FABULOUS NEWSLETTER

FDMA Access By Using Low-cost Optical Network Units in Silicon photonics

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STREP Contract 318704
Objective ICT-2011-3.5: Core and disruptive photonic technologies

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FABULOUS at a glance:

Start date: 1st October 2012
Duration: 36+9 months
Total project cost: 4,2M€
EU financing: 2,9M€

FABULOUS comes to the end

The FABULOUS project has then come to the end. It's been a long time since the last newsletter issue, as the project partners had asked for a 9-months project extension; such extension was needed as, on the 25th of April 2015, a major fire accident hit the clean rooms of one member of the consortium, generating a certain delay in the delivery of the integrated components. Thus, the commission accepted to extend the duration of the activities by 9 months to accomplish the most possible of the project targets, without any change in the budget.

During the nearly four years of the project, the activities have followed two main north stars:

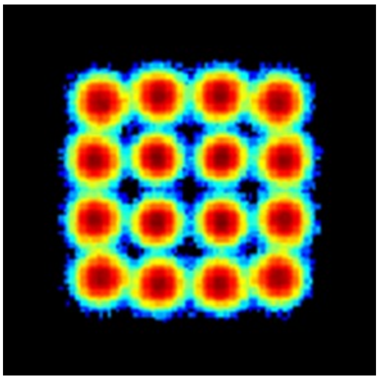
1) the demonstration of the effectiveness of a passive optical network architecture alternative to what has been standardized as NG-PON2

2) the realization of new silicon-based photonic integrated circuits, in order to demonstrate the potentialities of silicon photonics for the telecom market.

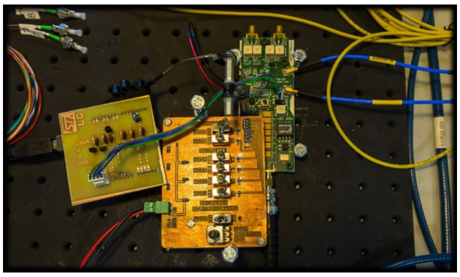
In terms of the architecture, we have demonstrated that a self-coherent reflective PON that relies on Frequency Division Multiplexing at the electrical level, on a per-wavelength bases, can take advantage of powerful, yet reasonably implementable on FPGA or ASIC platforms, Digital Signal Processing: this allows to target high-bit rates and to recover the challenging power budget due to the reflective configuration, even to the point of compliance with some classes of Optical Distribution Network standardized by ITU-T (up to 31dB of ODN loss when targeting 32Gbps of aggregate upstream capacity). We have also demonstrated that the architecture is suitable for other niche applications, in particular such as the so called Passive Optical Local Area Networks, and in additions some of the concepts and competences created during this project can be of great interest for 5G front-hauling networks.

In terms of components, the consortium has been working on several directions overcoming the state-of-the-art from several points of view. First meaningful results were due to a careful optimization of a 2D grating coupler to optimize coupling between optical fiber and silicon waveguides: this is a key point for keeping the devices losses low. Then, an hybrid III-V/Si optical amplifier with an internal gain of 28dB has been demonstrated: this can be a key enabling factor for silicon photonics development in most fields of optical communications, either in the Datacom or the Telecom field. In the end, we demonstrated the reflective upstream transmitter made up of a Silicon photonic integrated circuit (Si-PIC) comprising a reflective Mach Zehnder modulator and its flip-chipped CMOS electronic integrated circuit driver, the two ICs being interconnected by means of high density and low parasitic copper micro pillars.

Not only technical are the lessons we learned during the Fabulous project, but also "phylosophical" and/or procedural: we learned that for fully exploiting the Silicon Photonics potential, co-design of system and components is fundamental: tayloring the system on the platform peculiarities and the component on the system are of paramount importance for allowing silicon devices to finally enter the telecom market, and this also requieres the creation of new cross-competences.



16-QAM constellation at 1Gbps transmitted by the integrated ONU, in back-to-back conditions, after equalization and rotation compensation



Integrated ONU with support boards for operation in the system demonstrator

"We tailored a network architecture on a silicon device, and vice-versa. "

Summary on the achievements at system level

FABULOUS was originally conceived and proposed when the so-called NG-PON2 was mostly a "wish-list" set by telecom operators, whose main requirements were feeder capacity greater than 40 Gbps, a sustained data-rate close to 1 Gbps in the downstream direction (from Central Office to user) and to 500 Mbps in the upstream and compatibility with legacy infrastructure. Such requirements gave birth to recommendation ITU-T G.989, that in brief is based on 4 wavelengths each capable of 10 Gbps in downstream and 2,5 Gbps in upstream, where the multiplexing at the electrical level is made in Time Division.

In FABULOUS we wanted to reach high capacity while being compatible with legacy infrastructures, but at the same time solving some typical PON problems while facing the huge challenge of introducing silicon-photonics in the telecommunications market. In the end, we re-thought a PON architecture without considering existing standards, and we tailored a network architecture o a silicon device, and vice-versa.

First of all, we decided to realize a network without laser sources at the customer premises (the ONU), and we then implemented a **reflective PON**, in which the CW seed used by the ONU for the upstream is received, together with the downstream signal, from the central office (OLT). This approach, while being challenging from the point of view of the power budget, avoids the network the risk of uncontrolled wavelengths travelling the network when a ONU is switched-on, and for domestic users prevents from the risks due to the presence of laser sources at home; in this way, most of the complexity due to wavelength division multiplexing is left at the OLT, while at the ONU only tunable optical filters, that can be realized in silicon, are needed. To overcome the transmission impairments for such a challenging type of transmission when high bit-rates are needed, we decide to heavily rely on Digital Signal Processing (DSP): a powerful equalizer and a long Forward Error Correction scheme, that coupled to multi-level modulation formats on the electrical side can grant distance and bit-rate. This approach is not feasible, at least at a reasonable cost, when the multiplexing is performed on time division bases, as the use has to run at the full system speed but for short periods of time, so we also decided to adopt **Frequency Division Multiplexing**: in this way, it is possible to process the user signal at lower speed (that is: the user's speed) and with a continuous bit-stream, allowing long correction schemes and easing the processing.

The system was first set-up with discrete commercial components, to assess the maximum performances and then to assess a benchmark for the integrated component developed in this project as well. In the table at the page bottom a summary of the performances achieved for different modulation formats and different numbers of users per wavelength, and the figure of merit is expressed by the ODN Loss, that in turn is related to the maximum link distance; standards specify at least 29 dB for the lowest class, and such value is achieved for most of the cases. In particular, **32 users at 1 Gbps each over 31 dB** was one of the main targets of the project, while if lower ODN loss is needed, then it is possible to increase the total capacity up to 48 Gbps: definitely the FABULOUS architecture is setting a benchmark for reflective PON!

As **FABULOUS heavily relies on DSP**, we also evaluated the feasibility of such DSP and how it could be implemented on mass-production platforms, such as ASICS. We then experimentally shown, on an FPGA platform, that a real-time system can be set-up with negligible penalties with respect to infinite maths implementations, and then evaluated that it could be realized on a 7mm^2 CMOS chip, for an estimated power consumption lower than 4W: definitely reasonable values for device integration. Then, when very first releases of the Silicon Photonics integrated ONU were available, we tested it with the FPGA, measuring 22 ODN loss with 500 Mbps per user: a very promising result for a not yet fully mature technology!

Modulation format	Number of users	Net bit-rate per user	Maximum ODN loss
64-QAM	16	3 Gbps	23.0 dB
64-QAM	8	6 Gbps	23.0 dB
16-QAM	32	1 Gbps	31.0 dB
16-QAM	6	5 Gbps	30.5 dB
16-QAM	3	10 Gbps	28.0 dB
QPSK	128	100 Mbps	41.0 dB
QPSK	32	500 Mbps	38.0 dB
QPSK	8	2.5 Gbps	34.5 dB
QPSK	3	5 Gbps	32.5 dB
BPSK	32	250 Mbps	40.5 dB
OOK	1	10 Gbps	38.5 dB

Summary of the performances achievable exploiting FDM flexibility, using discrete components.

Summary on the achievements at component level

FABULOUS had the ambitious goal of integrating many different functions onto a single chip realized in Silicon Photonics technology, so that the dream of a single-chip ONU (Optical Network Unit) would come true. The FABULOUS ONU integrates the functionalities detailed in the table at the bottom of the page, each of which is implemented by a specifically dedicated device.

The different devices have been designed, developed, fabricated and tested individually. Then, after a round of performance optimization, the devices have been finally realized onto a single chip that integrates all the functions and sub-devices. This has been allowed by the Silicon Photonics technology of CEA-Leti, complemented by the hybrid III-V integration technology of III-V Labs, the CMOS silicon foundry of ST, and, last but not least, the packaging technology of Tyndall Institute that made possible the realization of the single-chip ONU by flip-chip bonding of the electronic modulator driver, fiber pigtailing, and thermal management using a Peltier cell.

The final single-chip ONU was tested in the transmission system test-bed, and proved to allow for 22 dB of ODN, with the possibility of serving 32 users, each with an upstream bit-rate of 500 Mbit/s, for a total aggregate upstream capacity of 16 Gb/s.

The performance of individual components has been pushed to state-of-the-art levels, by combining smart design and careful experimental testing.

The **2D polarization splitting grating coupler** designed at the University of Pavia showed -4.4 dB coupling efficiency (36%) with a 1 dB bandwidth of 44 nm, and 1 dB alignment tolerance of 4 μm. This performance was achieved with an etch-depth of 120nm, hole-radius of 179 nm, and a grating pitch of 630 nm. Light is coupled into and out of the grating using optical fibres lying horizontally, with an edge-cut at 40° that allows the light from the fibre to impinge onto the grating with the desired 10° angle.

The **ring-based tunable bandpass filter** has been fabricated in different versions, including 2 and 3 cascaded rings, with circular or racetrack shapes. The filtering performance has been in line with the specifications, achieving 39 GHz bandwidth at -3 dB, with 96 GHz width at -20 dB, and a total device loss of 0.8 dB. Tuning is accomplished via thermal effects generated by integrated heaters, with a power/wavelength tuning efficiency of 4.8 mW/nm.

A **bidirectional, travelling-wave Mach-Zehnder intensity modulator** with 4 mm arm length showed suitable characteristics to enable efficient implementation of the OFDM modulation, including 8 dB insertion loss, a figure of merit of 4.6 Vp×cm, a 3 dB bandwidth of 10 GHz.

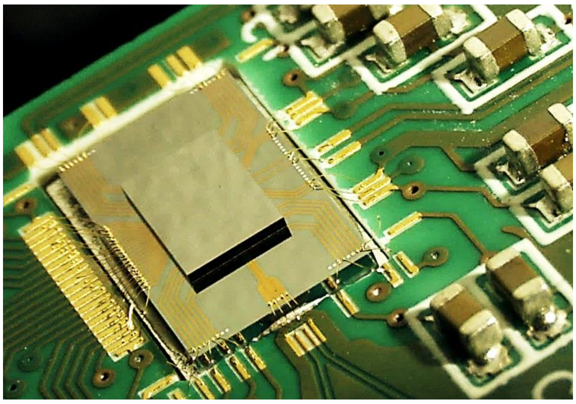
We also realized a non-travelling-wave version of the modulator, with a special **CMOS electrical driver** designed with 12 stages, and 6 of them were applied in push-pull configuration to the 6 cascaded electrodes of the MZM using discrete delay-lines, to achieve the desired travelling-wave modulation. The 3 dB small-signal bandwidth is 8 GHz. The combination of driver + MZM allowed to achieve a 10^{-3} bit-error rate using 16-QAM modulation.

The **semiconductor optical amplifier** realized with hybrid integration of a III-V gain chip on silicon is the only device that has not been so far integrated in the ONU. In a stand-alone version, it showed up to 20 dB waveguide-to-waveguide gain, a value that is by far sufficient for the two SOAs that will be included in the future in the integrated ONU to compensate for the insertion losses of the different devices, still allowing for a good power margin for the upstream transmission in a PON configuration.

The FABULOUS ONU is surely one of the best examples of multi-functional photonic integrated circuited, and has pioneered the use of Silicon Photonics for large deployment consumer applications.

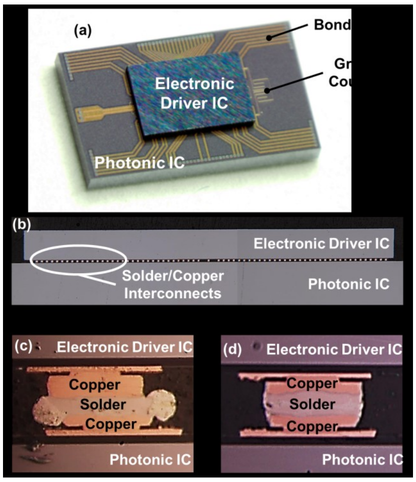
Function	Device
Coupling of light from and to an external optical fibre, with polarization splitting into two distinct optical waveguides	2D, grating coupler
Bandpass spectral filtering of an unmodulated CW optical carrier, chosen among several WDM carriers	Ring-based tunable filter
Modulation of the optical carrier with OFDM upstream signal, with Faraday polarization rotation	Bidirectional Mach-Zehnder intensity modulator
Impression of electrical ODFM signal onto the optical carrier	Electrical high-speed driver realized in CMOS technology
On-chip optical amplification to compensate the coupling losses and the individual device losses	Hybrid-integrated, III-V on silicon semiconductor optical amplifier

Summary of the functions implemented in the FABULOUS PIC (in grey: future version)



Photograph of an electronic-IC (EIC) flip-chip integrated on top of a photonic integrated circuit (PIC), with DC and RF wire-bond connections to printed circuit board (PCB) driver electronics, on which are mounted the front-end electronics for the FABULOUS module.

"The FABULOUS ONU is surely one of the best examples of multi-functional photonic integrated circuited"



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A flexible architecture, compatible with current infrastructures, and low cost components and network units based on silicon photonics: the keys for mass Fiber-To-The-Home deployment.

The FABULOUS Project has been conceived and is being carried out by a balanced mix of *universities, research centers, industries and operators*; such a consortium is very heterogeneous, in order to cover all the many different technological aspects required by the work-plan. In particular, two main different category of aspects can be identified in the project structure:

- **System aspects**, main duty of Istituto Superiore Mario Boella, Politecnico di Torino and France Telecom
- **Optoelectronic, silicon photonics and packaging aspects**, main duty of CEA-LETI, II-V Labs, University of Pavia, Tyndall National Institute, STMicroelectronics.

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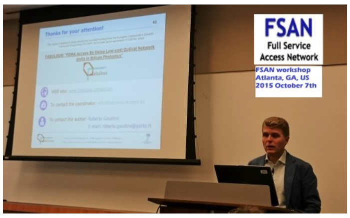
EVENTS and DISSEMINATION



Roberto Gaudino at an FSAN meeting

Besides the research activities that have been carried out during the course of the project, the FABULOUS partners have been widely active from the point of view of dissemination, granting the project wide visibility in conferences and on journals. Over 40 papers were published, including some high-impact-factor journals such as *IEEE Journal of Lightwave Technology* and *OSA Optics Express*. The full list of papers is available on the project website.

In addition to the typical scientific conferences adressed by the optical community, Fabulous representatives were also invited to more indistry-related events, reported in the following.

Prof. Roberto Gaudino, was invited to participate to an open workshop organized by FSAN (*the Full Service Access Network). The Mission of FSAN is to drive existing standards into the services and products in the industry, while simultaneously advancing its own specifications into the appropriate standard bodies, for more information see* *http://www.fsan.org/*). The workshop, titled "Future Access Technology" took place in Atlanta, GE, USA on 2015 October 7th and was aimed at openly discussing new trends for the forthcoming standards in PON. Prof. Roberto Gaudino was invited to present results on self-coherent reflective PON architectures, and gave a 20 minutes talk in front of the FSAN meeting, constituted by approximately 50 people (representatives of telecom operators and vendors interested in PON). The talk presented also the latest result of the FABULOUS EU project, in particular focusing on the FDMA-PON self-coherent approach proposed in FABULOUS for the upstream.

Silvio Abrate was invited and the "PIC International" (www.picinternational.net), held in Brussels in March 2016. Giving a keynote speech in the session "Increasing the capability of optical networks", he described the FABULOUS experience about the need to co-design devices and networks to fully exploit the potentialities of silicon photonics.

Silvio Abrate at the PIC International 2016