BOOK REVIEW

Nonlinear Laser Dynamics: From Quantum Dots to Cryptography

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Semiconductor lasers—or as they are often called, diode lasers—are an integral part of modern technology. They are used in numerous devices from laser pointers to high-throughput laser printers to the light sources that power the optical-fiber communication behind the internet. At the fundamental level, a laser is a combination of a resonant optical cavity (such as a pair of mirrors facing each other a given distance apart so that only certain wavelengths can fit neatly between the mirrors) and a gain medium (which amplifies the light at one or more of those wavelengths). Turn up the gain to the point where it balances the losses due to absorption and leakage out of the cavity, and you have a laser.

Many laser systems have low gain and so can be modeled with reasonable accuracy by quasi-linear systems of rate equations. Semiconductor lasers, on the other hand, have very high gain and so must be modeled with correspondingly complex rate equations. If some of the output light is fed back into the laser cavity delayed by a time which is longer than the lasers internal relaxation time, then a delay term must be included in the rate equations, leading to an infinite phase space. This has interesting and unexpected effects on the temporal behavior of the laser such as periodic intensity spiking, chaos, and synchronous operation of nominally random uncoupled lasers.

All these effects and more are discussed in detail in the 15 chapters of this book, with each chapter averaging about 25 pages. The book is divided into three Parts: nanostructured devices (chapters 1-5), coupled laser devices (chapters 6-10), and synchronization and cryptography (chapters 11-15).

Chapter 1 by Lüdge describes the rate equations used to model quantum-dot-based laser devices. The origin of the various terms in the rate equation are given and both numerical and analytical results are presented. Chapter 2 by Zamora-Munt and Masoller discusses noise and polarization bistability in vertical-cavity surface emitting lasers (VCSELs). The analysis is based on a spin-flip model which is a set of rate equations that treats the two orthogonal polarization states of a VCSEL as effectively up and down spins. The authors show how these equations lead to bistability, under what conditions current modulation in the presence of noise can produce rapid intensity pulsing, and how to use current modulation to perform AND and OR logic operations.

Chapter 3 by Sciamanna shows how competition between modes drives nonlinear laser dynamics. Unless specifically designed not to, diode lasers will have many wavelengths inside the gain bandwidth and so can lase on multiple modes, each with a different wavelength. Simulation results showing low-frequency polarization switching in VCSELs and fast pulsing in edge-emitting lasers (EELs) with external cavity feedback are presented. The rate equations used are not presented but are said to be similar to an extension of the standard Lang-Kobayashi rate equations to cover multimode lasers. Chapter 4 by Wacker discusses the basic physics of quantum cascade lasers (QCLs) and briefly describes how their dynamics can be modeled using either density matrices or nonequilibrium Greens functions. Examples of the gain spectrum and the optical mode distribution inside a device derived using non-equilibrium Green's functions are presented along with a brief history of the development of continuous wave QCLs.

Chapter 5 by Greenway, Balanov and Fromhold discusses charge-domain dynamics in semiconductor superlattices which are spatially periodic quantum well structures. This chapter is not about lasers. It presents a model and detailed results of charge moving in a voltage-biased semiconductor superlattice when a magnetic field is applied to the superlattice at various angles. The type of behavior that occurs is a form of *weak* chaos which does not obey the Kolmogorov-Arnold-Moser (KAM) theorem.

Chapter 6 by Otto, Lüdge, Viktorov and Erneux describes how quantum-dot lasers respond to optical feedback. There is extensive discussion of the rate equations for various configurations with and without an external cavity, for one or two types of change carrier and for various parameter values. Chapter 7 by Krauskopf and Walker discusses dynamics of a diode laser with a saturable absorber and delayed optical feedback. The saturable absorber causes the laser to self-pulse, a phenomenon known as passive Q-switching. The authors show how optical feedback in such a system produces a very rich variety of phase space portraits including an effect known as *excitability*, wherein the off state is an unstable equilibrium point but all trajectories that pass close to that point eventually lead back to it. The goal is to understand how to produce pulses with very tightly controlled periodicity. Chapter 8 by Vladimirov, Rachinskii and Wolfrum develops a model of a passively mode-locked laser where the mode locking is due to a saturable absorber. The model is highly nonlinear but detailed numerical and analytic results are presented. Again, the goal is to find regimes where the laser pulses have a very tight periodicity.

In Chapter 9, Gonzalez, Soriano, Torrent, Garcia-Ojalvo and Fischer discuss both numerically and experimentally the dynamics of diode lasers coupled to each other with a long (relative to the internal dynamics) time delay. In the low-noise regime, two very similar lasers will alternate output pulses. But with the same noise source injected into both, they will synchronize and pulse simultaneously. Chapter 10 by Amann describes the behavior of complex networks based on coupled two-mode lasers, i.e., lasers that operate at two distinct wavelengths. The basic idea of building a complex network using lasers is discussed first, followed by an analysis of a Fabry-Perot type cavity designed to lase at two wavelength. Other than Chapter 4 this is the only chapter that discusses the optical modes of cavities. Rate equations are then used to model the coupled dynamics. The resulting phase diagram and time traces display a wide range of types of bifurcation including torus, period doubling, saddle node, Hopf and saddle node limit cycle.

Chapter 11 by Wieczorek uses rate equations to examine noise synchronization and stochastic bifurcation in diode lasers. Noise synchronization occurs when the total intensity of a group of similar lasers, all injected with the same noisy signal, scales quadratically rather than linearly with the number of lasers. The transition is shown to occur slowly with increasing noise amplitude. At a high noise level and for a nonzero linewidth enhancement factor (i.e., nonzero coupling between the amplitude and the phase of each laser), there is a drop-off in the synchronization—due to a bifurcation in the phase diagram of the dynamics when the linewidth enhancement factor is nonzero. Chapter 12 by Lücken and Yanchuk examines the emergence of cluster states in coupled oscillators. In two-cluster states, one group of oscillators pulses at the same time and the remaining oscillators at a different time. Pulsed coupled-phase oscillators are used to model the dynamics and explore the phase space of such systems. The phase of each oscillator is taken to increase linearly with time; but when one oscillator reaches 2π, its phase is reset to zero and the phases of all the other oscillators are shifted by an amount depending on their present value. This system of equations is studied both numerically and analytically and the conditions and stability of one and two cluster is determined. The analysis is general and not explicitly related to diode lasers.

Chapter 13 by Callan, Illing and Gauthier is focused on broadband chaos via a model of delayed feedback with gain. The system can be implemented experimentally as an optoelectronic oscillator by using a Mach-Zehnder modulator (MZM) combined with an optical fiber for delay. With the MZM biased to be near the peak of a fringe, the voltage detected at the end of the fiber is fed back to the MZM multiplied by an adjustable factor. The nonlinearity in this case comes from the MZM itself, not the diode laser. The transition to chaos is studied both analytically and numerically with the broadband aspect verified experimentally via an essentially flat power spectrum.

Chapter 14 by Kanter and Kinzel discusses secure communication using based on synchronization of chaotic networks. Coupled Bernoulli maps are used to provide a simple mathematical format for describing chaotic lasers and their synchronization via both unidirectional and bidirectional coupling. The authors show that chaos can only be induced by including optical feedback in either one or both of the coupled lasers and they discuss various ways of encoding information on the chaotic laser beam(s) to enable them to carry a secure message. Details of how to implement this type of communication with diode laser are discussed along with chaos pass filters, information protocols, private filters and networks.

The final, Chapter 15, by Shore has the alliterative title *Desultory Dynamics in Diode-Lasers: Drift, Diffusion and Delay*. It provides a historical account of the development of diode lasers, including VCSELs and QCLs. Chaos synchronization for message transmission using

VCSELs is described and configurations of chaotic laser communication systems which operate isochronously, i.e., with no time of flight delay are discussed along with the robustness of such systems for communications.

In general, each chapter is well written, is reasonably complete, and provides an extensive list of references. The downside, as with any book where each chapter is written by different authors, is that there is significant overlap and repeated material between the chapters. But it should be noted that many chapters do refer the reader to more detailed discussions in other chapters. The upside of this multiple-author format is that each chapter functions as a review article which can be read on its own without the necessity of referring to the other chapters. On the whole, I would recommend it to anyone interested in nonlinear dynamics in general and in the nonlinear dynamics of diode lasers in particular.