–3
[10] Chung D K, Lee K H, Jeong J and Chu C N 2014 International Journal of Precision Engineering and Manufacturing 9 1785
[11] Liu Q, Zhang Q, Zhu G, Wang K, Zhang J and Dong J 2016 MMP 43 391
[12] Gold G and Helmreich K A 2012 European Integrated Circuits Microwave Conference Proc. 42
[13] Hammerstad E O and Bekkadal F 1975 Microstrip Handbook (Norwegian Institute of Technology)
[14] Groiss S, Bardi I, Biro O, Preis K and Richter K R 1996 IEEE Transactions on Magnetics 3 894–7