# Topological Model of Laser Emission Parameters Research

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***Abstact – The research paper presents a model for studying both the parameters and dynamics of laser light as a nonlinear dynamic system. The model provides for the measurement of the values of physical quantities by non-linear metrology methods and the analysis of the research findings with topological tools. The model is based on the assumption of interval values of the measured values and the possibility of changing the stationary dynamics into the random one. The model contains an experiment scheme and a procedure for evaluating measurement results. The peculiarity of the model lies in its systemic approach and suitability for measuring and researching stationary and chaotic modes. The model provides for the measurement of the emission parameter values intervals in various modes, of their stability values and time series prediction. Classification of the system dynamics is performed using the fractal dimension. The model can be used both to ensure the stability of the laser light parameters, and to obtain and control random emission.***

***Keywords — chaos, fractal dimension, laser emission parameters stability***

## I. INTRODUCTION

Research in the promising areas of photonics, optoinformatics and laser engineering have been conducted at the Photonics Research Laboratory of the Kharkov National University of Radio Electronics. Among them, there are: topological photonics, quantum and chaotic cryptography, laser cooling, laser-based objects manipulation, fiber and nanoscale lasers, single-photon sources and receivers. The research area of both stabilization and enhancement of the laser emission characteristics remains fundamental.

Study and control of laser emission modes remains an urgent task since its inception [1]. The possibility of random emission modes in both multimode [2] and single mode [3] lasers, which affects the values and stability of laser emission parameters, was shown theoretically and in practice.

There are two areas of studying randomness in lasers. The first is aimed at combating random modes. Randomness leads to deterioration in the emission stability, which is unacceptable for lasers used in measuring, medical and information technologies [4]. The second covers the task of generating and controlling random emission modes for use in information systems [5]. Information in such systems is transmitted in the form of a double message, hidden in a random optical carrier [6]. From this perspective, the possibility of generating laser pulses with a controlled level of stability of the radiation frequency, repetition frequency, amplitude, carrier frequency, etc. are matters of inter-est. For this purpose, the mechanisms of destruction of the mode-locking mode, and other processes leading to randomness, are being studied [2].

The success of the studies described depends on the correctness of the measurement models. Methods of measuring the laser emission parameters and analyzing their results are governed by standards ([7], [8], etc.) and are based on the classical measurement theory with the postulates about the uniqueness of the true value, ergodicity, and the fulfillment of the central limit theorem.

Through the spectacle of the theories for studying complex systems, the laser is a nonlinear dynamic system with a self-organization function (NDS), and the emission parameters are dynamic variables (DV). In [9], [10] research papers and in others, it was shown that in the case of NDS, the hypotheses of the classical measurement theory are not confirmed. A special theory of measurements (nonlinear metrology) is being developed [10] in order to provide both study and control of NDS. Its application to measure laser emission parameters in stationary and chaotic modes contributes to the solution of both the problem of combating randomness, and the production and use of random emission. Methods for analyzing the results of nonlinear metrology measurements involve using topological tools of qualitative theories of open systems. The phase portrait, Lyapunov expo-nents, time series prediction and fractal dimension are used in particular.

The research paper objective is to create a model for studying the parameters and dynamics of laser emission as a nonlinear dynamic system. The model provides for the measurement of the values of physical quantities by nonlinear metrology methods and the analysis of the research findings with topological tools.

## II. CHAOS IN LASERS

Chaotic dynamics is an inherent property of a wide class of systems, demonstrating their transi-tion to states in which both deterministic behavior and unpredictability are detected.

$$r = \max_{1 \le j \le m} x(j,m) - \min_{1 \le j \le m} x(j,m); \quad x(j,m) = \sum_{j=1}^{m} (x_j - \bar{x}_j). \quad (13)$$

Classification of the DV dynamics is performed using formulas (11)-(13). In case $D = 1$, the process is strictly deterministic and the DV values can be predicted over a long period of time. In case $D = 2$, the scatter of values is very large and it is impossible to conclude on the DV dynamics. In case $D = 1{,}5$, the process has a random nature. In case 1< $D$ <1,5 and 1,5< $D$ <2, the process is non-Markovian, random, persistent and antipersistent, respectively. In the first case, the DV dynamics retains its trend (deterministic chaos), and in the second case, it changes to the opposite (non-deterministic chaos). The fractal dimension (11) can be associated with the value expression for the DV stability (6) through the standard deviation $s$ of equation of the following form:

$$\Delta x = \pm \frac{2r}{\bar{x}(m/2)^{2-D}}. \quad (14)$$

From the value expression (14) it follows that the absolute value of the DV stability $\Delta x$ decreases with increasing fractal dimension $D$. In case $D$=1, $\Delta x$ takes the minimum value and increases with increasing the $D$ value. The deterministic DV dynamics ($D$=1) ensures the best stability of the parameter. Increased randomness leads to the stability deterioration. For the case when the fractal dimension exceeds the value characteristic of the random process $D$=1.5, the stability tends to its minimum value, which is explained by the antipersistency of the process, local instability and a large scatter of values in case of $D \to 2$. Thus, the fractal dimension can be used to assess the DV stability in the case when the laser operates in both stationary and random modes. The value expression (14) can be also used to obtain random signals with a given stability.

The next matter to be solved is the horizon period of the DV time series prediction [10]. The peculiarity of the random NDS lies in the fact that a small-amplitude perturbation of the initial conditions, or a small change in the parameters of the system itself, leads to the unpredictability of the resulting motion in a finite amount of the forecast time $T_{for}$ :

$$T_{for}(\lambda) \sim \frac{1}{\lambda_{\max}} \log \frac{1}{\varepsilon}, \quad (15)$$

here $\lambda_{\max}$ is maximum Lyapunov exponent, $\varepsilon$ is divergence value of two close trajectories.

In practice, the value of time series prediction is often considered using the simplified formula:

$$T_{for}(\lambda) \sim 1/\lambda_{\max} \quad (16)$$

The "time series prediction" concept is important for predicting the DP values of the NDS. The value expression (16) together with the DV stability value expression (14) can be used to estimate and control the random modes of laser emission.

Thus, the presented theoretical model for measuring laser emission parameters is based on a system approach to a laser, like to a NDS with a self-organizing function. The model is designed to measure and study the laser emission parameters in both stationary and random modes. The suggested schematic course of the experiment (figure) and the procedure for evaluating measurement results (9)-(16) can be used both to ensure high stability of the emission parameters and to obtain and control random laser emission. The results obtained in the research paper develop the theory of measurements in NDS and, through the use of such topological characteristics as the fractal dimension and Lyapunov exponents, contribute to the development of topological photonics, expanding its scientific challenges scope from photonic crystals to laser emission.

## VI. CONCLUSION

The research paper presents a model for studying the parameters and dynamics of laser emission as a nonlinear dynamic system. The model provides for the measurement of the physical quantity values under the nonlinear metrology methods, and for the analysis of the research findings with topological tools. The model is based on the assumption of interval values of the measured quantities and the possibility of changing the stationary dynamics into a random one. The model contains a schematic course of the experiment and a procedure for evaluating measurement results. The peculiarity of the model lies in its systemic approach and suitability for both measuring and researching stationary and random modes. The model provides for the measurement of intervals in radiation parameters in various modes, the values of their stability and the time series prediction. Classification of the system dynamics is conducted using the fractal dimension. The model can be used both to ensure the stability of the laser emission parameters, and to obtain and control random emission.

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