The Annual Conference of the IEEE Photonics Society

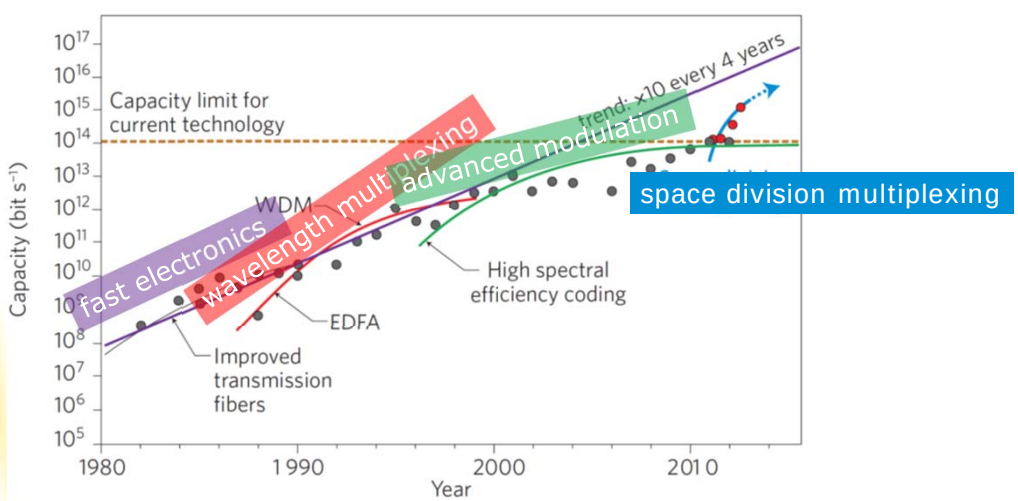
IPC

Shaping optical fibers to mode division multiplex without MIMO

Leslie A. Rusch
Canada Research Chair

UL COPL Centre d'optique, photonique et laser

Next wave of capacity increase?



UL COPL Centre d'optique, photonique et laser

D. J. Richardson, J. M. Fini, and L. E. Nelson, "Space-division multiplexing in optical fibres," *Nature Photonics*, vol. 7, p. 354, 04/29/2013.

Spatial Multiplexing in New Fibers

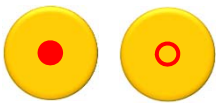
a single core, a single mode

UL COPL Centre d'optique, photonique et laser

Focus of this talk

a single core, a single mode

multiple cores, each a single mode



a single core, multiple modes

and eventually ....
multiple cores, multiple modes

UL COPL Centre d'optique, photonique et laser

4

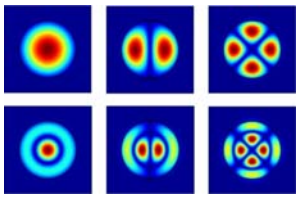
Outline

- Motivation for study of vector modes
  - Contrast scalar mode solutions
  - Focus on impact on receiver and network architectures
- Vector modes example
  - Orbital angular momentum modes
  - Description & reason they are of interest
- Fiber designs & challenges
- Review of some experimental demonstration
- Conclusion

UL COPL Centre d'optique, photonique et laser

LP

scalar modes

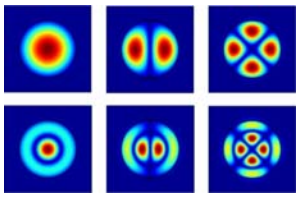


- Rich set of components
  - coupling and muxing
- LP modes from eigenmodes that necessarily interact
  - high crosstalk
  - limited channel count
- Requires MIMO processing and multiplexed receivers

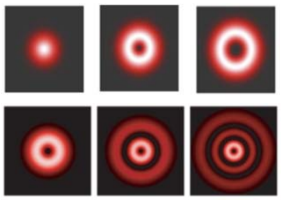
UL COPL Centre d'optique, photonique et laser

LP vs. OAM

scalar modes



- Rich set of components
  - coupling and muxing
- LP modes from eigenmodes that necessarily interact
  - high crosstalk
  - limited channel count
- Requires MIMO processing and multiplexed receivers



vector modes

- Early stages of research
  - coupling performance still open
- OAM modes from eigenmodes that can be designed to avoid interaction
  - low crosstalk
  - better channel count
- DSP & RX simpler
  - Target standard 2×2 MIMO processing

Different Strategies

embrace strong fiber interactions to simplify components; exploit MIMO / target very low fiber interactions, but what about splices, etc.?; avoid MIMO

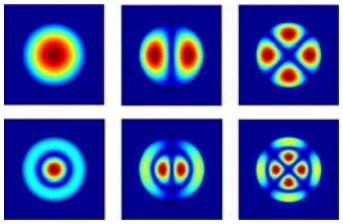
UL

Centre d'optique, photonique et laser

7

LP modes or scalar modes

- LP for Spatial division multiplexing



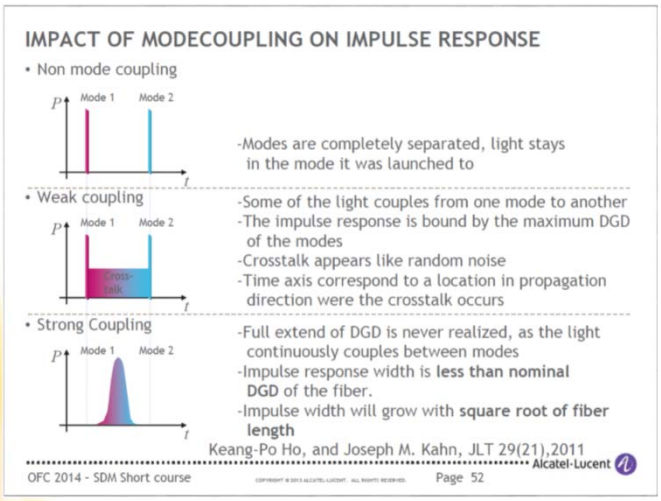
- Modal interactions mix transmitted signals
- Digital signal processing at RX can undo this
  - Multiple input Multiple output (MIMO) processing

UL

COPL Centre d'optique, photonique et laser

8

DSP requirements for LP mode multiplexing



Short Course Notes
OFC 2014
SC408• Space Division Multiplexing
Roland Ryf, *Bell Labs, Alcate-Lucent*

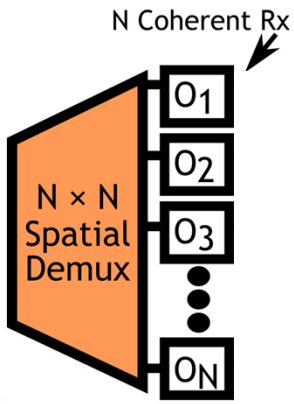
UL COPL Centre d'optique, photonique et laser

Electronic MIMO Demultiplexing

UL COPL Centre d'optique, photonique et laser

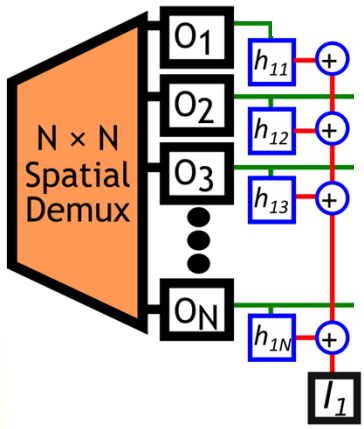
10

Electronic MIMO Demultiplexing



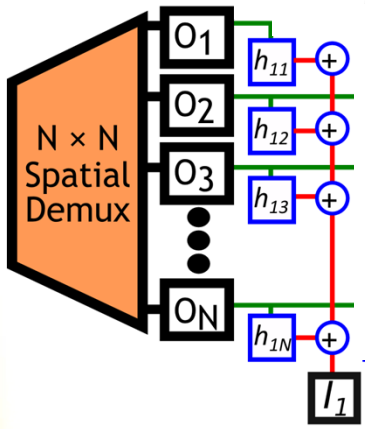
Coherent receivers time synchronized and colocated

Electronic MIMO Demultiplexing



$$I_1 = h_{11}O_1 + h_{12}O_2 + h_{13}O_3 + h_{14}O_4 + \ldots + h_{1N}O_N$$

Electronic MIMO Demultiplexing



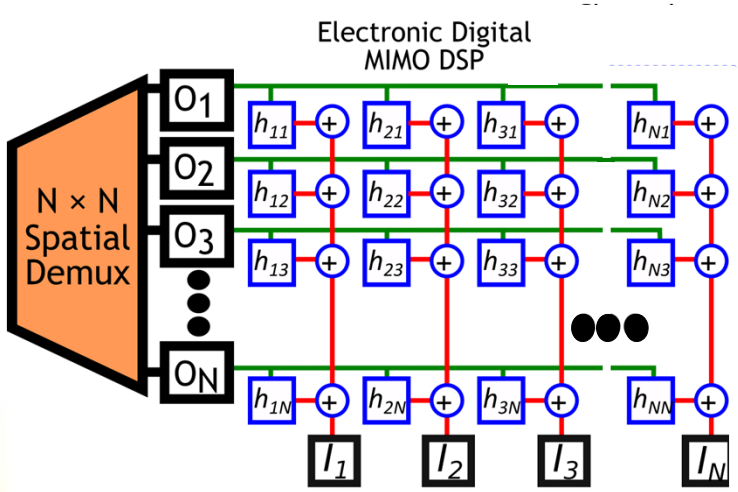
Need the complex filter (time varying amplitudes/phases) for each mode output

$$I_1 = h_{11}O_1 + h_{12}O_2 + h_{13}O_3 + h_{14}O_4 + \ldots + h_{1N}O_N$$

UL COPL Centre d'optique, photonique et laser

13

Electronic MIMO Demultiplexing

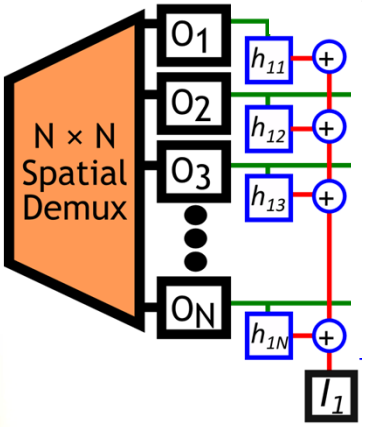


Number of filters scales with the square of number of modes

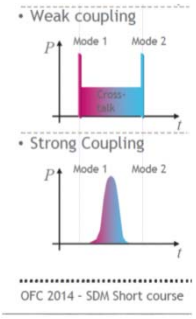
UL COPL Centre d'optique, photonique et laser

14

Electronic MIMO Demultiplexing



Filter size and power consumption determined by modal dispersion

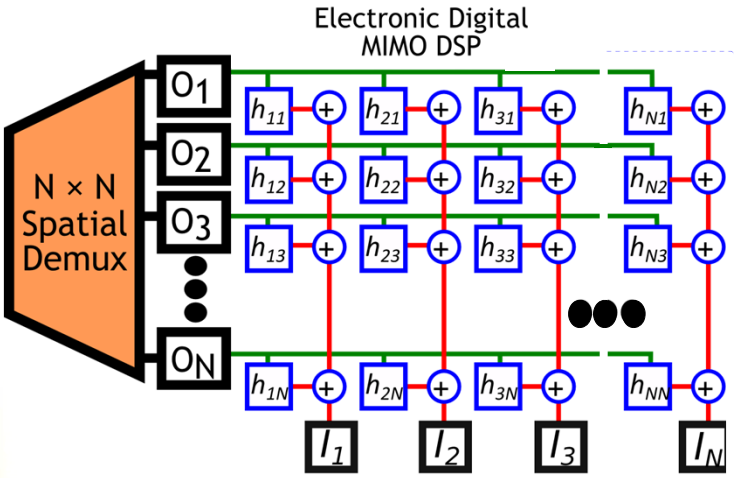


$$I_1 = h_{11}O_1 + h_{12}O_2 + h_{13}O_3 + h_{14}O_4 + \ldots + h_{1N}O_N$$

UL COPL Centre d'optique, photonique et laser

15

Electronic MIMO Demultiplexing



Filter performance impacted by mode dependent loss

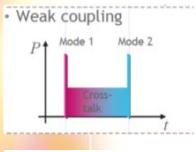
UL COPL Centre d'optique, photonique et laser

16

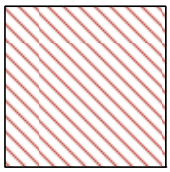
MIMO solutions

- *M separate modes*, 2M separate channels with PolMux

LP modes
Full MIMO



coupling across all modes



2M×2M

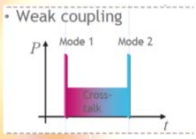
number of equalizer blocks

MIMO solutions

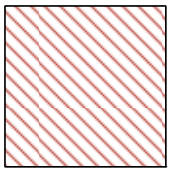
- *M separate modes*, 2M separate channels with PolMux

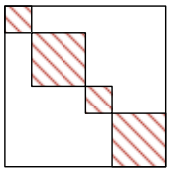
LP modes
Full MIMO

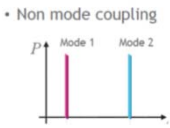
LP
modes (groups)



coupling across all modes







uncoupled mode groups

2M×2M

(4:16)M

number of equalizer blocks

MIMO solutions

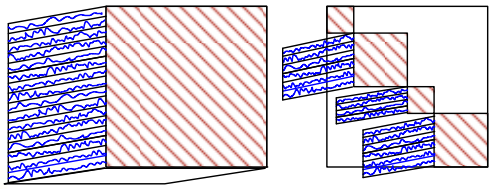
- *M separate modes*, 2M separate channels with PolMux

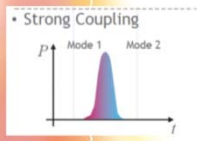
LP modes
Full MIMO

LP
modes (groups)

OAM/LPV
modes (pairs)

LPV
MIMO-free





2M×2M

(4:16)M

impact of differential mode group delay

MIMO solutions

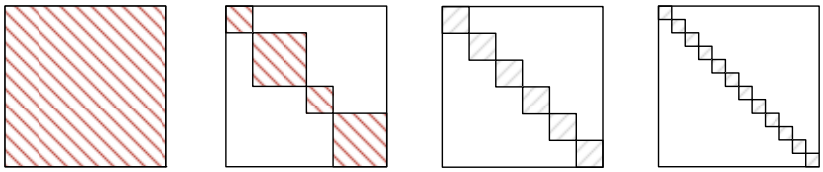
- *M separate modes*, 2M separate channels with PolMux

LP modes
Full MIMO

LP
modes (groups)

OAM/LPV
modes (pairs)

LPV
MIMO-free



2M×2M

(4:16)M

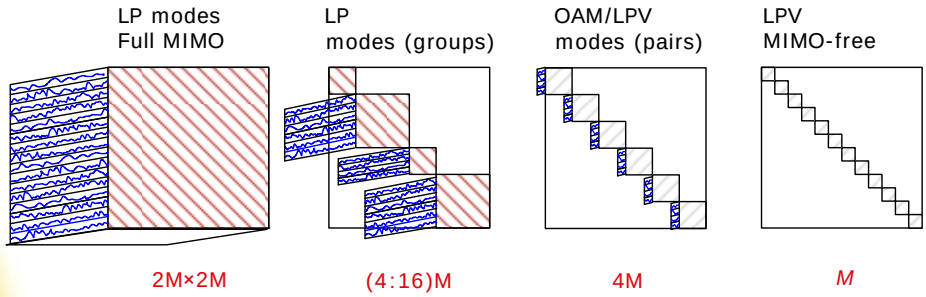
4M

M

number of equalizer blocks

MIMO solutions

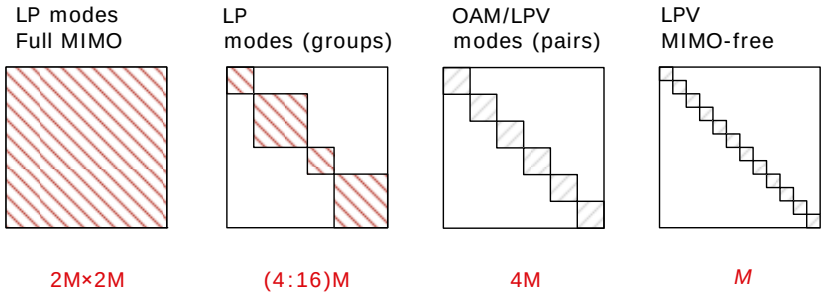
- *M separate modes*, 2M separate channels with PolMux



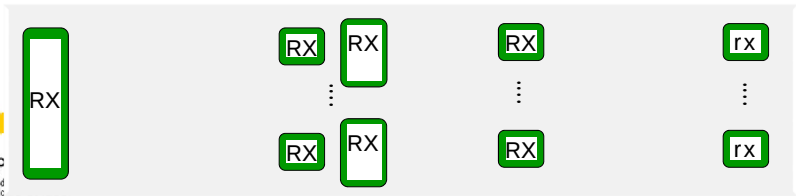
impact of differential mode group delay

MIMO solutions

- *M* separate modes, 2M separate channels with PolMux

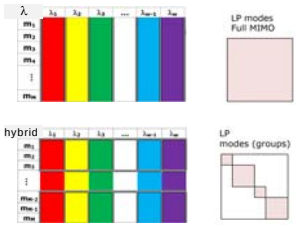


receiver front end



High vs. Low Crosstalk and Switching

- High crosstalk
  - MIMO required
  - Restricted architectures



Dan Marom at HU working on new WSS with an input for each mode

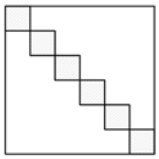
WSS

UL COPL Centre d'optique, photonique et laser

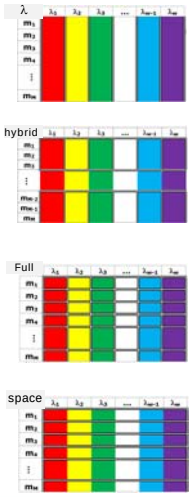
23

High vs. Low Crosstalk and Switching

OAM/LPV modes (pairs)



- No crosstalk
  - No MIMO
  - All architectures available



WSS

standard WSS suffice, but in greater number

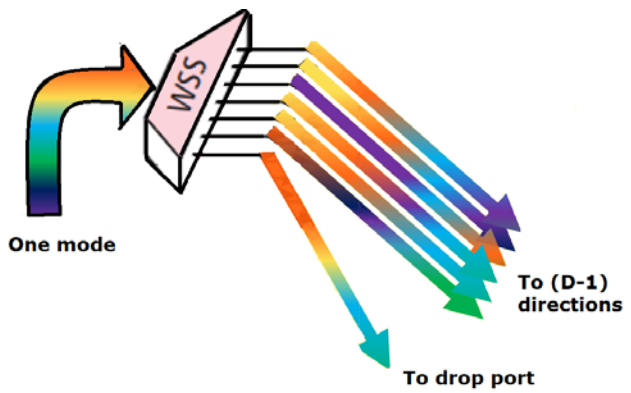
WSS

UL COPL Centre d'optique, photonique et laser

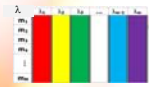
24

Full Granularity: Hardware Complexity

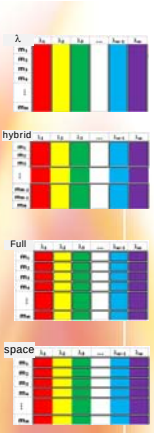
- Configuration of WSS → M×(I×O)



Summary advantages / disadvantages

	Switching Strategy	Flexibility level	conventional devices
	Wavelength Granularity	Coarse	No
	Hybrid Granularity	Intermediate	No
	Full Granularity	Finest	Yes
	Space Granularity	Coarse	Yes

Qualifying advantages / disadvantages

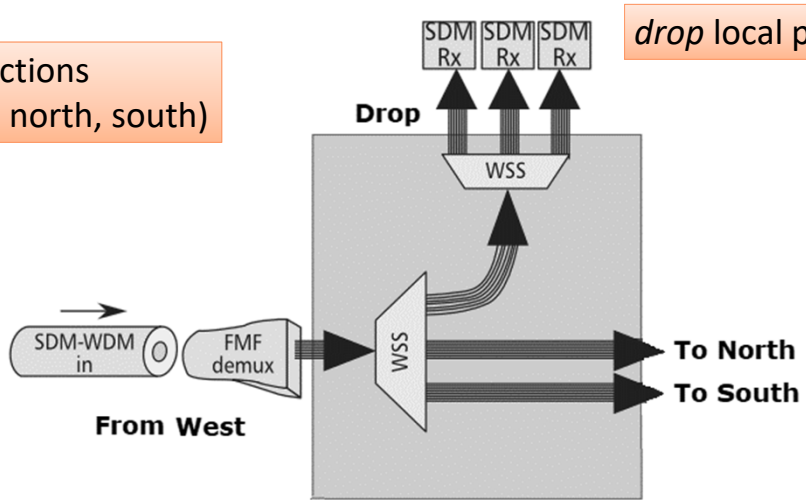


Switching Strategy	Flexibility level	conventional devices	
Wavelength Granularity	Coarse	No	WSS
Hybrid Granularity	Intermediate	No	WSS
Full Granularity	Finest	Yes	WSS
Space Granularity	Coarse	Yes	WSS

Quantifying hardware count: example

D directions (west, north, south)

drop local ports



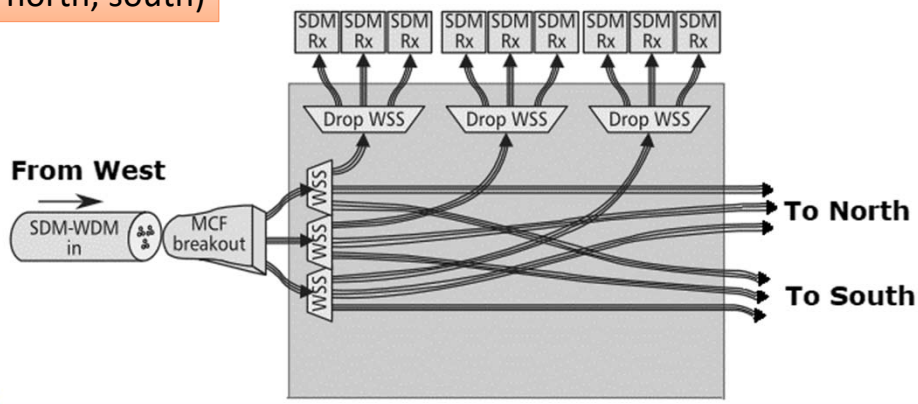
D. M. Marom and M. Blau, *IEEE Commun. Mag.*, vol. 53, no. 2, 2015

Quantifying hardware count: example

D directions
(west, north, south)

drop local ports

N mode groups



D. M. Marom and M. Blau, *IEEE Commun. Mag.*, vol. 53, no. 2, 2015

29

Summary on Complexity

Switching Strategy	Switching Hardware Port Count	Required WSS per Node
Wavelength Granularity	$M(D-1+drop)$ WSSs	2
Hybrid Granularity	$M_1(N(D-1)+drop)$WSSs	$2N$
Full Granularity	$M(D-1)+drop$ WSSs	$2M$
Space Granularity	$DM \times DM$ OXC	*depends on* A/D

30

Trade-offs

- Why we might want to avoid MIMO in SDM
  - Complexity of DSP and receiver
  - More robust to DMGD & mode dependent loss
  - Routing flexibility
    - MIMO requires all modes on a λ
    - OAM/LPV may be able to use existing WDM routers
  - Progressive rollout
    - FMF fiber deployed & RX added as modes "lit"
- What MIMO with LP modes enables for SDM
  - Handles mux/demux imperfections
  - Proven techniques at moderate distances, including amplification
  - Richer set of components

UL COPL Centre d'optique, photonique et laser

Outline

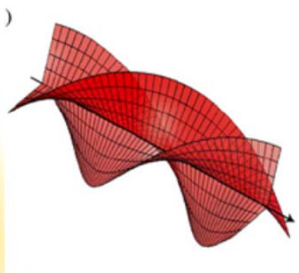
- Motivation for study of vector modes
  - Contrast scalar mode solutions
  - Focus on impact on receiver and network architectures
- Vector modes example
  - Orbital angular momentum modes
  - Description & reason they are of interest
- Fiber designs & challenges
- Review of some experimental demonstration
- Conclusion

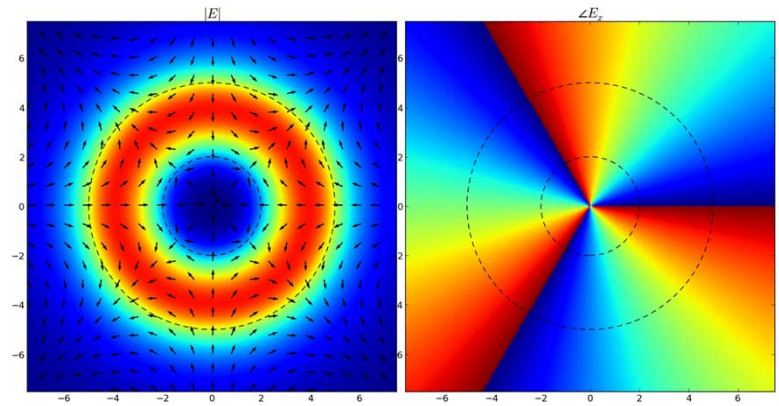
UL COPL Centre d'optique, photonique et laser

OAM example – 3rd order mode

- Annular field intensity profile ($m=1$)
- Helical phase front $(e^{\pm i\ell\varphi})$
- Circular Polarization (±)

$OAM_{3,1}$

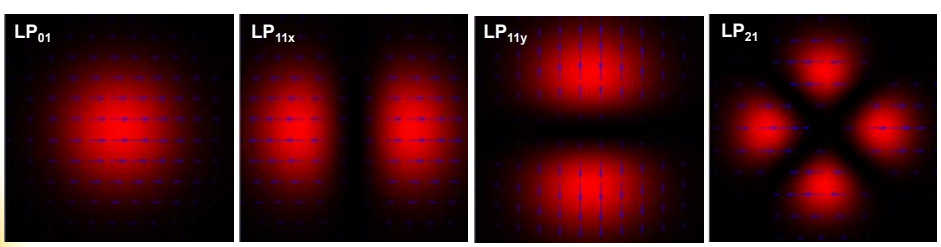




Linearly polarized (LP) Modes

Different eigenmodes travel at different speeds

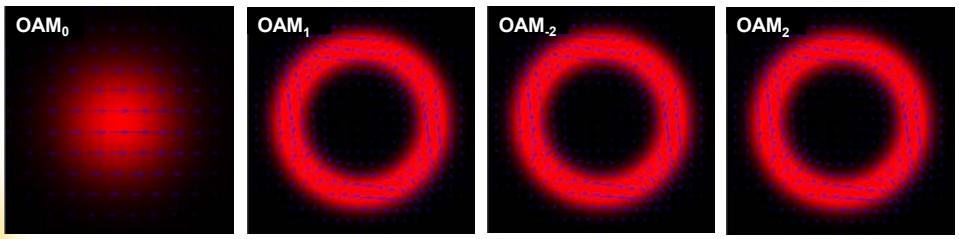
modal birefringence & crosstalk



β_1	β_2 , β_3	β_4 , β_3	β_5, β_6
HE_{11}	TE_{01} + HE_{21}	TM_{01} + HE_{21}	EH_{11} + HE_{31}

OAM Modes

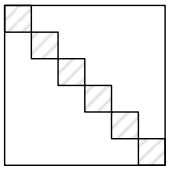
Eigenmodes combined differently for OAM …



β_1	β_3	β_5	β_6
HE_{11}	$HE_{21}^{even} + jHE_{21}^{odd}$	$EH_{11}^{even} + jEH_{11}^{odd}$	$HE_{31}^{even} + jHE_{31}^{odd}$
OAM(0)	OAM(1)	OAM(-2)	OAM(+2)

Avoid LP modes and favor OAM modes

Instead of group velocity, think of effective index for the mode



"Fence off" modes

Keep effective index separation high to avoid coupling in the fiber…

$\Delta n_{eff} > 10^{-4}$

n_{eff1}	n_{eff3}	n_{eff5}	n_{eff6}
HE_{11}	$HE_{21}^{even} + jHE_{21}^{odd}$	$EH_{11}^{even} + jEH_{11}^{odd}$	$HE_{31}^{even} + jHE_{31}^{odd}$
OAM(0)	OAM(1)	OAM(-2)	OAM(+2)

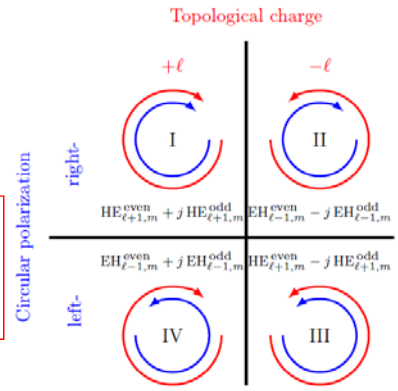
OAM Fiber Modes

$$\mathrm{OAM}^{\pm}_{\pm l,\mathrm{m}} = \mathrm{HE}^{\mathrm{even}}_{l+1,\mathrm{m}} \pm j\mathrm{HE}^{\mathrm{odd}}_{l+1,\mathrm{m}}$$

$$\mathrm{OAM}^{\mp}_{\pm l,\mathrm{m}} = \mathrm{EH}^{\mathrm{even}}_{l-1,\mathrm{m}} \pm j\mathrm{HE}^{\mathrm{odd}}_{l-1,\mathrm{m}}$$

HE vector modes ⇨ spin-orbit aligned

EH vector modes ⇨ spin-orbit anti-aligned



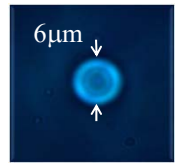
[2] C. Brunet, P. Vaity, Y. Messaddeq, S. LaRochelle and L. A. Rusch, *Design, fabrication and validation of an OAM fiber supporting 36 states*, *Opt. Express*, 2014, **22**, 26117-26127.

OAM fibers

- Index profile matches OAM mode field intensity profile (ring shaped)
- Vector modes with well separated effective indices
  - ⇒ avoid degeneracy into LP modes
  - (i.e. at least 10^{-4})
- Effective index separation ⇒ high refractive index contrast
  - (violates the weakly guiding approximation)

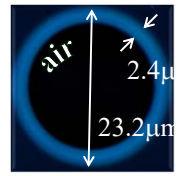
Ring core fibers for OAM at UL

- Inverse Parabolic Graded Index Fiber (IPGIF)
  - Smooth gradient profile
  - Gradient varied to achieve modal separation



IPGIF

- Hollow core fiber
  - Hollow core to maximize index contrast
  - Probe maximum number of modes



Hollow core

- Ring core fiber
  - Analytical tools for designing step index OAM fiber

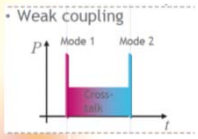
Ring core

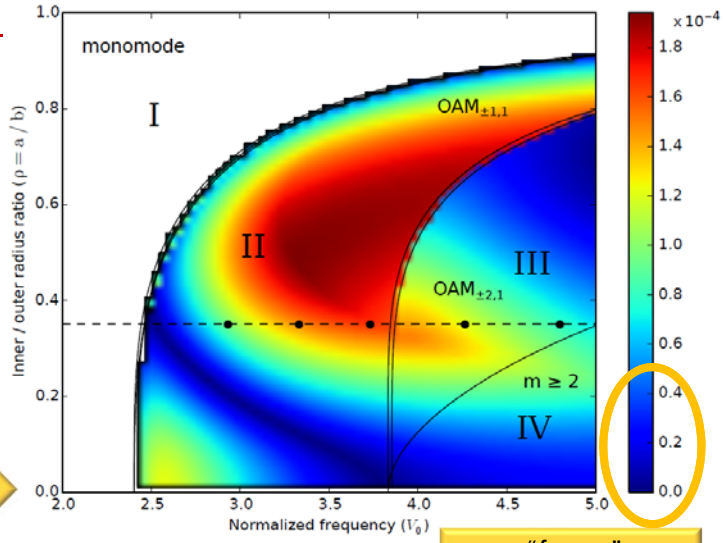
UL COPL Centre d'optique, photonique et laser

39

Predicting Δn_{eff}

more red,
lower pedestal





SCF fiber ρ→0

Ring core

no "fence" ⇒ vector modes mix to form LP

PL
a d'optique,
onique et laser

40

OAM Fiber Mode Purity

Assumption:

$$HE^{even}_{l+1,m} + jHE^{odd}_{l+1,m} \longrightarrow \circlearrowright \quad \textbf{RCP} \quad l$$

$$HE^{even}_{l+1,m} - jHE^{odd}_{l+1,m} \longrightarrow \circlearrowleft \quad \textbf{LCP} \quad l$$

In reality:

$$HE^{even}_{l+1,m} + jHE^{odd}_{l+1,m} \xrightarrow{} \circlearrowright \quad \textbf{RCP} \quad l \longrightarrow \text{most of the power}$$

and

$$\xrightarrow{} \circlearrowleft \quad \textbf{LCP} \quad l+2 \longrightarrow \text{crosstalk}$$

L. Wang, A. Corsi, L. A. Rusch, and S. LaRochelle, "Investigation of Orbital Angular Momentum Mode Purity in Air-Core Optical Fibers," in *IEEE Photonics Society Summer Topicals, Newport Beach, USA, p. We1.3, 2016.*

41

Why do we call it OAM?

- Electromagnetic radiation carries both energy and momentum
- The momentum may have both linear and angular contributions
- Angular momentum has a spin part associated with polarization and an orbital part associated with spatial distribution

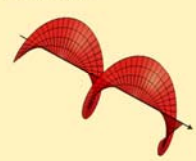
Spin Angular Momentum

The *polarization vector* of electric field rotates around the beam axis.

- Associated with the photon spin
- Is manifest as circular polarization

Orbital Angular Momentum

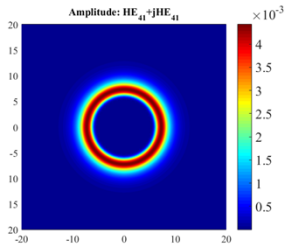
The *phase structure* of the beam of light rotates around the beam axis.



- Associated with spatial distribution

42

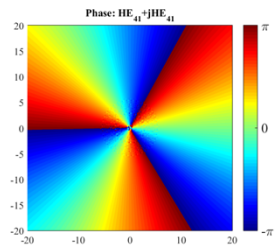
OAM Fiber Mode Purity



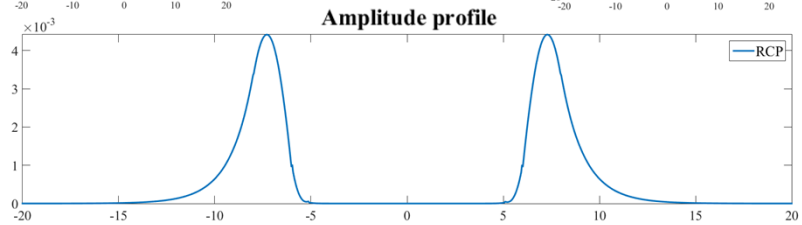
$s = 1 \quad l = +3$

$s + l = 4$

$HE_{4,1}^{even} + jHE_{4,1}^{odd}$



Amplitude profile

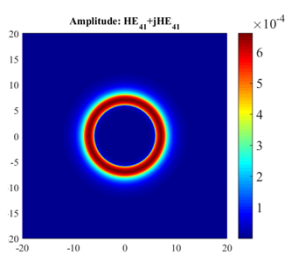


Hollow core

$R_a = 6\ \mu m;\ R_b = 8\ \mu m$

43

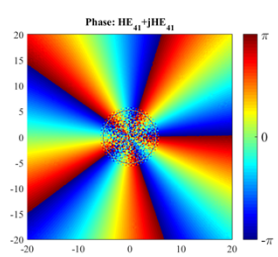
OAM Fiber Mode Purity



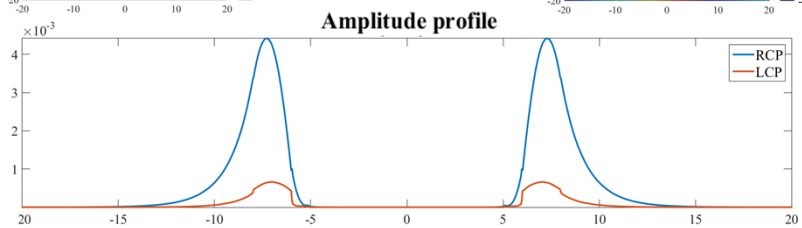
$s = -1 \quad l = +5$

$s + l = 4$

$HE_{4,1}^{even} + jHE_{4,1}^{odd}$



Amplitude profile



Hollow core

$R_a = 6\ \mu m;\ R_b = 8\ \mu m$

44

Particularities in working with OAM

- High contrast required
  - cost is added fabrication difficulty
  - improvement in working with air core probably not justified …
- Mode order
  - stability increases with mode order
  - purity and effective index separation varies with mode order
- Lack of components
  - couplers and multiplexers still subject of research
  - for now, assume single intensity core desirable
  - for now, assume circular polarization desirable
- Design criteria needs to evolve
  - how do we devise a system centric approach to designing better fibers?

UL COPL Centre d'optique, photonique et laser

45

Outline

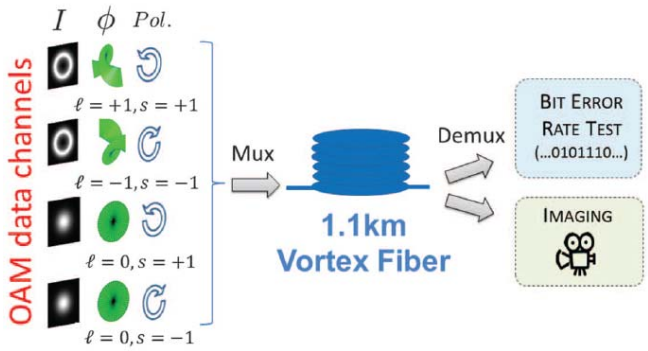
- Motivation for study of vector modes
  - Contrast scalar mode solutions
  - Focus on impact on receiver and network architectures
- Vector modes example
  - Orbital angular momentum modes
  - Description & reason they are of interest
- Fiber designs & challenges
- Review of some experimental demonstration
- Conclusion

UL COPL Centre d'optique, photonique et laser

46

First proof of concept

- Optical control of polarization
- Mode separation facilitated by this control
- No MIMO processing required



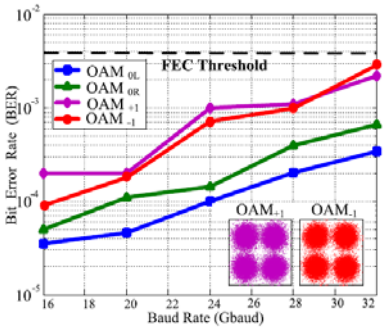
N. Bozinovic, et al., "Terabit-Scale Orbital Angular Momentum Mode Division Multiplexing in Fibers," *Science*, vol. 340, pp. 1545-1548, June 28, 2013.

47

Electronic polarization demultiplexing

- Single port reception
- 1.4 km transmission
- Standard 2×2 MIMO
- No polarization tuning

Ring core



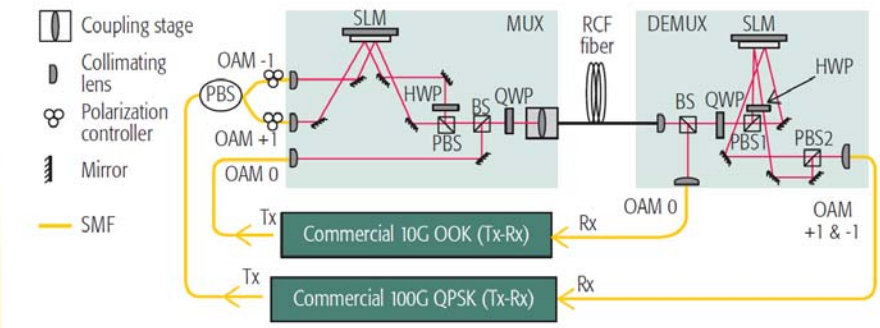
R. Mirzaei Nejad, et al., "Mode Division Multiplexing using Orbital Angular Momentum Modes over 1.4 km Ring Core Fiber," *IEEE/OSA Journal of Lightwave Technology*, vol. 34, pp. 4252-4258, 15 Sep 2016.

48

Commercial Receivers & OAM Fiber

- Heterogeneous transmission (OOK/QPSK)
- OAM states separated by commercial 2x2 MIMO

Ring core

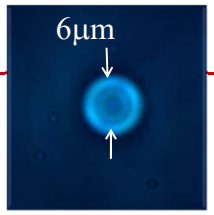


L. A. Rusch, M. M. Rad, K. Allahverdyan, I. Fazal, and E. Bernier, "Carrying data on the orbital angular momentum of light," *IEEE Communications Magazine*, vol. 56, pp. 219 - 224, February 2018.

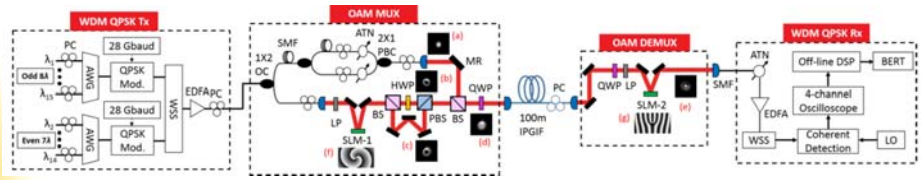
49

Second order OAM

- OAM2 in IPGIF fiber



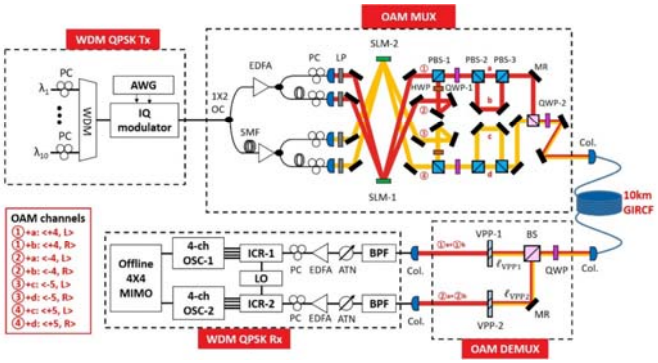
IPGIF



J. Zhu, et al., "3.36-Tbit/s OAM and Wavelength Multiplexed Transmission over an Inverse-Parabolic Graded Index Fiber," in CLEO 2017, San Jose, p. SW4I.3, May 2017.

50

Higher order OAM



4×4 MIMO over one OAM |order|

8 channels
OAM |4|
OAM |5|

G. Zhu, et al., "Scalable mode division multiplexed transmission over a 10-km ring-core fiber using high-order orbital angular momentum modes," *Optics Express*, vol. 26, pp. 594-604, 2018/01/22.

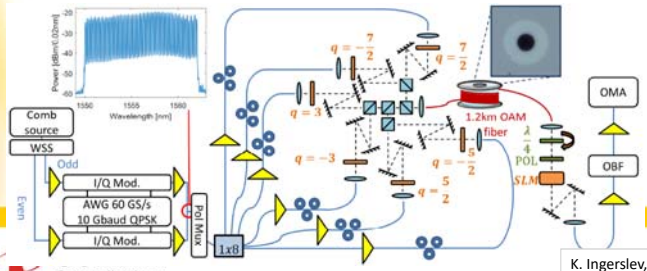
Higher order OAM

no MIMO; but mode groups, ¼ of channels exploited

L. Zhu, et al., "18 km low-crosstalk OAM+WDM transmission with 224 individual channels enabled by a ring-core fiber with large high-order mode group separation," *Optics Letters*, vol. 43, pp. 1890-1893, 2018/04/15.

Higher order OAM

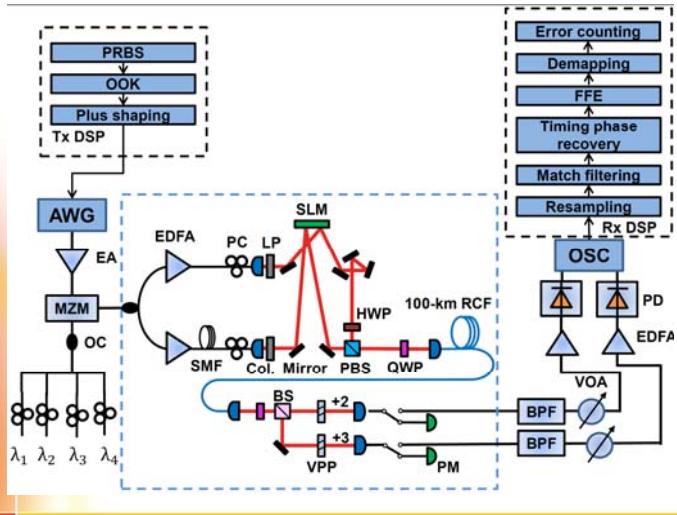
optical pre-MIMO; stability once modes adjusted for TX



12 channels
OAM |5|
OAM |6|
OAM |7|

K. Ingerslev, et al., "12 mode, WDM, MIMO-free orbital angular momentum transmission," Opt. Express 26, 20225-20232 (2018).

Longest distance



optical pre-MIMO

2 channels
OAM |2|
OAM |3|

Shen, et al., "MIMO-Free WDM-MDM Transmission Over 100-Km Single-Span Ring-Core Fibre," in ECOC 2019, Dublin, W.2.A.4.

Conclusion

- A systems perspective motivates MIMO free (or 2×2 MIMO) mode multiplexing
- High contrast fibers violating the weakly guiding principle are required
- Vector modes (such as orbital angular momentum modes) can be exploited
- Optimizing of fibers is challenging
  - Effective index separation
  - Modal purity issues with OAM
  - New optimization methods needed
- Experimental demonstrations are tantalizing, but more work is needed

UL COPL Centre d'optique, photonique et laser