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OPTIMIZATION OF THE PARAMETERS OF DISK-SHAPED PIEZOELECTRIC TRANSFORMERS

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Abstract
This paper presents a study of the impact of the width b and displacement l of the linear isolation gap between the electrodes of disk-shaped piezoelectric transformers on their characteristics and the maximum voltage gain G_{Vm} in accordance with an optimal composed design of the experiment. The effect of the load resistance Rt on piezoelectric transformer parameters has also been studied. A regression model of full second degree has been derived for the maximum voltage gain of disk-shaped piezoelectric transformers with linear isolation gap. On the basis of this model, employing a genetic algorithm, optimal values of parameters b and l of the isolation gap have been obtained in order to reach the maximum value of G_{Vm} of disk-shaped piezoelectric transformers. The maximum voltage gain of the optimal sample obtained by experiment is in good agreement with the theoretically determined maximum value of this parameter.

Keywords: piezoelectric transformer, isolation gap, regression model, optimization

INTRODUCTION

Piezoelectric transformers (PTs) which developed as an alternative to electromagnetic transformers, are used most frequently in electronic devices, portable computers, personal digital assistants (PDA), etc. The development of technologies and of new ceramic materials widens their application fields in medical devices and measurement instrumentation [1]. This is due to their advantages over electromagnetic transformers as: high efficiency at resonance, possibility of miniaturization, insensibility to electromagnetic fields, operation in a wide frequency range, simple production technology, etc. [2].

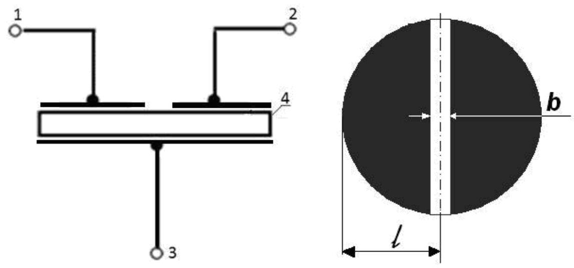
A number of publications present the studies of monolayer and multilayer PTs and the possibilities of their application to various devices [3-6]. There are few investigations of the influence of the shape and geometric dimensions of the electrodes and isolation gap between them on the PTs characteristics and parameters [7-10].

This paper presents the results of the studies of the impact of the width and displacement of the linear isolation gap between the electrodes of disk-shaped PTs on the basis of designing the experiment and optimization of these parameters with respect to the maximum voltage gain of PTs.

LAYOUT OF PTs WITH LINEAR ISOLATION GAP

PT converts electrical energy into electrical on the basis of inverse and direct piezoelectric effect in a plate at a frequency close to the resonance frequency. PTs are usually made using piezoceramic, and they can be rectangular, disk or ring-shaped [1, 4, 11, 12]. Disk-shaped PTs are more common since they convert mechanical energy into electrical energy more effectively [13].

PTs usually have three electrodes. The layout of the studied disk-shaped PTs with linear isolation gap between electrodes is shown in Fig. 1. The isolation gap is positioned on a chord or on the diameter of disk-shaped PTs, depending on the value of displacement *l* of this gap.



1 – electrode of the excitation section
2 – electrode of the generator section
3 – common electrode
4 – piezo-ceramic plate

Fig. 1. Layout of disk-shaped PTs with linear isolation gap between electrodes

The parameters which can be varied are width *b* and displacement *l* of the isolation gap. When applying sinusoidal input voltage U_i between electrodes 1 and 3 of the excitation section, it results in respective sinusoidal output voltage U_o between electrodes 2 and 3 of the generator section. The change in the linear isolation gap parameters *b* and *l* affects the voltage gain G_V of PT, which is determined as

$$G_V = U_o / U_i \quad . \tag{1}$$

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Voltage gain G_V depends also on frequency f of the excitation voltage and its maximum value for a certain PT will be denoted by G_{Vm}.

DESIGNING THE EXPERIMENT

In order to synthesize a PT with the highest voltage gain which will favor the attainment of a greater output signal, the experiment has been designed for disk-shaped piezoelectric transformer elements with a diameter of 30mm and a thickness of 2.5mm of SPZT-8 piezoceramic.

- *Defining of input variables and objective parameters*

Parameters b and l of the isolation gap are considered as input variables (independent factors), and the maximum value of voltage gain G_{Vm} – as an objective parameter.

The following denotations have been accepted:

isolation gap width $b \rightarrow x_1$
isolation gap displacement $l \rightarrow x_2$
maximum voltage gain $G_{Vm} \rightarrow y$.

It is required that the objective parameter should have as high as possible values.

- *Design of the experiment*

An optimal composed design of the experiment has been used for n = 2 factors which are varied at 3 levels. They are presented in Table 1.

Table 1. Factor levels in the experimental design

Factors		Factor levels		
		- 1	0	+ 1
x_1	b, mm	0.5	1.5	2.5
x_2	l, mm	7.5	15	22.5

The number of experiments is:

$$N = 2^n + 2n + 1 = 9. \quad (2)$$

The experimental design in coded and natural variables is given in Table 2.

Table 2. Experimental design

No	Coded variables		Natural variables	
	X_1	X_2	x_1	x_2
	-	-	b, mm	l, mm
1	-1	-1	0.5	7.5
2	+1	-1	2.5	7.5
3	-1	+1	0.5	22.5
4	+1	+1	2.5	22.5
5	-1	0	0.5	15
6	+1	0	2.5	15
7	0	-1	1.5	7.5
8	0	+1	1.5	22.5
9	0	0	1.5	15

Fig. 2. Piezoelectric transformers with a linear isolation gap

Fig. 2 shows PTs with a linear isolation gap made on the basis of the developed experimental design.

EXPERIMENTAL RESULTS

In order to determine the maximum voltage gain G_{Vm} for each of the obtained samples their respective amplitude-frequency characteristics have been studied. The study of the piezoelectric transformer elements is conducted according to the measurement system shown in Fig. 3.

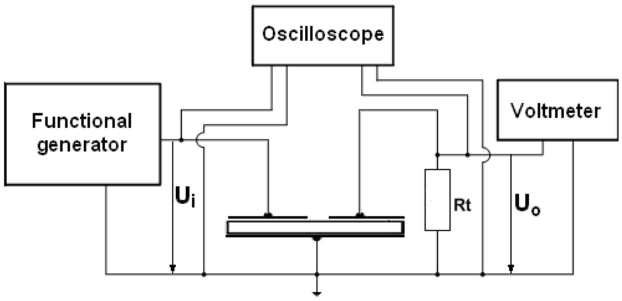


Fig. 3. Measurement system

The measurements have been taken with HAMEG HM8150 functional generator and B3-57 voltmeter. Philips PM3212 oscilloscope (25MHz) has been employed to control the form of the input and output signals. As load Rt of PT standard resistors P331 with values of 1kΩ, 100kΩ and P4010 with a value of 1MΩ have been used. Measurements have been taken also in an open output circuit of PT.

Amplitude-frequency characteristics of all PTs have been investigated at input sinusoidal signal with an amplitude of 2V in the frequency range from 71kHz to 93kHz for different values of Rt. The characteristics $G_V = F(f)$ are obtained on their basis, and they reflect the variation in voltage gain G_V at different values of b and l when frequency f of the input voltage varies. From the characteristics $G_V = F(f)$ the maximum voltage gain G_{Vm} is determined. Fig. 4 shows $G_V = F(f)$ characteristics of the investigated PTs with linear isolation gap when l=22.5mm and at different values of b, and Fig. 5 shows the characteristics when b=2.5mm and at different values of l.

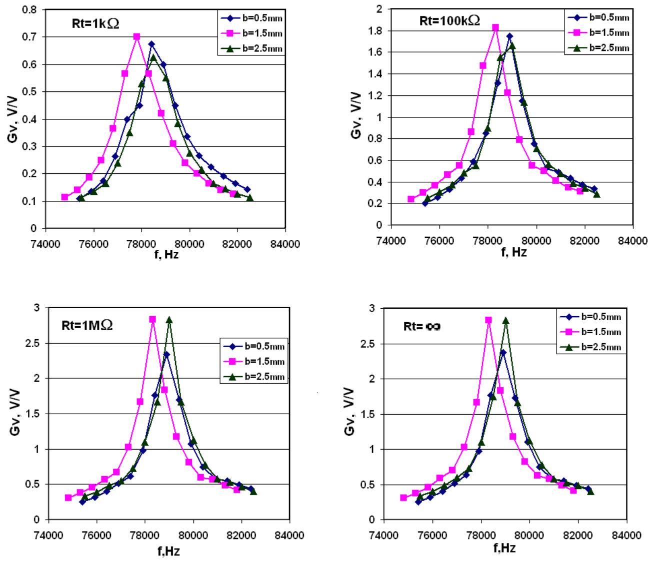


Fig. 4. Characteristics $G_V = F(f)$ of the studied PTs with linear insulation gap when l=22.5mm

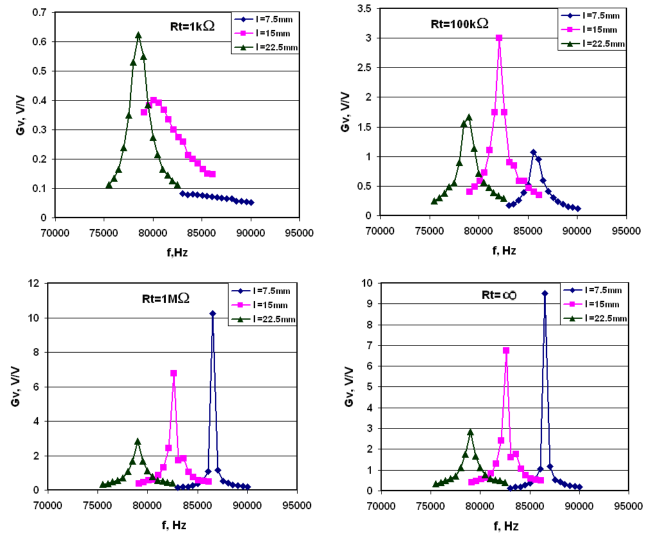
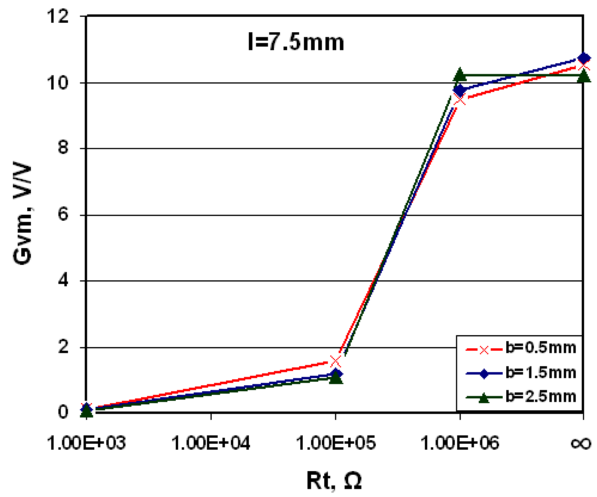


Fig. 5. Characteristics $G_V = F(f)$ of the studied PTs with linear insulation gap when b=2.5mm

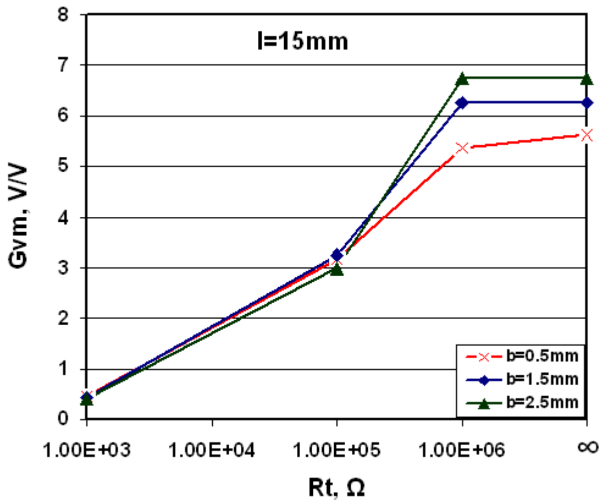
From these characteristics it is found that in the studied samples with an increase in l there is a decrease in the frequency f_{GVm}, at which the maximum voltage gain G_{Vm} is obtained for the respective sample. The variation in b also has an impact on this frequency but it is less significant and depends both on the value of l, and on Rt. In the studied samples there is a difference in f_{GVm} of about 5kHz when l=7.5mm and l=22.5mm.

Moreover, it is established that with an increase in Rt the respective maximum voltage gain G_{Vm} increases and thus the performance of the piezoelectric transformer enhances. The impact of Rt on G_{Vm} at different values of b and l is shown in Fig. 6.

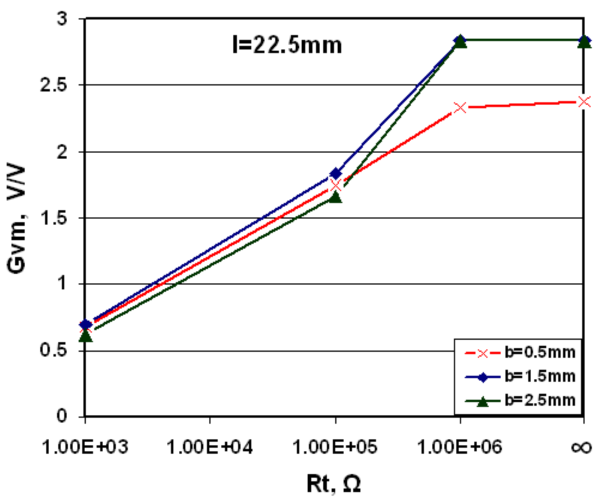
On the basis of these characteristics is established, that the increase in Rt from 1kΩ to 1MΩ leads to an increase in G_{Vm} for each sample and after that up to reaching $Rt = \infty$ (open circuit) the increase in G_{Vm} is insignificant.



a)



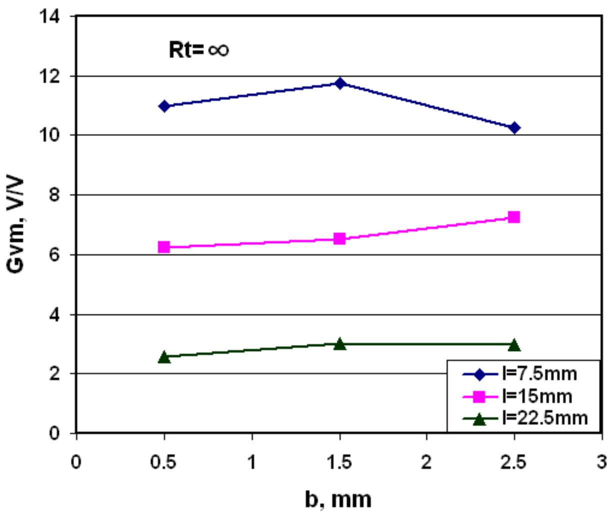
b)



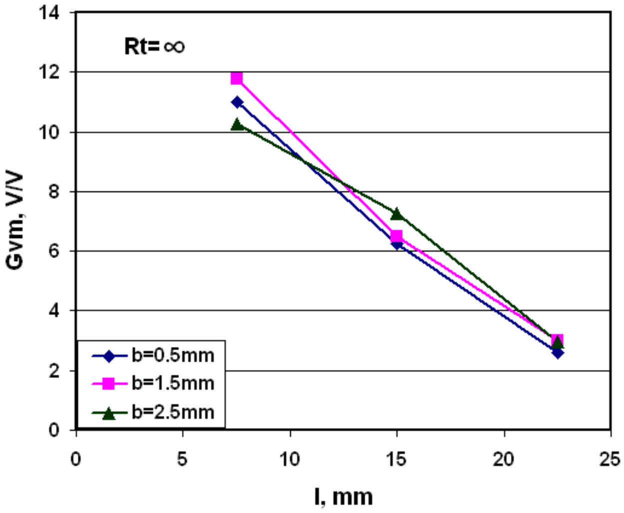
c)

Fig. 6. Characteristics $G_{Vm} = f(Rt)$ when: a) l=7.5mm; b) l=15mm; c) l=22.5mm

Based on the obtained characteristics $G_{Vm} = f(Rt)$ the characteristics $G_{Vm} = f(b)$ and $G_{Vm} = f(l)$ of the studied samples are compared as a result of the variation in parameters b and l, respectively, when $Rt = \infty$. These characteristics are presented in Fig. 7.



a)



b)

Fig. 7. Characteristics: a) $G_{Vm}=f(b)$ when l=7.5mm; 15mm; 22.5mm and b) $G_{Vm}=f(l)$ when b=0.5; 1.5mm; 2.5mm

From the obtained characteristics it is found that when $Rt=\infty$, the displacement of the isolation gap l has a major effect on the maximum voltage gain G_{Vm}, leading to a decrease in G_{Vm}. The effect of b within the specified range is smaller and depends on the values of l. The parameter variation of the insulation gap and mainly in l, has an effect on the area of the excitation and generator electrodes. An increase in l, leading to an increase in the area of the excitation electrode and a decrease in the area of the generator electrode results in a decrease in the maximum voltage gain G_{Vm} and vice versa.

OPTIMIZATION OF ISOLATION GAP PARAMETERS

On the basis of the measurements taken according to the design of the experiment and the obtained values for the maximum voltage gain G_{Vm}, employing QStatLab software [14, 15], regression model of full second degree has been derived for objective parameter y (G_{Vm}). It is of the type

$$y=b_0+\sum_{i=1}^{2}b_i x_i+\sum_{i=1}^{2}b_{ii}x_i^2+\sum_{\substack{i=1\\ i<m}}^{2}b_{im}x_i x_m \,. \qquad (2)$$

Coefficients b_0, b_i, b_{ii}, b_{im} of the regression equation for y with the natural values of variables x_i (i = 1, 2), the calculated F_c and the tabular values $F_{T(\alpha,\nu_1,\nu_2)}$ of Fisher criterion at significance level α =0.05 and degrees of freedom $\nu_1=k-1=5$ and $\nu_2=N-k=9-6=3$, where k is the number of the coefficients, as well as the calculated for the equation coefficient of determination R^2 are given in Table 3.

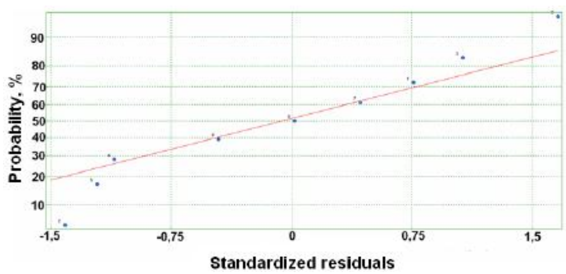
Table 3. Coefficients of the regression equation for y and statistic characteristics of the equation

y
b_0 = 15,40312500
b_1 = 0,53500000
b_2 = -0,76072222
b_{11} = -0,22250000
b_{22} = 0,00680000
b_{12} = 0,02366667
F_c = 146,28702
$F_{T\,(0.05,\,5,\,3)}$ = 9,01346
R^2 = 0,99592

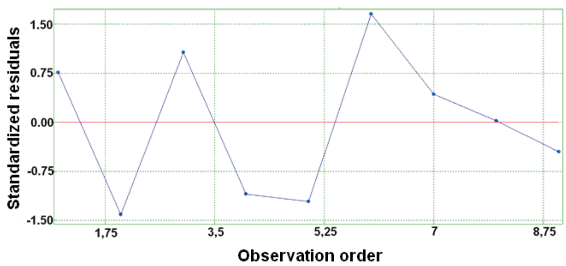
The regression model for PT with a linear gap is provided in the equation

$$y=15.4030+0.5350\,x_1-0.7607\,x_2-0.2225\,x_1^2+ \\ +0.0068\,x_2^2+0.02367\,x_1\,x_2 \,. \qquad (3)$$

The regression equation meets the adequacy condition since $F_c > F_{T\,(0.05,\,5,\,3)}$ at a confidence level of 95%. Fig. 8 shows the normal graph of standardized residuals and the graph of standardized residuals by observation order. All standardized residuals are within $\pm 2\sigma$.



a)



b)

Fig. 8. Residual graph: a) normal graph of standardized

residuals; b) standardized residuals by observation order

Since the regression equation is adequate, it has been used in an optimization procedure.

To find the maximum of G_{Vm} by the derived regression model (3) has been applied a genetic algorithm for optimization from QStatLab software [15, 16]. Fig. 9 shows the lines of constant values for y (G_{Vm}) in the space of x_1 and x_2 (b and l are in natural values).

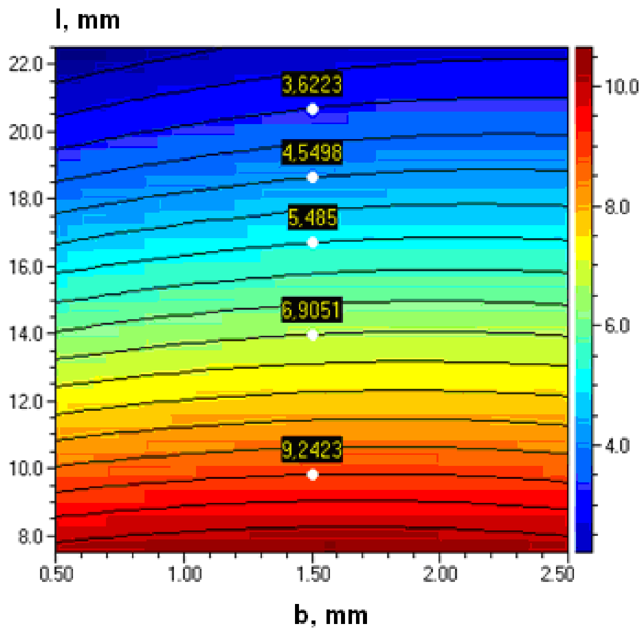


Fig. 9. Lines of constant values for y

The found optimal solution is presented in Table 4.

Table 4. Optimal values of parameters b and l of the isolation gap for achieving maximum value of G_{Vm} of PT

x_{1opt}^{*} (b, mm)	x_{2opt}^{*} (l, mm)	y_{max} ($G_{Vm\,max}$,V/V)
1.6012	7.5	10.6506

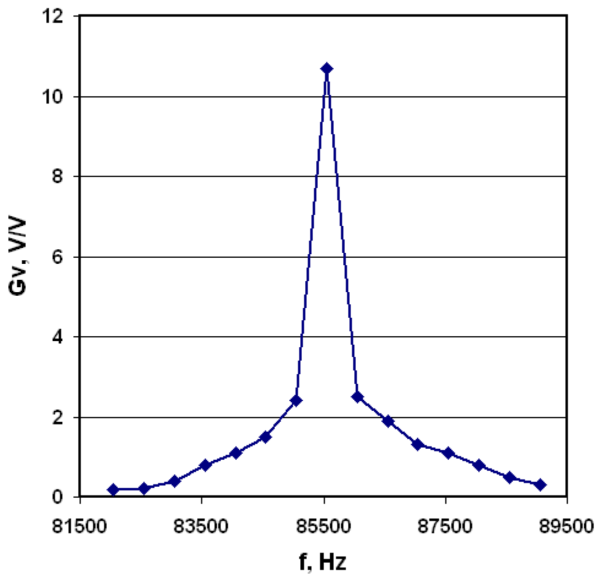


Fig. 10. Experimental characteristic $G_V = F(f)$ *for the optimal sample*

The experimental characteristic $G_V = F(f)$ for the optimal sample is shown in Fig. 10.

The maximum voltage gain is G_{Vm}=10.7 V/V, which conforms to the theoretically obtained maximum value $G_{Vm\,max}$ of this parameter for the optimal sample.

CONCLUSIONS

On the basis of the conducted studies of the impact of the parameters of the linear isolation gap between electrodes on the characteristics and voltage gain of disk-shaped piezoelectric transformers, the following conclusions can be made:

- an increase in load resistance value Rt leads to an increase in maximum voltage gain G_{Vm} of disk-shaped PTs which reaches its highest value when $Rt = \infty$ (open circuit);
- an increase in displacement l decreases the frequency f_{GVm}, at which the maximum voltage gain G_{Vm} for the specific sample is obtained;
- displacement l of the isolation gap has a substantial effect on the value of G_{Vm}. An increase in l leads to a decrease in G_{Vm};
- the influence of the isolation gap width b is smaller and depends on the value of l;
- a variation in isolation gap parameters results in a change in electrode areas. When the excitation electrode area decreases and generator electrode area increases, G_{Vm} increases;
- a regression model of full second degree has been derived for the voltage gain of disk-shaped PT with linear isolation gap from variations in b and l;
- on the basis of the derived regression model employing the genetic algorithm, optimal values of parameters b and l of the isolation gap have been obtained for achieving maximum value of G_{Vm} of PTs;
- the experimentally obtained maximum voltage gain of the realized disk-shaped PT with optimal dimensions of the isolation gap is conformable to the theoretically determined maximum value of this parameter.

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