PROJECT FINAL REPORT (PUBLIC)

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Project website Fehler! Textmarke nicht definiert. **address: http://www.ict-galactico.eu**

List of Abbreviations

ASE	Amplified Spontaneous Emission
BER	Bit Error Ratio
CA	Consortium Agreement
CMA	Constant Modulus Algorithm
CW	Continuous Wave
DCF	Dispersion Compensating Fiber
DCM	Dispersion Compensating Module
DFB	Distributed Feedback Laser
DI	Delay Interferometer
DP	Dual Polarization
DQPSK	Differential Quadrature Phase Shift Keying
DSP	Digital Signal Processing
DWDM	Dense Wavelength Division Multiplexing
ECL	External Cavity Laser
EDFA	Erbium Doped Fiber Amplifier
ER	Extinction Ratio
FEC	Forward Error Correction
FIR	Finite Impulse Response
FSE	Fractionally-Spaced Equalizer
FSR	Free Spectral Range
FSPO	Free Space Polarization Optics
GA	Grant Agreement
GaAs	Gallium Arsenide
HBT	Heterojunction Bipolar Transistor
IC	Integrated Circuit
InP	Indium Phosphide
ISI	Inter-Symbol Interference

LO	Local Oscillator
MMI	Multi-mode Interference
MZM	Mach Zehnder Modulator
OIF	Optical Internetworking Forum
OOK	On-Off Keying
OSA	Optical Spectrum Analyzer
OSNR	Optical Signal to Noise Ratio
OTN	Optical Transport Network
PDFS	Polarization Dependent Frequency Shift
PDL	Polarization Dependent Loss
PMD	Polarization Mode Dispersion
PM-QPSK	Polarization Multiplexed Quadrature Phase Shift Keying
PPG	Pulse Pattern Generator
PRBS	Pseudo-Random Bit Sequence
QAM	Quadrature Amplitude Modulation
ROADM	Reconfigurable Add-drop Multiplexer
SiGe	Silicon Germanium
SOI	Silicon-on-Insulator
SOP	State of Polarization
WAN	Wide Area Networks
WSS	Wavelength Selective Switch

1. Final publishable summary report

1.1 Executive summary

GALACTICO aim was to develop the photonic integration technology to disrupt the current transition from 10/40Gb/s to 100GbE optical long haul networks and at the same time address the next capacity increase towards 400 Gb/s and beyond. To achieve this goal, GALACTICO has demonstrated photonic integrated circuits and modules combining technical and economic feasibility as well as a broad market potential. GALACTICO has invested in two technologies that leverage cost-effective PIC fabrication in foundries; a) Silicon Photonics (SiPh) to implement the receiver interfaces and b) GaAs to implement the transmitter modulation interfaces.

On the "receive-side", GALACTICO fabricated and demonstrated silicon nano-waveguide PICs that squeeze all the optical (signal coupling, polarization splitting, mixing) and opto-electronic (optical to electrical conversion) receive functionalities in record tiny, few-mm-scale chips. Fabrication was done using the standard toolset of a silicon foundry and through BiCMOS processes, opening the way for truly cost-effective "photonic BiCMOS". On the "transmit-side", GALACTICO fabricated GaAs modulator chips that integrate tightly all optical and opto-electronic functionalities (signal splitting, electro-optic modulation, polarization rotation/multiplexing) in modules that are well smaller than the current 100G standards set by the photonics industry. Fabrication was done leveraging cost effective fabrication in GaAs foundries that serve the mobile industry and run thousands of wafers per year.

GALACTICO delivered the receiver and modulator PICs as fully packaged modules and tested them in a series of lab experiments and field trials demonstrating the feasibility of delivering >200 Gb/s line rates using polarization multiplexed and multi-level coded signals (DP-QPSK, DP-16-64 QAM) being well aligned with upcoming optical transport system upgrades that foresee migration from 100G DP-QPSK to >200G DP-16QAM modulation formats. Being fully in line with development in Ethernet Alliance and IEEE 400G Ethernet Group, GALACTICO devices will be qualified for integration in system portfolios that will deploy 400G interfaces with fully integrated optics hitting the right cost, size and technical feasibility points; i.e. all the requirements for quick and volume deployment of 100G systems as well as the sustained entry of 400G technology. By so doing, GALACTICO enables key European industrial players to formulate and capture the growing OTN market, ultimately leading to new opportunities for high technology jobs within Europe.

1.2 Summary description of project context and objectives

The standardization of 100G technologies and the continuous reporting of new technologies beyond 100G - during the past three years – have created a dynamically changing landscape in next generation Optical Transport Network (OTN) systems. During this course, it has become clear that new technologies addressing the jump to 100G should also be leveraged for the next capacity increase towards 400G and even 1 Tb/s; the new-gen products should deliver high performance in lower-cost and footprint and offer optimum manufacturability and return-of-investment; vendors want to leverage technology to have a meaningful payback from their R&D investment. In this context GALACTICO objectives were formulated to satisfy the need for speed, small size, reduced cost and enhanced functionality.

Silicon technology objectives

- ✓ Design and fabrication of a full family of silicon nano-photonic components for ultra-compact dual polarization coherent receivers
- ✓ Design and fabrication of high performance (>30 GHz) Ge diodes for integration on SiPh coherent receiver boards
- ✓ Design and fabrication of mm-scale SiPh nano-waveguide dual polarization coherent receiver boards
- ✓ Fabrication of miniaturized SiPh DP coherent receiver modules enabling >100G systems
- ✓ Design and fabrication of SiGe BiCMOS multi-level driver IC

III-V technology (InP and GaAs) objectives

- ✓ Design and fabrication of single element IQ GaAs modulator module (building block for dual polarization and array devices)
- ✓ Design and fabrication of IQ GaAs modulator array chips
- ✓ Design and fabrication of dual polarization (DP)-IQ GaAs modulator module
- ✓ Design GaAs modulators to be flip-chip compatible with silicon photonic boards for future hybrid integrated modules and define hybrid integration assembly process
- ✓ Design and fabrication of flip-chip compatible InP photodetector arrays for first generation 100G hybrid integrated DP coherent receiver chips
- ✓ Fabrication of hybrid 100G InP/Si DP coherent receiver module employing SiPh receiver board and flip-chip InP PDs (precursor towards full silicon integration with nano-waveguides and Ge diodes)

Component & module testing objectives

- ✓ Perform lab trials and benchmark against commercially available modulators with QPSK and 16/32 QAM modulation formats at 28-32 Gbaud
- ✓ Perform field trial and evaluate performance under co-existence with commercial DWDM OTN platforms with QPSK modulation formats at 28-32 Gbaud

1.3 Main S&T results/foregrounds

GALACTICO SiPh coherent receivers

On the receiver side work was focused on breaking the PIC size limits with the fabrication of coherent receiver SiPh PICs on nano-waveguides and the employment of high speed Ge diodes and electronics using a BiCMOS process. GALACTICO implemented this route progressively;

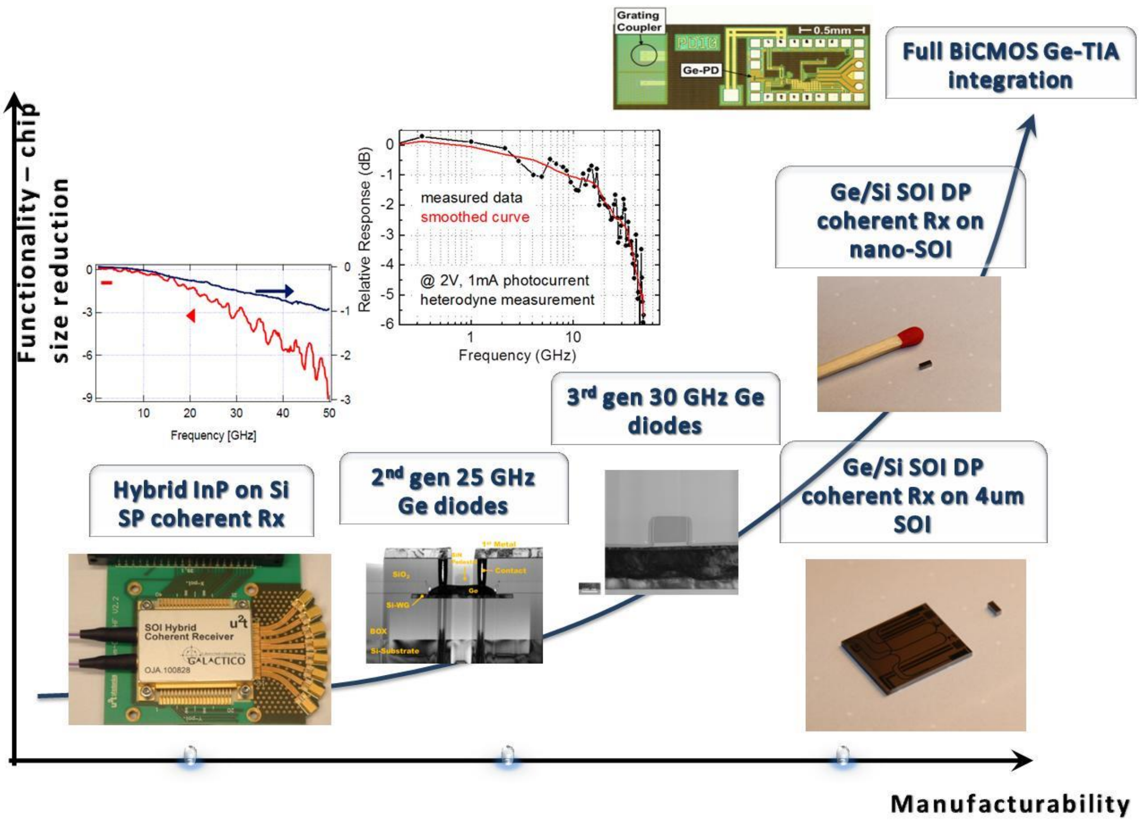
- "First gen" GALACTICO: the first gen GALACTICO DP coherent receiver modules relied on the cost-effective hybrid integration of high performance pre-fabricated InP potodetectors on medium index contrast 4 um SiPh boards.
- "Next gen" GALACTICO: the final gen GALACTICO DP coherent receiver modules relied on the unique combination of Ge diodes and SiPh nano-waveguide boards leveraging the strengths of BiCMOS fabrication.

More specifically GALACTICO demonstrated:

1. Fabrication of SP and DP hybrid integrated InP on Si coherent receiver module.
2. Fabrication of Ge diodes demonstrating cut-off frequencies well above 30 GHz and internal responsivity of approximately 0.7 A/W
3. Design of a complete family of SiPh nano-waveguide components for miniaturized coherent receivers including 2D gratings for optical coupling and polarization splitting and optical hybrid for phase decoding
4. Fabrication & characterization of record small nano-waveguide Si/Ge dual polarization coherent receiver PIC. The PIC demonstrates a 100-fold reduction in size with respect to low/medium index contrast waveguide technologies squeezing optical, coupling, polarization splitting and photodetection in a record small PIC area of 5.3 mm x 2.2 mm.

One of the most interesting aspects of the Ge diode integration was that the baseline fabrication process was designed to fit into the BiCMOS full flow to allow for a later BiCMOS integration, which would be the next step to address manufacturability, cost and volume production with the most efficient way. In the final project phase - and although not originally planned - GALACTICO realized this next step by demonstrating a full flow BiCMOS integration with the fabrication of a BiCMOS integrated Ge-PD with transimpedance amplifier. The component testing provided a very promising result at 20 Gb/s; through GALACTICO "photonic BiCMOS" are on their way and are fully capable to be further exploited for future component generations.

As already mentioned, the key advantage of GALACTICO coherent receiver technology is the reduction of the coherent receiver chips incorporating the PBS, the optical 90° hybrids as well as the Ge photodetector array down to a record size of just 2 mm x 1 mm making the coherent receiver compatible with the upcoming CFP, CFP2 and CFP4 form factors. Compared to its counterparts in InP technology, where the PBS is not integrated on the one hand and which is bigger in size on the other hand, this technology is considered an enabling technology for next generation ultra-compact SIP modules. The size advantage of the coherent receiver in nanowaveguide technology is however enabling even more compact sub-systems compared to present sub-systems if we take the perspective of electronic-photonic co-integration on a single chip, as demonstrated during GALACTICO. The GALACTICO dual-polarization coherent receiver photonic integrated circuit may be merged with high-speed transimpedance amplifier circuits in BiCMOS technology. This has been illustrated in the following figure by merging layouts of the respective circuits, indicating the strong potential for footprint reduction in case of electronic-photonic integration solutions based on silicon nanowaveguide technology. Such small sub-systems are enabled by SiPh electronic-photonic integrated circuits.



Evolution of GALACTICO coherent receiver fabrication. The figure illustrates the progressive migration from hybrid integrated InP/Si to Ge/4 um SOI and finally to Ge/nano-SOI DP coherent receiver PICs to achieve a 100x chip size reduction accommodated by a significant advantage in manufacturability; coherent receiver PICs can be cost-effectively fabricated in CMOS foundries using standard micro-electronics toolset.

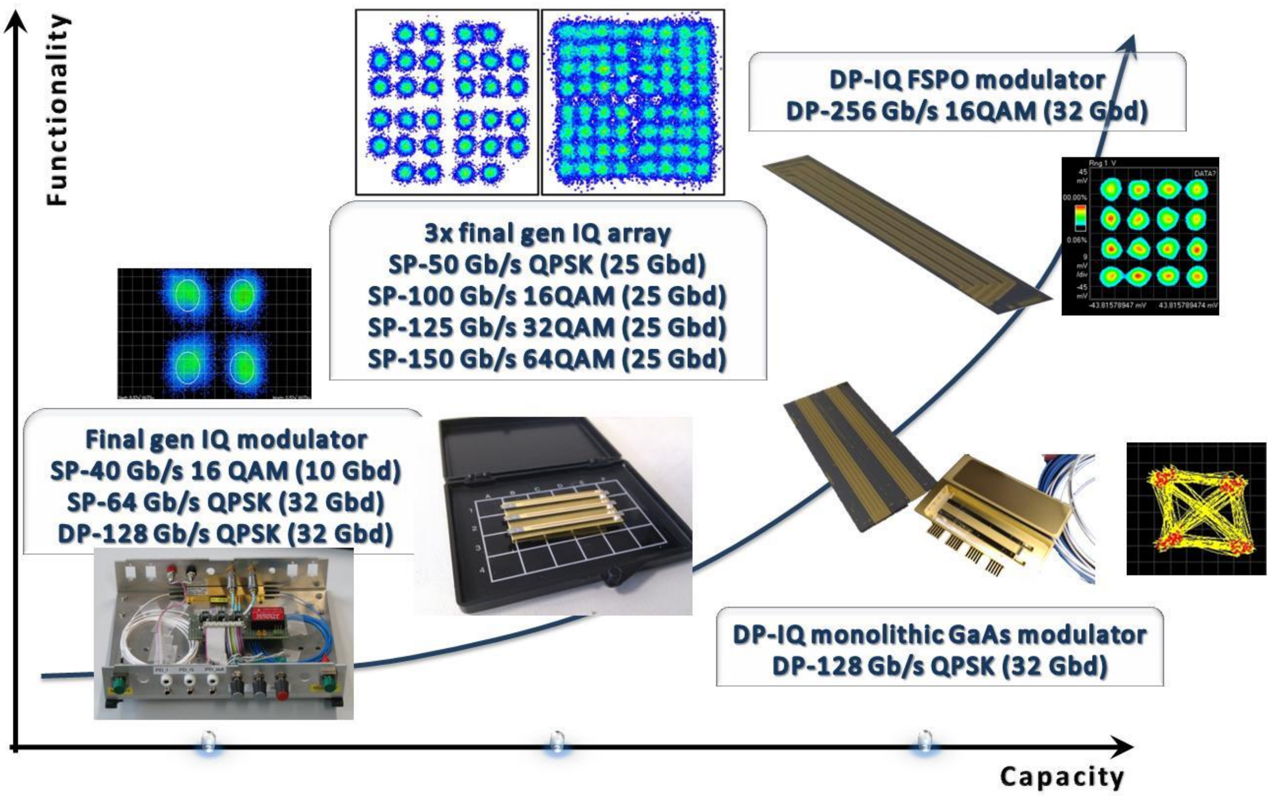
GALACTICO modulators

GALACTICO modulator development route started with the optimization of the basic building block (IQ modulator) to address the bandwidth and size targets and progressively moved towards functionality and line rate increase. The “final gen” GALACTICO modulator prototypes performed the dual polarization functionality on the module level and were demonstrated to generate DP-QPSK and DP-16 QAM modulation formats at symbol rates as high as 32 Gbaud.

GALACTICO implemented this route through the following steps:

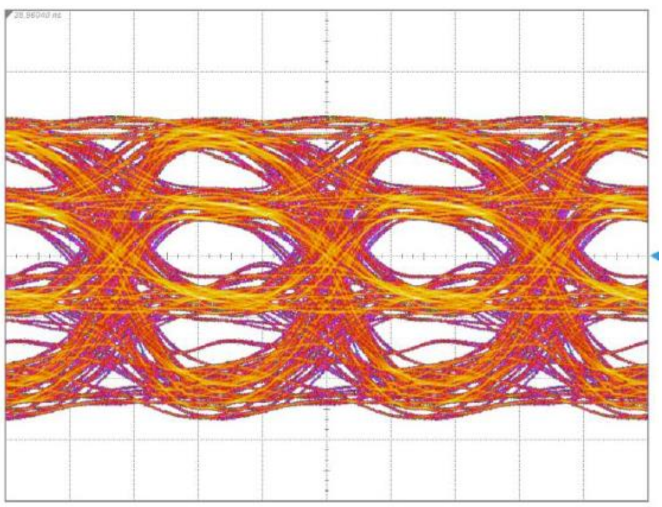
1. the fabrication of an optimized GaAs IQ modulator and modulator array reaching a 3-dB bandwidth of >27 GHz and 20 dB ER addressing the symbol rate requirement of 28-32 Gbaud
2. the testing of the GaAs IQ modulator array with QPSK, 16 QAM, 32 QAM and 64 QAM at 25 Gbaud demonstrating successfully the scaling of the single polarization line rate from 50 up to 150 Gb/s
3. the module assembly of the final optimized high-speed GaAs IQ modulator and its successful system testing with up to 32 Gbaud DP-QPSK (128 Gb/s) in both lab and field trials (DP emulation)
4. the demonstration of a monolithic GaAs DP-IQ modulator and its successful testing with DP-QPSK at 25 Gbaud (100 Gb/s)
5. the demonstration of optimized DP functionality with the assembly of a GALACTICO twin GaAs IQ modulator with free space polarization optics (FSPO) and its testing with DP-QPSK and DP-16 QAM at up to 32 Gbaud, demonstrating 256 Gb/s line rate
6. the direct benchmarking of the IQ and DP-IQ GaAs modulators against commercially available 100G DP modules and the interoperability testing with commercial 100G OTN platforms

The graph below illustrates the fabrication course and the advancements in terms of demonstrated bit rates in the various lab and system trials. The course involved fabrication of diverse component generations (optimized IQ, monolithic DP, FSPO-DP) and 4 different system test rounds executed in ICCS labs, Coriant labs, TILAB lab and installed link and Karlsruhe Institute of technology (KIT) labs (part of a cross FP7-ICT project collaboration).



Evolution of GALACTICO modulator development. The figure illustrates the progressive development from high speed IQ GaAs to DP-IQ GaAs modulators and their demonstrations in a series of system trials with QPSK, 16 QAM, 32 QAM and 64 QAM at 25-32 Gbaud symbol rates. The demonstrated single polarization bit rate is stretched up to 150 Gb/s and the demonstrated DP bit rate has reached 256 Gb/s meeting the targets of upcoming "mini super-channel" 400G and beyond systems

Regarding transmitter devices modulator results have been complemented by adequate electronic driver design implementing multi-level modulator drive capability.



Performance of GALACTICO multi-level driver IC in IHP high-performance SiGe BiCMOS. Exemplifying, single-ended multilevel eye-diagram at 30 Gbaud. In a DP-QPSK scheme, this would enable an implementation with 240Gbps.

GALACTICO module testing

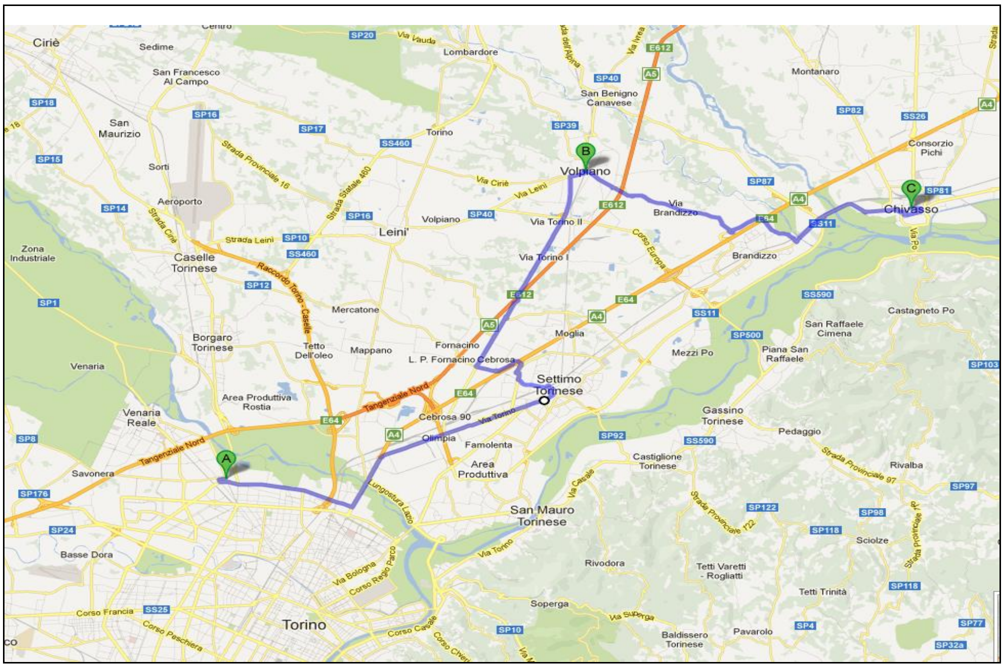
GALACTICO modules have been tested in a series of lab and field trials demonstrating performance at various symbol rates spanning from 22 up to 32 Gbaud and with a broad series of modulation formats spanning from the current 100G DP-QPSK standard to upcoming DP-16 QAM and DP-32 QAM and up to “more futuristic” DP-64 QAM.

GALACTICO testing activity involved:

1. demonstration of up to 25 Gbaud SP-QPSK, SP-16 QAM, SP-32 QAM, SP-64 QAM in lab trials
2. demonstration of 28-32 Gbaud DP-QPSK and 10 Gbaud DP-16 QAM in lab trial
3. demonstration of 28-32 Gbaud DP-QPSK and DP-16 QAM in lab trial
4. demonstration of 28-32 Gbaud DP-QPSK WDM field trial

Highlight results are illustrated in the figure above. Lab trials were executed in ICCS labs, Coriant labs, TILAB lab and Karlsruhe Institute of Technology (KIT) labs as part of a cross FP7-ICT project collaboration. Here we summarize the activity of the field trial done using an installed fibre link in Telecom Italia Regional Network. The trial involved transmission of 32 Gbaud QPSK signals generated by GALACTICO modulators and the transmission with commercial 100G WDM OTN platforms.

The field trial had the goal of testing the provided optical platform in a real DWDM system configuration, focusing on interoperability of existing and commercially available 40 Gb/s and 100 Gb/s channels with the channels provided by the project. This has been done by inserting them in a DWDM system employing G.652 fibres installed in the regional Telecom Italia network.

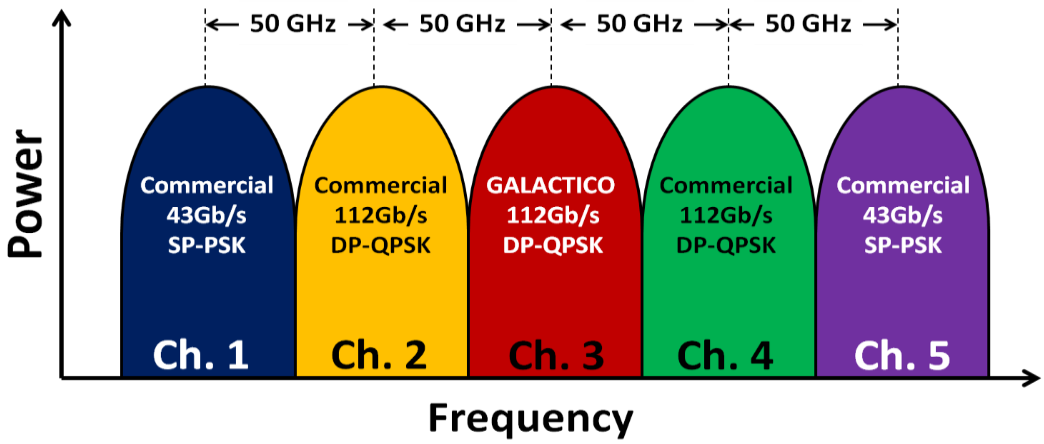


Geographical map with network exchange sites (Torino, Settimo, Volpiano, Chivasso)

Eight fibre pairs in Telecom Italia domestic metro regional network were devoted to GALACTICO experiments. Each pair starts in TILAB "Optical Transmission Lab" and ends around 40 km far, in Chivasso **Fehler! Verweisquelle konnte nicht gefunden werden.**Figure above). Each fibre belongs to the metro regional Telecom Italia network and has a unique fibre and cable identifier code; some network exchanges are placed in between; intra-exchange optical interconnections were made with optical patch-cords into network exchange distribution optical patch panels.

Optical interconnections have been made in various network exchanges for the trial period. The overall link is composed by five sections of different length. In order to obtain a fibre span starting and terminating in TILAB, a hardware physical loop was done in Chivasso site: in the end, eight 80 km spans were available for the trial, each of them starting and terminating in TILAB. Some experimental activities were performed on the installed fibre plant. Preliminary cable OTDR measurements have been made; afterwards optical line amplifiers were inserted after each 80 km span in order to concatenate them and realize a long haul transmission link.

The figure below shows the spectrum allocation of the wavelength channels that were used for the field-trial experiment at TILAB premises, in order to validate and compare the performance of the GALACTICO IQ modulator, operating together with commercial 40 and 100 Gb/s line-cards. A total number of five equidistant data channels in a 50 GHz WDM grid were launched with an optical power of 2 dBm per channel and OSNR of ~45dB in the field-installed fibre, with channel 3 (the middle one) occupied by the GALACTICO transmitter at a wavelength of 1554.422 nm. Its adjacent channels (channels 2 and 4) were selected to be commercial 112 Gb/s DP-QPSK line cards as well, whereas channels 1 and 5 were chosen to be 43Gb/s DP -PSK linecards. At the entry point of the network, all channels were filtered by a 50 GHz wavelength selective switch (WSS), amplified and power-equalized in order to have the same power level, and coupled for fibre transmission in the link.



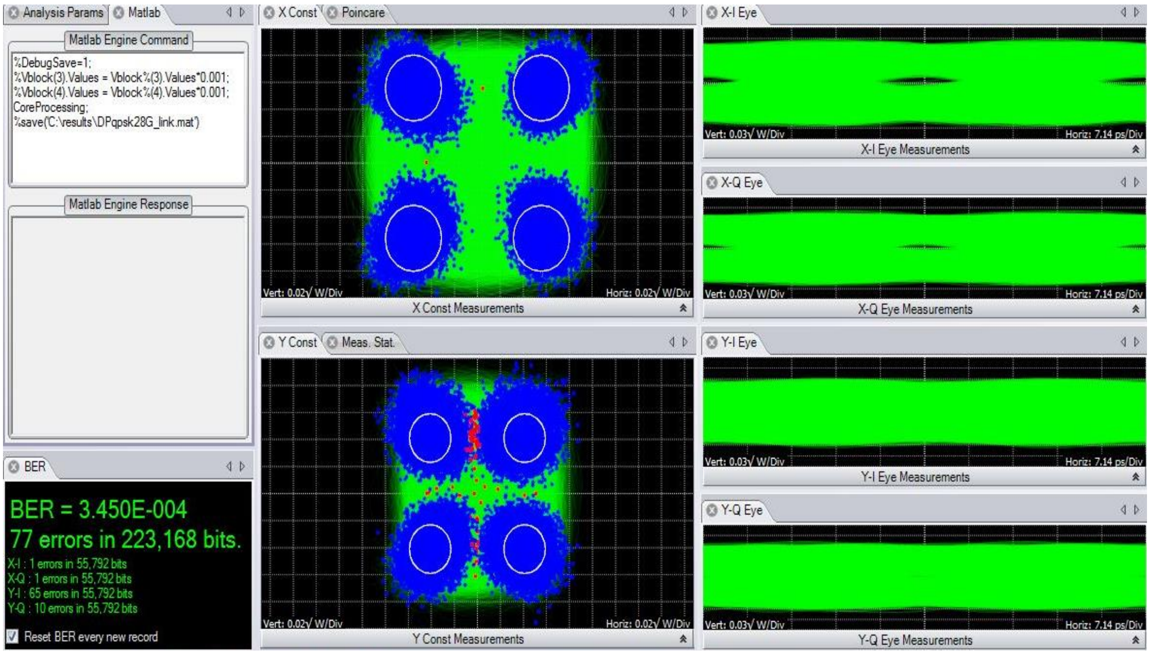
Spectrum allocation of the WDM field trial in a 50 GHz grid

GALACTICO transmitter achieved error-free transmission below the FEC limit ($1\cdot10^{-3}$) with a BER of $3.45\cdot10^{-4}$, over seven 80 km fibre-spans, that correspond to a total transmission length of 560 km SMF fibre. It should be noted that even though the GALACTICO transmitter was operated with half the required voltage swing, its performance was similar to its adjacent 112 Gb/s DP-QPSK channels. More specifically, channels 2 and 4 were also evaluated at the end of the transmission seven span linkand achieved a BER of $2.4 \cdot 10^{-4}$ and $5.6 \cdot 10^{-4}$ respectively.

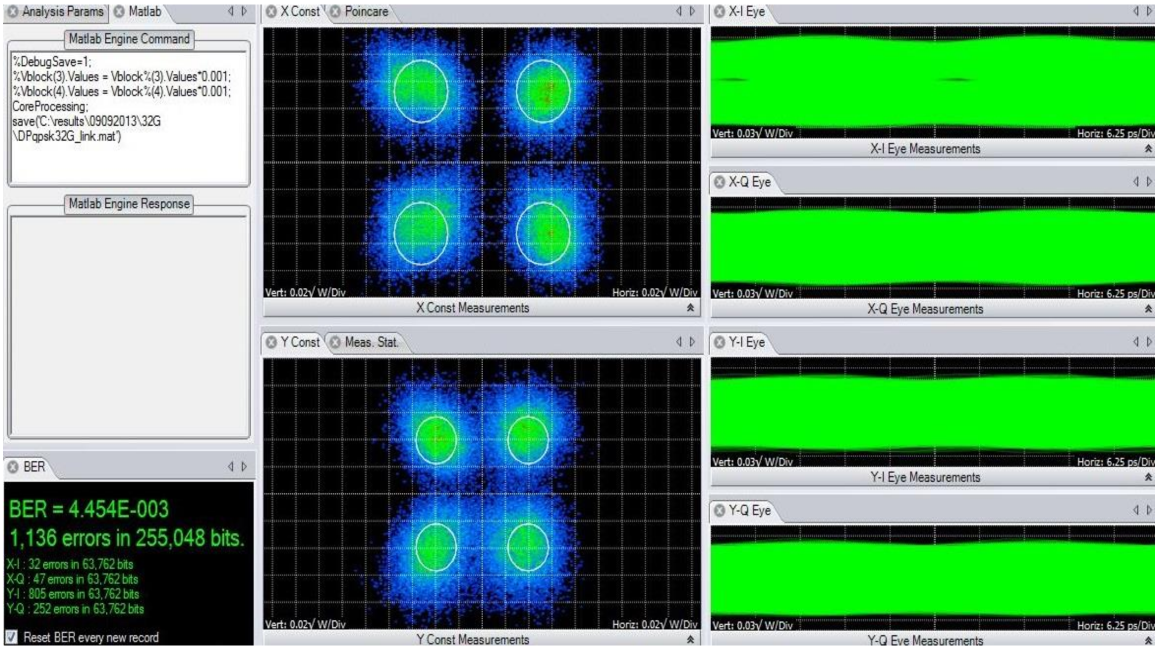
The BER evaluation of these channels was performed individually, through their embedded monitoring software of their linecards. GALACTICO transmitter successfully achieved 560 km transmission in realistic network conditions with a BER of $4.45 \cdot 10^{-3}$, which is well below the soft-decision FEC limit of $2 \cdot 10^{-2}$.

The GALACTICO transmitter operating symbol rate was stretched to 32 Gbaud. Under these conditions GALACTICO transmitter successfully achieved 560 km transmission in realistic network conditions with a BER of $4.45 \cdot 10^{-3}$, which is well below the soft-decision FEC limit of $2 \cdot 10^{-2}$.

The figures below illustrate typical results with 28 and 32 Gbaud QPSK format at the link output.



Constellation diagrams and BER of 28 Gbaud DP-QPSK at the link output, with the GALACTICO IQ modulator.



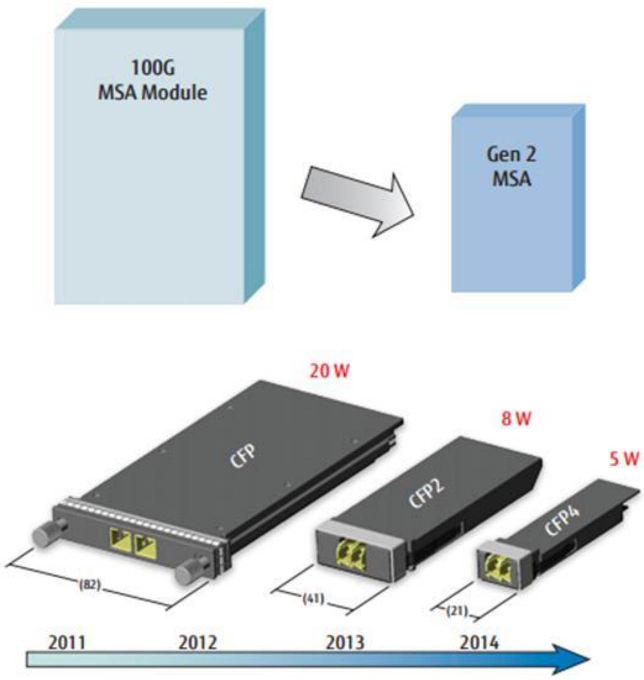
Constellation diagrams and BER of 32 Gbaud DP-QPSK at the link output, with the GALACTICO IQ modulator.

1.4 Potential impact

The major potential for impact of the GALACTICO project is lower cost and miniaturization of components and modules by future scientific and economical exploitation of the developments undertaken in the areas of silicon photonics nanowaveguide receiver technology and GaAs-modulator technology.

Technology

The existing DP-QPSK modulator devices are targeted at line speeds of 100Gbits/s; the next generation is proffered at 400Gbits/s. The dual DP-QPSK module developed as part of the GALACTICO project offers an excellent foundation to addresses the 400Gbits/s next generation line speed. It is unlikely that a single DP-QPSK device will achieve long-haul line speeds of 400Gbits. A more likely scenario is via the use of n-QAM modulation format such that a single DP-QPSK device will achieve 200Gbits/s. (This project has demonstrated the possibility of a single DP-QPSK device achieving speeds of 300Gbit/s – 150Gbits/s per QPSK (IQ) modulator arm). Thus to achieve a line speed of 400Gbits/s two DP-QPSK devices would be required.



This module evolution is now considered very relevant for the next steps towards 400G. At the time GALACTICO was starting the debate for the next standard (400G or 1T) was still open. However under strong guidance by the system vendor and continuous monitoring of the standardization efforts, the project focus was shifted towards 400G mini-super-channels – an approach that is now becoming the technology of choice for OIF.

At present, the technology of choice for coherent receivers is based on InP as it is almost mature. However, due to the extremely high pressure on the market because of prices, cost reduction actions are highly needed. The coherent receiver modules developed in the frame of the GALACTICO project have already shown that silicon photonic technology has the potential to highly reduce the costs. This is not only due to the fact that silicon technology has strong ability to reduce cost per die, but also because, compared to its InP counterpart where e.g. additional PBS optics are needed, fully functional chips (including PBS, 90° hybrids and PDs) at much smaller sizes can be realized. As a consequence of both, lower cost and miniaturization, silicon photonics technology can perfectly match the requirements for next generation devices and also opens an access to the emerging CFP module market.

In summary it can be stated that the lessons learnt via the GALACTICO project enable an efficient way for keeping or increasing the strong market position for coherent receivers as, due to the high cost pressure at the market, it is indispensable to reduce the complete manufacturing costs of the modules in order to keep the gross margin high. Furthermore, due to the extremely small footprint of the fully functional chips it offers a way for easy integrating inside CFP modules needed for the upcoming pluggable transceiver market.

Manufacturing

IHP and TUB have established the JointLab initiative - a research collaboration relationship for technology transfer from academia to industry. In order to sustain and further develop the technology transfer process, the two organizations are seeking for activities that will trigger photonics R&D focusing on the industrialization of silicon photonics technology with fabrication done using a qualified BiCMOS toolset.

Within the third year of GALACTICO, the technology transfer from TUB to IHP has been concluded through the design and fabrication of nano-waveguide coherent receiver chipsets. The nano-waveguides are fabricated using the IHP foundry BiCMOS toolset and the receiver chips re-present a 100-fold chip real estate reduction with respect to low/medium contrast photonic integration platforms (e.g. silica on silicon) that require specialized fabrication facilities. The IHP – TUB collaboration was effective in realizing the project's strategic decision (taken during Y2) to switch from the SOI micro-meter scale rib waveguide technology to the nano-meter scale waveguide SOI platform in order to overcome chip size and manufacturability issues. Part of the photonic circuit design and chip characterization was done at TUB and the chip fabrication was done at IHP. The incorporation of Ge diodes fabricated at IHP on the nano-waveguide coherent receivers, has opened the way for monolithic silicon coherent receiver chips that combine high performance with low production cost. The value chain was completed ideally with the assembly of the chipsets into standardized coherent receiver modules by U2t-DE, a European leader in the development and commercialization of receiver modules. Going beyond the lifetime of the project, the target is to investigate the further steps required so that the process/foundry service becomes qualified for commercial production as well as to address the production qualification of the new receiver components.

GALACTICO has been pivotal at the first steps of IHP toward industrialization of Silicon photonics technology. Today, there are several international entities promising Silicon photonic commercialization to potential customers. Most efforts focus on pure SiPh PIC (photonic integrated circuit) technology, i.e. without drive and receive electronics. The reasons for that is speed limitation of CMOS technology, which requires very advanced CMOS nodes (both bulk and SOI) to achieve the transisitor frequency required for future line rates. Since the commercial case for full SiPh integration in CMOS technologies is not clear, there is a push for advanced packaging technologies to integrate SiPh with electronics (copper nail technology or microbumps and through Si-via (TSV) technology). These approaches are less compatible with SME-type prototype and development strategies due to involved costs and the problems associated with IP safety.

Here IHP developments discriminate from all other providers. IHP targets front-end integrated photonic BiCMOS. The advantages of photonic BiCMOS are in tight integration and high-speed bipolar transistors, offering next generation performance capabilities at reduced NRE (non-recurring engineering) costs. The Germanium photodetector development undertaken within the project has been a key element for the first generation of fully integrated receivers in photonic BiCMOS.

Several preliminary requirements for industrialization of IHP photonic BiCMOS technology have been addressed in course of the project due to the development targets defined by the consortium partners.

2. Use and dissemination of foreground

This section describes the dissemination measures, including any scientific publications relating to foreground generated during project execution. Information and public-domain results were facilitated through the following dissemination mechanisms:

- ✓ Project website
- ✓ Issuing of press releases
- ✓ Interviews with analysts
- ✓ Organization of events
- ✓ Publishing of technical publications (invited and contributed)
- ✓ Project posters and flyers
- ✓ dissemination through electronic or printed media (mainstream technology websites and magazines)

Depending on the nature of the audience in each action, different aspects and information was conveyed for reaching the scientific community, the industry and the general public.

Scientific Publications

	Year - Conference	**Paper title**
	2014	
1	SPIE Ph West 2014	Stefanos Dris, Christos Spatharakis, Paraskevas Bakopoulos, Ioannis Lazarou, Hercules Avramopoulos, “Blind SNR estimation for QAM constellations based on the signal magnitude statistics,” accepted for presentation at SPIE Photonics West, San Francisco, USA, Feb. 1-6, 2014.

2	SPIE Ph West 2014	Ioannis Lazarou, Christos Spatharakis, Vasilis Katopodis, Stefanos Dris, Paraskevas Bakopoulos, Bernhard Schrenk, Hercules Avramopoulos, “Ioannis Lazarou, Christos Spatharakis, Vasilis Katopodis, Stefanos Dris, Paraskevas Bakopoulos, Bernhard Schrenk, Hercules Avramopoulos,” accepted for presentation at SPIE Photonics West, San Francisco, USA, Feb. 1-6, 2014.
	2013	
3	ICTON 2013	Marcel Kroh et al., "Photonic-Electronic platform for next generation optical transport network," In Proc. ICTON '13, We.c2.1, pp.1-5, Cartagena, Spain, 2013.
4	ICAIT 2013	L. Zimmermann et al., "Mixed technology platform for terabit optical Ethernet applications," in Proc. ICAIT '13, pp.149-150, Singapore, Aug. 24–25, 2013.
5	ACP 2013	Sascha Fedderwitz, Tino Brast, Karsten Voigt, Giovani Preve, John Lazarou, Stefanos Dris, Paraskevas Bakopoulos, Hercules Avramopoulos, Lars Zimmermann, Andreas Steffan, "Cost-Efficient SOI Hybrid Coherent Receiver," accepted for presentation at Asia Communications and Photonics Conference (ACP), Bejing, China, Nov. 12-15, 2013.
6	ECOC 2013	L Stampoulidis, E Giacoumidis, M F O'Keefe, I Aldaya, R G Walker, Y Zhou, N Cameron, E Kehayas, A Tsokanos, I Tomkos, N J Doran, L Zimmermann; “Cost-effective Broadband GaAs IQ Modulator Array for Long-Reach OFDM-PONs”, paper We.1.F.4
7	FiO 2013	Freude et al, “Non-linear nano-photonics”, Conference Paper Frontiers in Optics Orlando, Florida United States October 6-10, 2013, Nonlinear Optics in Micro/Nano-Optical Structures II (FTu4C)
8	OFC 2013	First Monolithic GaAs IQ Electro-optic Modulator, Demonstrated at 150 Gbit/s with 64-QAM, Dietmar Korn, Philipp C. Schindler, Christos Stamatiadis, Matthew F. O'Keefe, Leontios Stampoulidis, Rene M. Schmogrow, Panagiotis Zakynthinos, Robert Palmer, Nigel Cameron, Yi Zhou, Robert G. Walker, Efstratios Kehayas, Ioannis Tomkos, Lars Zimmermann, Klaus Petermann, Wolfgang Freude, Christian Koos, and Juerg Leuthold, OFC 2013, PDP

9	OFC 2013	L. Stampoulidis, M.F. O'Keefe, E. Giacoumidis, R. G. Walker, Y. Zhou, N. Cameron, E. Kehayas, I. Tomkos, L. Zimmermann, Proc. Optical Fiber Communication Conference and Exposition/National Fiber Optic Engineers Conference (OFC/NFOEC 2013), Fabrication of the First High-speed GaAs IQ Electro-optic Modulators Arrays and Applicability Study for Low-Cost Tb/s Direct-Detedction Optical OFDM Networks.
10	FOTONICA 2013	D. Roccato, M. Quagliotti, E. Riccardi and A. Pagano "Network scalability and techno-economic issues in next generation optical networks: results from the Galactico project", paper A4.6, 15. Nat. Conf. of Phot. Techn., FOTONICA 2013, Milano, Italy, May 2013.
11	JLT 2013	P. Schindler, et al, Monolithic GaAs Electro-Optic IQ Modulator Demonstrated at 150 Gbit/s with 64QAM, Lightwave Technology, Journal of (Volume:PP , Issue: 99)
	2012	
12	ECOC 2012	S. Dris, et al, "Flexible Optical QAM Generation with a Low-Complexity Amplified InP SOA/EAM-Based Modulator", 16-20 September, Amsterdam, Netherlands, 2012.
13	ECOC 2012	S. Dris, et al, "Octary QAM as Capacity Extension for Coherent UDWDM PON", 16-20 September, Amsterdam, Netherlands, 2012.
14	GFP 2012	L. Zimmermann et al., "Hybrid Integration of Coherent Receivers for Terabit Ethernet on SOI Waveguide PLC", ThA, 29-31 Aug, San Diego, California, 2012.
15	NOC 2012	C. Spalter, "Advances in Networking", TS6, Vilanova i la Geltru, Spain, June 2012.
16	CLEO 2012	S. Dris, et al, "Frequency Offset Estimation in M-QAM Coherent Optical Systems Using Phase Entropy", CF1F.2, May 6, San Jose, California, 2012.
17	OFC 2012	S. Dris, et al "Phase Entropy-Based Frequency Offset Estimation for Coherent Optical QAM Systems", OTu2G.4, March 4, Los Angeles, California, 2012.

18	Opt. Lett.	Bernhard Schrenk, Stefanos Dris, Paraskevas Bakopoulos, Ioannis Lazarou, Karsten Voigt, Lars Zimmermann, and Hercules Avramopoulos, "Flexible quadrature amplitude modulation with semiconductor optical amplifier and electroabsorption modulator," Opt. Lett. 37, 3222-3224 (2012).
	2011	
19	ECOC 2011	K. Voigt et al, “Fully passive Si-photonic 90° hybrid for coherent receiver applications”, Tu.3.LeSaleve.3, Sept. 2011, Geneva, Switzerland, 2011.
20	SPIE Ph West 2011	L. Stampoulidis et al, “Hybrid photonic integrated circuits for faster and greener optical communication networks”, Proceedings Vol. 7941, San Francisco Jan. 2011.
21	IEEE Photonics Society Summer Topicals 2011	L. Stampoulidis et al, “The European Galactico project: Coherent Terabit Ethernet systems using 4 µm rib waveguide silicon-on-insulator technology and GaAs electro-optic modulators” Page(s): 151-152, 18-20 July 2011, Montreal, Canada, 2011.
22	PTL 2011	K. Voigt et al, "C-Band Optical 90 Hybrids in Silicon Nanowaveguide Technology."

Exhibition booths

	Exhibition	Beneficiary involved	Activity
1	ECOC 2013 UK	U2t	Exhibtion of GaAs IQ modulator prototype
2	OFC 2013 US	U2t	Brochure distribution Live demo of GaAs IQ modulator prototype
3	ECOC 2012 Amsterdam	U2t Constelex	Brochure distribution Live demo of GaAs IQ modulator prototype

4	OFC 2012 US	U2t	Brochure distribution
5	ECOC 2011 Geneva	U2t Constelex ICCS/NTUA (EURO-FOS)	Brochure distribution Exhibition of silicon photonic hybrid prototype
6	OFC 2011	U2t ICCS/NTUA	Brochure distribution Exhibition of silicon photonic hybrid prototype

Workshops

	Where	**Beneficiary involved**
1	39th International Symposium on Compound Semiconductors 2012	U2t. Speaker: Andreas Umbach
2	OIDA 2012: Photonic Integration for Advanced Modulation Format Transmission at 100Gb/s and Beyond – Status of the Industry and Challenges Ahead	U2t. Speaker: Andreas Umbach
3	ECOC 2011: Optical integration, Workshop 2, ECOC 2011, Sun, 18 Sept., 2011	U2t. Speaker: Andreas Umbach
4	OFC 2011 US: Photonic Integration: More Technologies than Applications? Category 8. Optoelectronic Devices	U2t. Speaker: Steve Clements
5	ECOC 2010: Workshop on Petabit Routing	Constelex. Speaker: Leontios Stampoulidis

Standardization bodies

	Standardization body	**Beneficiary involved**

1	- Optical Internetworking Forum – OIF - International Telecommunication Union – ITU-T - Institute of Electrical and Electronics Engineers - IEEE 802.3 - Metro Ethernet Forum – (MEF) - European Telecommunication Standards Institute – ETSI - Internet Engineering Task Force – IETF - Telecommunications Industry Association - TIA	Coriant Chair in OIF physical layer working group (PLUG)
2	Optical Internetworking Forum – OIF	U2t

Other dissemination activities

	Type	Type of Audience - Activity description	Beneficiary involved
1	Presentation	**Students higher education**: Presentation to members of the Electrical Engineering Students European Association EESTEC	Constelex
2	Presentation	**General Public**: Invited presentation to Entrepreneurship& Carrier Forum 2012 session trend in micro/nano technology.	Constelex
3	Presentation	**Industry Aerospace sector - European Space Agency (ESA)**: GALACTICO presentation to ESA telecom managers (ESA premises)	Constelex
4	Presentation	**Students - high school**: Presentation to students of the Greek YES Program - Youth Entrepreneurship Summer Program	Constelex
5	Presentation	**Students - University:** dissemination to undergraduate and post-graduate students	ICCS/NTUA, TU Berlin
6	Interview	**General public:** GALACTICO technical manager interview in BBC. “Greek geeks seek hi-tech recovery”.	Constelex

7	Interview	**General public:** GALACTICO technical manager interview in ARD German radio station, “Made in Germany” program of Deutsche Welle TV and «ΗΜΕΡΗΣΙΑ» high circulation Greek newspaper.	Constelex
8	Interview	**Industry ICT sector, Industry photonic components:** "u2t Photonics pushes balanced detectors to 70GHz", GazettaByte http://www.gazettabyte.com/home/2013/6/6/u2t-photonics-pushes-balanced-detectors-to-70ghz.html	U2t
9	Interview	**Industry ICT sector, Industry photonic components:** u2t Photonics: Adapting to a changing marketplace, GazettaByte http://www.gazettabyte.com/home/2010/12/23/u2t-photonics-adapting-to-a-changing-marketplace.html	U2t
10	Press echoing	**Industry ICT sector:** General: 3/2013: Palomar Communications,"High-Speed Optical Networks: Breakthrough Modulators in New Material" http://blog.palomarcomm.com/post/47378230009/high-speed-optical-networks-breakthrough-modulators-in	All, echoing from OFC 2013
11	Press echoing	**Industry ICT sector:** 7/2/2011: Semiconductor Today: Nokia Siemens joins EC’s GALACTICO 100GbE transponder project http://www.semiconductor-today.com/news_items/2011/FEB/NOKIA_070211.htm	Coriant
12	Press echoing	**Industry ICT sector:** 7/2/2011: Optical Keyhole: NSN joins EC GALACTICO project developing integrated silicon-based photonic circuits http://www.opticalkeyhole.com/eventtext.asp?ID=102480&pd=2/7/2011&bhcp=1	Coriant
13	Press echoing	**Industry ICT sector:** 7/2/2011: Converge! Network Digest: NSN Joins GALACTICO Terabit Ethernet Project	Coriant

		http://www.convergedigest.com/2011/02/nsn-joins-galactico-terabit-ethernet.html	
14	Press echoing	**Industry ICT sector:** 23/11/2010: ICTplus covers participation of Constelex in GALACTICO (Greek) http://www.ictplus.gr/default.asp?pid=30&rID=12885&ct=1&la=1	Constelex
15	Press echoing	**General public:** http://www.bloomberg.com/apps/news?pid=newsarchive&sid=a.ddTMc09zVI	Coriant
16	Press echoing	**Industry ICT sector:** http://www.ttkn.com/technology/nokia-siemens-networks-supports-european-effort-to-develop-standardized-optical-ethernet-transponders-8198.html/	Coriant
17	Press echoing	**Industry ICT sector:** http://www.opticalkeyhole.com/eventtext.asp?ID=102480&pd=2/7/2011&bhcp=1	Coriant
18	Press echoing	**Industry ICT sector:** http://www.highbeam.com/doc/1G1-255840149.html	Coriant
19	Press release	**Industry ICT sector:** 14/2/2013: TILAB press release: "Galactico opens the way for future high-capacity Terabit Ethernet networks" http://www.telecomitalia.com/tit/en/innovation/hot-topics/international_projects/Galactico-opens-way-for-future-high-capacity.html	TILAB
20	Press release	**Industry ICT sector:** 15/11/2010: Telecom Italia Labs announces GALACTICO (English/Italian) http://77.238.10.113/tit/en/innovation/hot-topics/international_projects/progetto-galactico.html	TILAB
21	Press Release	**R&D and Industry photonics sector:** 1/1/2011: IHP Microelectronics announces participation in GALACTICO http://www.ihp-microelectronics.com/en/research/technology-platform-for-wireless-and-broadband/projects/galactico.html http://www.ihp-microelectronics.com/en/infocenter/news-center/press-	IHP

		releases/article/project-galactico-will-push-silicon-photonics-for-tbit-ethernet.html	
22	Press Release	**Industry ICT sector:** 7/2/2011: Nokia Siemens Networks announces participation in GALACTICO (English)	Coriant
23	Press release	**Industry photonics:** http://www.constelex.eu/index.php/press-releases/27-designing-the-next-generation-terabit-optical-ethernet	Constelex
24	Flyers	GALACTICO brochure distributed in exhibition booths	Constelex
25	Flim/video	GALACTICO youtube video	Constelex
26	Film/Video	GALACTICO Turin trial video	TILAB