Orbital Angular Momentum (OAM) based Mode Division Multiplexing (MDM) over a km-length Fiber

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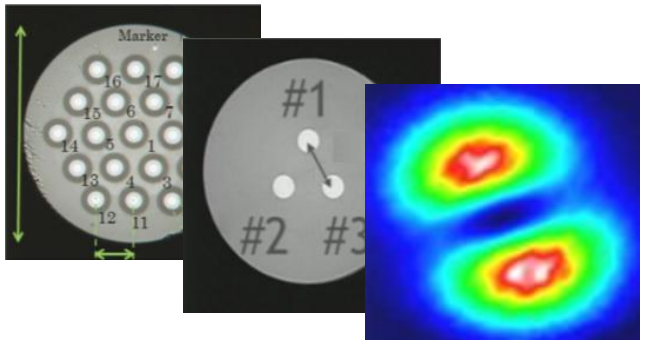
ECOC, September 20th 2012

OAM multiplexing

- Space division multiplexing (SDM)
  - Multi-core (Y. Sakaguchi et al., Proc. OFC, PDP5C.1, 2012)
  - Few-core (R. Ryf et al., Proc. OFC, PDP5C.2, 2012).
  - Few-mode (L. Gruner-Nielsen et al., Proc. OFC, PDP5A.1 2012).
  - Orbital angular momentum (OAM) approach



Free-space

$$u_{lm}(\rho, \phi, z = 0) \propto F(\rho)e^{il\phi}$$

Allan et al, Phys. *Rev. A, vol. 45, p. 8185, 1992.*

Fiber

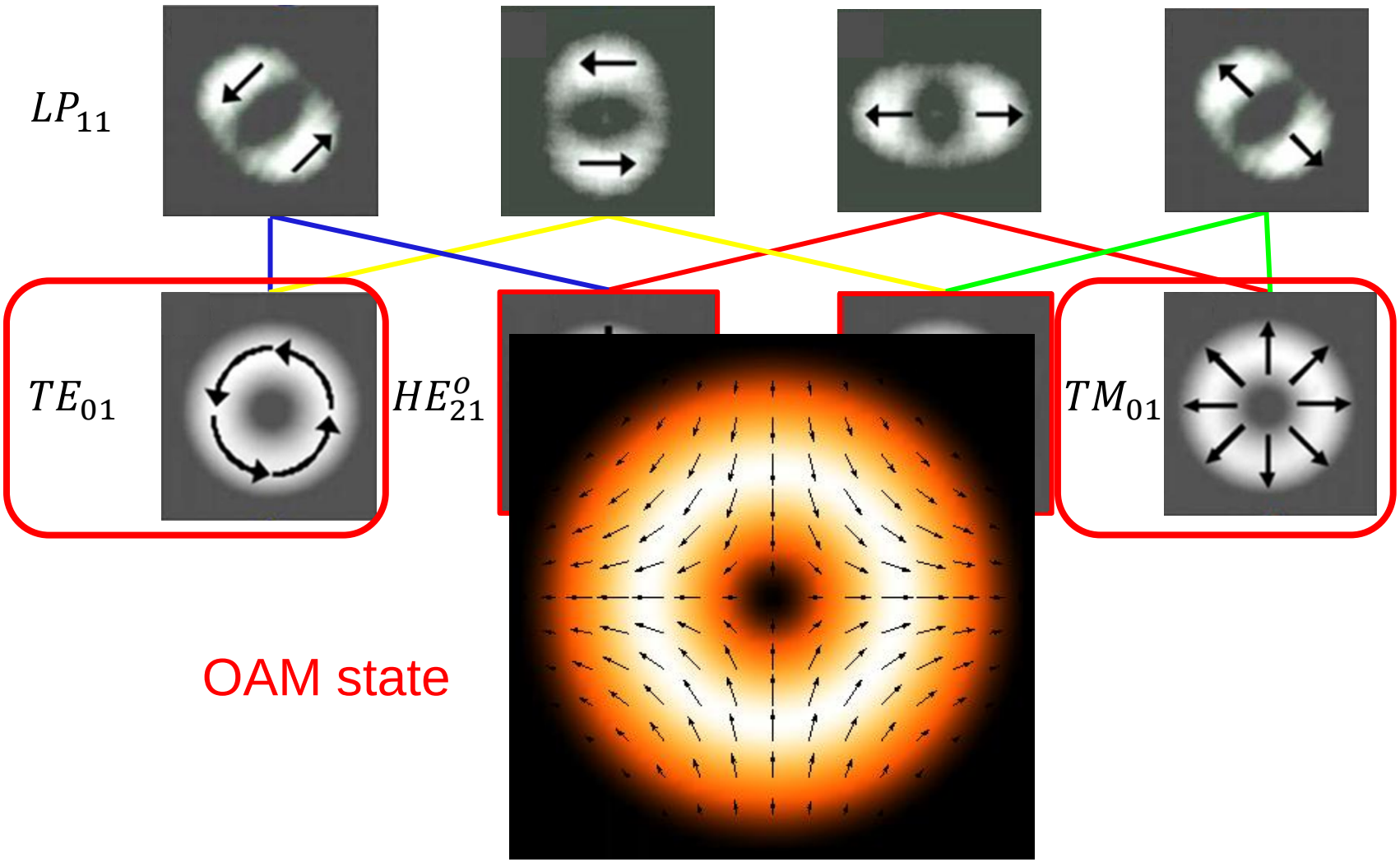
Can we apply OAM multiplexing concept in a fiber?

Potential advantages:

- Easier MUX/DEMUX
- Low mode coupling ⇨ ⇨ low complexity MIMO

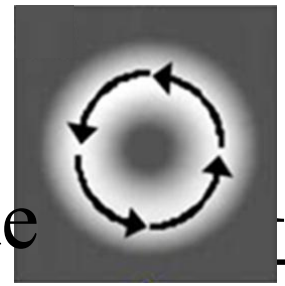
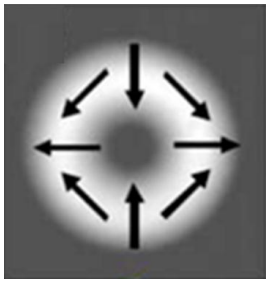
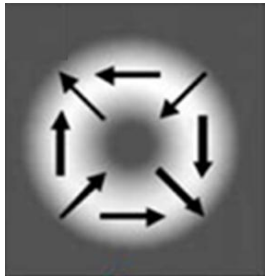
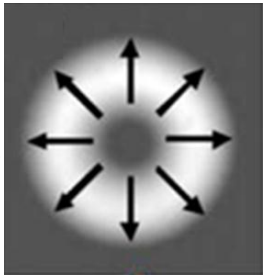
G. Berkhout et al, *PRL*, v. 105, p. 8, 2010.
P. Bierdz et al, Proc. CLEO, JTu3K, 2012.
T. Su *et al, OE*, v. 20, p. 9396, 2012

Modes of a step index fiber



S. Ramachandran et al. *Optics Letters, vol.* 34, p. 2525, 2009

Mode coupling

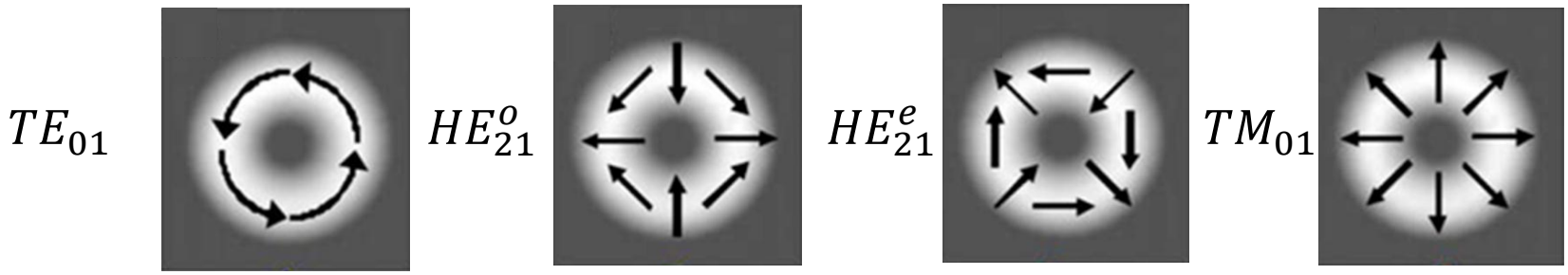
TE_{01}  HE_{21}^{o}  HE_{21}^{e}  TM_{01} 

Mode coupling

Δn_{eff}

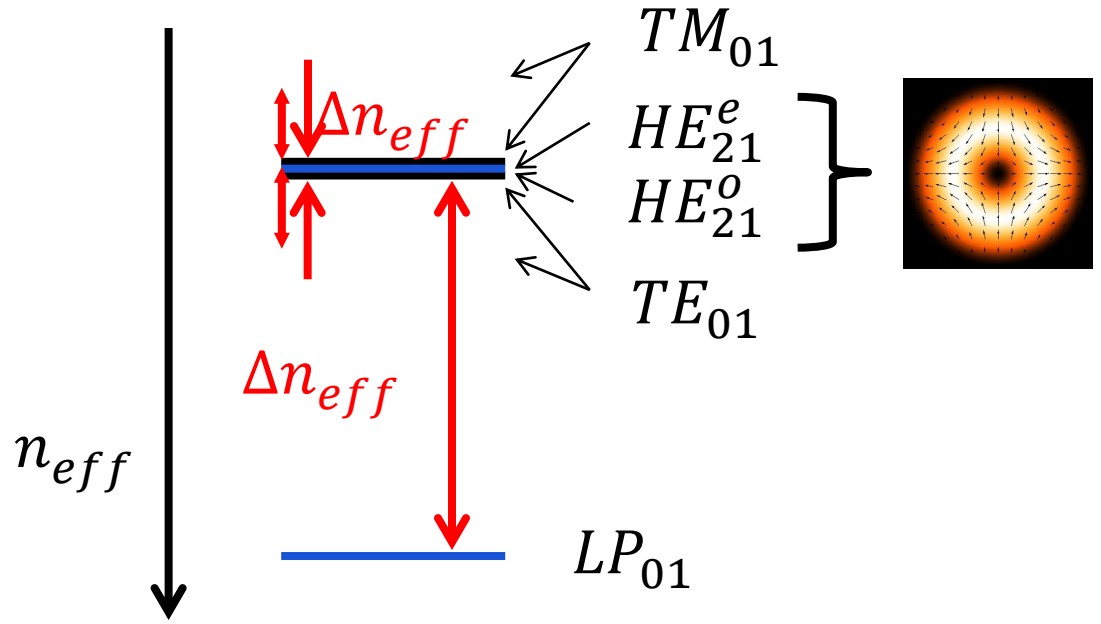
R. Olshansky, Applied Optics, vol. 14, no. 4, 1975.

Mode coupling



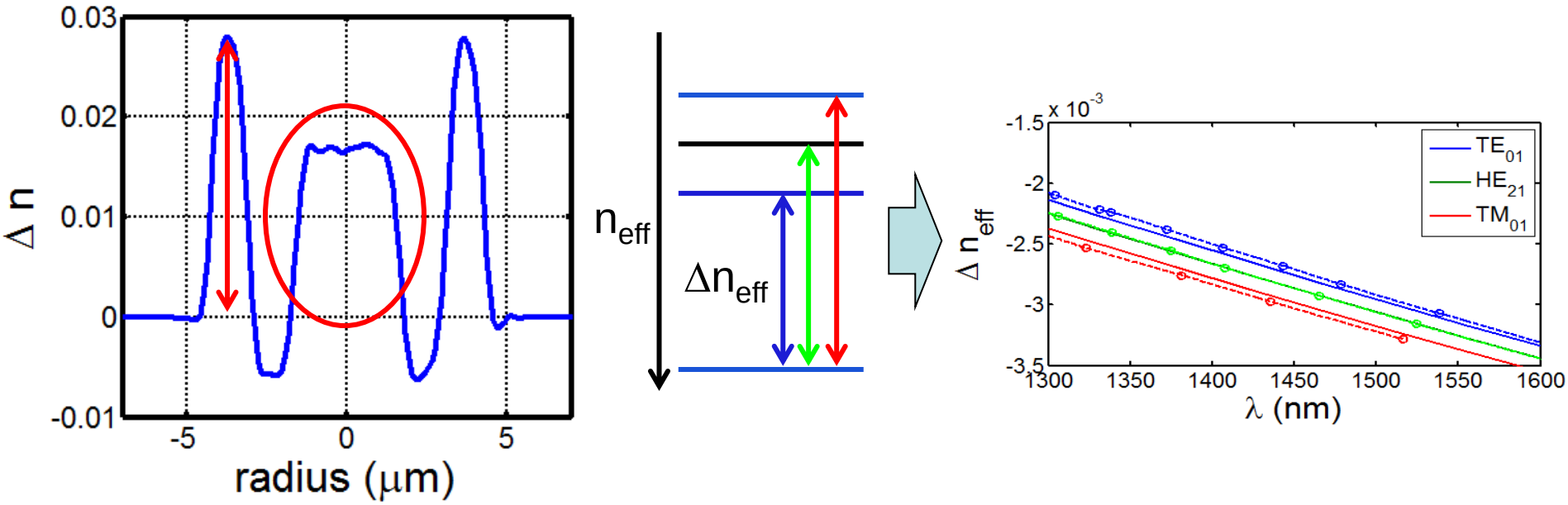
Step index multimode fiber

$$\text{Mode coupling} \sim \frac{1}{\Delta n_{eff}}$$



R. Olshansky, Applied Optics, vol. 14, no. 4, 1975.

Vortex fiber

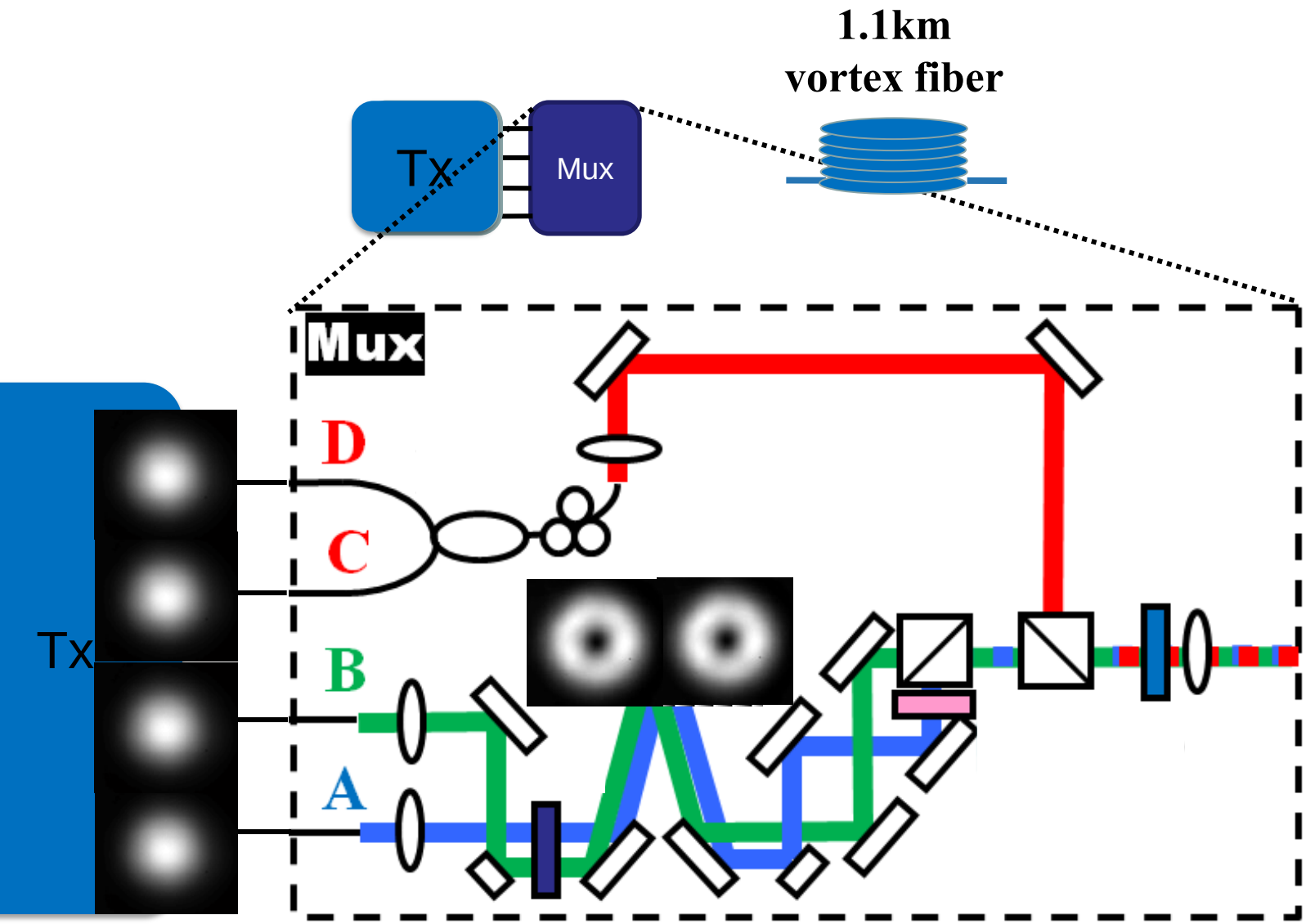


Vortex fiber properties @1550nm

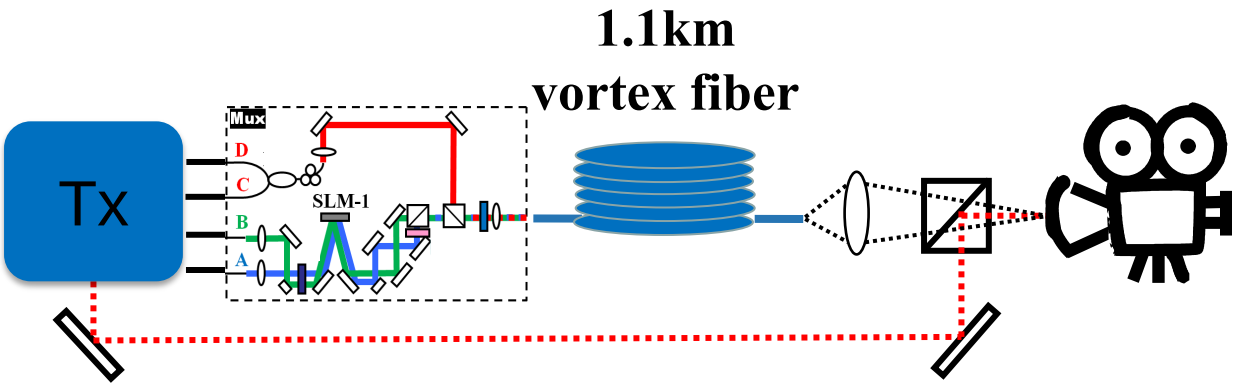
	n_{eff}	A_{eff} (μm^2)	D (ps/nm-km)	Loss (dB/km) (exp.)
LP_{01}	1.451	82	2.0	1.3
OAM	1.448	88	0.6	1.6

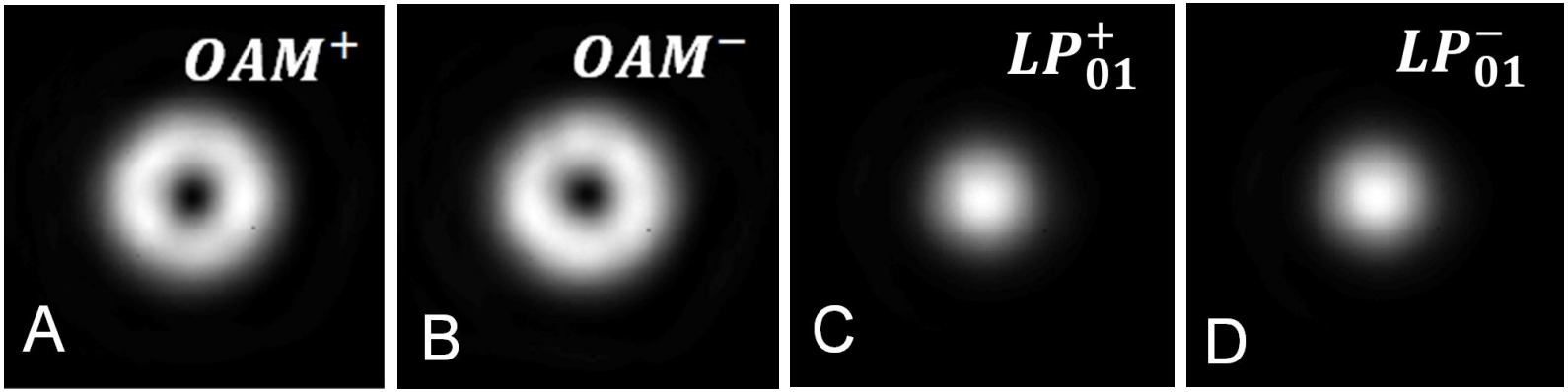
S. Ramachandran et al. *Optics Letters, vol.* 34, p. 2525, 2009

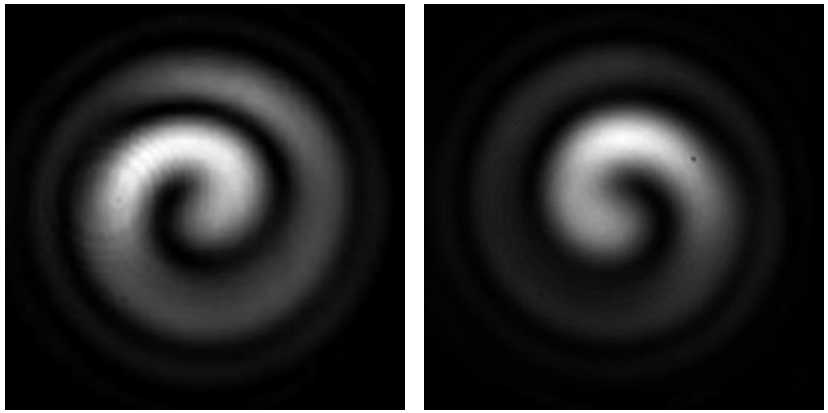
Mode conversion and Mux



Imaging



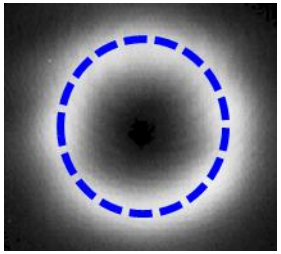




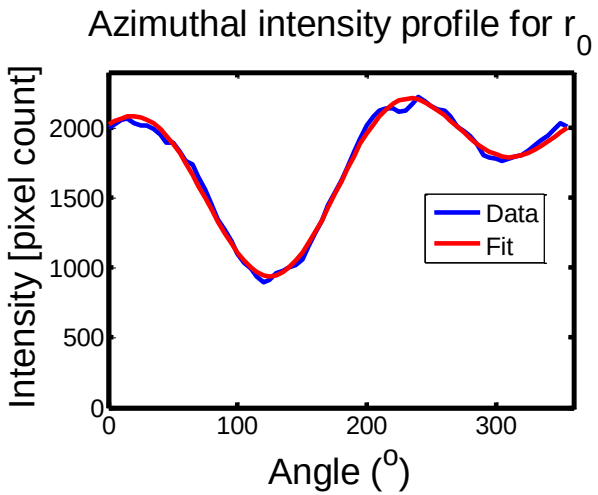
$\ell = 0$
$s = +1$

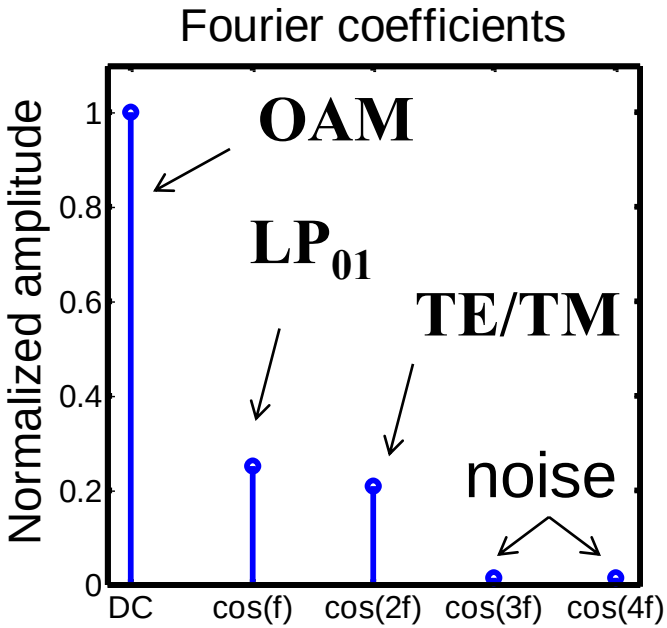
$\ell = 0$
$s = -1$

Mode purity



Source: ECL
$\Delta\nu$ = 100kHz)





Cross-talk (dB)

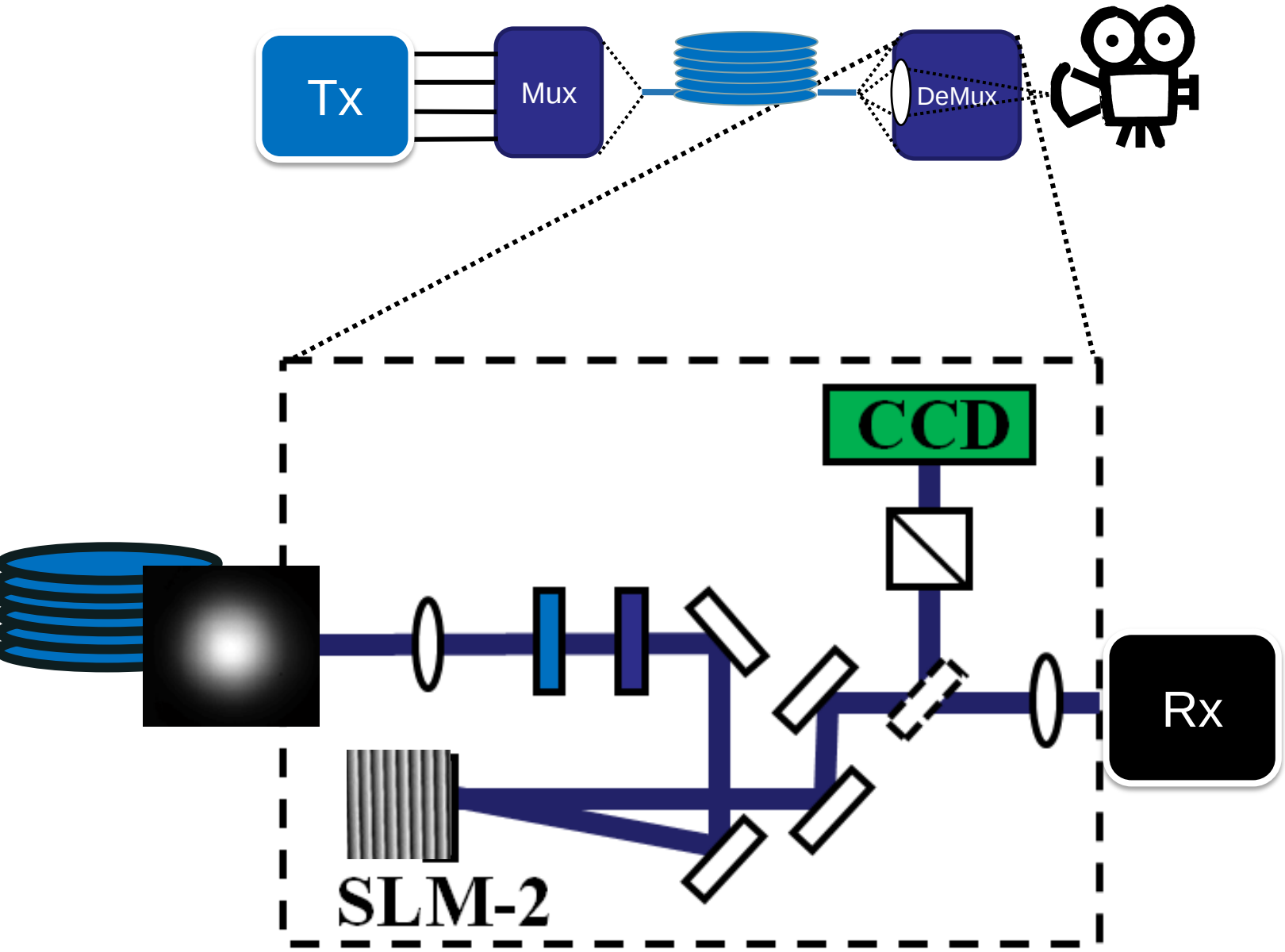
Fiber length	TE+TM	LP_{01}
6m	<-20.8	<-21.4
1.1km Within 1h	Min = -13.6 Max = -8.9	Min = -23.7 Max = -18.5

Due to Mux

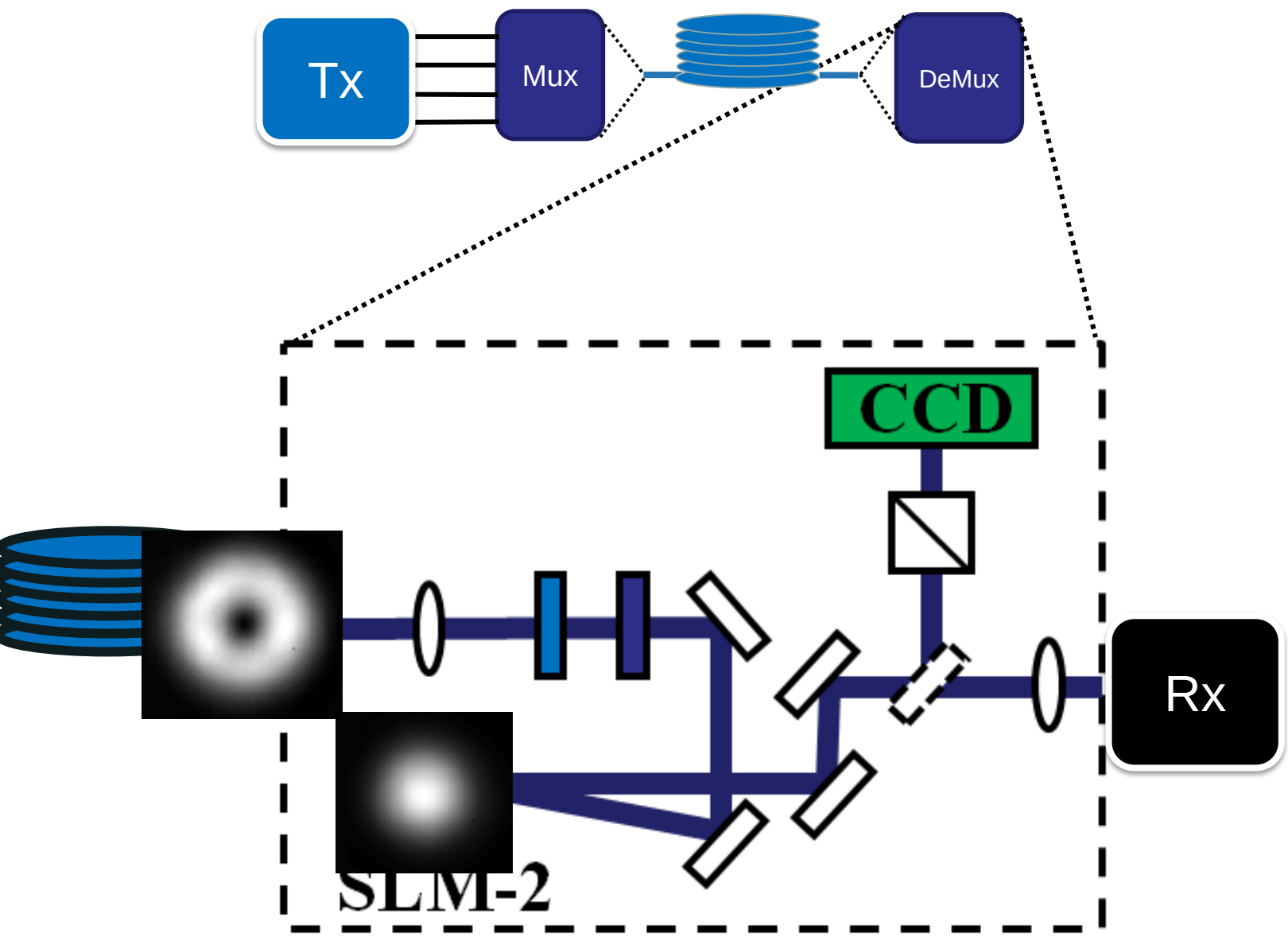
Due to Mux + propagation

N. Bozinovic et al. *Optics Letters*, vol. 37, p. 2451, 2012.

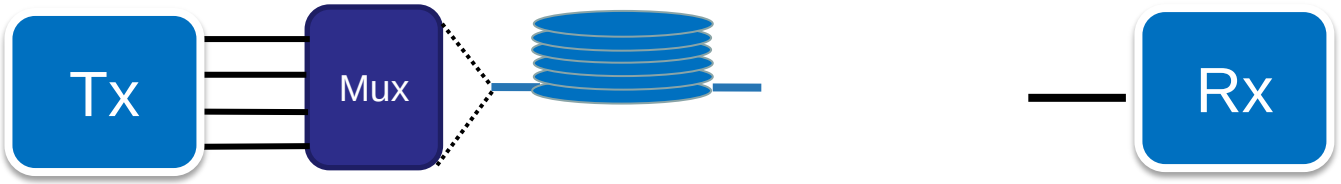
Demux



Demux



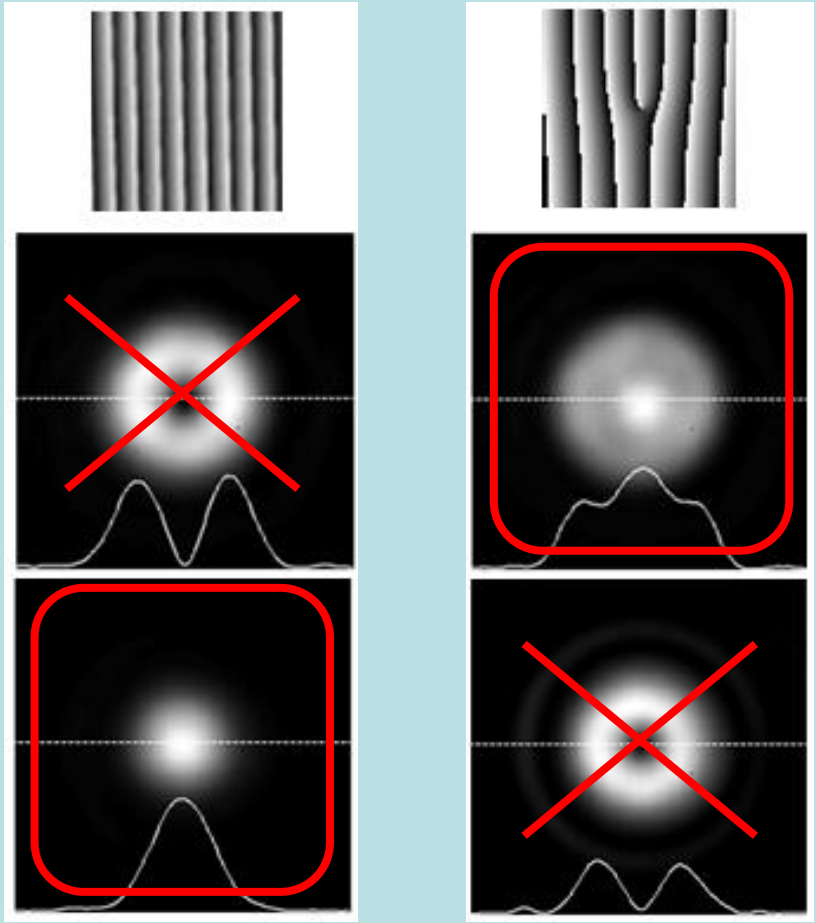
Demux



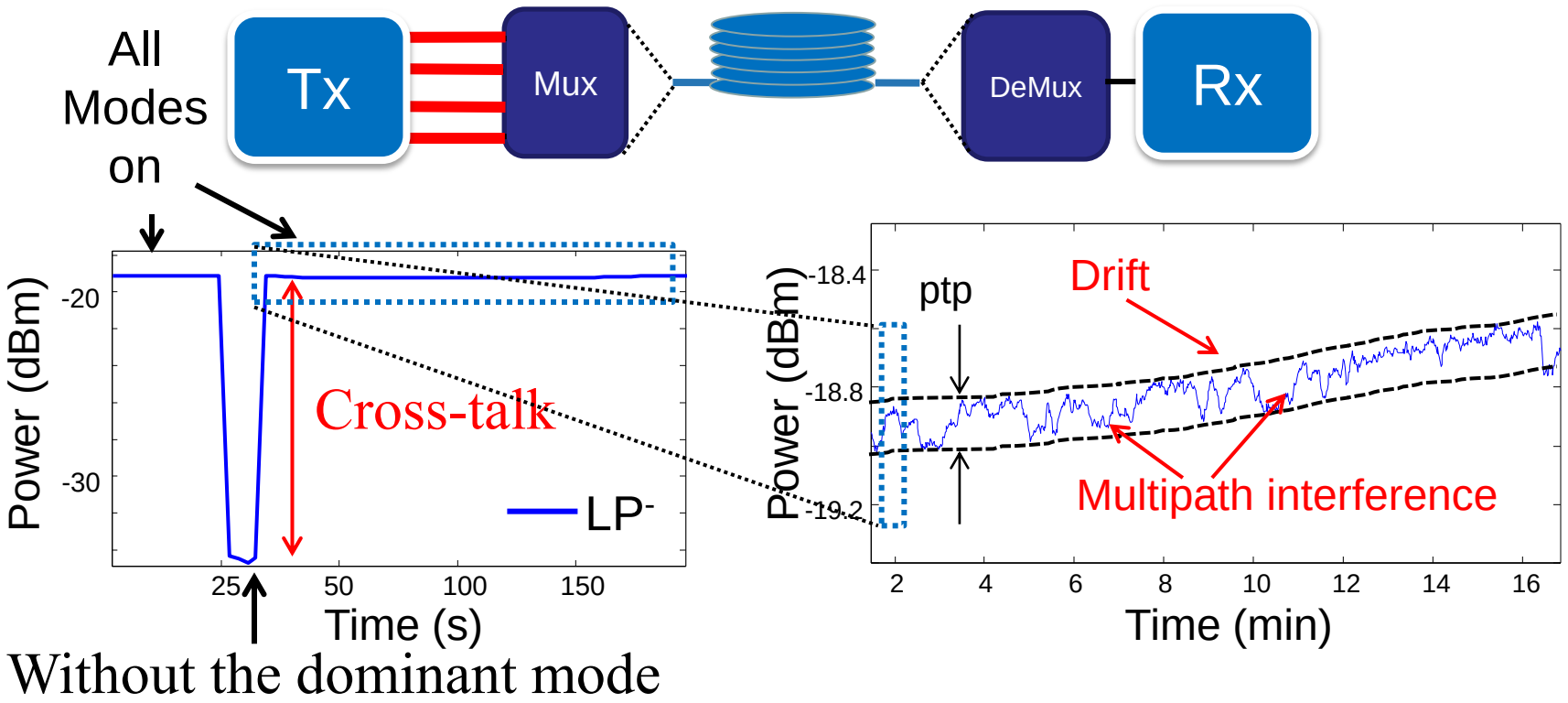
SLM pattern

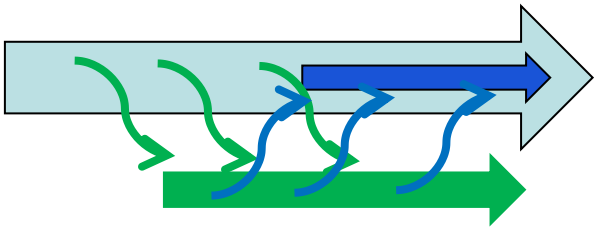
OAM mode

LP_{01} mode



Cross-talk and multipath interference (MPI)

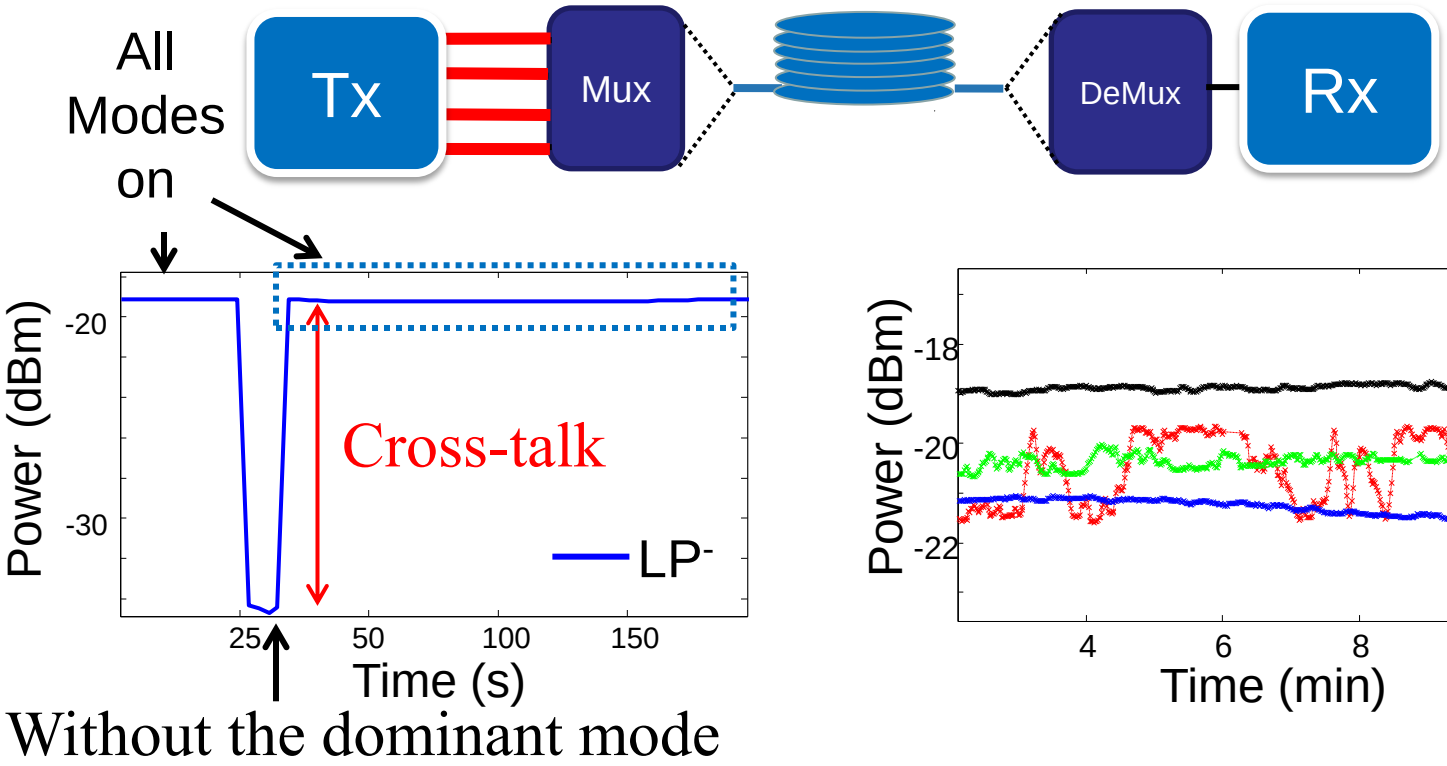




$$MPI = 20\log_{10}\left(\frac{10^{ptp/20}-1}{10^{ptp/20}+1}\right)$$

Ramachandran et al, IEEE Pho. Tech. Lett., vol. 15, p. 1171, 2003

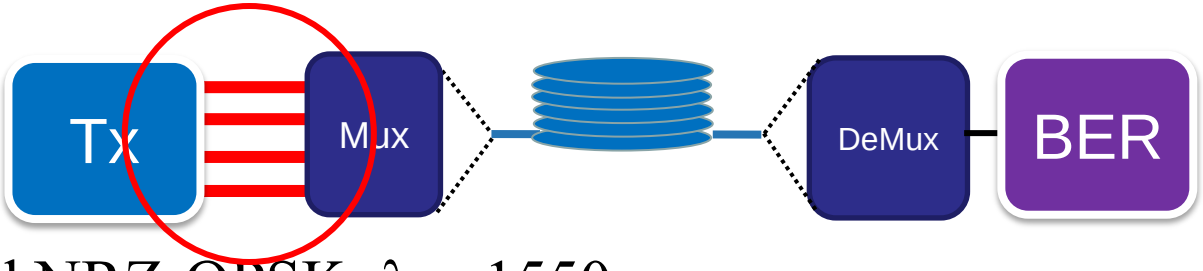
Cross-talk and multipath interference (MPI)



	OAM^{+}	OAM^{-}	LP_{01}^{+}	LP_{01}^{-}
Cross-talk (dB)	**-14.8**	**-15.5**	**-16.1**	**-15.2**
MPI (dB)	**-19.7**	**-30.2**	**-32.1**	**-35.3**

Due to Mux + Propagation + Demux

Data transmission

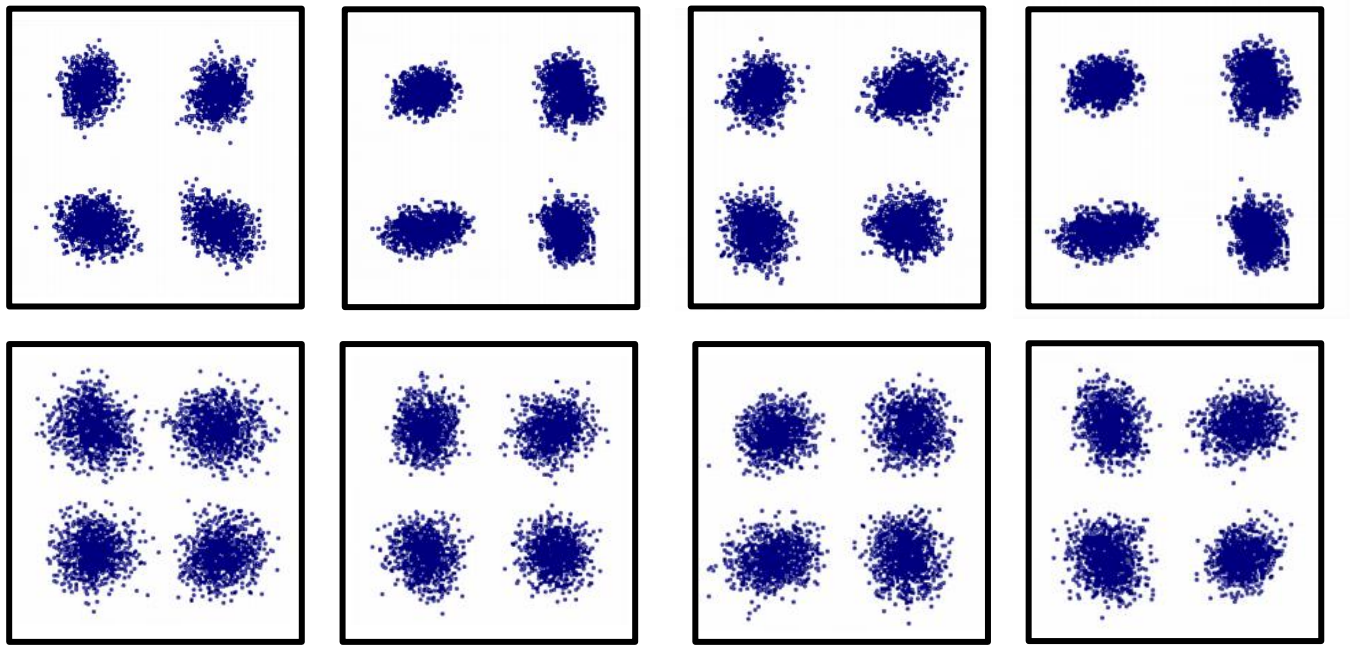


50Gbaud NRZ-QPSK, $\lambda = 1550nm$

Single-mode case

B2B

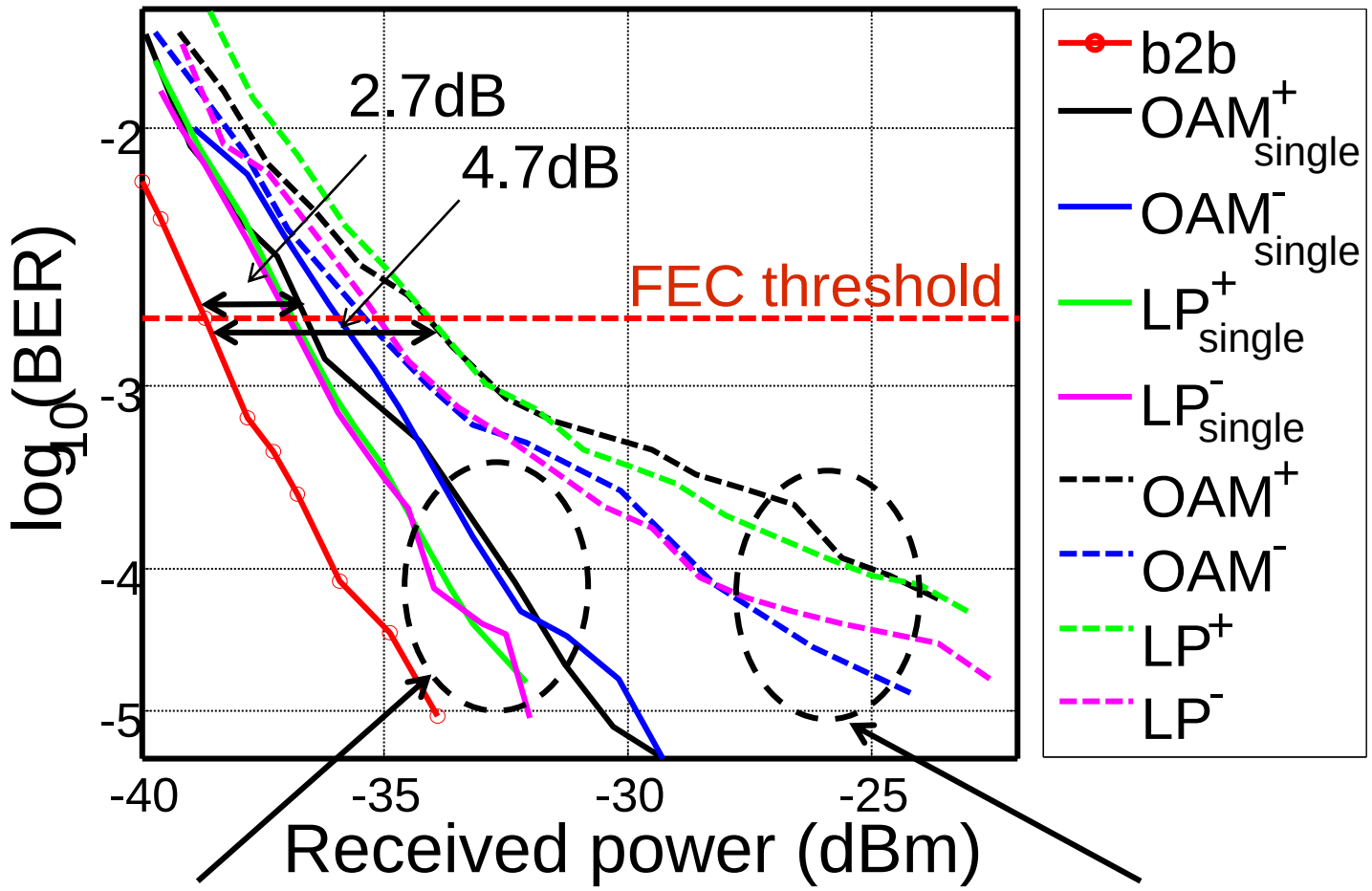
All-mode case



BER curves

Single-mode case

All-mode case

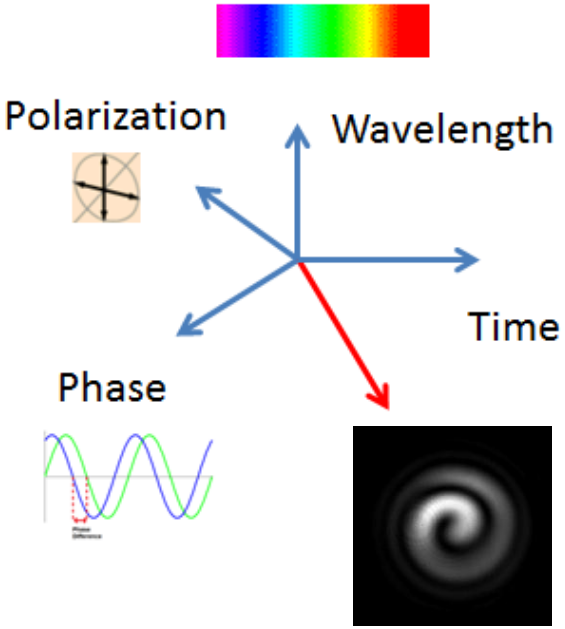


Due to MPI

Due to cross-talk

Summary

- Successfully MUXed/DEMUXed multiple OAM states into a fiber
  - <-20.8dB coupling cross-talk.
- Propagated OAM states over 1.1-km using vortex fiber
  - crosstalk <-14.8dB
  - multipath interference <-19.7dB
- Transmitted 50Gbaud QPSK data, at a single wavelength 1550nm, below FEC threshold, without using MIMO - total of 400Gb/s.



Thank you