Energy-Efficient Colourless Photonic Technologies for Next-Generation DWDM Metro and Access Networks

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***Abstract*—Within the scope of our EU FP7 C3PO project, we are developing novel, energy-efficient, colourless photonic technologies for low-cost, next-generation dense wavelength-division-multiplexed metro transport and access networks. The colourless transmitters use reflective arrayed photonic integrated circuits, particularly hybrid reflective electroabsorption modulators, and multi-wavelength laser sources, with custom power-efficient driver circuitry. A low-loss piezoelectric beam-steering optical matrix switch allows for dynamic wavelength reconfigurability. Simplifying the required optical and electronic hardware, as well as avoiding the need for expensive, thermally-stabilised tuneable lasers, will yield cost and energy savings for data switching applications in future metro, access, and datacentre interconnection networks. We report on recent advancement towards these low-power optical networks, providing the latest systems results achieved with key enabling hybrid photonic integrated devices and electronic driver/receiver arrays for our targeted applications.**

***Index Terms*—Optical fibre communication, optical fibre networks, photonic integrated circuits.**

I. Introduction

Realising energy-efficient, high-bandwidth network architectures and photonic components is imperative to ensure the future scaling of metro and access network infrastructures. In current state-of-the-art networks, dense wavelength-division-multiplexing (DWDM) offers terabit-scale fibre capacities; however, exponentially-increasing traffic demands are emphasising the need for innovative next-generation DWDM technologies with reduced energy consumption and cost-per-bit. This will likely entail a simplification and/or redesign of the network infrastructure in order to avoid unnecessary optical/electrical/optical (O/E/O) conversions, which arise from attaching grey (uncoloured) switching/router interfaces to DWDM transponders for wavelength conversion and long-distance transmission. One possible redesign approach is to deploy DWDM interfaces, which utilise tuneable lasers; however, many host devices do not support the tuning functionality required to set the laser transmitters to the appropriate wavelength, rendering the approach not viable for deployment. Within the EU FP7 C3PO project [1], we adopt a radically different, much simpler, power-efficient IP over DWDM (IPoDWDM) solution based on fully colourless, reflective transmitter modules located on routers' linecards.

Our approach will enable wavelength-flexible network interfaces that use cost-effective photonic integrated circuits (PICs) without requiring expensive tuneable lasers. The colourless PIC transmitter modules leverage reflective electroabsorption modulator (REAM)-based phase and amplitude modulators seeded with continuous wave (CW) optical carriers, which are generated by a multi-frequency laser (MFL). Under the assumption that the MFL and deployed wavelength multiplexers use the same wavelength grid and can operate athermally, this reflective approach does not require active wavelength control of the laser sources. In order to achieve the desired cost, power consumption, and compact footprint metrics, the reflective transmitter designs rely on hybrid array-integrated PICs, with custom low-power electronic driver integrated circuits (ICs) based on SiGe BiCMOS technology.

The PICs will support per-lane/wavelength line rates of 25Gb/s or higher, to enable low-cost 4×25Gb/s approaches to 100Gb/s channel provisioning, with intermediate spectral efficiencies (0.5-1bits/s/Hz). Since the envisioned system will need to operate up to metro-reach distances (~500km), the PICs will support modulation formats with greater dispersion tolerance and higher information spectral density than the conventional non-return-to-zero on-off keying (NRZ-OOK) format used in access networks. Duobinary (DB) modulation [2] is suitable for C3PO targeted applications owing to its use of simple direct detection receivers; compact REAM-based array-integrated PIC modules will enable efficient DB transmission. Reconfigurable optical add-drop multiplexer (ROADM) functionality is provided by low-loss, high-port-count piezoelectric beam-steering optical matrix switches.

In addition to designing the complete system architectures, C3PO project partners are developing the key enabling component building blocks to fulfil the intended requirements. These include: low-power optical matrix switches; several distinct colourless reflective hybrid PIC devices; and the accompanying driver and receiver ICs. High-capacity system test-beds are currently under development that will be used to prove the technology in a number of targeted network scenarios. Successful C3PO technology will enable low-cost, power-efficient reconfigurable router interfaces with wavelength agility for short-reach inter-datacentre links, wavelength-reconfigurable DWDM metro-transport networks, and WDM-PON access networks.

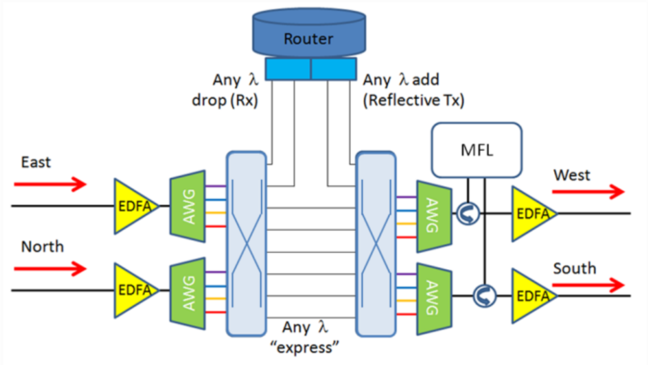

Fig. 1. Colourless reflective metro node structure.

II. System Architectures

The project addresses the following three network scenarios: (a) short-reach, high-capacity point-to-point links for datacentre networks (<40km); (b) dynamic IPoDWDM metro transport networks with ROADM capabilities (~500km); and (c) WDM-PON access networks (20-60km). We are developing 4×25Gb/s reflective DB transmitter and receiver arrays for cases (a) and (b), and 10×11Gb/s PICs for case (c), with the associated low-power driver electronics. System test-beds are being implemented to evaluate developed C3PO prototypes and demonstrate their performance within the diverse constraints posed by each of the above applications.

As a representative system design example: aimed at (b), we have demonstrated a colourless reflective metro node architecture (Fig. 1) that avoids the need for tuneable lasers. Simple colourless REAM-based transmitter PICs will be directly mounted on densely-packed router linecards. The MFL generates all the required wavelengths and feeds the reflective modulators. Wavelength and optical path selection use an arrayed waveguide grating (AWG) and an N-degree optical matrix switch, which is connected to all the reflective transmitters and realises 'add'/'drop' functionality. The node supports 'express' wavelength channels, avoiding router traversals (and consequently unnecessary O/E/O conversions). The overall design creates a colourless wavelength-agile interface with full ROADM capabilities.

To validate our system-level efforts, we are undertaking network simulations to study the competitive advantage of C3PO-developed technologies and designs. Initial modeling results assessing the transmission, reach, and bit-rate limits, show that, in case (b), for example, our REAM-based components should be able to achieve metro-scale transmission (6×80km) in a dispersion-managed system, with 1bits/s/Hz efficiency.

III. Piezoelectric Optical Matrix Switch

ROADM capabilities are provided by a colourless, directionless, non-blocking optical space switch [3]. Our design relies on the matrix switch exhibiting low insertion loss and good return loss, allowing lightpaths to be steered independently of optical power, wavelength, or direction. The use of piezo technology achieves record low power consumption jointly with high port counts (<0.2W/port).

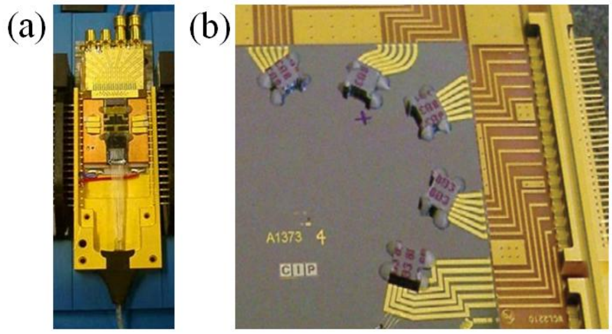

Fig. 2. Photographs of (a) REAM-based modulator and (b) comb source.

IV. Hybrid Photonic Integrated Circuits

A. REAM-Based Modulator

For the colourless metro node in Fig. 1, a crucial enabling component is a reflective REAM-based PIC. We are thus developing a novel hybrid PIC (Fig. 2a) that can support DB modulation at the required single-channel data rates, which will be monolithically integrated to produce a high-throughput, multi-channel EAM-based transmitter array specifically aimed towards 100Gb/s aggregate rates (i.e. with either 4×25Gb/s or 10×11Gb/s modules). The reflective DB PIC features an array of multiple quantum well (MQW) REAMs [4], which incorporate mode expanders to allow hybrid integration with silica waveguides. The silica planar motherboard contains a hybrid Michelson interferometer circuit with a 2×2 multimode interference (MMI) coupler. The phase difference between the two interferometer arms is adjusted using heater elements, which are deposited on the motherboard. The relatively small size of the REAM chip (~0.2mm in length) allows for further integration of multiple DB transmitters on a single compact board. Also, the reflective design benefits from shorter high-speed drive traces, since these are taken from the edge of the motherboard, thereby further reducing RF losses and crosstalk. To increase the reach, the REAM structures will be monolithically integrated with semiconductor amplifiers (SOAs) to achieve lossless performance [5].

B. Multi-Frequency Laser

A MFL is required to generate multiple seed optical carriers; in the IPoDWDM metro design, this laser source would be local to the transmitter PICs. Tests are ongoing to evaluate an SOA-based athermal CW comb source (Fig. 2b). The device provides ten channels of 100GHz spaced wavelength channels (ranging from 1541nm to 1549nm). The key goal of the source is to achieve performance similar to that of DWDM lasers, with the low cost and simplicity of CWDM sources.

V. Low-Power Driver and Receiver ICs

We are also developing the electronic driver and transimpedance amplifier (TIA) arrays associated with the DWDM REAM modulator and photodiode receiver arrays. The close integration of several driver and TIA circuits on a single chip poses several design challenges with respect to low power consumption, reduced footprint, and low RF crosstalk without external components (such as bias tees).

A 10×11Gb/s EAM driver array (Fig. 3), a 2×28Gb/s DB EAM driver array, and a 4×28Gb/s TIA array were

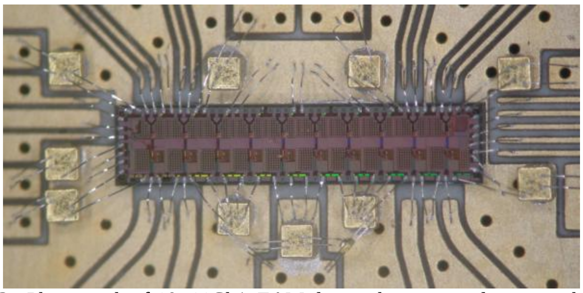

Fig. 3. Photograph of 10×11Gb/s EAM driver chip mounted on a test board for evaluating the electrical performance of the outer channels.

developed in 130nm SiGe BiCMOS technology. These first-generation devices are being tested and integrated in the hybrid optoelectronic platform at the time of writing. It was shown that the concurrent design improves optoelectronic performance by co-optimising the key parameters of these E/O and O/E devices. Particularly, the co-design of the driver arrays, the interconnection to the EAM, and the terminating impedance levels allows for a drastic reduction of the 10×11Gb/s driver array's power consumption by 50% compared with the state-of-the-art [6].

For the 28Gb/s DB driver, the focus was not only on power consumption, but also on the efficient and reliable on-chip conversion of NRZ data to DB signals. The selected technique is robust to temperature, process, and supply variations, and allows operation over a range of data rates, which is not possible with conventional approaches based on low-pass filters (LPFs). Open eye diagrams were obtained, and, though the DB encoder and precoder add some power consumption, the IC chip's power-per-bit performance remains below the state-of-the-art. The optical DB signals are directly decoded by a conventional receiver, thus the 4×28Gb/s PIN-TIA receiver is suited for both NRZ and optical DB modulation. The PIN-TIA receivers were optimised for high receiver sensitivity, taking into account channel crosstalk and low power consumptions. Based on these initial promising results, second-generation driver and TIA electronic ICs will be developed to further improve performance and integration with the photonic devices.

VI. Single-Channel REAM-Based DB Modulator

A. 10Gb/s Duobinary Performance

Using the first-generation, single-channel reflective REAM-based PIC above, we show error-free 10Gb/s DB transmission over 215km of standard single mode fibre (SSMF), with comparable performance to a commercial $LiNbO_3$ Mach-Zehnder modulator [7]. The REAMs are modulated with 3Vpp 10Gb/s NRZ data signals containing a pseudo random bit sequence (PRBS), and are filtered with fourth-order Bessel-Thomson LPFs. For distances up to 215km, bit-error rate (BER) measurements show BERs less than 10^{-10} with no error floors (Fig. 4a); substantial eye openings are obtained (Fig. 4b). For distances greater than 240km, an error floor appears at BER~10^{-9}, due to chromatic dispersion and subsequent eye closure.

B. 25Gb/s Duobinary Performance

Preliminary results show that the same REAM-based PIC device can also support the error-free transmission of 25Gb/s DB modulated signals, with colourless operation over the C-band [8]. This result indicates that our approach

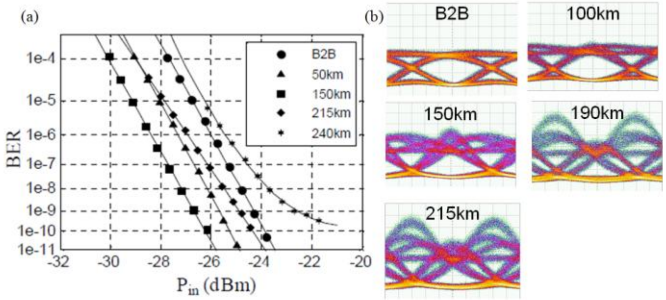

Fig. 4. (a) BER as a function of P_{in} for the DB reflective modulator at 10 Gb/s; (b) Transmitted 10Gb/s DB eye diagrams.

has potential for realising a four-channel arrayed PIC for 100Gb/s data rates, with adequate dispersion tolerance and signal quality performance.

VII. Conclusion

Driven by the need to deliver low-power, decreased cost-per-bit, wavelength-dynamic photonic technologies for next-generation metro, access, and datacentre-interconnection networks, the C3PO project is adopting a reflective approach that is based on energy-efficient, colourless components. The resulting transmitter and receiver arrays will leverage reflective photonic-integrated technologies with dedicated power-efficient electronics. Here, we report on our recent progress towards these reflective designs, showcasing several key enabling technologies and presenting latest systems performance results. The ultimate deliverables of the project will consist of arrayed hybrid PIC modules with ultra-high energy efficiencies to enable low-cost 100Gb/s Ethernet metro DWDM transport networks and high-capacity short-reach interconnects.

Acknowledgment

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