Towards a compact laser for chaos encryption

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Abstract: *We demonstrate an integrated laser device that shows well-defined and controllable nonlinear dynamics and even chaos. This makes our laser suited for encryption of data that has to be transmitted in a secure way, using chaos encryption.*

Introduction

As the world becomes more dependent on optical telecommunication, the issue of the security of the transmitted information takes a more prominent role. Since today virtually all information and most transactions are performed using contemporary telecommunications infrastructure, sensitive information such as bank transactions, patient information and government secrets require additional security measure, as compared to for instance a streaming video.

Software level encryption scheme have existed since the birth of information technology, but they are prone to human errors, i.e. the user may forget to encrypt the sensitive data or the encryption key may become public. More reliable hybrid software-hardware level encryption schemes have also been devised, among which the most prominent is the Quantum encryption scheme [1]. This scheme relies on the fundamental properties of quantum mechanical systems to transmit a software encryption key. This key is then used to encrypt the data, which is thereafter transmitted over a conventional line.

Recently the feasibility of a purely hardware level encryption scheme based on chaos was demonstrated over the metro fiber-network of Athens, Greece [2]. The optical data signal was hidden in the chaotic output of a semiconductor laser with electro-optical feedback and thereafter transmitted over a conventional fiber link. At the receiver side, an identical chaos generator was employed to generate a chaotic signal, which was subtracted from the incoming signal and the original data message was recovered. The key factor in this hardware level encryption scheme is that the chaos on the transmitter side and the receiver side must be identical. Once that is achieved, the two chaotic oscillators will synchronize, resulting in identical chaotic signals on the receiver and transmitter sides [3].

Nonlinear dynamics and chaos in the output of semiconductor lasers appear because of the resonant interplay between the field and matter in the laser [4]. These dynamics are generally damped, meaning that if the laser is left alone, any perturbation will die out after a few cycles. If the laser is perturbed, say by external resonant optical injection, then it will display nonlinear dynamics, which can evolve into fully blown chaos. This has been the focus of the field of laser dynamics for the past three decades and researchers have gained substantial insight into the underlying fundamental physics [4]. The workhorse of the field has been table-top setups, consisting of semiconductor lasers in various configurations, including semiconductor lasers with external optical injection and lasers subject to optical or opto-electronic feedback [4]. The large sizes of these setups (~ 1m) make them impractical for applications and also handicaps the systems when it comes to alignment and synchronization issues. Moreover, since the complexity of the chaos, i.e. the bandwidth of the chaotic signal, is proportional to the time and lengthscales of the chaos generating system, table-top setups tend to exhibit ‘slow’ (a few GHz) chaos as compared to comtemporary telecommunications standards (a few tens of GHz). It is therefore natural to look towards Photonic Integrated Circuits (PIC) for a fast, compact and controllable chaos generator.

A first step towards such Chaotic Photonic Integrated Circuit (C-PIC) is the demonstration of the existence of chaos in PICs. For this purpose we choose a device that has been fabricated using InGaAsP/InP based COBRA-integration technology: the Colliding Pulse Mode Locked Laser (CPMLL). This device consists of two front-to-front coupled ridge-type Semiconductor Optical Amplifiers (SOA), which are coupled through a ridge Saturable Absorber (SA). The small reflection off the absorber will result in each SOA section having its own modecomb and the CPMLL having a complex compound-cavity modecomb. The form of the CPMLL-modecomb will change with the operation conditions of the CPMLL and for certain values of the parameters (pump current and absorber voltage) the two modecombs will be resonant and the two SOAs will resonantly inject eachother. This is an ideal scenario for the generation of nonlinear dynamics and chaos.

Using a novel method, we demonstrate structured nonlinear dynamics in the output of the CPMLL by constructing a phase space for this system and identifying and reconstructing the attractors on which the system operates. Moreover, as a function of the common pump current over the SOAs, we can identify a Hopf-bifurcation [5], evolving into a period-doubling sequence (Feignbaum-sequence) [5], which eventually evolves into fully-blown chaos [5].

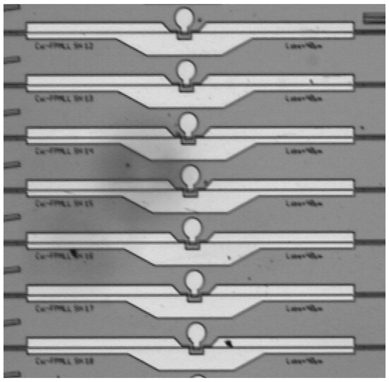

Figure 1: A picture of an array of seven CPMLL's. The SOA's have a common contact and the (round) pad contacts the 40 µm long SA, which is surrounded by 15 µm long isolation sections. The whole chip-width (facet-to-facet) is 1985 µm

These are typical characteristics of a dynamical system and we can therefore claim the existence of C-PICs [5].

In the next section the fabrication of the device and the experimental setup are described. Thereafter we present the nonlinear dynamics of the system and end with a conclusions and outlook section.

The device and experimental setup

The material for the device was epitaxially grown by the PSN-group of the COBRA institute, and consists of a 350 or 400 nm thick n-type InP substrate, on which a 120 nm thick $\lambda = 1.5$ µm bulk InGaAsP layer has been grown between two 190nm thick $\lambda = 1.25$ µm InGaAsP layers. The film is capped by 1500nm gradually doped layers of InP ending with a 200 nm thick highly doped InGaAs layer for contacting purposes. The material was MOVPE grown using all metal-organic precursors.

Five mask sets were used for the processing. The sample was coated with 70 nm SiN_x using Plasma Enhanced Chemical Vapor Deposition (PECVD), after which the first waveguide mask pattern was etched into the SiN_x using a Freon Reactive Ion Etching (RIE) process. The pattern was then transferred to the wafer using a second step of Methane-Hydrogen based RIE [6]. Since both shallow and deep etched ridge waveguides were present on the mask, the RIE etch of the total InP structure was performed in several steps, using 2 other masks (deep regions and isolation section) to achieve the desired surface topology. Next, the sample was passivated and planarized by spinning and curing six layers of polyimide (PI-2737) on the sample. The polyimide was then etched back to open the contact openings, resulting in a surface suitable for self-aligned metallization. Next, the metallization mask was used to define the contact regions, where 65/70/400 nm of Ti/Pt/Au was evaporated to create the contacts. Finally, a 500 nm thick plating gold layer was grown using electro plating techniques. At this stage a 65/70/500 nm of Ti/Pt/Au was deposited on the backside of the sample to achieve an n-contact. The sample was then annealed to create the Ohmic contacts and the different components were cleaved apart for characterization.

The device under study is part of a series of Colliding Pulse Mode Locked Lasers (CPMLL), an array of which are depicted in Figure 1. The design consists of 2 µm wide ridge-Semiconductor Optical Amplifier (SOA) terminated by cleaved facets (R=0.35) at the two ends. With our layer stack, the 2 µm wide ridge is designed to sustain the fundamental transverse mode in the structure, while the first order mode is cut-off. Through removal of the contact layer and ~700 nm InP, a short section (20 or 40 µm long) located around the centre of the device is isolated from the SOAs. This section is electrically contacted and by setting a reverse bias a Saturable Absorber (SA) is realized. Both the amplifier sections are connected to the same contact for the current supply. The chip is 1985µm long in order to obtain 39.8 GHz repetition rates for mode-locking operation [7]. The locations of the 40µm long SAs are varied gradually from the centre over the series of lasers. This guarantees that after cleaving we have at least one laser where the SA is centered symmetrically between the two SOAs and which will be well suited for mode-locking operation. Two separate batches of devices were produced with material gain centered at 1520 and 1550 nm, respectively. Each batch contained 20 CPMLLs with 40 µm long SA sections and 20 CPMLLs with 20 µm long SA sections. Also, each of the device sets was produced with both deep and shallow etched ridge waveguides. The deep etched devices were quite stable and did not show nonlinear dynamics and will therefore be disregarded in the current analysis. Of the 40 shallow etched CPMLLs, the ones with long absorber sections showed strongest nonlinear dynamics in the ~ 1 GHz range. The work presented in this paper is from the most asymmetric of the shallow etched devices with a 40 µm long SA section, surrounded by 15 µm of isolations on both sides and the SA is ~ 40µm off from the center. In what follows, this device will be refereed to as the CPMLL.

Under normal operation conditions, the symmetric device is expected to show mode-locking operation at 39.8 GHz repetition rate with 2.4 ps wide pulses [7]. The asymmetric devices are not expected to show optimal mode-locking and generally show nonlinear dynamics in the ~1 GHz range. The most prominent cause of these nonlinear dynamics is the asymmetry in the mode spacing of the two gain section, which due to the low reflectance off the absorber section, form two cavities with slightly different optical path lengths, resulting in slightly different mode-combs. As the index is varied, by for instance changing the pump current, the optial path lengths in the device changes and a resonant injection scenarion may be

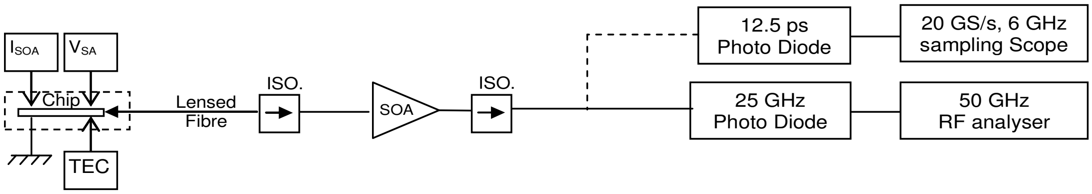

Figure 2: The experimental setup. The chip (left) was mounted on a (grounded) temperature mount and contacted. The light was collected by a lensed fiber and passed trough a SOA between two isolators. Thereafter two 25 GHz photodiodes were used to detect the light and pass it into an RF analyzer and a sampling scope

achived. Intuitively, the device can therefore be seen as two front-to-front coupled lasers with mutual injection, where the nonlinear dynamics are caused by the beating between of the longitudinal modes of the unequal mode combs.

The CPMLL chip was glued on a temperature controlled copper mount, which was attached to a heat reservoir that was kept at constant temperature of 14°C using a (cooled) water pump to facilitate constant alignment of the facet into a fiber (Figure 2). The current to the two amplifier sections and the reverse bias voltage of the saturable absorber were applied through two probes, using an ILX Lighwave LDX-3900 laser deriver and a Keithly Model 2400 stabilized voltage source, respectively. Light from the laser output waveguides was collected using a lensed fiber. The signal of the 1520 nm gain centered chip was amplified using a SOA between two optical isolators in order to avoid feedback into the laser, while the signal of the chip with gain centered at 1550 nm was amplified using an EDFA between two optical isolators. The extracted light was analyzed using a 25 GHz bandwidth NewFocus-photodiode connected to a 50GHz electrical spectrum analyzer [Agilent E4448A], or to a 20 GS/s oscilloscope with 6 GHz bandwidth and 8 MegaSamples per channel memory [LeCroy WaveMaster 8160].

It is quite clear, already from a quick overview of the data (see for instance Figure 3, right column) that the CPMLL operates on many dynamical attractors, including some chaotic ones. We found that for a reverse bias of –1.6 V on the absorber the device shows nonlinear dynamics which are characteristic for a large number of devices in the series. The common pump current of the device was used as the bifurcation parameter. It is essential from a bifurcational theoretical point of view that a single bifurcation parameter is used for the analysis, in order to be able to conclude on specific routes in parameter space that cause certain sequence of bifurcations, or phase transitions [5]. The threshold of the CPMLL was at 128 mA and the current was varied between 137 and 150 mA in this work.

Data analysis

Using the method of Ref [8], we constructed a three dimensional phase space $\mathbf{\Sigma}$ for the system and analyzed the phase space trajectory, consisting of $\vec{X}(t) = (P(t+\tau), P(t), dP(t)/dt)$. Here $P(t)$ is the detected output power of the CPMLL. Analogous to [8], the full three dimensional phase space is used for the analysis, while for the sake of simplicity only the two dimensional projections of the phase space trajectory on the $(P(t+\tau),P(t))$ and $(P(t), dP(t)/dt)$-planes are displayed.

Figure 3 shows one bifurcation sequence of the CPMLL as a function of the pump current. The left column shows the $(P(t+\tau),P(t))$-plane, the middle column is the $(P(t),dP(t)/dt)$-plane and the right column shows the RF-spectrum on a 0 to 3 GHz scale.

Above a pump current of 148.4 mA, the CPMLL operates on a fixed-point, i.e. CW-operation (not shown). It is in this region that one should search for mode locking behaviour. At 148.4 mA, the fixed point has already destabilized slightly and any deviation from the fixed point results in a spiraling trajectory towards the fixed point value. Due to the presence of noise in the system, the bifurcations i.e. the transitions between various kinds of dynamics, are not very clear. It is therefore not possible to distinguish the spiraling behaviour exhibited in Figure 3, top row, from a very low amplitude limit cycle (self-oscillations). As the pump is decreased to 145.2 mA, the Hopf-bifurcation (appearance of self-oscillations) becomes more stable and a clear limit cycle with an oscillation frequency of ~ 1.25 GHz appears in the output. This limitcycle undergoes a period-doubling cascade wich eventually results in chaotic behaviour at I=140.4 mA. The noise-like RF-spectra at 140.4 mA clearly identifies the chaotic nature of the dynamics. This pocket of chaos is exited through a quasi-periodic attractor (torus) at I=139.7 mA and the torus eventually changes into a period-2 limitcycle at I=137.2 mA. This is a scenario which occurs in many dynamical systems. We have also performed similar analysis on other device in both the batches that were fabricated and they all show similar nonlinear dynamical scenarios.

For chaos encryption applications, it would be desireable to be able to follow the period doubling sequence leading to the chaos at I=140.4 mA. This will allow one to draw conclusions on the exact nature of the chaotic attractor at I=140.4 mA and thus

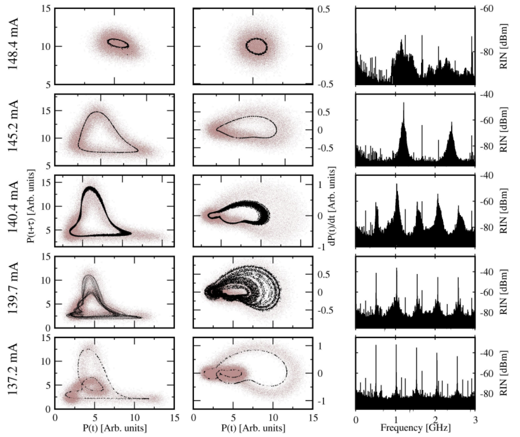

Figure 3: Left column shows the ($P(t+\tau)$,$P(t)$)-plane, the middle column is ($P(t)$,$dP(t)/dt$) projection and the right column shows the RF-spectra up to 3 GHz scale. (Top to bottom) In the top row the fixed point operation has just destabilized and is followed by a limitcycle in row 2, which evolves into chaotic dynamics in row 3 which is then exited through a torus in row. Finally the CPMLL ends up on a period-2 limit cycle attractor. The narrow peak at ~1.7 GHz in the RF-spectra is from the oscilloscope or photodiode and should be disregarded. Black dots are the reconstructed trajectory and gray are the experimental data points.

facilitate synchronization of two chaos generators. Unfortunately, the parameter range over which the CPMLL shows nonlinear dynamcis is very small. This is because the CPMLL was originally designed for mode locking applications and thus does not have any specific built-in control mechanism with which one can vary the interaction between the two SOAs. Future C-PIC designs, consisting of coupled lasers, must therefore contain mechnaims for the control of the coupling between the lasers. At COBRA, we are currently fabricating integrated laterally coupled ridge lasers and laterally coupled tunable ridge lasers (with built-in phase shifters) for chaos encryption purposes. Furthermore, our future devices will be fabricated on COBRA-Active/Passive platform, allowing us separate control of the spectral and gain properties and thus further increasing the impact of the control parameters on the chaotic output.

Conclusions and outlook

We have fabricated a set of Colliding Pulse Mode-Locked semiconductor Lasers, on a photonic integrated circuit. The device, originally intended for mode locking applications, show well-structured nonlinear dynamics in its most asymmetric form, i.e. when the absorber is placed about 40 µm away from its symmetri point.

Using a novel method of analysis, we were able to visualize the attractors and show a clear transition in and out of chaos as a function of a single bifurcation parameter, namely the pump current. From a dynamcial system point of view, this is strong evidence of well-structured nonlinear dynamics in the CPMLL. Unfortunatelty, the small current range over which all these transitions occur make the CPMLL a bad candidate for chaos encryption. For this purpose, we at COBRA are fabricating novel Active/Passive based C-PICs with higher level of control over the nonlinear dyanmcis.

One aspect most PICs have in common is that they consist of networks of monolithically coupled components. In this respect, the CPMLL analyzed here is not unique at all and confronts us with the fact that photonic integrated devices will inevitably exhibit deterministic nonlinear dynamics. This is good news, since the nonlinear dynamics exhibited by the CPMLL are stable over the life time of the device, reproducible from batch to batch and generally faster than their table-top counterparts.

Acknowledgments

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