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New Routes to Self-Organization in Semiconductor Lasers

Multi-section lasers represent a new class of optical devices. The combination of nonlinearity and feedback creates novel dynamical scenarios that resemble self-organization strategies in complex chemical, biological or even sociological systems. Smallness, robustness, wide tunability as well as flexible modes of operation make multi-section lasers promising candidates for the application in existing and future optical communication networks.

The use of photons, propagating at the highest possible velocity of $c = 3\times10^{10}$ cm/s, has triggered an enormous progress in communication technologies during the last decade. Fast, dense, and secure data communication has become an inherent feature of our today world. On the other hand, existing optical communication networks have already reached a complexity that faces considerable problems. Principally new concepts are required to overcome these diffculties. Nature has developed different strategies to communicate and to process information. Self-organization based on the complex nonlinear character of the system is here a central issue. In this article, we summarize our recent efforts to develop similar strategies in the area of optical data communication.

The semiconductor laser

The semiconductor laser is a key component of optical communication networks. An injection current I creates optical gain by inversion of the carrier states in the semiconductor. The interaction of this carrier-mediated gain with the photons travelling in the resonator makes the laser a strongly nonlinear system. When I is continuously increased, the laser output undergoes a transition from dark to bright at a certain threshold (Fig. 1a). In particular, distributed feedback (DFB) lasers (Fig. 1b) are excellent single-mode emitters with highly coherent continuous-wave output above threshold [1]. Modulation of the injection current creates an optical transmitter sending out signal pulses injected in an optical fiber (Fig. 1c). However, when travelling through the network, the optical pulses are repeatedly transformed back in electric signals, subsequently processed by electronic circuits. As a consequence, the communication speed slows-down, while complexity, error rate, and costs increase. In addition, an essential feature of light – the optical phase – is lost, as photo-detectors are only sensitive to the field intensity. There is hence a demand to develop routes that allow to perform major data processing operations directly in the optical domain.

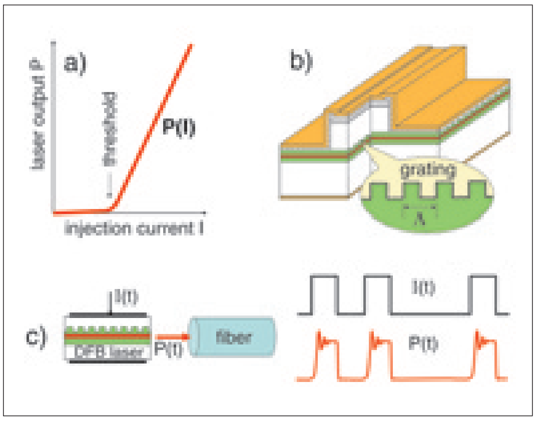


Fig. 1
The semiconductor laser. a) Optical output characteristics. b) Schematics of a DFB laser. The period Λ of the Bragg grating, typically about 250 nm, allows for to tune the emission to the standardized communication wavelengths. Due to their waveguide design, DFB lasers are extremely small: The active region depicted in red is a few hundred µm long, a few µm wide, and only few hundred nm thick. c) DFB laser as optical signal transmitter. Data rates as high as 10 Gbit/s are used.

New and unexpected scenarios occur when the laser is subjected to optical feedback. The basic principle is schematized in Fig. 2: An external mirror placed at a distance L from the laser reflects a part of the output back into the device. Such kind of reflection occurs frequently in optical networks, for instance, at fiber pigtails or in optical disc applications. In this context, feedback has been considered for a long time as a perturbation that destabilizes the laser. However, as we will demonstrate below, novel and useful phenomena arise when the feedback can be properly adjusted and controlled. Basically, three parameters govern the response of the laser. First, there is a feedback time $\tau=2L/c$ passing before the light re-enters the laser. This time has to be compared with the time-scale of the internal laser dynamics defined by the period τ_{RO} of the relaxation oscillations by which the laser returns to steady state after disturbance. Second, an extra cavity is formed by the external mirror. A crucial parameter is hence the phase shift $\phi=4\pi L/\lambda$ per round trip. The laser can only operate on wavelengths λ where ϕ is an integer multiple of 2π, i.e., for constructive interference between output and feedback field. A third parameter is the amplitude fraction K of the output re-injected in the laser, determining how strong the feedback affects the gain.

Multi-section DFB lasers

When using a distant external mirror, L is several centimeters or more. In this »long-cavity« limit, the mode spacing $\lambda^2/2L$ ($\lambda\approx1.5$ µm) of the external resonator is extremely small. The active mode of the solitary laser interacts thus with a quasi-continuous spectrum of external modes. The consequence is an irregular response with collapse of coherence and stochastic power drop-outs. In close cooperation with our partners at the Heinrich-Hertz-Institut [2], Berlin, we have developed devices that behave entirely different (Fig. 2) [3, 4]. Laser and feedback part are integrated on a single chip, both with the same length dimensions of a few hundred micrometers only. In typical semiconductor lasers, the period of the relaxation oscillations ranges between 0.1 and 1 ns, whereas the delay time is now as short as $\tau\approx0.1$ ps. The multi-section devices materialize hence the »ultra-short-cavity« limit where $\tau/\tau_{RO} \ll 1$.

A further outstanding feature is that the feedback parameters can be tuned by injection currents. In the passive feedback laser (PFL), ϕ can be tailored by an extra current I_P on the phase section via the carrier-induced change of the refractive index. An amplifier section, biased with a third current I_A, is added in the active feedback laser (AFL), allowing to realize strong feedback ($K \approx 1$). Third, going beyond the external-feedback configuration, even the mutual coupling of two lasers can be investigated with an integrated tandem device (ITD). All these devices can be manufactured in a set-up, ready for application in optical communication networks.

In a more general view, the quantities τ, ϕ, and K represent control parameters. The dynamical behavior of complex nonlinear systems depends in a nontrivial way on those parameters: smooth changes may cause also smooth changes in the dynamics, however, at certain constellations, sudden transitions to qualitatively different behavior occur. Such transition is termed »bifurcation« [5]. A certain type of bifurcation is correlated with a particular dynamical scenario, irrespective of the specifc physical, chemical, or biological nature of the system under consideration. In the present case, the optical fields and the carrier density obey a complex system of partial-differential equations in space and time [4, 6]. In collaboration with mathematicians at the Weierstraß-Institut, Berlin, we have developed tools to treat these equations and to uncover the possible bifurcations in multi-section lasers [4]. In what follows, we present some illustrative examples how these bifurcations can be translated in useful modes of device operation.

Self-pulsations

A fundamental mode of self-organization is associated with the Hopf bifurcation. Here, one from the otherwise unstable oscillators in the system becomes undamped. A prominent example is the laser threshold itself where a collective oscillation of the atomic dipoles and the electromagnetic field is born. In the multi-section devices, the interaction of the solitary optical mode with the adjacent external cavity modes creates another type of collective oscillator that can become undamped under appropriate feedback [7]. As a result, the device output switches suddenly from continuous-wave to a periodic sequence of optical pulses, so-called »self-pulsations« (SP). As shown in Fig. 3a, this transition occurs for the PFL at a certain value of the feedback phase. Another degree of freedom is the injection current I_{DFB} on the DFB laser itself. Setting I_{DFB} and I_P appropriately, the frequency of the SPs can be adjusted

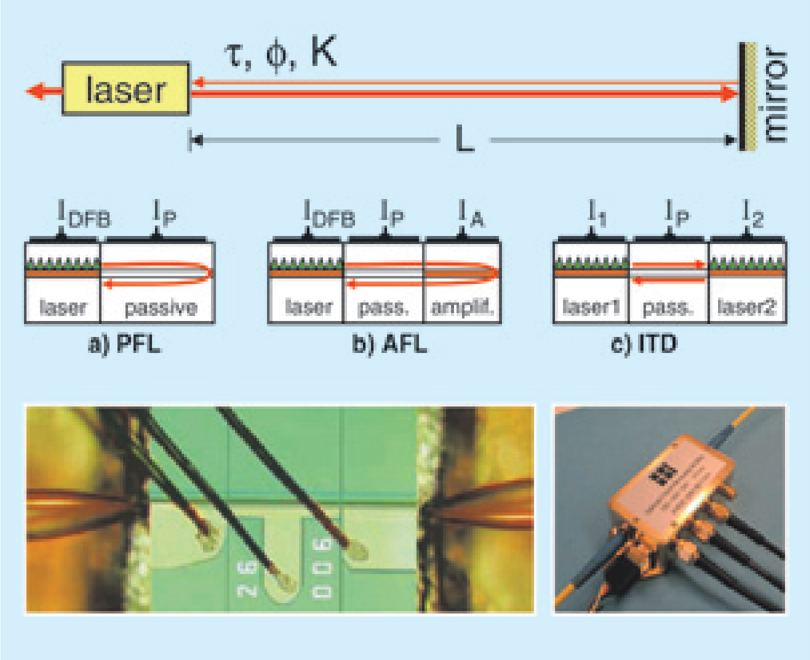


Fig. 2

Upper pannel: Schematics of a laser subjected to optical feedback. Middle panel: Three types of multi-section DFB devices. a) Passive feedback laser: A single-mode 1.5 µm InGaAsP DFB laser is combined with a passive phase section of larger band-gap with a cleaved facet acting as mirror ($K \approx 0.1$). b) Active feedback laser: A third amplifier section, similarly designed as the laser section, omitting however the DFB grating, is added. c) Integrated tandem configuration: Two lasers are separated by a phase section. In a)–c), the air-edges of the laser sections are anti-reflection coated. Lower panel: Right – a complete device as manufactured by FhG-HHI [2]. In the lower right corner, the cables of the three injection currents I_{DFB}, I_P, and I_A are seen. The output is selected by the two optical fibres on the front and end face of the device. The black plug is the temperature control. Left – the multi-section chip only with a total length of about 1 mm, biased by three currents tips, and fiber pigtails left and right.

Selbstorganisation in Halbleiterlasern

Mehrsektions-DFB-Laser sind eine neue Klasse optischer Baulemente. Die Kombination von Nichtlinearität und Rückkopplung erzeugt neue dynamische Szenarien, welche den Selbstorganisations-Strategien von komplexen chemischen, biologischen oder sogar sozialen Systemen ähneln. Mehrsektionslaser zeichnen sich durch Kleinheit, Robustheit, gute Durchstimmbarkeit sowie flexible Funktionsweise aus. Das macht sie zu viel versprechenden Kandidaten für Anwendungen in gegenwärtigen und zukünftigen optischen Kommunikationsnetzen.

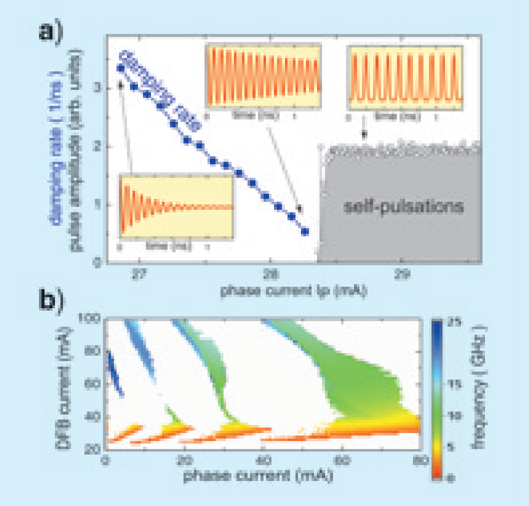


Fig. 3
Emergence of self-pulsations by a Hopf bifurcation in the PFL. a) Modulation amplitude (open circles) and damping rate (blue circles) of the device output versus phase current. The insets illustrate undamping of the relaxation oscillations towards a fully developed SP. b) SP regions in the plane of the two currents I_P and I_{DFB}. The color codes the frequency of the major peak in the power spectrum (right hand scale, white: no pulsations.)

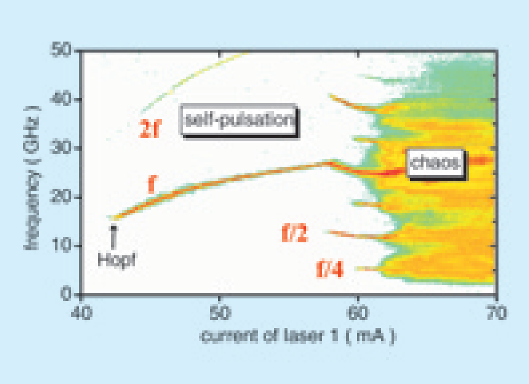


Fig. 5
Period-doubling route towards chaos of an integrated tandem device. The frequencies are taken from power spectra. The color coding represents the intensity of the respective frequency component with the red regions being most intense.

(Fig. 3b). Being the result of a self-organization process, the SP emerge without any external modulation. This feature is of high technical relevance. Optical pulse sources driven by dc currents are much easier to handle than devices requiring supply of modulated currents, in particular at GHz frequencies. Already the simple PFL allows to reach SP frequencies up to 25 GHz just by changing dc currents. The AFL and ITD exhibit even higher tuning ranges covering all communication bit rates of current use. On this base, the Heinrich-Hertz-Institut has developed a series of commercial applications, e.g., for optical clock recovery.

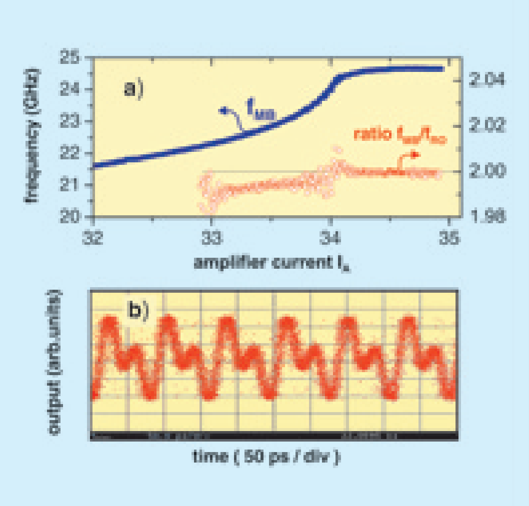


Fig. 4
Synchronization in the active feedback laser.
a) Frequency of the fast SP and frequency ratio of the two SPs versus amplifier current. Beyond I_A = 34 mA, frequency locking is clearly seen. I_P= 27 mA and I_{DFB}=70 mA are fixed.
b) Device output under injection of 24.6 GHz optical master signal at the entrance of the DFB section.

Synchronization

Synchronization is a fundamental requirement in communication networks. In this context, a useful feature of self-organization in multi-section lasers is that the internal oscillators synchronize to each other or to an external signal under appropriate conditions. Close to the boundaries of the SP islands (see Fig. 3b), a torus bifurcation appears for sufficiently strong feedback. Here, a second stable SP of different frequency is created. In a certain range of injection, the two SPs lock on a fixed frequency ratio of 2:1, independent on the control currents (Fig. 4a). When an optical pulse train is injected in the device, the output becomes indeed fully synchronous to this input. In Fig. 4b, the frequency of the external train is close to the frequency of the faster SP. The device emits a superposition of both pulsations where all signals – external train as well as slow and fast SP – have fixed phase relations. The synchronized device output provides a high-precision time base, indispensable for all subsequent data processing operations.

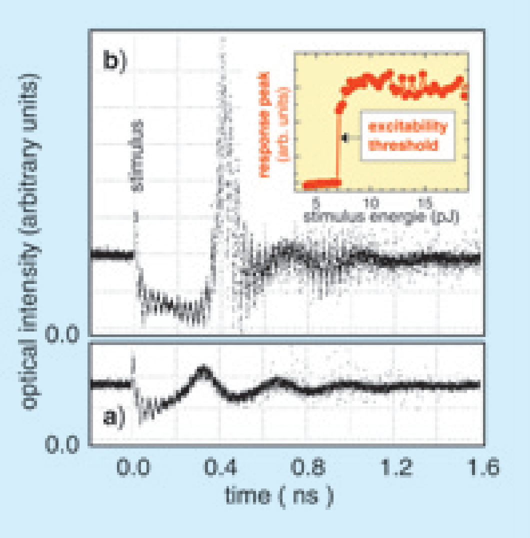
Chaos

Dynamical systems can become chaotic when undergoing certain sequences of bifurcations. In multisection lasers, this transition can be systematically pursued and controlled. One example, the so-called Feigenbaum cascade, is depicted in Fig. 5 for the ITD. The current on one of the lasers is tuned, while the other is kept fixed. Increasing the control current, the device follows initially the route described above: a SP of frequency f is born in a Hopf bifurcation. At higher current, oscillations with half and quarter frequency as well as their mirrors with respect to f come up, ending finally in the emergence of a broad frequency band that signifies chaotic emission. The properties of this chaos, influenced by unavoidable instrumental and internal noise, are still a matter of our current research. At first glance, chaotic emission seems to be incompatible with present data communication techniques based on regular bit sequences. However, lasers of this type can serve as transmitter and receiver elements for secure communication with encrypted signals [8]. Miniature design, robustness, and, in particular, the ability to control the chaotic operation make multi-section lasers promising candidates for this goal.

Excitability

Signal processing in the brain relies to a large extend on the excitability of individual neurons [9]. Excitable systems in general are characterized by an extremely nonlinear response to an external stimulus: Below a marked threshold, there is no reaction, while the response is strong but independent on the strength of the stimulation above. In addition, a refractory time has to elapse before the system can be excited again. All these features are met in many biological and chemical systems. The key for achieving excitability of multi-section lasers is a homoclinic bifurcation [6]. In Fig. 6, a 5 ps optical pulse incident on the DFB section of an AFL serves as stimulus. The device returns either to steady-state output by small-amplitude relaxation oscillations or responds with emission of a strong pulse. The refractory time of the device is 0.4 ns. Among many other applications, excitable lasers might serve as switching elements in optical neural networks [10].

Fig. 6
Response of an active feedback laser on an optical stimulus of 5 ps duration. a) below and b) above threshold. Inset: Output peak as a function of the stimulus strength demonstrating existence of sharp threshold of 7 pJ pulse energy.



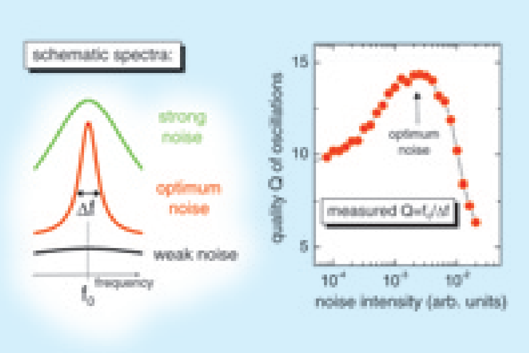


Fig. 7
Coherence resonance. Left panel: Schematic evolution of the power spectrum of a damped oscillator with increasing noise level. Right panel: Quality of the SPs in an AFL versus the intensity of electrical noise.

Coherence Resonance

Noise is usually believed to degrade the performance of technical systems. However, noise in conjunction with nonlinearity can also play a constructive role (see e.g. [11]). In coherence resonance, the regularity of an oscillation is improved by adding noise of optimum intensity. Fig. 7 demonstrates the existence of coherence resonance for the AFL. Electrical noise is added to one injection current. It has zero meanvalue, 15 GHz bandwidth, and the noise intensity can be varied by several orders of magnitude. The response of the device to the noise depends sensitively on the point of operation. Coherence resonance appears prior to the Hopf bifurcation where the SPs are still weakly damped. The coherence of an oscillation is measured by the quality factor $Q = f_0/\Delta f$. f_0 and Δf represent position and width, respectively, of the line associated with the oscillation in the power spectrum. Indeed, the quality factor of the SPs increases up to an optimum noise level and declines rapidly for stronger noise.

Conclusion

Multi-section DFB lasers exhibit a variety of dynamical scenarios that resemble self-organization strategies found in complex chemical, biological or even sociological systems. Their exploration has just begun and many other novel and specific phenomena can still be expected. The devices can be fabricated in a compact design, fully functional for application in optical communication networks.

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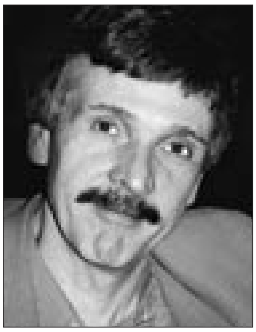

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