Chaos Generation and Synchronization Using an Integrated Source With an Air Gap

V. Z. Tronciu, C. Mirasso, P. Colet, M. Hamacher, M. Benedetti, V. Vercesi, and V. Annovazzi-Lodi

Abstract—We discuss experimentally and numerically the dynamical behavior of a novel integrated semiconductor laser subject to multiple optical feedback loops. The laser's structure consists of distributed feedback section coupled to a waveguide, an air gap section and two phase sections. It is found that the laser, due to the multiple feedback loops and under certain operating conditions, displays chaotic behaviors appropriate for chaos-based communications. The synchronization properties of two unidirectionally coupled (master-slave) systems are also studied. Finally, we find numerically the conditions for message encryption/extraction using the multiple-feedback lasers.

Index Terms—Air gap, chaos-based communications, multiple feedback, semiconductor lasers.

I. INTRODUCTION

THE PHENOMENON of synchronization has been the subject of numerous theoretical and experimental investigations in many research areas [1]. In particular, synchronized chaotic waveforms have found applications in chaos-based communication systems. Different setups for chaotic data transmission have been proposed in [2]–[7]. From the application point of view, chaos-based communications have become an option to improve privacy and security in data transmission, especially after the field demonstration over the metropolitan fiber network of Athens [8].

In optical chaos-based communications, the chaotic waveform is usually generated by semiconductor lasers subject to either all-optical [9]–[13] or electro-optical [14]–[16] feed-

back. Configurations using Fabry–Perot resonators providing the optical feedback, the so-called frequency selective feedback, have also been considered [17]–[20]. In this case the feedback can either destabilize the laser emission or improve the stability of the continuous wave (CW) emission allowing the control of the laser in a non-invasive way [17]. Recently, the chaos modulation technique [21] and the on/off phase shift keying encryption method [26] have been successfully applied to an integrated device composed of a semiconductor laser and a double cavity, which provides optical feedback.

It is now well accepted that secure all optical chaos-based communications rely on the closed loop scheme, after it has been shown that the open loop scheme requires a larger amplitude message, which could be detected by simple linear filtering techniques [22]. However, the closed loop scheme requires a precise matching between the emitter and receiver external cavities [24], [25]. Free space cavities are not sufficiently stable and integrated sources are required. Recently, a novel photonic monolithic integrated device consisting of a distributed feedback (DFB) laser, a passive resonator, and active elements that control the optical feedback properties, has been designed, fabricated, and evaluated as a compact potential chaotic emitter in optical communications [23]. Different operating regimes, including stable solutions, periodic states, and broadband chaotic dynamics have been identified.

It is our aim in this paper to further investigate the possibility of developing new integrated, mechanically stable, operating sources capable of generating chaotic light for its potential use in chaos based communication systems. To this end we propose, fabricate and test, both experimentally and numerically, an integrated optical source composed of a DFB laser, two passive sections, two phase sections, and a narrow air gap.

This paper is structured as follows. We start in Section II by describing the laser setup and the theoretical model. In Section III the experimental results are presented. Section IV presents a study of the dynamics of a laser under the influence of multiple feedback loops. The synchronization properties and the chaos modulation (CM) encryption method are also demonstrated. Finally, the summary and conclusions are given in Section V.

II. LASER STRUCTURE AND THEORETICAL MODEL

A sketch of the investigated integrated laser is shown in Fig. 1 and comprises a DFB section coupled to two phase sections, two optically transparent straight waveguides and an

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V. Z. Tronciu is with the Weierstrass Institute for Applied Analysis and Stochastics, Berlin 10117, Germany, on leave from the Technical University of Moldova, Chisinau MD-2005, Republic of Moldova (e-mail: tronciu@wias-berlin.de).

C. Mirasso and P. Colet are with the Instituto de Física Interdisciplinar y Sistemas Complejos (IFISC) CSIC-UIB, Campus Universitat de les Illes Balears, Palma de Mallorca E-07122, Spain (e-mail: claudio@ifisc.uib-csic.es; pere@ifisc.uib-csic.es).

M. Hamacher is with the Fraunhofer Institute for Telecommunications, Heinrich-Hertz-Institute, Berlin D-10587, Germany (e-mail: michael.hamacher@hhi.fraunhofer.de).

M. Benedetti, V. Vercesi, and V. Annovazzi-Lodi are with the Dipartimento di Elettronica, Università di Pavia, Pavia I-27100, Italy (e-mail: mauro.benedetti@unipv.it; valeria.vercesi@unipv.it; valerio.annovazzi@unipv.it).

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Fig. 1. Picture of the proposed integrated device for chaos generation, synchronization and message encoding using a semiconductor laser under the influence of multiple optical feedback loops. The lengths of the air gap section is $l_a = 5 \mu\text{m}$. The reflection between air gap and both waveguide and phase sections is $\sim 30\%$. The image is not to scale.

air gap. Both the highly reflective coated chip facet and the air gap form multiple internal cavities. The phase sections have been introduced to control the feedback phases of the external cavities. By adjusting the bias current of such sections, we may trim the chaos spectrum; more important, we can optimize chaos synchronization of two matched modules, by compensating their residual parameter difference (Section III). Also, one of the phase sections could be used to insert the message, in a future transmission scheme based on phase modulation.

The lengths of each section are $300 \mu\text{m}$ for the DFB-section, $200 \mu\text{m}$ for the phase sections, 5 mm for the passive waveguides, and $5 \mu\text{m}$ for the air gap. The front chip facet is anti-reflection coated to maximize the output power. For the design of the laser, the phase shifters and the optical transparent waveguide, a buried heterostructure (BH) is used. This helps to keep the inevitable butt-joint losses at the active/passive interface as low as possible. For the DFB section, the BH-design based on eight quantum wells, supports high-oscillation frequency, good thermal characteristics and stable beam pattern. The fabrication follows that of standard BH-lasers comprising four epitaxial growth steps. The material wavelength of the laser core fits the emission wavelength around $1.55 \mu\text{m}$. A non-intentionally doped quaternary layer with a bandgap of $1.25 \mu\text{m}$, grown in an additional epitaxial run by selective area re-growth, assures a strictly single mode propagation of the light and acts as the optical transparent waveguide.

The theoretical analysis is based on the structure of the fabricated laser samples. In the present study, the laser dynamics is analyzed in the framework of the extended Lang-Kobayashi equations for the complex field amplitude E and the excess carrier density N [26]

$$\begin{aligned} \frac{dE_{t,r}}{dt} = & (1 + i\alpha) \left[\frac{g(N_{t,r} - N_0)}{1 + s|E_{t,r}|^2} - \frac{1}{\tau_{ph}} \right] \frac{E_{t,r}}{2} \\ & + \gamma_1 e^{i\varphi} E_{t,r}(t - \tau_1) + \gamma_2 e^{i\psi} E_{t,r}(t - \tau_2) \\ & + \gamma_3 e^{i\phi} E_{t,r}(t - \tau_3) + k_r E_t \end{aligned} \quad (1)$$

$$\frac{dN_{t,r}}{dt} = \frac{I_{t,r}}{e} - \frac{1}{\tau_e} N_{t,r} - \frac{g(N_{t,r} - N_0)}{1 + s|E_{t,r}|^2} |E_{t,r}|^2. \quad (2)$$

The subscripts t and r refer to transmitter and receiver lasers, respectively. The last term in (1) is present only in receiver laser and describes the unidirectional coupling

between transmitter and receiver. Parameter k_r is the coupling strength given by $k_r = \sqrt{1 - R}\eta_{ext}/(\tau_c\sqrt{R})$ where R is facet power reflectivity of the slave laser ($R = 30\%$), τ_c is the cavity roundtrip time of the light within the laser ($\tau_c = 10 \text{ ps}$), η_{ext} accounts for losses different than those introduced by the laser facet ($\eta_{ext} = 0.5$) resulting in $\kappa = 75 \text{ ns}^{-1}$; τ_1 , τ_2 , and τ_3 are the roundtrip delays; γ_1 , γ_2 and γ_3 are the feedback strengths governed by the reflectivities R_1 , R_2 , and R_3 , respectively. In the model we assume single reflexion in each cavity. $\varphi = \omega_0\tau_1$, $\psi = \omega_0\tau_2$, and $\phi = \omega_0\tau_3$ are the accumulated optical phases, which, without loss of generality, can be assumed to take values between 0 and 2π . The other parameter values are $\alpha = 4$ the linewidth enhancement factor, $g = 1.5 \times 10^{-8} \text{ ps}^{-1}$ the differential gain parameter, $s = 4 \times 10^{-7}$ the gain saturation coefficient, $\tau_{ph} = 2 \text{ ps}$ and $\tau_e = 2 \text{ ns}$ the photon and carrier lifetimes, respectively, and $N_0 = 1.5 \times 10^8$ the carrier number at transparency. These parameters, which are considered identical for both lasers, are used for the calculated results shown in all figures in the paper. The injection current is fixed at $I = 40 \text{ mA}$ ($I_{th} = 15 \text{ mA}$).

III. EXPERIMENTAL RESULTS

The air gap modules described in the previous section were extensively characterized experimentally as chaos generators and in terms of their synchronization properties. Back-to-back transmission experiments were also performed. In the following, we show the main results for a $5 \mu\text{m}$ -m air gap device. Similar results have been found for modules with different values of the gap in the range $2\text{--}10 \mu\text{m}$. Due to the influence of the multiple feedbacks, the laser behavior has been found to be chaotic for a large range of parameters and laser bias currents. By acting on the bias of the phase sections, the chaos amplitude and bandwidth could also be trimmed.

Fig. 2(a) shows the experimentally measured optical spectra as a function of the temperature. The trimmability of the emission wavelength ($0.2 \text{ nm}/^\circ\text{K}$) is typical of a DFB laser. The large width of the optical spectrum is characteristic of a chaotic behavior and decreases with temperature at constant bias current because the laser threshold has a positive temperature dependence. The optical spectra are also shown in Fig. 2(b) as a function of the laser bias current I .

The properties of the chaos generated by the air gap modules are more clearly visible in Fig. 3. Fig. 3(a) shows the RF spectrum for different laser bias currents. Chaos starts to develop just above threshold ($I_{th} = 18 \text{ mA}$) and the spectrum becomes to be wide and almost flat at a bias current of about $I = 2 I_{th}$ where its frequency span is over 7 GHz . A time series for $I = 40 \text{ mA}$ is shown in Fig. 3(b).

In view of secure transmission experiments, the synchronization properties of different pairs of devices were tested in a typical master-slave close-loop configuration [8]. It was found that selecting the devices based on their position on the wafer (i.e., selecting devices grown close to each other) was essential for achieving a good synchronization quality, highlighting the importance of the fabrication process and the device selection. However, to get the best results, a further selection based on threshold current and spectrum was also required.

Fig. 2. Optical spectra of 5- μ m air gap modules as (a) function of temperature, and (b) function of the laser supply current.

Fig. 3. (a) RF spectra as function of the laser supply current I with the phase sections unbiased, i.e., operating as open circuits, and (b) time series for $I = 40$ mA.

The synchronization quality was evaluated, as usual, by diagrams such as that in Fig. 4, where the master and master-slave difference RF spectra are compared. Master-slave cancellations from low frequency up to 7 GHz were observed in optimized conditions by accurately trimming the bias of the phase sections. It is interesting to observe that a different optimization of the bias values could offer a somehow better cancellation on the chaos peak (at 1.5 GHz), reducing, however, the frequency cancellation span. In the inset in Fig. 4, synchronized master and slave time series are also shown.

Finally, a couple of synchronized modules were tested for a back-to-back digital signal transmission. A pseudo-random

Fig. 4. Synchronization diagram for two unidirectionally coupled modules in a close loop master/slave configuration. The inset shows the synchronized time series of the master and slave lasers.

Fig. 5. Eye diagrams for (a) 1 Gb/s chaos masked NRZ pseudo-random encoded digital signal, and (b) signal decoded at the receiver output.

NRZ bit sequence at 1 Gb/s was applied to the master input by using an external amplitude modulator. Signal decoding was performed at the slave side by measuring the chaos cancellation. An efficient masking was achieved [see Fig. 5(a)] while getting a clearly readable decoded message [Fig. 5(b)]. By a proper trimming of the message amplitude, a relatively small BER ($\approx 10^{-4}$) for the decoded signal could be obtained at the system output while the BER of the masked signal was larger than 10^{-1} . In these experiments, a low-pass filter with a cut-off frequency close to the bit rate frequency (1 GHz) was used to improve the SNR and eliminate the high-frequency components of the chaos. It is worth mentioning that for a BER of 10^{-4} in the decoded message, suitable forward error correction methods yield error-free transmission.

Fig. 6. Pulse traces of (a) output power, and (b) power spectrum for $\gamma_1 = 20 \text{ ns}^{-1}$, $\gamma_2 = 10 \text{ ns}^{-1}$, $\gamma_3 = 15 \text{ ns}^{-1}$. $\psi_m = 0$, $\varphi_m = -\pi/2$, and $\phi_m = \pi/2$.

IV. NUMERICAL RESULTS

A. Transmitter Laser Dynamics

In this section we numerically analyze the proposed device. Both experiments and theoretical calculations demonstrate the presence of chaotic behaviors in the laser dynamics. For small enough feedback strengths the laser operates under CW or in a pulsating regime. Chaotic behavior appears for a large enough feedback strength. Fig. 6(a) and (b) illustrates the numerically obtained time traces and the power spectra of a semiconductor laser under the influence of multiple feedbacks for a 40 mA injection current. It can be observed that the multiple feedbacks induce a robust chaotic behavior. The calculation of the autocorrelation time using (3) and (4) [28] yields $T_C \approx 50 \text{ ps}$. These results corroborate the fact that multiple feedbacks render the laser behavior more complex compared with that of a single mirror [21], [26].

It is well known that the autocorrelation time is related to the complexity of the generated chaos. The shorter the correlation time is, the more chaotic and less predictable the dynamics are. Fig. 7 shows the calculated autocorrelation time for a laser under the influence of multiple feedbacks in the $(\phi - \varphi)$ plane and for a fix air gap phase. Darker regions correspond to the lower autocorrelation time. It can be clearly seen how the autocorrelation time changes and, in particular, how for specific phases the autocorrelation time becomes much shorter providing more secure conditions for chaos-based communications. The black point A shows the operating point for the pulse trace shown in Fig. 6.

We next examine the laser dynamics in terms of the bifurcation diagrams. Fig. 8 displays bifurcation diagrams of a

Fig. 7. Autocorrelation time as a function of the phases φ and ϕ for $\psi = 0$. Other parameters are $\gamma_1 = 20 \text{ ns}^{-1}$, $\gamma_2 = 10 \text{ ns}^{-1}$, $\gamma_3 = 15 \text{ ns}^{-1}$. Phases are varied in 0.05 radians steps.

Fig. 8. Bifurcation diagram of the output power as a function of: (a) feedback strength γ_3 for $\varphi = \pi/2$, $\phi = \pi/2$, $\psi = 0$, and $\gamma_1 = 20 \text{ ns}^{-1}$, $\gamma_2 = 10 \text{ ns}^{-1}$; (b) phase φ for $\phi = \pi/2$, $\psi = 0$, and $\gamma_1 = 20 \text{ ns}^{-1}$, $\gamma_2 = 10 \text{ ns}^{-1}$, $\gamma_3 = 15 \text{ ns}^{-1}$; and (c) phase ϕ for $\varphi = \pi/2$, $\psi = 0$, and $\gamma_1 = 20 \text{ ns}^{-1}$, $\gamma_2 = 10 \text{ ns}^{-1}$. Each dot represents a peak of the output power.

Fig. 9. Scheme of chaos modulation technique of message encoding and decoding.

semiconductor laser under the influence of multiple feedbacks, as a function of the feedback strength γ_3 and the different phases, acting as bifurcation parameters. For each value of the feedback strength, the figure displays the values of the maxima of the time traces of the emitted power. It is well known that, as the feedback strength is increased, a scenario compatible with quasiperiodic route to chaos emerges. As shown in Fig. 8(a), even for low values of the feedback strength γ_3 , the dynamics of the laser is already chaotic, due to the influence of the feedbacks γ_1 and γ_2 . It can be noticed from Fig. 8(b) that the fully developed chaotic dynamics is found for any value of the phase ϕ , except for few small windows of CW operation. On the other hand, fully developed chaotic dynamics is found for any value of the phase ϕ .

B. Synchronization and Message Transmission

So far we have discussed different aspects of the transmitter laser dynamics under the influence of multiple feedbacks. In what follows, we focus on the transmitter–receiver configuration, evaluate the synchronization properties and make use of these integrated devices for message encoding and decoding in chaos-based communications. In the chaos modulation technique the message is encoded as a small amplitude modulation of the emitted field of the master (see Fig. 9), so that the signal transmitted to the receiver is

$$E_T = E_t(1 + \zeta m(t)) \quad (3)$$

where $m(t)$ is the message, and ζ is the message amplitude. At the receiver system the message is decoded by making the difference between the input of the receiver with its output, which is ideally synchronized to the carrier, that is

$$m_{\text{decoded}} = \sqrt{P_T/P_S} - 1. \quad (4)$$

First we consider the synchronization quality as function of the feedback phases. Fig. 10 displays the value of the correlation function in the $(\varphi - \psi)$ parameter space for feedback strengths $\gamma_1 = 20 \text{ ns}^{-1}$, $\gamma_2 = 10 \text{ ns}^{-1}$, $\gamma_3 = 15 \text{ ns}^{-1}$ and for a coupling coefficient $\kappa = 75 \text{ ns}^{-1}$. It can be clearly seen that the region of high-correlation coefficients is wide, while regions of low correlation hardly appear. The black circle in Fig. 10 corresponds to the operating point that will be considered for message encoding and decoding in Fig. 11.

Fig. 11 illustrates the transmission of a 5 Gbit/s NRZ pseudorandom message. The system parameters correspond to the operation point shown as a white star in Fig. 10. The top panel shows the transmitted message. The other panels show the chaotic carrier before codifying the message and the transmitted signal (carrier with message). The fourth panel shows the message decoded following (4). Finally the decoded

Fig. 10. Cross-correlation coefficient as function of the feedback phases for $\gamma_1 = 20 \text{ ns}^{-1}$, $\gamma_2 = 10 \text{ ns}^{-1}$, $\gamma_3 = 15 \text{ ns}^{-1}$, and $\kappa = 75 \text{ ns}^{-1}$. High degree of synchronization is characterized by light grey level. Phases are varied in 0.05 radians steps. Other parameters are identical for the master and slave lasers.

Fig. 11. Numerical results of encoding and decoding of a 5 Gbit s⁻¹ digital message using chaos modulation technique for a closed loop scheme and identical parameters in the master and slave lasers. (a) Encoded message. (b) Output of the master laser without the message. (c) Transmitted signal (with message) (d) Decoded message. (e) Recovered message after filtering (solid line) and input message (dotted line). Other parameters are as in Fig. 10.

message can be smoothed by using an appropriate band-pass filter [6], leading to the recovered message shown in the bottom panel. As can be seen in the figure, the message is well recovered.

V. SUMMARY AND CONCLUSION

We have carried out experimental and numerical investigations of the dynamics of an integrated semiconductor laser under the influence of multiple feedback loops. The results presented in this paper show that under appropriate conditions

the laser is capable of generating a robust chaotic behavior appropriate for chaos-based communication purposes. Moreover, it has been shown that two matched devices can synchronize, in a master-slave configuration, when operating in a chaotic regime. Finally, we have shown that chaos modulation encryption can be successfully applied at a rate of few Gbit/s.

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Vasile Z. Tronciu received his first degree in physics from the State University of Moldova, Chisinau, Moldova, in 1990, and the Ph.D. degree in physical and mathematical sciences from the Institute of Applied Physics, Academy of Science, Chisinau, in 1995.

He is a Senior Scientific Researcher with the Technical University of Moldova, Chisinau. Recently, he was a Senior Research Associate with the Weierstrass Institute for Applied Analysis and Stochastics, Berlin, Germany, and previously with the Institute for Cross-Disciplinary Physics and Complex Systems, University of the Balearic Islands Palma de Mallorca, Palma, Spain. From 2001 to 2003 he was with the Japan Society for the Promotion of Science as a Post-Doctoral Fellow in the Department of Electrical and Electronic Engineering, Kanazawa University, Kanazawa, Japan. Before that he held a Royal Society/NATO Post-Doctoral Fellowship in Durham, U.K. From 1998 to 1999, he was an Alexander von Humboldt Foundation Post-Doctoral Fellow with the Photonics Group, Institute of Physics, Humboldt University, Berlin, Germany. During his research career, he has worked on a number of topics, including optical bistability, switching, self-pulsation, excitability, and chaos in various optical devices. In recent years, he has concentrated his attention on the phenomena of self-pulsation, excitability and synchronization in semiconductor lasers.

Claudio R. Mirasso was born in Buenos Aires, Argentina, in 1960. He received the M.Sc. and Ph.D. degrees in physics from the Universidad Nacional de La Plata, Buenos Aires, Argentina, in 1984 and 1989, respectively.

After several Post-Doctoral positions in Spain and the Netherlands, he became a member of the Physics Department, Universitat de les Illes Balears, Palma, Spain, in 1996. He is currently a Full Professor and Researcher with the Instituto de Física Interdisciplinar y Sistemas Complejos, Palma de Mallorca, Spain. He has authored or co-authored over 140 publications including about 110 journal papers. His current research interests include instabilities in semiconductor lasers, synchronization, and control of chaotic semiconductor

lasers, dynamics and applications of delayed coupled semiconductor lasers, and applications of nonlinear dynamics.

Pere Colet was born in Vilafranca del Penedés, Barcelona, Spain, on April 21, 1964. He received the M.S. degree in physics from the Universitat de Barcelona, Barcelona, Spain, in 1987, and the Ph.D. degree in physics from the Universitat de les Illes Balears, Palma de Mallorca, Spain, in 1991.

In 1991, he became a Teaching Assistant with the Departament de Física, Universitat de les Illes Balears. From 1991 to 1993, and in 1994, he was a Post-Doctoral Fulbright Fellow with the School of Physics, Georgia Institute of Technology, Atlanta. In 1994, he was with the Departament de Física, Universitat de les Illes Balears. Since 1995, he has had a permanent research position with the Spanish Consejo Superior de Investigaciones Científicas. He is currently a Research Professor with the Instituto de Física Interdisciplinar y Sistemas Complejos, Palma de Mallorca. He has co-authored over 95 papers in international journals as well as 30 other scientific publications. His current research interests include fluctuations and nonlinear dynamics of semiconductor lasers, synchronization of chaotic lasers and encoded communications, synchronization of coupled nonlinear oscillators, pattern formation, and quantum fluctuations in nonlinear optical cavities and dynamics of dissipative solitons.

Valerio Annovazzi-Lodi (M'89–SM'99) was born in Novara, Italy, on November 7, 1955. He received his degree in electronic engineering from the University of Pavia, Pavia, Italy, in 1979.

Since then, he has been with the Dipartimento di Elettronica, University of Pavia, in the fields of electronics and electro-optics. In 1983, he was a Staff Researcher with the Department of Electronics, University of Pavia. In 1992, he became an Associate Professor, and in 2001, a Full Professor of the same institution. His current research interests include injection phenomena and chaos in oscillators and lasers, cryptography, optical sensors, passive fiber components for telecommunications and sensing, optical amplifiers, transmission via diffused infrared radiation, and micromechanical systems. He is the author of more than 100 papers and holds four patents.

Dr. Annovazzi-Lodi is a member of Associazione Elettrotecnica ed Elettronica Italiana.

Mauro Benedetti (M'05) was born in Pontevico, Italy, in 1975. He received his first degree in microelectronics engineering and the Ph.D. degree in electronics engineering from the University of Pavia, Pavia, Italy, in 2002 and 2006, respectively.

He is currently a Post-Doctoral Researcher with the Optoelectronics Group, Dipartimento di Elettronica, University of Pavia. His current research interests include nonlinear dynamics in optically injected semiconductor lasers, with regard in particular to optical chaos synchronization and cryptography in fiber-optic communications, characterization of MEMS/MOEMS devices, and photonic crystals.

Michael Hamacher was born in 1962. He received the Dipl.Ing. degree from the Nat.-Techn. Akademie, Isny, in 1988.

He has been with the Fraunhofer Institute for Telecommunications, Heinrich-Hertz-Institute, Berlin, Germany, since 1988. Since then, he has taken an active role in the development, fabrication, and characterization of optoelectronic/photonic integrated circuits on InP with different functionalities (e.g., polarization insensitive heterodyne receiver, balanced receivers, bidirectional 1.5/1.3 μm transceivers, ring lasers, chaos emitters) for future optical communication systems. At the moment his main focus is on the development of fast Mach-Zehnder modulators with 3 dB bandwidth beyond 50 GHz as key components for metro and long haul fibre networks. He has authored and co-authored more than 80 publications.

Valeria Vercesi was born in Pavia, Italy, in 1983. She received the B.S. degree in electronics and telecommunications engineering, and the M.S. degree in electronic engineering from the University of Pavia, Pavia, in 2006 and 2008, respectively. Since 2008, she has been pursuing the Ph.D. degree from the Optoelectronics Group, Dipartimento di Elettronica in the same University.

Her scientific activity concerns optical cryptography, and, in particular, characterization of semiconductor lasers, synchronization of chaotic sources and experiments of message-encoded transmission.

Ms. Vercesi was the recipient of a grant from the European PICASSO Project in 2008.