Reflective PON architectures

10 years of useless researches or a promising alternative?

FSAN meeting, Atlanta, 2015 October 7th
Future Access Technology Workshop

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FABULOUS at-a-glance

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ARCHITECTURE

SYSTEM PARAMETERS

This part is almost over after 2.5 years of work inside the EU project.

This presentation is a "final" presentation on the System workpackage of the project

NEW integrated optoelectronic COMPONENTS for the ONU

Acknowledgements

OPTCOM

All the Partners of the EU project titled "FABULOUS"
http://www.fabulous-project.eu/

My colleagues at POLITO and ISMB

Politecnico di Torino,
Corso Duca degli Abruzzi 24, 10129 Torino, Italy

Istituto Superiore "Mario Boella" (ISMB),
Via P. C. Boggio 61, 10138 Torino, Italy

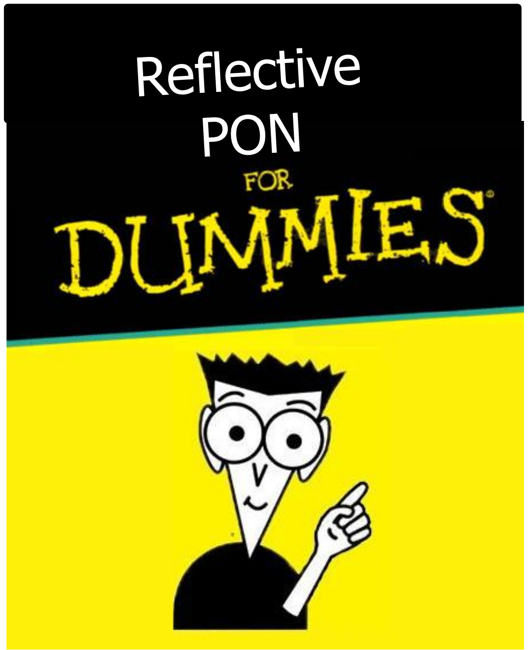
The Telecom Italia team in Torino
Headed by Maurizio Valvo

Fabrizio Forghieri
CISCO Photonics,
Via Philips 12, 20059, Monza, Milan, Italy

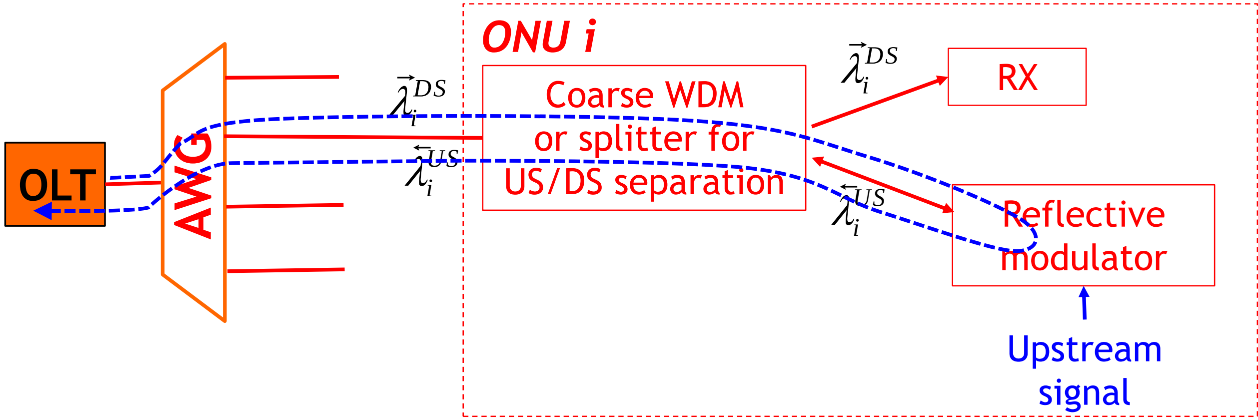
Outline of the presentation

OPTCOM

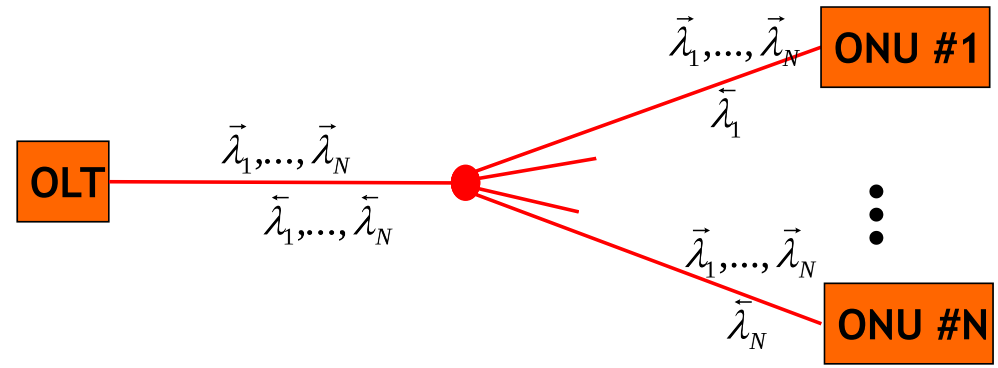
- A review of reflective PON architectures
  - Do they still make sense after ITU-T G.989 decisions?
- Our research activity #1: Self-coherent reflective PON in a TDMA-based or P2P flavour
- Our research activity #2: FDMA-PON
  - The EU project FABULOUS
- Discussion and conclusion



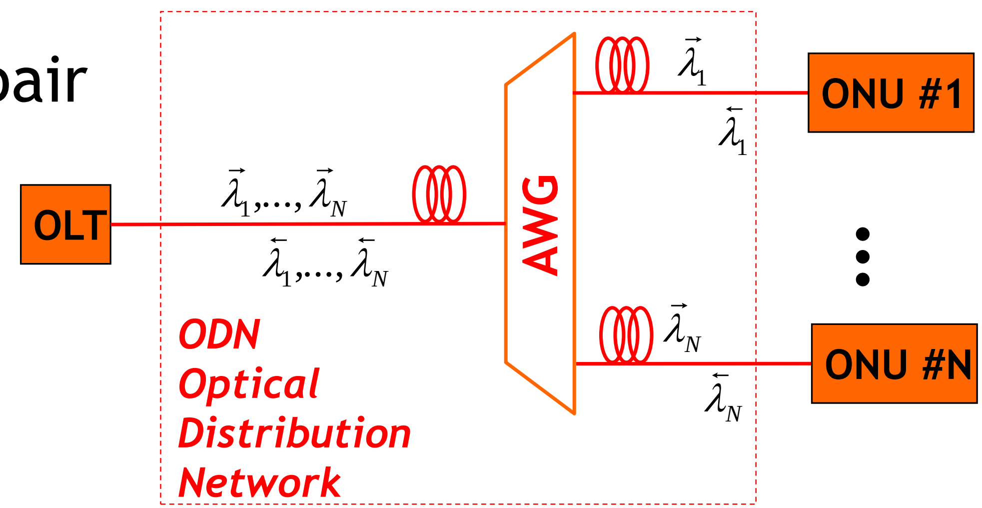
Reflective solutions for PON upstream modulation



- Splitter-based Optical Distribution Network



- Optical filter-based Optical Distribution Network
  - Dedicated wavelength pair for each ONU



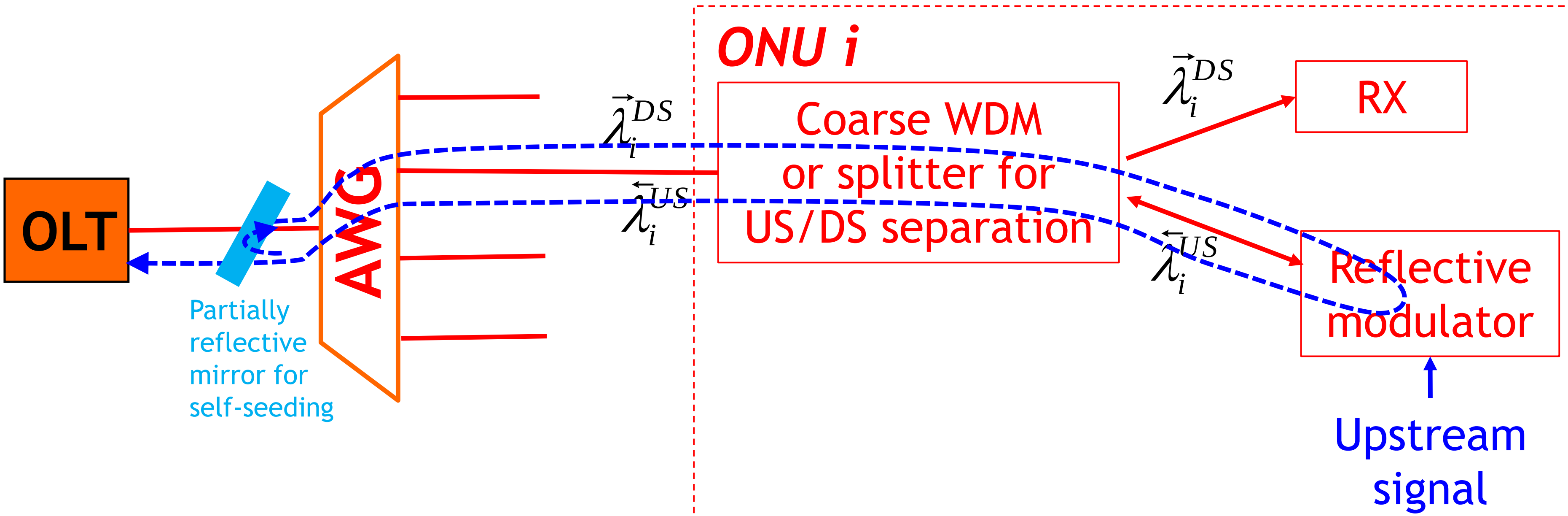
Reflective PON basics

The key ideas (all related to upstream transmission)

- The upstream wavelengths are generated outside the ONU using one of these two options:
  1. Wavelengths generated using one of the many different forms of self-seeding “long cavity” lasers
  2. Wavelengths generated (usually as CW) in the central office (OLT)
- The ONU reflects back a given wavelength modulating it with upstream traffic

The “mainstream” reflective PON proposals

- Most proposals refer to **filter-based** optical distribution networks
  - **Dedicated wavelength** per ONU
  - Usually with **self-seeding** for wavelength generation



Let's consider ODN specified by ITU-T…

Despite hundreds (if not thousands) of scientific papers on these "mainstream" reflective solutions, they are a **"NO GO"**

for the ODN specified by ITU-T which requires:

- Splitter-based PON
- High ODN loss (29 dB minimum in G.989)
  - In fact, most reflective PON proposals can tolerate much lower ODN loss, due to spurious backreflections limitation
- Up to 40 Km SMF fiber around C or L band
  - Which rules out most self-seeding architecture due to chromatic dispersion limitations

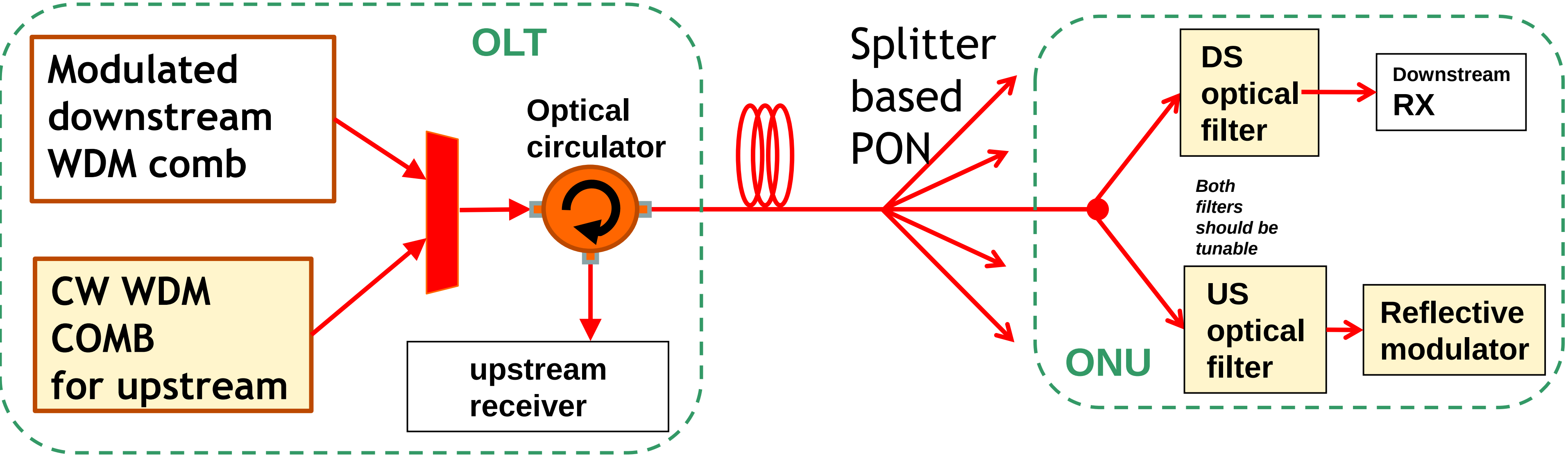
So why did I fly 7000 miles from Turin to here to present you a reflective PON architecture??

A key advantage of reflective PON

- Let's assume for a moment we can solve the key problems of "mainstream" reflective PON, that can be summarized as follows:
  - Requirement of filter-based PON
  - Low resilience to ODN loss
  - Low resilience to chromatic dispersion (for self-seeded solutions)
  - Dedicated wavelength per user
- There would be a key advantage: laser-less ONU
  - Much easier handling of upstream wavelengths
  - … which I feel is still an open issue in practical realization of ITU-T G.989 NG-PON2
    - Particularly if a 50 GHz grid will be used with 8-16 wavelengths

Our reflective PON proposal compliant with ITU-T ODN requirements

Centralized λ generation over splitter-based PON



- In the architecture above, the upstream wavelength grid is generated at the central office
  - Its accuracy is thus set by the CO
  - The ONU has to select its upstream wavelength with a tuneable optical filter
    - Its tunability is "easy" (since it is on an externally generated precise λ)

The key advantage

- Laser-less and colour-less ONU
- Laser sidelobes (or modulation sidelobes) significantly suppressed by the double pass through an optical filter

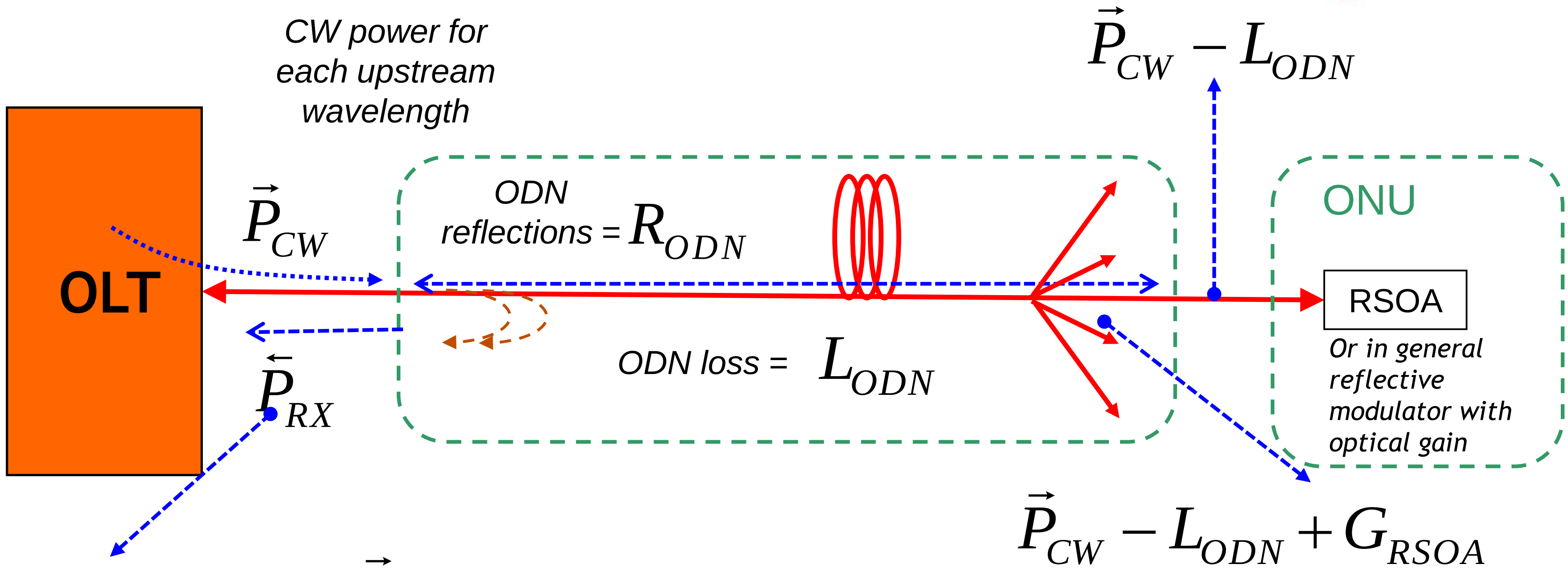
- The strong temperature variations expected at the ONU side (particular for residential FTTH) should be more easily handled by a tunable filter rather than a tunable laser
  - It can be significant in a PON using 8-16 wavelengths on a tight grid (as already envisioned by ITU-T G.989 if both PtP and TWDM are present on the same ODN)

The key problem to be solved for R-PON

From a transmission point of view:

- CONs:
  - Limited ODN power budget ("ODN loss" in the following) due to several spurious effects, including:
    - Rayleigh Back-Scattering (RBS) and concentrated reflections
    - Limited receiver power

Impact of spurious back-reflections



$$Useful\ signal: \vec{P}_{CW} - 2 \cdot L_{ODN} + G_{RSOA}$$

$$Reflected\ signal: \vec{P}_{CW} - R_{ODN}$$

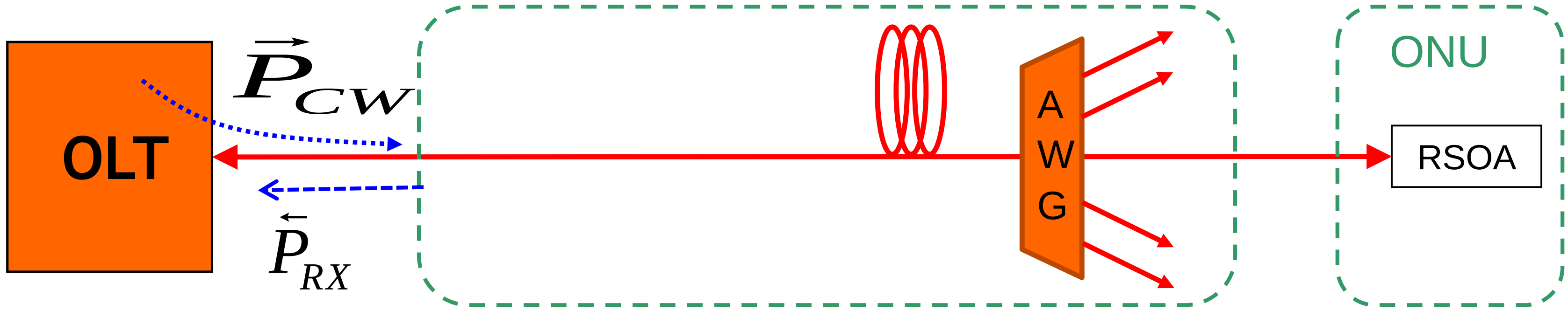
Signal to interferent ratio= $\left(\frac{S}{I}\right)_{dB} = -2 \cdot L_{ODN} + G_{RSOA} + R_{ODN}$

Signal-to-interference ratio

$$\left(\frac{S}{I}\right)_{dB} = -2 \cdot L_{ODN} + G_{RSOA} + R_{ODN}$$

- Let's assume for instance:
  - ODN loss =30 dB
  - ODN spurious reflections=35 dB
  - RSOA gain=20 dB
    - (S/I)= -5 dB
    - The interference is at the same wavelength as the useful signal
- For a standard direct-detection receiver, even for the best tricks proposed in the literature to mitigate RBS:

(S/I)>5-10 dB



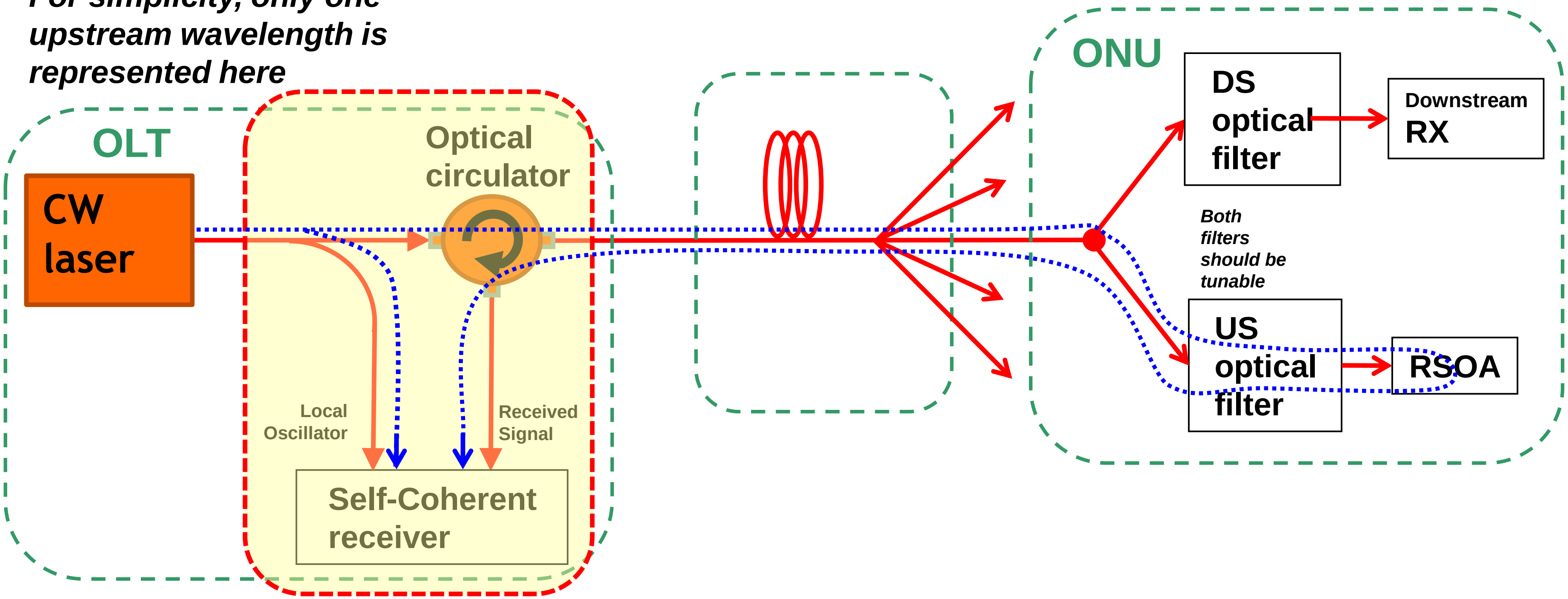
$$P_{RX} = \vec{P}_{CW} - 2 \cdot L_{ODN} + G_{RSOA}$$

- Even neglecting the RBS issue, the received power quickly decreases for increasing L_{ODN}, since it counts twice
- Let's assume for instance:
  - ODN loss =35 dB (Class C+), RSOA gain=20 dB, and P_{CW}=10 dBm
  - We get P_{RX}= -40 dBm

Introducing self-coherent detection in the OLT receiver

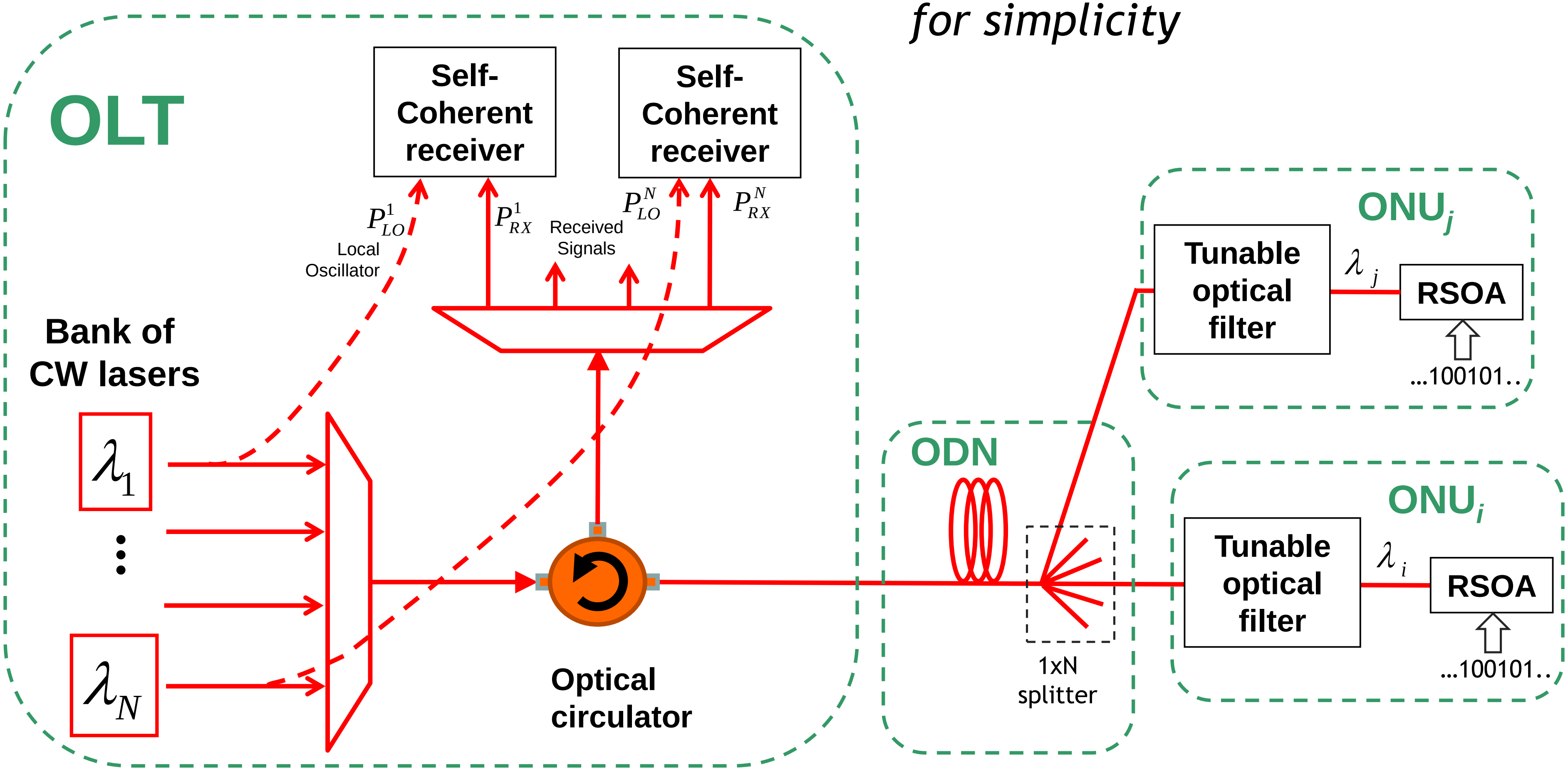
Self-coherent reflective PON

For simplicity, only one upstream wavelength is represented here



The overall reflective, self-coherent architecture

ONLY upstream shown for simplicity



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Version 1 of our proposal

OPTCOM

- Pure OOK NRZ modulation at ONU using:
  - Semiconductor Optical Amplifier (SOA) + reflective Electro Absorption modulator for US experiments

- We showed that by proper digital signal processing techniques at the coherent receiver DSP level the spurious back-reflection issue can be almost completely solved
- Moreover, coherent detection brings always much better sensitivity than direct detection

  - *This work was carried out under a research grant by Cisco Photonics*

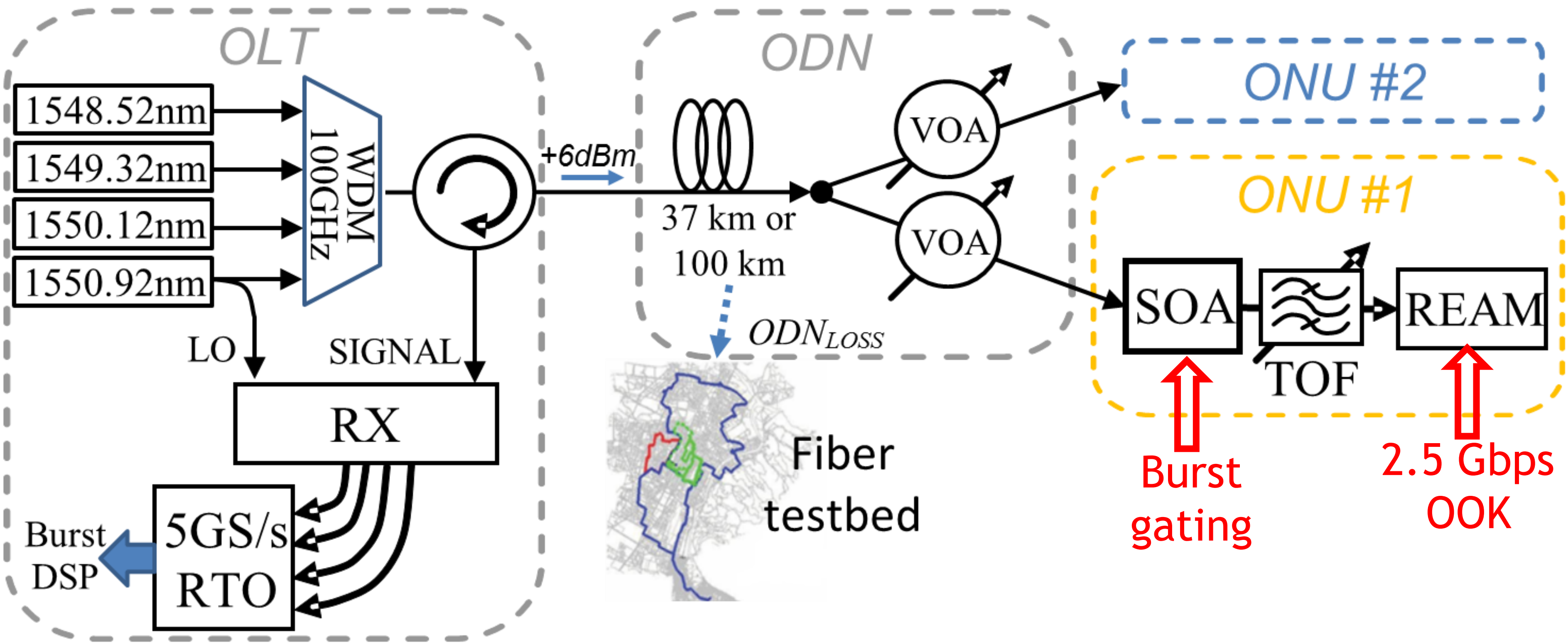
CISCO

Best results for this architecture - 4x2.5 Gbps

Extended TWDM-PON demonstration up to 100 km and 35 dB ODN loss on Burst-Mode Coherent Reflective PON

S. Straullu[1*], F. Forghieri[3], G. Bosco[2], V. Ferrero[2] and R. Gaudino[2]
[1]ISMB, Istituto Superiore Mario Boella, Via P.C. Boggio 61 – 10138 Torino, Italy, email: straullu@ismb.it
[2]Politecnico di Torino, C.so Duca degli Abruzzi 24 – 10129 Torino, Italy
[3]CISCO Photonics, Via Philips 12, 20059, Monza, Milano, Italy

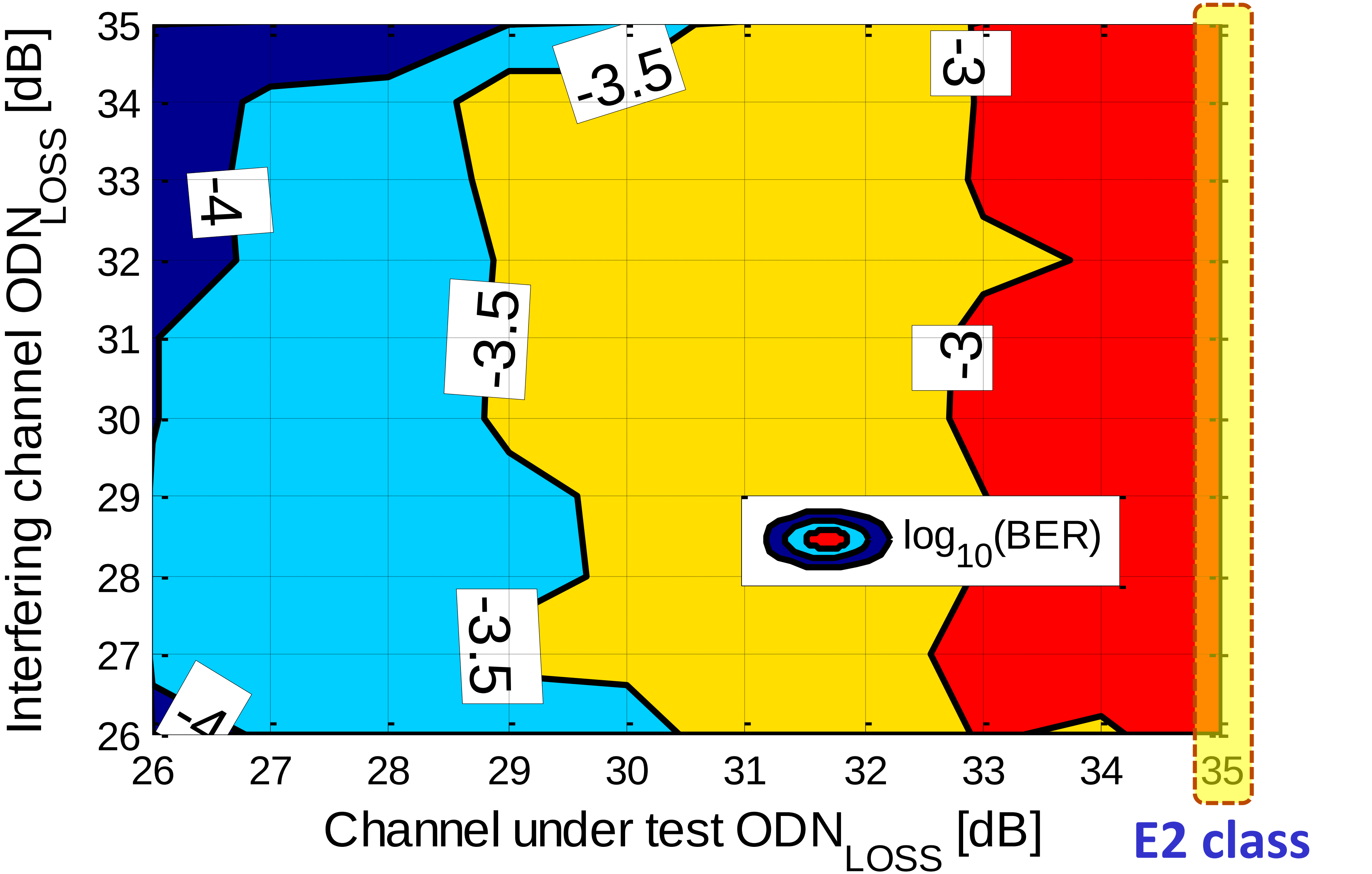
OFC 2014
The future of optical networking and communications is here.



Burst gating

2.5 Gbps OOK

Experimental results: 100 km, 4 λ, 2.5 Gbps each

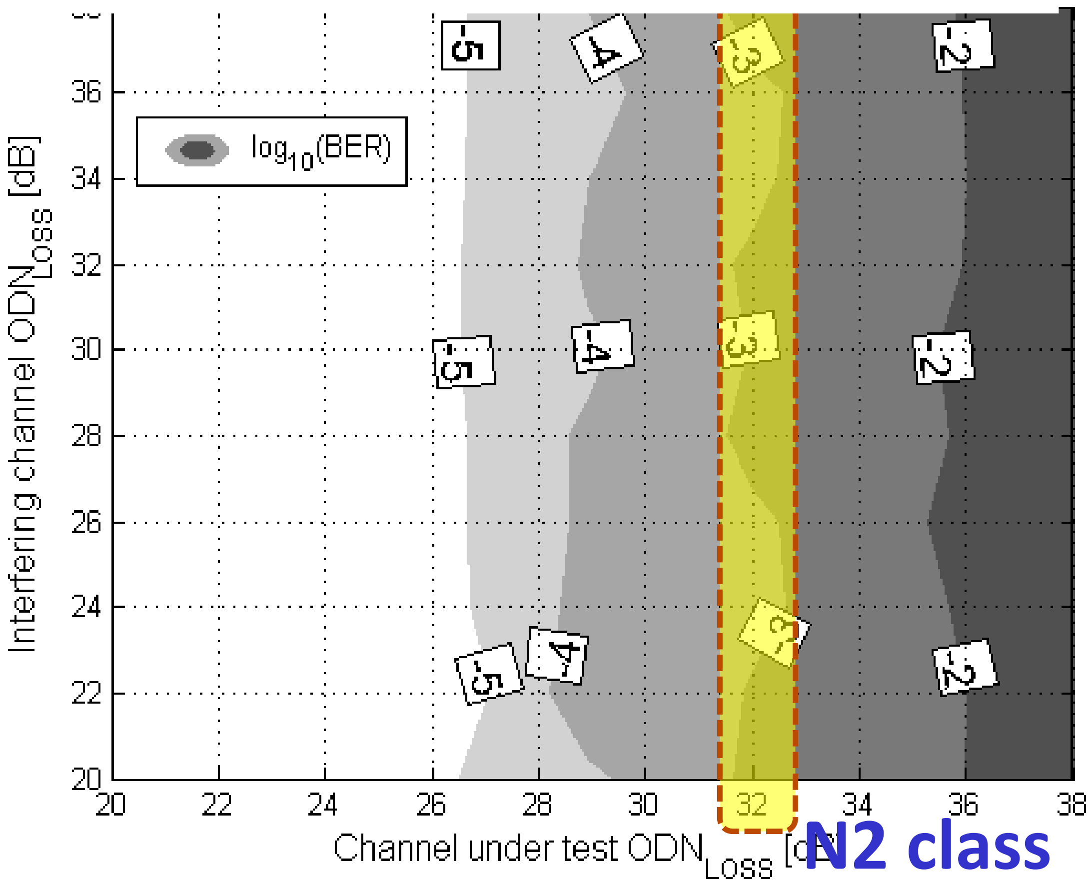


Upgrade to 10 Gbps

TWDM-PON-compatible 10 Gbps Burst-mode coherent reflective ONU achieving 31 dB ODN loss using DFB lasers

S. Straullu[1], J. Chang[2], G. Bosco[2], V. Ferrero[2], S. Abrate[1], F. Forghieri[3] and R. Gaudino[2]

[1] ISMB, Istituto Superiore Mario Boella, Via P.C. Boggio 61 – 10138 Torino, straullu@ismb.it
[2] Politecnico di Torino, C.so Duca degli Abruzzi 24 – 10129 Torino, Italy, roberto.gaudino@polito.it
[3] CISCO Photonics, Via Philips 12, 20900, Monza, Italy



Our journal papers on this topic

- Compatibility between coherent reflective burst-mode PON and TWDM-PON physical layers, **Straullu, S.; Forghieri, F.; Bosco, G.; Ferrero, V.; Gaudino, R., 2014,** Optics Express **22**(1) 9-14
- Optimization of self-coherent reflective PON to achieve a new record 42 dB ODN power budget after 100 km at 1.25 Gbps, **Straullu, S.; Forghieri, F.; Ferrero, V.; Gaudino, R.,** Optics Express **20**(28)
- Characterization of uncooled RSOA for upstream transmission in WDM reflective PONs, **Straullu, S.; Abrate, S.; Forghieri, F.; Rizzelli, G.; Ferrero, V.; Gaudino, R.,** Optics Express **20**(26)

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The (ongoing) EU research project

Fabulous

- Stick with self-coherent reflective PON idea but upgrade it with the following targets
  1. Higher upstream bit rate (towards 30+ Gbps) thanks to more spectrally efficient modulation formats
     - M-QAM modulation on each electrical subcarrier
  2. Frequency division multiplexing (FDMA): dedicated electrical bandwidth slice to each ONU
     - No need to handle burst mode transmission issue
  3. Advanced structure for the ONU reflective Mach-Zehender structure implementable on Silicon Photonics

FABULOUS at-a-glance

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NEW integrated optoelectronic COMPONENTS for the ONU

SEVENTH FRAMEWORK PROGRAMME

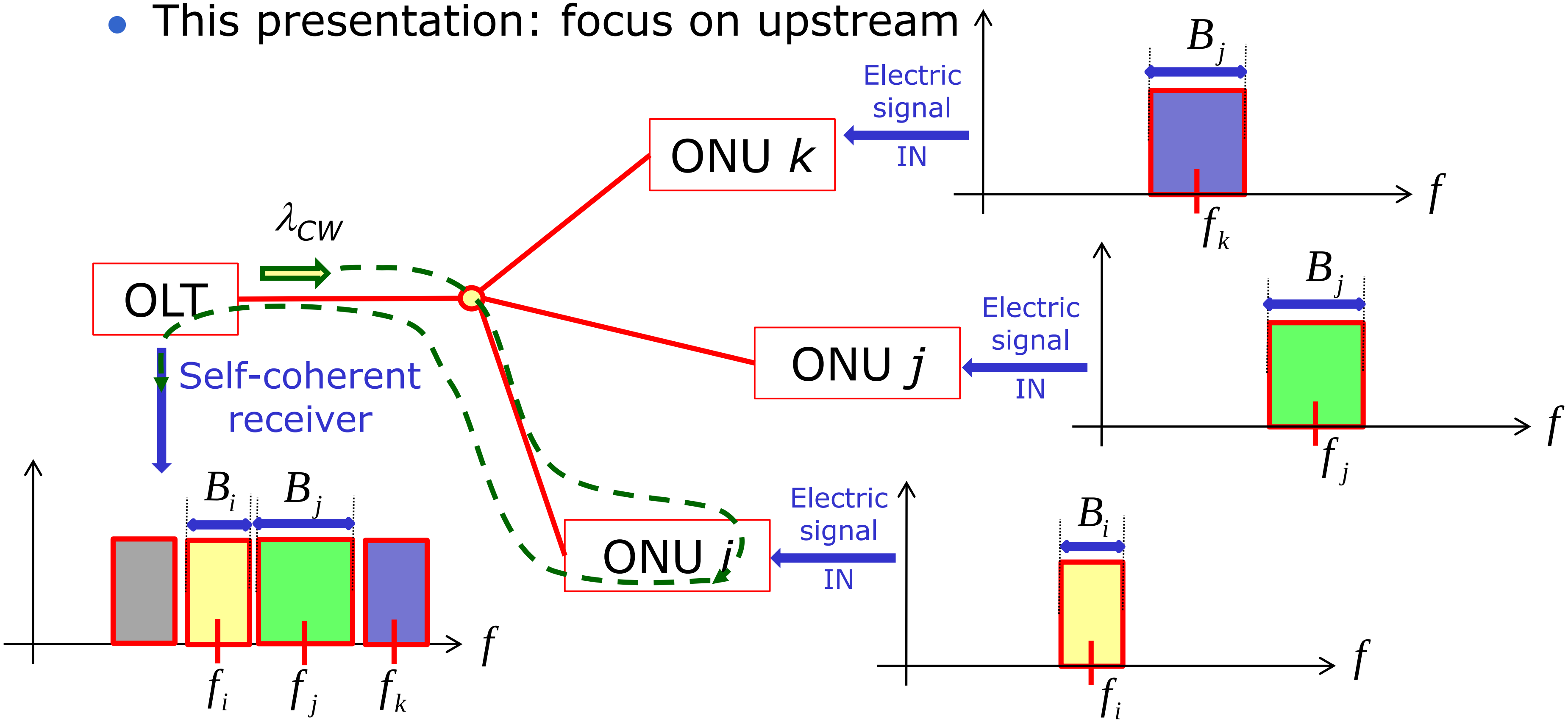
Silicon Photonics and FDMA-PON: Insight from the EU FP7 FABULOUS Project

Partners list

Istituto Superiore Mario Boella

Upstream FDMA-PON architecture

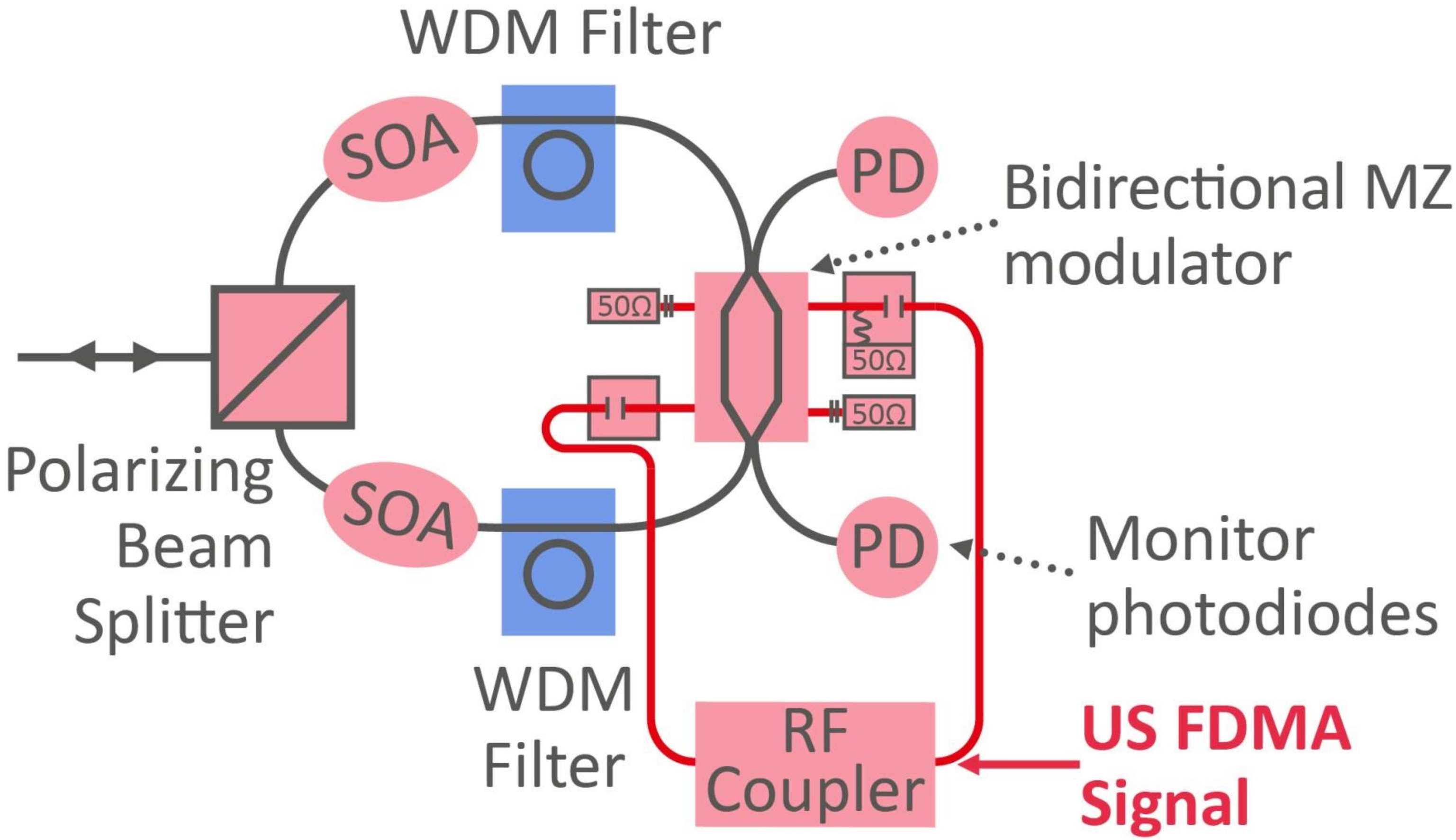
- PON based on electrical subcarrier FDM/FDMA in both directions
  - "standard" Optical Distribution Network (ODN)
    - 1x64 splitter-based ODN
  - This presentation: focus on upstream



The ONU

The ONU reflects the CW seed signal and modulates it using M-QAM + FDMA approach

One of the goals of the project is to integrate the ONU in a Silicon Photonics PIC

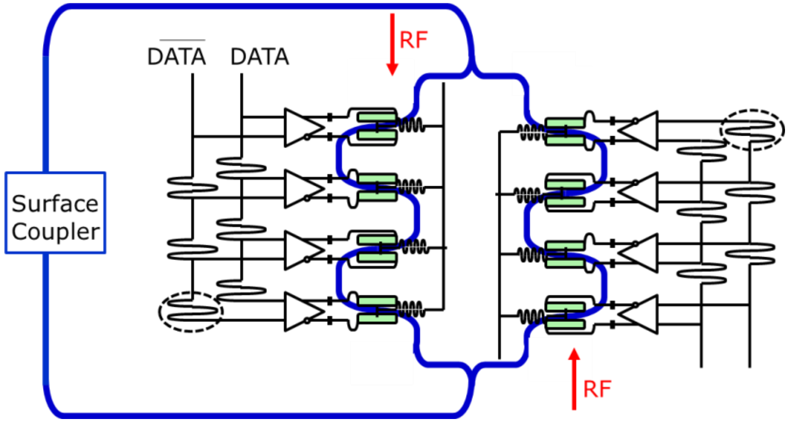


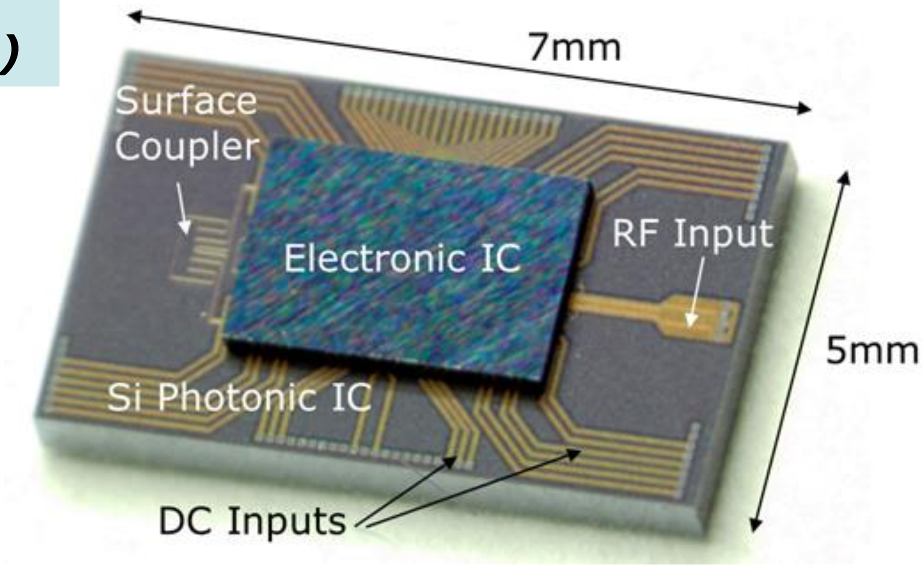
R-MZ Modulator and Driver integration

Distributed driving architecture

*Photonic IC = Silicon Photonics **(CEA)***

*Elec IC = BiCMOS **(ST Microelectronics)***

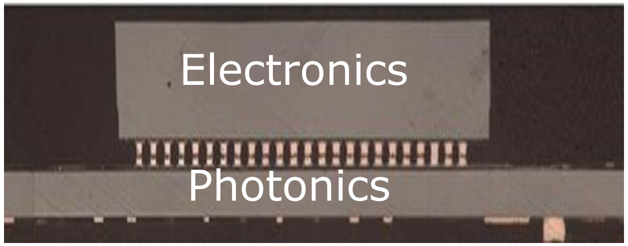




3D integration of Photonic & Electronic ICs

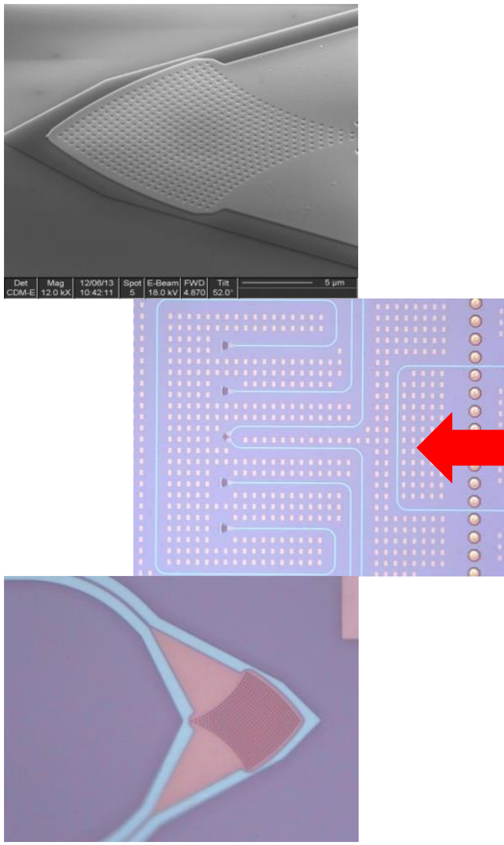
Micro bumps from 3D standard process (CEA)

- ➔ *reduced parasitic capacitance*
- ➔ *Dense interconnections (40µm-pitch)*

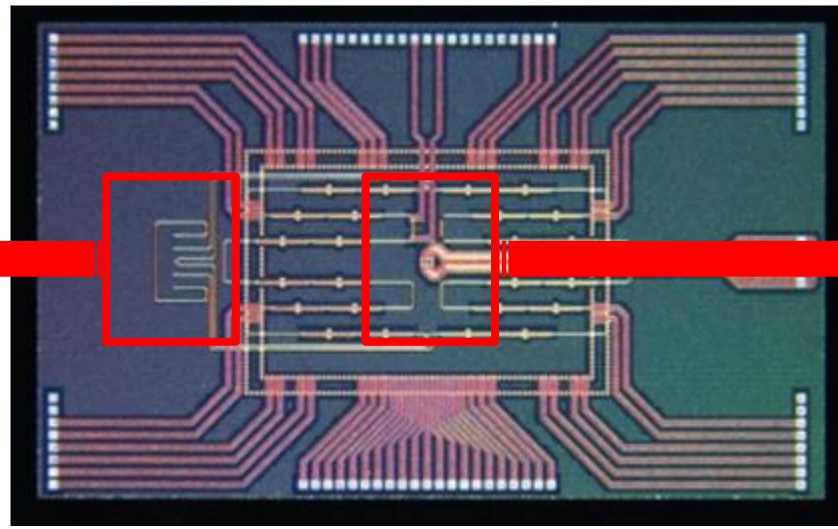


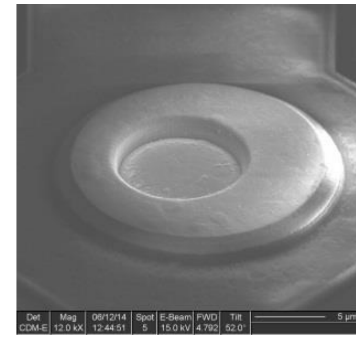
Photonic Integrated Circuit Manufacturing

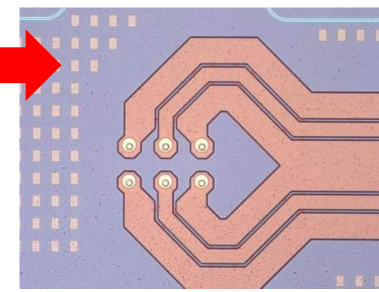
SOI 220nm/2000nm Oxide technology
Processed at Leti on 200mm wafer



Optical Coupling structures







RF electrodes with pads for bump interconnections

Best result so far for UPSTREAM transmission

(Invited paper at OFC 2015)

DATA RATE PER USER SET AT 1 GBPS

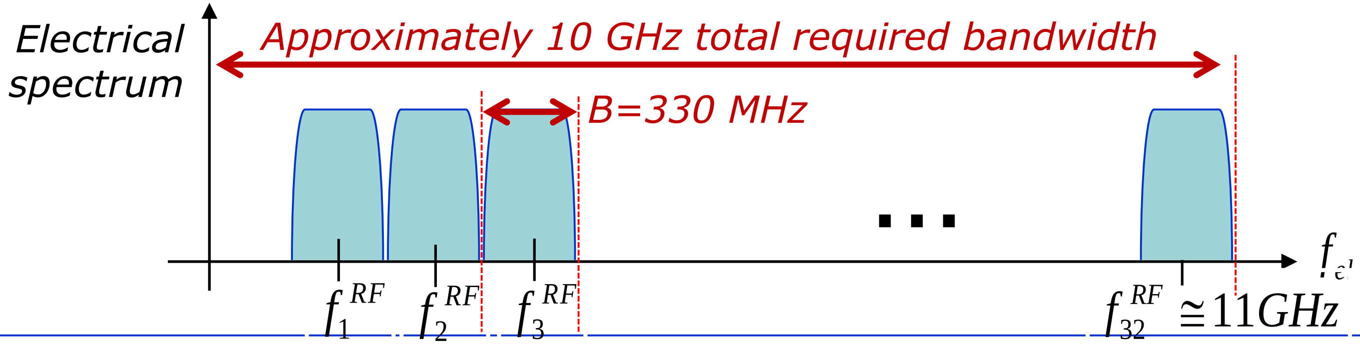
- net data rate, giving a gross rate of 1.2 Gbps including FEC, overhead and line coding

MODULATION FORMAT SET AT 16-QAM using electrical subcarriers

- Requires *B*~330 MHz per user
  - Using Raised cosine spectrum, roll-off=0.1

32 USERS PER WAVELENGTH on the 11 GHz available electrical band → **32 Gbit/s upstream capacity on a single λ**

ODN loss up to 31 dB (class N2)

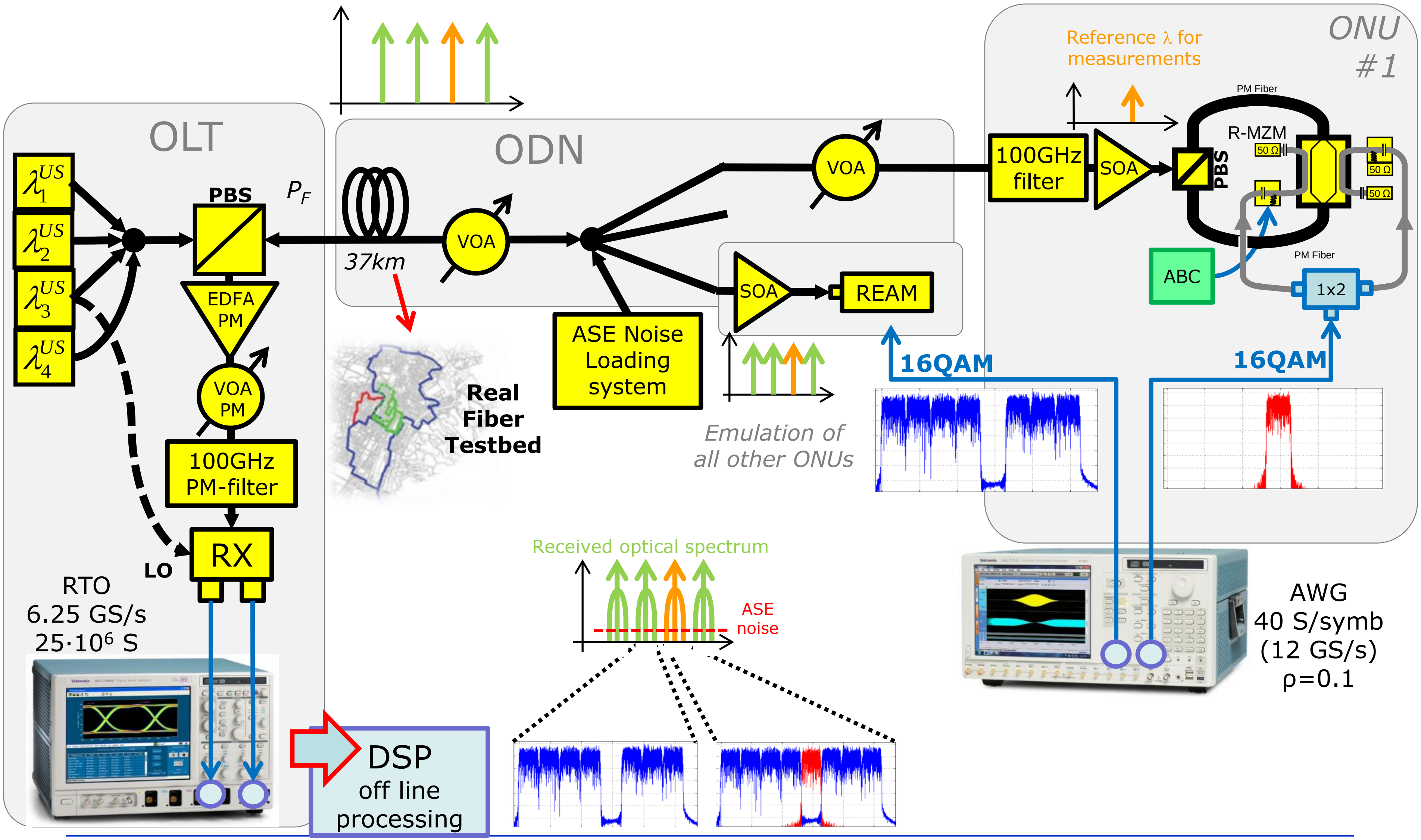


4 λ WDM setup, NET bitrate per ONU= 1Gbps

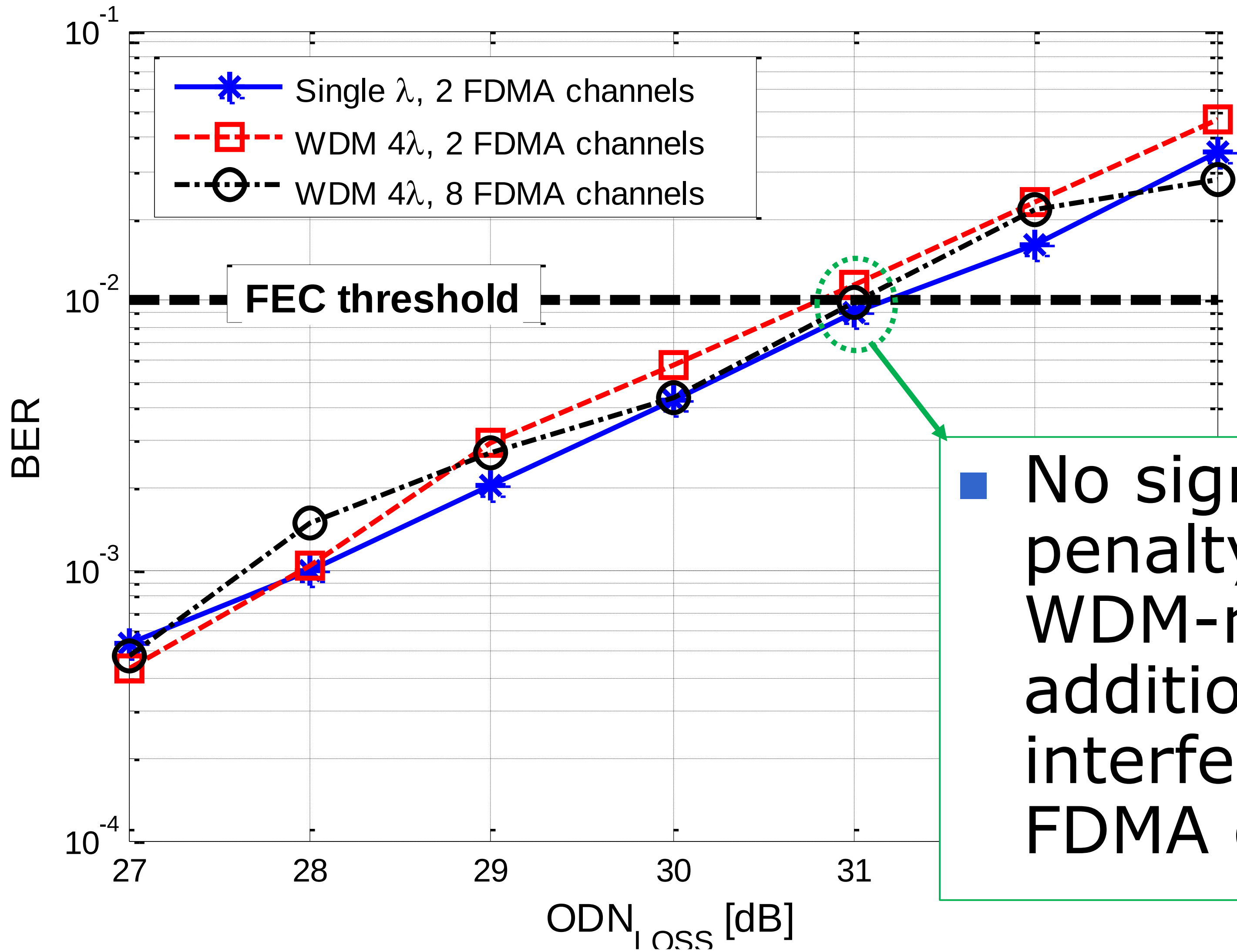
(Presented last week at ECOC 2015)

- We used 4 wavelengths on a 100 GHz grid
  - Similarly to what is set for TWDM-PON in NG-PON2 ITU-T G.989
- We wanted to check if WDM introduced significant impairments
  - We focused again only on upstream
  - On each wavelength: same 16-QAM over electrical FDMA approach as in OFC2015
- We thus transmitted 4x32=128 Gbit/s (net) for upstream transmission

4λ WDM setup, NET bitrate per ONU= 1Gbps



NET 1Gbps x 32 ONUs = 32 Gbps per λ



- No significant penalty due to WDM-related additional interference on FDMA channels

Our journal papers on this topic

- Straullu, S.; Savio, P.; Chang, J.; Ferrero, V.; Nespola, A.; Gaudino, R.; Abrate, S., "Optimization of Reflective FDMA-PON Architecture to Achieve 32 Gb/s Per Upstream Wavelength Over 31 dB ODN Loss," in *IEEE Journal of Lightwave Technology,* vol.33, no.2, pp.474-480, Jan.15, 15 2015, doi: 10.1109/JLT.2015.2389871

- Straullu, S.; Chang, J.; Cigliutti, R.; Ferrero, V.; Nespola, A.; Vinci, A.; Abrate, S.; Gaudino, R., "Single-Wavelength Downstream FDMA-PON at 32 Gbps and 34 dB ODN Loss," in *Photonics Technology Letters, IEEE* , vol.27, no.7, pp.774-777, April1, 1 2015 doi:10.1109/LPT.2015.2392151

- Abrate, S.; Straullu, S.; Nespola, A.; Savio, P.; Chang, J.; Ferrero, V.; Charbonnier, B.; Gaudino, R., "Overview of the FABULOUS EU Project: final system performance assessment with discrete components," in *IEEE Journal of Lightwave Technology*, vol.PP, no.99, pp.1-1 doi:10.1109/JLT.2015.2482226

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Conclusions

- We showed two solutions targeting respectively 10Gbps and 32 Gbps per wavelength in upstream direction
  - Solution #1 is TDMA-compliant so it can in principle be adapted to NG-PON2 requirements (TWDM and PtP)
  - Solution #2 is FDMA-based and would thus require a significant chance in the PON standard paradigm

A caveat on different topics…

Our collaboration with Telecom Italia (Maurizio Valvo's group) is actually on other topics strictly related to NG-PON2 G.989:

- AMCC techniques for upstream signaling in TWDM-PON ("photon ranging")

Photon Ranging for Upstream ONU Activation Signaling in TWDM-PON

L. Bertignono, V. Ferrero, *Member, IEEE*, M. Valvo and R. Gaudino *Senior Member, IEEE*

Already available on IEEE Journal of Ligthwave Technology (also in open access) at *http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=7273822*
DOI: 10.1109/JLT.2015.2480962

- Exact estimation of the different kinds of interferences in upstream NG-PON2

Thanks for your attention!

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

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