ROAM

Revolutionising optical fiber transmission and networking using the Orbital Angular Momentum of light

Research and Innovation actions

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CNIT-Italy

ECOC 2015 symposium: Optical Communications and Networks for Datacenters
FERIA Valencia 27/09/2015

ROAM Motivation

The capacity of optical systems for data centers has increased in the last decades reaching the near-full utilization of the large bandwidth of the optical fiber thanks to the use of a combination of dense frequency division multiplexing, high order modulation formats and coherent detection

More recently, spatial or mode division multiplexing schemes have been used

Technology	WDM	OFDM	Multicore fiber	MDM
Limitations	Fiber bandwidth	Fiber bandwidth	inter-core coupling	major technical challenge, MIMO processing
SoA	full use of the 11.4 THz C+L band		1Tb/s over 50 km, using a 12 cores (demonstrated up to 49 cores)	6-mode 73.7 Tb/s system over 119 km

Their potential have now been nearly exhausted

1. *R. J. Essiambre, et al., 'Capacity Limits of Optical Fiber Networks', J. Lightw. Technol., vol. 28, no.4, pp. 662-701, 2010.*
2. *A. Ellis, et al., "Approaching the non-linear Shannon limit" J. Lightw. Technol., vol. 28, no.4, pp. 423-433, 2010.*
3. *H. Takara, et al., "1.01-Pb/s (12 SDM/222 WDM/456 Gb/s) Crosstalk-managed Transmission with 91.4-b/s/Hz Aggregate Spectral Efficiency," presented at the ECOC'2012, Amsterdam, The Netherlands, Jun. 2012*
4. V.A.J.M. Sleiffer, et al.,"73.7 Tb/s (96 x 3 x 256 Gb/s) mode division multiplexed DP16QAM transmission with inline MMEDFA," presented at the ECOC'2012, Amsterdam, The Netherlands, Jun. 2012

ROAM Motivation

The orbital angular momentum (**OAM**) of the light can be exploited for further increasing the total capacity of the data centers, exploiting their inherent orthogonality

ROAM main target

ROAM proposes to explore the use of the OAM modes as additional multiplexing domain (OAM multiplexing) for:

- ✓high throughputs optical switches
- ✓high capacity optical fiber transmission

OAM Concept

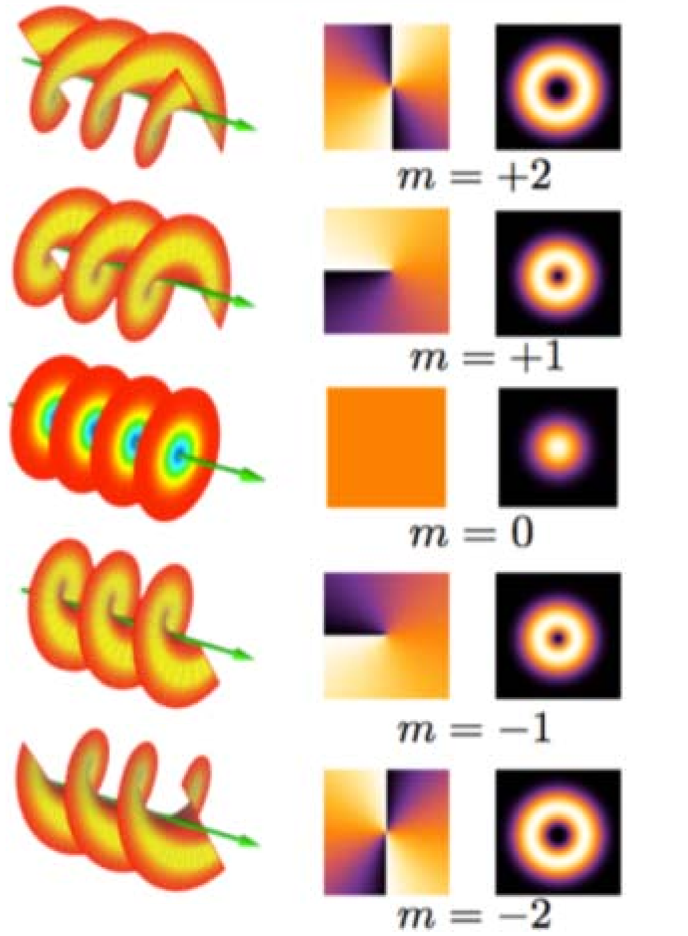
In 1992[1] researchers realised that the

Orbital angular momentum = OAM

of photons is associated with the helical phase front of optical modes

Helically phased beams comprising an azimuthal phase term exp($im\theta$), have an OAM of *m*h per photon (where *m* is topological charge, θ is azimuthal angle, and h is Plank's constant h divided by 2π).

the theoretically unlimited values of *m*, in principle, provide an infinite range of possibly achievable OAM states.
OAM therefore has the potential to tremendously increase the capacity of communication systems, using OAM beams as information carriers for multiplexing



beam helical structures **phase fronts** **Intensity distributions**

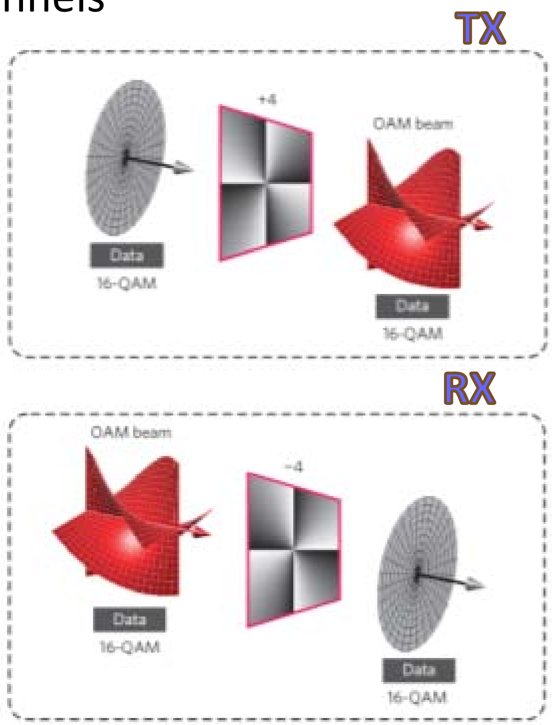
Allen, et al., "Orbital angular momentum of light and the transformation of Laguerre–Gaussian laser modes ", Phys. Rev. A 45, 8185–8189 (1992).

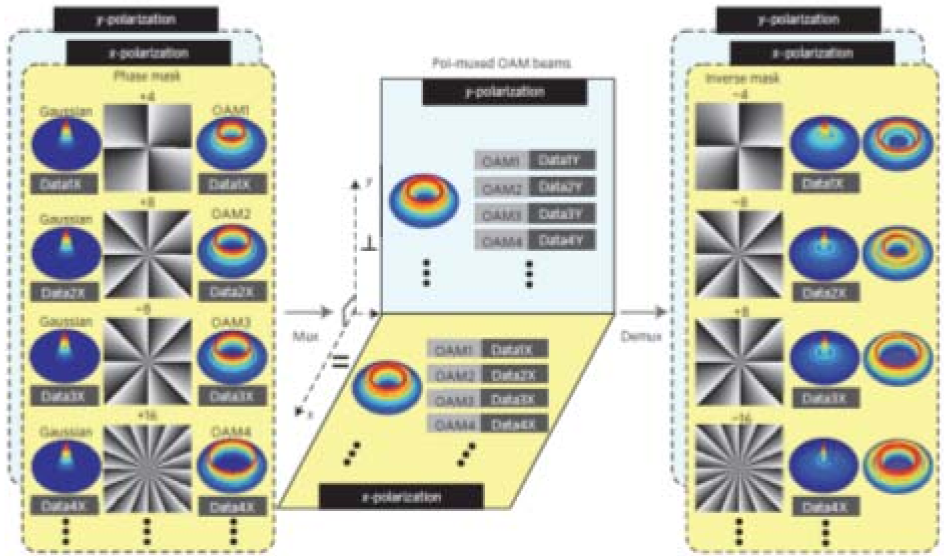
State of the art: concept

The concept of OAM multiplexed communication and networking has been pioneered by Alan Willner's group at University of Southern California

demonstrating the principles using free space optical channels and bulk optics components

- ✓ 2.5 Tb/s overall capacity and the 95.7 bit/Hz spectral efficiency over meter-length free space channels





J. Wang, et al., "Terabit free-space data transmission employing orbital angular momentum multiplexing," Nature Photon.,vol. 6, pp. 488-496, 2012.

State of the art: transmission in fiber

The transmission in optical fiber of OAM multiplexed signals has been explored by a collaboration of Boston University, USC, Tel Aviv University and OFS-Fitel[1]

demonstrating the transmission of:
- ✓ 400 Gb/s data using 16 QAM at 20 GBaud traffic and four OAMs at a single wavelength
- ✓ 1.6Tb/s data using 16 QAM at 20 GBaud traffic and two OAMs over 10 wavelengths

Demonstration of OAM fiber by Université Laval

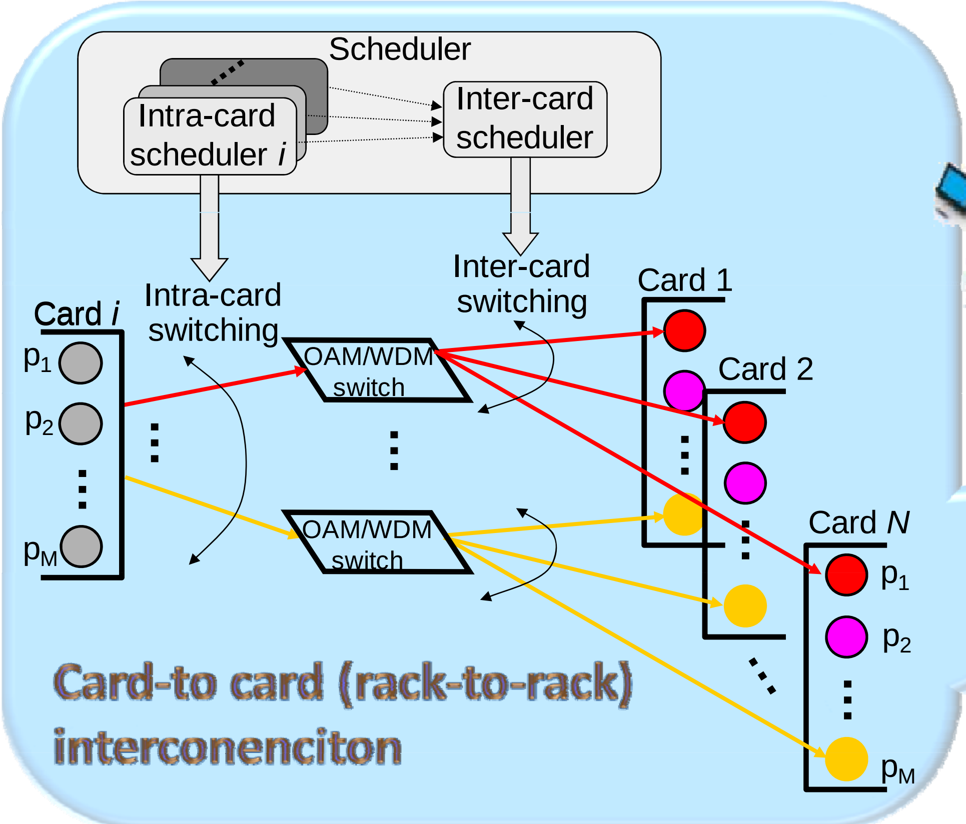
- ✓ Optical air core fiber supproting 36 OAM-based channels [2]
- ✓ Inverseparabolic graded-index profile fiber few OAM modes up 1.1 km [3]

1. *Nenad Bozinovic et al, 'Terabit-Scale Orbital Angular Momentum Mode Division Multiplexing in Fibers', Science 340, 1545 (2013).*
2. *C. Brunet, et al., "Design, fabrication and validation of an OAM fiber supporting 36 states", optics Express, Vol. 22, n.21 (2014)*
3. *B. Ung at al., "Few-mode fiber with inverse-parabolic gradedindex profile for transmission of OAM-carrying modes", Optics Express, Vol. 22, n. 15 (2014)*

State of the art: multi-layer optical switches

OAM has never been applied to multi-layer optical switches

CNIT proposed a patent on multi-layer interconnection network based on OAM multiplexing and WDM switching



Scaffardi M, et al,. Multi-layer interconnection network based on optical angular momentum multiplexing and wavelength division multiplexing switching, patent # WO 2015024595 A1 (*2013)*

State of the art: components technologies

optical vortices generation carried out passing free space light beams through bulk optic components including

- ✓ cylindrical lens pairs[1]
- ✓ computer generated holograms[2]
- ✓ spiral phase plates[3]
- ✓ q-plates[4]
- ✓ sub-wavelength grating[5]
- ✓ nano-antenna[6]
- ✓ fibers[7]
- ✓ etc.

1. L. Allen, M. W. Beijersbergen, R. J. C. Spreeuw, and J. P. Woerdman, “Orbital angular momentum of light and the transformation of Laguerre-Gaussian laser mo des,” Phys. Rev. A 45, pp.8185–8189 (1992).
2. *G. Gibson, et al. "Free-space information transfer using light beams carrying orbital angular momentum," Opt. Express 12 5448-5456 (2004).*
3. *M. W. Beijersbergen, et al., “Helical-wavefront laser beams produced with a spiral phaseplate,” Opt. Commun. 112(5-6), 321–327 (1994).*
4. *L. Marrucci, et al., “Optical Spin-to-Orbital Angular Momentum Conversion in Inhomogeneous Anisotropic Media”, Phys. Rev. Lett. 96, 163905 (2006)*
5. *G. Biener, et al., "Formation of helical beams by use of Pancharatnam-Berry phase optical elements," Opt. Lett.* ***27****, 1875-1877 (2002)*
6. *X Cai et al, “Integrated compact optical vortex beam emitters,” Science, vol. 338, pp. 363-366 (2012).*
7. *S. Li, et al., “Controllable all-fiber orbital angular momentum mode converter”, optics Letters, Vol.40, n. 18 (2015)*

State of the art: components techonlogies

optical vortices mux and demux

- ✓ Free-space beam combiners
- ✓ Spatial light modulators (SLM)

1. *https://www.thorlabs.de/navigation.cfm?guide_id=18*
2. *http://holoeye.com/spatial-light-modulators/*
3. *https://www.thorlabs.de/navigation.cfm?guide_id=18*

State of the art: integrated technologies

Glasgow University developed OAMs emitters/receivers on silicon waveguide substrate, based on

- ✓ an angular grating / azimuthal excitation scheme [1]

Bell Laboratories, Alcatel-Lucent developed OAMs emitters/receivers, multiplexing and demultiplexing on silicon waveguide substrate, based on

- ✓ a circular grating / radial excitation scheme [2,3]

1. *X Cai et al, "Integrated compact optical vortex beam emitters," Science, vol. 338, pp. 363-366 (2012).*
2. *C. R. Doerr and L. L. Buhl, "Circular grating coupler for creating focused azimuthally and radially polarized beams," Opt. Lett. 36, 1209-1211 (2011).*
3. *N. K. Fontaine, et al., "Efficient multiplexing and demultiplexing of free-space orbital angular momentum using photonic integrated circuits", OFC 2012 (2012)*

ROAM objectives

1. To develop a OAM/WDM switch to significantly improve the scalability and the power consumption in data-centers applications

2. To develop new OAM fibers and to demostrate an increased transmission capacity for short-reach high data density applications as data centers

ROAM Objective 1: OAM-based switching

Parameter	ROAM targeted value	state of the art
Number of ports	160	105
Bit rate per port [Gb/s, Ethernet]	20	10 to 40
Bandwidth [Tb/s, full duplex]	6.4	2.56
Configuration time [ns]	100 *	850**
Total power consumption [W]	22.4	150
Power consumption/Gb/s [mW]	3.5	58

*single ring configuration time
**port-to-port latency time

ROAM Objective 2: OAM fiber transmission

Parameter	ROAM targeted value	state of the art
Total capacity	16Tb/s	1.6Tb/s
WDM channels	16	
OAM channels	10	
Single ch bit rate	100 Gb/s	
Fiber length	2 km	1.1 km

The objective of this project if successful will have progress beyond the state of art by

- ✓ 10x in terms of capacity (1.6 Tb/s to 16 Tb/s)
- ✓2x in terms of distance
- ✓20x in terms of capacity – distance product.

ROAM Progress on OAM components technologies

1. **Very fast tuning of the OAM state**

2. **Emitting or receiving of multiple co-axial OAM modes with precise control of the OAM features**

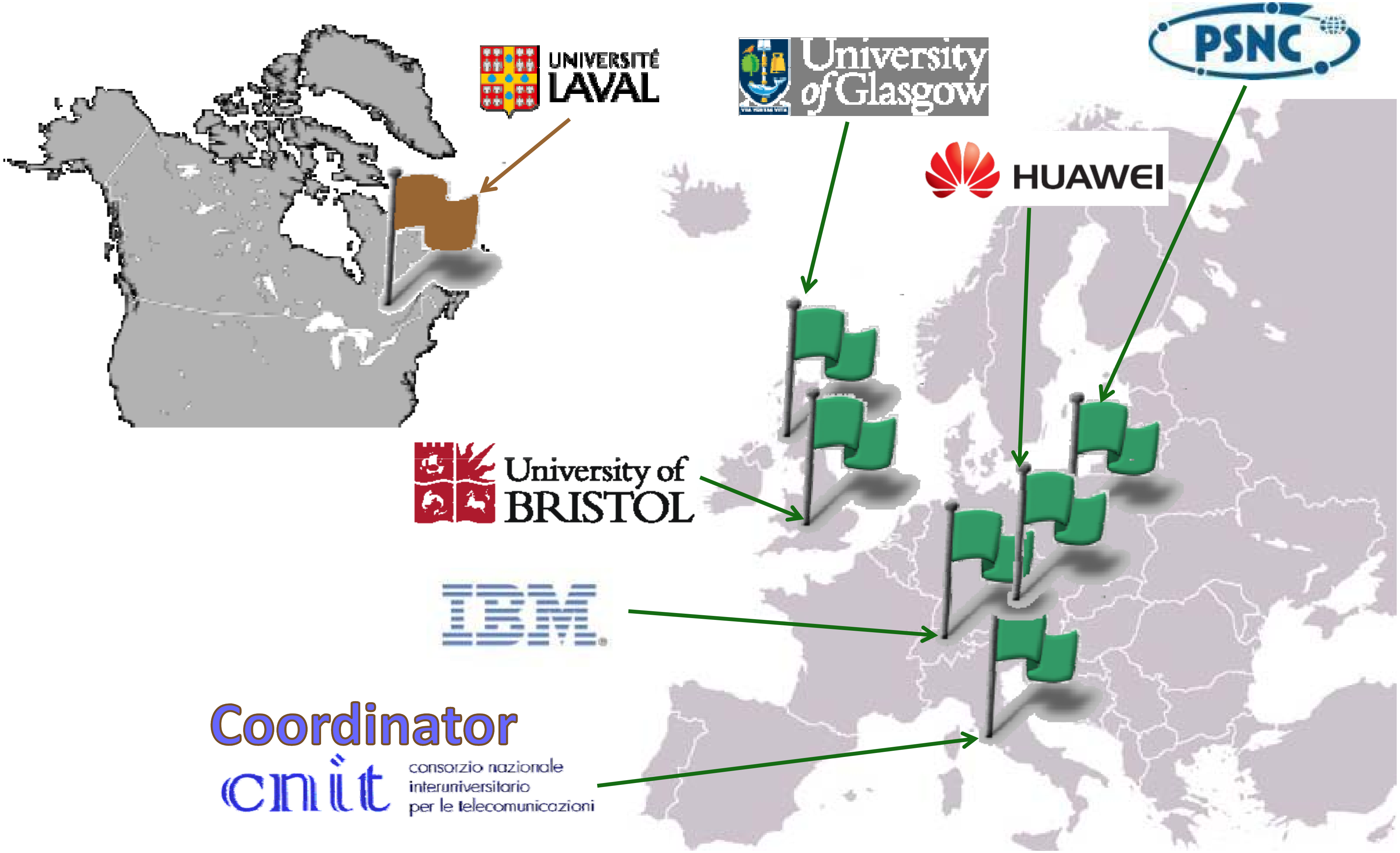
   (including order, relative phase and polarisation)

3. **Very compact devices**

   Single emitters can be as small as 10 μm in diameter

4. **Optoelectronic integration**

ROAM consortium



Coordinator

cnit consorzio nazionale interuniversitario per le telecomunicazioni

ROAM roadmap

Specifications

OAM mode transmission in optical fibers

OAM transceiver and networking components

OAM division multiplexing communications in fiber

OAM domain-based networking schemes and techniques

Requirements

Components

Subsystems

System demonstration

OAM-based transmission and switching demonstration

ROAM duration

February 2015 – January 2018

Project Management

Specifications

OAM mode transmission in optical fibres

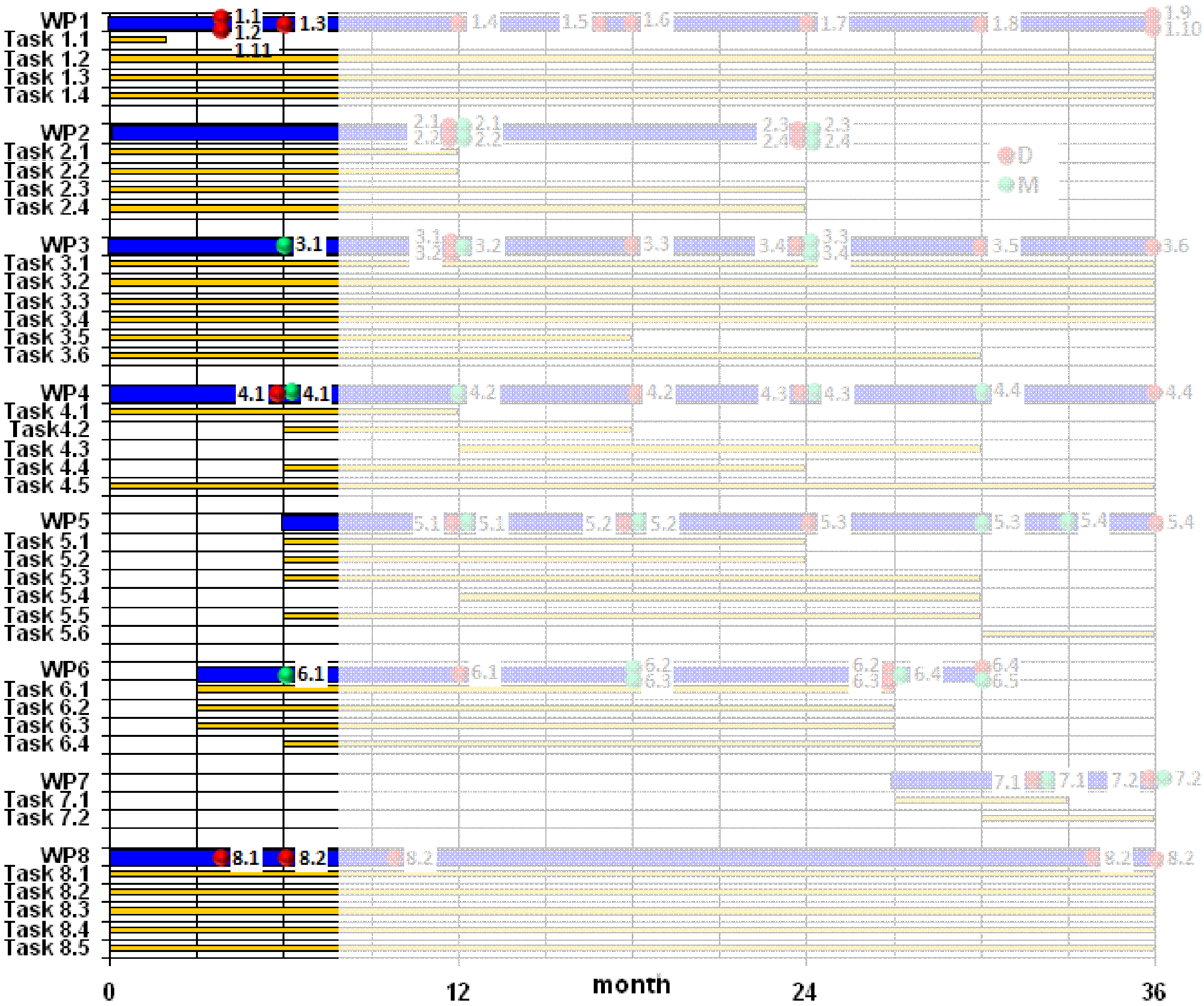
Development of the OAM transceiver and networking components

OAM division multiplexing communications in fibre

OAM domain-based networking schemes and techniques

OAM-based transmission and switching demonstration

Dissemination, exploitation and communication



ROAM activities: specification definition

Further specifications to be defined within the project

✓Maximum crosstalk among the OAM modes (Depending on no. of OAM modes and the modulation format)
✓The complexity of the DSP for the OAM transmission
✓Etc..

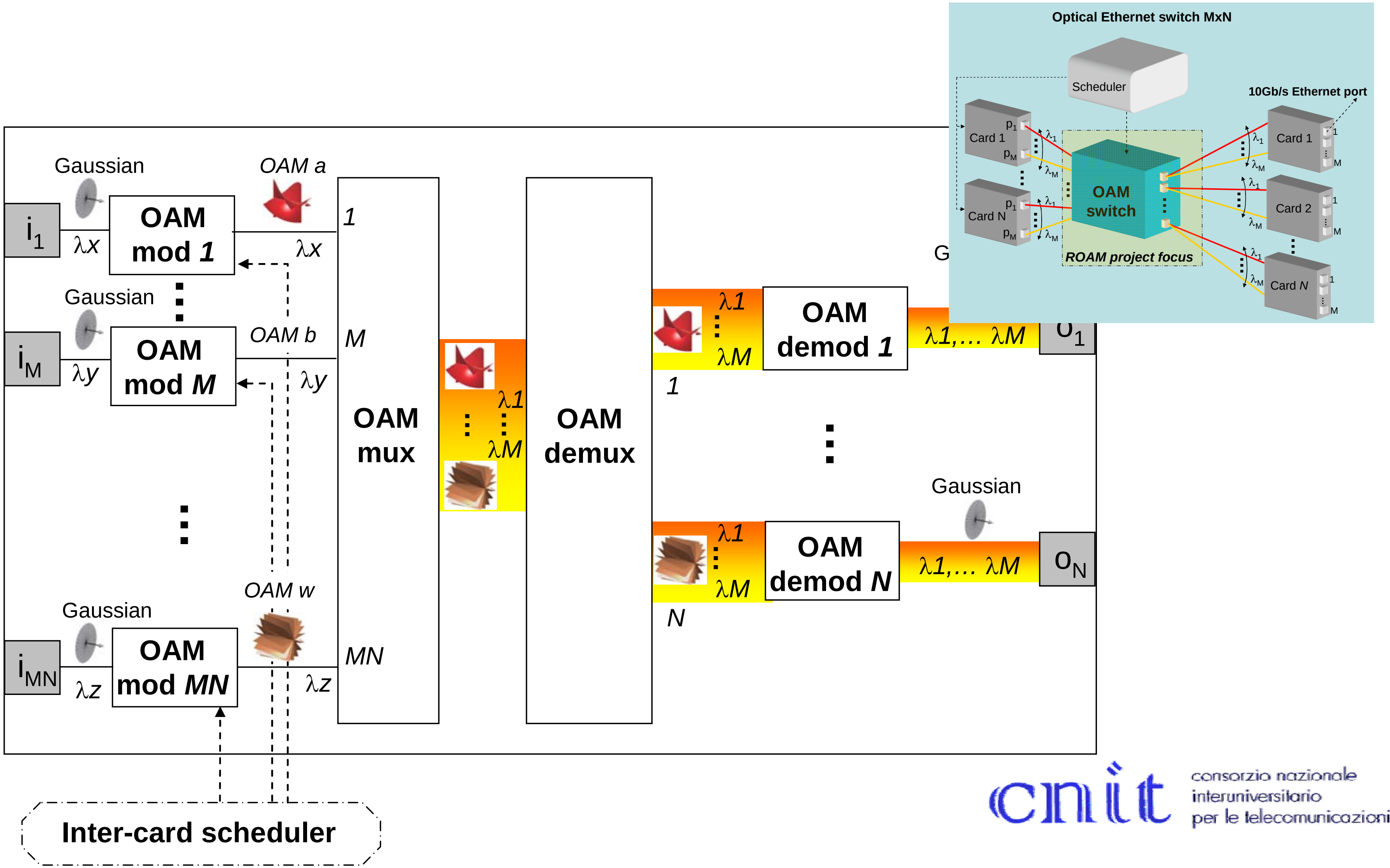
For comparison, the specifications of a typical Ethernet switch also need to be defined. Analysis for combination of Ethernet switches and OAM switches as core element should also be carried out. The main parameters of Ethernet switches to be determined are:

✓No. of ports
✓Bit rate per port
✓Data modulation format
✓Configuration time
✓Power consumption/Gb/s

Spec. of the integrated components

✓Footprint:
✓ Coupling efficiency to/from optical fibers
✓OAM emission efficiency

ROAM activities: OAM-based switching design

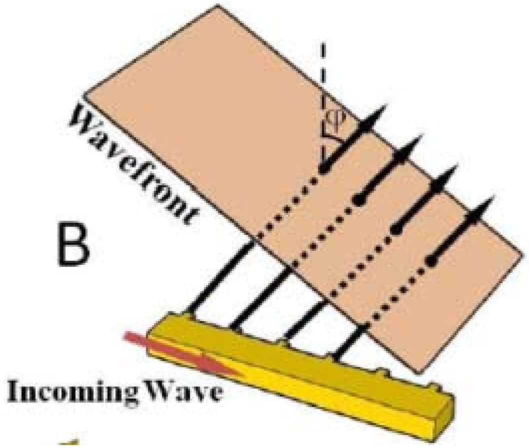


ROAM activities:
OAM integrated components design

✓ Theory and numeric tools

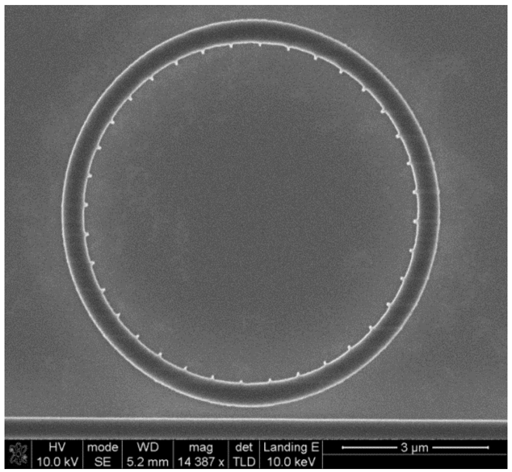
- Mode coupling theory in cylindrical coordinate
- highly efficient semi-analytical numeric model
- Rapid design and optimisation of integrated OAM components

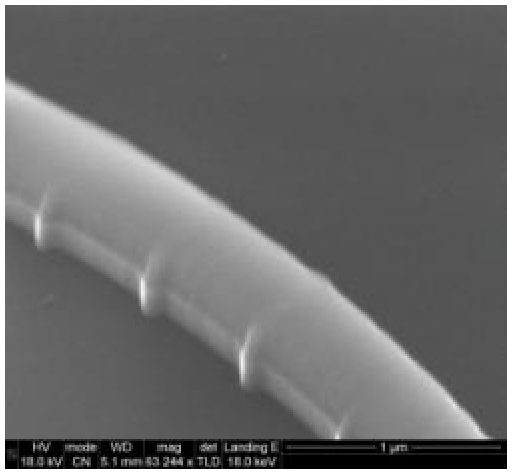
ROAM activities: integrated components: emitters

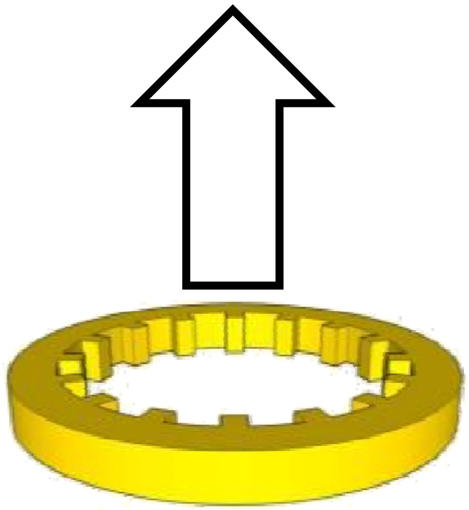


Diffraction gratings are widely used for vertical emission in SOI

Nanometre scale gratings on 3um radius rings







ROAM activities: integrated components: emitters

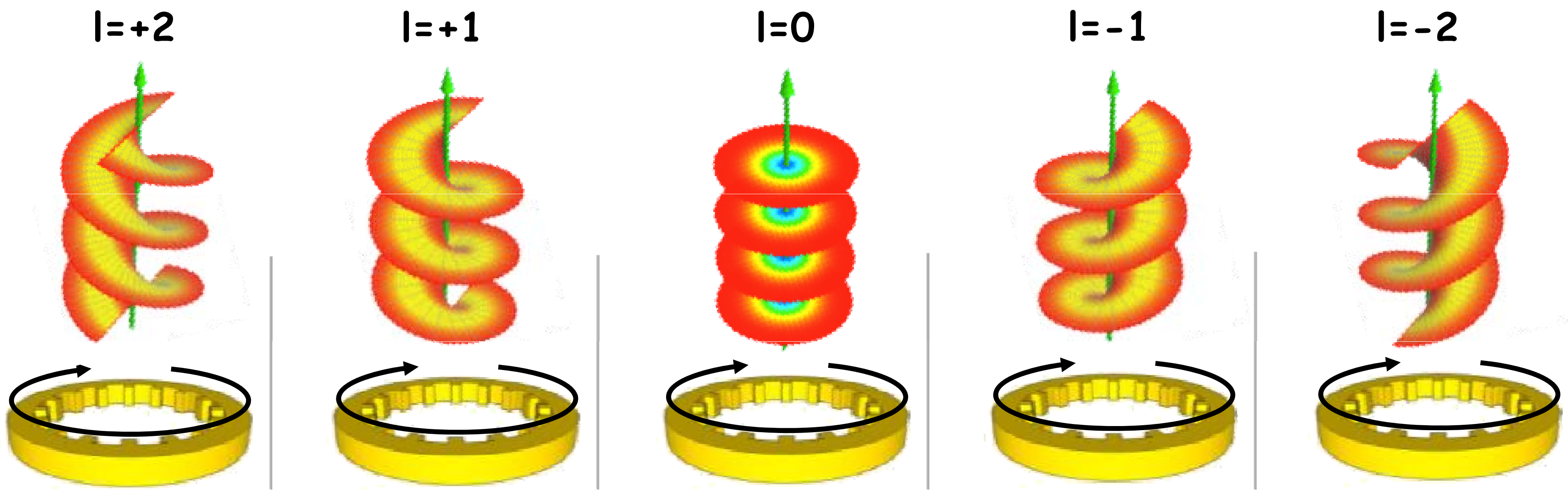
- Microring with diffractive elements can generate helical or twisted wavefronts
- These beams carry orbital angular momentum (OAM)

p is the azimuthal mode order (i.e. number of optical periods around the resonator)

q is the number of grating elements

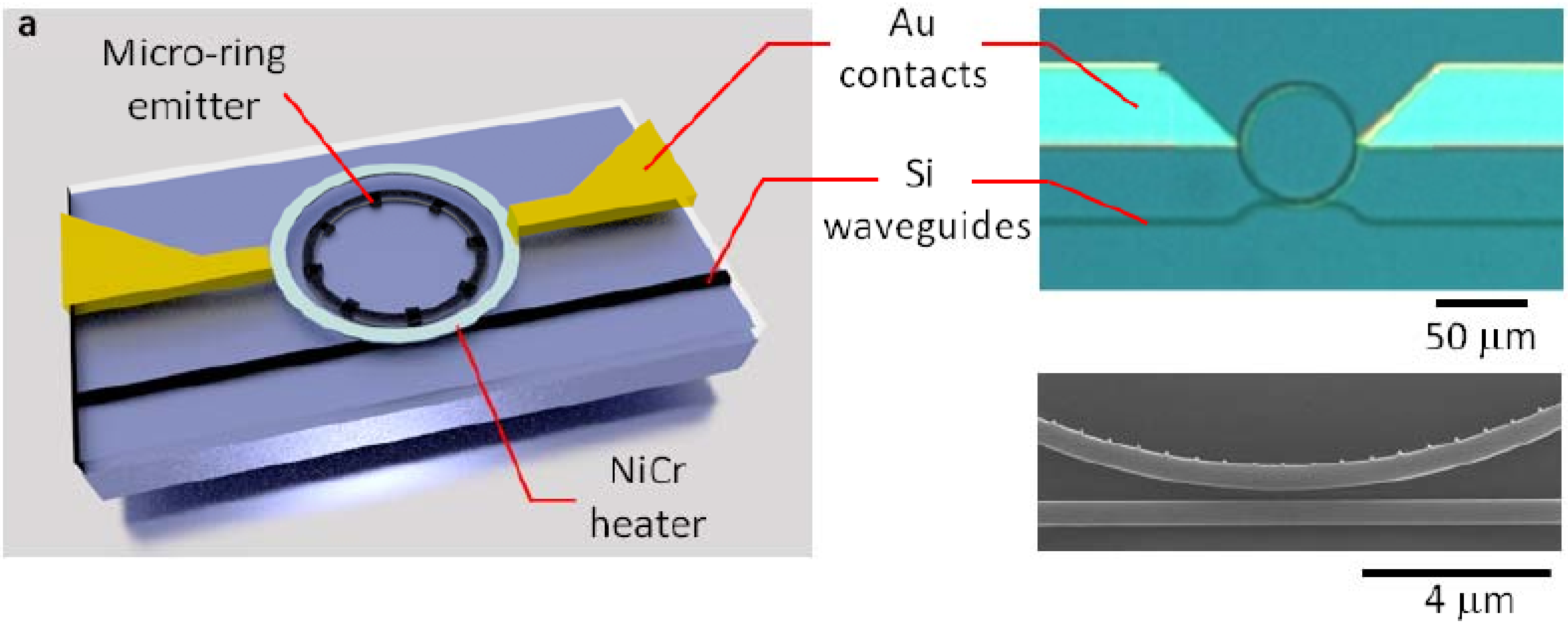
The OAM order (or topological charge) is defined simply by

$$l = sign(p) * (|p| - q)$$



ROAM activities: integrated components: modulators

Modulation of the optical cavity length provide on/off modulation and reconfigurability of the OAM beams

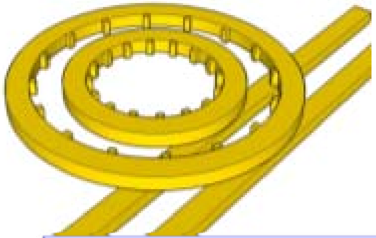


Tunability of the ring resonance is achieved by a heating element defined in proximity of the ring waveguide

1. *Strain, MJ, et al. , 'Fast electrical switching of orbital angular momentum modes using ultra-compact integrated vortex emitters'. Nature Communications, vol 5., pp. 4856 (2014)*

ROAM activities: integrated components

❑ Multiple input/output ←→ multiple OAM states



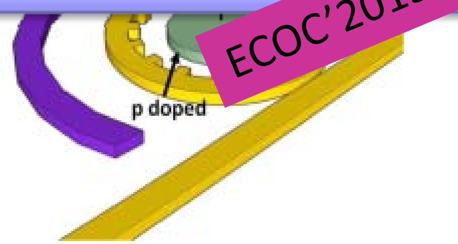
Use of a double core layer to separate access waveguide layer from device layer

❑ Fas

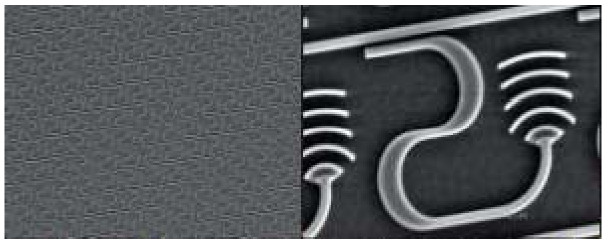
Marc Sorel" Photonic Integrated Devices for Exploiting the Orbital Angular Momentum (OAM) of Light in Optical Communications", INVITED paper we.1.6.1 • 08:45-09:15.

ECOC'2015

wavegudies for ~ns tuning speed



❑ More integration[1]

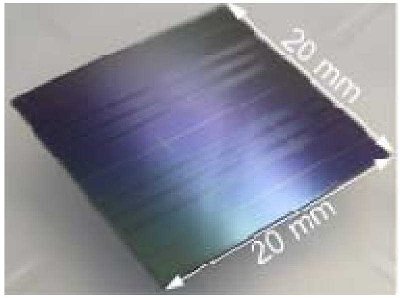


Si photonics allows for unprecedented levels of complexity in integrated photonics

1. *J.Sun et al, "Large-scale nanophotonic phased array", Nature 493, 195–199, (2013)*

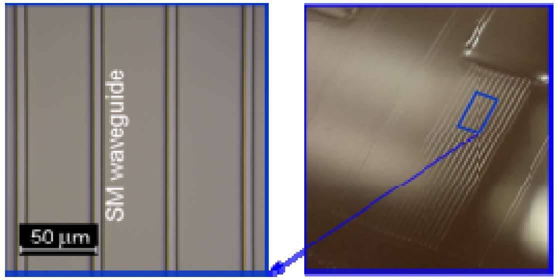
Polymer waveguide enabled assembly of OAM silicon photonics devices

Single mode polymer waveguide technology was established



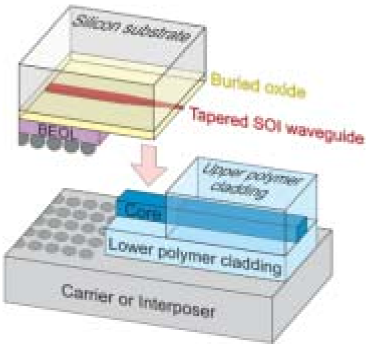
On silicon

On thin sheets

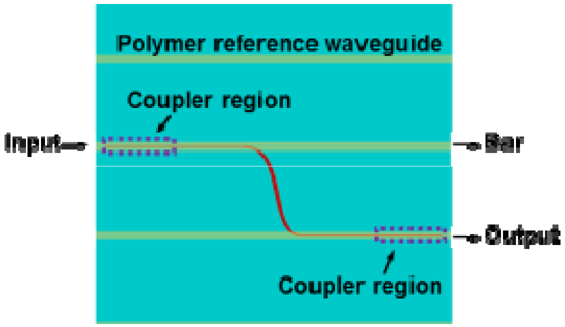


Microscope view

Low loss optical coupling to silicon photonics demonstrated



Adiabatic optical coupling



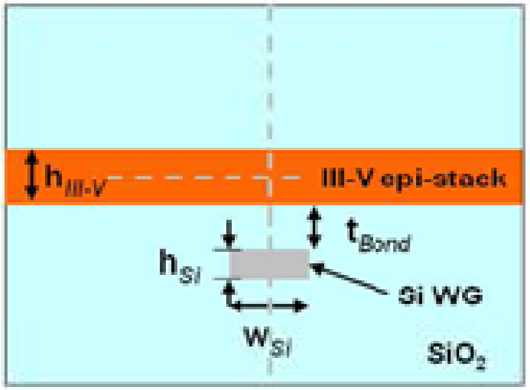
Measurement concept

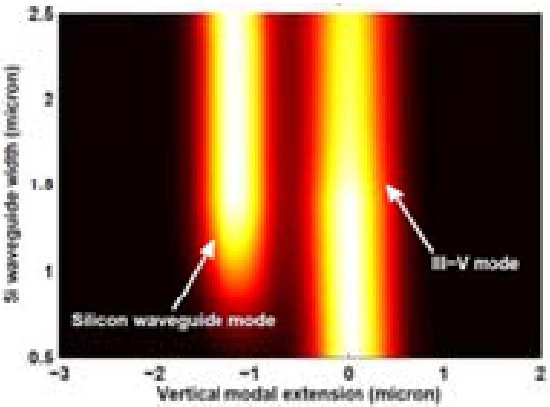
Si to polymer waveguide optical coupling demonstrated with losses < 1 dB

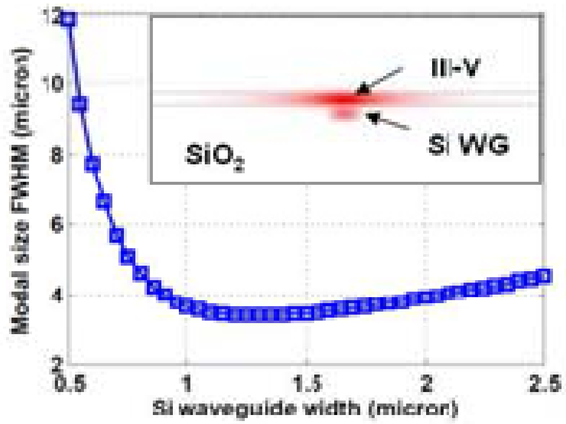
Status

III-V on silicon laser integration

Monolith integration of III-V on Si lasers for OAM transmission

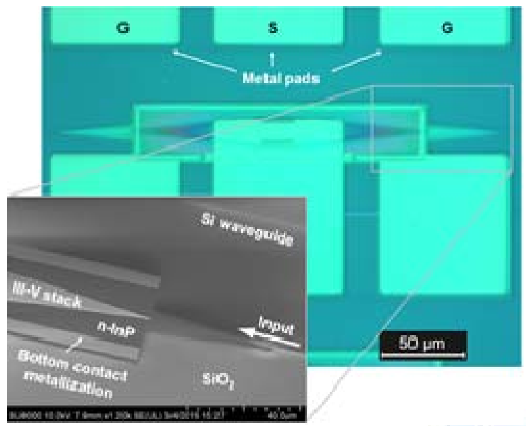






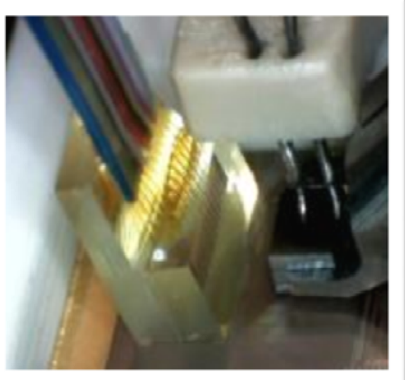
By applying a thin III-V QW stack on silicon, excellent modal overlap with the III-V gain medium can be obtained

First III-V on Si laser structures were fabricated



ROAM activities: integrated component packaging & testing

Main packaging processes @ CNIT



- Vertical and horizontal alignment and pigtailing
- Die Bonding, Flip-Chip Bonding (+/- 4 microns tolerances)
- Tacking, In situ reflow, Eutetic bonding
- Thermocompression
- Single-Step solder ball placement
- Flux less / solder paste / void free soldering
- Wafer bump reflow
- Wire bonding
- Ribbon Bonding
- Splicing

Characterization System

✓Single OAM components:

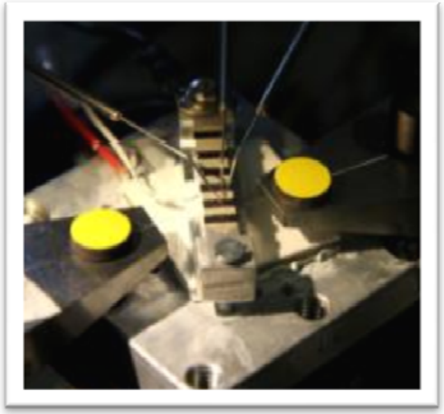
- •Optimized and experimentally verified high efficiency and improved mode purity
- •Experimentally verified mode selective detection of OAM modes by integrated OAM components

✓OAM multiplexer / demultiplexer:

- •Ω-devices (4x OAM multiplexers) designed and experimentally verified

✓World's first OAM laser

- •VCSEL based OAM emitter at 850nm
- •Single and multi-OAM superpositional state emission achieved



1. H. Li et al, "Integrated Optical Vortex Vertical-Cavity Surface-Emitting Lasers" PDP JTh5A.4 CLEO 2015

ROAM activities: modeling of OAM fiber propagation

- ✓ Starting from the state of the art, development of a model for nonlinear propagation in OAM fiber suitable for step and graded index fibers over short distances where spatial modes do not significantly mix because of sharp group-velocity mismatch[1-3].
- ✓ Critical study of algorithms for calculation of nonlinear coupling coefficients in strongly-guiding waveguides such as OAM with hollow core[4,5]
- ✓ Carried out numerical simulation of OAM mode transmission through perturbed OAM fibers (bended fibre in particular)

1. A. Mecozzi, C. Antonelli, M. Shtaif, "Nonlinear propagation in multi-mode fibers in the strong coupling regime" Opt. Express vol. 20, pp. 11673-11678, May 2012
2. A. Mecozzi, C. Antonelli, M. Shtaif, "Coupled Manakov equations in multimode fibers with strongly coupled groups of modes" Opt. Express, vol. 20, pp. 23436-23441, Oct. 2012
3. S. Mumtaz, R.-J. Essiambre and G. P. Agrawal, "Nonlinear Propagation in Multimode and Multicore Fibers: Generalization of the Manakov Equations" J. Lightw. Technol, vol. 31, pp. 398-406, Feb 2013
4. S. Afshar and T. M. Monro, "A full vectorial model for pulse propagation in emerging waveguides with subwavelength structures; part I: Kerr nonlinearity" Opt Express, vol. 17, pp. 2298-, Feb. 2009
5. F. Poletti and P. Horak, "Description of ultrashort pulse propagation in multimode optical fibers" J. Opt. Soc. Am. B, vol. 25, pp. 1645-1654, Oct. 2008.

ROAM activities: OAM fibers

Université Laval

COPL
Centre d'optique, photonique et laser

- Preform via MCVD
- Drawing towers
- Characterization via FBG
- High speed transmission testbed

ROAM activities: OAM fibers

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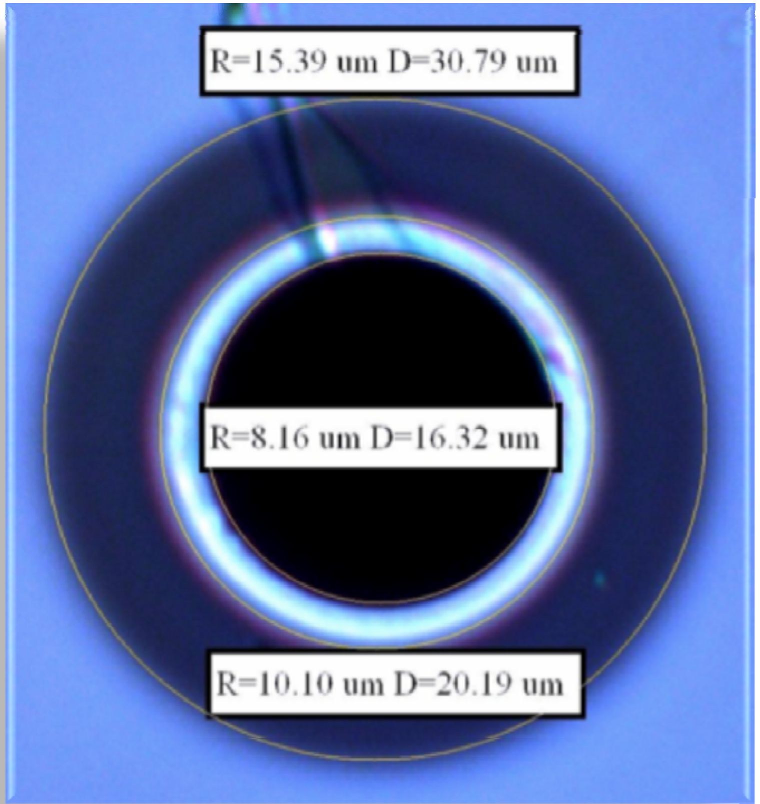
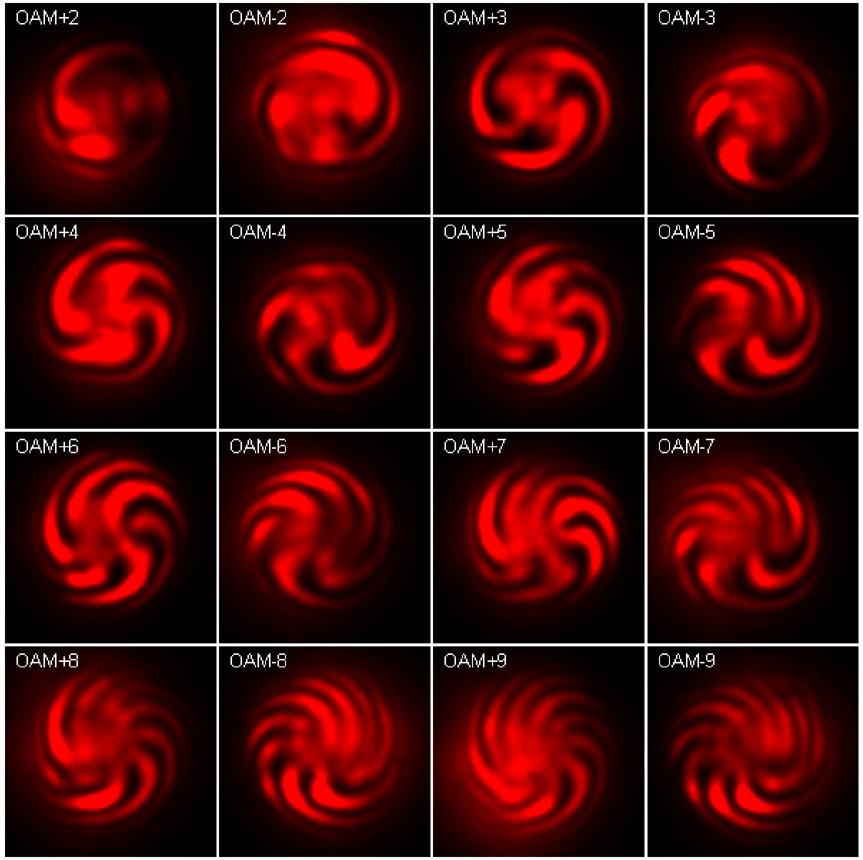
Centre d'optique, photonique et laser

Hollow-center (air) ring-core fiber



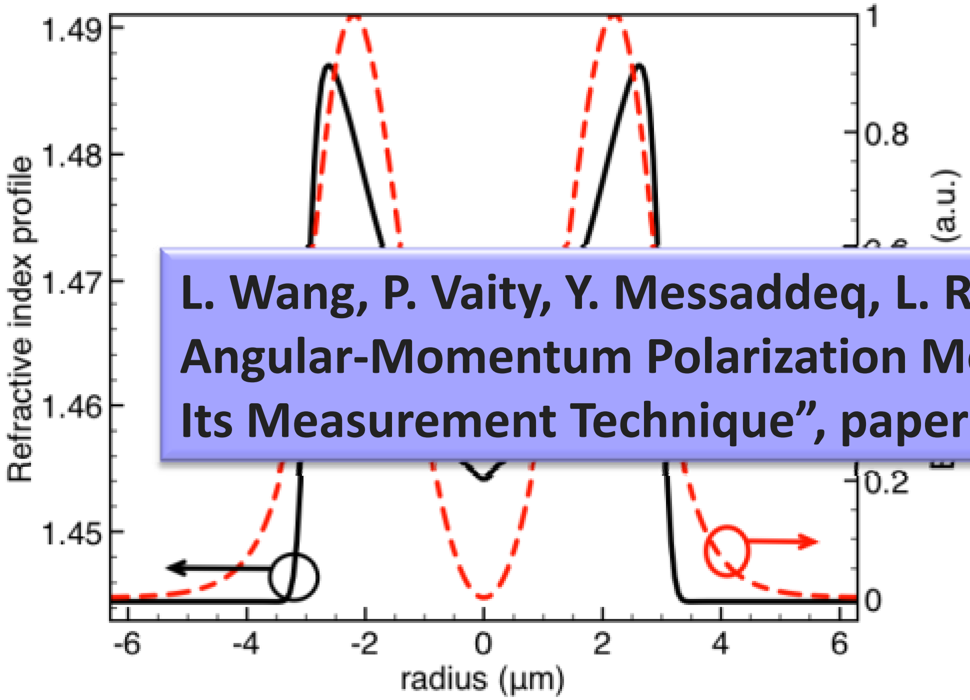
- 9 OAM modes (36 channels)
- Loss few dB/m
- $\Delta n_{eff}>1.1\text{x}10^{-4}$

Output (1 m) right polarization



ROAM activities: OAM fibers

Inverse parabolic graded index



L. Wang, P. Vaity, Y. Messaddeq, L. Rusch and S. LaRochelle, "Orbital-Angular-Momentum Polarization Mode Dispersion in Optical Fibers and Its Measurement Technique", paper Tu.3.3.4 • 15:00-15:15.

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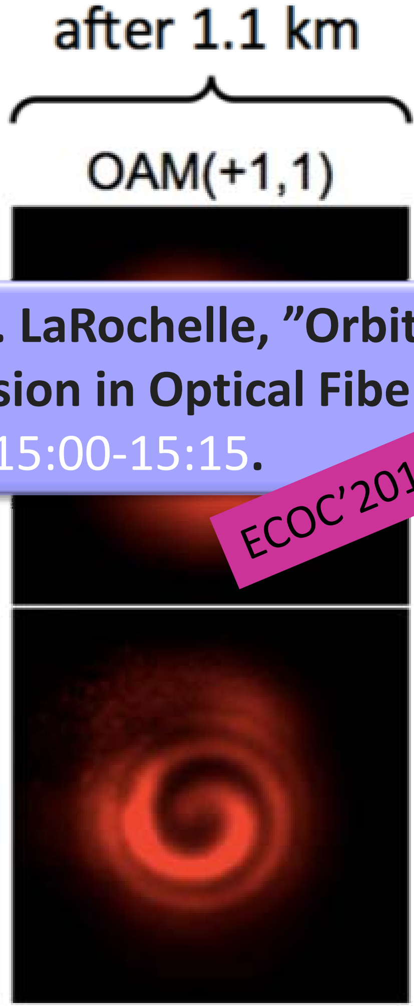


- 2 OAM modes (8 channels)
- Loss 8.6 dB/km
- $\Delta n_{eff} > 2.1 \times 10^{-4}$

ROAM activities: OAM fiber testing

- ✓ Qualitative Interferometry testing (spiral interferograms)
- ✓ Quantitative SLM-based OAM output spectrum analysis

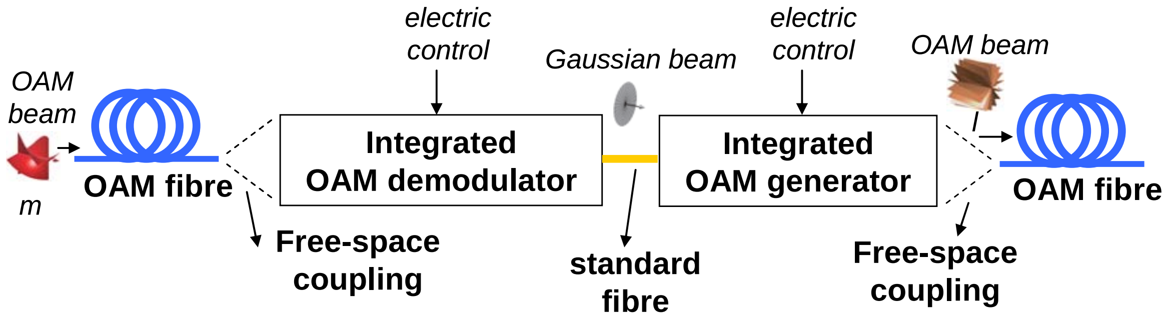
Testing fibers

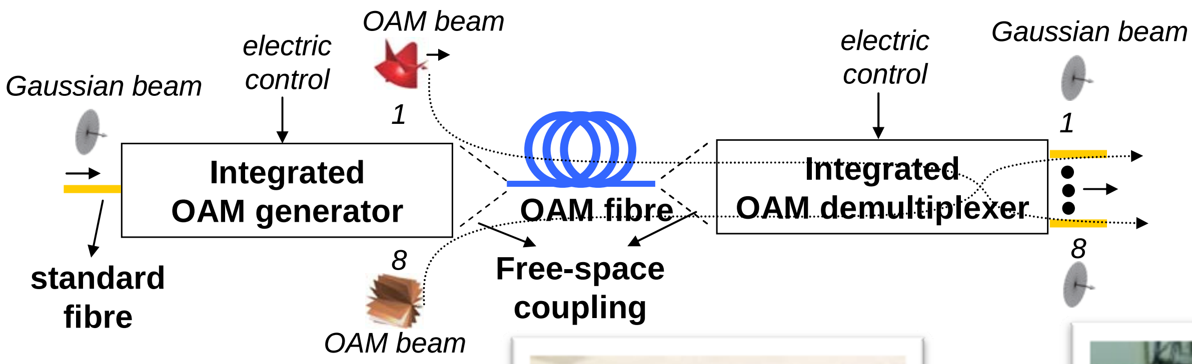
- ✓ air core fiber
- ✓ inverse-parabolic graded-index fiber (IPGIF)
- ✓ Other available fibers.

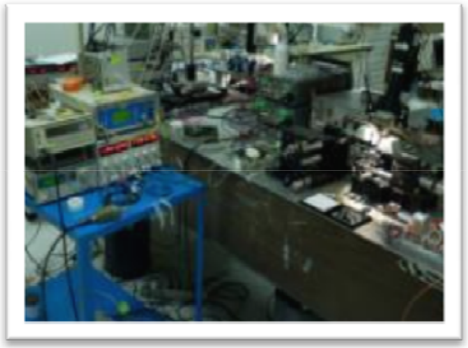
Coupling between OAM components and OAM fibers

- ✓ Designed lens system for coupling
- ✓ Targeted coupling loss of $\approx$ 4 dB

ROAM activities: transmission and networking demonstration @ CNIT

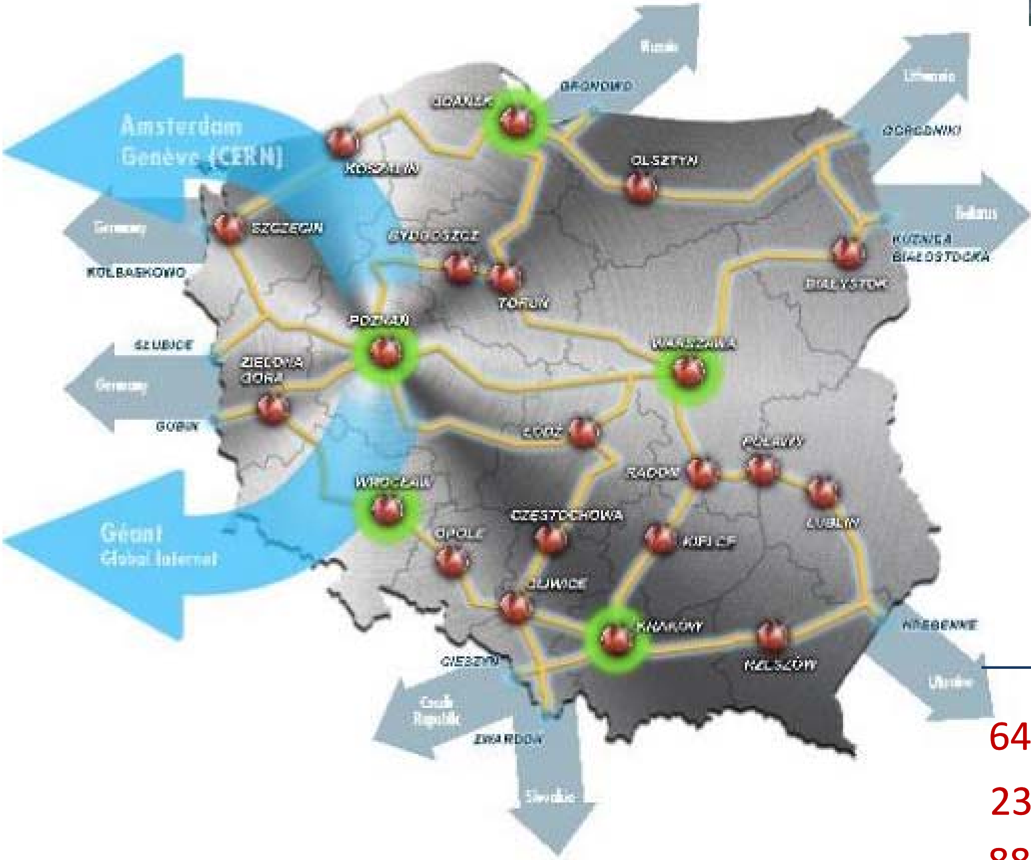






ROam

ROAM activities: PIONEER testbed



- Area — 312k sq km
- Population — 38M
- Main academic centers — 21
- State universities — 165+
- Students — 2M+
- R&D institutions and Univ. interconnected via PIONIER network — 700+

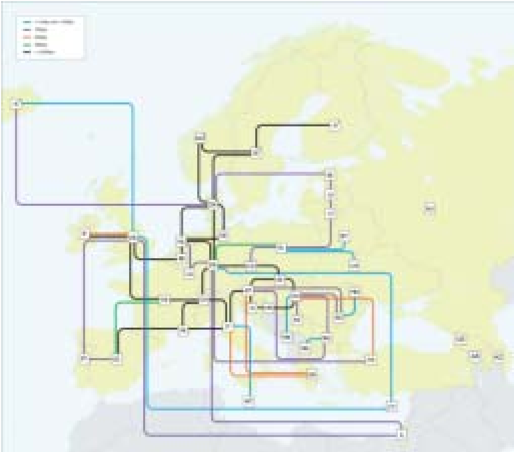
6479 km of fiber infrastructure in Poland

2359 km of fiber in Europe (IRU)

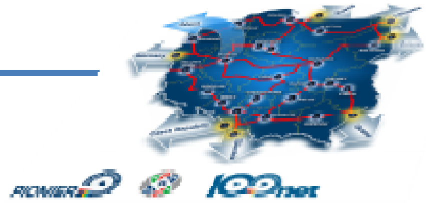
8838 km of fiber in total

21 MANs and 5 HPC Centers in PIONIER Consortium with PSNC as Operator

ROAM activities: PIONEER testbed



GÉANT



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PIONIER EU

ROAM activities: PIONEER testbed

1. **Demonstration of transmission of OAM multiplexed signals in an actual networking scenario.**
2. **Demonstration of a two-layer OAM and wavelength-based switch in an actual data-centre scenario**.

Field trials on the implemented OAM fibre and OAM-based switch in actual networking and data centre scenarios are planned to be performed exploiting Ethernet signals coming from different apparatus .

In the first experiment, the OAM fibre will be tested with transmission of up to 10 OAM modes carrying Ethernet signals.

In the second experiment a two-layer optical switching architecture will be tested by switching in both the wavelength domain and the OAM domain by exploiting 16 wavelengths and 10 OAM modes.

A comparison with standard transmission and networking through single-mode fibre and Ethernet electrical cable will be done

For more details on ROAM

1. Huanlu Li, Michael J Strain, Laura Meriggi, Lifeng Chen, Jiangbo Zhu, Kenan Cicek, Jianwei Wang, Xinlun Cai, Marc Sorel, Mark G Thompson, Siyuan Yu, 'Pattern manipulation via on-chip phase modulation between orbital angular momentum beams', Applied Physics Letters, Volume 107, Issue 5, 2015/8/3

2. Huanlu Li, David B Phillips, Xuyang Wang, Ying-Lung Daniel Ho, Lifeng Chen, Xiaoqi Zhou, Jiangbo Zhu, Siyuan Yu, Xinlun Cai, 'Orbital angular momentum vertical-cavity surface-emitting lasers', Optica, Volume 2, Issue 6, 2015/6/20.

3. Huanlu Li, David B Phillips, Xuyang Wang, Dainel Ho, Xiaoqi Zhou, Jiangbo Zhu, Siyuan Yu, Xinlun Cai, 'Integrated Optical Vortex Vertical-Cavity Surface-Emitting Lasers', CLEO 2015, Postdeadline paper.JTh5A. 4

4. Siyuan Yu (invited paper), 'Manipulating Optical Vortices Using Photonic Integration', AAPPS Bulletin, Volume 25, Issue 2.

5. Siyuan Yu, Xinlun Cai, Ning Zhang (invited talk) 'High index contrast integrated optics in the cylindrical coordinate', SPIE OPTO, Photonics West 2015.

6. Siyuan Yu (invited paper) 'Potentials and challenges of using orbital angular momentum communications in optical interconnects', Optics express 23 (3).

7. P. Vaity and L. Rusch, "Perfect vortex beam: Fourier transformation of a Bessel beam," Optics Letters, vol. 40, pp. 597-600, 2015/02/15.

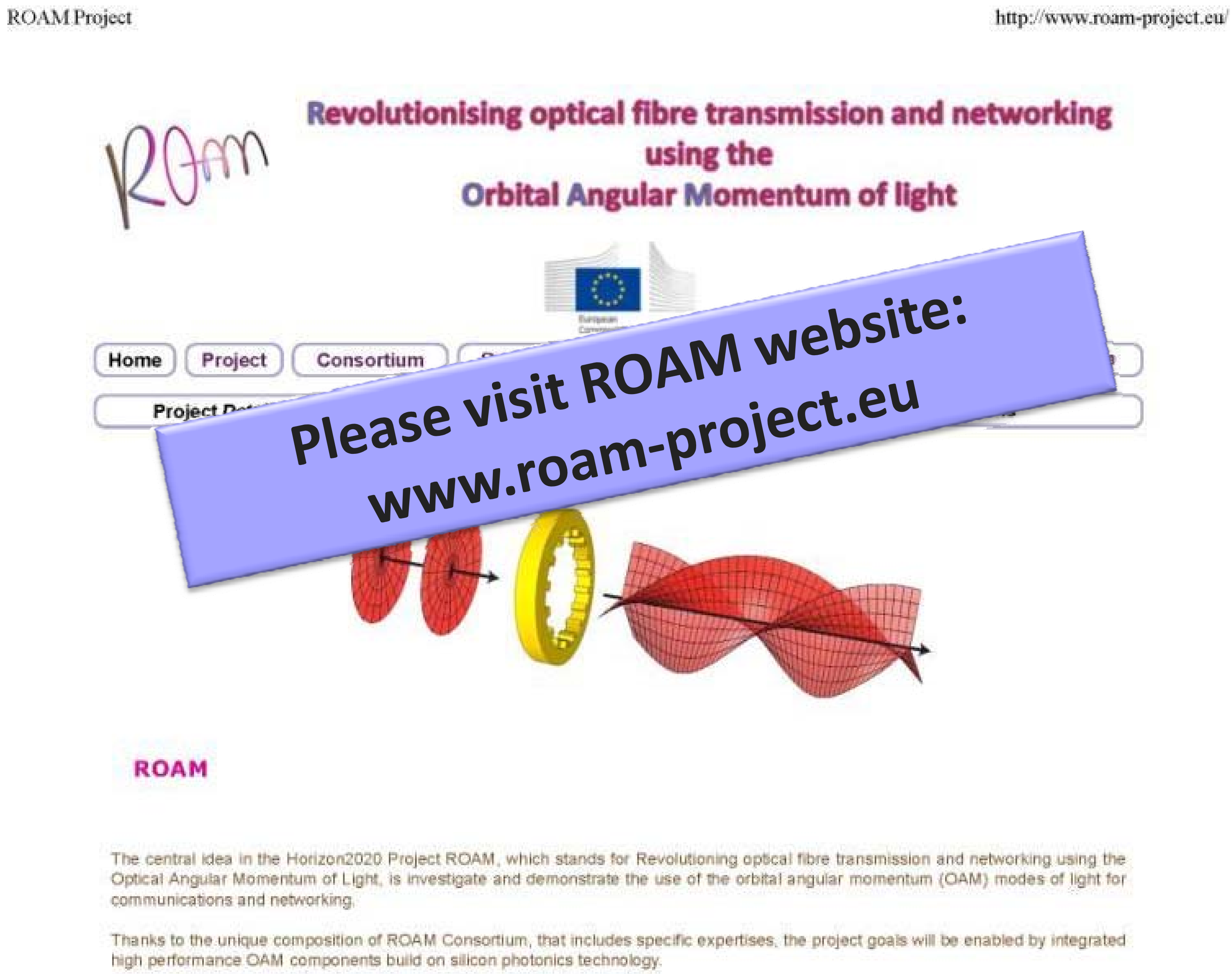
8. L. A. Rusch and S. LaRochelle, "Designing optical fiber for OAM mode transmission," in International Conf. on Orbital Angular Momentum (ICOAM), New York, invited, August 2015.

9. L. A. Rusch and S. LaRochelle, "Spatial Division Multiplexing using Ring Core Fibers for OAM," in IEEE European Conf. on Network and Optical Communications (NOC), London, keynote, July 2015.

10. C. Brunet, P. Vaity, B. Ung, Y. Messaddeq, S. LaRochelle, and L. A. Rusch, "Design of a family of ring-core fiber for OAM," in IEEE Optical Fiber Communications Conference (OFC 2015), Los Angeles, p. M3D.1, March 2015.

11. C. Brunet, B. Ung, L. Wang, Y. Messaddeq, S. LaRochelle, and L. A. Rusch, "Design of a family of ring-core fibres for OAM transmission studies," Optics Express, vol. 23, pp. 10553-10563, 15 April 2015.

For more details on ROAM



to

for their collaboration within ROAM!

Mirco Scaffardi – CNIT (Photonic Network National Lab, Pisa) IT

Alberto Bononi – CNIT (University of Parma) IT

Marc Sorel – University of Glasgow UK

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Bert Offrein – IBM Research GmbH CH

Yabin Ye – Huawei Technologies Duesseldorf GmbH D

Piotr Rydlichowki – Instytut Chemii Bioorganicznej Pan PL

Sophie Larochelle – Université Laval Canada

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HORIZON 2020

Thank you

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