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The European project ROAM "Revolutionising optical fiber transmission and networking using the Orbital Angular Momentum of light": motivations and recent outcomes

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Asia Communications and Photonics Conference

Workshop: ***Exploiting the Space Domain of Electromagnetic Waves: The Ongoing Frontiers – Part II: Space-division Multiplexing (SDM) Communications***

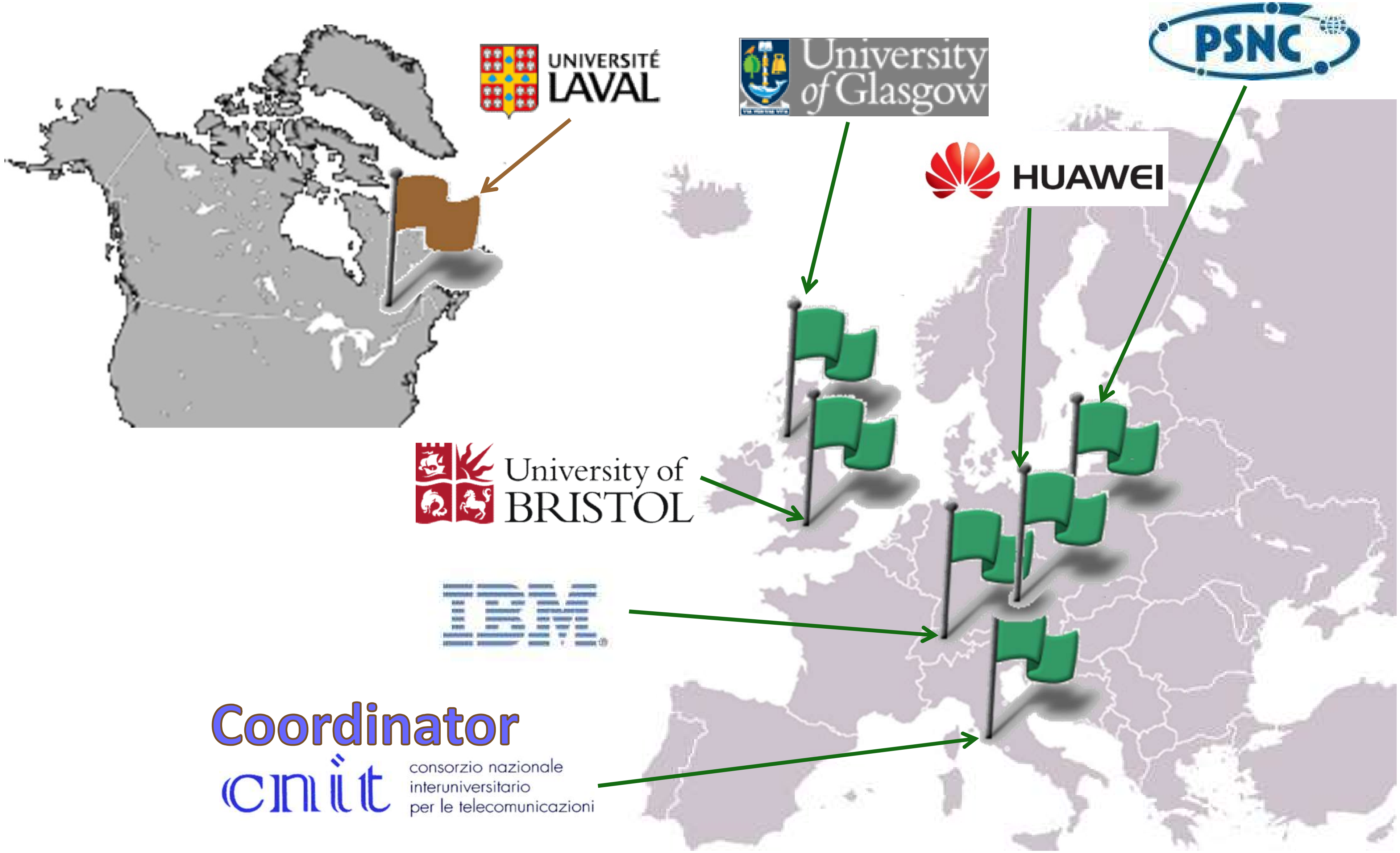
November 10, 2017 - Guangzhou, China

cnit · University of Bristol · University of Glasgow · IBM · HUAWEI · PSNC · Université Laval

Outline

- Introduction and motivation for ROAM project
- State of the art of OAM technologies and systems
- Key OAM components
- Main achieved results: OAM-based switching and fibre transmission
- Conclusions

ROAM consortium



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 main targets

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

- ✓ short-range high capacity optical **fiber transmission**
- ✓ high throughputs optical **switches**

State of the art: OAM fiber transmission

1. 2 OAM x 10 WDM 20 GB/s 16-QAM channels in 1.1 km of OAM fiber (2013) (Total capacity: 1.6 Tb/s)
2. 2 OAM 1GB/s QPSK channels up to 50 km of few mode fiber (2015) (0.002Tb/s)
3. 12 OAM x 60 WDM 10GB/s QPSK channels in 1.2km of OAM fiber (2017) (7.2 Tb/s)
4. 8 OAM x 10 WDM 20 GB/s QPSK channels in 10 km of OAM fiber (2017) (1.6 Tb/s) in collaboration with ROAM

We targeted 10 OAM x 16 WDM 28 GB/s 16 QAM channels in1 km of OAM fiber

Total capacity: 17.9 Tb/s

1. Y. Yue et al., "1.6-Tbit/s Muxing, Transmission and Demuxing through 1.1-km of Vortex Fiber Carrying 2 OAM Beams Each with 10 Wavelength Channels" OFC 2013, OTh4G.2.

2. A. Wang et al., "Characterization of LDPC-coded orbital angular momentum modes transmission and multiplexing overa 50-km fiber", Optics Express, Vol. 24, No. 11, 11716-11726, May 2016. (Ma è a 1 Gbaud, non 10).

3. K. Ingerslev et al., "12 Mode, MIMO-Free OAM Transmission", OFC 2017, M2D.1.

4. G. Zhu et al., "Scalable Orbital Angular Momentum Mode-Division-Multiplexed Transmission over 10-km Graded-Index Ring-Core Fiber", ECOC2017, Tu1.F.2.

State of the art: OAM fiber transmission

In particular we targeted:

- ✓ Development of new OAM fibers
- ✓ Nonlinear effect investigation
- ✓ Transmission experiments

State of the art: OAM-based switch

OAM has been exploited for 2x2 optical switching of 50-Gbaud QPSK channels by A.E. Willner group, exploiting **discrete elements**

We targeted an interconnection network solution based on a combination of two layer 10 OAM x16 WDM optical switches realized through **integrated photonic circuits**

Ahmed N. et al., "Reconfigurable 2× 2 orbital angular momentum based optical switching of 50-Gbaud QPSK channels", Optics Express, vol. 22, no1, 2014

State of the art: integrated technologies

1. 3 OAM not-tunable mux/demux with 20 Gb/s QPSK data (2012)
2. 9 OAM not-tunable mux/demux without data (2012)
3. Tunable OAM emitter (2012) ROAM consortium

We targeted **OAM mux/demux integrated devices tunable over 10 OAM modes**

1. *N. K. Fontaine, et al., "Efficient multiplexing and demultiplexing of free-space orbital angular momentum using photonic integrated circuits", OFC 2012*
2. *T. Su, et al., "Demonstration of free space coherent optical communication using integrated silicon photonic orbital angul momentum devices" Optics Express vol. 20, pp. 9396, 2012*
3. *X Cai et al, "Integrated compact optical vortex beam emitters," Science, vol. 338, pp. 363-366, 2012*

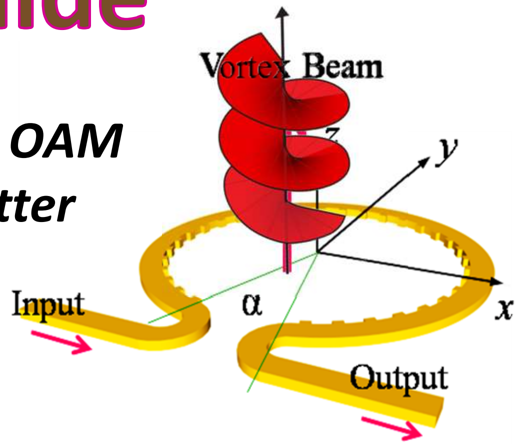
Multi-OAM emitter/mux based on Ω-shaped waveguide

- Ω-shaped waveguides avoid double-core layer structure.
- Non-resonant structure: higher bandwidth.
- Angle α must be small to have high mode purity.

$$l_{OAM} = \frac{(2\pi - \alpha)Rn_{eff}}{\lambda} - q$$

Topological charge of OAM beam — Input optical wavelength — Grating number

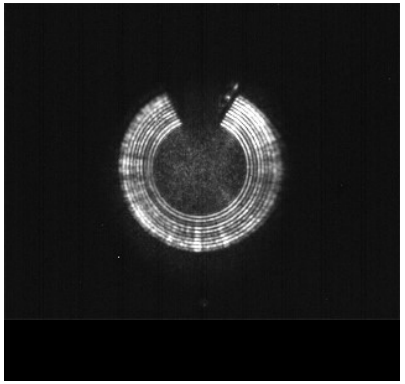
Single OAM emitter

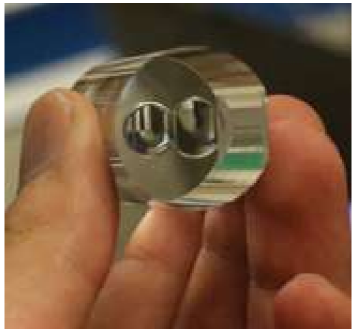


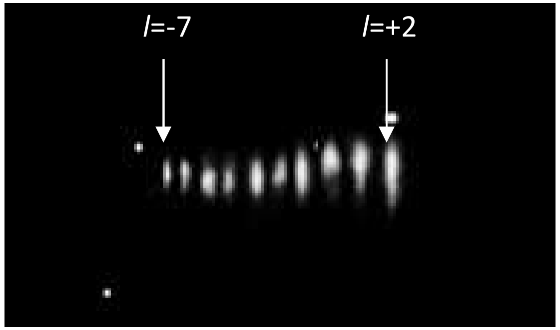
OAM multi-emitter/mux

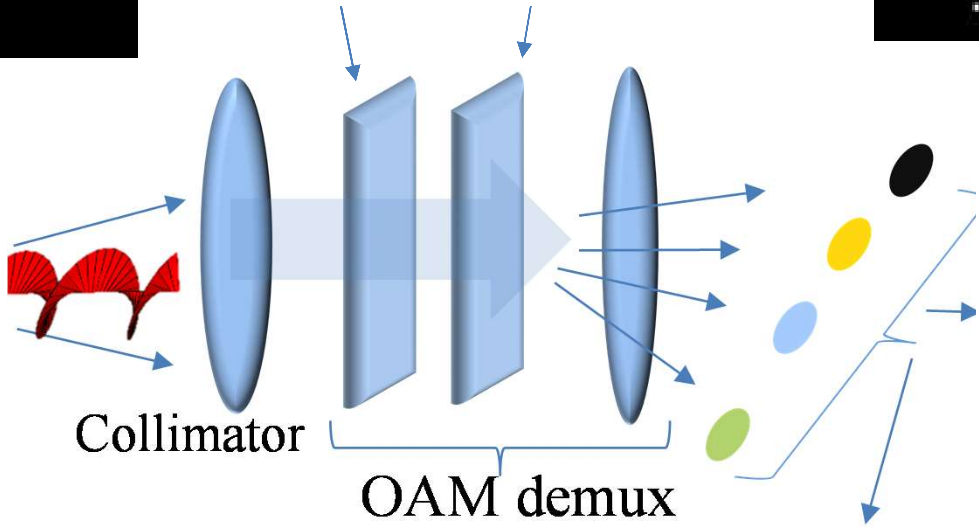
- ❑ **Multiple inputs**
- ❑ **OAM modes indipendently tunable**

OAM demodulator/demux









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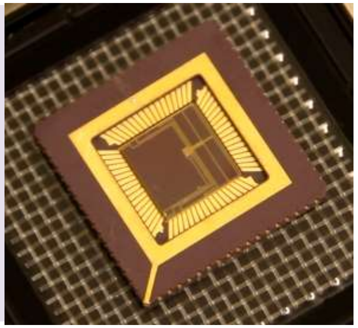
Characterization of exploited devices

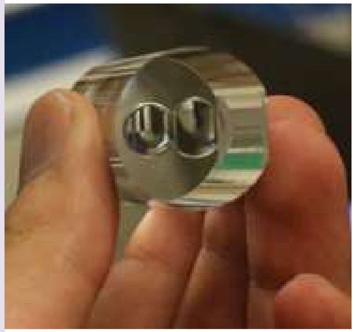
10 OAM generation/mod/mux

- Switching time < 1µs (target: 100ns)
- Mode crosstalk: <4.5dB (OSNR penalty)
- Insertion loss <6 dB
- Wavelength range: C-band
- Tested up to 10 OAM modes
- Dimensions: 2x2x0.5 cm
- Power consumption: < 2mW/Gb/s



10 OAM demod/demux based on refrective elements (sorter)

- Switching time: not applicable (all chs instantaneously available)
- Mode cross-talk >10dB
- Insertion loss<3dB
- Wavelength range: C-band
- Tested with up to 32 OAM modes.
- Dimensions: 10x2x2 cm (expected 3x2x2)
- No power consumption (passive)



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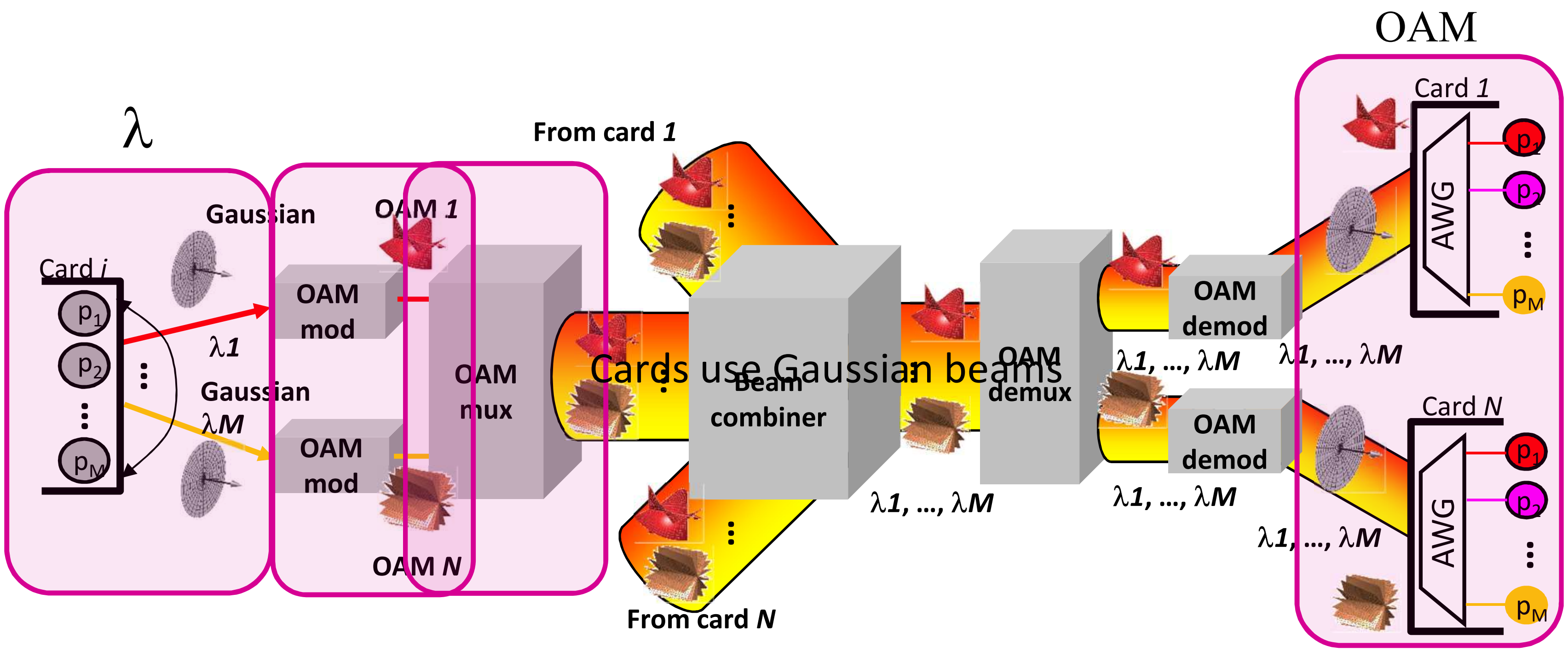
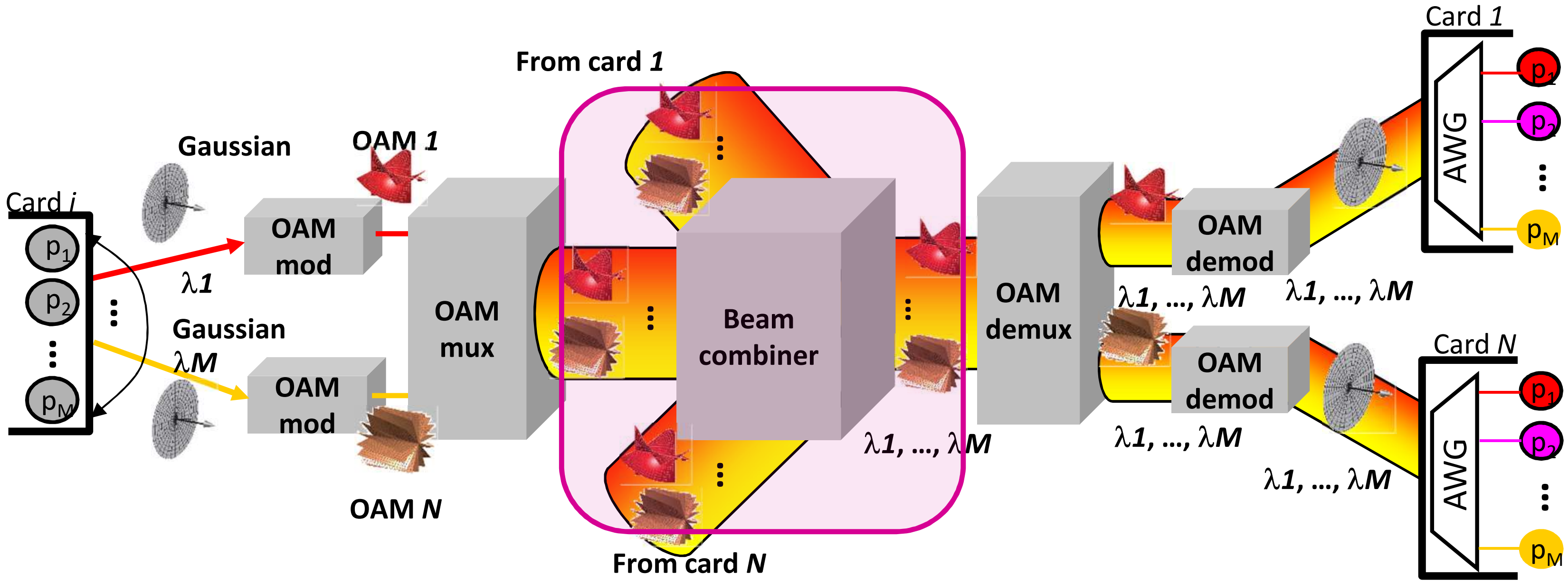
Switching network concept

- Ports addressed by wavelength, cards by OAM order.
- For each input port, an OAM modulator converts the signal onto an OAM mode of order *l* among a set of *N* OAM modes depending on the targeted output card.



Switching network concept

- OAM demod separates all the OAM modes of different *l* and the OAM demux convert them to Gaussian.
- Number of OAM mod integrated on the OAM mux = Number of ports.



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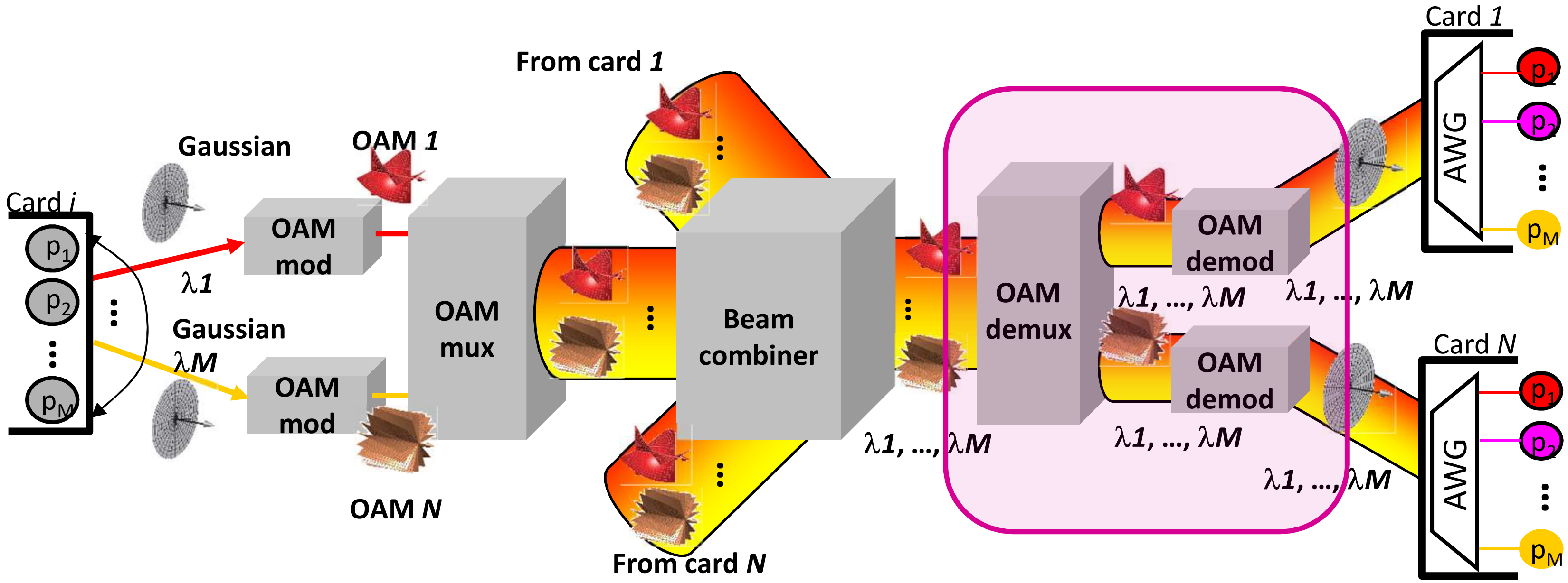

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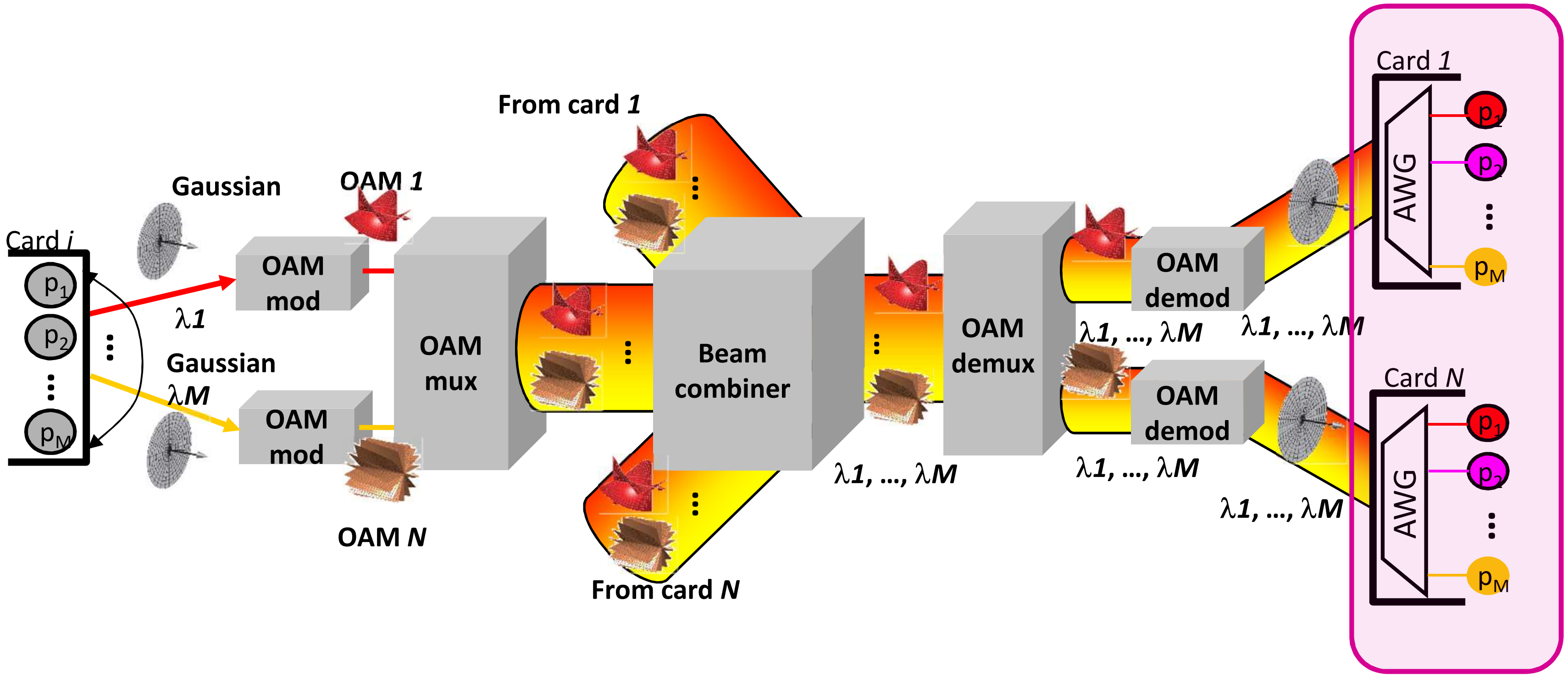
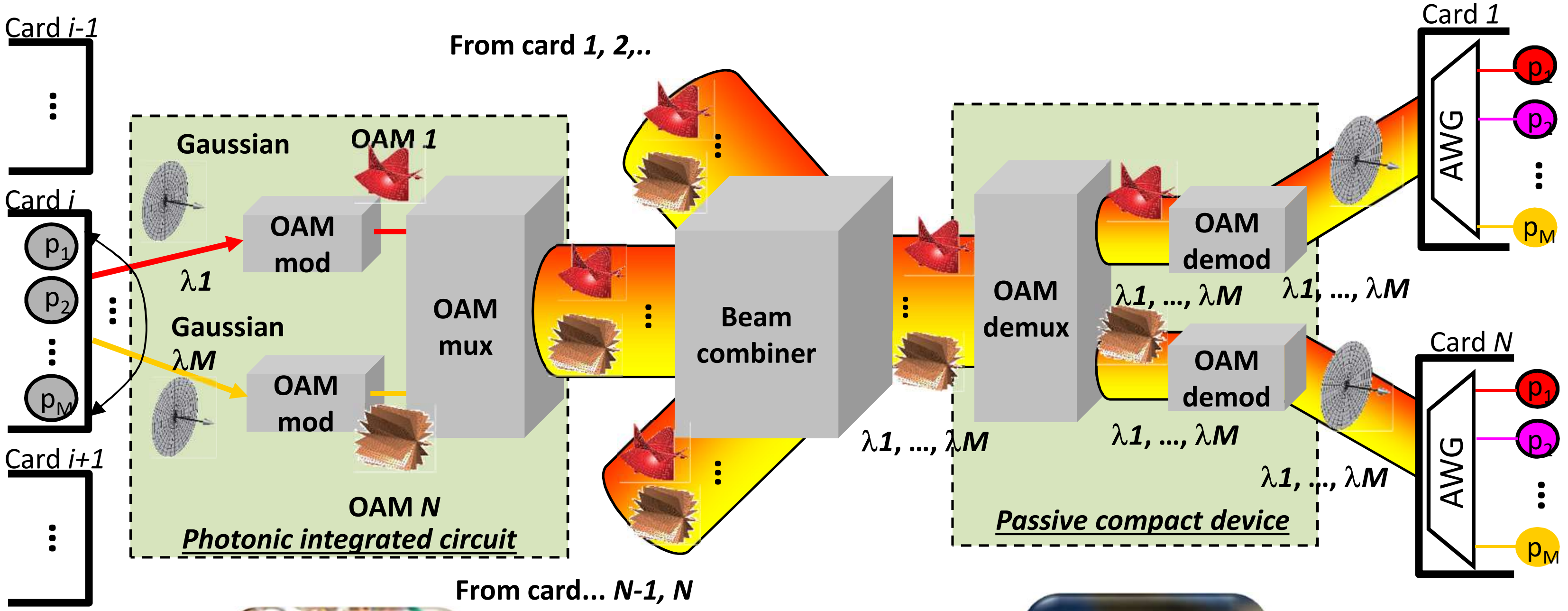
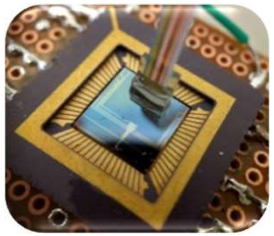


Switching network concept





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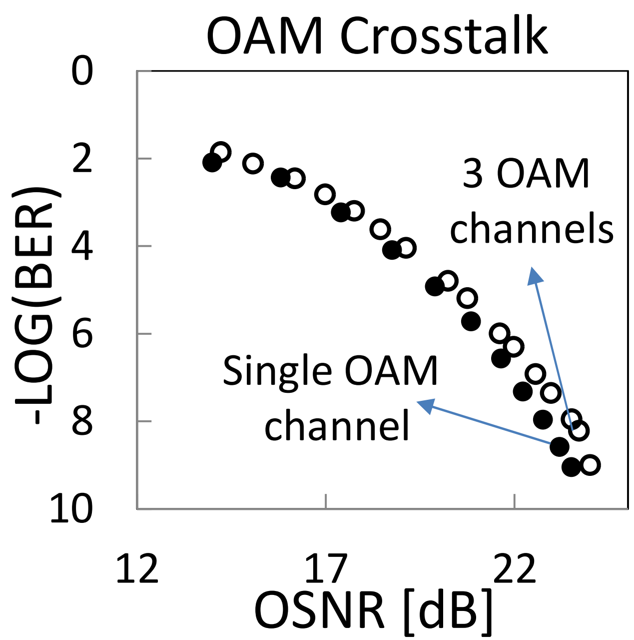
Switching network scalability

As a function of

- ✓Number of devices
- ✓Number of generated OAM channels/device
- ✓Power budget
- ✓Crosstalk

> 128 ports can be obtained

Scalability: OAM crosstalk



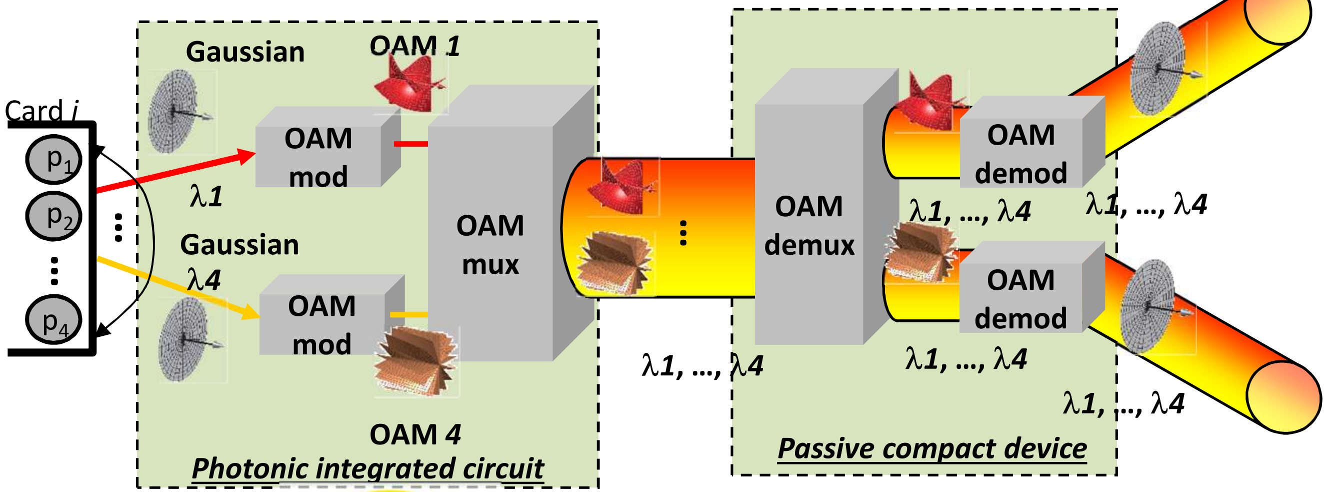
Crosstalk measurements:

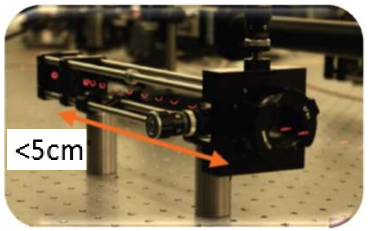
- 3 consecutive OAM modes generated at the same wavelength (worst case) by 3 concentric OAM emitters
- Modulation: OOK and 16-QAM at 30Gbaud

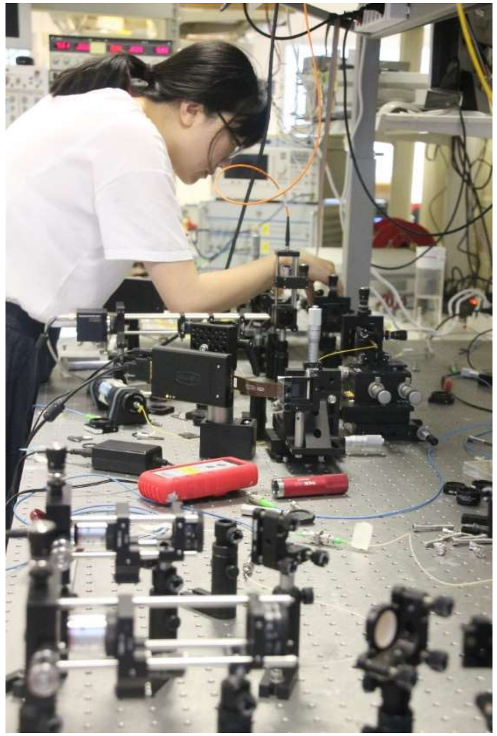
Crosstalk induced penalty <1dB.
Not significant impact on power and OSNR budget analysis.

OAM/wavelength switching experiments

4x4 switch





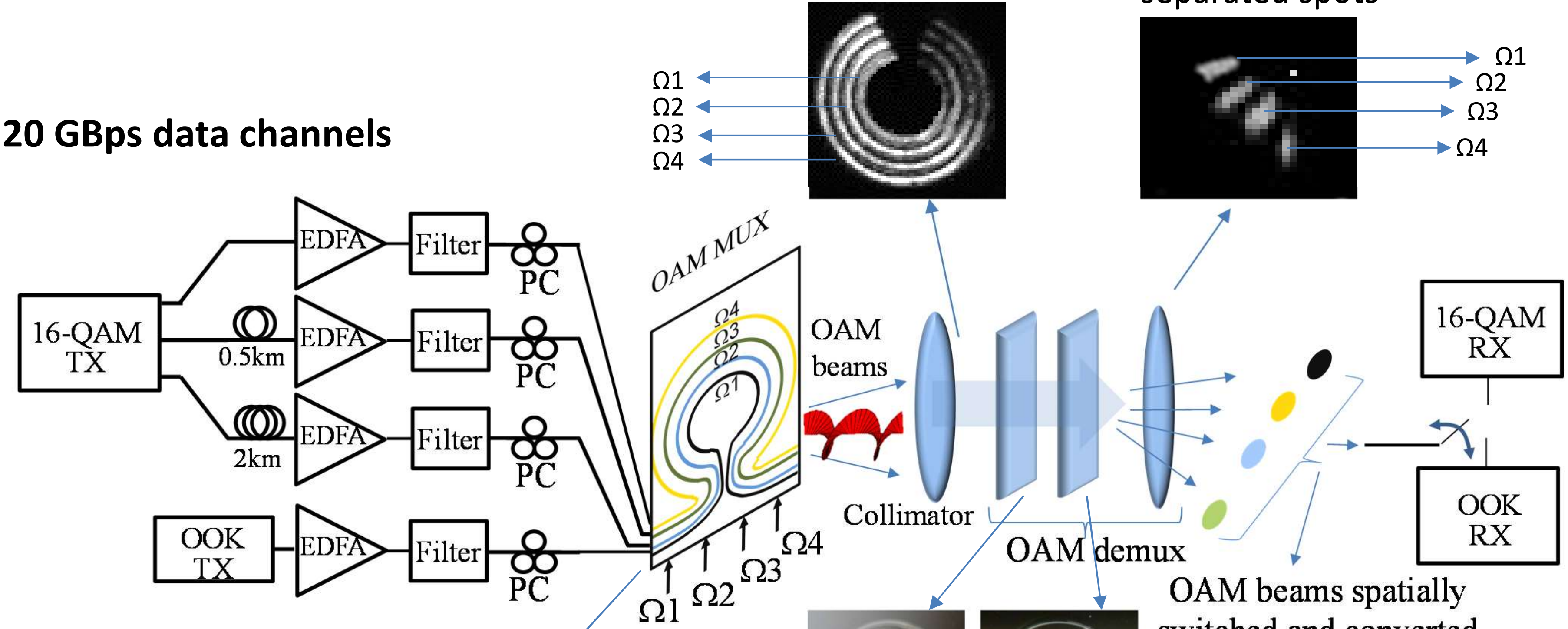


Experimental setup

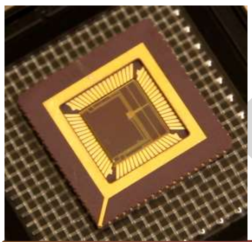
20 GBps data channels

Near-field distribution

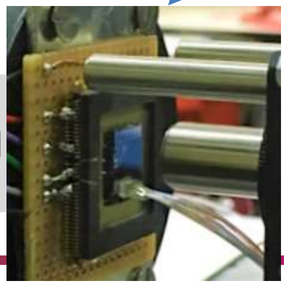
Demultiplexed spatially separated spots



OAM beams spatially switched and converted to plane waves



Packaged and mounted OAM multiplexer



Refractive elements of the OAM mode sorter

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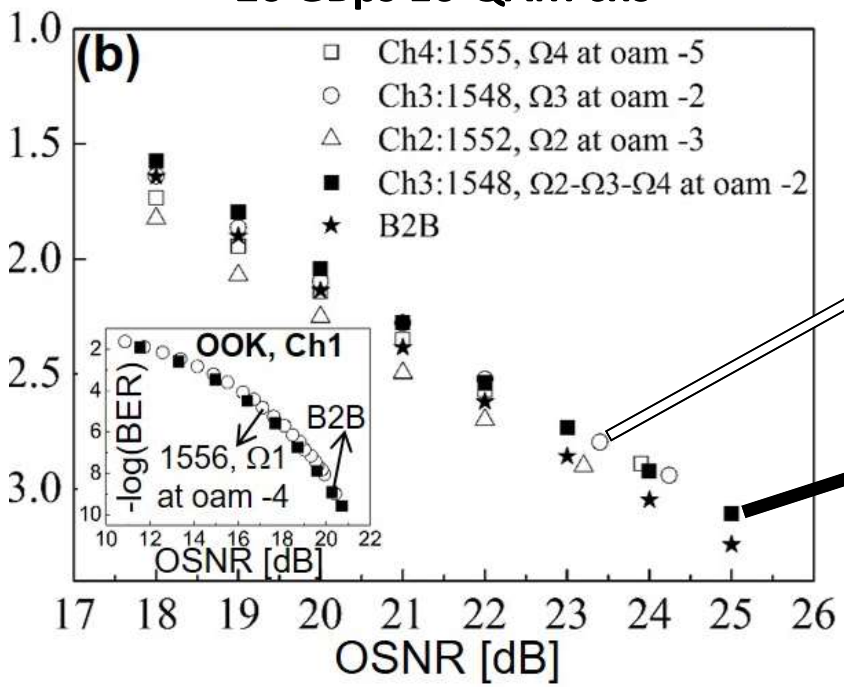
Results

20 GBps 16-QAM chs



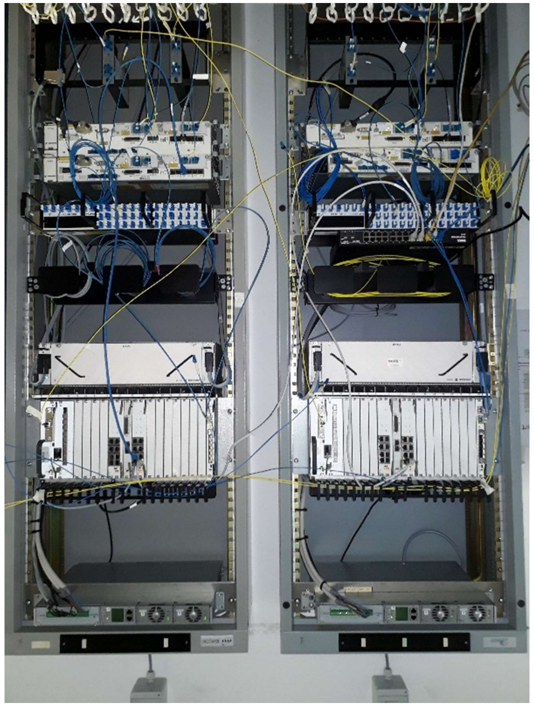
Each QAM ch is modulated at different OAM modes

All the QAM chs are modulated at the same OAM mode

- **Performance independent of the switching configuration** (for 16QAM and OOK signals)
- Switch total **power consumption/Gb/s <0.6mW** for the tuning of the whole OAM multiplexer

Real traffic experiment

4x4 switch, with 100Gb/s QPSK coherent pol-mux traffic



Commercial network card

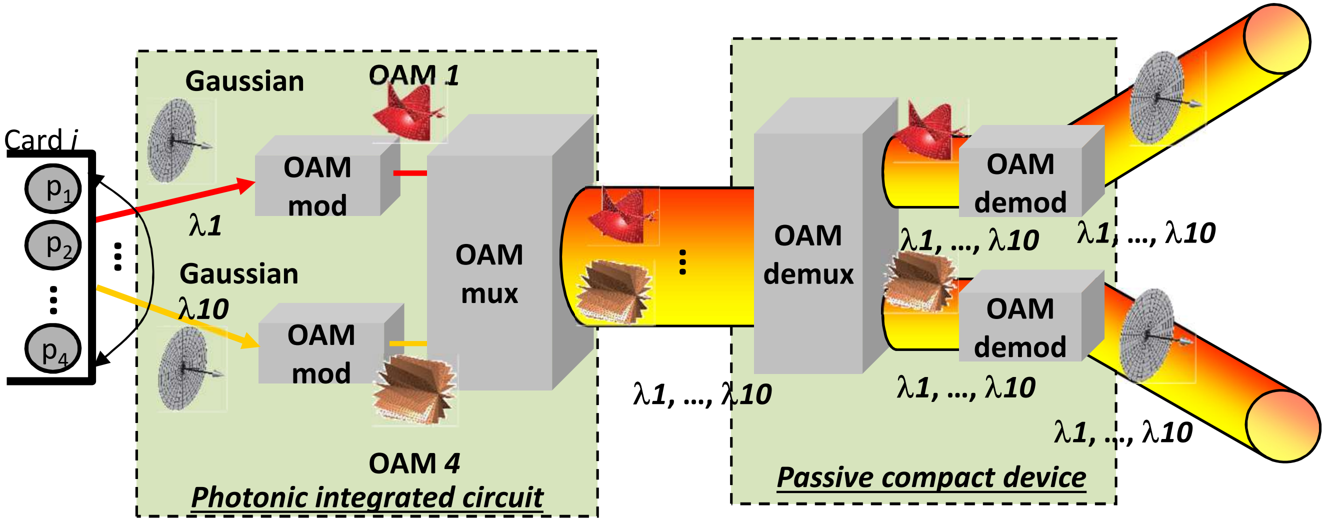
Card software interface in two different OAM switch configurations

Ω2 →OAM -3 Ω4 →OAM 0		Ω2 →OAM -3 Ω4 →OAM -1	
Attributes		**Attributes**	
Elapsed Time	01m:52s	Elapsed Time	02m:00s
Corrected Bits Last Second	1.26E08	Corrected Bits Last Second	2.41E07
Corrected Bits	1.20E10	Corrected Bits	2.16E09
Corrected Bits Ratio	1.03E-03	Corrected Bits Ratio	1.71E-04
Status and administration		**Status and administration**	
Administrative Status	in service	**Administrative Status**	in service
Operational Status	up	Operational Status	up

The system recovers all the errors, demonstrating the **operability with real-traffic equipment after OAM switching**

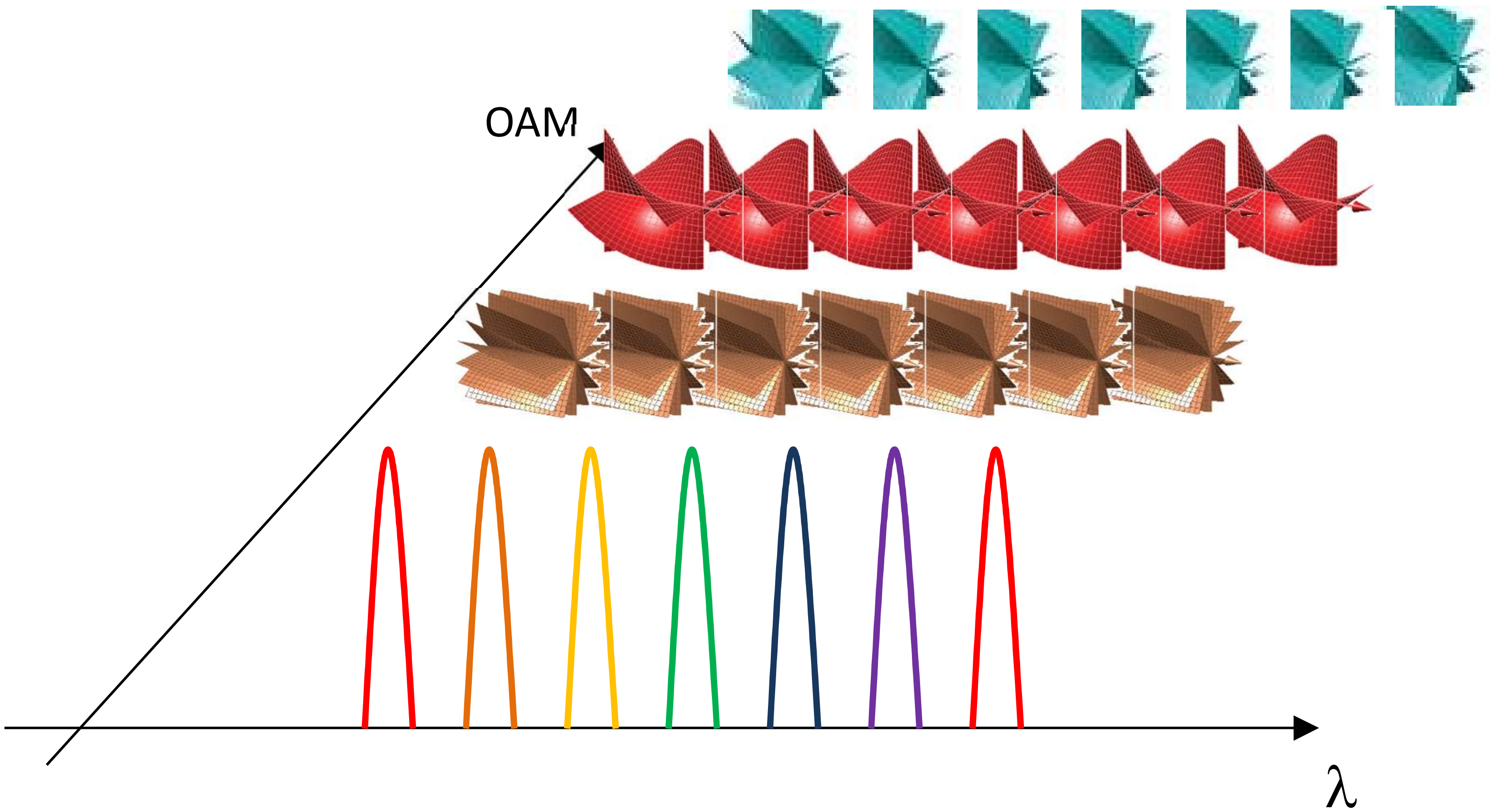
OAM/wavelength switching experiments

10x Omega device has been developed and a 10x10 switch is under characteriaztion

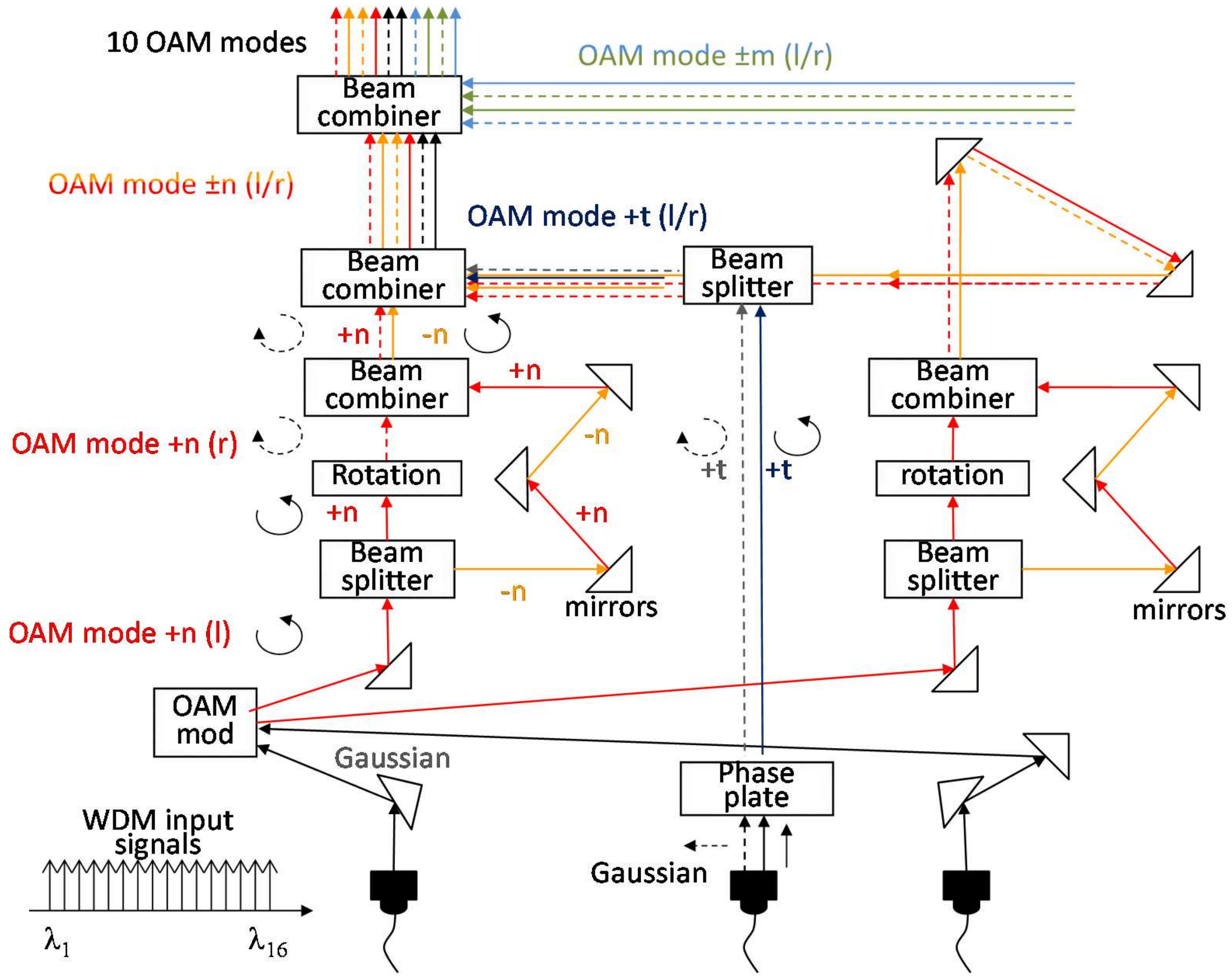


OAM-wavelength multiplexing in fibre

Two multiplexing domains

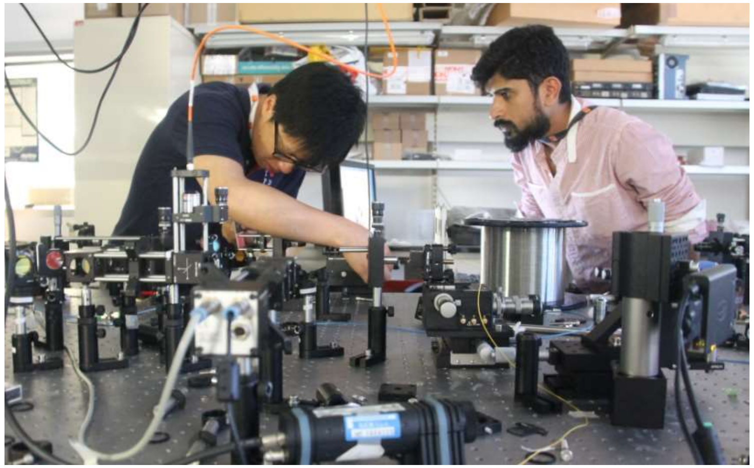


Transmission experiment: setup



Transmission experiments: results

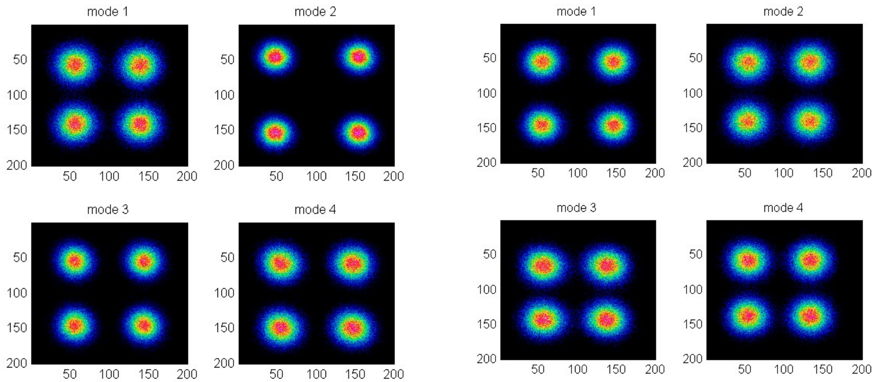
✓Set up available for 10 OAM x 16 WDM MIMO-aided transmission
✓8 OAM x 16 WDM MIMO-aided transmission ongoing
✓4 OAM x 16 WDM MIMO-aided transmission implemented



Preliminary experiments with 16-QAM data have been also carried out

Received 4-QAM 28GBaud channels

4 OAM x 1 WDM chs | 4 OAM x 16 WDM chs



Transmission over Ring Core Fiber (1Km)

Conclusions

ROAM is pioneering OAM-based technologies and systems for:

- ✓ **Fiber transmission: ≈ 18 Tb/s over 1km of OAM fiber**
- ✓ **Switching net: 10 OAM x 16 WDM switch with ≈ 18 Tb/s input traffic**

Developing new OAM integrated devices for 10 OAM x 16 WDM channels

Work in progress

- ✓ **OAM fiber transmission and switching demos based on real data-center traffic**

For more information, please refer to the following Journals

1. M. Scaffardi, M. N. Malik, E. Lazzeri, G. Meloni, F. Fresi, L. Poti, N. Andriolli, I. Cerutti, C. Klitis, L. Meriggi, N. Zhang, M. Sorel, and A. Bogoni, “A Silicon Microring Optical 2x2 Switch Exploiting Orbital Angular Momentum for Interconnection Networks up to 20Gbaud,” IEEE Journal of Lightwave Technologies, vol. 35, n. 15, August 1 2017

2. F.J. Vaquero Caballero , F. Pittalà , G. Goeger , M. Wang , Y. Ye and I. Tafur Monroy, “Novel Equalization Techniques for Space Division Multiplexing Based on Stokes Space Update Rule”, MDPI Photonics, Vo. 2, n.12, 20 February 2017.

3. M. Wang, L. Zong, L. Mao, A. Marquez, Y. Ye, H. Zhao and F. J. V. Caballero, “LCoS SLM Study and Its Application in Wavelength Selective Switch”, MDPI Photonics, Vo. 4, n. 22, 23 March 2017

4. S. Li, W. Yu, L. Meriggi, Q. Xiao, Z. Nong, X. Cai, M. Sorel, and S. Yu, “High-directional vortex beam emitter based on Archimedean spiral adiabatic waveguides,” Optics Letters Vol. 42, n. 5, pp. 975-978, February 2017

5. R. Mirzaei Nejad, L. Wang, J. Lin, S. LaRochelle, and L. A. Rusch, “The Impact of Modal Impairments on Receiver Performance in OAM-MDM Systems,” to be published on IEEE/OSA J. Lightwave Technol..

6. M. Scaffardi, M.N. Malik, E. Lazzeri, C. Klitis, L. Meriggi, N. Zhang, M. Sorel, and A. Bogoni, “Optical Switching by Exploiting Vortex Beam Emitters based on Silicon Microrings with Superimposed Gratings,” accepted for publication on Optics Letters, August 2017.

7. K. Cicek, Z. Hu, J. Zhu, L. Meriggi, S. Li, Z. Nong, S. Gao, N. Zhang, X. Wang, X. Cai, M. Sorel, and S. Yu, “ Integrated optical vortex beam receivers”, Optics Express Vol. 24, n. 25, pp. 28529-28539, December 2016

8. R. Mirzaei Nejad, K. Allahverdyan, P. Vaity, S. Amiralizadeh, C. Brunet, Y. Messaddeq, S. LaRochelle, and L. A. Rusch, “Orbital Angular Momentum Mode Division Multiplexing over 1.4 km Ring Core Fiber”, Journal of Lightwave technology, Volume 34, n. 18, pp. 4252-4258, 15 September 2016

9. L. Wang, P. Vaity, S. Chatigny, Y. Messaddeq, L. A. Rusch, S. LaRochelle “Orbital-Angular-Momentum Polarization Mode Dispersion in Optical Fibers”, Journal of Lightwave Technology, Volume 34, n. 8, pp. 1661-1671, 15 April 2016

10. Q. Xiao, C. Klitis, S. Li, Y. Chen, X. Cai, M. Sorel, S. Yu, “Generation of photonic orbital angular momentum superposition states using vortex beam emitters with superimposed gratings”, Optics Express, Volume 24, Issue 4, pp. 3168-3176, February 2016

11. H. Li, M. J. Strain, L. Meriggi, L. Chen, J. Zhu, K. Cicek, J. Wang, X. Cai, M. Sorel, M. G. Thompson, S. Yu, “Pattern manipulation via on-chip phase modulation between orbital angular momentum beams”, Applied Physics Letters, Volume 107, Issue 5, 3 August 2015

12. ....

Acknowledgments

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http://www.roam-project.eu/

Thank you!

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