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Semiconductor lasers: coherence and localized states

Stéphane Barland, Massimo Giudici,
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Abstract Semiconductor lasers are tiny optoelectronic devices that are routinely used in countless applications ranging from computer pointing devices to optical data transmission. In addition to this, they can also serve as a versatile experimental platform for the exploration of dynamical systems and complex phenomena. In the following we discuss two phenomena that can take place (in markedly different situations) at the laser light emission threshold: the emergence of coherence and the formation of optical localized states.

1 Introduction

Semiconductor lasers are ubiquitous in modern life and the fundamental mechanisms that govern their light emission properties are most of the time completely transparent to the user. However, in spite of their robustness and apparent simplicity, those devices rely on delicate processes of interaction between light and matter. Among these, the one which is at the origin

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of their name is the process of light amplification by stimulated emission of radiation. In this process, energy supplied to matter (in most cases via the application of an electrical current) is converted into light. Thus, light is amplified and matter is de-excited, which of course implies a nonlinear mutual interaction. Since light that is generated by this process constantly escapes the laser (it is a light emitting device), this amplification process must be strong enough to overcome the exiting light flow. This balance implies the existence of an energy input *threshold* for the stationary emission of laser light. This simplified description hides a profound analysis of the laser threshold, which proves it to be an example of phase transition in a system out of thermodynamical equilibrium, since energy is constantly flowing in and out. Thus, semiconductor lasers can be used as model systems for the analysis of very general phenomena that can take place at phase transitions. In the following, we illustrate this approach by discussing two specific phenomena: the emergence of *coherence* and that of *localized states*.

2 Collective behavior of small systems: threshold crossing in micro- and nanolasers

A change in macroscopic state is a feature that occurs in a multitude of physical and non-physical systems. In everyday life this can be observed, for instance, in the change between ice and liquid water, or in the ordered state (magnetic) vs. the disordered state (non-magnetic) in iron. Lasers belong to this same class of phenomena even though their property, unlike the two previous examples, may not be intuitively associated with a phase transition. One basic feature, which is common to the first two systems, is the large number of “elements” that participate in the interaction: in the case of water and iron, the atomic density is so large that even a tiny volume (say 1mm^3) includes upwards of 10^{18} atoms (or molecules), thus justifying the so-called thermodynamic limit, i.e., the limit of infinite system size. In lasers the “elements” are the number of modes of the electromagnetic field resonant in the cavity¹ volume (i.e., in three dimensions): this number, though not quite as large as that of the previous examples, easily amounts to $10^5 - 10^6$ even for a tiny semiconductor laser (e.g., a laser pointer), thus the thermodynamic limit still represents a good approximation [1].

Recent progress in miniaturization has led to the investigation of phenomena at the nanoscale, opening up new questions rooted in the finite size of the sample where the collective behavior is sought. Lasers play a substantial role in this quest thanks to their comparatively already small number of

¹ cavity: an optical resonator, in many cases consisting of mirrors facing each other.

constituents compared to solids or liquids. As such, they play a double role of model system on the one hand, and of actual devices on the other hand, on which one can experiment and understand the modifications that the finite size brings to the collective behavior. In addition to the fundamental aspects of small sample behavior, nanolasers (i.e., lasers with submicrometric cavity volumes) are very appealing, for instance, as candidates for sources of coherent light directly integrated into future all-optical chips to replace today's electronics, but also as probes at the cellular scale for biomedical applications. However, in order to obtain a "correct" lasing behavior (i.e., coherent light) these nanodevices have to undergo the phase transition typical of their larger counterparts. This is easier said than done: the technological construction progress has certainly led to sub-wavelength light emitting sources but the questions on their "phase transition" have remained largely unanswered for the past thirty years. Two main elements are responsible for this failure: the lack of instrumentation capable of giving a thorough characterization of laser output at the very low photon flux emitted by a nanodevice, and the difficulty in setting up and treating models capable of handling a finite, but not small, number of components (here, emitters and cavity modes).

Rather than tackling the problem of the smallest devices, for the past few years we have been working on the characterization, both experimental [2] and numerical [3], of increasingly smaller lasers, starting from the usual macroscopic ones and leading towards the nanoscale. This choice presents the double advantage of following the gradual evolution of the features of the phase transition away from the thermodynamic limit, while allowing for a complete experimental characterization, thanks to the use of the most advanced instrumentation, still usable at the photon flux levels typical of the mesoscopic scale (intermediate between the macro- and the nanoscale) [4]. Our main findings, presented in detail in [4] together with other results on this topic, can be summarized by Fig. 1, which shows the "unfolding" of the laser threshold – i.e., the sharp transition of the macroscopic device (blue sketch in the bottom right corner of the figure) – into an ensemble of points. Each distinctive point is characterized by a physical feature and occurs at well-separated values of the energy supplied to the device – all points collapse together onto a single value for the power supplied to the device in macroscopic systems. Point B corresponds to the emergence of coherent oscillations between the two main variables that describe the physics of lasers (photon number and population inversion); point C to the largest amplitude self-induced oscillations in the output power and point D to the reaching of fully coherent emission (the Poisson statistics typical of *proper* lasing). Point A corresponds to desultory and uncorrelated laser pulses, interspersed with exclusively spontaneous photons, which precede the true continuous emission lasing. It is important to realize that these different regimes correspond

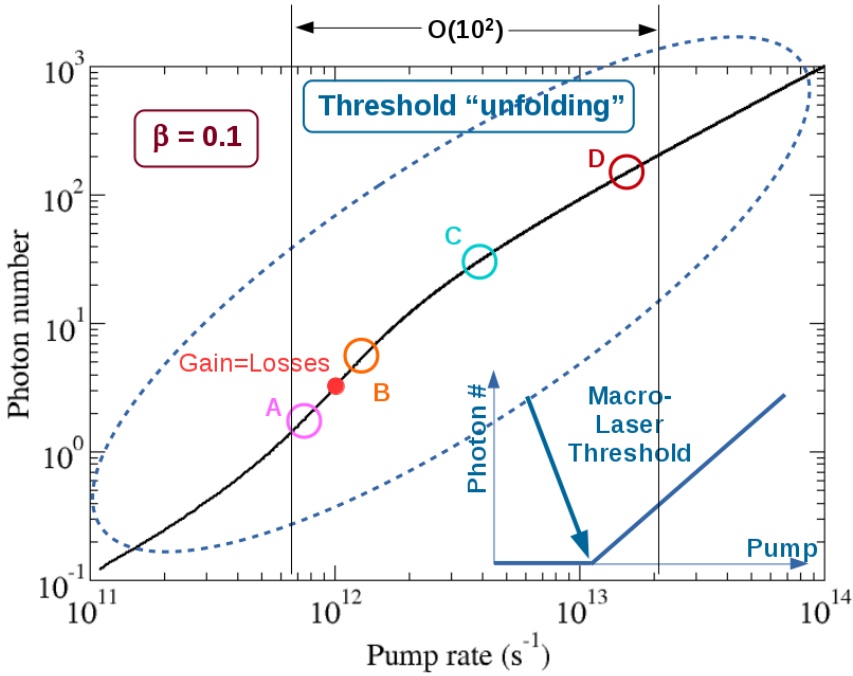


Fig. 1 Schematic of the principle of the response – output number of photons – of a nanolaser ($\beta = 0.1$: fraction of the spontaneous emission coupled into the lasing mode) to external excitation – number of excited emitters per second (pump rate). The average photon lifetime in the cavity is taken to be 10^{-11} s, thus at any time there are a few tens or hundred emitters excited, whence the relatively small number of photons available. The blue diagram, bottom right, represents the schematic shape of the response of a macrolaser, with its characteristic break in the line (threshold) of laser output. For the nanolaser the curve is smooth and threshold “unfolds” into an ensemble of separate points, as discussed in the text. The red point corresponds to the balance between the gain (from the external energy input) and losses, one of the criteria used to identify the macrolaser threshold.

to independent characterizations of threshold given for macroscopic lasers and collapse into a single point in large systems.

One important feature of these small devices is that they can also serve as generic models systems for complex systems. One example taken from everyday life is the dynamics of applause [5]. We know from experience that large groups can spontaneously produce synchronized clapping but that in smaller groups – barring previous agreements or signals in the crowd – synchronization does not easily occur (the group size could be mapped into the pump rate in Fig. 1). As an analogy, we could connect the first regime (A)

with the clapping of a few isolated people in an audience, (B) with the starting of applause that becomes more vigorous, yet disorderly, in (C) and may eventually reach synchronization (D). Of course this is only an analogy, but the information that can be gathered from a simpler system (in a laser there is no influence of group psychology or other *external* effects) may help identifying basic features that are common to many other complex systems as a function of system size.

3 Localized states

The spontaneous formation of spatial structures is a fascinating phenomenon whose understanding made a giant leap with the seminal work of Alan Turing on the chemical basis of morphogenesis in the biological realm [6]. Since that work, the dominant role of spatial coupling and nonlinear interactions in the formation of spatial structures has been established in many contexts such as liquid crystals, chemical reactions, solidification or fluid dynamics to name a few (see *e.g.*, [7]). With that in mind, one can expect that semiconductor lasers, out of equilibrium systems where (diffracting) light and (diffusing) matter interact nonlinearly, can support the formation of spatial structures. One particularly interesting case is that of so called *localized structures*, which can be generally viewed as domains of finite size enclosed by stationary fronts [8]. Such structures have been observed in a variety of systems, from plant ecology to nonlinear optics [9]. Of course, such structures whose formation is dominated by nonlinearity and which are only mildly influenced by boundary conditions can only exist in systems whose spatial extension is large enough. Thus, in contrast to the case discussed above in section 2 where the laser device was chosen to have an extremely small spatial extension, here we consider semiconductor lasers that are large enough to host optical localized states. In this specific context we focus much less on the statistical or spectral properties of the electric field and a very efficient description of the device can be obtained by considering the mean field dynamics, which describes the slowly varying amplitude of a coherent electric field without considering spontaneous emission. Then, the laser phase transition described in section 2 is described in terms of a supercritical Hopf bifurcation. On the other hand, localized states appear as a result of a *subcritical* bifurcation since they must connect asymptotically to some other stable solution. This can be achieved in a variety of ways and we have demonstrated experimentally the existence of optical localized states in several configurations, including applying an external forcing [10] or inserting in the laser

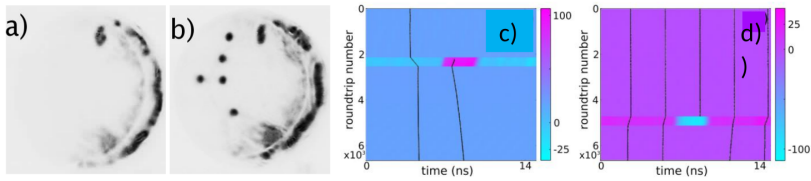


Fig. 2 Generation of localized states in a broad area semiconductor laser. a) stable homogeneous solution. Full width of the image is 200 micrometers. b) bistable and mutually independent localized states consisting of high light intensity emission can be addressed by suitable optical perturbations. From [10] c,d): Temporal localized states generation in the output of a semiconductor laser. Localized states in the cavity are represented by the black trace while the bias current pulse used for writing the localized state is represented in color code. Panel c) writing of a temporal localized states by an electrical pulse in the pumping current starting from a situation where one localized state was present before the addressing pulse. Panel d) shows the erasing of one temporal localized state by a negative electrical pulse from a situation where five localized states were present. From [12].

device an element whose optical absorption varies with the amount of light it receives [11].

3.1 Localized states along propagation direction

One common point of those experiments is that the spatial extension of the device was *transverse* to the direction of propagation of the field. In more recent works we have addressed the question of whether the concept of localized states can be extended to the time domain or, equivalently, to the propagation direction of the electromagnetic field where localized states appear in the form of pulses of light. In this context, the system size is given by the longitudinal dimension of the resonator and the notion of large-aspect ratio can be formulated by requiring that the cavity round-trip time T must be much larger than the active material timescales τ . We have implemented temporal localized states in a passively pulsing mode-locked semiconductor external cavity lasers in the limit $T \gg \tau$, see Fig. 2 c,d). For the proper system parameter the bifurcation from stationary solution to mode-locked pulsing occurs subcritically, thus leading to a favorable situation for generation of localized states [13].

These results pave the way towards observation of spatio-temporal localized structures, also called Light Bullets. Since the pioneer work of Silberberg in the beginning of '90, these light bullets have been actively sought in the last 25 years. Despite the efforts made, robust light bullets have never

been observed experimentally because the equilibrium between nonlinearities and spatio-temporal mechanisms spreading the pulse is very fragile. Beyond their fundamental interest, light bullets are very attractive for their applications. In particular, when used as fundamental bits for information processing, they are forecasted to enable reaching a THz bandwidth. The above described results suggest that dissipative light may be obtained in a broad-area semiconductor laser coupled to a distant saturable absorber. In a dissipative environment light bullets will be robust and individually addressable, thus allowing for three dimensional optical buffering of light bits.

3.2 *Spatially extended or delayed systems*

As described above, localized states can form in spatially extended media. However, we have recently been extending this idea to the case of *delayed* dynamical systems, which is a scheme which can be explored experimentally very conveniently with semiconductor lasers. In practice, the approach is to consider the semiconductor laser as a nonlinear node of essentially vanishing spatial extension (therefore, modeled as a low dimensional dynamical system) and to place in front of it a mirror that will reinject into the nonlinear node some of the light it has emitted some time before. Such a configuration can be conveniently modeled by adding to the nonlinear node a delayed term which represents this optical reinjection. It was shown many years ago [14] that a simple nonlinear node near a supercritical Hopf bifurcation can, in the presence of delayed feedback, give rise to convective-type instabilities and that large classes of delayed dynamical systems can be mapped onto an evolution rule for a spatially extended system with drift and diffusion. The extension of these results to other situations (vicinity of subcritical bifurcations for instance) is nontrivial and fascinating, with the observation in [15] of front dynamics very similar to those observed in spatially extended media. In [16,17], we have demonstrated experimentally that repulsive front interactions, which would normally lead to one phase filling the whole delayed system, can be tamed by pinning fronts to a temporal modulation. We have developed similar arguments in the neighborhood of a saddle-node on a circle bifurcation, *i.e.*, in a case where the nonlinear element is a "neuron-like" *excitable* node, subject to a delayed retro-action. In that case, we have observed attractive and repulsive interactions as well as elastic collisions of localized states of light [18,19]. Although mathematical demonstrations are lacking, our results strongly suggest that very similar mechanisms of homoclinic snaking can be invoked to describe the stability property of localized states in spatially extended and delayed systems.

4 Conclusion

In the preceding pages we have briefly reviewed some recent research topics that can be conveniently addressed using semiconductor lasers as an experimental platform. Of course, the ideas put forward here are far from exhaustive and many other general phenomena can be studied on these devices. Due to the typical time scales of semiconductor lasers (nanosecond and below), very large experimental data sets can be collected relatively easily, rendering these experiments particularly appealing for the analysis of low- or high-dimensional chaos, synchronization, slow-fast dynamics, phase transitions, stochastic phenomena, dissipative solitons and rare or extreme events. In addition, the ubiquity of these devices in modern data transmission systems also make them ideal candidates for the design of novel data processing schemes, which leverage nonlinear optical dynamics. In this direction, the chase of light bullets as three dimensional light bubbles able to carry optical information, or the exploration of neuromimetic optical dynamics for bio-inspired optical information processing are current research projects at the Institut de Physique de Nice.

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