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Photonics Research Labs (PRL) Annual Research Report 2016/2017

Prof. Dr. Dr. José Capmany
Group Leader – Photonics Research Labs

The Photonics Research Labs (PRL) are currently formed by more than 30 telecom engineers and physicists. The PRL mission is to produce high-quality scientific knowledge in the field of optics, quantum optics and photonics, through research projects, R&D contracts and collaboration agreements with the private sector. The PRL research activity is focused on several applications of photonics, mainly on optical communications of analog and digital signals, radio-over-fiber systems and photonic integrated circuits. Part of the research is also performed in the field of fiber optic sensor and industrial photonics. Among others, PRL has been granted two Excellent Projects by the European Research Council (ERC).

MAIN ACTIVITIES

Microwave Photonics

Among the most productive research lines, PRL is considered a world-leading group in Microwave Photonics (MWP), principally due to its contributions to the field of microwave photonic signal processing, a fundamental technology for the convergence of fixed and wireless telecommunication networks. The research is focused in tunable and reconfigurable microwave filters based in fibre gratings and delay lines for the processing of radiofrequency, microwave and milimetric signals, directly in the optical domain, remote antenna array feeders by means of optical delay lines (beamforming and beam stearing), signal processing and distribution over space-division multiplexing (SDM) optical fibers, Slow and Fast Light (SFL) effects applied to Microwave Photonics. Implementation of tunable broadband microwave phase shifting and true time delay functionalities by means of different SFL technologies as Coherent Population Oscillations in Semiconductor Optical Amplifiers and stimulated Brillouin scattering in optical fibers, RADAR and Ultra Wide Band (UWB) applications and Optical Frequency Division Multiplexing (OFDM) techniques. Recently, we explore the combination of MWP and Low Coherence Interferometry (LCI) for applications such as medical imagen, components characterization or sensing.

Photonic integrated circuits

Design of integrated photonic devices for multiple applications (optical telecom, optical signal processing, sensing, biophotonics): Silica or PLC (SiO_2), Silicon-on-Insulator (SOI), Silicon Nitride (Si_3N_4), active devices in InP.

Cryptography and quantum information

The research line is focused on the applications of Quantum Mechanic principles to information processing in optical telecommunication systems (Entanglement, Quantum state teleportation and Encryption).

Fibre Bragg Gratings

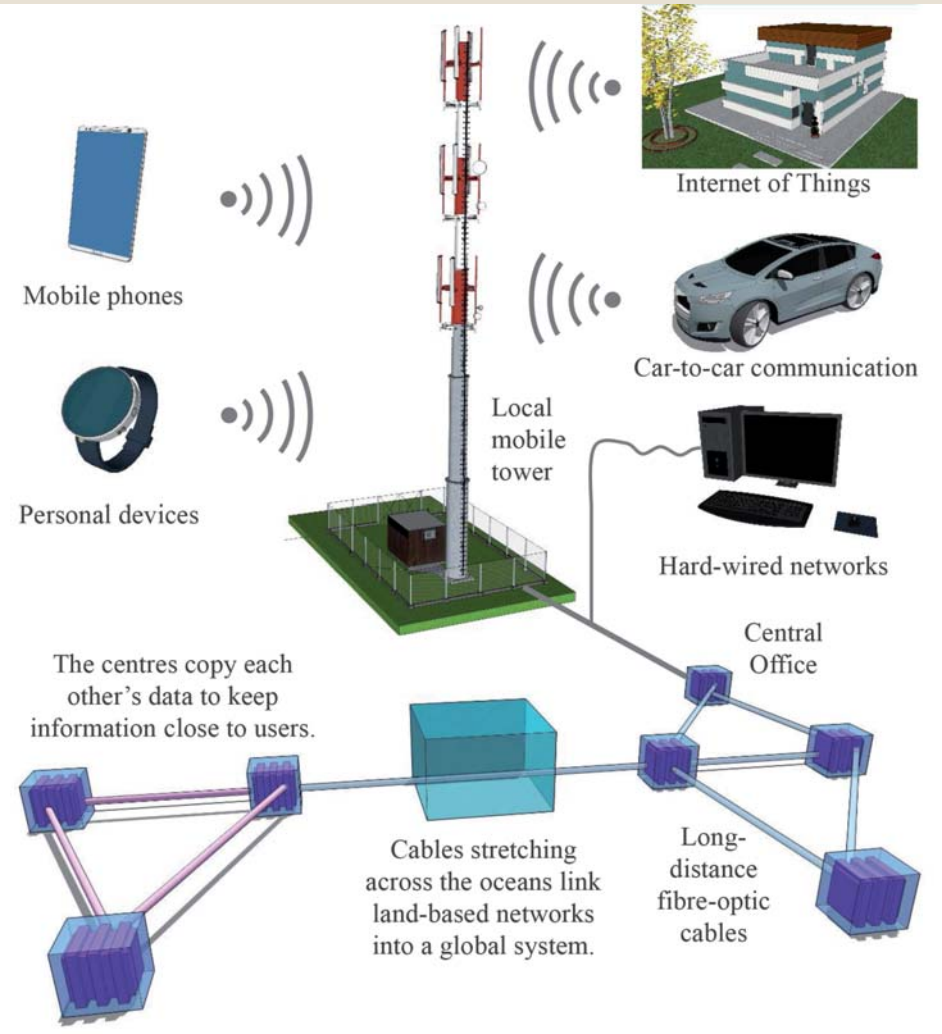
Design and fabrication of Fibre Bragg Gratings for communication networks (Dispersion compensation and optical filters) and Sensing applications (high temperature, stress, pressure, chemical).

Optical Networks

Optical links conform a large part of the current global communication network, and the trend is growing with the latest. deployments of Fiber-to-the-Home, (FTTH) networks and fiber backhauling of mobile and radio networks. With this background, the PRL develops it's research in the following lines: Architectures in optical path switching networks, Architectures in optical packets switching networks, Photonic systems based on code division multiplexing for access networks and Reconfiguration in access and in-building networks, Optical processing of signals in Broadband Networks and Access Networks. Also, Advanced modulation formats, such as OFDM in optical networks, are being deeply theoretically and experimentally explored in different configurations in order to optimize the design paremeters to maximize the networks performance.

OFDM-based Optical Communications Systems

The use of the OFDM modulation in optical communication has attracted a high interest in recent years thanks to the possibility of simple equalization with moderate implementation complexity using digital signal processing techniques. The objectives of this research line are: development of algorithms for direct detection optical OFDM, analysis and evaluation of nonlinear optical effects in optical OFDM, implementation of a real-time demonstrator using high speed data converters.



ERC Advanced Grant – UMWP-Chip.
Universal microwave photonics programmable processor for seamlessly interfacing wireless and optical ICT systems.

FLAGSHIP PROJECTS

ERC Advanced Grant awarded to Prof. José Capmany – UMWP-Chip: Universal microwave photonics programmable processor for seamlessly interfacing wireless and optical ICT systems.

ERC Consolidator Grant awarded to Dr. Ivana Gasulla – InnoSpace: Revolutionizing fibre-wireless communications through space-division multiplexed photonics.

RESEARCH HIGHLIGHTS

1. I. Gasulla, D. Barrera, J. Hervás and S. Sales, "Spatial Division Multiplexed Microwave Signal processing by selective grating inscription in homogeneous multicore fibers," **Scientific Reports**, 7, 41727 (2017)

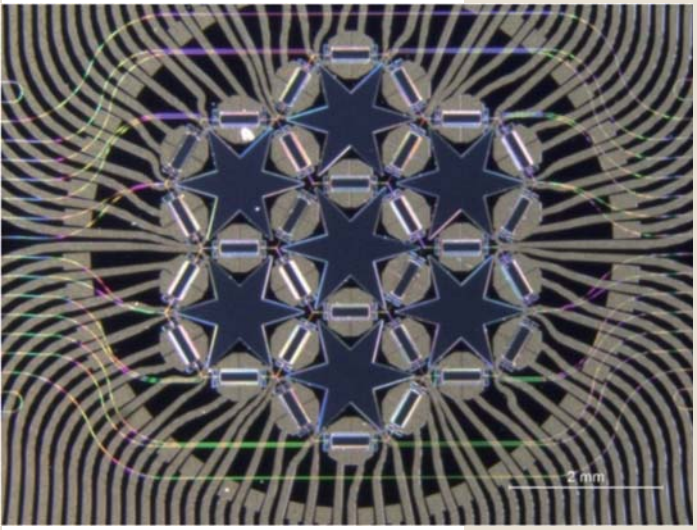
2. J. S. Fandiño, P. Muñoz, D. Doménech and J. Capmany, "A monolithic integrated photonic microwave filter, " **Nature Photonics** 11, 124–129 (2017)

3. J. Wang, R. Ashrafi, R. Adams, I. Glesk, I. Gasulla, J. Capmany and L. R. Chen, "Subwavelength grating enabled on-chip ultra-compact optical true time delay line," **Scientific Reports**, 6, 30235 (2016)

4. C. Abellan, W. Amaya, D. Domenech, P. Muñoz, J. Capmany, S. Longhi, M. W. Mitchell, and V. Pruneri, "Quantum entropy source on an InP photonic integrated circuit for random number generation," **Optica** 3, 989-994 (2016).

5. G. Muñoz-Matutano, D. Barrera, C.R. Fernández-Pousa, R. Chulia-Jordan, L. Seravalli, G. Trevisi, P. Frigeri, S. Sales, and J.P. Martínez-Pastor, "All-Optical Fiber Hanbury Brown & Twiss Interferometer to study 1300 nm single photon emission of a metamorphic InAs Quantum Dot", **Scientific Reports**, 6, 27214 (2016),

6. J. Capmany, I. Gasulla and D. Pérez, "Microwave photonics: The programmable processor," **Nature Photonics**, 10, pp.6-8 (2016).



Reconfigurable photonic integrated processor.

7. F.I. Chicharro, B. Ortega, M. de Diego, J. Mora, "OOFDM signal transmission using a single optical broadband source", **IEEE Photonics Technology Letters**, vol. 29, pp. 563-566 (2017).

8. D. Sáez-Rodriguez; R.Min, B.Ortega, K.Nielsen and D.J. Webb, "Passive and Portable Polymer Optical Fiber Cleaver" **IEEE Photonics Technology Letters**, vol. 28, pp. 2834-2837 (2016).

9. A. Triana, D. Pastor and M. Varón, "Code Division Multiplexing Applied to FBG Sensing Networks: FBG Sensors Designed as Discrete Prolate Spheroidal Sequences (DPSS-FBG Sensors)," in **Journal of Lightwave Technology**, vol. 35, no. 14, pp. 2880-2886, July15, 15 2017.

10. C. Triana, D. Pastor, and M. Varón, "Enhancing the Multiplexing Capabilities of Sensing Networks Using Spectrally Encoded Fiber Bragg Grating Sensors," **J. Lightwave Technol**. 34, 4466-4472 (2016).

11. J. Benítez, M. Bolea, and J. Mora, "Demonstration of multiplexed sensor system combining low coherence interferometry and microwave photonics," **Optics Express** 25, 12182-12187 (2017).

SPIN-OFF COMPANIES

VLC Photonics (2011)

VLC's mission is to provide engineering solutions that allow our customers to harness the benefits of photonic integration, as well as to build up on our providers technologies. The mission spans from the initial work of drafting high-level optical system architectures to the final part of specifying its deepest technical details, all the while under a customized approach to the specific application domain at hand.

VLC Photonics aims at being a fundamental global actor of the complex and evolving photonic integration ecosystem, contributing to the development of synergies among different international players, and to the expansion of photonic integration technologies and the growth of their markets.

CalSENS (2013)

Cálculo y Estructuras Sensadas, CALSENS SL, offers services of monitoring of processes and structures, of advice in the evaluation of its security and of decision making to guarantee its correct operation. It was born from the union of telecommunications engineering professionals and of roads, channels and ports that collaborate since 2004 in photonic technology research projects applied to the monitoring of processes and structures.

At present CALSENS has a multidisciplinary team with a high degree of experience in R & D projects and technology transfer in the fields of civil engineering, photonic technologies, signal processing, materials engineering or computing. This allows us to offer the customer an optimal solution adapted to their needs in the fields of civil engineering, aerospace, transportation and energy.

ePHOOX Technologies (2016)

EPHOOX Technology S.L. has the objective of introducing innovative products on the market basing all of its activity on the principle of excellence as a guarantee of an added value. In particular, EPHOOX adapts and develops solutions based on Microwave Photonics technology for specific environments such as 5G, taking into consideration its emerging deployment. Its main focus is the design and manufacture of advanced instrumentation for characterization and monitorization of photonic devices and hybrid RoF systems.

EPHOOX has developed the OVNA-P100X to measure both passive and active photonic, opto-electronic and electro-optic devices by means of a complete combined solution composed of a radiofrequency (RF) Vector Network Analyzer (VNA) and an advanced photonic module. This module is compatible with any RF VNA in the market.

DETAILED ACTIVITIES

A complete list of research activities can be found at http://www.iteam.upv.es/area/photonics.html

1.- Project activities

1.1.- Ongoing projects

ERC Advanced Grant: Universal microwave photonics programmable processor for seamlessly interfacing wireless and optical ICT systems (UMWP-Chip)

IP: José Capmany Francoy

2017 - 2022. European Funding - European Research Council (ERC)

Summary: Information and communication technology (ICT) systems are expanding at an awesome pace in terms of capacity demand, number of connected end-users and required infrastructure. To cope with these rapidly increasing growth rates there is a need for a flexible, scalable and future-proof solution for seamlessly interfacing the wireless and photonic segments of communication networks. RF or Microwave photonics (MWP), is the best positioned technology to provide the required flexible, adaptive and future-proof physical layer with unrivalled characteristics. Its widespread use is however limited by the high-cost, non-compact and heavy nature of its systems. Integrated Microwave Photonics (IMWP) targets the incorporation of MWP functionalities in photonic chips to obtain cost-effective and reduced space, weight and power consumption systems. IMWP has demonstrated some functionalities in through application specific photonic circuits (ASPICs), yielding almost as many technologies as applications and preventing cost-effective industrial manufacturing processes. A radically different approach is based on a universal or general-purpose programmable photonic integrated circuit (PIC) capable of performing with the same hardware architecture the main required functionalities. The aim of this project is the design, implementation and validation of such a processor based on the novel concept of photonic waveguide mesh optical core and its integration in a Silicon Photonics chip.

ERC Consolidator Grant: Revolutionizing fibre-wireless communications through space-division multiplexed photonics (InnoSpace)

IP: Ivana Gasulla Mestre

2017 - 2022. European Funding - European Research Council (ERC)

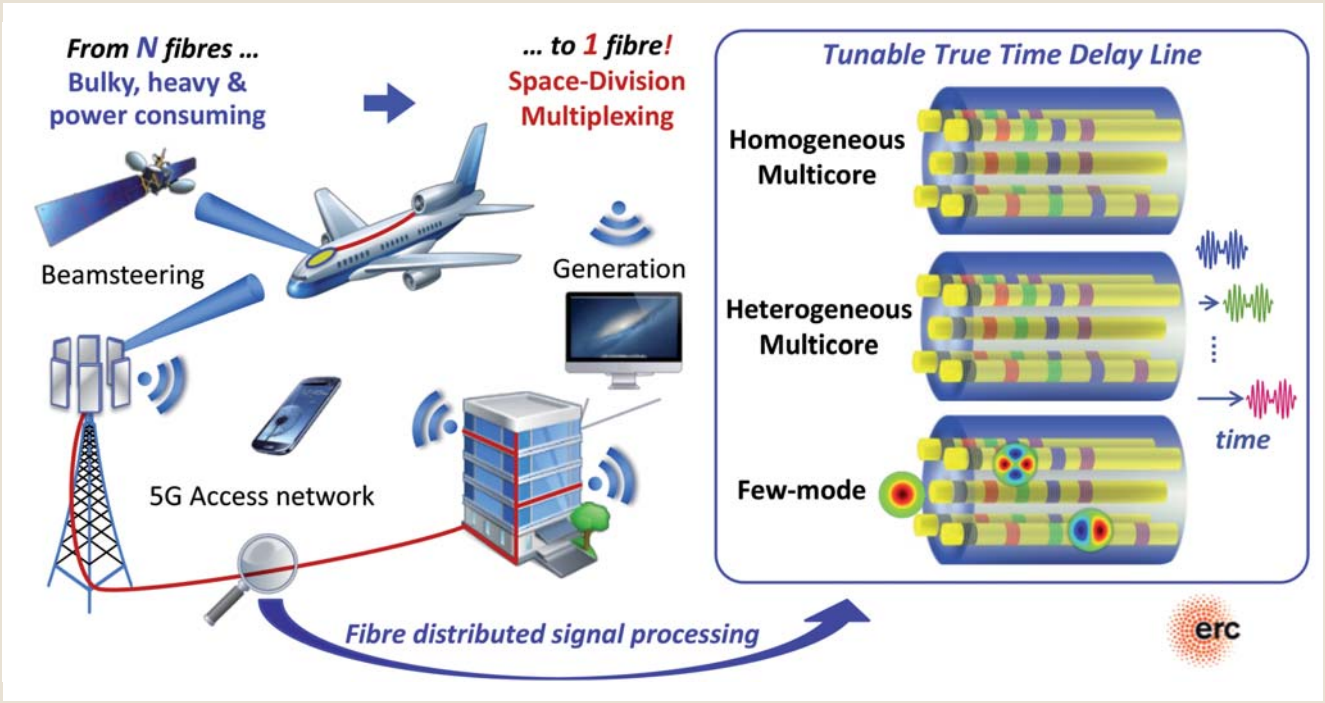
Summary: InnoSpace aims to revolutionize next generation fibre-wireless communications by pioneering the use of the photonic Space dimension. Emerging communications paradigms with massive penetration, such as 5G systems and Internet of Things, will require new technologies to address the current limitations on massive capacity, connectivity and flexibility. The key will lie in a full integration between the optical fiber network and the wireless network segments. The present fiber-wireless landscape is characterized, first, by radio-over-fiber distribution architectures that are static and inefficient, (with a replication of bundles of optical fibers) and, second, by radiofrequency signal processing systems, such as antenna beamsteering or signal generation, which are nowadays bulky, heavy and power consuming. To overcome these limitations, we propose the application of Space-Division multiplexing, which are currently restricted to long-haul digital communications, to fiber-wireless scenarios. The goal of InnoSpace is to provide "simultaneously" in a single optical fiber, a compact approach for both distribution and processing functionalities. This leads to the novel concept of "fiber distributed signal processing". Most of these signal processing applications rely on a key optical component: the true time delay line. We propose to exploit the inherent parallelism of space-division multiplexing fibers to implement a compact true time delay line with more versatility, and flexibility.

H2020 BlueSPACE: Building on the Use of Spatial Multiplexing 5G Networks Infrastructures and Showcasing Advanced technologies and Networking Capabilities

IP: Salvador Sales Maicas

2017 - 2020. European Funding – H2020

Summary: The core concept of BLUESPACE is to exploit the added value of Spatial Division Multiplexing (SDM) in the Radio Access Network (RAN) with efficient optical beamforming interface for the pragmatic Ka-band wireless transmission band. Both being seamlessly integrable in next generation optical access networks infrastructures with massive beam steering capabilities and with flexible network management control. The main objectives targeted by the BLUESPACE project are BlueSpace are: to develop a truly viable and efficient path for 5G wireless communications with a 1000-fold increase in capacity, connectivity for over 1 billion users, strict latency control, and network software programming. BlueSPACE targets a disruptive yet pragmatic approach for the deployment of scalable, reconfigurable and future-proof fronthaul solutions for 5G communications, offering unrivalled characteristics that include: a) increased bandwidth provision by naturally enabling and supporting massive multiple Input Multiple Output (MIMO) transmission starting/ending in the fiber medium by enabling space diversity in the RF domain by supporting RF beam steering in the photonic domain, b) compact infrastructure that is reconfigurable by means of Software Defined (SDN) and Network Function Virtualization (NFV) paradigms and c) the possibility of providing full integration with other existing approaches for the implementation of access networks, such as Passive Optical Networks (PONs). This approach relies on the core concept of this project, which is the introduction of Spatial Division Multiplexing (SDM) in the fronthaul of the mobile access network.



ERC Consolidator Grant INNOSPACE granted to Ivana Gasulla: Revolutionizing fibre-wireless communications through space-division multiplexed photonics.

Fibre Nervous Sensing Systems (MSCA-ITN-2016-ETN)

IP: Salvador Sales Maicas

2016 - 2020. European Funding - European Commission

Summary: : FINESSE (FIbre NErvous Sensing SystEms) is a collaborative research and training network, gathering together 26 European universities, research centers and industrial partners with complementary expertise with the ultimate vision of a widespread implementation of distributed optical fibre sensor systems for a safer society. The objective behind FINESSE (FIbre NErvous Sensing SystEms) is to mimic the nervous system of living bodies by turning man-made and natural structures into objects that are sensitive to external stimuli owing to advanced distributed fibre-optic sensor technology, with the objective to either give early warning in case of possible danger or occurrence of damage, or to optimise the operation of the structure to allow for a sustainable use of natural resources and assets. Enabling such functionalities will greatly contribute to realizing a safe, secure and energy efficient Europe, which is an identified societal concern.

Website: http://itn-finesse.eu/

Photonic integrated circuits accessible to everyone

IP: Pascual Muñoz Muñoz

2016 - 2019. Public Funding - European Commission

Summary: The aim of the PICs4All CSA is to establish a European network of Application Support Centres (ASC's) in the field of Photonic Integrated Circuits (PICs) technology. The main task of these ASC's is to lower the barrier to Researchers and SMEs for applying advanced Photonic IC technology, in particular InP and TriPleX based, and thus to increase the awareness of the existence of this worldwide unique facility. This will be done by actively scouting new application opportunities throughout Europe, helping the candidates to determine the technical and/or economic viability when applying integrated optical solutions and supporting them in the design, manufacturing and evaluation phase of their Application Specific Photonic IC's (ASPICs).

Website: http://pics4all.jeppix.eu/

Photonic IC lab open access grant (PTA2015-11309-I)

IP: Pascual Muñoz Muñoz

2017 - 2019. Public Funding - Ministerio de Economía y Competitividad

Summary: The project aims at establishing the access mechanisms to the photonic integrated circuit characterization facilities of the Photonic Research Labs.

Desarrollo de sistemas de caracterizacion y monitorizacion basados en fotonica de microondas de aplicacion en el mercado emergente de redes 5G (CARACTER) (RTC-2016-5343-7)

IP: José Mora Almerich

2017 - 2019. Public Funding - Ministerio de Economía y Competitividad

Summary: The main objective of the project is to develop a family of characterization systems based on the advanced control of high performance microwave photonic components and a competitive price determinant for the implementation of new generation networks. The interest of the consortium in the present project is to analyze the feasibility of the Microwave Photonic technology for the development and implementation of an advanced performance analyzer for the characterization of devices and monitoring of hybrid radio-fiber systems that is capable of operating until the 70 GHz.

Silicon Nitride Spectrometers (TEC2016-80385-P)

IPs: Pascual Muñoz Muñoz, Daniel Pastor Abellán

2017 - 2020. Public Funding - Ministerio de Economía y Competitividad

Summary: Spectrometric devices are employed in multitude of disciplines, as information technologies, analytical chemistry, bio/life sciences and safety & security. The wavelength range spanning the upper part of the Near Infra-Red (NIR), wavelengths in the range of 1.5-4.0 μm, has recently raised considerable interest both for telecom due to the fiber capacity crunch, and non-telecom applications, since inorganic and organic molecules of fluids, and gases, exhibit fingerprint vibrations in this part of the spectrum. Compact integrated optics spectrometers on photonic integrated circuits (PICs) are comparatively smaller, but to the date they have not achieved the reconfiguration capabilities of the conventional bulk instruments, apart from, comparatively very limited, tuning within the wavelength range of operation. Among the different PIC technologies, Silicon Nitride on Silicon Oxide waveguiding platforms have received considerable interest in the recent years, due to their broad wavelength range of operation, from visible to the lower part of the mid infrared (400-4000 nm), serving to photonic applications in multiple disciplines (physics, engineering, bio/life sciences, safety & security, to name a few).

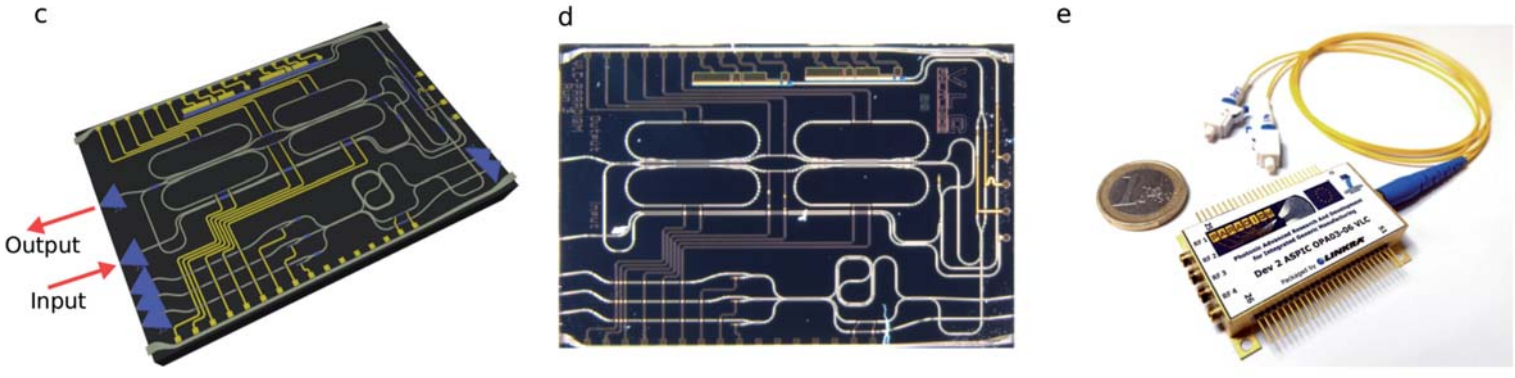
The problem to be solved in this project is to bring the reconfiguration features of conventional bulk spectrometers into compact, reconfigurable PIC spectrometers, of application on the telecom and sensing wavelength range of 1.5-4.0 μm based on ultra-broadband Silicon Nitride technologies.

Multicore fibers for next-generation fiber-wireless applications (TEC2016-80150-R)

IP: Ivana Gasulla Mestre

2017 - 2020. Public Funding - Ministerio de Economía y Competitividad

Summary: The pioneering idea of FITNESS is to develop a novel area of application for Space-Division Multiplexing by exploiting, for the first time, the inherent parallelism of multicore fibres to implement a broadband tuneable true time delay line for radiofrequency signals, which is the basis of multiple Microwave Photonics functionalities. More specifically, we propose in this project an innovative optical technology built upon the heterogeneous multicore fibres, where each one of the different cores that comprise it will feature an independent group delay. This implies the development of a group index variable delay line with the corresponding new design algorithms, theoretical analysis techniques, as well as fabrication and experimental characterization procedures. By tailoring the chromatic dispersion properties of each core, we will obtain 2D (2 dimensional) true



Monolithic Integrated Microwave Photonics Filter.

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Optical Vector Network Analyzer – Instrument for microwave photonics characterization.

time delay operation characterized by a basic differential delay that can be obtained by exploiting either the spatial diversity dimension or the optical wavelength diversity dimension. Once the envisioned true time delay lines are implemented, we will apply them as a proof of concept to a set of representative Microwave Photonics applications that are required in broadband fibre-wireless communications scenarios.

Desarrollo de láseres de pulsos ultracortos con prestaciones avanzadas y bajo coste para su aplicación en la nueva industria (ULTRALASER) RTC-2015-3631-5

IP: José Mora Almerich

2016 - 2018. Public Funding - Ministerio de Economía y Competitividad

Summary: This project is focused on the development of high-efficiency pulses and femtoseconds based on modular technology with a competitive price adapted to the advanced applications of the small industry. The family of lasers obtained in the project will be composed of an ultra-short pulse laser of moderate energy, essentially in the range of the picoseconds whose compression to the range of the hundreds of femtoseconds will be studied throughout the project. A solid-state ultra-short pulse laser (up to 50 fs) and a laser system (laser plus modules for pulse processing) combining fiber technology and compression and amplification technology by free space propagation for very high performance.

Photonic integrated circuits for telecom & bio

IP: Pascual Muñoz Muñoz

2015 - 2018. Public Funding - Ministerio de Economía y Competitividad

Summary: This thematic network of excellence addresses photonic integrated circuit design and is motivated by: a) photonic integrated circuit design is a widely transversal competence that is creating an enormous amount of research and business opportunities, b) Spain has strong worldwide leading research groups on photonic integrated circuits and its applications and c) in a highly competitive R&D and market, joining efforts is a must. The general goal of this network of excellence is to integrate the research efforts in Spain on photonic integrated circuits design for telecom and bio applications, broken into four objectives: i) to educate the next generation of photonic integrated circuit designers, ii) to integrate the research groups and their technical activities, iii) to create a common pool of resources, iv) to raise awareness on these technologies and their applications.

2.- Research results

2.1.- Featured publications

I. Gasulla, D. Barrera, J. Hervás and S. Sales, "Spatial Division Multiplexed Microwave Signal processing by selective grating inscription in homogeneous multicore fibers," **Scientific Reports**, 7, 41727 (2017).

The use of Spatial Division Multiplexing for Microwave Photonics signal processing is proposed and experimentally demonstrated, for the first time to our knowledge, based on the selective inscription of Bragg gratings in homogeneous multicore fibers. The fabricated devices behave as sampled true time delay elements for radiofrequency signals offering a wide range of operation possibilities within the same optical fiber. The key to processing flexibility comes from the implementation of novel multi-cavity configurations by inscribing a variety of different fiber Bragg gratings along the different cores of a 7-core fiber. This entails the development of the first fabrication method to inscribe high-quality gratings characterized by arbitrary frequency spectra and located in arbitrary longitudinal positions along the individual cores of a multicore fiber. Our work opens the way towards the development of unique compact fiber-based solutions that enable the implementation of a wide variety of 2D (spatial and wavelength diversity) signal processing functionalities that will be key in future fiber-wireless communications scenarios. We envisage that Microwave Photonics systems and networks will benefit from this technology in terms of compactness, operation versatility and performance stability.

J. S. Fandiño, P. Muñoz, D. Doménech and J. Capmany, "A monolithic integrated photonic microwave filter" **Nature Photonics** 11, 124–129 (2017).

Meeting the increasing demand for capacity in wireless networks requires the harnessing of higher regions in the radiofrequency spectrum, reducing cell size, as well as more compact, agile and power-efficient base stations that are capable of smoothly interfacing the radio and fibre segments. Fully functional microwave photonic chips are promising candidates in attempts to meet these goals. In recent years, many integrated microwave photonic chips have been reported in different technologies. To the best of our knowledge, none has monolithically integrated all the main active and passive optoelectronic components. Here, we report the first demonstration of a tunable microwave photonics filter that is monolithically integrated into an indium phosphide chip. The reconfigurable radiofrequency photonic filter includes all the necessary elements (for example, lasers, modulators and photodetectors), and its response can be tuned by means of control electric currents. This is an important step in demonstrating the feasibility of integrated and programmable microwave photonic processors.

J. Wang, R. Ashrafi, R. Adams, I. Glesk, I. Gasulla, J. Capmany and L. R. Chen. **Scientific Reports**, 6, 30235.

An optical true time delay line (OTTDL) is a basic photonic building block that enables many microwave photonic and optical processing operations. The conventional design for an integrated OTTDL that is based on spatial diversity uses a length-variable waveguide array to create the optical time delays, which can introduce complexities in the integrated circuit design. Here we report the first ever demonstration of an integrated index-variable OTTDL that exploits spatial diversity in an equal length waveguide array. The approach uses subwavelength grating waveguides in silicon-on-insulator (SOI), which enables the realization of OTTDLs having a simple geometry and that occupy a compact chip area. Moreover, compared to conventional wavelength-variable delay lines with a few THz operation bandwidth, our index-variable OTTDL has an extremely broad operation bandwidth practically exceeding several tens of THz, which supports operation for various input optical signals with broad ranges of central wavelength and bandwidth.

2.2.- Patents

1. P. Muñoz, J. Capmany, M.M. de Lima, & P.V. Santos, "Tuneable AWG device for multiplexing and demultiplexing signals and method for tuning said device", U.S. Patent No. 9,239,425. Washington, DC: U.S. Patent and Trademark Office (2016).

2. B. Gargallo, P. Muñoz, J. Capmany, J.S. Fandiño, "Dispositivo AWG reflectante con respuesta espectral configurable implementado con reflectores de Sagnac", P201331792/ES2540378, concesión 10 Mayo 2016, prioridad 5 Diciembre 2013. Licencia de explotación: VLC Photonics SL.

3. J. Capmany, I. Gasulla & S. Sales, "Módulo de fibra óptica multinúcleo de compensación de la dispersión", P201530642, (2016).

4. J. Capmany, I. Gasulla & S. Sales, "Arquitectura de fibra multinúcleo y método de control", P201630119, (2017).

5. G. Muñoz-Matutano, J. Raul, J.M. Martínez-Pastor, S. Sales, "Sistema, método y programa de ordenador para la medida y análisis de señales luminosas temporales", P201431646, (2106).

6. P. Muñoz, B. Gargallo, G. Micó, D. Pastor, "Dispositivo fotónico sensor, método de análisis de muestras que hace uso del mismo y usos de dicho dispositivo" OEPM P201631544, (2016)

2.3.- Awards.

1. Amelia Lavinia Ricchiuti, Premio Extraordinario Tesis Doctoral UPV, 2017, "Design and fabrication of customized fiber gratings to improve the interrogation of optical fiber sensor".

2. Daniel Pérez López, IEEE Photonics Society Graduate Student Fellowship, 2017.