Multivariate Analysis For Investigating The Output Characteristics Of UV Cu + Ne-Cubr Laser

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Abstract: The subject of investigation is a CuBr laser emitting in the deep ultraviolet spectrum (248.6, 252.9, 259.7, 260.0 and 270.3 nm). Ten operating laser characteristics and the dependent characteristics – average output laser power, are examined by applying multivariate statistical analysis (cluster, factor, and regression analysis). The relationships between the 10 independent variables and the degree of their influence on output power are established. The results are analyzed and interpreted from a physical point-of-view.

Index Terms: Ultraviolet ion Copper bromide vapor laser, laser output power, cluster analysis, factor analysis, regression analysis, regression model.

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1 INTRODUCTION

The copper ion laser with copper bromide vapor is an innovative product with great potential stemming from its unique properties and stable operation. The first lasers of this type were developed by the Laboratory of Metal Vapor Lasers at the Georgi Nadjakov Institute of Solid State Physics, of the Bulgarian Academy of Sciences in 1999. This laser emits in the ultraviolet spectrum at five wavelengths. It is characterized by high quality of the laser beam and high output power. It finds applications in medicine, microelectronics, microbiology, photolithography, genetic engineering, etc. During the last decade, these lasers have been the subject of extensive experimental studies and their characteristics have been improved significantly [1, 2]. It is to be developed for industrial applications. The experiment data accumulated in past few years [1, 3-6] makes it possible to perform statistical investigations on this type of laser. The goal of the developed statistical models is to investigate the complex physical processes within the active laser volume. Parametric and nonparametric regression models were constructed to predict laser generation and efficiency in [7 - 13]. This would allow for the process of engineering design to be automated when creating new laser sources and improving existing ones. The goal of this paper is to continue the investigation of the processes in the laser medium using multivariate statistical analysis methods, including cluster, factor, and regression analysis with the help of the SPSS software package.

2 OBJECT OF STUDY

Ultraviolet laser generation can be achieved using copper or gold ions. The new Ne-CuBr laser with a nanosecond longitudinal impulse discharge solved the design problems typical for copper ion lasers, where copper is deposited along the interior wall of the tube and the discharge temperature is much higher.

Copper ion lasers with copper bromide vapor emit in the deep ultraviolet spectrum at five lines 248.6, 252.9, 259.7, 260.0 and 270.3 nm. Experimentally, the maximum mean output power of 1.3 W was achieved for all five lines and 0.85 W for the 248.6 nm line. It was also established that adding small amounts of hydrogen (0.02-0.04 torr) doubles laser output. A general schematic of the laser tube is given in Fig. 1. Laser generation was also achieved using gold ions which is outside the scope of this paper. Due to the narrow emission range at several spectral lines and the high coherency of the beam, coper ion lasers with copper bromide vapor are used for processing which requires high-definition, data recording, fluorescence, fine drilling, cutting, clearing, modifying new materials, etc. [1, 2, 15, 16]. This paper considers 10 independent and 1 dependent quantity. The independent variables represent the data for the following 10 basic laser characteristics: *D*, mm – inside diameter of the UV laser tube; *L*, cm – the length of active laser volume (electrode distance); *PNE*, Torr – pressure of the buffer gas neon; *PRF,* kHz – repetition frequency of pulses; *PIN2*, kW – supplied electric power to the discharge; *PH2*, Torr – pressure of the additional gas hydrogen; *TR*, ^{o}C – temperature of the CuBr reservoirs; *DR*, mm – the inside diameter of the rings in the tube; *PL*2, W.cm^{-1} - supplied power per unit length of the tube reduced for 50% loses; *C*, nF - equivalent capacitance of the capacitor battery. The dependent variable is the output laser power *Pout*, mW. The study is based on 238 experiments. They have been published in [1, 3 - 6].

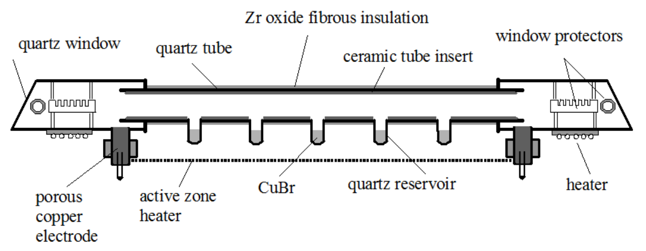

Fig. 1. *Construction of the laser tube of ultraviolet ion CuBr laser.*

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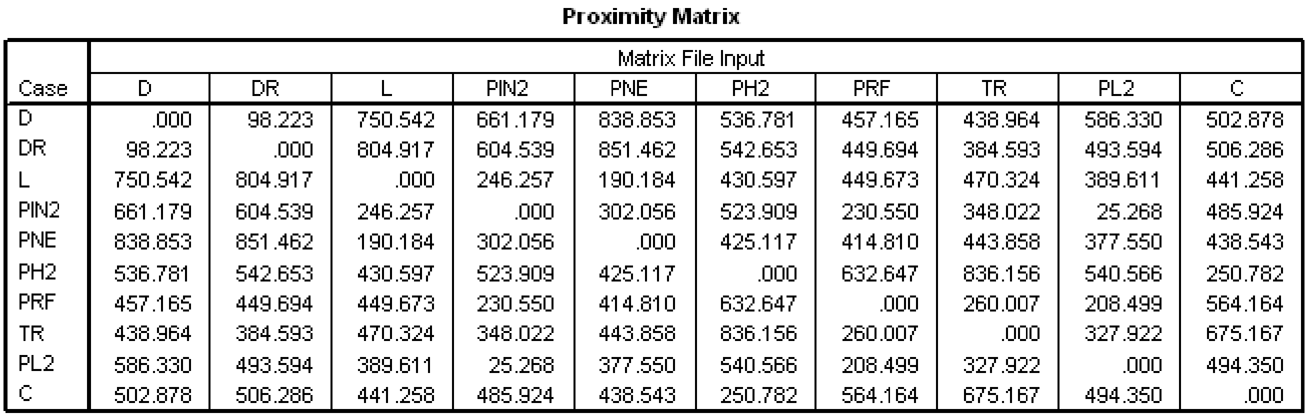
3 CLUSTER ANALYSIS OF PARAMETERS OF A UV CU+ NE-CU LASER

Cluster analysis (CA) is the name given to a group of various calculation procedures used to classify objects. It allows the discovery of new relationships and properties in a laser system, which cannot be determined using other known theoretical or experimental methods. The goal of CA is to find the optimum grouping of observations (or the variables) where the elements within a given cluster are similar but the clusters themselves are clearly distinguishable from one another. Formed groups (clusters) need to be mutually homogeneous within and heterogeneous without according to specified characteristics. The quantitative assessment of the term "similarity" is related to the term "metric". With this similarity approach, events are presented as points in coordinate space. The established similarities and differences between points are determined depending on the distance between them. A very detailed description of a large number of techniques and methods for CA is given in [16-18]. For our data we have applied the hierarchical cluster analysis to classify the groups of the ten investigated variables, with the Euclidean distance as a metric. The proximity matrix for 10 initial independent quantities given in Table 1 was obtained at a first step. The smallest distance (by Euclidean distance) in this table is 25.268 between *PIN*2 and *PL*2, which forms the first cluster. It needs to be noted that we are working with standardized values. Fig. 2 represents the dendrogram of all clusters, constructed using average linkage between groups clustering method.

TABLE 1

PROXIMITY MATRIX FOR THE 10 INDEPENDENT QUANTITIES ON THE FIRST STEP OF CLUSTER ANALYSIS PROCEDURE (SPSS OUTPOUT).



Proximity Matrix

	Matrix File Input									
Case	D	DR	L	PIN2	PNE	PH2	PRF	TR	PL2	C
D	.000	98.223	750.542	661.179	838.853	536.781	457.165	438.964	586.330	502.878
DR	98.223	.000	804.917	604.539	851.462	542.653	449.694	384.593	493.594	506.286
L	750.542	804.917	.000	246.257	190.184	430.597	449.673	470.324	389.611	441.258
PIN2	661.179	604.539	246.257	.000	302.056	523.909	230.550	348.022	25.268	485.924
PNE	838.853	851.462	190.184	302.056	.000	425.117	414.810	443.858	377.550	438.543
PH2	536.781	542.653	430.597	523.909	425.117	.000	632.647	836.156	540.566	250.782
PRF	457.165	449.694	449.673	230.550	414.810	632.647	.000	260.007	208.499	564.164
TR	438.964	384.593	470.324	348.022	443.858	836.156	260.007	.000	327.922	675.167
PL2	586.330	493.594	389.611	25.268	377.550	540.566	208.499	327.922	.000	494.350
C	502.878	506.286	441.258	485.924	438.543	250.782	564.164	675.167	494.350	.000

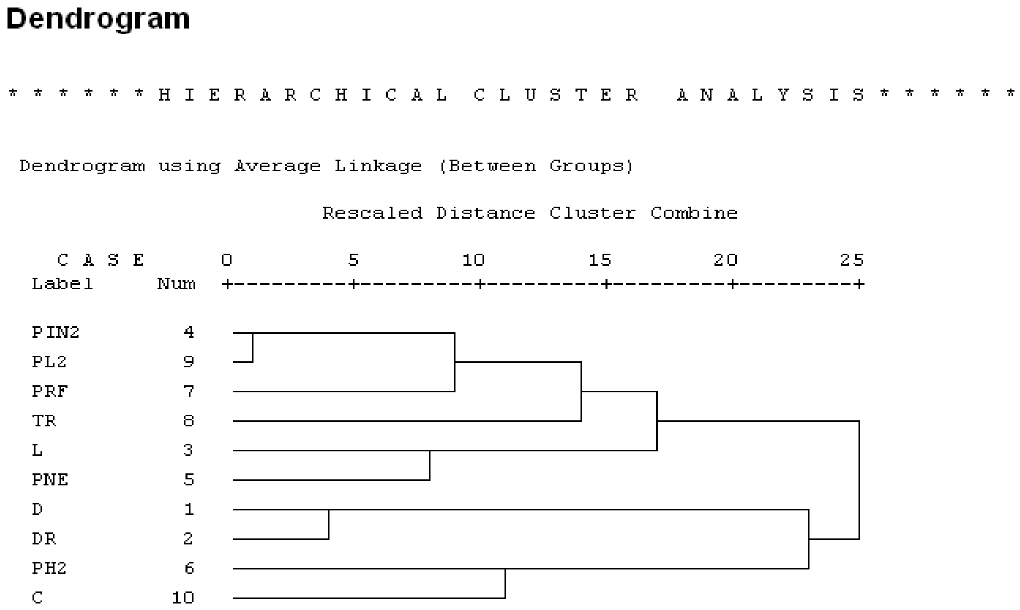


Fig. 2. *Dendrogram of 10 independent quantities obtained using average linkage between groups.*

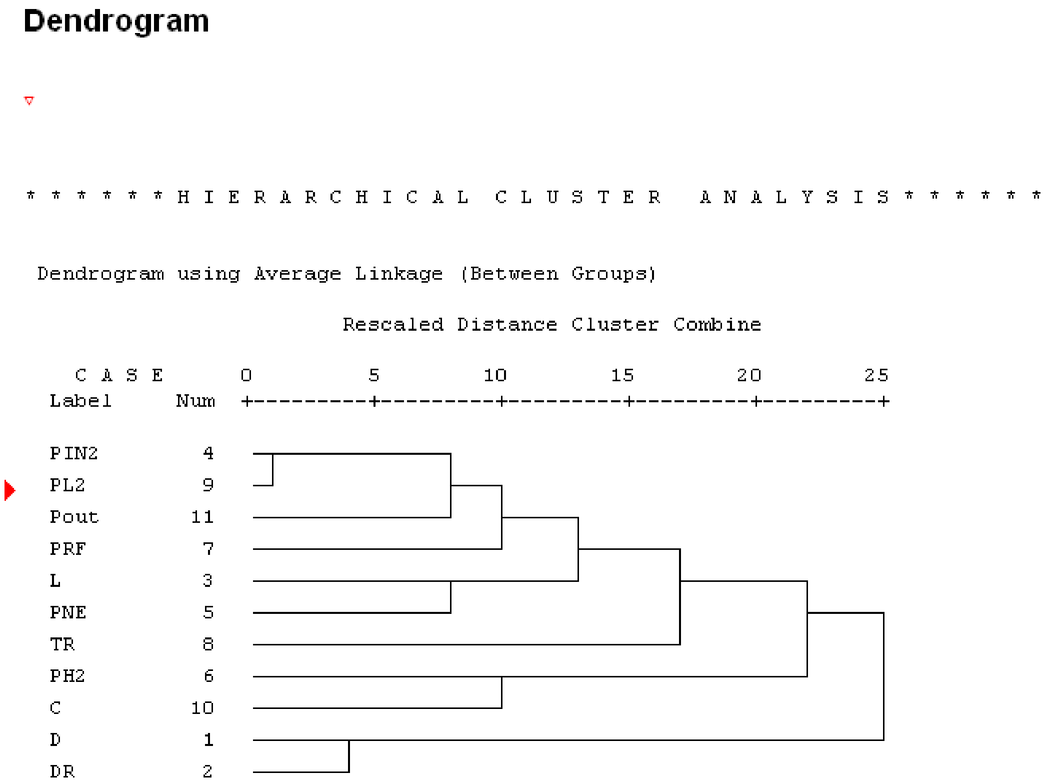


Fig. 3. *Dendrogram of 10 independent quantities and the dependent output quantity Pout, obtained using average linkage between groups.*

Following [7, 16], the optimal clustering solution from the dendrogram is where the biggest gap is situated with at least rescaled distance of 5 units. In Fig. 2 this is in the interval [1.7, 2.3] in rescaled distance. Thus the optimal clustering solution consists of the following 3 clusters:

$$\begin{aligned} &Cluster\ 1 = \{PIN2,\ PL2,\ PRF,\ TR,\ L,\ PNE\},\\ &Cluster\ 2 = \{PH2,\ C\},\\ &Cluster\ 3 = \{D,\ DR\}. \end{aligned} \quad (1)$$

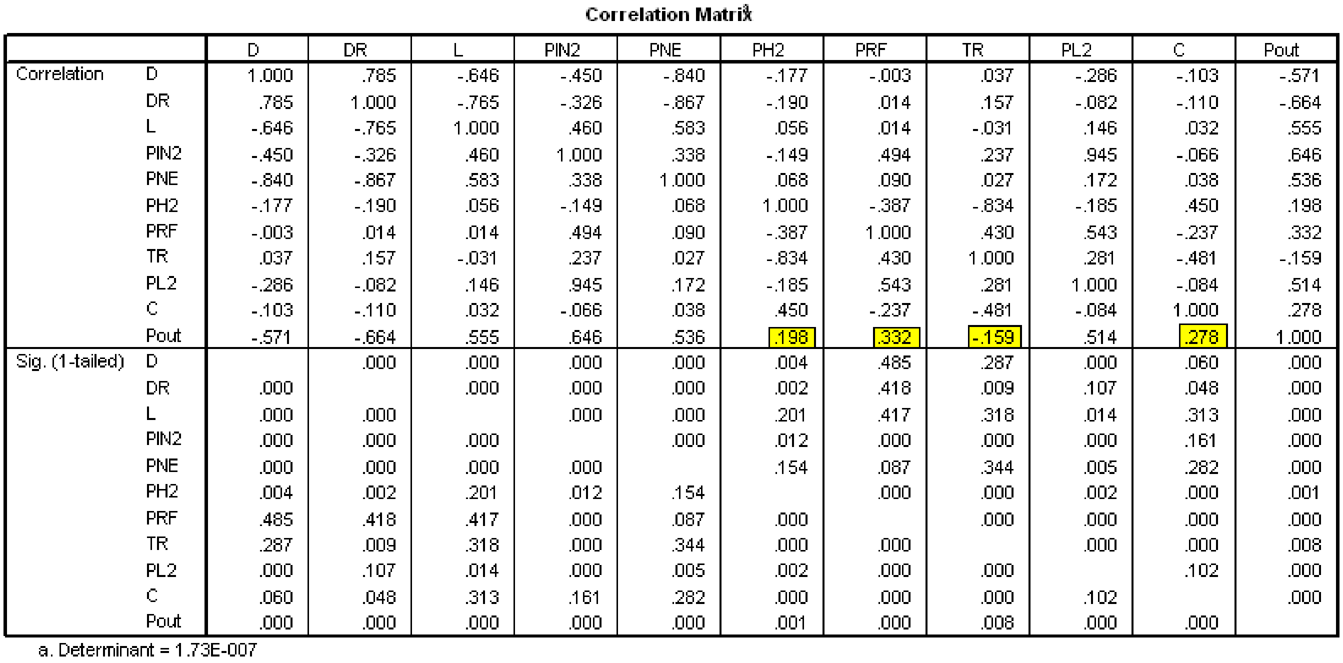
The next important step is to determine the position of the dependent variable - laser output power *Pout* among the classified 10 independent variables. To this end, Fig. 3 presents the respective dendrogram obtained using average linkage between groups clustering method. It is seen, that *Pout* is classified in *Cluster* 1, in a cluster group with *PIN*2 and *PL*2. This is then used for analysis and physical interpretation of the results following factor and regression analysis.

4 Factor Analysis of UV Cu+ Ne-Cu Laser Data

Factor analysis is a statistical technique intended for transforming sets of correlating data into a new set of non-correlated artificial variables or factors, which describe as best as possible the general variation of the output data [17]. This technique allows for a reduction in the number of initial variables by grouping those which correlate with each other into a common factor and the division of non-correlating ones into different factors. Mathematically this is achieved by reducing the dimensionality of the initial range through the setup of a new basis of variables (factors). There are numerous publications related to FA, including ones where specialized software is used (see [16, 17, 7] and given there literature). Factor analysis is applied to obtain the correlation matrix of all examined laser variables, as is given in Table 2. All results are calculated with standardized values. There are observed high correlation coefficients and a small determinant, which indicate the availability of high multicollinearity, respectively the adequacy of factor analysis procedure. There are 4 independent variables which have correlation coefficients with *Pout* under 0.3. These are the data variables *PH*2, *PRF*, *PRF* and *C*. Thus, within the experimentally established optimum values, these variables show small direct correlations with *Pout*, and therefore may be disregarded in future consideration. The correlation coefficient between *Pout* and all other variables are found to be bigger than 0.5 and statistically significant. We will get back to this during the analysis and physical interpretation of the results. Another important result is that the correlation coefficients between *Pout* and any of variables *D* and *DR* are negative. Therefore, in future experiments for the development of new laser sources with enhanced output, its values could be taken to be decreasing.

TABLE 2

CORRELATION MATRIX OF THE 10 INDEPENDENT VARIABLES AND THE DEPENDENT VARIABLE POUT (SPSS OUTPOUT).



Correlation Matrix[a]

		D	DR	L	PIN2	PNE	PH2	PRF	TR	PL2	C	Pout
Correlation	D	1.000	.785	-.646	-.450	-.840	-.177	-.003	.037	-.286	-.103	-.571
	DR	.785	1.000	-.765	-.326	-.867	-.190	.014	.157	-.082	-.110	-.664
	L	-.646	-.765	1.000	.460	.583	.056	.014	-.031	.146	.032	.555
	PIN2	-.450	-.326	.460	1.000	.338	-.149	.494	.237	.945	-.066	.646
	PNE	-.840	-.867	.583	.338	1.000	.068	.090	.027	.172	.038	.536
	PH2	-.177	-.190	.056	-.149	.068	1.000	-.387	-.834	-.185	.450	.198
	PRF	-.003	.014	.014	.494	.090	-.387	1.000	.430	.543	-.237	.332
	TR	.037	.157	-.031	.237	.027	-.834	.430	1.000	.281	-.481	-.159
	PL2	-.286	-.082	.146	.945	.172	-.185	.543	.281	1.000	-.084	.514
	C	-.103	-.110	.032	-.066	.038	.450	-.237	-.481	-.084	1.000	.278
	Pout	-.571	-.664	.555	.646	.536	.198	.332	-.159	.514	.278	1.000
Sig. (1-tailed)	D		.000	.000	.000	.000	.004	.485	.287	.000	.060	.000
	DR	.000		.000	.000	.000	.002	.418	.009	.107	.048	.000
	L	.000	.000		.000	.000	.201	.417	.318	.014	.313	.000
	PIN2	.000	.000	.000		.000	.012	.000	.000	.000	.161	.000
	PNE	.000	.000	.000	.000		.154	.087	.344	.005	.282	.000
	PH2	.004	.002	.201	.012	.154		.000	.000	.002	.000	.001
	PRF	.485	.418	.417	.000	.087	.000		.000	.000	.000	.000
	TR	.287	.009	.318	.000	.344	.000	.000		.000	.000	.008
	PL2	.000	.107	.014	.000	.005	.002	.000	.000		.102	.000
	C	.060	.048	.313	.161	.282	.000	.000	.000	.102		.000
	Pout	.000	.000	.000	.000	.000	.001	.000	.008	.000	.000	

a. Determinant = 1.73E-007

Another important result is that the correlation coefficients between *Pout* and any of variables *D* and *DR* are negative. Therefore, in future experiments for the development of new laser sources with enhanced output, its values could be taken to be decreasing. Table 3 shows the grouping of significant 6 independent variables *PNE*, *D*, *DR*, *PL*2, *PIN*2 and *L* into factors. The factor loadings less than 0.3 are omitted [7]. The given table indicates that the first factor includes variables *PNE*, *D* and *DR*, and the second: *PL*2 and *PIN*2. The unique variable in the third factor is *L*. In this manner, by applying the procedure for factor analysis, the 9 real independent physical variables are reduced to 3 artificial grouping variables, called factors. Once again, it has to be noted that the quantities in each factor are strongly correlated and need to be modified simultaneously, while the quantities *D* and *DR* must be decreased.

TABLE 3

GROUPING OF MAIN 6 VARIABLES INTO FACTORS. ROTATED COMPONENT MATRIXA

	Component (Factor)		
	F1	F2	F3
PNE	-0.951		
D	0.871		
DR	0.817		
*PL*2		0.996	
*PIN*2		0.944	
L			0.887

^{A} Extraction Method: Principal Component Analysis.
Rotation Method: Varimax with Kaiser Normalization.
Rotation converged in 4 iterations.

The next Table 4 shows the grouping of the same 6 main independent variables and the dependent variable *Pout* into factors. *Pout* participates in the second factor together with *PIN*2 and *PL*2. This means that these two quantities have the greatest influence on laser output power. The dendrogram in Fig. 3 shows that these two variables are the closest to *Pout*. The results from the cluster and factor analysis are similar with regard to the strong influence of *PIN*2 and *PL*2 on the values of *Pout*.

TABLE 4

GROUPING OF MAIN 6 VARIABLES AND POUT INTO FACTORS. ROTATED COMPONENT MATRIXA.

	Component (Factor)		
	F1	F2	F3
PNE	-0.920		
D	0.847		
DR	0.730		
*PL*2		0.994	
*PIN*2		0.931	
L			0.885
Pout		0.588	

^{A} Extraction Method: Principal Component Analysis.
Rotation Method: Varimax with Kaiser Normalization.
Rotation converged in 5 iterations.

5 REGRESSION ANALYSIS FOR A UV CU+ NE-CU LASER

Multivariate regression analysis (RA) is one of the most powerful statistical techniques with a wide range of applications in various fields. It is used to construct models which describe quantitatively the relationships between several independent variables (predictors or regressors)

$$(x_1, x_2, \dots, x_p)$$

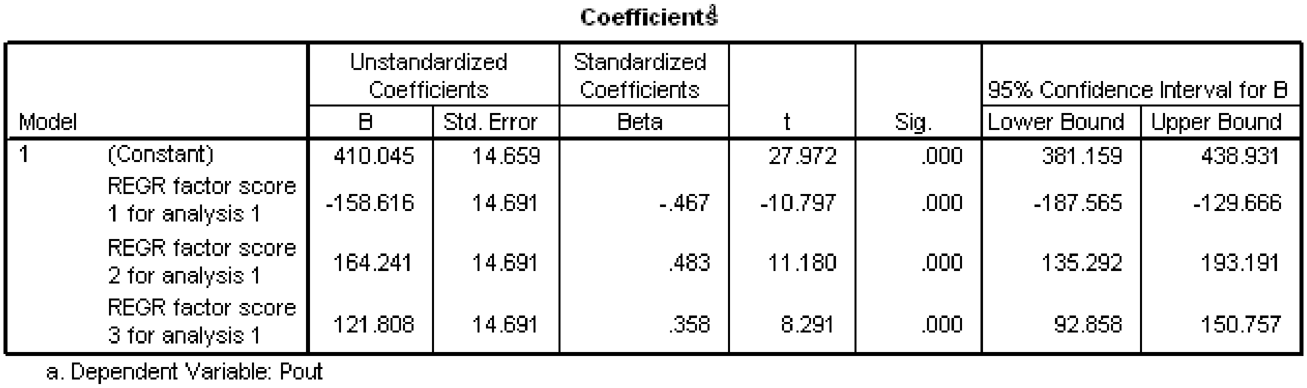
and one (or more) dependent variable(s) (response). In this case, based on the mutual population distribution, a functional dependence is to be found in the form

$$\hat{y} = f(x_1, x_2, ..., x_p; a_1, a_2, ..., a_m), \qquad (2)$$

explicitly expressesing the influence of separate independent variable(s) on the dependent one. Equation (2) is called a regression model or a regression equation of y relative to $(x_1, x_2, ..., x_p)$. Here $(a_1, a_2, ..., a_m)$ are the regression coefficients (parameters) subject to defining. There are numerous publications related to multivariate RA. Practically oriented examples (including the application of specialized software) can be found for example in [16, 18]. Due to the multicollinearity of input laser characteristics, we will apply regression analysis using the factors, known as a method of Principal Component Regression (PCR). We are looking for a regression equation in the form (2). The resulting values and statistics from the regression analysis carried out by means of SPSS for the standardized and non-standardized coefficients are given in Table 5.

TABLE 5

VALUES OF NON-STANDARDIZED AND STANDARDIZED COEFFICIENTS FOR THE REGRESSION ANALYSIS (SPSS OUTPOUT).



Coefficients^a

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.	95% Confidence Interval for B	
		B	Std. Error	Beta			Lower Bound	Upper Bound
1	(Constant)	410.045	14.659		27.972	.000	381.159	438.931
	REGR factor score 1 for analysis 1	-158.616	14.691	-.467	-10.797	.000	-187.565	-129.666
	REGR factor score 2 for analysis 1	164.241	14.691	.483	11.180	.000	135.292	193.191
	REGR factor score 3 for analysis 1	121.808	14.691	.358	8.291	.000	92.858	150.757

a. Dependent Variable: Pout

Based on the results, the following non-standardized and the respective standardized equation may be written down:

$$Pout \approx 410.045 - 158.616F_1 + 164.241F_2 + 121.808F_3 \qquad (3)$$

$$\overline{Pout} \approx -0.467F_1 + 0.483F_2 + 0.358F_3 \qquad (4)$$

The coefficients in the standardized equation (4) indicate the relative influence of each factor. The highest coefficient is that before the second factor, which means the variables it includes (*PIN*2 and *PL*2) have the strongest influence on *Pout*. The obtained regression analysis results correspond to those from the cluster and factor analysis. It needs to be noted that the modulus of the coefficient before the first factor in equation (4) is much closer to the coefficient before the second factor. This means the variables included in the first factor: *PNE*, *D* and *DR*, also have an influence which cannot be ignored. The coefficient of the first factor is negative. Therefore, *F*1 has to decrease in order to increase *Pout*. According to Table 4, the following may be approximately written for the first factor:

$$F1 \approx -0.951PNE + 0.871D + 0.817DR \qquad (5)$$

The negative coefficient before *F*1 in equation (4) indicates that in equation (5) the quantity *PNE* needs to increase, and values of *D* and *DR* to decrease, which corresponds exactly to the correlation matrix, Table 2.

6 ANALYSIS AND PHYSICAL INTERPRETATION OF THE PERFORMED MULTIVARIATE ANALYSIS

It is first necessary to consider the physical basis for laser generation in the UV spectrum. To this end, a diagram is provided with the energy levels of the system in Fig. 4. The presented figure shows that the upper laser level $5s^3D_{1,2,3}$ (line 248.6 nm) is directly under the basis state of Ne+. The energy difference is small (~ 0.2 eV), so it can easily be populated using a kinetic equation

$$Ne^+ + Cu_0 \to (Cu^+)^*(5s) + Ne + \Delta E \,.$$

The lower laser level $4p^3F_0$ is populated mainly by spontaneous UV emissions at levels $4s^3D_{1,2,3}$, which are metastable. The lower laser level and the metastable levels can easily be populated by a Penning mechanism on a metastable level of neon Ne^m by a kinetic equation:

$$Ne^m + Cu_0 \to (Cu^+)^*(4p) + Ne \,.$$

The predominant population at these levels may lead to a reduction in the inverse population.

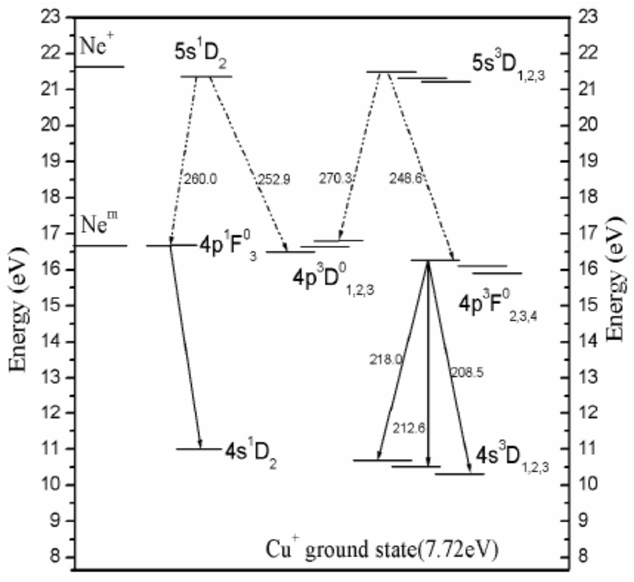


Fig. 4. *Diagram of the energy levels within a Cu+ and Ne system.*

The brief analysis of the main kinetic processes of UV radiation showed the significant role played by the neon buffer gas. For this reason, it is very important for laser generation. The results from the cluster, factor, and regression analysis confirm this conclusion. High electron energy and voltage between electrodes are needed to excite the upper laser levels and the Ne+ level. For this reason, the most crucial parameter for laser generation is once again the supplied electric power *PIN2*. The relative quantity *PL2* is positive. Therefore, the supplied electric power has to increase at a faster rate than the distance between electrodes (*PL2*=*PIN*2/*L*). This guarantees the rapid expansion of the longitudinal electric field ($E=U_{el}/L$) and the related increase of electron energy. Quantities *D* and *DR* have to be reduced to increase output laser generation *Pout*. Reducing the diameter of the tube makes it possible to increase the relative influence of scattering, drift, and recombination of particles on tube walls. Higher loss of electrons at the expense of their recombination along the tube walls without changing the supplied electric power, leads to an increase in the voltage between electrodes and the longitudinal electric field. This increases the energy of the electrons. The scattering of copper atoms from the lower laser level and the metastable atoms to the tube walls allows for their further population, discharging their energy into the tube. Thus, along with the main population process (spontaneous UV emission), an additional alternative arises, which would allow for an enhanced inverse population. Somewhat unexpectedly, the role of hydrogen remains underestimated since this quantity did not participate in the performed factor analysis. In this sense, it has to be considered that the established optimum values for hydrogen pressure of 0.02-0.04 Torr need to be maintained in future experiment investigations.

ACKNOWLEDGMENT

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