A photonic brain

Professors Ingo Fischer and **Claudio Mirasso** discuss the challenges and opportunities of their cross-disciplinary research into photonic systems and their endeavours to create a photonic brain

Could you outline your academic backgrounds and explain how they have helped in your current roles?

IF: I am a physicist by training. Initially, I worked in experimental semiconductor physics, laser physics and nonlinear dynamics of semiconductor lasers. Later, my interests broadened towards neuroscience and information processing. I have held positions in Marburg and Darmstadt in Germany, then in Kyoto in Japan, Brussels in Belgium, and as a professor in Edinburgh, UK. I now work in Palma de Mallorca, Spain. I have always worked in environments where interdisciplinary and cross-disciplinary approaches to science were encouraged. It is at the interfaces of the aforementioned areas that I find the most fascinating scientific questions and novel applications.

CM: I received my PhD in Physics from the University of La Plata, Argentina. Since 1990, when I arrived at Palma de Mallorca as a postdoctoral researcher, I have worked from a theoretical point of view on the dynamical properties of semiconductor lasers. I have spent time at the University of Cantabria and the Instituto de Estructura de la Materia, both in Spain, and the Vrije Universiteit Amsterdam, The Netherlands. In 1996, I became Associate Professor at the University of the Balearic Islands, Spain, and then Full Professor in 2009. Since 2004, I have been researching the computational aspects of brain circuits, studying the cross-fertilisation between neuroscience, photonics and information processing.

What are the main aims of the Institute for Cross-Disciplinary Physics and Complex Systems (IFISC)? Can you describe the special focus of the Institute and list your collaborative partners?

CM&IF: IFISC aims to develop interdisciplinary and strategic research in emerging areas beyond the traditional subjects of physics, while using a physics approach. We work with various strategic partners, from neuroscientists, engineers, climate researchers and biologists to airport controllers, internet companies, photonics industries and even city councils. Our partners are mostly based in Europe, but we also work with colleagues from the Americas, Japan and Australia.

What is the biggest challenge you have faced in the course of implementing photonic reservoir computing and how did you overcome it?

IF: The biggest challenge for a photonics implementation was discovering how to implement a sufficiently complex network with photonics components. Despite the advantages of photonic systems, integrated photonic systems are not yet at the level of integration that is standard for electronics. Our approach was to question the minimum hardware requirements for such a system to work. We ended up with a radically simplified reservoir, a single nonlinear node and a delayed feedback implemented by a standard optical fibre. To our surprise, even the simplest configuration shows outstanding performance and opens an enormous amount of possibilities for the future.

You have been active in organising and speaking at international conferences and interdisciplinary meetings. How important are these activities to your roles?

IF&CM: Bringing together and addressing the right audience is key, particularly in our interdisciplinary field of science. We are planning to speak at several events this year, including conferences on statistical physics, complex systems and photonics meetings, as well as at neuroscience institutes. We aim to raise awareness of the opportunities in our interdisciplinary approach and find collaborators for the further development of this field.

How has your research been received, and what future developments do you expect to see?

CM: Recently, other groups have shown an increasing interest in our approach and are launching new studies along these lines. In fact, there are a couple of initiatives in the USA that are also looking for support to research optical reservoir computing. However, it is a young field and there is a need for more funding opportunities.

IF: At first, it was difficult to raise interest for our new, interdisciplinary approach and to get it published. Even finding referees willing to review our work was a challenge; however, we receive a lot of recognition and interest from all over the world and from different fields of research. At the moment, we are seeing a scientific field emerging with many different branches, exploring the opportunities that arise from our approach. We believe that photonics-based brain-inspired computers – a sort of 'photonic brain' – could be developed in the future.

Neuro-inspired photonics

A interdisciplinary group of international researchers at the **Institute for Cross-Disciplinary Physics and Complex Systems**, based in the **University of the Balearic Islands**, Spain, is collaborating to forge a deeper understanding of nonlinear laser networks and neural-based information processing systems

IN A WORLD that is dependent on computers, there is a growing demand for fast data processing and transmission. While fibre-optic data transmission has revolutionised modern communication systems, computers are still almost exclusively reliant on electronic systems. Optical information processing represents an enormous challenge, demanding the handling and processing of huge amounts of data. While there have been advances in this field over the past few years, there are still significant challenges to confront and an urgent need for new and innovative approaches.

The Institute for Cross-Disciplinary Physics and Complex Systems (IFISC), a joint centre between the University of the Balearic Islands and the Spanish National Research Council (CSIC), hosts an international group of researchers who are combining their skills to investigate complex systems. One of the Institute's foci is nonlinear photonics. Drawing on methodologies from dynamical systems, computational methods, statistical physics, experimental techniques, information science and quantum mechanics, its cutting-edge research moves beyond the bounds of traditional physics. Professors Ingo Fischer and Claudio Mirasso are two prominent researchers based at the Institute; physicists by training, they are passionate about working with scientists from different backgrounds to discover new approaches to scientific problems, such as neuro-inspired photonic computing.

STRONGER TOGETHER

The IFISC is particularly well placed for photonics research and has made great strides in this area. In addition to several scientists who are experts in this field, other colleagues specialise in complex systems, neuronal systems, quantum optics and information science. Together, they are working to provide fascinating insights into photonics at the interface of their different disciplines.

The launch of the Institute's Nonlinear Photonics Laboratory in 2009 has further advanced its strategic research in this field: "This environment encourages us to address photonics from an unusual angle by studying uncommon photonics systems, such as nonlinear optical networks, and to aspire to design applications such as neuro-inspired photonic information processing and chaos-based encryption," explains Fischer.

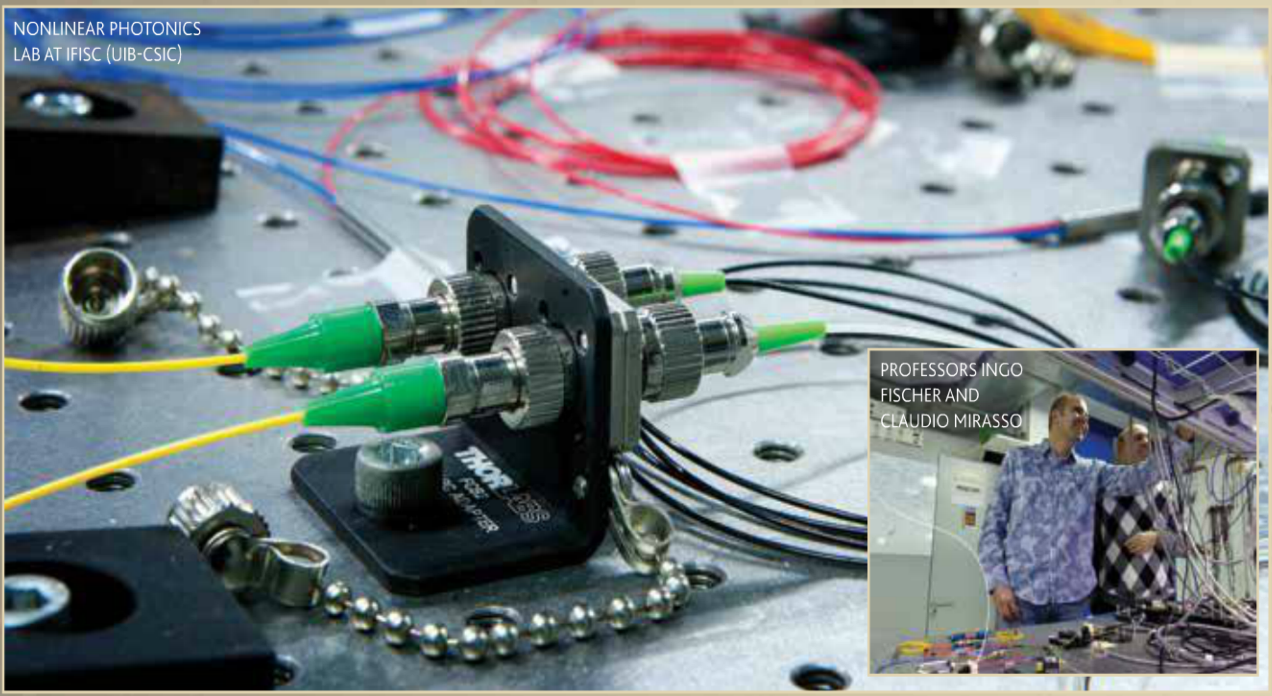
A PIONEERING PROJECT

Coordinated by Mirasso, an innovative project 'Towards a PHOtonic liquid state machine based on delay-CoUpled Systems' (PHOCUS) ran between January 2010 and December 2012. The project was funded by the EU's Seventh Framework Programme (FP7), and brought together seven research groups from four European countries to explore the concept of photonic information processing. Mirasso and Fischer were the principal investigators of two of the groups: "Our aim was to explore whether it would be possible to translate ideas from neuroscience and machine learning to mimic information processing in the brain and to implement them in photonics with all their fascinating capabilities," Mirasso explains.

With each member of the consortium playing a key role in achieving the project's goals, the IFISC developed and then tested the concept of all-optical photonic information processing. This involved delving into one of the most significant unresolved questions in brain research: how the electrical discharge of billions of neurons is able to deliver correct answers so quickly. For example, recognising a familiar face in a large crowd of people is a hugely complex task for the brain, yet it can take a human as little as a fraction of a second to do this. One recent neuro-inspired model, named reservoir computing, is helping to shed light on this mystery. In this approach, the brain's response to external stimuli is compared to the response of liquid to external perturbations such as a pebble being thrown into water. The temporary, or transient, ripples generated by the impact make it possible to surmise when and where the pebble hit the surface, suggesting it could also be possible to glean information about external stimuli from the fleeting responses of neural networks.

RESERVOIR COMPUTING

Traditional reservoir computing is based on computation performed using complex


NONLINEAR PHOTONICS LAB AT IFISC (UIB-CSIC)

PROFESSORS INGO FISCHER AND CLAUDIO MIRASSO

PHOTONICS AT IFISC

OBJECTIVES

The Institute for Cross-Disciplinary Physics and Complex Systems (IFISC), led by Professor M San Miguel, aims to develop interdisciplinary and strategic research in emerging areas beyond the traditional subjects of physics, while using a physics approach. In the area of photonics, IFISC works with strategic partners from different areas, including mathematicians, engineers, neuroscientists and photonics industries

KEY COLLABORATORS

Professor Laurent Larger, University of Franche-Comté, Besançon, France • **Professor Luis Pesquera**, University of Cantabria, Spain • **Professor Jan Danckaert**, Vrije Universiteit Brussels, Belgium • **Professor Eckehard Schöll**, Technical University of Berlin, Germany • **Professor Jordi Garcia-Ojalvo**, Pompeu Fabra University, Spain • **Professor Gordon Pipa**, University of Osnabrück, Germany

FUNDING

TRIPHOP, Plan Nacional de I+D+i (TEC2012-36335), Spain

Intense@cosyp Plan Nacional de I+D+i (FIS2012-30634), Spain

CONTACT

Professor Ingo Fischer

IFISC (UIB-CSIC)
University of the Balearic Islands
E-07122 Palma de Mallorca, Spain

T +34 971 25 98 78
E ingo@ifisc.uib-csic.es

Professor Claudio Mirasso

T +34 971 17 27 83
E claudio@ifisc.uib-csic.es

ifisc.uib-csic.es/

INGO FISCHER has worked in laser physics, nonlinear dynamics of semiconductor lasers, nonlinear photonics and complex systems. More recently, his interests include neuroscience and information processing. Fischer is focusing on the cross-fertilisation between these fields and looking for resulting applications. He is currently Professor of the Spanish National Research Council (CSIC) in Palma de Mallorca, Spain.

CLAUDIO MIRASSO received his PhD in Physics from the University of La Plata, Argentina. Since 1990, he has been working on the dynamical properties of semiconductor lasers. Since 2004, Mirasso has been working in computational aspects of brain circuits. He is currently Full Professor at the University of the Balearic Islands, Spain.

Instituto de Física Interdisciplinar y Sistemas Complejos

recurrent networks (the reservoir) with some inherent memory, fed by information input. The input induces a multitude of transient responses in the network. Remarkably, the conversion into these many responses makes it much easier to process the input streams and, in turn, to classify them. Classification is achieved by summing up the states of the network's nodes with specific weights, which are obtained by a learning procedure. Once the network has been trained, new inputs of the same kind can be computed.

The PHOCUS project was aimed at drastically simplifying the reservoir computing concept such that hardware implementations would become feasible. Using photonic systems with delayed feedback (and in particular semiconductor lasers), the PHOCUS consortium implemented a novel approach: realising the reservoir with one or a few photonic components. This method turned out to be extremely successful. Even in computationally difficult tasks such as speech recognition, the photonic information processing system performed with unprecedented speed and relatively low power consumption: "This approach bears a lot of potential for future information processing systems in a large number of fields such as optical communications, sensing and medical diagnosis," enthuses Fischer.

FAR-REACHING FINDINGS

With the PHOCUS project highlighting the potential capabilities of delay-coupled systems for photonic information processing, Fischer and Mirasso proceeded with their exploration of the potentials of this novel approach. Along with two colleagues – Drs Daniel Brunner and Miguel Soriano – they wrote an article on parallel photonic information processing at gigabyte-per-second data rates using transient states. Published in *Nature Communications* in January 2013, the article outlined an important experiment that showed the exciting potential of simple photonic architecture capable of processing information at unprecedented rates through a learning-based approach. Significantly, their approach connects photonic information processing with cognitive and information science, opening up a completely new field of opportunities for future research.

Fischer has also collaborated with Brunner and Soriano on a second article exploring the use of induced transient dynamics of telecommunication lasers performing optical computation at high data rates. Published in *IEEE Photonics Technology Letters* in September 2013, the article outlines the success of their experimental research into high-speed algebraic vector and matrix operations, using off-the-shelf telecommunication components. The researchers believe that the physical implementation of their innovative concept could lead to increased opportunities for high-speed, all-optical information processing systems based on machine learning techniques.

FUTURE DIRECTIONS

Upcoming research at the IFISC is dependent on securing funding for the different projects, and in view of its new and unorthodox field of study, this can be challenging. Yet, looking ahead, the researchers at the IFISC are eager to continue investigating the enormous potential of complex photonic systems. They particularly want to explore the neuro-inspired information processing approach in relation to different photonic, electronic and hybrid systems, to find out where their concept can be applied and which novel applications may be implemented. They are also keen to apply their reservoir computing approach to other research fields, such as biomedical applications. Working between disciplines with ingenuity and expertise, the researchers at the IFISC are eager to continue bringing new insights into the potential of processing systems.

Master's degree in Physics of Complex Systems

- **Duration:** 1 academic year (60 ECTS)
- **Language:** English
- **Required Qualification:** BSc, preferably in Natural Sciences, Mathematics or Engineering
- **Mobility:** Fellowships available

The aim of this Master's programme is to prepare the next generation of professionals and researchers to apply knowledge and methodologies from statistical physics and nonlinear dynamics in order to analyse, model, simulate, characterise and implement complex systems. Complex phenomena from social and brain dynamics, evolution, ecology and ocean transport as well as photonics, nanoscience, quantum optics and information science will be covered.

Visit **www.ifisc.uib-csic.es/master** for more information.