PRINCIPLES OF LASER DYNAMICS

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Foreword

The resonant interaction between an atomic system and a laser field is the main link in the functional chain of a laser. This interaction is accompanied by the energy state redistribution, which implies that laser medium nonlinearity is ineradicable in principle. Lasing is also sensitive to other nonlinearities inherent in the media inside the resonant cavity.

Analysis of the role of such interactions and effects, their influence on the temporal, spatial and spectral characteristics of laser radiation, and justification of the practical methods of laser control – these are the objectives of laser dynamics.

Three decades of the laser dynamics history have witnessed two booms. There was a surge of interest in this field with the advent of solid-state lasers. It was stimulated by the lack of satisfactory interpretation of the experimentally observed spikes in laser generation. Universality of the spiking regime and the absence of apparent causes of its origin led researchers to believe that instability is a natural property of the induced emission of condensed laser media in the optical cavity. Therefore, the early papers focused on a search for likely instability mechanisms of this process.

The first boom in the 60s was extremely fruitful for laser dynamics. Major achievements of that period include formulation of the basic models and a general study on their properties, investigation of free-running generation, laying the foundations of the giant pulse formation and mode locking theory. Slightly paraphrasing the well-known definition of radiophysics, given by S.M. Rytov, we may call that time a period of *physics for lasers*.[1] It was over in the early 70s, when solid-state lasers spikes were found out to relate mainly to the technical fluctuations of laser parameters, and when other requirements relevant for laser applications were met.

The 70s have brought neither high activity, nor much progress in the laser dynamics field. Gaps remained, but they seemed to be not so many. Say, the undamped coherent pulsations much spoken about by the theoreticians had not been obtained experimentally. Scientists were still uncertain about the true causes of the random-looking sequences of spikes. Not much had been done in the ring laser theory. It seemed, nevertheless, that little room was left for further research, and any outstanding achievements in laser dynamics would hardly be possible.

Still, those years witnessed a rapid progress in general dynamics of nonlinear systems. The conceptions of deterministic chaos and strange attractor had become

[1] In the Introduction to his book "The Statistical Radio Physics" (Nauka, Moscow, 1976) S.M. Rytov divided the radiophysics into *physics for radio* and *radio for physics*.

current in the physicists community. The new ideas of nonlinear dynamics had been fruitful for the development of various fields of human knowledge.

In that period it was understood that a laser not only belongs to the systems of a complicated behavior, but also is best suited for investigation into the regularities of nonlinear dynamics.

This was the basis for a new upsurge of laser dynamics, which started in the 80s and proceeded, unlike the first period, under the motto *lasers for physics*. A lively discussion of the possibility to observe deterministic chaos in lasers had led to the first successful experiments in 1982. At present there is a wide choice of original literature on this subject, which covers both experimental and theoretical investigations of a complicated laser behavior. This branch of laser dynamics is treated in the recently published review paper *Dynamical Instabilities and Pulsations in Lasers* by N. Abraham, P. Mandel, L. Narducci (in: Progress in Optics, v. 25, ed. E. Wolf, North-Holland, Amsterdam, 1988) and in the book *Dynamics of Lasers* by C. Weiss and R. Vilaseca (Weinheim, N.Y., 1991).

The monographs dealing with laser dynamics are rather few. Nearly all of them are concerned with the period before the 80s and mostly belong to the Soviet authors. This should not be surprising, since the Soviet physicists' contribution to laser dynamics is rather weighty.[2] In this relation, we should mention *Molecular Oscillators* by A.N. Orayevsky (Nauka, Moscow, 1964), *Dynamics of Solid-State Free-Running Lasers* by K.G. Folin and A.V. Ghiner (Nauka, Novosibirsk, 1979), *Dynamics of Semiconductor Quantum Oscillators* by L.A. Rivlin (Sovetskoye Radio, Moscow, 1976), and *Dynamics and Spectra of Semiconductor Lasers* by L.A. Rivlin, A.T. Semyonov, and S.D. Yakubovich (Radio i Svyaz, Moscow, 1983). This list should be supplemented with the monograph *Self-Oscillations in Lasers* by A.M. Samson, L.A. Kotomtseva and N.A. Loyko (Nauka i Tekhnika, Moscow, 1990). Each monograph focuses either on a particular type or particular mode of operation of laser. A considerable contribution to the dynamical theory of lasers has been made by the famous German physicist H. Haken in his book *Laser Light Dynamics*, which was published by the North-Holland Publishing Co. in 1985.

An attempt at a systematic exposition of this subject and a state-of-the-art analysis was undertaken by the author in his previous book *Dynamics of Quantum Oscillators* (Sovetskoye Radio, Moscow, 1975). Of course, there has been a reappraisal of values since that time. Some papers that seemed to be of little significance have now taken the place they rightfully deserve. Others, on the contrary, turned out to be less important as they had seemed. With due account of the material presented in the *Dynamics of Quantum Oscillators*, which he believes to be time-proven, the author would like to offer a new book reflecting the state-of-the-art in the laser dynamics field of the early-90s.

This new book contains a comprehensive study of free-running lasers. In Chapters 3 to 5 the primary attention is given to the steady states and their stability, the laser behavior in the instability domain, the characteristics of regular and chaotic pulsations and the nature of their mechanisms.

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[2] A great number of Russian papers is included in the list of references.

Chapter 6 deals with the processes in a laser, accompanying the time variance of the laser parameters. Considerable attention is given to a laser response to weak low-frequency modulation of the parameters. The problems addressed therein are resonant modulation enhancement, transition to the nonlinear regime, chaotic response to periodic impact, spike-like generation due to variation of the cavity geometry and a laser rod temperature drift. This Chapter also focuses on spectrally swept lasers operated under the monotonically varied detuning between the selective resonator and the laser medium.

The laser behavior is subject to qualitative changes if its optical elements exhibit nonlinear properties. The action of a saturable absorber, which leads to a loss of laser stability and provides passive Q-modulation, is best investigated. To a much lesser degree the researchers' attention has been attracted by other nonlinear effects such as self-focusing, for example, which may have a strong influence on laser dynamics. All of these issues are discussed in Chapter 7.

Five main chapters are preceded by two introductory ones. Chapter 1 offers general consideration on quantum oscillators, formulates the requirements for the laser key elements and shows how these requirements are met in different laser systems. It also gives an idea of a diversified dynamic behavior of lasers, dependent on the relationship between the laser parameters. Chapter 2 proposes the mathematical models used in the semiclassical laser theory, discusses the approximations and simplifications in particular cases, and specifies the range of applicability of these models.

It is assumed that the reader is familiar with the fundamentals of the nonlinear dynamics. The minimum key information is provided in a compact form only in the special Glossary. More on the subject can be found in such a book, for example, as *Oscillations and Waves in Linear and Nonlinear Systems* by M.I. Rabinovich and D.I. Trubetskov (Kluwer Acad. Publ., Dordrecht, 1989), and in some books and papers cited below. In this connection the monograph by C. Weiss and R. Vilaseca cannot but be mentioned once again.

A few words about the branches of laser dynamics that, for some reason, have not been reflected in this monograph. Thus, the author has left out the scope of ideas concerning spatio-temporal dynamics in the laser field. This area of the nonlinear dynamics of optical systems is developing very rapidly now, but not a single book on the subject has appeared so far, the only exception being a course of lectures on *Multistability, Chaos and Spatio-Temporal Dynamics* by L.A. Lugiato and L.M. Narducci (Les Houches Session LIII/Fundamental Systems in Quantum Optics, eds J. Dalibard, J.M. Raimond and J. Zinn-Justin, Elsevier Science Publishers B.V., 1992). The inverse problems of laser dynamics are only touched upon in this book. This subject is of great practical importance and it is here that novel ideas based on the modern conceptions of the nonlinear dynamics are most welcome. Yet, we have just started out on this way.

The reader has obviously understood that he is offered a physical rather than mathematical version of the subject. This seems to be reasonable, since we are not speaking about the nonlinear dynamics in general, but focus on the laser dynamics which, above all, is the scientific interest of the author.

The laser dynamics is a live, fast-developing science rich in events occurring every day. It is perfectly clear, therefore, that such a book can not claim to be an exhaustive study on the subject; moreover, the incompleteness of presentation is bound to grow more sizable as time goes by. Yet, the established system of "eternal values" lends hope that the usefulness of this book will not pass too soon.

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Such an effort takes not only profound knowledge of the subject, but also a sincere human generosity.

Man is lucky to have friends like that.

In grateful acknowledgement of the efforts on behalf of the international science foundations such as ISF and INTAS, I would like to emphasize the vital importance of the support rendered Russian scientists by international community in so hard a time. With this support and encouragement the advanced science in Russia, no doubt, stands a better chance of survival and integration into the world science.

CHAPTER 1

Quantum Oscillators: General Considerations