PROJECT FINAL REPORT

Grant Agreement number: 257377

Project acronym: C3PO

Project title: Colourless and Coolerless Components for low Power Optical Networks

Funding Scheme: CP (Collaborative Project)

Period covered: from 1/6/2010 to 31/11/2013

Name, title and organisation of the scientific representative of the project's coordinator: Professor Paul Townsend

Tel: +353 (0) 21 490 4857

Fax: +353 (0) 21 490 4880

E-mail: paul.townsend@tyndall.ie

Name, title and organisation of the scientific representative of the project's technical manager: Dr Efstratios Kehayas

Tel: +30 211 800 5152

Fax: +30 211 800 5565

E-mail: ek@constelex.eu

Project website address: www.greenc3po.eu

Contents

List of abbreviations

AC	Alternating Current
AGC	Automatic Gain Control
AWG	Arrayed Waveguide Grating
B2B	Back to Back
BER	Bit Error Rate
BIANCHO	BIsmide And Nitride Components for High temperature Operation (FP7)
BiCMOS	Bipolar Complementary Metal–Oxide–Semiconductor
CD	Chromatic Dispersion
CLEC	Competitive Local Exchange Carrier
CML	Current Mode Logic
CST	Computer Simulation Technology
DC	Direct Current
DCF	Dispersion Compensating Fibre
DFB	Distributed Feedback (Laser)
DoW	Description of Work
DWDM	Dense Wavelength Division Multiplexing
E/O	Electro-Optical
EAM	Electro-Absorption Modulator
ECL	External Cavity Laser
EDFA	Erbium Doped Fibre Amplifier
ESD	Electrostatic Discharge
FC	Fibre Channel
FEC	Forward Error Correction
FSAN	Full Service Access Network
FTTx	Fibre To The “x”
G	Gain
Gb/s	Gigabit(s) per second
GbE	Gigabit Ethernet
GbEthernet	Gigabit Ethernet
ILEC	Incumbent Local Exchange Carrier
InP	Indium Phosphide
IP	*Depending on context:* *Intellectual Property* *Internet Protocol*
IPoDWDM	IP over DWDM
LAN	Local Area Network

NF	Noise Figure
NG-PON	Next Generation PON
NRZ	Non-Return-to-Zero
ODB	Optical Duobinary
OLT	Optical Line Terminal
ONU	Optical Network Unit
OSM	Optical Switch Module
OSNR	Optical Signal to Noise Ratio
OTDR	Optical Time Domain Reflectometer
PG	Pulse Generator
PIC	Photonic Integrated Circuit
PON	Passive Optical Network
PR	Public Relations
R&D	Research and Development
REAM	Reflective EAM
RF	Radio Frequency
ROADM	Reconfigurable Optical Add-Drop Multiplexer
RSOA	Reflective SOA
S&T	Scientific and Technical
SAN	Storage Area Network
SiGe	Silicon Germanium
SME	Small-Medium-Enterprise
SMF	Single Mode Fibre
SOA	Semiconductor Optical Amplifier
SPI	Serial Peripheral Interface
TBF	Tuneable Bandpass Filter
TE	Transverse Electric
TIA	Trans-Impedance Amplifier
VOA	Variable Optical Attenuator
VSB	Vestigial Sideband Modulation
WDM	Wavelength Division Multiplexing

1 Final publishable summary report

1.1 Executive summary

The C3PO project aimed to develop new generation of ‘green’ photonic components that can reduce the overall network power consumption, whilst enabling bandwidth growth and constraining cost. C3PO proposed a disruptive approach on designing new generation of Gbit access and 100Gbit metro networks, using a single cost-effective photonic integration platform and exploiting reflective active components and high-port count optical switches. C3PO hardware can be deployed for building next generation high-speed metro nodes collocated with optical access terminals, significantly reducing complexity and cost in architectures where fibre reaches the end-user. Design work carried out by photonic and electronics experts has led to new approaches in developing optoelectronic components, with unified design rules and methodologies. These design rules introduce important optimizations on the component level that ultimately lead to lower power, highly integrated components with high efficiency. New reflective photonic arrays of modulators and lasers were developed, driven by new ultra-low power electronic drivers, making the complete system ideal for green network applications. C3PO also experimentally demonstrated the concepts of building dynamic metropolitan area networks at 100Gbit/sec and 10Gb/s fiber-to-the-home networks using such reflective photonic prototypes, verifying that the system and network concepts described can be successfully implemented. The strong exploitation potential of the project laid strong foundations for enhancing the European competitiveness in the global telecommunications market and ultimately leading to new high technology jobs for Europeans.

1.2 Project objectives

1.2.1 New energy-efficient networks required

The internet has become the ubiquitous tool that has transformed the lives of so many citizens across the world. Commerce, government, industry, healthcare and social interactions are all increasingly using internet applications to improve and facilitate communications. This is especially true for video-enabled applications, which now demand much higher data rates and quality from the data networks. High definition TV streaming services are emerging and these again will significantly push the demand for widely deployed, high-bandwidth services. FTTH networks are also being installed across Europe that give end customers access to data bandwidths (>100Mb/s) that used to be the preserve of telecom carriers entirely on their own.

In parallel, there is a growing need to reduce the energy consumption of such networks; reducing the power consumption of the optical components for such network equipment is very important, since each optical component can use significant power today (several Watts to 10's of Watts). The optical networks of today cannot be simply and cost-effectively scaled to provide the capacity for tomorrow's users. There is a serious photonic component perspective to the energy consumption issue – increasing the integration density of components will be severely limited if the optoelectronics cannot be run at high temperature without active cooling. Every watt of power consumed by the optoelectronics can be multiplied by a factor of 6 if we consider the power needed to drive the thermoelectric cooler to maintain a 25°C operating temperature and the power used by the air conditioning system to remove the generated heat from the building. Also, a recent trend is to increase the operating temperature of the electronics on equipment cards, with the aim of reducing rack cooling costs. This will obviously increase the power load on today's thermoelectric cooled optoelectronic devices, as they will have to work even harder at higher ambient temperatures.

1.2.2 Reducing power through reflective architectures

1.2.2.1 IPoDWDM and metro networks

Within the C3PO project, a radically different and power-efficient solution is proposed that is based on colourless, coolerless and reflective photonic integrated transceiver modules and optical switches. In one possible scenario (IPoDWDM), the C3PO 'linecards' are implemented using transceivers with reflective transmitters and can be directly mounted onto the IP router. The WDM channels required as inputs to the transceiver linecards are provided by a multi-wavelength laser source that plays the role of a centralized light source powering all transceivers on the router. When the "reflective" rationale of the technology is combined with a low-loss, NxN optical switch matrix, then unprecedented wavelength dynamicity can be offered to the transport network. Optical switches are interconnected with Arrayed Waveguide Gratings (AWGs) for providing any-to-any channel reconfiguration without the need for tuneable transmitters. Moreover, the array of reflective transceivers can be also used to create a 'reflective' Reconfigurable Optical Add Drop Multiplexers (ROADMs) that can achieve full re-configuration of Dense Wavelength Division Multiplexed (DWDM) channels without the need for any manual patching.

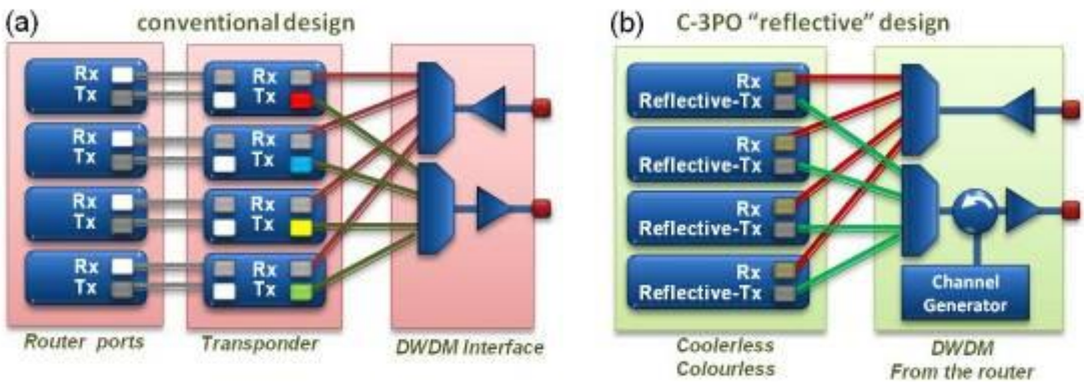


Figure 1: (a) conventional transport network design and (b) C-3PO architecture for DWDM linecards using reflective components and multi-wavelength optical source as "channel generator"

1.2.2.2 Access networks

A promising approach for building high-capacity access networks that circumvents the requirement for tuneable lasers is the employment of reflective photonic components used as the fundamental building block of Optical Line Terminals (OLTs) and optical network units (ONUs) that are "powered" by multi-wavelength optical sources. The OLT is housed at the central office (CO), and the transmitting part is based on reflective transmitter arrays with a multi-wavelength optical source providing all the required wavelengths. Such a multi-wavelength source is also used to provide carrier signals for the upstream signal in the WDM-PON. These CW channels (L-band wavelength range) are transmitted with the downstream modulated data (C-band wavelength range), and are modulated with user traffic at the ONU, where they are reflected back and fed into an array of receivers at the OLT. In this way, a transmitter is avoided at the customer end.

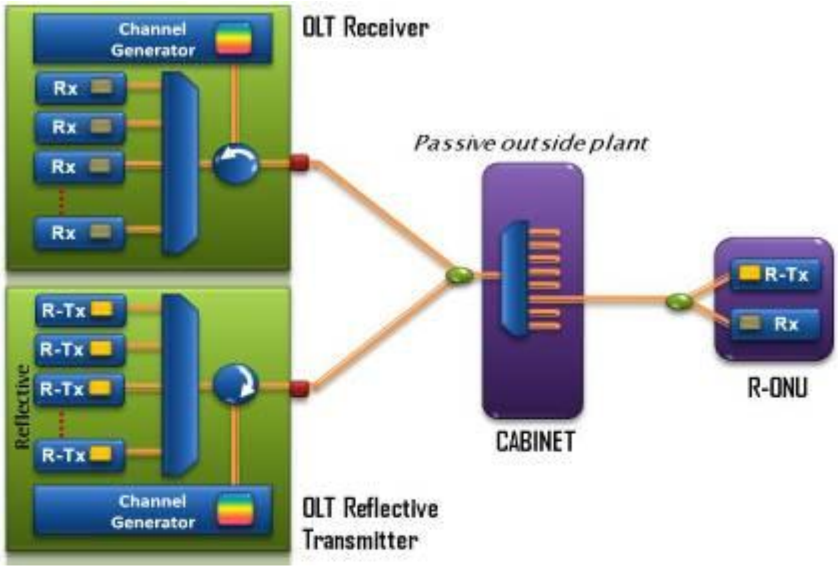


Figure 2: C-3PO WDM-PON design with low-cost, coolerless and colourless photonics at the OLT/ONU

1.2.3 S&T objectives

C3PO was an industry-driven project aiming to design and develop a new generation of energy-efficient photonic components and electronic ICs, hybrid photonic integrated circuits (PICs) and apply them to next-generation access and high-speed metro-core networks.

C-3PO objectives were to realize:

1) Coolerless & colourless reflective Indium Phosphide (InP) component arrays
2) Coolerless hybrid integrated multi-wavelength optical sources
3) Low-loss and athermal hybrid silica-on-silicon platform allowing for coolerless/semi-cooled operation
4) Record low-power SiGe BiCMOS driver arrays
5) Low-power optical switching components based on piezo beam steering technology

1.3 Project results

C-3PO systematically pursued the design, fabrication and assembly of new functional, low-cost and low-power PICs. These devices exploited Indium Phosphide material and Silicon Germanium BiCMOS electronics, integrated on a silica hybrid platform. The technology proposed and components developed share R&D costs as they can be applied in core, metro, access and storage area networks without the need for re-design or R&D costs per application.

In the following section, the project most significant results and highlights are presented.

1.3.1 InP reflective monolithic arrays

The reflective network sub-systems of C3PO rely on the design and development of Indium Phosphide reflective arrays as the active medium for light generation, amplification and modulation. C3PO's core active elements are Reflective Semiconductor Optical Amplifiers (RSOAs), monolithically integrated Reflective Electro-Absorption Modulators (REAMs) with SOAs, and array receivers. This simplification for the network architecture brings significant technical challenges for the InP devices to enable both coolerless and colourless operation, both in multiple quantum well materials used and in specific device design. The InP devices are particularly challenging to operate coolerless. Devices were developed in discrete form for the reflective single channel transceivers and ONUs, as well as in array form for the channel generators, array transmitters and receivers at the OLT. New generation of devices were developed and operated semi-cooled (40°C to 75°C), whereas full coolerless operation can be achieved by exploiting fundamental research performed within the complementary project BIANCHO.

1.3.1.1 InP SOA arrays

RSOA devices were designed and developed within the first two years of the project. These devices are capable of operating coolerless from 5° to 75°C and they are used as a gain element in the DWDM channel generator of the C3PO architecture. A range of device types and material systems have been investigated including both buried heterostructure and ridge waveguide devices with different material compositions.

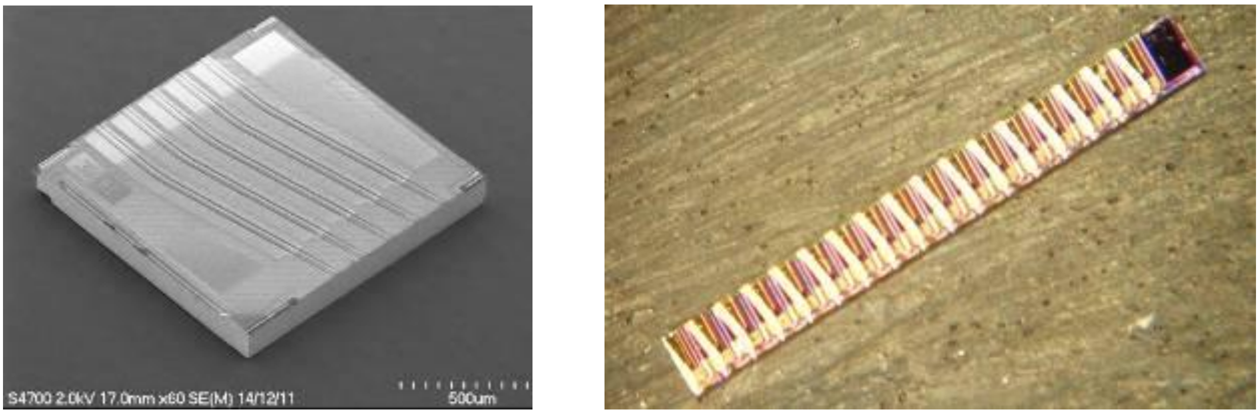


Figure 3: Reflective InP devices fabricated: RSOA array (left) and R-EAM-SOA array (right)

1.3.1.2 REAMs and R-EAM-SOAs

This activity within the C3PO project was to develop arrays of R-EAMs and R-EAM-SOAs necessary for realizing transmitters for access and metro networks respectively. The latter devices combine high speed electro-absorption modulator with the SOA into a compact, high performance monolithic chip. Both double buried heterostructures as well as ridge waveguide devices were investigated and fabrication of high performance chips ready to be hybrid integrated into dense photonic integrated chips was achieved.

1.3.1.3 InGaAs photodetectors

The aim of this activity within the project was to develop InGaAs photodetector arrays suitable for further integration with both planar lightwave circuits (PLC) and fibre arrays, co-packaged with electronic components. The key issues were:

- ✓ High responsivity
- ✓ fast carrier transit time
- ✓ Low voltage operation

Within the project both 10Gb/s and 25Gb/s detector arrays were successfully developed.

Figure 4: Photodetector arrays fabricated: 4x28G (left) and 10x11G (right)

1.3.2 Silicon Germanium BiCMOS electronics: highlights

C-3PO developed energy-efficient coolerless electronic driver arrays at the throughput of 100Gb/s (10 channels of 11Gb/s and 4 channels of 28Gb/s), by using advanced SiGe BiCMOS technology at a lower voltage and by employing innovative electronic circuit topologies and concurrent optimization of both electronics and photonics.

1.3.2.1 113Gb/s (10 x 11.3Gb/s) record-low power EAM driver arrays

Within C3PO, an array of 10 EAM drivers each operating at 10-11.3Gb/s was designed and fabricated, to achieve a total data rate of 113Gb/s. To the best of our knowledge such EAM driver arrays are not currently available on the open market, nor published in the literature. This is the first 10 channel driver array for EAMs and the lowest power consumption for an EAM driver so far reported, 50% below the state of the art.

The driver fabricated includes an input that is differentially matched to 100Ω, a predriver block to amplify the input signal and to drive the large capacitive input of the driver output stage. This predriver can also control the pulse width to compensate for the non-linearity of the (R)EAM. The predriver is directly followed by an EAM driver stage, which can control the bias current and modulation current of the EAM modulator. The control is implemented using a serial peripheral interface (SPI), which can set both the bias and modulation current with a 4-bit resolution. The bias and modulation current can be set independently for every channel to optimize the settings of the 10 EAMs according to the transmitted wavelength.

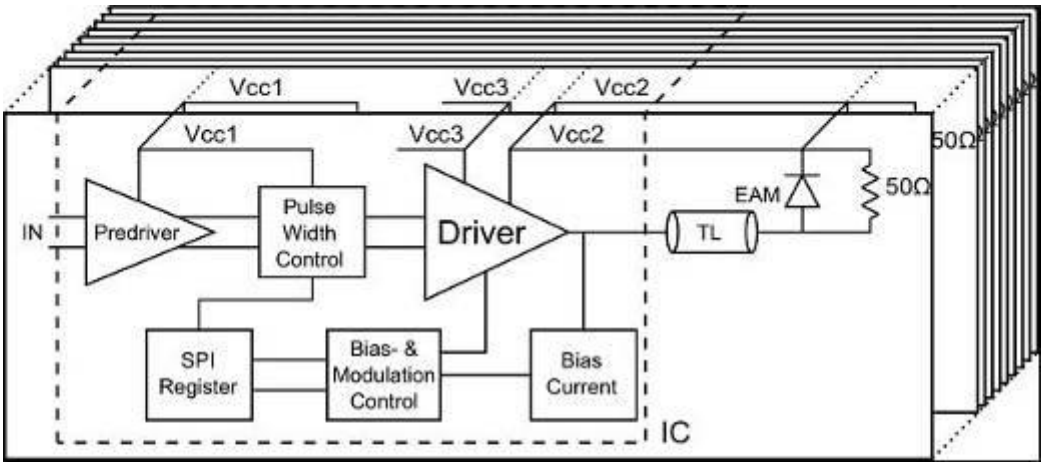


Figure 5: 10x11.3Gb/s EAM driver array block diagram

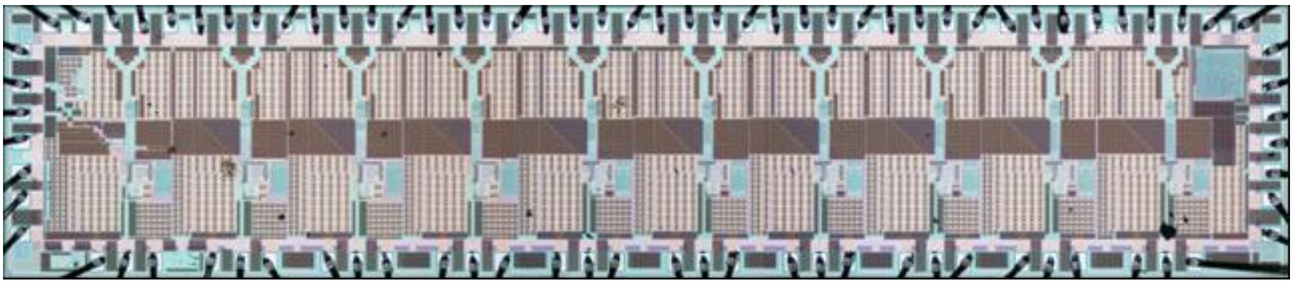


Figure 6: Photo of fabricated 10x11.3Gb/s EAM driver IC

1.3.2.2 2x28Gb/s DB R-EAM driver array

A 4x28.5Gb/s optical duobinary (ODB) transmitter (Tx) array was designed with a particular focus on the RF bandwidth and the electronic modulator driver with low power consumption. The 4x28Gb/s ODB IC was used to drive 4 monolithically fabricated R-SOA-EAM pairs, each in a Michelson interferometric structure. The 2-channel duobinary EAM driver arrays were to be connected to the motherboard by wire bonds. RF design work was required to optimise the performance of this driver to the EAM interface.

The duobinary driver consists of a predriver, an EAM driver, a bias current source, and an SPI register to control the bias and modulation current settings. In addition to a simple NRZ driver, the duobinary driver is more complex and also includes a duobinary precoder and a duobinary encoder.

- ✓ The duobinary precoder terminates the incoming differential data line and transforms the 28Gb/s NRZ signal into two drive signals for the dual-arm EAM. It ensures that the optical signal corresponds with the input signal (so that it is directly decoded by the NRZ receiver).
- ✓ The duobinary encoder encodes the 2-level signal into a 3-level duobinary signal. It shapes the drive signals to a certain bandwidth with minimum group delay variation.

Similar techniques that were applied to the 10x11Gb/s driver design were also followed for the design of the 28Gb/s drivers in order to achieve low-power consumption and sufficient bandwidth. The design realized within C3PO advanced the state-of-the-art for the 28Gb/s drivers by reducing the IC power consumption by 35% when compared to state-of-the-art EAM drivers.

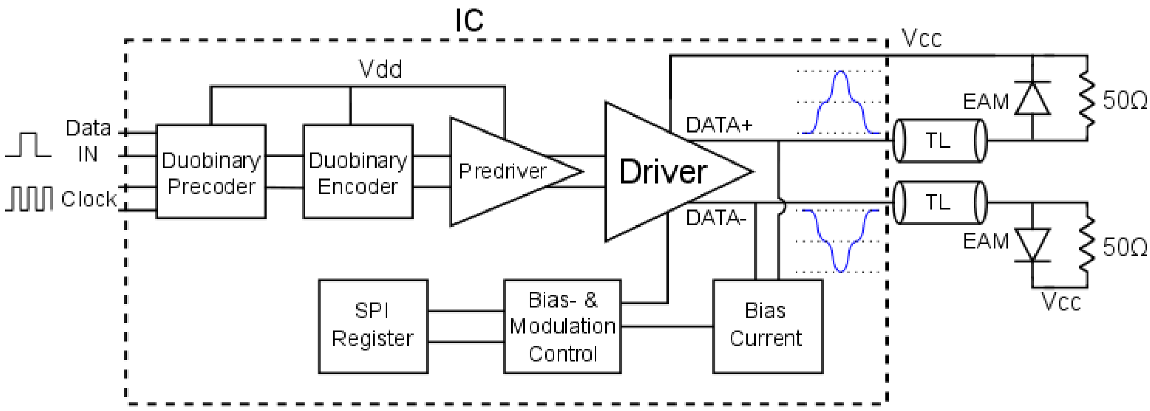


Figure 7: Block diagram of the 28.5Gb/s duobinary driver

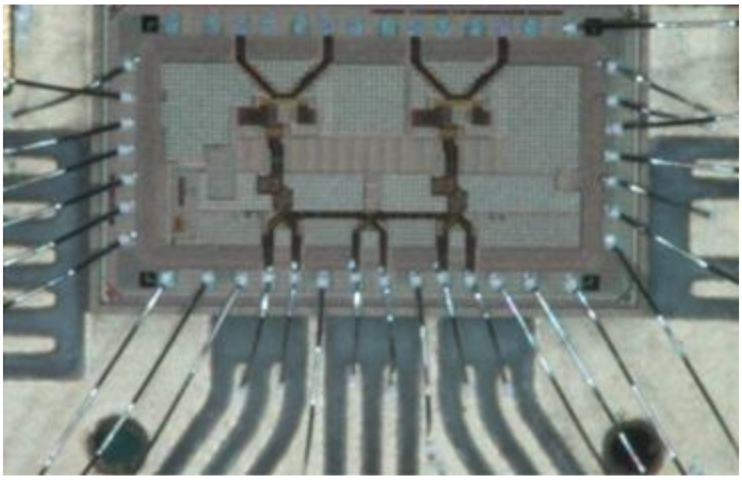


Figure 8: close-up of the bonded 28.5Gb/s duobinary driver die

1.3.3 Advanced hybrid photonic integrated Circuits

Achieving a practical path towards high level of photonic integration was a key driver within the C3PO project. The enabling technology was CIP's HyBoard™ platform that is designed for hybrid integration of InP active optoelectronic devices with passive planar silica waveguide devices. This platform has been successfully used in the past to develop functionally specific PICs, such as optical flip-flops, array regenerators, optical phase locked loops and tunable lasers.

Mode expanded and precision cleaved InP devices are passively assembled on micromachined silicon submounts against lateral and vertical alignment stops. This daughterboard is then passively assembled on the motherboard. The passive assembly is a key requirement for low cost. Current discrete devices are actively assembled with lensed fibres. This alignment and packaging constitutes ~70% of the final device costs and is the reason why this assembly work has been off-shored to low wage economies. In contrast, the HyBoard approach can be assembled using automated flip chip bonding machines providing a viable manufacturing route within Europe.

1.3.3.1 Integration of DWDM channel generator

The channel generator is an array of lasers integrated with a waveguide multiplexer. The channel number and channel spacing is determined by the arrayed waveguide grating used as the wavelength selective element in the design. Within C3PO, 5-and 10-channel devices covering the C- and L-bands were designed and developed.

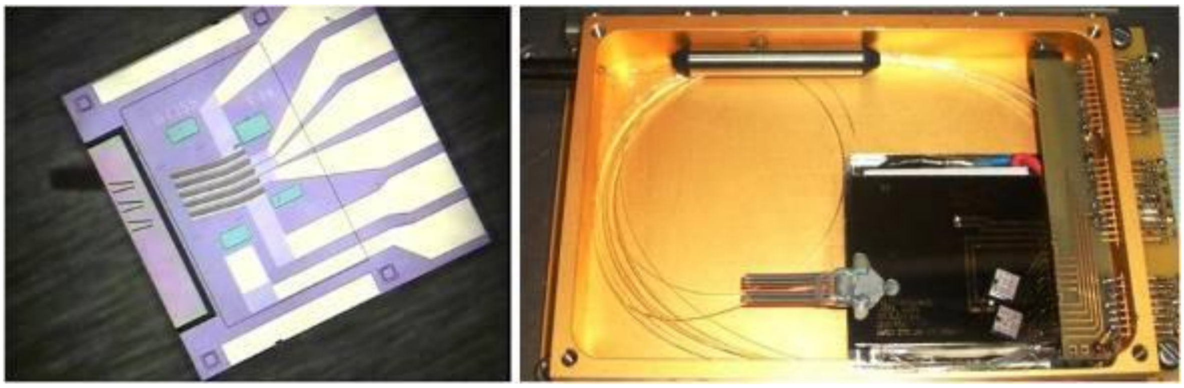


Figure 9: 10-channel multi-wavelength laser source developed within C3PO. Silicon daughterboard with quin SOAs (left) and assembled and pigtailed device (right)

1.3.3.2 Integration of hybrid 10x11Gb/s transmitter array

The multi-channel transmitter assembly is composed of a single array of ten ridge structure-based InP REAMs hybrid integrated on a PIC with an arrayed waveguide grating (AWG) multiplexer, and the 10×11.3Gb/s REAM driver array. The 10-channel AWG had 100GHz spacing and was athermalised using polymer filled slots to avoid wavelength drift with temperature. The REAM array was mounted on a silicon submount and aligned to the AWG silica planar motherboard. The integrated assembly featured a single input/output (I/O) fibre such that the transmitter operates in reflective mode. The transmitter was successfully evaluated in a system environment and exhibited record-low power consumption.

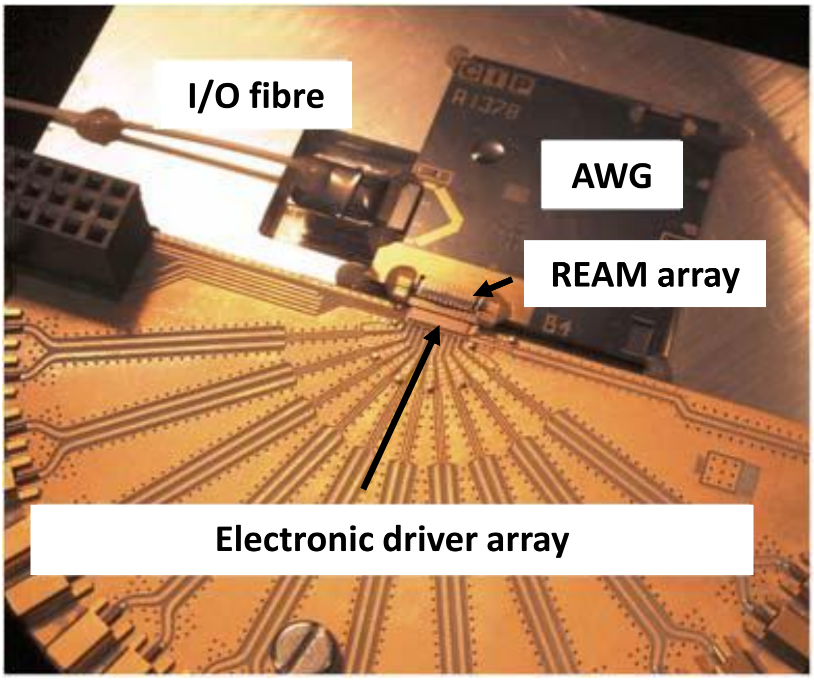


Figure 10: Photograph of the 10x11Gb/s transmitter assembly

1.3.3.3 Integration of 10x11Gb/s receiver array

Based on the network architecture of C3PO, a 10-element array operating at 10Gb/s is required for the realization of a high-speed access network based on WDM-PON topology. Within the frames of C3PO a new 10x11Gb/s arrayed receiver device was developed, based on hybrid integration of photodiode arrays with Transimpedance amplifier arrays.

Figure 11: Assembled 10x11Gb/s receiver array (left) and close-up of bonded IC and PDs

1.3.3.4 Integration of hybrid 4x28Gb/s duobinary transmitter array

An ODB multi-channel transmitter module was designed and fabricated within the C3PO project with application in low-cost 100Gb/s metro networks. The transmitter design relies on hybrid integration and assembly of monolithic R-EAM-SOA arrays, SiGe BiCMOS driver arrays and an AWG. The REAM-SOAs are mode expanded buried heterostructure devices, whereas the packaged device only needs a single fibre input and output at the east and west sides of the PLC motherboard respectively.

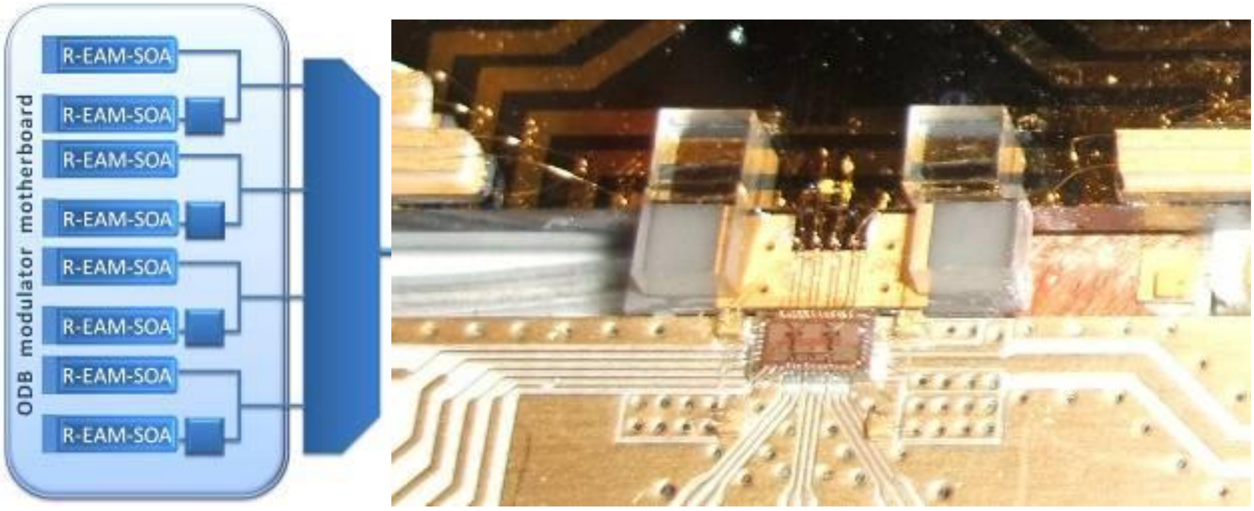


Figure 12: 4x28Gb/s ODB transmitter block diagram (left) and close-up of assembled array (right)

1.3.3.5 Integration of hybrid 4x28Gb/s receiver array

High-speed photodetector arrays were developed within C3PO, supporting the 100Gb/s metro application scenarios. The photodetector array was flip-chipped onto a silicon daughterboard which was subsequently flip-chipped onto the silicon motherboard. This technique can enable passive alignment if sufficient control of device, daughterboard and motherboard dimensions is achieved together with a sufficiently precise assembly process. The Rx connects to the motherboard/daughterboard assembly with wire bonds. The distances between the photodiode and the electronics were kept to a minimum in a hybrid integrated assembly to meet the high bandwidth requirement. Electrical and optical crosstalk between Rx channels was minimised to limit the associated Rx sensitivity penalty.

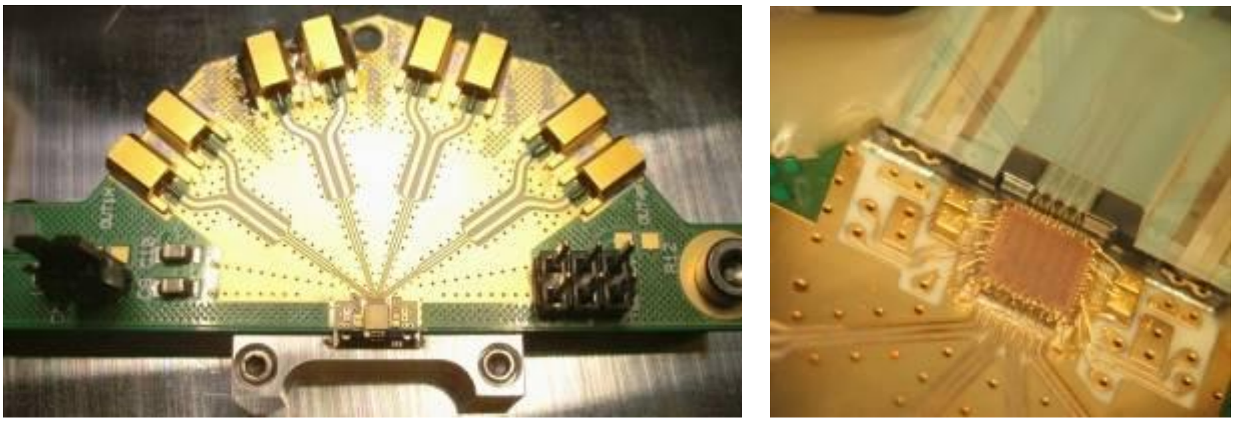


Figure 13: Assembled 4x28Gb/s receiver array (left) and close-up of the bonded ICs with PDs

1.3.4 Low-loss optical switches

The unique, patented, Polatis DirectLight technology was employed for developing low-power and high-port count switches within the project. The switching technology combines piezoelectric actuation with integrated position sensors to provide non-blocking connectivity between 2D arrays of collimated fibres directly in free space, thus avoiding the performance impairments associated with conventional MEMS micro-mirrors. Switching occurs completely independently of the power level, colour or direction of light on the path, enabling pre-provisioning of dark fibre and avoiding concatenation of switching delays across mesh or multi-stage switched optical networks.

Within C3PO, the following techniques were employed for reducing power consumption of DirectLight optical matrix switches:

- Adapting control update rate to maintain required optical performance in any given operating environment
- Matching analogue and power block capacity to desired reconfiguration rates
- Updating control processors to those with advanced power management features
- Including some measure of thermal and vibration isolation to minimise the need for active position control

Implementation of the above optimizations can reduce power consumption of a 96x96 OXC from the current 35W to the range 5-20W through use of power-aware control methods which can ultimately can be applied to any required matrix size. Within C3PO a 32x32 OXC was developed for use in system level performance evaluation of IPoDWDM network nodes. Moreover, power management features were incorporated to new controller architectures for larger OXCs (>80x80) for introducing 4-10x power saving.

1.3.5 System-level performance evaluation

1.3.5.1 Reflective ODB transmitter at 10Gb/s

The prototype REAM-based PIC was demonstrated to support error-free 10Gb/s DB transmission over 215km of standard single-mode fibre (SSMF) with comparable performance to an off-the-shelf LiNbO3 Mach-Zehnder modulator. A continuous wave (CW) optical carrier (wavelength λ=1550nm) was generated using an external cavity tuneable laser and injected into the reflective modulator through its polarisation-maintaining input fibre. The heater in one of the arms of the Michelson interferometer is biased in order to provide a $\pi/2$ phase shift, which resulted in the optical signal in one arm experiencing a π phase shift relative to the other after the double pass through the modulator. Both REAMs were modulated at 10Gb/s with non-return-to-zero (NRZ) data ($2^{31}-1$ pseudo random bit sequence (PRBS)) superimposed on a DC bias. One REAM is driven with the NRZ data, while the other is driven with the logically inverted NRZ data (i.e. the device operates in ‘push-pull’ configuration). Both 10Gb/s NRZ data signals are filtered with fourth-order Bessel-Thomson low-pass filters (LPFs), with a −3dB bandwidth of 2.5GHz or 2.8GHz (depending on the case), before modulating the REAMs. The quasi-three-level waveforms generated by low-pass filtering are used to drive the REAMs between the high-, intermediate-, and low-reflecting states.

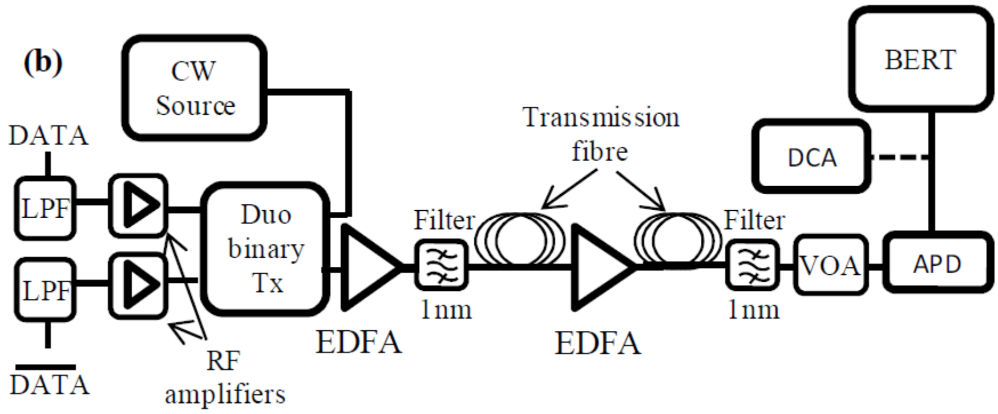


Figure 14: Experimental setup for evaluating the integrated single channel ODB at 10Gb/s

BER less than 10^{-10} was achieved for distances up to 215km with no error floors present. For transmission distances greater than 240km, an error floor begins to appear at the relatively low error rate of 10^{-9}, due to chromatic dispersion, which causes inter-symbol interference and subsequent eye closure. A commercial LiNbO3 MZM optimised for duobinary operation was tested over the same transmission distances. The performance of the reflective modulator compares very favourably with the commercial device. The transmitted duobinary eye diagrams for the reflective modulator (using 2.5GHz LPFs) from B2B up to 215km are shown below. It can be noted significant eye opening is obtained for distances up to 215km.

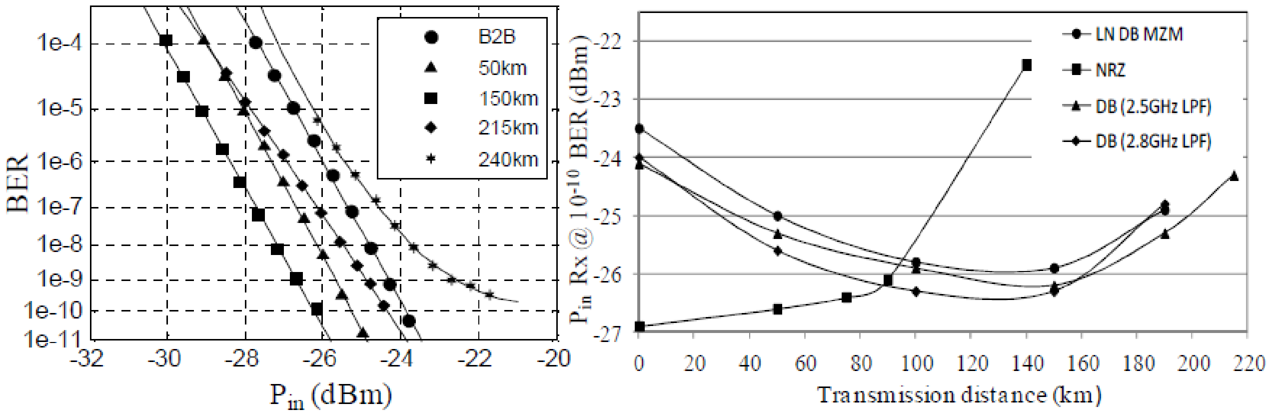


Figure 15: (left) BER as a function of receiver power (Pin) for the reflective modulator; (right) Pin at 10^{-10} BER as a function of transmission distance

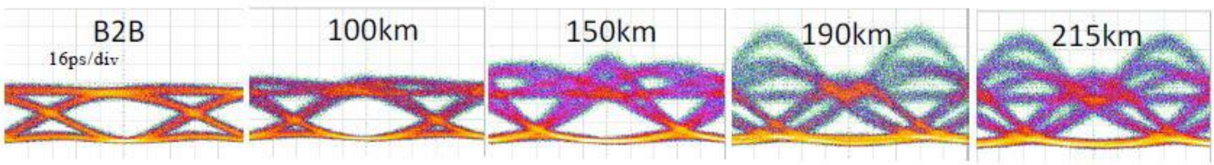


Figure 16: Transmitted DB eye diagrams corresponding to the DB modulator performance over a representative set of transmission distances

1.3.5.2 Reflective ODB transmitter at 25Gb/s

The C3PO fabricated ODB prototype device was performance evaluated at 25Gb/s to assess applicability in 100Gb/s metro networks using 4x25Gb/s optical signals. The figure below shows the experimental setup for generating and evaluating the 25.3Gb/s DB modulated signals.

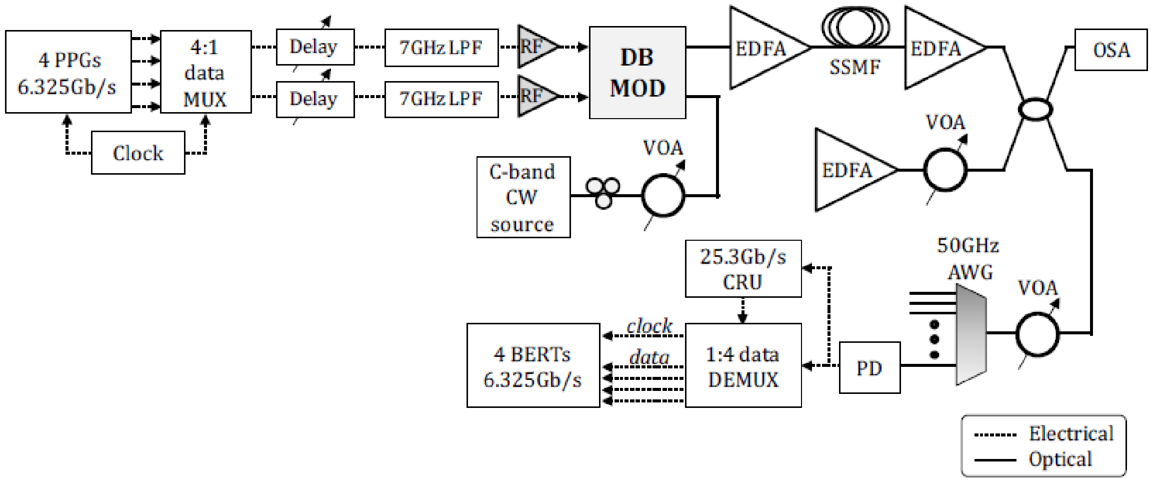


Figure 17: Experimental setup for the ODB modulator's 25.3Gb/s performance evaluation

The OSNR is degraded by increasing the ASE power from the third EDFA, and the BER is measured for a representative set of transmission lengths. The BER as a function of the required OSNR at λ=1549.65nm is given below. The measured OSNR penalty for the B2B case at BER=10^{-3} is within 2dB of the expected theoretical value for DB modulation with a MZM and similar receiver bandwidth. This penalty is likely attributed to slight patterning on the one level, resulting in some eye closure. We observe the reduction in required OSNR expected with DB transmission as the distance increases initially from 0km to 16km, and subsequent increase for distances beyond 16km. Error-free operation (with an average BER<1×10^{-12}) is maintained up to 35km. A significant change in the BER curve's slope is observed at 41km, indicating the likely onset of an error floor below a 10^{-9} BER (measurement limited by maximum achievable OSNR). This performance degradation is due to chromatic dispersion, causing inter-symbol interference and subsequent eye closure. This is consistent with prior results obtained at 10Gb/s, as the dispersion-limited reach at 25.3Gb/s is reduced by approximately the square of the bit rate. The optical eye diagrams at 25.3Gb/s (λ=1549.65nm) at six representative transmission lengths are shown below. A substantial eye opening is achieved at all distances except for 41km, where the transmitted eye is significantly degraded.

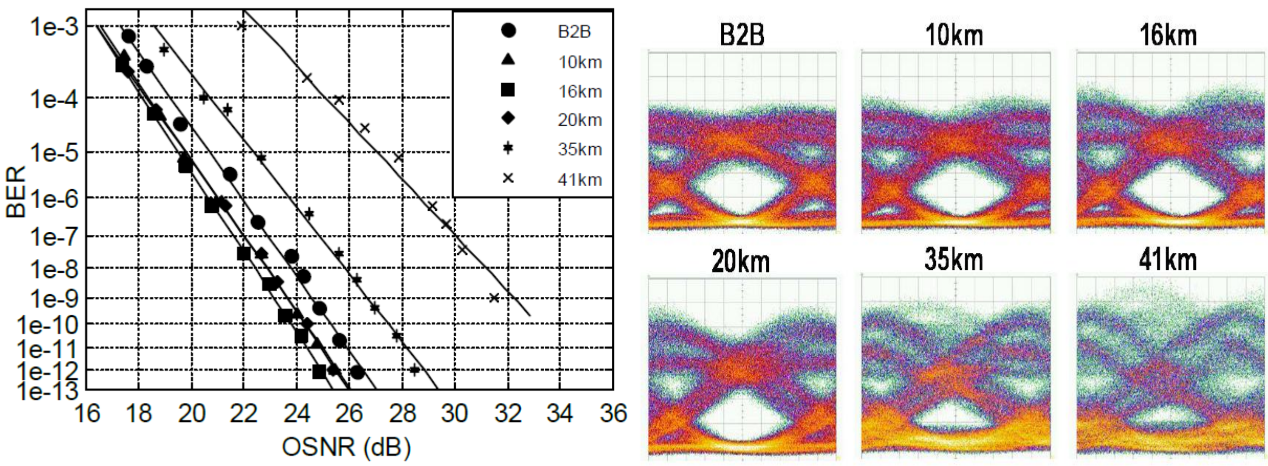


Figure 18: BER as a function of the required OSNR for the reflective modulator generating 25.3Gb/s duobinary modulated signals and for operation at λ=1549.65nm (left) and 25.3Gb/s optical eye diagrams corresponding to the indicated SSMF lengths for modulator operation at λ=1549.65nm (right)

The colourless nature of the DB modulator is further validated in a similar fashion by evaluating the BER performance as a function of the measured OSNR at the greatest error-free distance (35km), for several wavelengths in the C-band on the 50GHz ITU grid. The BER curves for four representative wavelength channels between 1535.04nm and 1560.61nm and the OSNR required to achieve a BER of 1×10^{-10} for eight uniformly spaced wavelengths is shown below. We see that comparable performance is achieved within the anticipated operating spectrum of the device, noting a small 1.2dB difference in OSNR values within this >25nm span. Measurements were not feasible at wavelengths shorter than 1535nm due to the vicinity of the REAM band-edge, which leads to high device insertion loss.

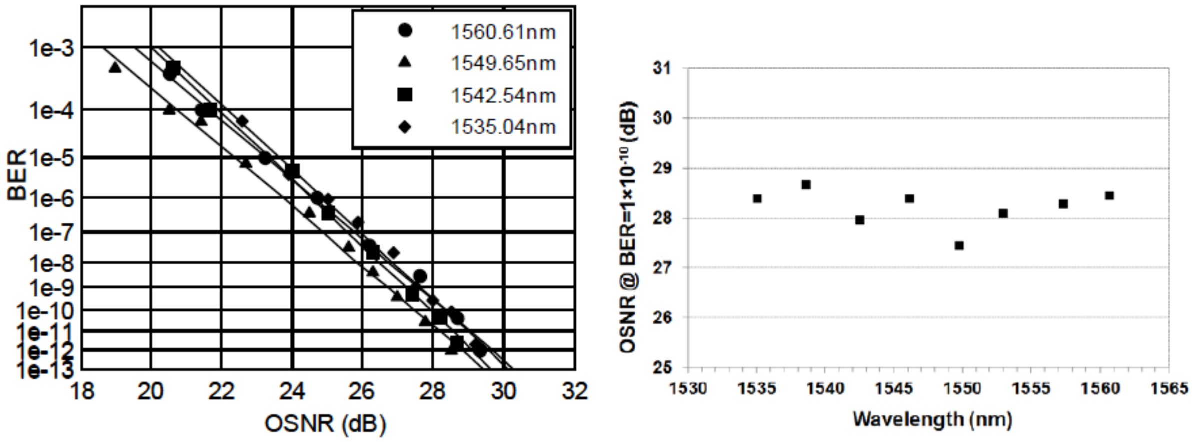


Figure 19: BER as a function of required OSNR for four wavelengths covering the C-band (left) and OSNR as a function of wavelength, for eight channels spanning the C-band, attesting to the DB modulator's colourless operation at 25.3Gb/s (right)

1.3.5.3 Multi-Channel 11.3Gb/s Integrated Reflective Transmitter for WDM-PON

The fabricated 10x11Gb/s transmitter was evaluated in a testbed to assess performance in a system environment. External cavity lasers were used to generate the required C-band CW carriers aligned to the transmitter's internal 100GHz AWG. The optical carriers were passively combined and injected into the reflective transmitter (TX) via a circulator which was connected to the assembly's I/O fibre. The 11.3Gb/s nonreturn-to-zero (NRZ) (2^{31}-1 pseudorandom bit sequence (PRBS)) drive signals for the transmitter array were simultaneously generated by separate de-correlated pulse pattern generators (PPGs). Each channel used a differential drive with a DC- or AC-coupled 500mVpp swing.

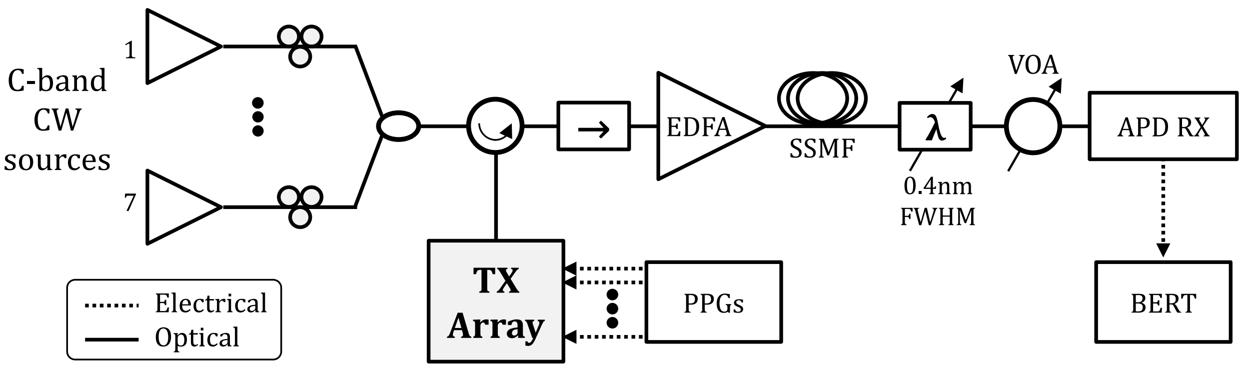
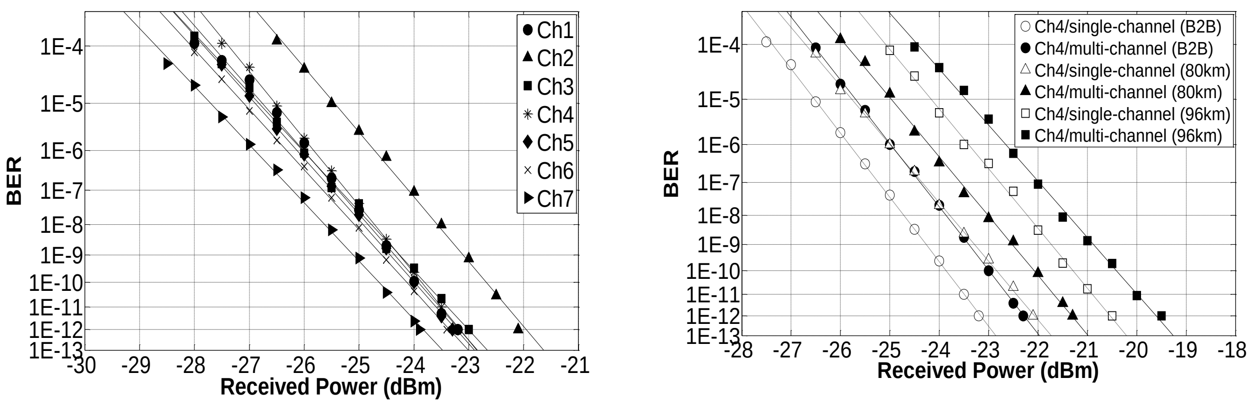


Figure 20: Experimental setup for evaluating the integrated transmitter array at 11.3Gb/s

The transmitter's modulated signals emerge from the output port of the circulator. Owing to the relatively high dynamic insertion loss of the arrayed assembly (approximately 25dB per channel), these output signals are then amplified by an erbium-doped fibre amplifier (EDFA). The array's transmission performance was evaluated using SSMF lengths varying from 0km (back-to-back (B2B)) to 96km. At the receive side, a tuneable wavelength filter with 0.4nm full-width half-maximum (FWHM) emulated the bandwidth of a 100GHz AWG and minimised the amplified spontaneous emission falling on the receiver (RX). The chosen wavelength channel was sent to a variable optical attenuator (VOA), then to a 10Gb/s APD RX coupled to a bit-error-rate tester (BERT) for BER analysis. The optical-signal-to-noise ratio was kept sufficiently high (>28dB) such that the receiver thermal noise floor provided the dominant impairment in the system. Error-free operation of each channel is achieved with BERs<1×10^{-12}, demonstrating comparable sensitivity performance across all the channels with a maximum of <2dB difference in sensitivity. The single-channel B2B optical eye diagrams for the seven channels were clear and open. The arrayed transmitter's multi-channel performance was also evaluated by operating all seven channels simultaneously. No error floor results from multi-channel operation, indicating no discernible crosstalk effects in the array. After 80km, the intended reach for WDM-PON applications, we observe an approximate 1dB power penalty for the target channel. This 80km transmission reach is consistent with prior results of EAMs at 10Gb/s. Further, error-free performance is maintained for distances up to 96km for both the single- and multi-channel cases. At these distances, the performance degradation is due to chromatic dispersion, which results in intersymbol interference and thus some eye closure. The extra <1dB penalty that arises from concurrently operating several channels seen in back-to-back is preserved at both 80km and 96km.



(a) **(b)**

Figure 21: (a) BER as a function of received power for each channel in single-channel operation at 11.3Gb/s (back-to-back) and (b) BER as a function of received power for the target channel (Ch4) in single-channel and multi-channel operation

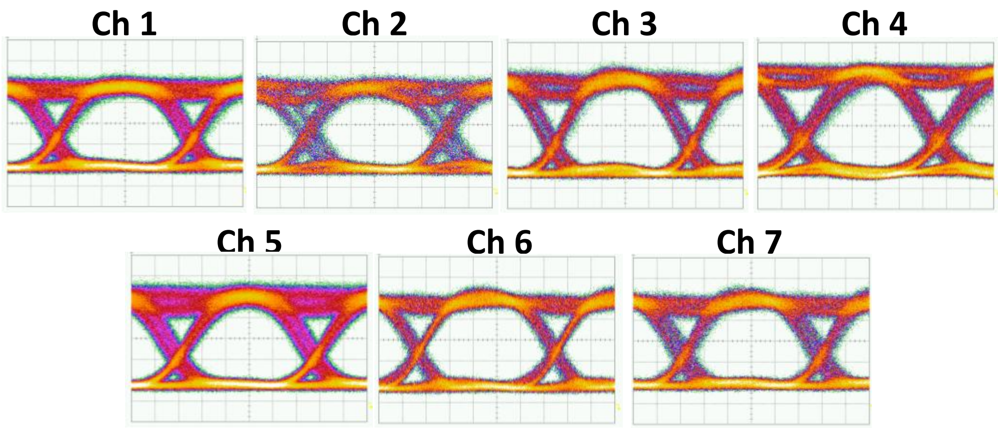


Figure 22: The 11.3Gb/s optical eye diagrams in single-channel operation (back-to-back, 15.2ps/div)

1.3.5.4 Multi-channel 4x25 Gb/s transmitter for metro networks

The test set-up for the multichannel transmitter is as shown in Figure 17, but with the electrical low pass filters removed (as the transmitter incorporates the new DB driver circuitry). At the time of writing characterisation of the transmitter is ongoing, but initial results have confirmed high speed 3-level electrical DB modulation of one of the EAM channels in a modulator pair as illustrated in Figure 23. The waveform shows the expected 3 electrical DB levels with the lower eye regions compressed due to the non-linearity of the EAM amplitude transfer function. The upper eye regions are clear and open indicating good potential for successful optical DB modulation performance under dual arm, interferometric operation. Work is currently ongoing to explore if this is possible with the current prototype.

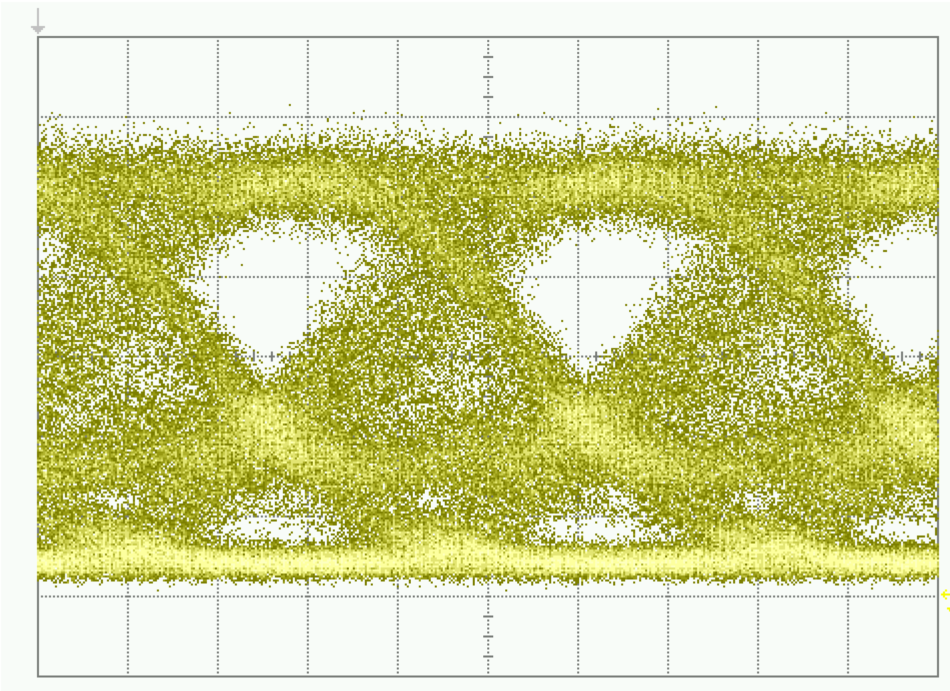


Figure 23: 25.3 Gb/s eye diagram (Single EAM channel, 10ps/div)

1.3.5.5 The C3PO WDM-PON

The WDM-PON system is identical in layout to the characterisation experiment shown in Figure 20, but with the DFB array replaced by the C3PO integrated comb source and the single APD receiver by the 10x11.3Gb/s integrated receiver. The system emulates the optical line terminal (OLT) equipment that generates the downstream channels in the WDM-PON. In a full system the array receiver would also be located at the OLT to detect the upstream channels, but here for simplicity we test its operation using the downstream channels. At the time of writing the receiver has been reworked following a fault and is awaiting test. If successful operation is achieved the WDM-PON experiment will be implemented.

1.3.5.6 The C3PO metro network

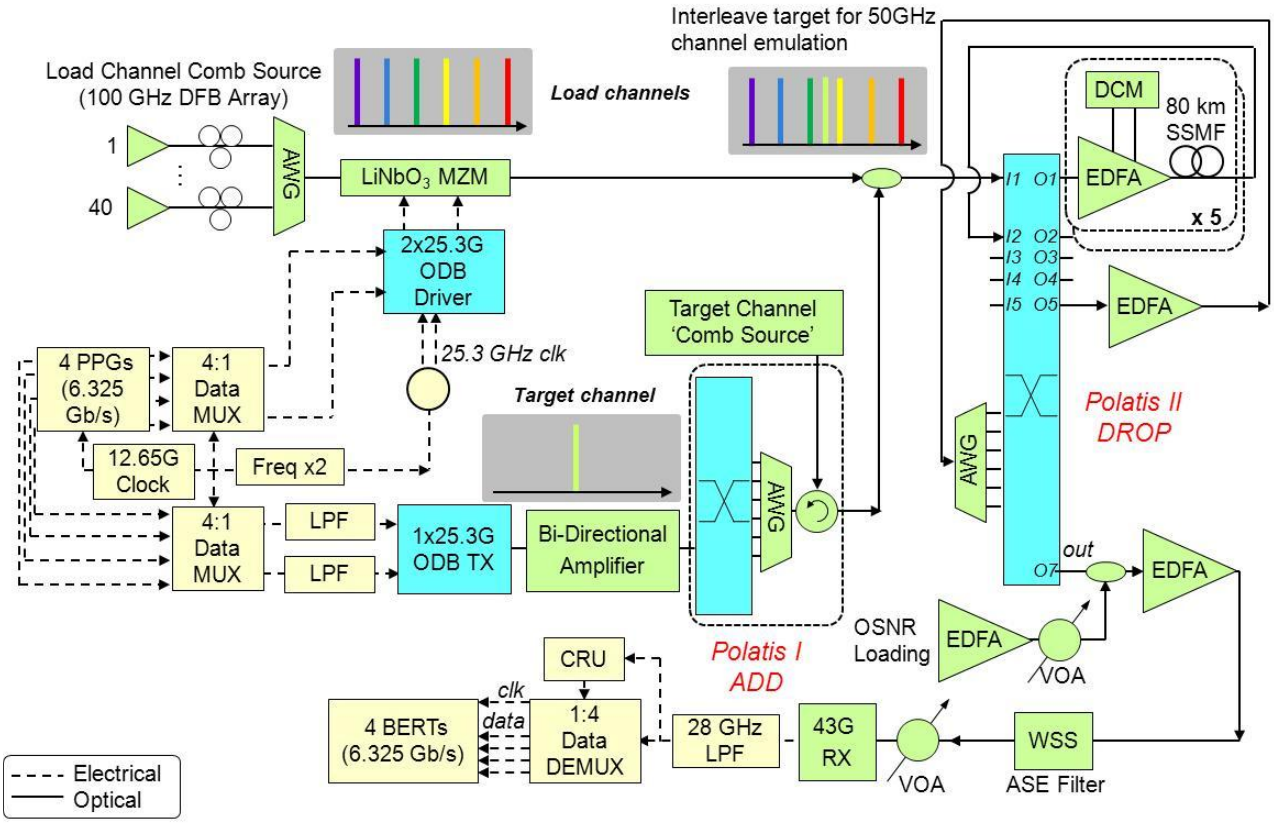


Figure 24: Metro network testbed (C3PO components shown in blue)

The C3PO metro network testbed is illustrated in Figure 24. Starting from the upper left hand part of the diagram, a 100GHz-spaced comb source based on an array of DFB lasers generates 40 continuous wave (CW) carriers which are uniformly spread across the C-band. These channels are modulated with 25.3Gb/s ODB data using a lithium niobate Mach-Zehnder modulator, which is driven by a C3PO ODB driver circuit. The differential drive signals (NRZ , 2^7-1 pseudo random bit sequence - PRBS) for the ODB driver are generated by electrically multiplexing the waveforms from the four pulse pattern generators (PPGs) of an Anritsu MP1800 BER tester (BERT), each running at 6.325Gb/s. These wavelengths are designated as load channels, which are used to fully load the erbium doped fibre amplifiers (EDFAs) in the metro fibre link. The C3PO ODB single channel modulator (as described in section 1.3.5.1) is used together with an emulated comb source to generate a target channel which is used for BER analysis. The target channel is interleaved with the load channels to emulate a system with 50GHz channel separation. The Polatis space switch (Polatis 1), selects any target wavelength for modulation (emulating the ROADM Add function). The target and load channels are multiplexed together and preamplified by an EDFA before being launched into the metro fibre. The latter, consists of five 80km spans of standard (G.652) single mode fibre (SSMF), linked by amplification nodes consisting of dual stage EDFAs with mid-stage dispersion compensating fibre modules (DCMs - the system is nominally fully compensated). A second Polatis space switch (Polatis II) is used to switch spans in and out of the transmission path in order to test the reach dependence of the system. The output from the final selected link is routed to an AWG which demultiplexes all channels into further unused ports of the switch in order to emulate the ROADM Drop function. The target channel selected by the switch is then detected by the 25Gb/s Receiver (Rx) and passed to the BERT for error rate evaluation following clock recovery (CRU) and electrical demultiplexing. An additional EDFA and variable optical attenuator (VOA) are also added to the input to the space switch to enable the system to be loaded with controllable levels of amplified spontaneous emission (ASE) to allow the BER performance to be evaluated as a function of optical signal to noise ratio (OSNR).

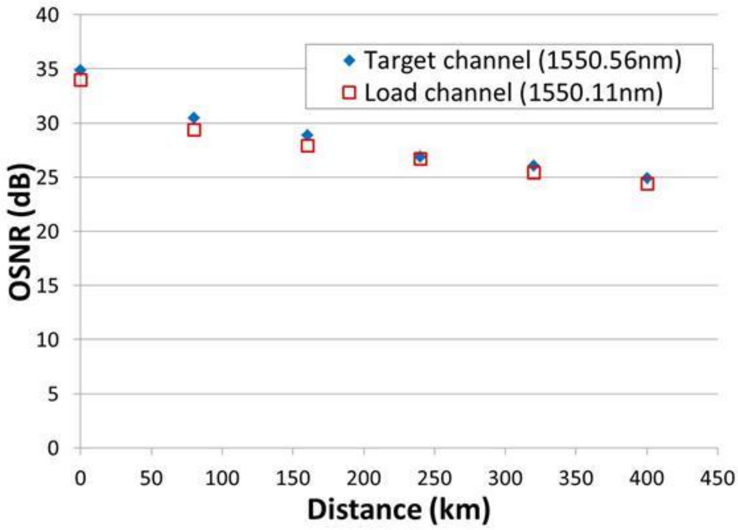


Figure 25: OSNR vs. distance for neighbouring target and load channels

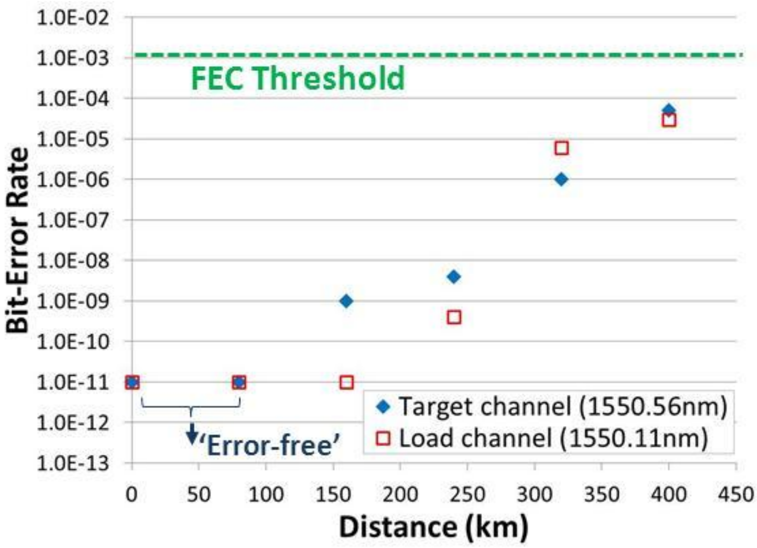


Figure 26: BER vs. distance for neighbouring target and load channels

The results shown in Figures 25 (OSNR) and 26 (BER) for two neighbouring channels show that below FEC-threshold BER performance can be obtained up to the maximum 400km reach, which is representative of typical metro network spans. Furthermore, the performance of the hybrid REAM-based ODB modulator (target channel) performance is found to be broadly comparable to that of the commercial Lithium Niobate MZM (load channel) within experimental variations. Finally, error free operation (defined as BER $<10^{-11}$) was attained for the first uncompensated 80km span as required for short reach applications using low cost transceivers which do not incorporate FEC. Further investigations are currently underway to determine the relative contributions of residual dispersion, non-linearities and OSNR reduction to the observed performance degradation with increasing span. Finally, subject to successful demonstration, the multichannel 28Gb/s ODB modulator and multichannel 28Gb/s receiver will also be incorporated into the system.

1.4 Potential impact

C-3PO coherently brought together five European companies, four of which were SMEs, under a technology-intensive research project that addressed the highly competitive area of photonics in telecommunications. The technology advancement on the photonic components level has created promising market opportunities in the domain of high-speed optical access and metro networks employing reflective components and sub-systems. Successful outcomes from this project would promote Europe as the leader in these new low-power, cost-effective network approaches.

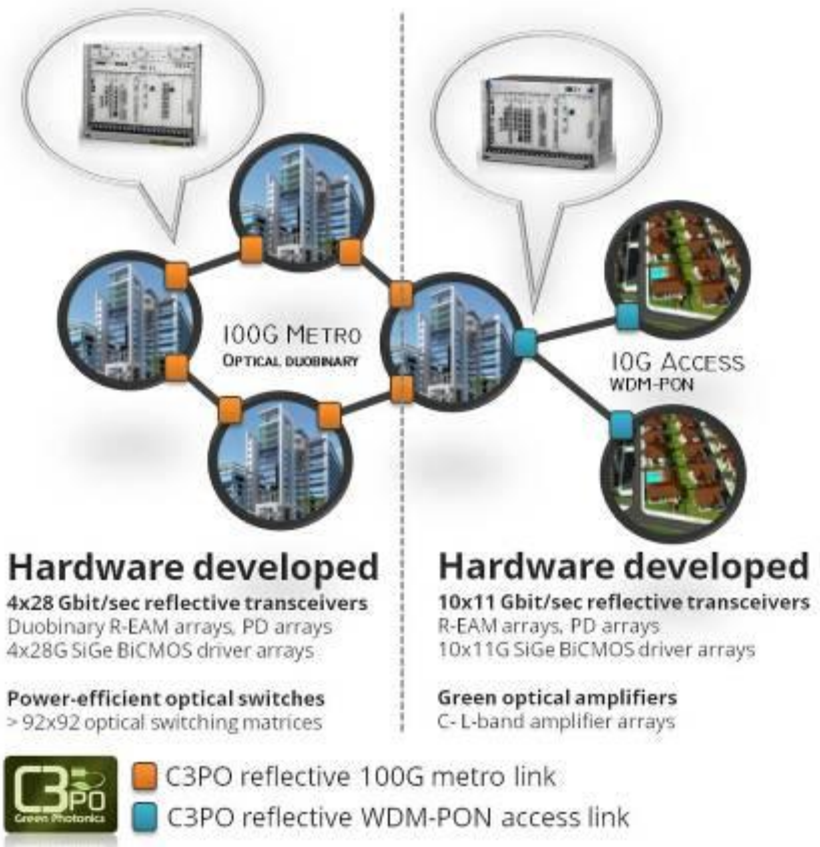


Figure 27: C3PO application scenarios

1.4.1 Application of C3PO technology

C3PO research activities focused on the design and development of a new family of low-power reflective transceivers and optical switches. The system integration of these components could lead to a new method for designing line-side and client-side equipment for 1-10Gb/s access and 100Gb/s metro networks. Hence, C3PO can have a competitive advantage in the following applications:

- ✓ **Short-reach optical networks** focusing on Local area and Storage area networks (LAN/SAN), inter-office and data-centre connectivity, where the use of DWDM creates the necessary bandwidth “highway” required.
- ✓ **Metropolitan transport networks** using C3PO alternative design approach based on low-cost and low-power reflective transceiver implementation combined with high-port count

optical switching for offering the flexibility sought by network operators. Using a high-port count and low-loss bidirectional switch, multi-degree and colourless add-drop multiplexers can also be designed as add-ons to existing networks.

- ✓ **WDM-PON access networks**, where wavelength-to-the-user can be offered by exploiting hybrid photonic integration capabilities and the on-chip capacity scaling possible. The integration of reflective transceivers in combination with a multi-wavelength channel generator, all on the same chip opens the way for high-capacity and low-cost OLT implementations.

1.4.2 C3PO-enabled future systems

1.4.2.1 Metro line-side equipment

C3PO focused on low-cost alternatives for building high-capacity links in the metro area, with ADVA leading the R&D road-mapping from a commercial point of view. The reflective transmitters and receiver arrays, combined with multi-wavelength source can be system integrated for creating a new family of hot pluggables for use in 4x28Gb/s line-card equipment. Moreover, development of 80x80- up to 256x256- port switching matrices can lead to versatile reflective ROADMs with low loss and power consumption and when combined with the reflective transmitters can lead to a new family of IPoDWDM line/client-side equipment.

1.4.2.2 OLT/ONU access equipment

Using the same hybrid integration platform and InP technology of C3PO, new generation of WDM-PON equipment can also be developed. Specifically, high-density, OLT reaching 400 Gb/s on-chip capacity with a few tens of millimetres of footprint is within the technological reach of C3PO for realizing WDM-PON links.

1.4.3 C3PO component applicability

On the component-side, C3PO systematically pushed photonic integration forward through the following activities and fronts:

1.4.3.1 Indium Phosphide and SiGe BiCMOS

C3PO in collaboration with ICT-BIACHO pushed the operational temperature of InP active devices aiming to achieve completely coolerless operation. Advancements in InP fabrication technology achieved within C3PO can be applied for the development of reflective components and modules based on RSOAs, REAMs and R-EAM-SOAs. Moreover, the design and development of arrays of high-speed and low-power electronic arrays achieved within C3PO represents a significant advancement in state-of-the-art with world-record power consumption values achieved within the lifetime of the project.

1.4.3.2 Hybrid integration platform

The applications addressed by C3PO impose stringent requirements on the photonic and electronic layer in terms of cost, power consumption and on-chip capacity. C3PO fundamental “vehicle” for realizing all the components within the project was the hybrid integration of InP elements (discrete and arrays) on a silica motherboard through intermediate silicon boards. C3PO hybrid integration technology increases on-chip capacity, functionality and total number of components, a prerequisite for achieving cost and power scaling. The application of hybrid integration is expected to be a more cost effective alternative to discrete DWDM transceivers. Integrated OLT transceivers for WDM-PON could ultimately be a high volume market.

1.4.3.3 Piezo-based beam steering

Research on piezoelectric beam steering components has a straight-forward exploitation path on the component level, as this is an important milestone for opening up several applications on the system-level within the telecoms and defence markets through the development of ROADMs and cross-connects in general.

1.4.4 Technology scalability

The combination of photonic components and electronics hybrid integrated into functional PICs can lead to cost effective solution for both metro as well as access networks.

1.4.4.1 Optical Line Terminal with 400Gb/s capacity

Employing C3PO photonic technology a cost-effective and power-efficient OLT can be designed using different C3PO PICs system integrated into linecards. The table below shows a comparison of a 400Gb/s OLT that uses C3PO technology and conventional photonic components.

<table>
<tr><th rowspan="2">TX/RX</th><th rowspan="2">Commercial (11G XFP)</th><th colspan="2">C3PO</th></tr>
<tr><th>Project Target</th><th>Achieved</th></tr>
<tr><td>Chip throughput</td><td>11 Gb/s</td><td>100 Gb/s</td><td>100 Gb/s</td></tr>
<tr><td rowspan="4">Power consump-tion</td><td rowspan="4">140 W
(cooled)

Based on XFP-MSA standard <3.5W/11G

scaled to 400G</td><td rowspan="4">20 W
(un-cooled)</td><td>C3PO (semi-cooled)</td></tr>
<tr><td>40 W
<u>Comb Source:</u>
4W RSOAs (0.1W per RSOA)
10W TECs (2.5W TEC per 10 element RSOA array)
<u>Modulator:</u>
4W REAM-SOAs (0.1W per REAM-SOA)
10W TECs (2.5W TEC per 10 element REAM-SOA array)
8.8W EAM driver (220mW per EAM)
<u>Receiver:</u>
3.2W TIAs (80mW per channel)</td></tr>
<tr><td>Long-term potential (C3PO + BIANCHO)</td></tr>
<tr><td>20W (un-cooled)
As above with TEC power consumption (20W) removed</td></tr>
</table>

Figure 28: C3PO scalability to 400G for OLT in access networks

1.4.4.2 100 Gb/s ODB metro networks

By employing the C3PO 4x28G ODB transceiver solution, the high-port count optical switches and the channel generator module, cost-effective direct-detection transmission systems can be built. The table below shows the performance of C3PO reflective transceiver solution compared to commercial electronic ICs and prototype photonic components reported in literature.

TX/RX	**Project Target**	**Achieved**	**State-of-the-art (III-V LAB R-EAM-SOA & GigOptix driver + Discovery TIAs)**
Chip t/p	100 Gb/s	100 Gb/s	50 Gb/s
Modulation format	4x25Gb/s ODB	4x25Gb/s ODB	(2x) 50Gb/s RZ-DQPSK
Spectral efficiency (bits/sec/Hz)	0.5	0.5	0.5
On-chip actives	8	8	4
Power	Modulator SOAs = 0.8 W Drivers 2.5 W TEC = 10 W Receiver TIAs = 0.36 W	Modulator SOAs = 0.8 W Drivers = 2.6 W TEC = 5 W Receiver TIAs = 0.36 W	Modulator SOAs + TECs = 24 W Drivers = 12 W Receiver TIAs = 0.8 W (x2 for 100G)
Total Power	**~13.7 Watt**	**~8.8 Watt**	**~37 Watt**

Figure 29: C3PO 100G solution for metro networks

1.4.4.3 Optical switches

The necessary re-configurability of C3PO network architectures can be achieved by using high port count, low-loss and low back-reflection switching matrices. Such an optical switch is a vital part of C3PO's reflective re-configurable metro nodes. The following table shows the performance achieved within C3PO lifetime.

	Project Target	**Achieved**	**State –of-art (POLATIS)**
Port count	80x80	192x192	32x32
Power	200mW/port	90mW/port	550mW/port
Median Loss	< 1dB	<1 dB	< 0.7dB (<1.4dB max)

Figure 30: C3PO optical switch performance metrics

1.5 Project website

1.5.1 Website address

The project website (www.greenc3po.eu) is maintained by Constelex.

Figure 31: C3PO homepage screenshot

1.5.2 Website statistics

The project website has been operational from the beginning of the project execution. Throughout the project lifetime, the website received more than 3,700 visitors (absolutely unique visitors >2.640) and more than 11,500 page views. The geographical distribution of the incoming traffic reveals that visitors are accessing the website through 85 countries with USA, Greece, UK, Ireland and Belgium in the top five, followed by Japan, Germany and China. The statistics also show a relatively high average time spent on site with almost 4 pages per visit, whereas more than half of the traffic is new visitors (70%).

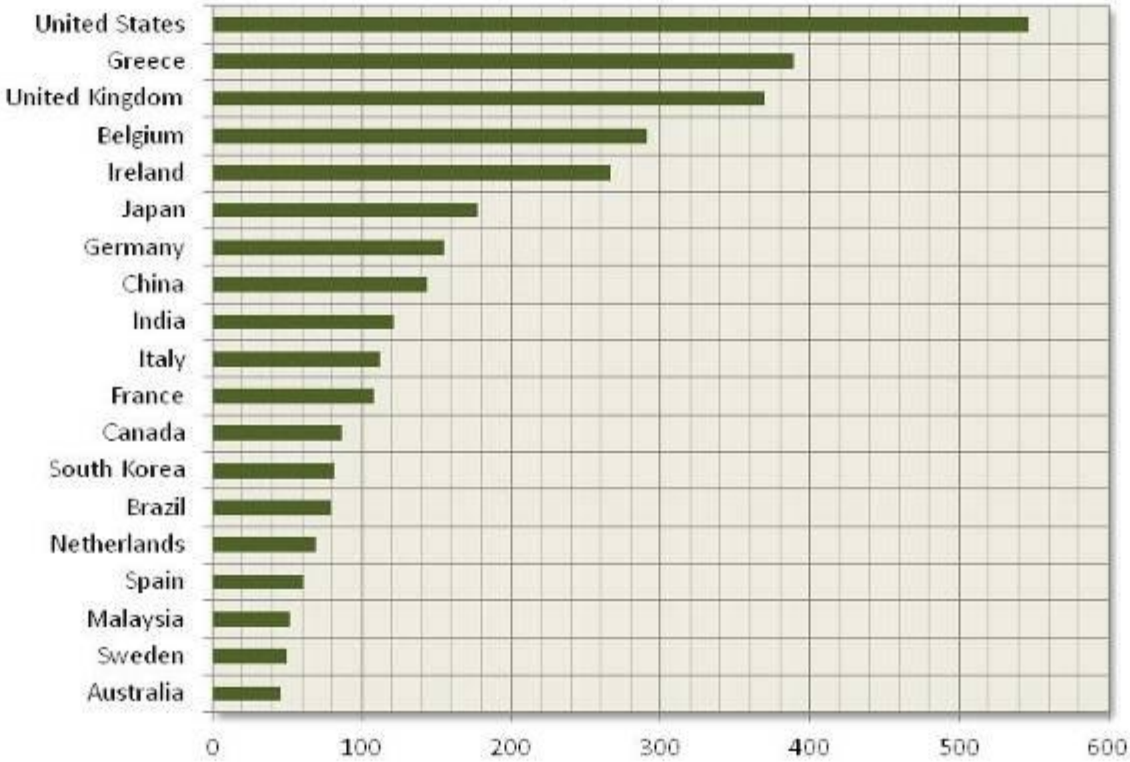


Figure 32: Website traffic per country (top 20) over the project duration (1 June 2010 – 31 November 2013)

1.6 Project consortium

C-3PO was an industry-driven project and followed a top-down approach. System specification and exploitation plans coming from a European systems vendor (ADVA) provided the target specifications, market potentials and exploitation plans for the technology developed and systems envisioned. These high-level requirements are transferred to the "technology innovators" that are European manufacturers (CIP, POLATIS, CONSTELEX) and R&D centres (IMEC, TYNDALL) that developed the necessary photonic/electronic components, sub-systems and integrated systems.

1.6.1 Tyndall National Institute (Ireland)

The Tyndall National Institute (Tyndall) at University College Cork is Ireland's largest ICT research centre, with more than 400 researchers, postgraduate students and support staff. The strengths of the institute at the present time lie in the area of photonics, electronics, materials and nanotechnologies and their applications in communications, healthcare, energy and the environment. Tyndall and its forerunner the National Micro-Electronics Centre (NMRC) have a proven track record in European Framework research programmes dating back nearly thirty years.

1.6.1 CIP Photonics Ltd (United Kingdom)

CIP is a European component manufacturer whose capability is based on 30 years experience as a world leading photonics research organization. This research was initially carried out within British Telecommunications plc, with the photonics research group being acquired by Corning Inc. in 2000 to form the Corning Research Centre (CRC). In January 2003, Corning Inc's photonics business was significantly affected by the downturn in the telecoms industry and the company sold CRC to the East of England Development Agency (EEDA). A financial arrangement was put in place to secure the financial viability of the facility, with funding to retain the equipment that is located at the centre, and to re-employ the key scientists and technologists that enables the Centre to operate with maximum effectiveness. The facility was renamed the Centre for Integrated Photonics to reflect its proven capability to turn advanced research ideas into manufacturable products for the photonics industry. Since January 2012 CIP operates as a wholly owned subsidiary of Huawei. Successful CIP designs are manufactured initially using in-house capability which is being expanded to provide additional manufacturing capacity.

1.6.2 IMEC (Belgium)

IMEC is an independent microelectronics research centre, founded by the Belgian Flemish Government in 1984. The Department of Information Technology (INTEC) of Ghent University acts as a division of IMEC since 1984. The IMEC-INTEC_design group (20 people) is very active in optoelectronics front-end design and high frequency/high speed electronics since the early eighties with a long track record. Various high speed photonic-electronic integrated prototypes, laboratory and field demonstrators were successfully developed within the frameworks of RACE, ESPRIT, ACTS, FP6 projects GIANT and PIEMAN and FP7 projects MARISE, EURO-FOS and C3PO. New developments are ongoing in the frame of FP7 projects Discus, Mirage, Phoxtrot and Spirit.

1.6.1 POLATIS (United Kingdom)

POLATIS develops and manufactures the world's lowest loss optical switching products for government and defence, telecommunications and data centre, test & measurement and video broadcast markets. Through a unique combination of proven technologies and new, innovative architectures, Polatis has achieved class-leading performance and reliability that solve some of today's toughest optical networking challenges. Polatis all-optical switching products are proven in more than 500 networks all over the world. Polatis Inc has headquarters is in Cambridge, UK where engineering, product development and new product introduction are located. Volume manufacturing is located in Krakow, Poland where much of the leading edge assembly of devices for this project will take place. Sales and marketing based in the US near Boston, MA. POLATIS currently employees 57 people and have approximately 50,000 sq ft of office and manufacturing space. Polatis is supported through investments by Alta Berkeley, JK&B, Prism Venture Partners, Flagship Ventures, Eontech, Boston Millennia, Harris & Harris, Gainesborough and Peponi, MTDC.

1.6.2 CONSTELEX Technology Enablers LLC - CONSTELEX (Greece)

CONSTELEX Technology Enablers (www.constelex.eu) is a designer and manufacturer of advanced photonic systems with the mission to offer reliable technology solutions enabled by optics, optoelectronics and photonics technologies applicable to telecoms, defence and space. The company designs, manufactures and markets high-performance and low-noise optical fibre amplifiers and lasers, as well as custom-made photonic systems. Constelex has a strong R&D focus, and in parallel with its business activities, concentrates on IP generation and creation of a strong patent portfolio. Constelex is part of Gooch & Housego, a global business specializing in photonic components and systems.

1.6.1 ADVA Optical Networking (Germany)

ADVA Optical Networking (FSE: ADV) is a global provider of telecommunications equipment. With innovative Optical/Ethernet transport solutions, ADVA builds the foundation for high-speed, next-generation networks. The company's FSP product family adds scalability and intelligence to customers' networks while removing complexity and cost. With a flexible and fast-moving organization, ADVA forges close partnerships with its customers to meet growing demand for data, storage, voice and video services. Thanks to reliable performance for more than 15 years, ADVA with its 1050 employees, has become a trusted partner for more than 200 carriers and 10,000 enterprises across the globe.

2 Use and dissemination of foreground

2.1 Dissemination of knowledge generated (Section A)

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.

Table 1: LIST OF SCIENTIFIC (PEER REVIEWED) PUBLICATIONS

No	Title	Main author	Title of the periodical or conference	Number, Date	Publisher	Place	Publication Year	Pages /session	Open Access?
INVITED PRESENTATIONS AVAILABLE IN CONFERENCE PROCEEDINGS									
1	Recent developments of transmitter and receiver integrated circuits for optical front-ends [invited]	J. Bauwelinck	IEICE Information and Communication Technology Forum (ICTF)	29-31 May	EICE	Sarajevo, Bosnia and Herzegovina	2013	i09	No
2	High-speed electronics or short-link communication [invited]	J. Bauwelinck	European Conference and Exhibition on Optical Communication	22-26 September	OSA/IET	London, UK	2013	Mo.4.F.4	No
3	Low-power colourless reflective components for energy-efficient optical networks [Invited]	C.P. Lai	International Conference on Transparent Optical Networks	2 – 5 July	IEEE	Coventry, UK	2012	We.A2.4	No
4	Energy Efficient Colourless Photonic Technologies for Next-Generation DWDM Metro and Access Networks [Invited paper]	C. P. Lai	Photonics in Switching Conference	11-14 September	IEEE/OSA	Corsica, France	2012	We-S11-I01	No
5	Optical Switch Architectures for Emerging Colorless/ Directionless/ Contentionless ROADM Networks [invited]	Rich Jensen	Optical Fiber Communications Conference	6-10 March	IEEE/OSA	Los Angeles, USA	2011	OThR3	No
6	Towards Colourless Coolerless Components for Low Power Optical Networks [Invited]	P. Townsend	European Conference and Exhibition on Optical Communication	18-22 September	IEEE/OSA	Geneva, Switzerland	2011	Tu.5.LeSale ve.4	No
7	Designing wavelength-division-multiplexed optical access networks using reflective photonic components [Invited]	E. Kehayas	International Conference on Transparent Optical Networks	June 27 - July 1	IEEE/OSA	Munich, Germany	2010	Mo.B4.	No
8	Reflective Based Active Semiconductor Components for Next Generation Optical Access Networks [Invited]	A. Borghesani	European Conference and Exhibition on Optical Communication	19-23 September	IEEE/OSA	Torino, Italy	2010	Mo.1.B.1	No
CONTRIBUTED PRESENTATIONS AVAILABLE IN CONFERENCE PROCEEDINGS									
9	Multi-Channel 11.3-Gb/s Integrated Reflective Transmitter for WDM-PON	C. P. Lai	European Conference and Exhibition on Optical Communication	22-26 September	IEEE/OSA	London, UK	2013	Tu.1.B.2	No

10	Error-Free 10Gb/s Duobinary Transmission over 215km of SSMF using a Hybrid Photonic Integrated Reflective Modulator	A. Naughton	Optical Fiber Communications Conference	4-8 March	IEEE/OSA	Los Angeles, USA	2012	OW4F.3	No
11	Demonstration of Error-Free 25Gb/s Duobinary Transmission using a Colourless Reflective Integrated Modulator	C. P. Lai	European Conference and Exhibition on Optical Communication	16-20 September	IEEE/OSA	Amsterdam, Netherlands	2012	We.1.E.4	No
12	A 113 Gb/s (10 x 11.3 Gb/s) Ultra-Low Power EAM Driver Array	R. Vaernewyck	European Conference and Exhibition on Optical Communication	16-20 September	IEEE/OSA	Amsterdam, Netherlands	2012	Mo.2.B.2	No
13	Demonstration of Wavelength Agile Metro Node using Reflective Colorless Components	A. M. Clarke	Optical Fiber Communications Conference	6-10 March	IEEE/OSA	Los Angeles, USA	2011	OMN2	No
PEER REVIEWED JOURNALS									
14	Multi-Channel 25 Gbit/s Low-Power Driver and Transimpedance Amplifier Integrated Circuits for 100 Gbit/s Optical Links (INVITED PAPER)	J. Verbrugghe	J. Lightwave Technology	Accepted for publication	IEEE/OSA	-	2014	TBD	No
15	Demonstration of Error-Free 25Gb/s Duobinary Transmission using a Colourless Reflective Integrated Modulator	C. P. Lai	OSA Optics Express	vol. 21, no. 1, January	OSA	-	2013	500-507	Yes
16	113 Gb/s (10 x 11.3 Gb/s) ultra-low power EAM driver array	R. Vaernewyck	OSA Optics Express	vol. 21, no. 1, January	OSA	-	2013	256-262	Yes
17	Diode string with reduced clamping-voltage for ESD-protection of RF-circuits	R. Pierco	IET Electronics Letters	March 15	IET	-	2012	317-318	No

Table 2: list of dissemination activities

NO.	Type of activities	Main leader	Title	Date/Period	Place / media	Type of audience	Size of audience	Countries addressed
1	Conference	J. Bauwelinck	Recent developments of transmitter and receiver integrated circuits for optical front-ends [invited], ICTF 2013	29-31 May 2013	Sarajevo, Bosnia and Herzegovina	Scientific Community, Industry	-	Worldwide
2	Conference	J. Bauwelinck	High-speed electronics or short-link communication [invited], ECOC 2013	22-26 September 2013	London, UK	Scientific Community, Industry, Medias, Policy Makers	>5.500	Worldwide
3	Conference	C.P. Lai	Low-power colourless reflective components for energy-efficient optical networks [Invited], ICTON 2012	2 – 5 July 2012	Coventry, UK	Scientific Community, Industry	>500	Worldwide, mainly Europe
4	Conference	C. P. Lai	Energy Efficient Colourless Photonic Technologies for Next-Generation DWDM Metro and Access Networks [Invited paper], PS 2012	11-14 September 2012	Corsica, France	Scientific Community, Industry	>200	Worldwide
5	Conference	Rich Jensen	Optical Switch Architectures for Emerging Colorless/ Directionless/ Contentionless ROADM Networks [invited], OFC 2011	4-8 March 2011	Los Angeles, USA	Scientific Community, Industry, Medias, Policy Makers	>10.000	Worldwide
6	Conference	P. Townsend	Towards Colourless Coolerless Components for Low Power Optical Networks [Invited], ECOC 2011	18-22 September 2011	Geneva, Switzerland	Scientific Community, Industry, Medias, Policy Makers	>4.900	Worldwide
7	Conference	E. Kehayas	Designing wavelength-division-multiplexed optical access networks using reflective photonic components, ICTON 2010	June 27 - July 1 2010	Munich, Germany	Scientific Community, Industry	>500	Worldwide, mainly Europe
8	Conference	A. Borghesani	Reflective Based Active Semiconductor Components for Next Generation Optical Access Networks, ECOC 2010	19-23 September 2010	Torino, Italy	Scientific Community, Industry, Medias, Policy Makers	>4.500	Worldwide
9	Conference	C. P. Lai	Multi-Channel 11.3-Gb/s Integrated Reflective Transmitter for WDM-PON, ECOC 2013	22-26 September 2012	London, UK	Scientific Community, Industry, Medias, Policy Makers	>5.500	Worldwide
10	Conference	A. Naughton	Error-Free 10Gb/s Duobinary Transmission over 215km of SSMF using a Hybrid Photonic Integrated Reflective Modulator, OFC 2012	4-8 March 2012	Los Angeles, USA	Scientific Community, Industry, Medias, Policy Makers	>10.000	Worldwide

11	Conference	C. P. Lai	Demonstration of Error-Free 25Gb/s Duobinary Transmission using a Colourless Reflective Integrated Modulator, ECOC 2012	16-20 September 2012	Amsterdam, Netherlands	Scientific Community, Industry, Medias, Policy Makers	>4.500	Worldwide
12	Conference	R. Vaernewyck	A 113 Gb/s (10 x 11.3 Gb/s) Ultra-Low Power EAM Driver Array, ECOC 2012	16-20 September 2012	Amsterdam, Netherlands	Scientific Community, Industry, Medias, Policy Makers	>4.500	Worldwide
13	Conference	A. M. Clarke	Demonstration of Wavelength Agile Metro Node using Reflective Colorless Components, OFC 2012	6-10 March 2011	Los Angeles, USA	Scientific Community, Industry, Medias, Policy Makers	> 10.000	Worldwide
14	Web	CIP	C-3PO Strives for Green Photonics	8th July 2010	Light-Reading online	Industry, Medias, Policy Makers	~1 million / month	Worldwide
15	Web	CIP	Reflecting light to save power	6th August 2010	GazettaByte online	Industry, Medias, Policy Makers	700 / month	Worldwide
16	Web	ADVA	Bringing WDM-PON to market	7th September 2010	GazettaByte online	Industry, Medias, Policy Makers	700 / month	Worldwide
17	Article	ADVA	Forschungsprojekt 3-CPO: Energieeffiziente optische Netze	19 November 2010	NTZ Magazine	Scientific Community, Industry, Medias, Policy Makers	-	Germany
18	Web	CIP	Things are heating up as DWDM makes its way to the home	21 September 2010	Electronic Engineering Times Europe	Scientific Community, Industry, Medias, Policy Makers	> 100.000 / month	Worldwide
19	Article	CONSTELEX	Πράσινα, γρήγορα και επεκτάσιμα οπτικά δίκτυα πρόσβασης νέας γενιάς	April 2011	On-line Magazine	Industry, Policy Makers	-	Greece
20	Web	CONSTELEX	C3PO	11 May 2012	Capacity Managine	Industry, Policy Makers	> 7.000 / month	Worldwide
21	Web	CONSTELEX	Εταιρεία από την Αθήνα πρωτοπορεί διεθνώς στις οπτικές ίνες" ("Company from Athens innovates in Fiber-optics	16 March 2012	GoodNews.gr	Industry, General public	-	Greece
22	Article	POLATIS	Fibre-layer switching enables greener data centres, ECOC Forum	18-22 September 2011	Geneva, Switzerland	Scientific Community, Industry, Medias, Policy Makers	>4.500	Worldwide
23	Article/ Interview	IMEC	A new design for robust on-chip ESD protection with improved clamping voltage and capacitance protection	15 March 2012	Interview by IEE Electronics Letters (Vol.48 No.6)	Scientific Community, Industry	-	Worldwide
24	Workshop	CIP	Mining the Wavelength Domain for Future Fibre Access: Technology and Cost challenges, Market Focus, ECOC	20 September 2010	Torino, Italy	Industry, Policy Makers	>4.500	Worldwide
25	Workshop	ADVA	Backbone Network Innovation Workshop, TERENA Networking	1 June 2010	Vilnius, Lithuania	Industry, Policy Makers	-	Worldwide

26	Workshop	IMEC	What Is Next for High-speed PON: Evolution or Revolution?, OFC Workshop	6 March 2011	Los Angeles	Scientific Community, Industry, Policy Makers	>10.000	Worldwide
27	Conference	CONSTELEX	Pan-Orama 2012, Recent progress in micro-electronics and nano-technology	18 May 2012	Athens, Greece	General public, Industry, Policy Makers	> 500	Greece
28	Conference	CONSTELEX, POLATIS	Photonics21 Annual Meeting	28 March 2012	Brussels, Belgium	Industry, Policy Makers	>200	Europe
29	Interview	CONSTELEX	Shadow an Entrepreneur	30 July 2013	initiative, thinkbiz	General public	10	Greece
30	Exhibition	POLATIS, CIP	ECOC 2010 exhibition	19-22 September 2010	Torino, Italy	Industry, Policy Makers	>4.500	Worldwide
31	Exhibition	POLATIS, CIP	OFC 2011 exhibition	6-9 March 2011	Los Angeles, USA	Industry, Policy Makers	>10.000	Worldwide
32	Exhibition	POLATIS, CIP, CONSTELEX	ECOC 2011 exhibition	18-21 September 2011	Geneva, Switzerland	Industry, Policy Makers	>4.500	Worldwide
33	Exhibition	POLATIS, CONSTELEX	ECOC 2012 exhibition	16-19 September 2012	Amsterdam, the Netherlands	Industry, Policy Makers	>4.500	Worldwide
34	Exhibition	POLATIS	OFC 2013 exhibition	17 - 21 March 2013	Los Angeles, USA	Industry, Policy Makers	>10.000	Worldwide
35	Exhibition	POLATIS	ECOC 2012 exhibition	22-26 September 2013	London, UK	Industry, Policy Makers	>4.500	Worldwide
36	Interview	POLATIS	192x192 switch presentation , ECOC 2012, by Total TeleVision	16-19 September 2012	Geneva, Switzerland	Industry, Policy Makers	-	Worldwide
37	Interview	POLATIS	48x48 optical switch, energy-efficient optical switch presentation, ECOC 2013, by Total TeleVision	22-26 September 2013	London, UK	Industry, Policy Makers	-	Worldwide

2.2 Exploitation of knowledge generated (Section B)

This section describes the exploitable foreground and provides the plans for exploitation.

2.2.1 Overview of C3PO exploitable knowledge

Detailed exploitation planning per beneficiary was continuously performed during the project execution where the exploitation elements of the project and each beneficiary's plans were described and assessed. The identification of the exploitable elements created by the C3PO project is summarized in the figure below. In terms of photonic components, two beneficiaries, CIP and IMEC, strongly worked together for developing new generation of transceivers, lasers electronic drivers and receivers. Beneficiary POLATIS together with IMEC worked on the development of high-port count and energy-efficient switches that are indispensable building blocks for all C3PO target applications.

On the system side, ADVA was primarily driving the exploitation planning and steering for a low-cost version of 100 Gb/s transport metro links. The successful commercialization of results on the system level strongly relies on the value chain created at the component fabrication and component design levels by the other beneficiaries, each contributing a part of the final systems envisaged.

The increasing interest in the L-band for extending the useable spectrum in the metro/core and amplifying the downstream signal in WDM-PONs has created an opportunity for green C/L-band optical amplifier arrays that was part of the exploitation planning of Constelex.

Finally, the design activities on the system- and network- level created valuable know-how that could be exploited in the future through new research contracts and deployment/network design services.

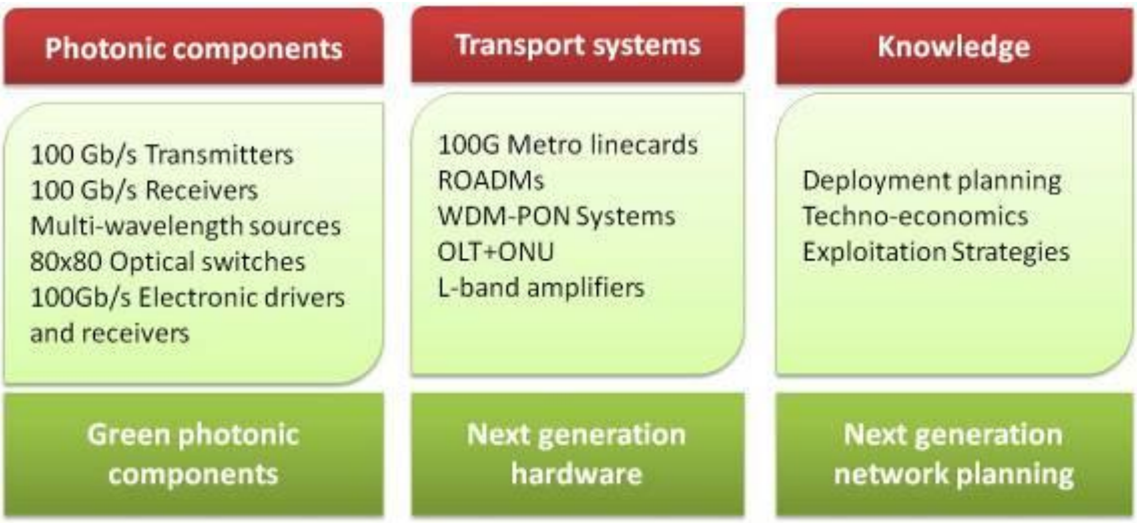


Figure 33: C3PO exploitable elements

2.2.2 Patent applications

Table 3: List of applications for patents					
Type of IP Rights	Confidential	Foreseen embargo date	Application reference	Subject or title of application	Applicant (s)
Patent	No	-	EP11180790.5	ESD protection device with reduced clamping voltage	Pierco Ramses, Bauwelinck Johan, Yin Xin
Patent	No	-	US 20130063846 A1	ESD protection device with reduced clamping voltage	Ramses Pierco, Johan Bauwelinck, Xin Yin
Patent	No	-	US 13/669067	Optical Fiber Amplifier Array	Leontios Stampoulidis, Efstratios Kehayas

2.2.3 Exploitable foreground

Table 4: List of exploitable foreground

Type of Exploitable Foreground	Description of exploitable foreground	Confidential Click on YES/NO	Foreseen embargo date	Exploitable product(s) or measure(s)	Sector(s) of application (NACE)	Timetable, commercial or any other use	Patents or other IPR exploitation (licences)	Owner
Commercial exploitation of R&D results	Reflective InP arrays and hybrid assembly processes	NO	-	Optical transceivers	J61.1.0 - Wired telecommunications activities	>2016	WO 2012093267 A1	CIP
Commercial exploitation of R&D results	ESD protection device with reduced clamping voltage	NO	-	Low-power electronic ICs	C26.1 - Manufacture of electronic components and boards	>2014	US 20130063846 A1	IMEC
Commercial exploitation of R&D results	Energy-efficient optical amplifiers	NO	-	Optical amplifier modules	J61.3 - Satellite telecommunications activities	2016-2020	US13/669067	CONSTELEX
Exploitation of R&D results via standards	Optical networks employing reflective components	NO	-	Optical transport systems	J61.1.0 - Wired telecommunications activities	>2016	ITU-T SG15-Q.6 FSAN SG15-Q.2	ADVA
Commercial exploitation of R&D results	Methods for reducing power consumption of optical switches	NO	-	Optical switching systems	J61.1.0 - Wired telecommunications activities	>2014	-	POLATIS
General advancement of knowledge	Reflective optical network links	NO	-	Know-how on reflective optical systems	J61.1.0 - Wired telecommunications activities	>2013	-	TYNDALL

2.2.4 Beneficiary exploitation plans

2.2.4.1 TYNDALL National Institute

TYNDALL, being an academic beneficiary, plans to exploit C3PO through the specialized knowledge gained through its participation in the project and also to further exploit the testbeds developed for further research activities or strengthening the links with industry and SMEs through testing services. An important aspect of TYNDALL exploitation is through the training of highly-specialized scientific personnel. To date 6 researchers have benefitted from involvement with C3PO.

A key element of Tyndall's exploitation strategy post C3PO is via a new academic-industry collaborative research centre known as the Irish Photonic Integration Centre (IPIC). This award to Tyndall (in collaboration with Cork Institute of Technology, Dublin City University and University College Cork) was made under the Science Foundation Ireland (SFI) Centres programme in June 2013 and represents a significant combined industry/SFI investment of some €23.2M in Irish photonics research over the period 2013-2019. IPIC brings together the internationally recognised Irish research capabilities in Photonics and Biomedical Science and 16 industrial partners, including indigenous start-ups and medium sized enterprises as well as large multi-national companies. Current partners include:

- Intel, BT, Verizon, Finisar, Intune Networks, X-Fab, Pilot Photonics, Firecomms, M/A ComTech, Lake Region Medical, Somex, SensL, InfiniLED, Radisens Diagnostics, Luxcel Biosciences and Eblana Photonics, with several others currently applying to join.

The specific goals of the centre will be to provide technological solutions via photonic integration to enable point-of care medical diagnostics, minimally invasive patient monitoring and screening procedures, and continued growth of communications systems and the internet. The majority of the industry collaborations within IPIC that fall into the communications application domain will build upon the capabilities and expertise developed under C3PO, in particular exploiting the system modelling and system testbed knowledge that was developed by Tyndall within C3PO. The C3PO Coordinator, Prof Paul Townsend, will be the Director of IPIC.

2.2.4.2 CIP Photonics

CIP, being a wholly owned subsidiary of Huawei, will perform technology exploitation through the parent company. Huawei is one of the major global equipment vendors, and is increasingly following a strategy of having both an internal supply chain and the more usual external supply chain through component and module vendors. The technologies developed under C3PO are being evaluated by other teams within Huawei with a view to seeing where they could be used and when the technology would coincide with the next generation product development cycle. Increasingly, 100Gb/s technology and advanced modulation formats are being built into products. C3PO technology is well positioned to feed into this trend.

2.2.4.3 IMEC

The C-3PO project significantly enhanced the IMEC/INTEC_design know-how on optical front-end ASIC design. This world-class expertise contributes to the INTEC_design courses on high-speed electronics and high-frequency design. The C-3PO project cooperation assists to attract new PhD students and to perform high-level PhD research. Delivering experienced postdocs to European industries effectively transfers this know-how to companies, giving them a head start in the field.

Within C-3PO, IMEC/INTEC_design developed 100Gb/s driver arrays with record low power consumption and 100Gb/s receiver arrays with low power consumption and high performance. This significantly assisted IMEC/INTEC_design to step into "Green" IC design. The advanced driver and TIA developments in C-3PO also considerably improved its visibility and reputation inside IMEC and Ghent University.

The most direct exploitation for IMEC resulting from the well-established collaboration in C-3PO is currently the bilateral contract with POLATIS on the design and development of a dedicated low-power high-voltage driver array IC for optical switches. This project already passed several milestones, of which the tape out was the most critical one. The extensive integration on chip and innovative circuit design significantly reduces the driver power consumption, footprint and bill of materials.

2.2.4.4 POLATIS

Participation in C3PO helps POLATIS to refine its understanding of the driving requirements for optical switching components and to focus development of next generation optical switch fabrics with low loss and low power consumption for telecom applications.

As an SME, POLATIS aims to market technology enhancements defined within C-3PO as soon as practicable and extend its portfolio of class-leading optical matrix switches to higher port counts. POLATIS exploitation activities focus on demonstrating the switch technology scalability, power consumption and the capability offered to build directionless, contentionless and colourless add-drop multiplexers. POLATIS is active in marketing the technology developed through live demonstrations and invited technical talks in conferences for attracting interest from key stakeholders. Demonstrating C3PO's timely execution and relevance to POLATIS product and R&D roadmap is the commercialization of its new line of low-power consumption optical switch. During year 3, POLATIS has successfully launched the new 'lite' platform at ECOC 2013, which increases energy efficiency whilst maintaining a small footprint. The Polatis Series 6000n Lite network optical switch is a high-performance, fully non-blocking all-optical 48x48 matrix switch that fits into a compact 1RU rack mounted chassis. POLATIS anticipates exploring further extensions to matrix size after the project ends. Moreover, POLATIS has entered into a bilateral contract with IMEC for the design and development of a dedicated low-power high-voltage driver array IC for optical switches. The collaboration will extend beyond the lifetime of the project and will assist POLATIS in further reducing the power consumption of its products through the design and development of new multi-channel driver arrays.

2.2.4.5 CONSTELEX Technology Enablers

Constelex exploitation plan focused on capitalizing on the knowledge gained from WDM-PON energy efficient reach extenders through the application of its fibre amplifier products. Overall, Constelex focused on the following activities:

- Deepen its knowledge on energy-efficient optical fiber amplifiers
- Generate know-how on physical-layer transmission modeling

- Proceed with Intellectual Property generation
- Update the company business plan and define unique company characteristics
- Identify its strengths and weaknesses and market opportunities
- Work on creating new products and target markets where Constelex has competitive advantages over competitors

An in-depth technology and business planning was initiated in order to create the path towards the commercialization of a new line of optical amplifiers suitable for space flight environment with the aim to capture portion of the larger harsh environment market sector. In 2012, the company took a strategic decision to diversify into new markets with the aim to expand its product portfolio and target specifically the Aerospace & Defence domain. By exploiting its technology base on optical fiber systems, the company plan was the expansion into the space domain, where unique advantages of Constelex technology can give the necessary competitive edge over its competitors and diversify its target market. In 2013, Constelex secured private services contracts and product development contracts with the European Space Agency focusing on optical amplifiers and pre-amplifiers for inter-satellite as well as satelite to ground optical links. Working with satellite vendors, Constelex is now developing its 1st generation of booster amplifiers for scheduled space missions.

In November 2013, Constelex was acquired by Gooch & Housego PLC, a European leading components and systems developer with a global footprint. The acquisition of Constelex is aligned with G&H's strategic objective of moving up the value chain by leveraging its leadership in components to develop a higher-added-value capability at the sub-systems and systems level. In February 2013 G&H established the Systems Technology Group (STG) at its Torquay, UK, facility to function as a separate business unit with a remit to design, develop and prototype systems-level products. The objective was to build a multi-disciplinary team with expertise in mechanical, electronic and software design and modelling and to integrate these technologies with G&H's expertise in photonics. The acquisition of Constelex represents a significant expansion of the capabilities of the STG and will enable G&H to make a unique and invaluable contribution to the ESA Advanced Research in Telecommunications Systems (ARTES) European Component Initiative. As a result, G&H is well positioned to fulfill its objective of becoming a global leader in space photonics, with design and manufacturing of space qualified hardware in both the USA and EU.

2.2.4.6 ADVA Optical Networking

ADVA intends to use several parts of the outcome of C-3PO, given commercial availability. For high-speed WDM transport for metro, backhaul, and data-centre connectivity applications at data rates of 100 Gb/s, ADVA currently has a low-cost product, using optical duobinary modulation. For the next generation of these cards, reflective modulators with a central light source are a promising solution, if components are commercially available.

For passive-WDM (pWDM) and WDM-PON access, ADVA intends to use the C-3PO results as multi-channel transmitters in the central-office equipment (head-end in G.metro, OLT in G.989). There is a strong requirement for pWDM and WDM-PON solutions which support services with bandwidths in the range of 10 Gb/s. This requirement is driven by various backhaul, business access, and mobile fronthaul (a.k.a. C-RAN) applications. Consequently, low-cost transmitters which cover 10 Gb/s are required. This holds for the central office equipment as well as for the customer-premises equipment (tail-end in G-metro, ONU in G.989). For the OLT, reflective transmitter arrays are seen as a very interesting alternative to laser arrays, due to their potential advantages w.r.t. density, complexity, and power consumption. For the ONU side, reflective transmitters and tuneable lasers are both possible solutions with different applications in terms of data rate and reach. While reflective solutions have been standardized in ITU-T Rec. G.698.3 (with strong input from the C-3PO project), new standards G.metro and G.989 will go into the direction of tuneable lasers.

More generally, high density and low power consumption are key requirements for the next-generation transmission products. Required symbol rates are either 10…11 or 28…30 GBaud. Here the results of C-3PO, especially low-power driver arrays, will be considered by ADVA as key components in high-density line cards together with multi-channel transmitter arrays.

In summary, the outcome of C-3PO will be exploited by ADVA, given the respective components have advantages w.r.t. cost, density, and energy consumption. Most importantly, however, the respective components need to be freely and commercially available.

3 List of figures

4 List of tables