ICTON 2017
19th International Conference on Transparent Optical Networks

# Final system results from the EU FP7 project FABULOUS

*S. Straullu, S. Abrate, Istituto Superiore Mario Boella (ISMB), Turin, Italy*

*V. Ferrero and R. Gaudino, Politecnico di Torino, Turin, Italy*

FP7-ICT-2011-8 Challenge 3.5 – STREP project n. 318704 – FABULOUS
FDMA Access By Using Low-cost Optical Network Units in Silicon photonics

# Outline

- General introduction to the EU FABULOUS project
- Implementation of the reflective-ONU in a silicon Photonic integrated chip
- Latest results on flexibility in terms of:
  - Bit rate
  - Number of users
  - Achievable ODN loss

# EU STREP project - FP7-ICT-2011-8

8 partners

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

The project started in October 2012 and ended at the beginning of 2016

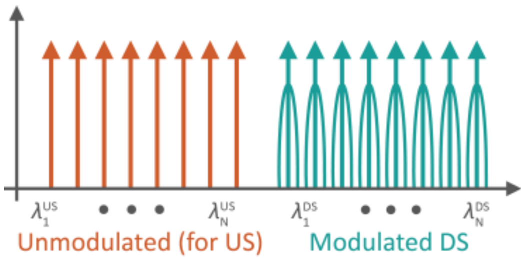
# The proposed Passive Optical Network (PON)

- Electrical FDMA in both US and DS
- A higher level of multiplexing using WDM
- Targeting bit rate per wavelength well above 10 Gbps

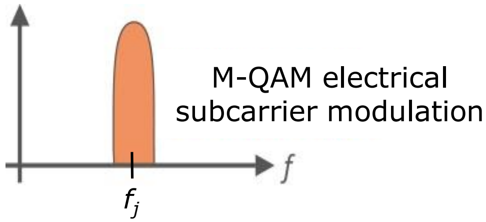
- For time limitation, this presentation focus only on the upstream, that is characterized by:
  - reflective modulation at ONU
    - No need for tunable lasers at ONU
    - Implemented using an ad-hoc silicon photonic chip
  - self-coherent detection at OLT
    - Implemented in real-time on an FPGA platform

# The system concept for the upstream

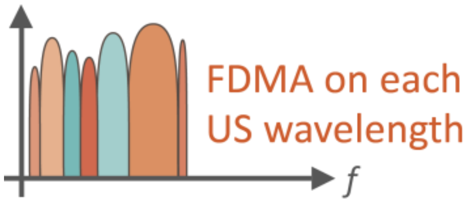
- The required upstream wavelengths are generated at the Central Office by CW lasers and sent downstream




- Each ONU:
  - Selects one wavelength
  - Modulates it in reflection using electrical QAM over a given electrical subcarrier




- The OLT receives all the Frequency Division Multiplexed signals with a self-coherent receiver



# An R-ONU suitable for Silicon Photonic

The ONU reflects the received signal, modulates it (subcarrier QAM) and performs 90° polarization rotation (allowing single pol. RX)

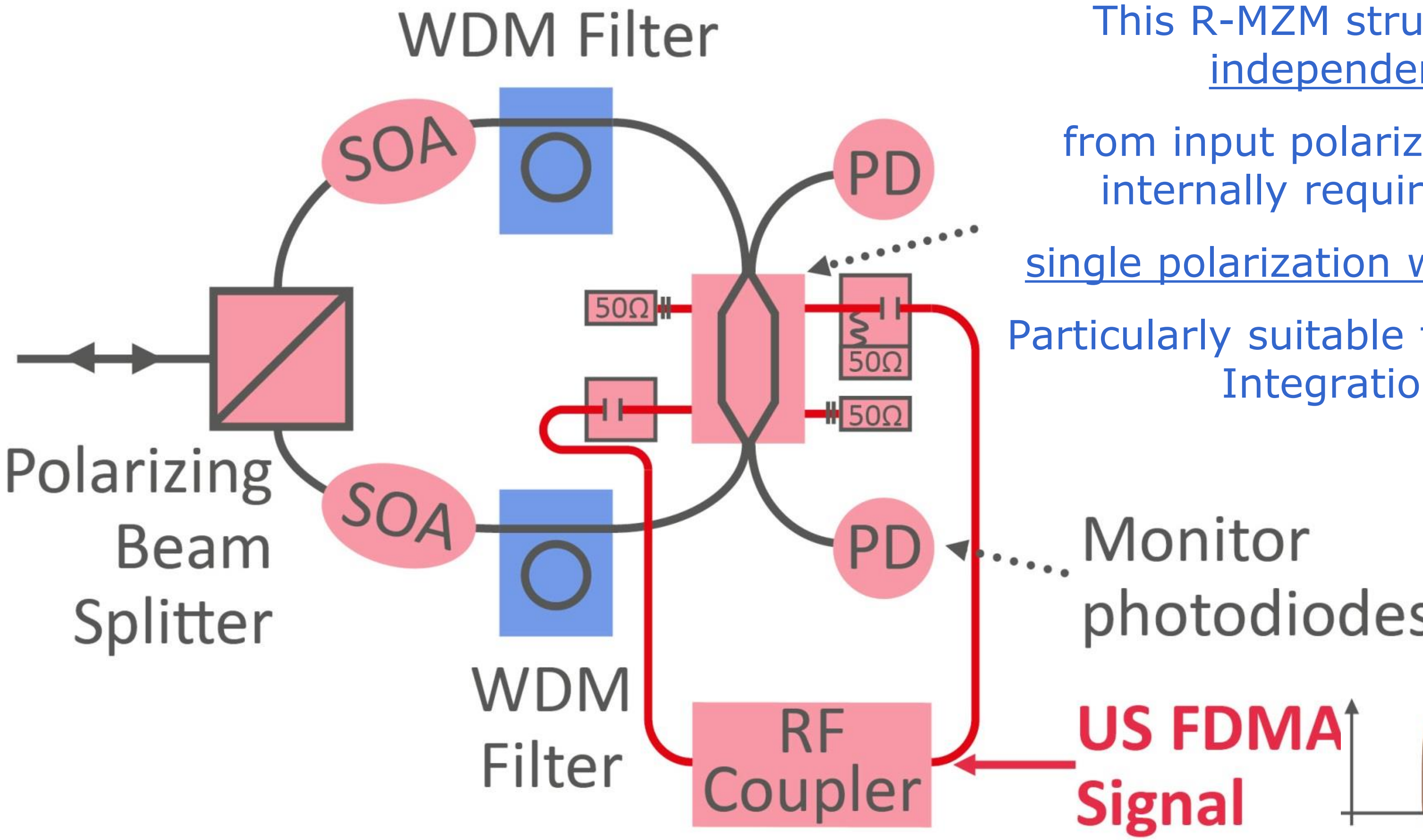
Purpose of the project is also to integrate the ONU on a Silicon Photonics PIC

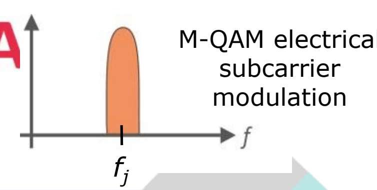
This R-MZM structure is <u>independent</u>

from input polarization but internally requires only

<u>single polarization waveguides</u>

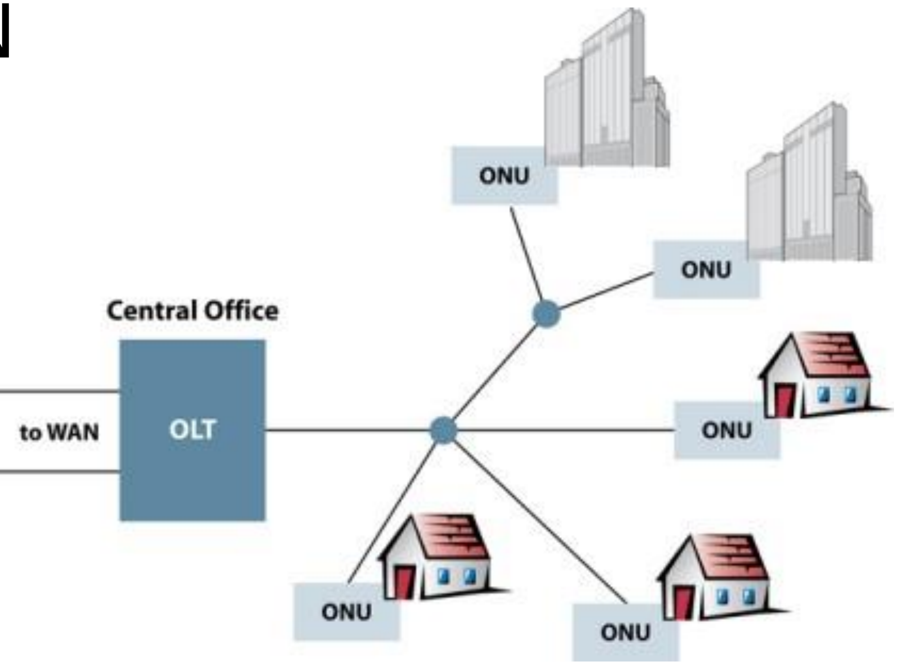
Particularly suitable for Photonic Integration



# Optical Distribution Network (ODN)

- ITU-T compliant ODN
- Splitter-based PON
- Targeting high ODN losses




- Compared to ITU-T and IEEE standards our proposal is thus:
  - "in the mainstream" for the ODN
  - "highly alternative" for the ONU and OLT

# PROs AND CONs vs. TWDM-PON (NG-PON2)

**PROs**

Most of WDM complexity and cost left at the OLT

No tunable lasers at ONU and thus

NO uncontrolled wavelength problems at ONU switch-on

Continuous data-stream, no burst mode thanks to FDMA

Thus strong FEC, M-QAM and easier DSP compared to burst-mode systems

Higher bit rate per wavelength

Using electrical frequency up/down converters

DSP can work at low sampling rate at baseband

**CONs**

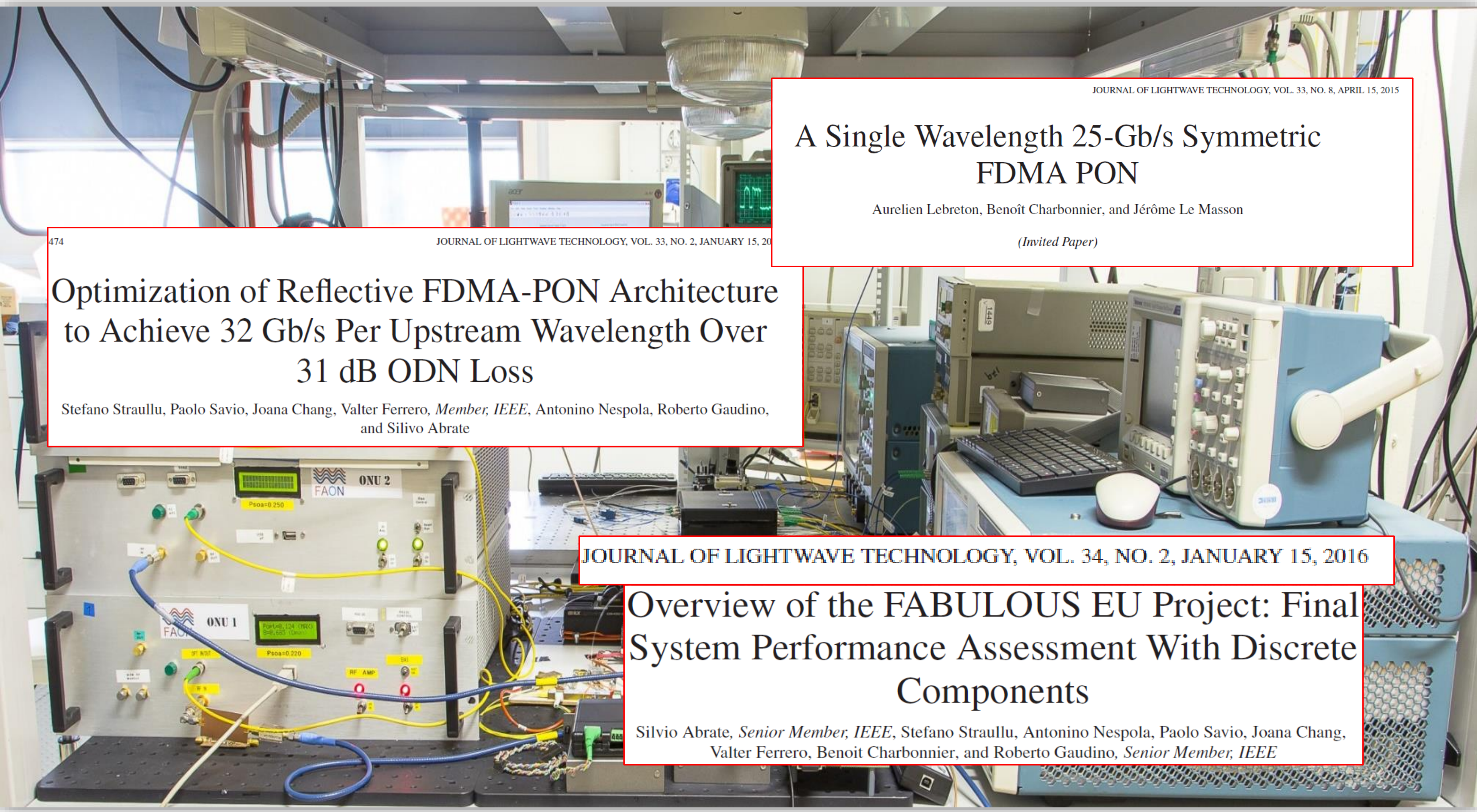
Modulator and tunable optical filter and SOA at the ONU

Need for a photonic integrated chip

Linear optoelectronics at both TX and RX

DSP-based, so that DAC and ADC required

# BENCHMARKING WITH COMMERCIAL AND DISCRETE OPTOELECTRONIC COMPONENTS




JOURNAL OF LIGHTWAVE TECHNOLOGY, VOL. 33, NO. 8, APRIL 15, 2015

## A Single Wavelength 25-Gb/s Symmetric FDMA PON

Aurelien Lebreton, Benoît Charbonnier, and Jérôme Le Masson

*(Invited Paper)*

474 JOURNAL OF LIGHTWAVE TECHNOLOGY, VOL. 33, NO. 2, JANUARY 15, 20

## Optimization of Reflective FDMA-PON Architecture to Achieve 32 Gb/s Per Upstream Wavelength Over 31 dB ODN Loss

Stefano Straullu, Paolo Savio, Joana Chang, Valter Ferrero, *Member, IEEE*, Antonino Nespola, Roberto Gaudino, and Silvio Abrate

JOURNAL OF LIGHTWAVE TECHNOLOGY, VOL. 34, NO. 2, JANUARY 15, 2016

## Overview of the FABULOUS EU Project: Final System Performance Assessment With Discrete Components

Silvio Abrate, *Senior Member, IEEE*, Stefano Straullu, Antonino Nespola, Paolo Savio, Joana Chang, Valter Ferrero, Benoit Charbonnier, and Roberto Gaudino, *Senior Member, IEEE*

# BENCHMARKING WITH DISCRETE COMPONENTS

| Modulation format | Electrical bandwidth per channel | Net bit-rate per user | Maximum ODN loss |
|---|---|---|---|
| 64-QAM | 660 MHz | 3 Gbps | 23.0 dB |
| 64-QAM | 1320 MHz | 6 Gbps | 23.0 dB |
| 16-QAM | 330 MHz | 1 Gbps | 31.0 dB |
| 16-QAM | 1650 MHz | 5 Gbps | 30.5 dB |
| [illegible] | [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] | [illegible] |
| QPSK | 1650 MHz | [illegible] | [illegible] |
| QPSK | 3300 MHz | [illegible] | [illegible] |
| BPSK | 330 MHz | [illegible] | [illegible] |
| OOK | 6250 MHz | [illegible] | [illegible] |

32 users per lambda

=32 Gbps US per lambda

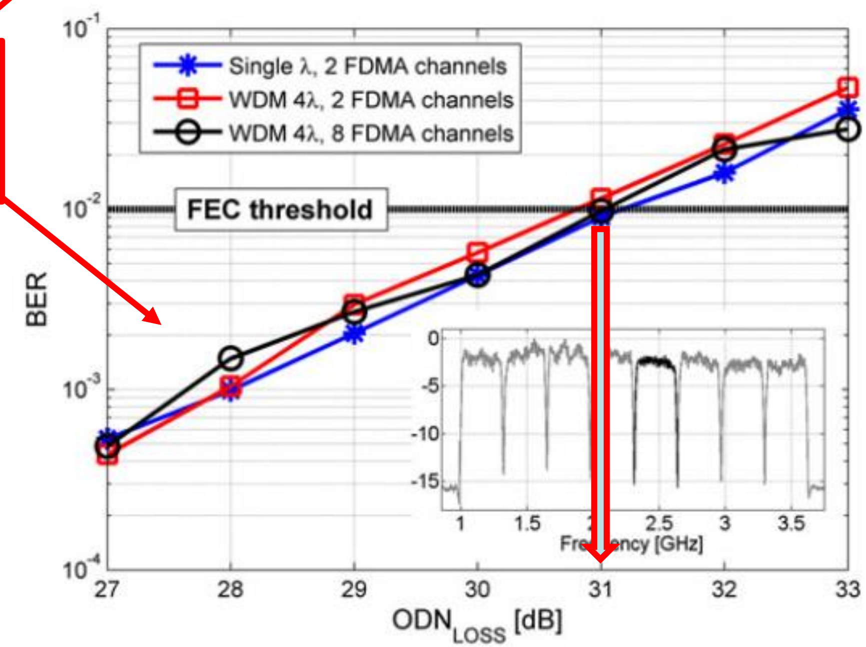



Fig. 2. Performance of the upstream transmission in terms of BER vs ODN loss with two active ONUs (32 emulated channels per wavelength using optical noise loading). It is evident that the simplified setup totally emulates the meaningful interferences.

# Outline

- General introduction to the FABULOUS project
- Implementation of the reflective-ONU in a silicon Photonic integrated chip
- Latest results on flexibility in terms of:
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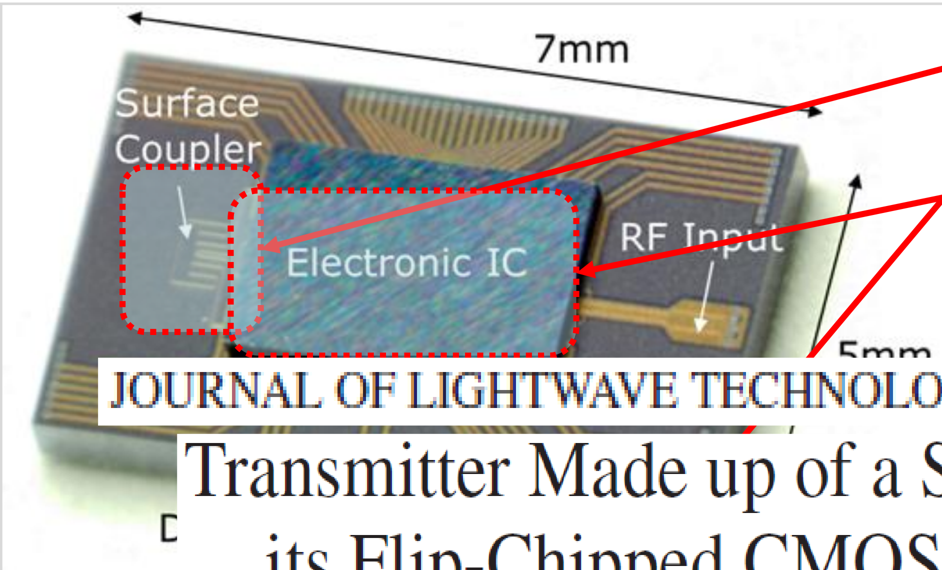
# THE INTEGRATED R-MZM IN SILICON PHOTONICS

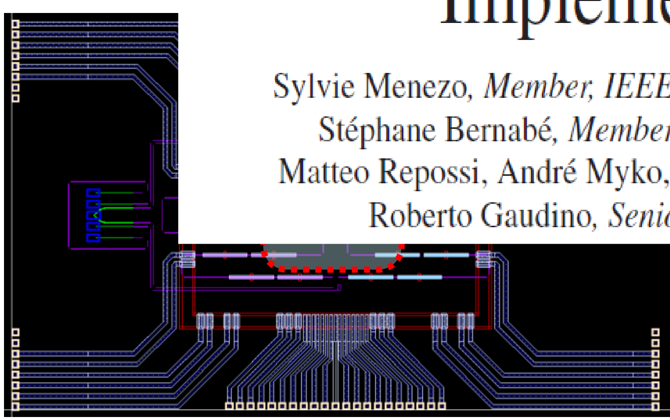


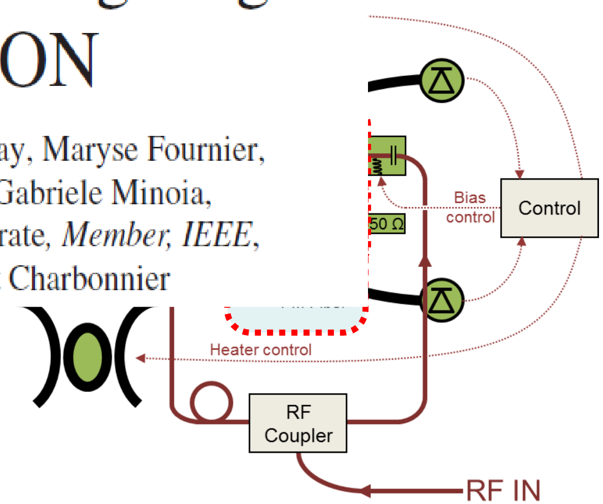

- Grating coupler with PBS
- Segmented MZ modulator
- CMOS electrical driver flip-chipped on top
- Low driving voltage and power ... g DSP)
- ... ersion
- ... (fiber to

JOURNAL OF LIGHTWAVE TECHNOLOGY, VOL. 34, NO. 10, MAY 15, 2016

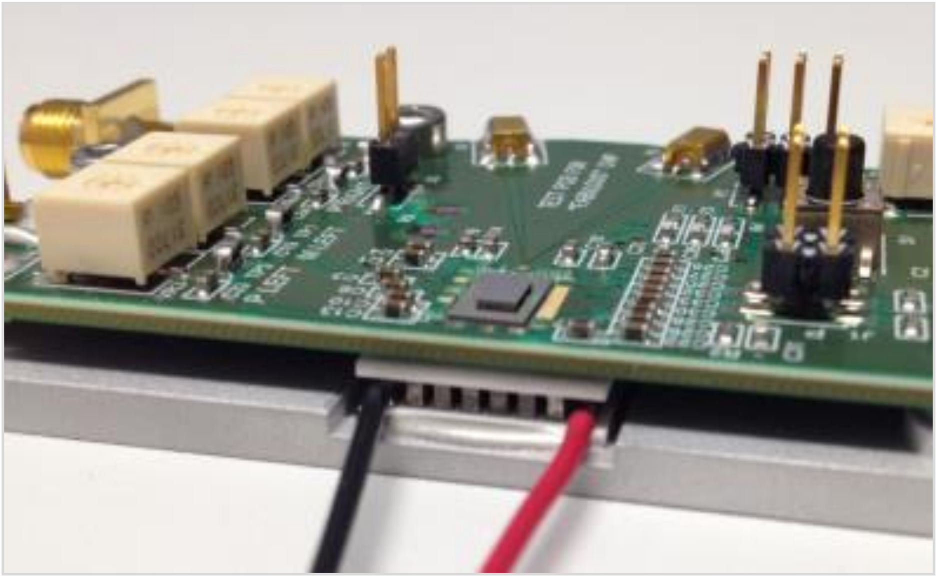
## Transmitter Made up of a Silicon Photonic IC and its Flip-Chipped CMOS IC Driver Targeting Implementation in FDMA-PON

Sylvie Menezo, *Member, IEEE*, Enrico Temporiti, Junsu Lee, Olivier Dubray, Maryse Fournier, Stéphane Bernabé, *Member, IEEE*, Daniele Baldi, Benjamin Blampey, Gabriele Minoia, Matteo Repossi, André Myko, Sonia Messaoudène, Lee Carroll, Silvio Abrate, *Member, IEEE*, Roberto Gaudino, *Senior Member, IEEE*, Peter O'Brien, and Benoit Charbonnier





# R-MZM Fully-packaged for system tests and demo

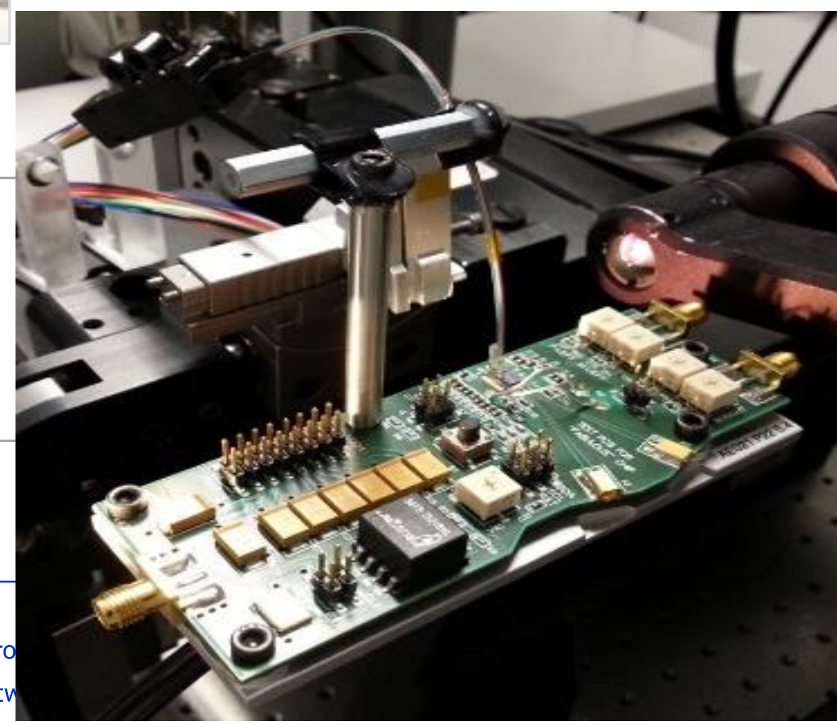


Tyndall National Institute

life.augmented

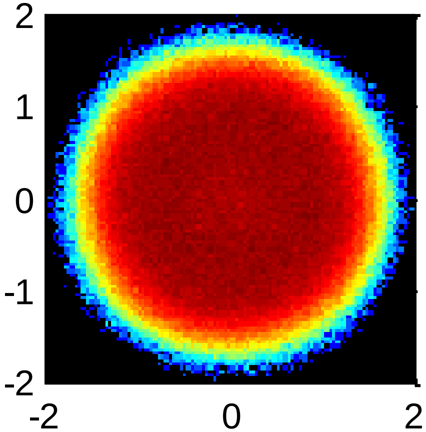
Integrated on a test-board for system experiments

with an external SOA placed before the chip

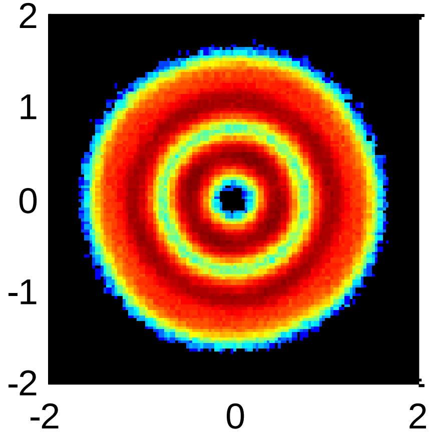


# 16QAM BACK-TO-BACK at 1 Gbps per user

Sampled Demod Output (2 SpS)

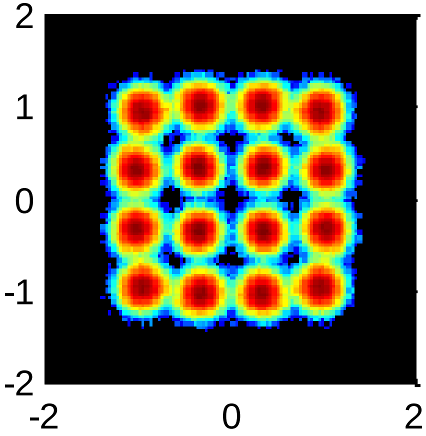



Equalized Signal (Blind Equalizer)

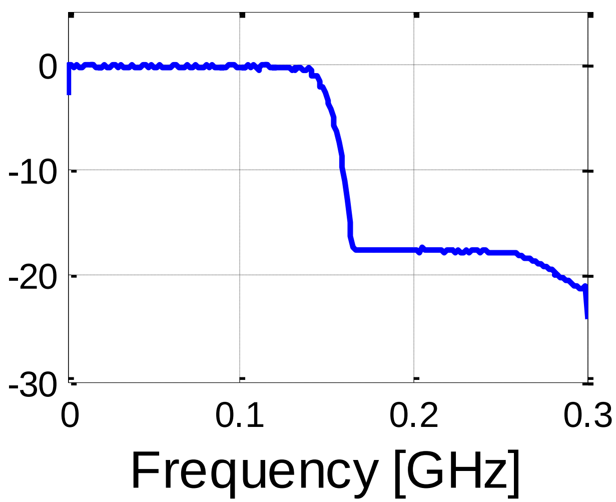



- $f_{ch}$ = 2 GHz
- Back-to-back
- EVM = 11%
- BER = $2 \cdot 10^{-3}$

Signal after CPE

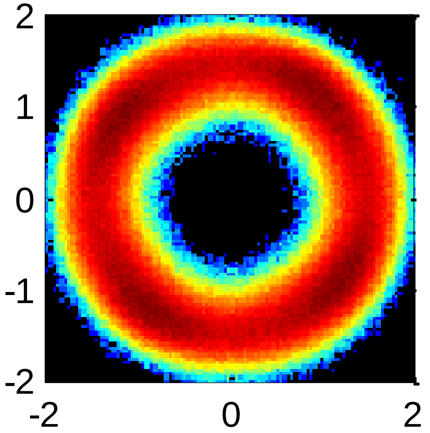



Normalized PSD [dB/Hz]

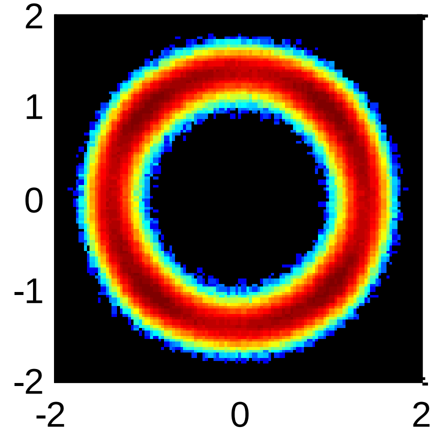


# QPSK BACK-TO-BACK at 500 Mbps per user

Sampled Demod Output (2 SpS)

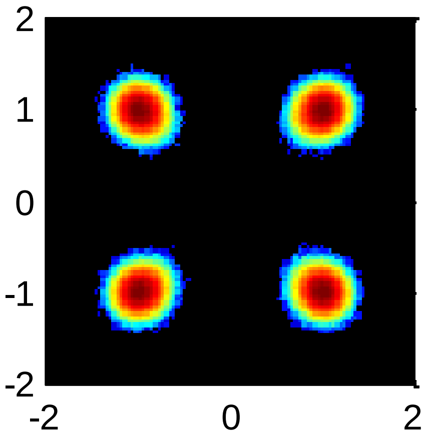



Equalized Signal (Blind Equalizer)

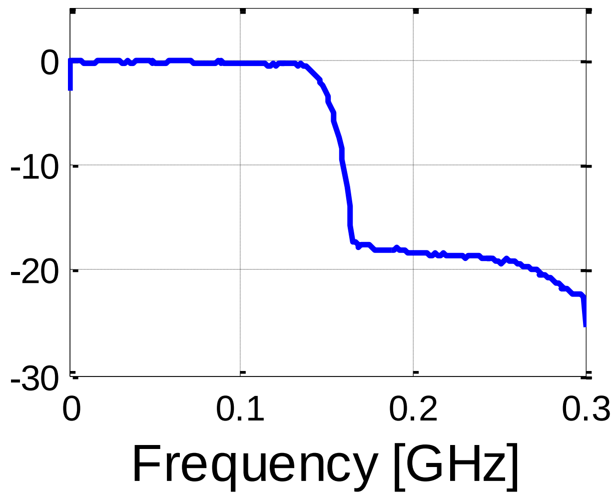



- $f_{ch}$ = 2 GHz
- Back-to-back
- EVM = 12%
- BER<$10^{-6}$

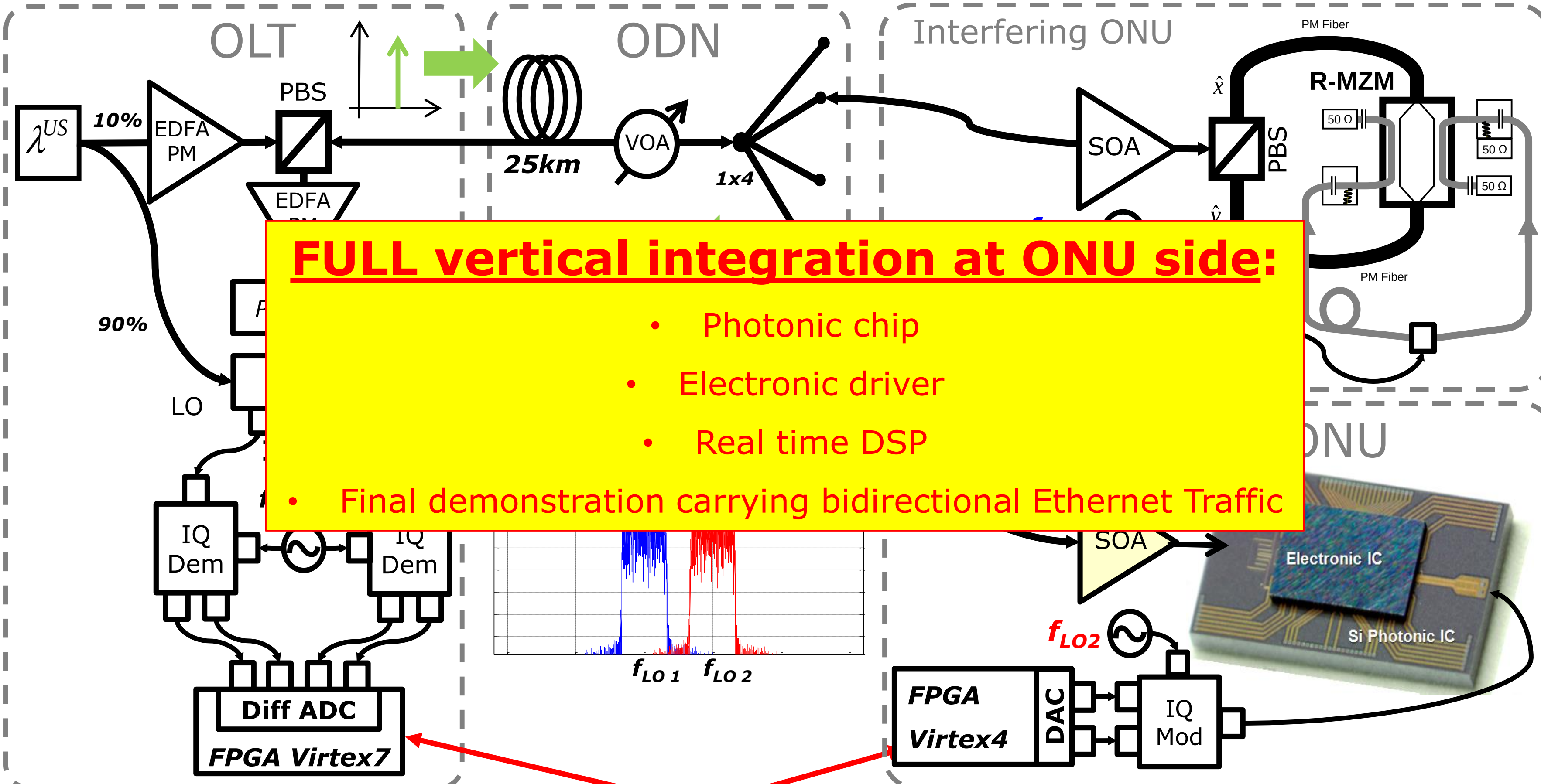
Signal after CPE




Normalized PSD [dB/Hz]



# EXPERIMENTAL SETUP



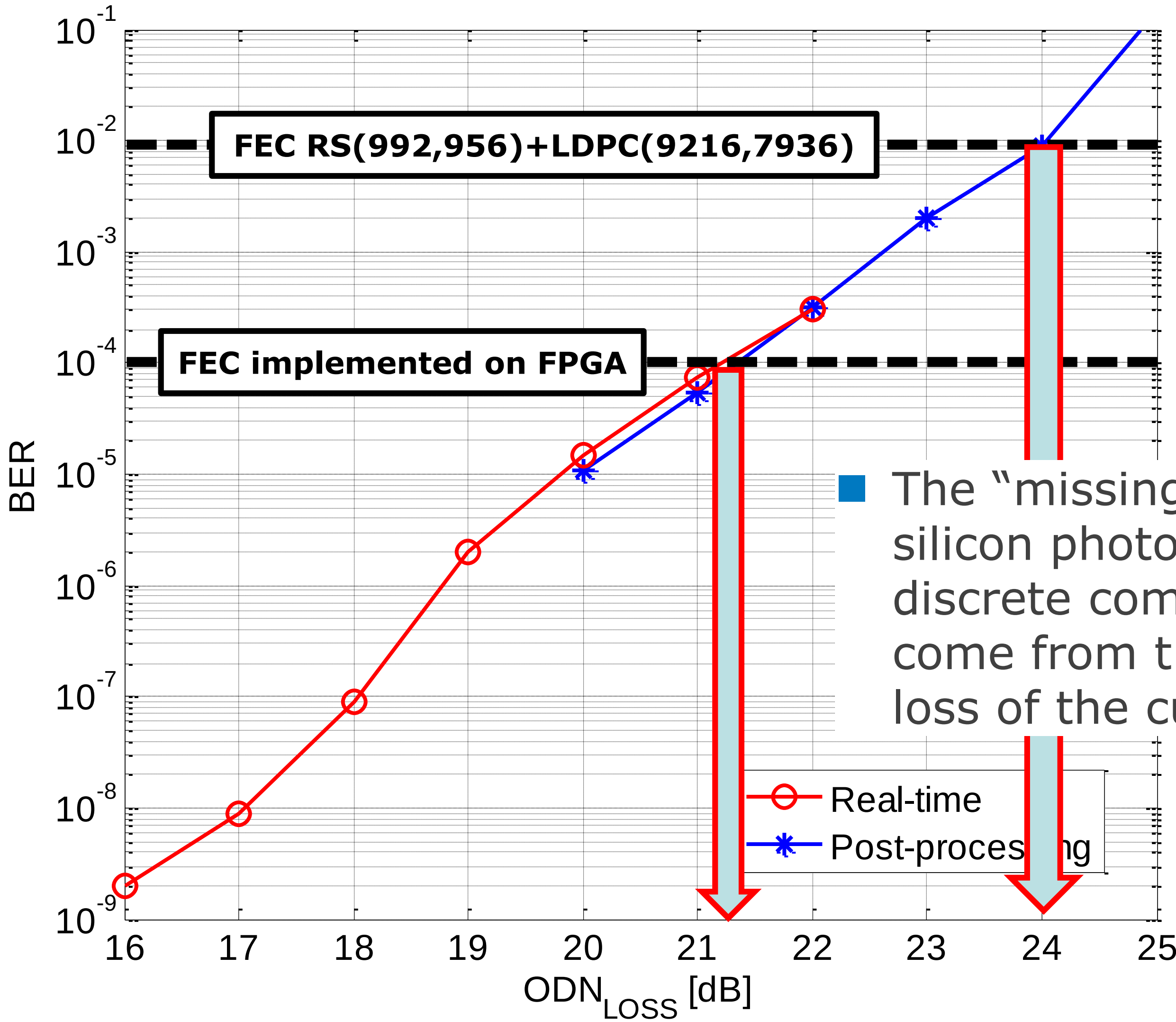

**FULL vertical integration at ONU side:**

- Photonic chip
- Electronic driver
- Real time DSP
- Final demonstration carrying bidirectional Ethernet Traffic

REAL TIME DSPs programmed on FGPA platforms

XILINX Virtex4 at ONU, Virtex 7 at OLT

# REAL-TIME BER VS. ODN-LOSS



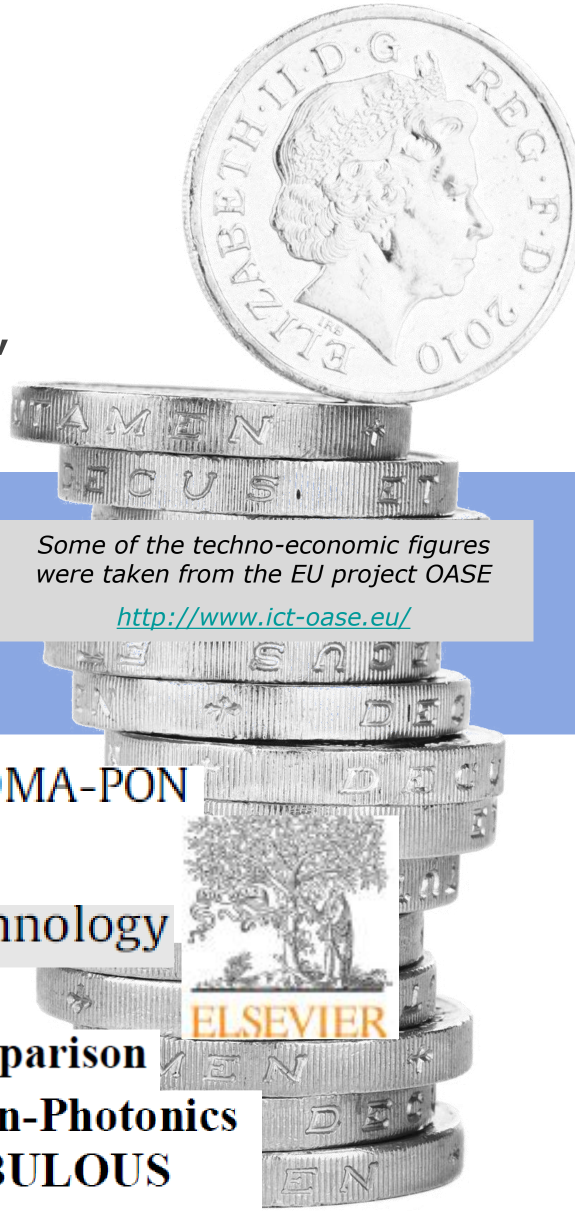

- QPSK
- 500 Mbps
- $f_{ch}$ = 2GHz
- 25 km SMF
- 1550 nm

- The “missing” 7 dB between the silicon photonic setup and the discrete components one mostly come from the higher insertion loss of the current prototype

# IS THE FULL ONU LOW COST?

Techno-economic study carried our in project. Considering:

>1.000.000 pieces/year, size of the SiP chip, SOA, electrical driver, commercial FDM IC




**ABOUT 80$**

**(70% DUE TO PACKAGING)**

*Some of the techno-economic figures were taken from the EU project OASE*

*http://www.ict-oase.eu/*

Review and comparative assessment of FDMA-PON vs. TDMA-PON for next-generation optical access networks

Silvio Abrate [a], Roberto Gaudino [b,*]

Optical Fiber Technology

ELSEVIER

**FDMA-PON and NG-PON2: Performance and Cost Comparison**

Papers presented at ICTON 2015

**Power Consumption Estimation for the Silicon-Photonics Reflective ONU Conceived within the FABULOUS European Project**

# Outline

- General introduction to the FABULOUS project
- Implementation of the reflective-ONU in a silicon Photonic integrated chip
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# Introducing flexibility in our architecture

- Most of the work during the duration of the project was focused on
  - 1 Gbit/s per user in the upstream
  - 16-QAM modulation on each subcarrier
  - 32 users per wavelength
  - ITU-T Class N1 ODN loss
- The architecture is potentially very flexible in terms of
  - Bit rate per user
  - Number of user per wavelength
  - Achievable ODN loss

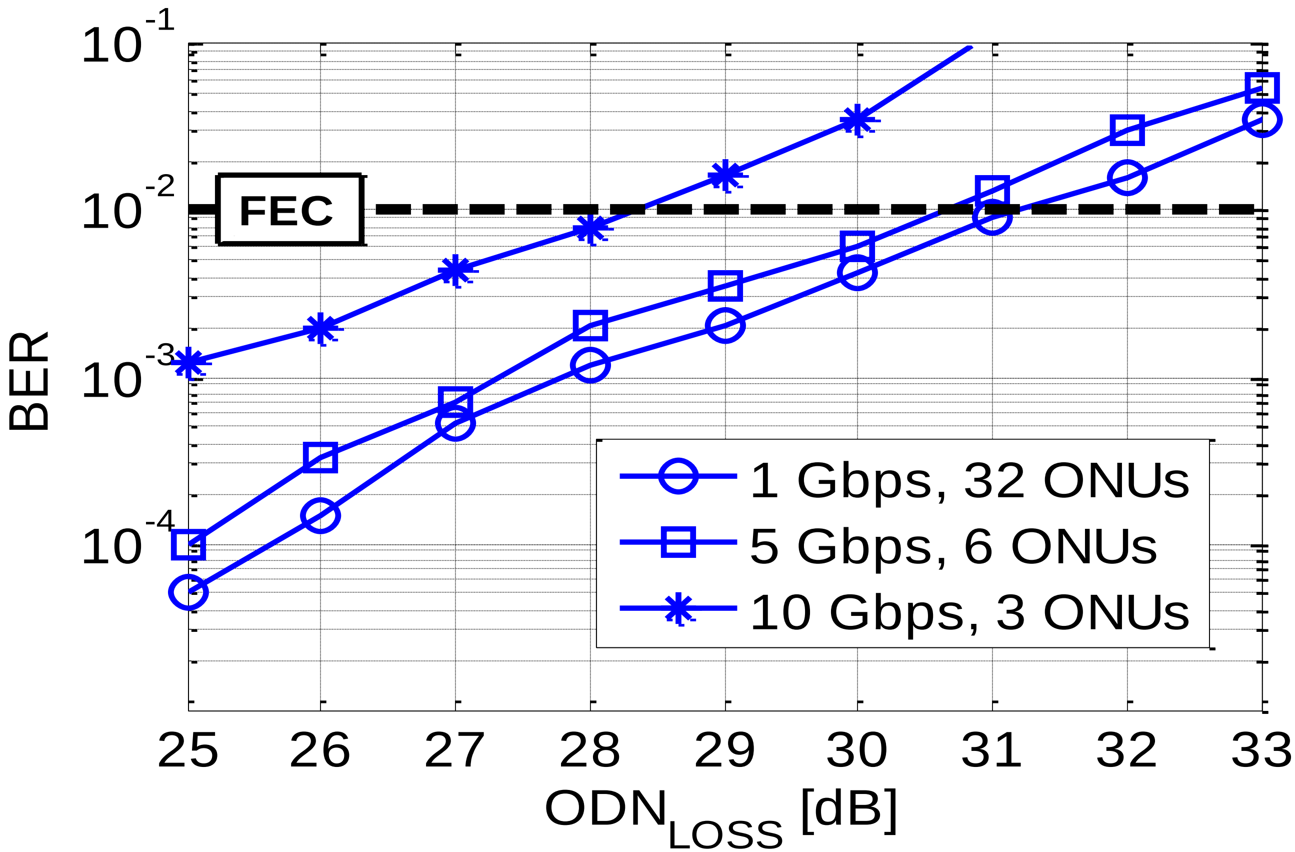
*Mostly thanks to the DSP-based transmission platform*

*AND*

*FDMA approach*

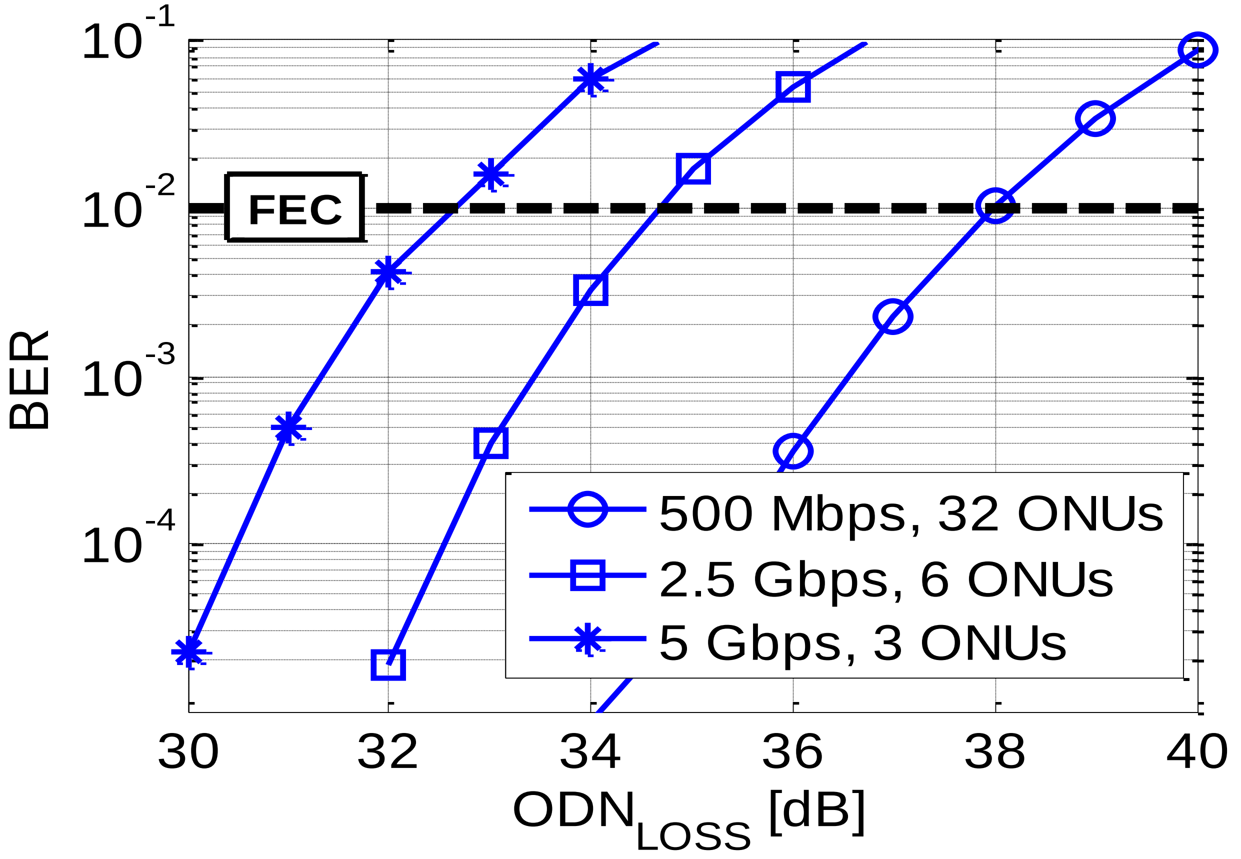
# Increasing the bit rate per user

- Different bit rates and number of user per wavelength



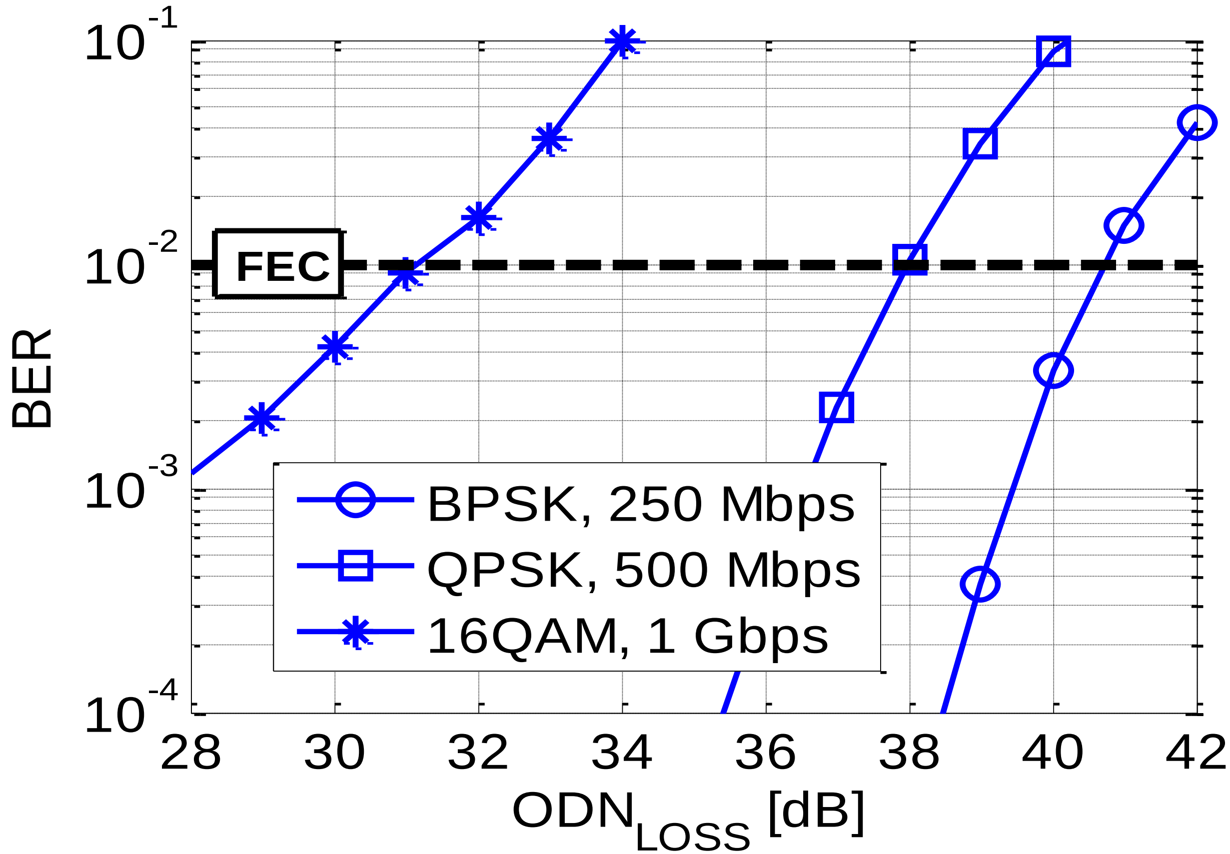
# Increasing the achievable ODN loss

- Moving from 16-QAM to more resilient QPSK



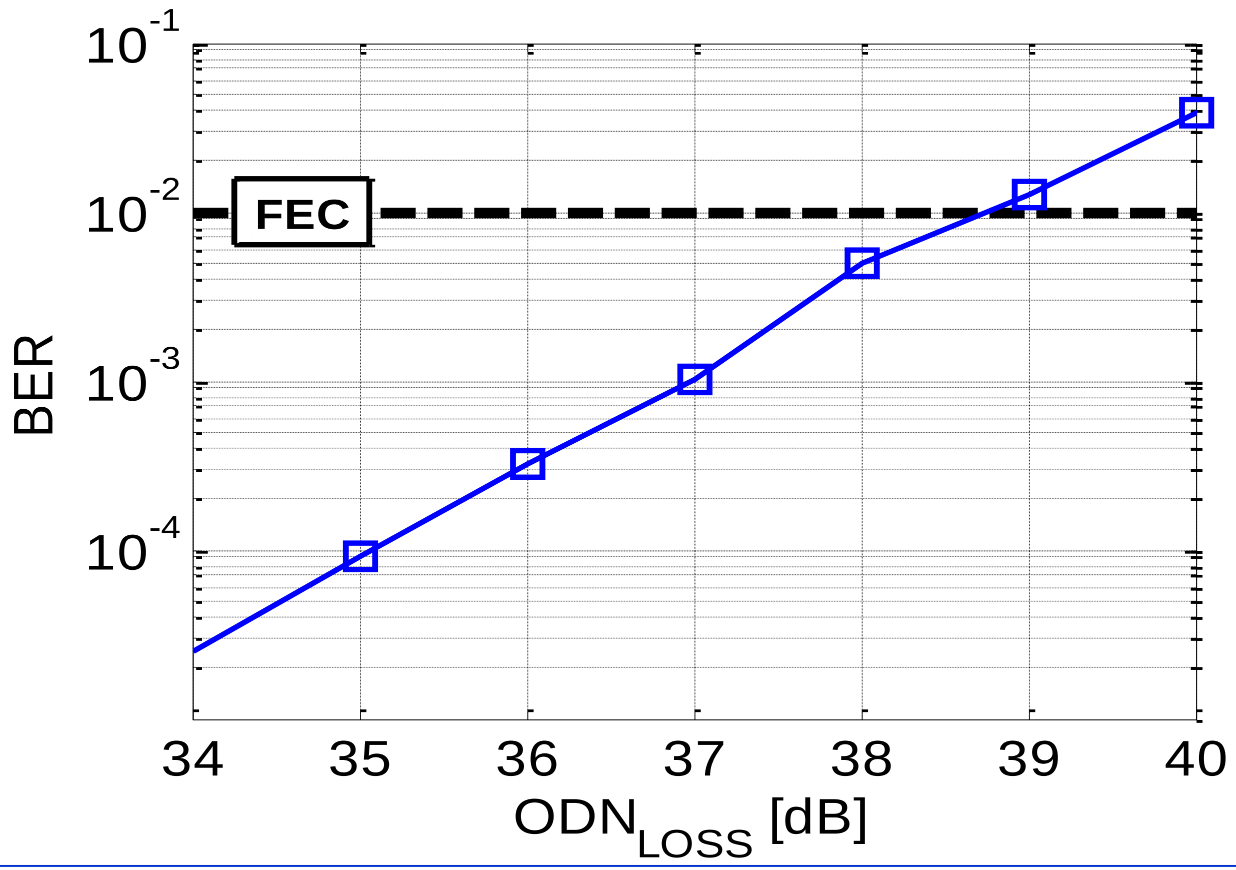
# Going to even higher ODN loss

- Comparison of different modulation formats: BPSK, QPSK and 16-QAM



# Increasing the bit rate per user AND the ODN loss

- ... even using a single OOK stream, single user at 10 Gbps



# Conclusion

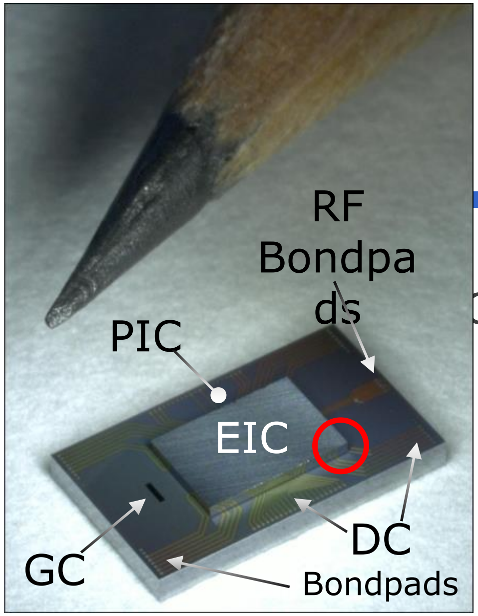
We have demonstrated

the effectiveness of a self-coherent reflective FDMA PON architecture in complying to ODN loss standard requirements

the feasibility of the required Photonic Integrated Circuits

and

Real time DSP




cost

ONU

+ Flexibility in the Architecture

# ACKNOWLEDGMENTS

The research leading to these results has received funding from the European Community's Seventh Framework Programme FP7/2007-2013 under grant agreement n°318704, titled:

**FABULOUS:**
**"FDMA Access By Using Low-cost Optical Network Units in Silicon Photonics"**

WEB site:
www.fabulous-project.eu

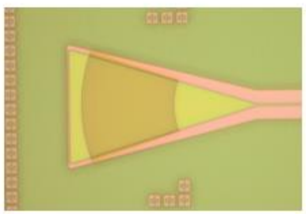
To contact us:
info@fabulous-project.eu
roberto.gaudino@polito.it

# BACKUP SLIDES

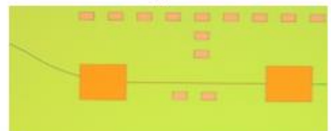
# PIC FABRICATION

- **Processed at CEA-LETI clean room**
- **200 mm wafers (8 inches)**
- **Used Substrate : HR-SOI with 2µm Buried Oxide and 220 nm Silicon**
- **Devices E/O characterizations on Cascade Elite wafer probers**

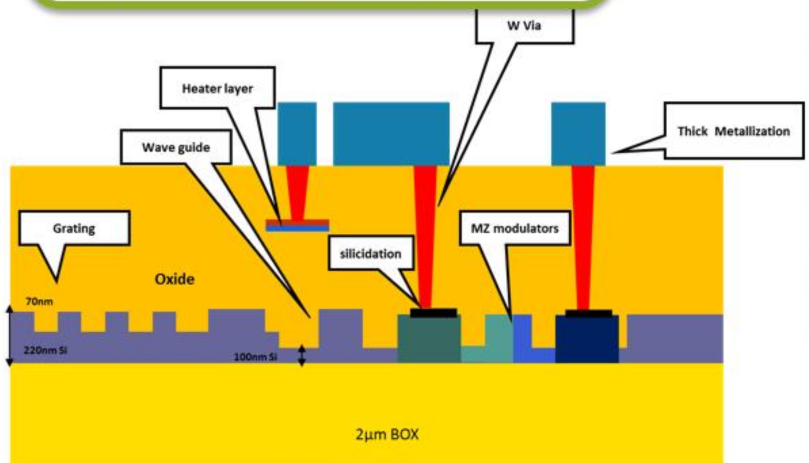
### *Couplers*
- footprint < 500mm2



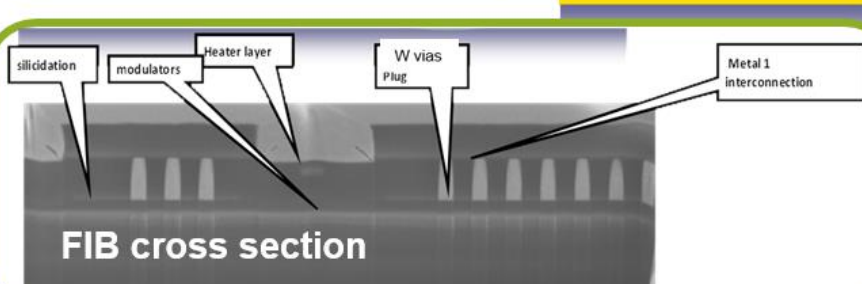
### *Heater R:2,2 K ohms*



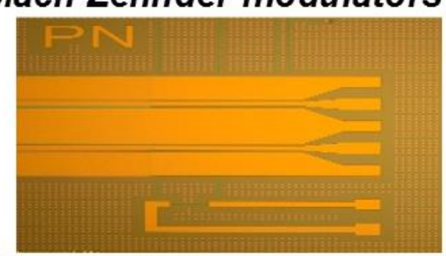
### *Waveguide Specifications*
- propagation loss <1.2dB/cm



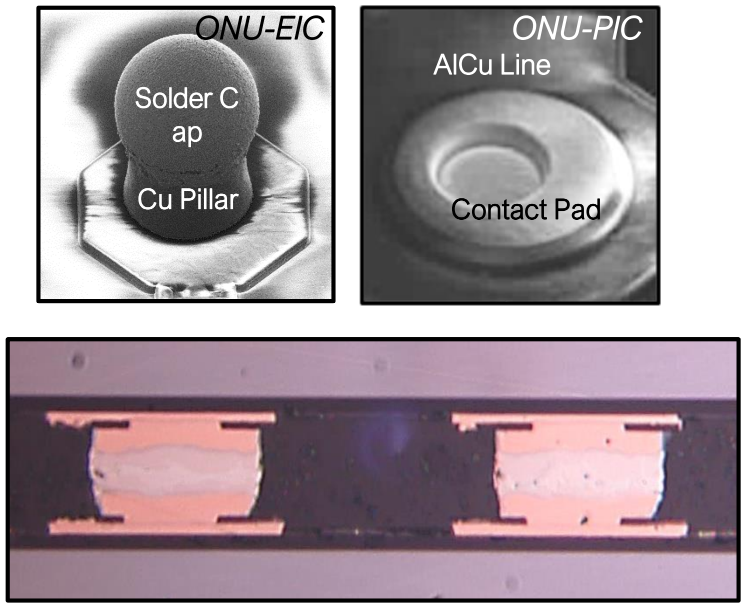

- Grating Coupler etching
- PN junction implantation
- Rib waveguide etching
- Heater & via
- Electrodes




### *Mach Zehnder modulators*



# Electronic driver flip-chip processed on the Silicon Photonic platform

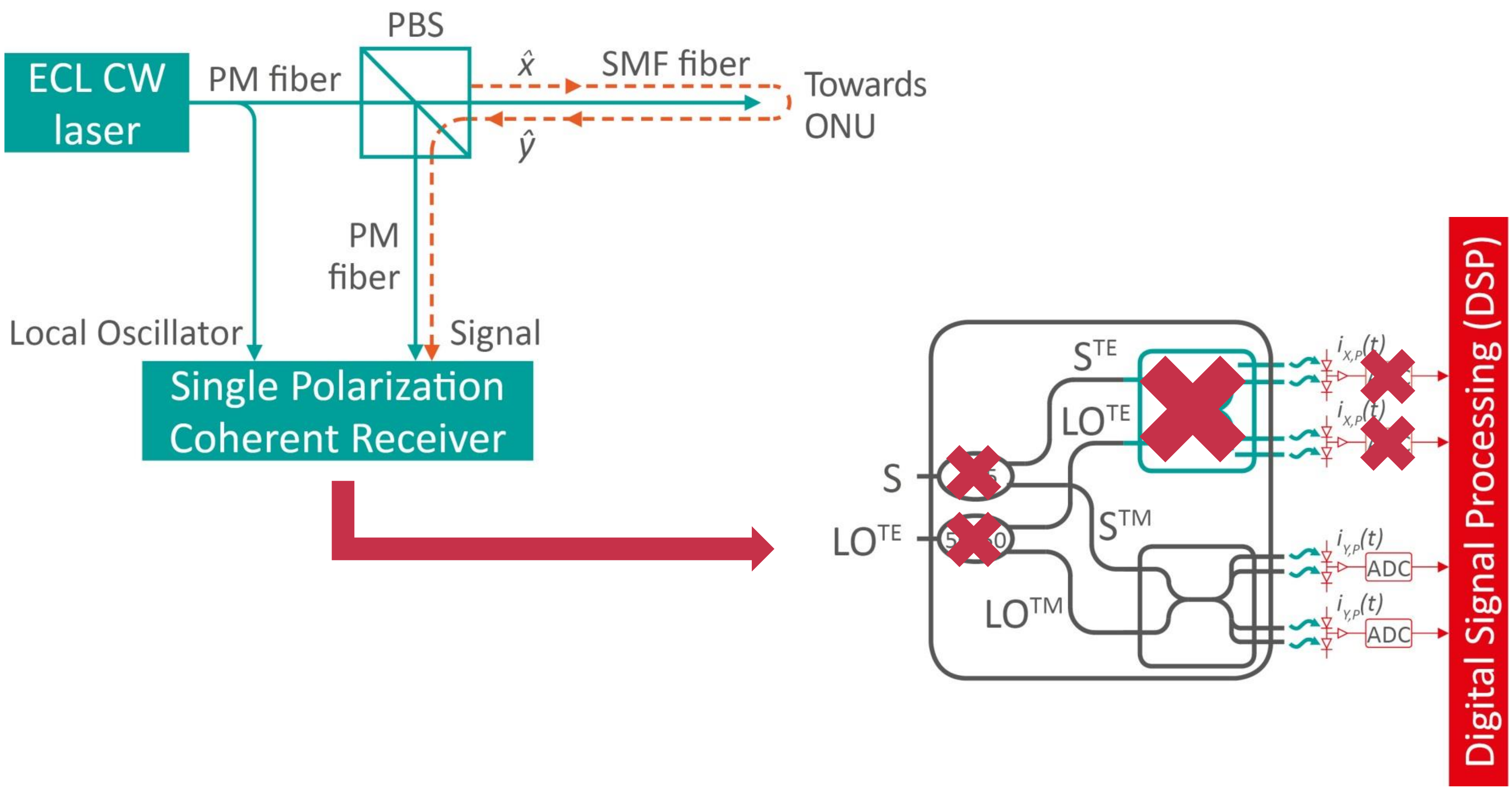



**20 μm Copper Pillar**

**SnAgCu Solder Cap**

# SIMPLIFIED COHERENT DETECTION

Faraday rotation at ONU allows simplified coherent detection at the OLT



## System experiments using discrete optoelectronics

- Main achievements for what concerns 1 Gbps per user experiments
  - 32 Gbps per wavelength for 32 users
  - Up to 31 dB of ODN loss
  - Demonstration of four-lambdas WDM
    - A joint demo including both Orange Labs and ISMB hardware prototypes wa
      experimental setup with

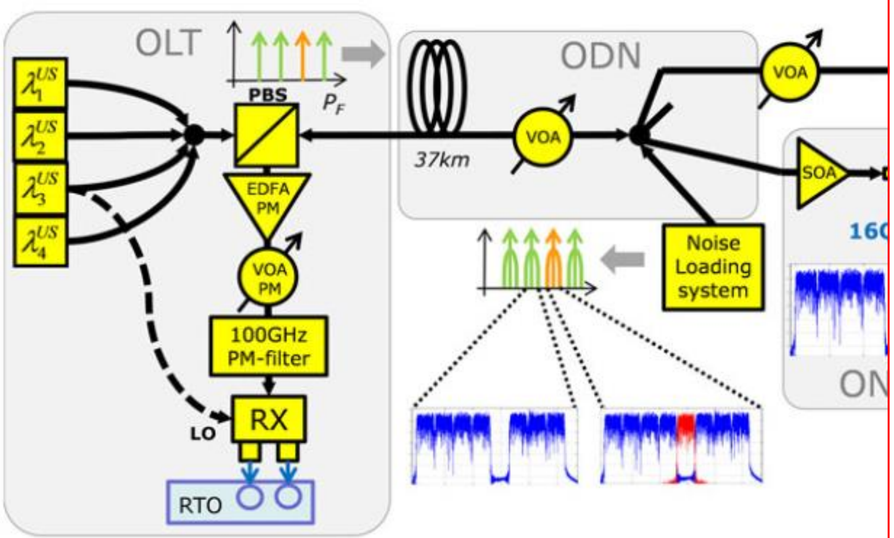



Fig. 1. Full off-line processing experimental setup with installed fiber, two active ONUs and r variable optical amplifier, RTO: real time oscilloscope, SOA: semiconductor optical amplifier, AB modulator, REAM: reflective electro absorption modulator).

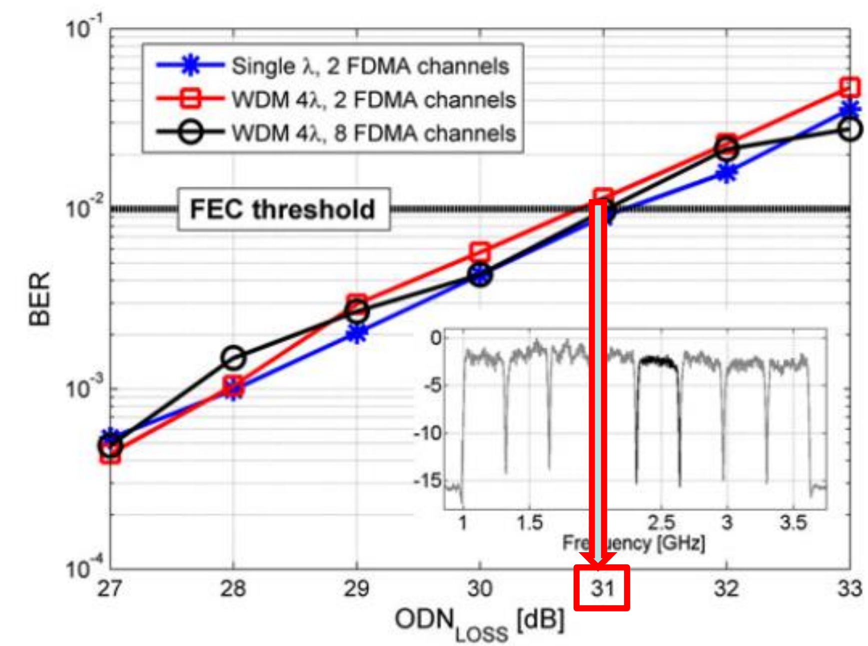



Fig. 2. Performance of the upstream transmission in terms of BER vs ODN loss with two active ONUs (32 emulated channels per wavelength using optical noise loading). It is evident that the simplified setup totally emulates the meaningful interferences.

# ONU power consumption

| Device | Power consumption [W] |
| --- | --- |
| Electronic chipset for modulation (Rx and Tx) | 1.1 |
| Optoelectronic receiver | 1.0 |
| R-MZM driver | 1.4 |
| Photonic integrated circuit (R-MZM) | 0.5 |
| SOA | 0.5 |
| Tuneable optical filters | 0.5 |
| TEC | 3 |
| TOTAL | ~~8 Watt~~ |

**6 Watt new estimation**

**Post-deliverable news**: the actual required power for the TEC in the final release of the PIC is significantly less

- The new estimate is 1 W to stabilize the PIC to 25 C
- The total power consumption of the ONU would thus decrease to 6 W

# Bill-of-Material costs: two scenarios

SCENARIO #1: Medium-term scenario in which the NG-PON implementation is based on TWDM-PON using 4 wavelengths per direction for an aggregated capacity of 40 Gbps DS and 10 Gbps US

| | FABULOUS | | TWDM PON | |
|---|---|---|---|---|
| | OLT | ONU | OLT | ONU |
| Cost | 1620 US$ | 78 US$ | 5150 US$ | 625 US$ |
| Power consumption | 88 W | 8W | 89 W | 10 W |

SCENARIO #2: Long-term scenario in which the NG-PON implementation is based on TWDM-PON using 16 wavelengths per direction for an aggregated capacity of at least 160 Gbps DS and 40 Gbps US

| | FABULOUS | | TWDM PON | |
|---|---|---|---|---|
| | OLT | ONU | OLT | ONU |
| Cost | 6026 US$ | 78 US$ | 19100 US$ | 625 US$ |
| Power consumption | 329 W | 8 W | 281 W | 10 W |