WELCOME

ECOC 2011 WORKSHOP

Space-Division Multiplexed Transmission in Strongly Coupled Few-Mode and Multi-Core Fibers

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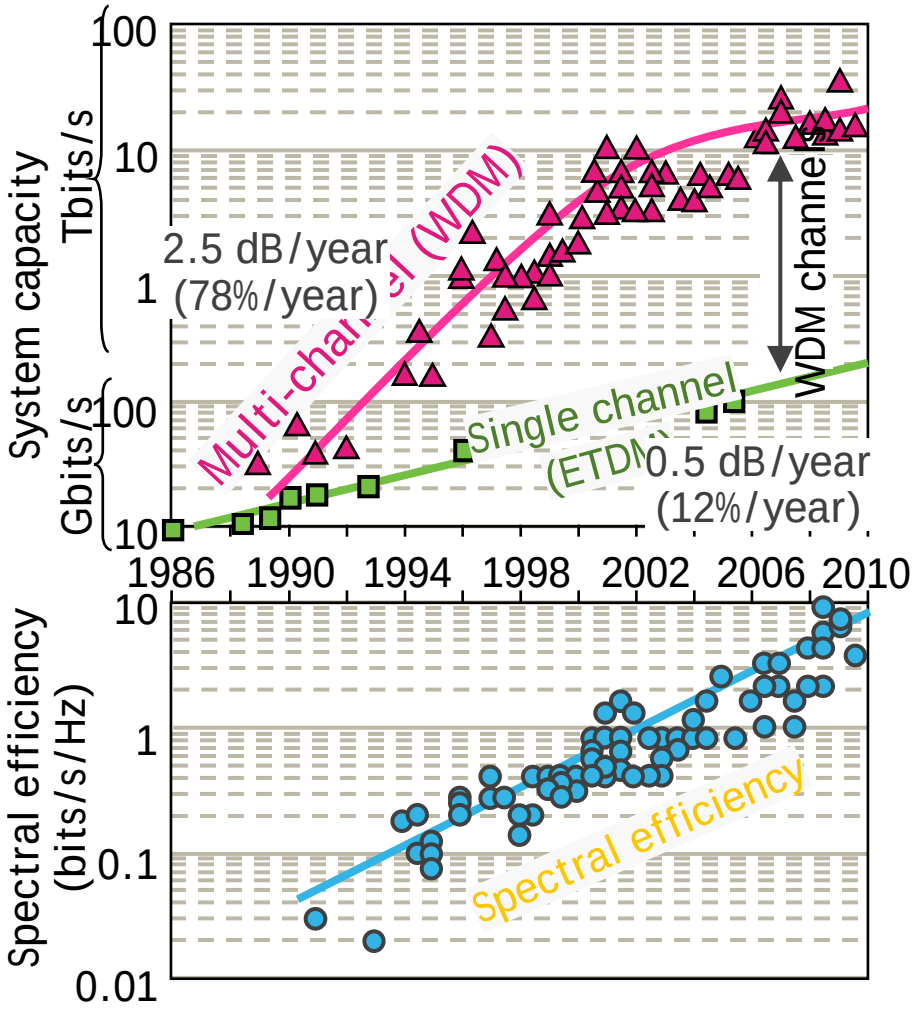
Alcatel·Lucent

CONTENTS

CAPACITY CRUNCH IN OPTICAL COMMUNICATION AND SPACE DIVISION MULTIPLEXING (SDM)

- Capacity of a single mode fiber is approaching the theoretical limit
- SDM by system duplication has an unfavorable cost structure
- SDM over a single fiber is the solution



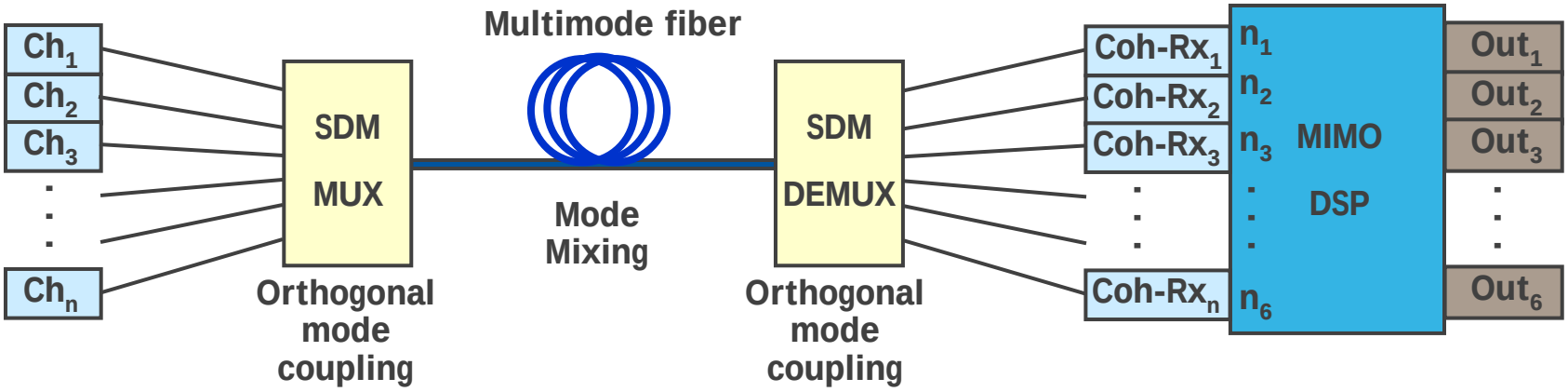
Essiambre et. al., JLT, v. 28, 2010.

SDM OVER A SINGLE FIBER
CROSSTALK FRIEND OR FOE?

- When multiple spatial path are introduced in an optical fiber crosstalk between the different paths is unavoidable. At the system level additional crosstalk is introduced by optical elements like couplers and switches
- Fundamentally two solutions are possible:

LOW CROSSTALK FIBER	ELECTRONIC CROSSTALK SUPRESSION
Advantages • Simple system design • Simple couplers **Drawbacks** • Limited number of spatial paths	**Advantages** • Large number of modes • Shared pump for optical amplification **Drawbacks** • Added complexity of the electronic crosstalk suppression • Low modal differential group delay required • Complex mode couplers required

COHERENT MIMO BASED TRANSMISSION AND ELECTRONIC CROSSTALK SUPRESSION

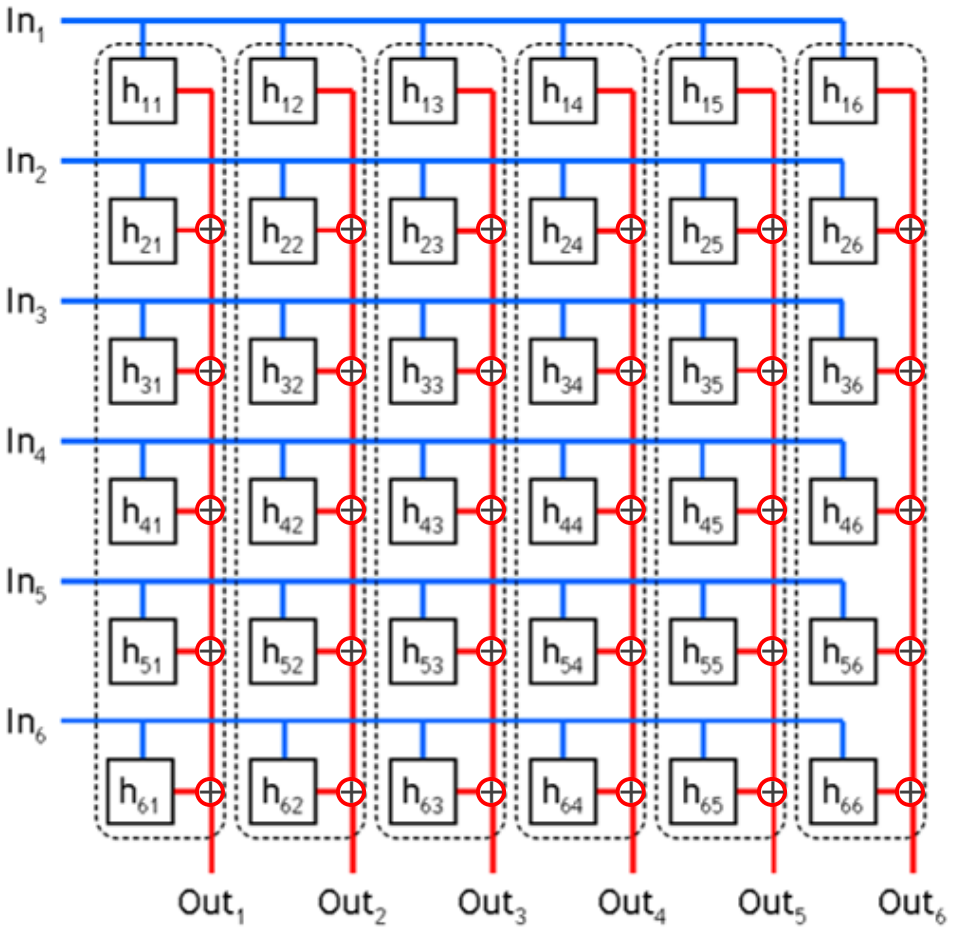


PD: Polarization Diversity

- All guided modes of the fiber are selectively launched
- Modes are strongly coupled during propagation in the fiber
- All guided modes are simultaneously detected with coherent receivers
- Digital signal processing decouples the received signals to recover the transmitted signal

COHERENT MIMO DIGITAL SIGNAL PROCESSING
SPACE DIVISION MULTIPLEXING IS THE SOLUTION

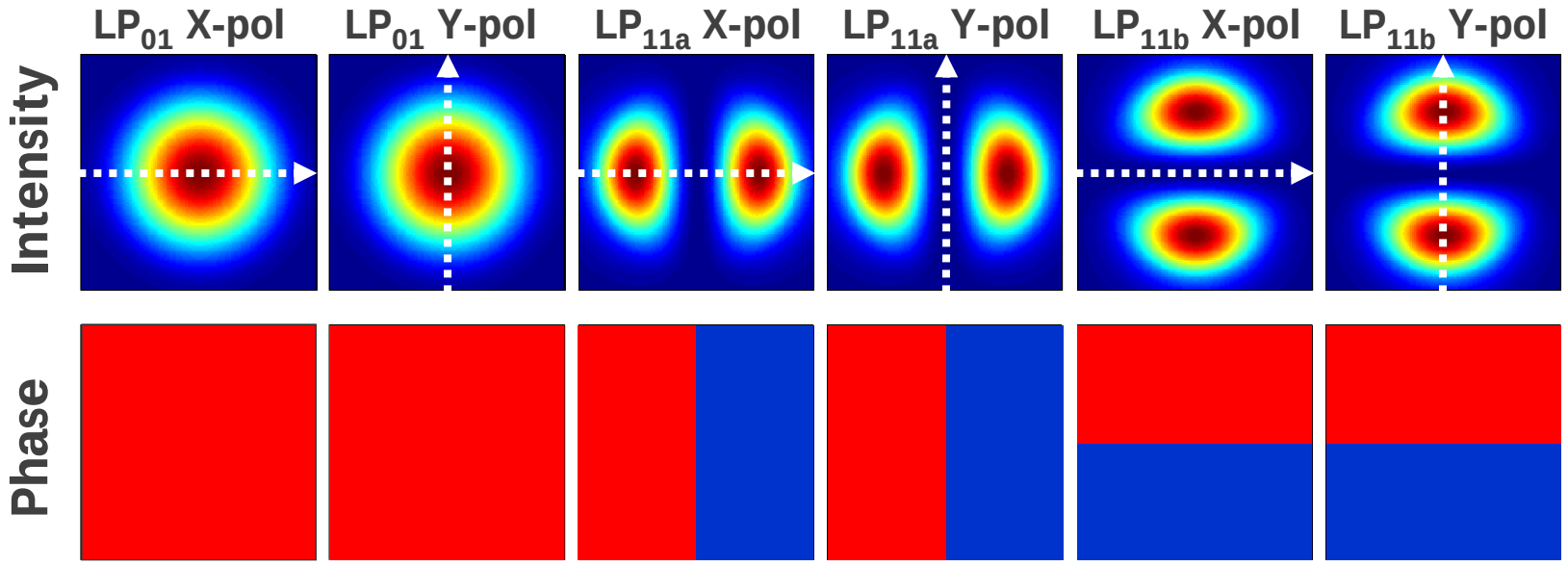
- The multiple-input multiple output (MIMO) digital signal processing (DSP) can be implemented by a Network of *n* x *n* feed-forward equalizers (FFEs)
- Number of taps *L* required depend on modal differential group delay (DGD)
- Numerous algorithm are available to determine the equalizer coefficients h_{ij}



Randel et. al., Opt. Exp., V. 19, N. 17, 2011

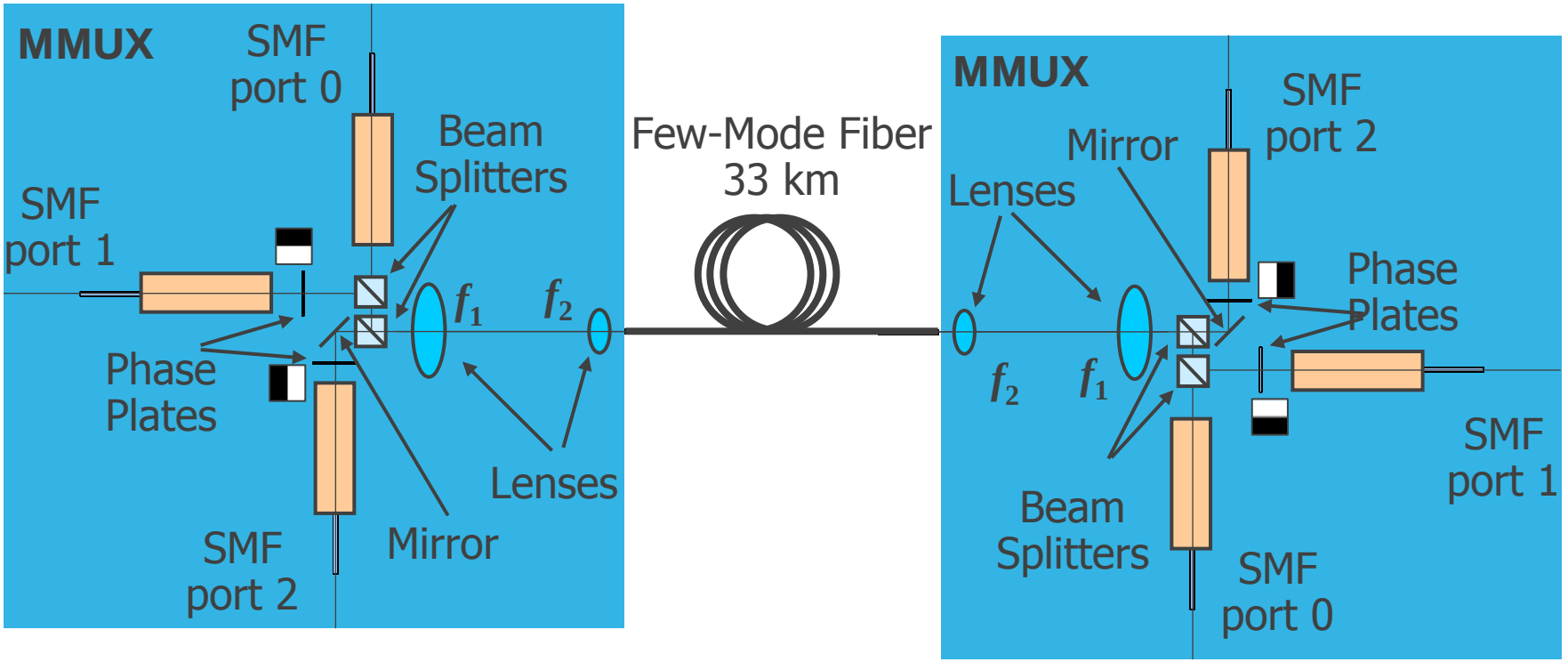
MODES IN A 6-MODE FEW-MODE FIBER (FMF)
THE LINEAR POLARIZED (LP) MODES

- Design: Depressed cladding index profile with V ≈ 5 at 1550 nm
- DGD (between LP_{01} and LP_{11} across C-band): <60 ps/km
- Loss: 0.205 dB/km, dispersion 20 ps/nm/km
- Effective Areas: 155 μm² for LP_{01} and 159 μm² for LP_{11}



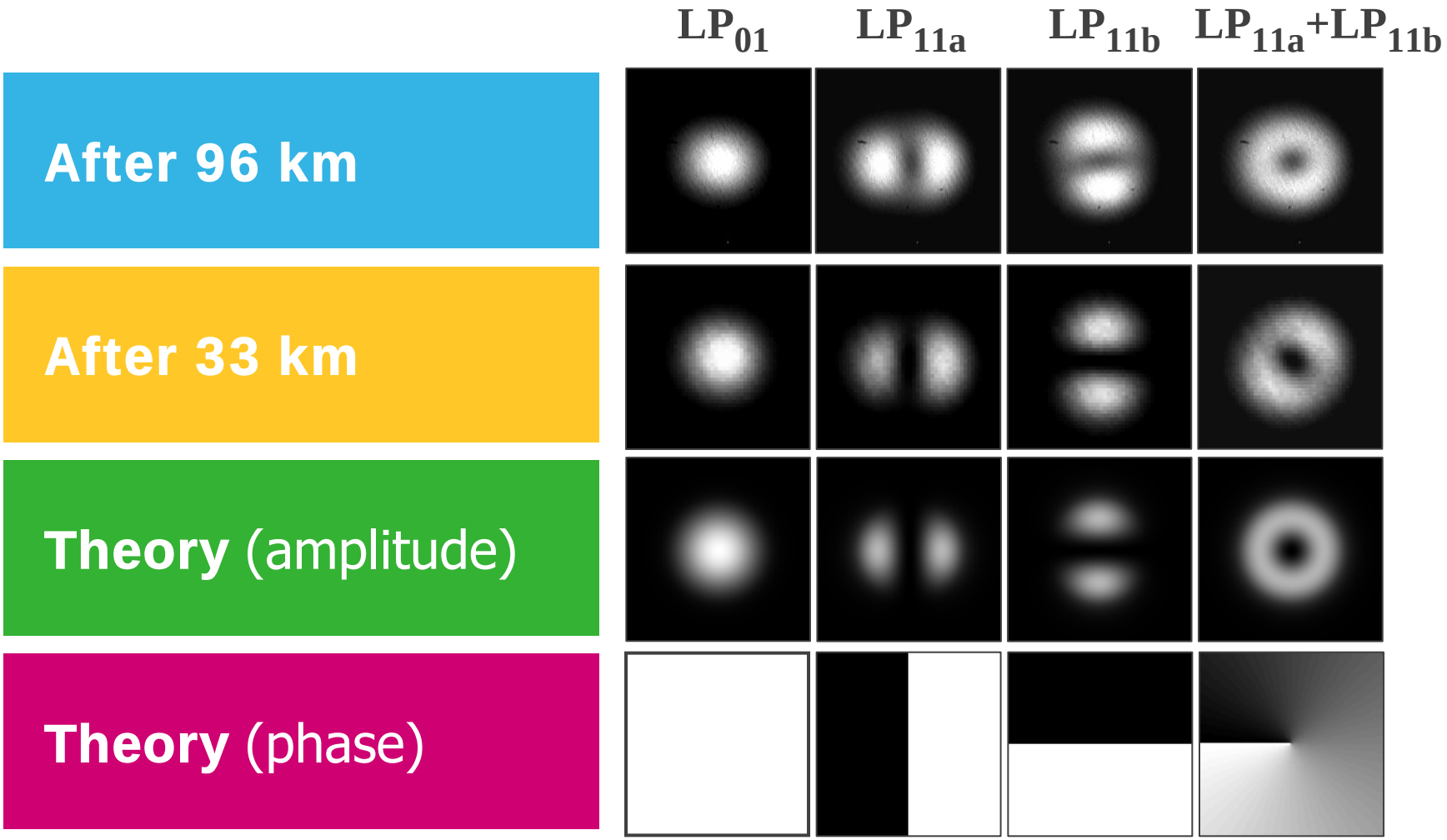
MODE MULTIPLEXER FOR FEW MODE FIBER
BASED ON PHASE PLATES

- Coupler loss: 8.3 dB / 9.0 dB / 10.6 dB for LP_{01} / LP_{11a} / LP_{11b} resp.
- Crosstalk rejection for MMUX pair > 28 dB



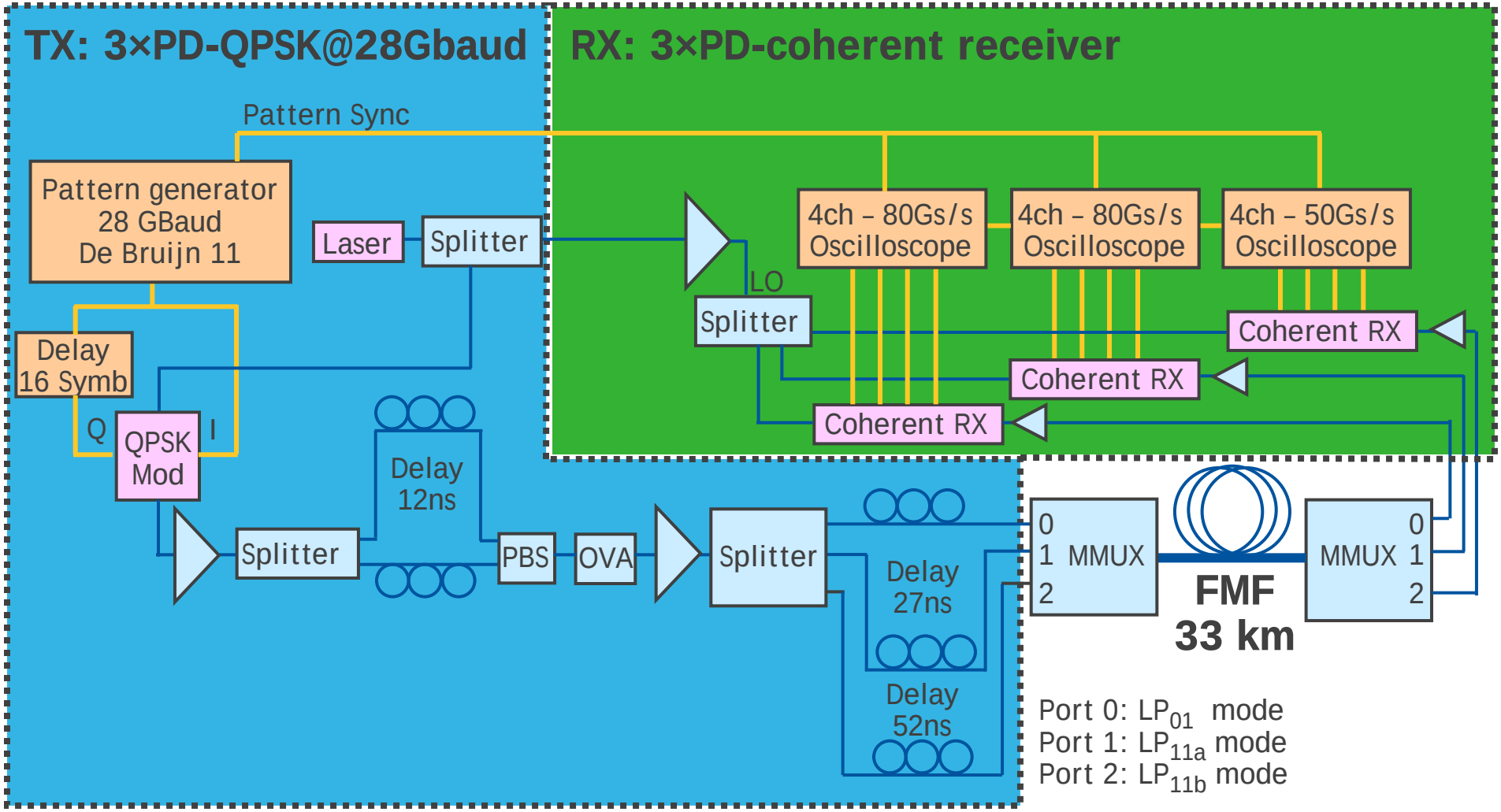
MODE PROFILES OF THE FEW MODE FIBER

MEASURED WITH IR CAMERA AT ONE END OF FIBER



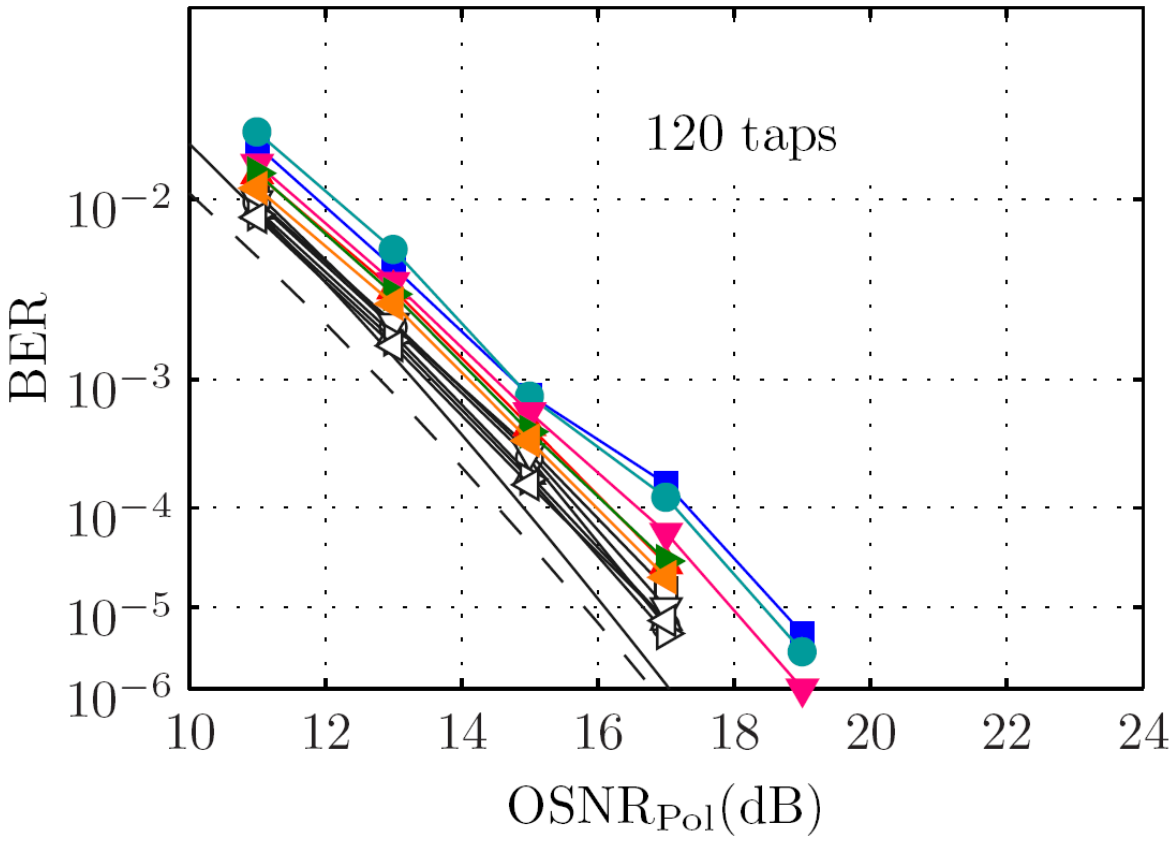
Ryf et. al., submitted to JLT, 2011

EXPERIMENTAL SETUP FOR MODE-MULTIPLEXING OVER FEW-MODE FIBER



BER FOR 6 x 6 MIMO TRANSMISSION OVER FMF
WITH 33 km LENGTH AND 6 x 28-Gbaud QPSK SIGNALS

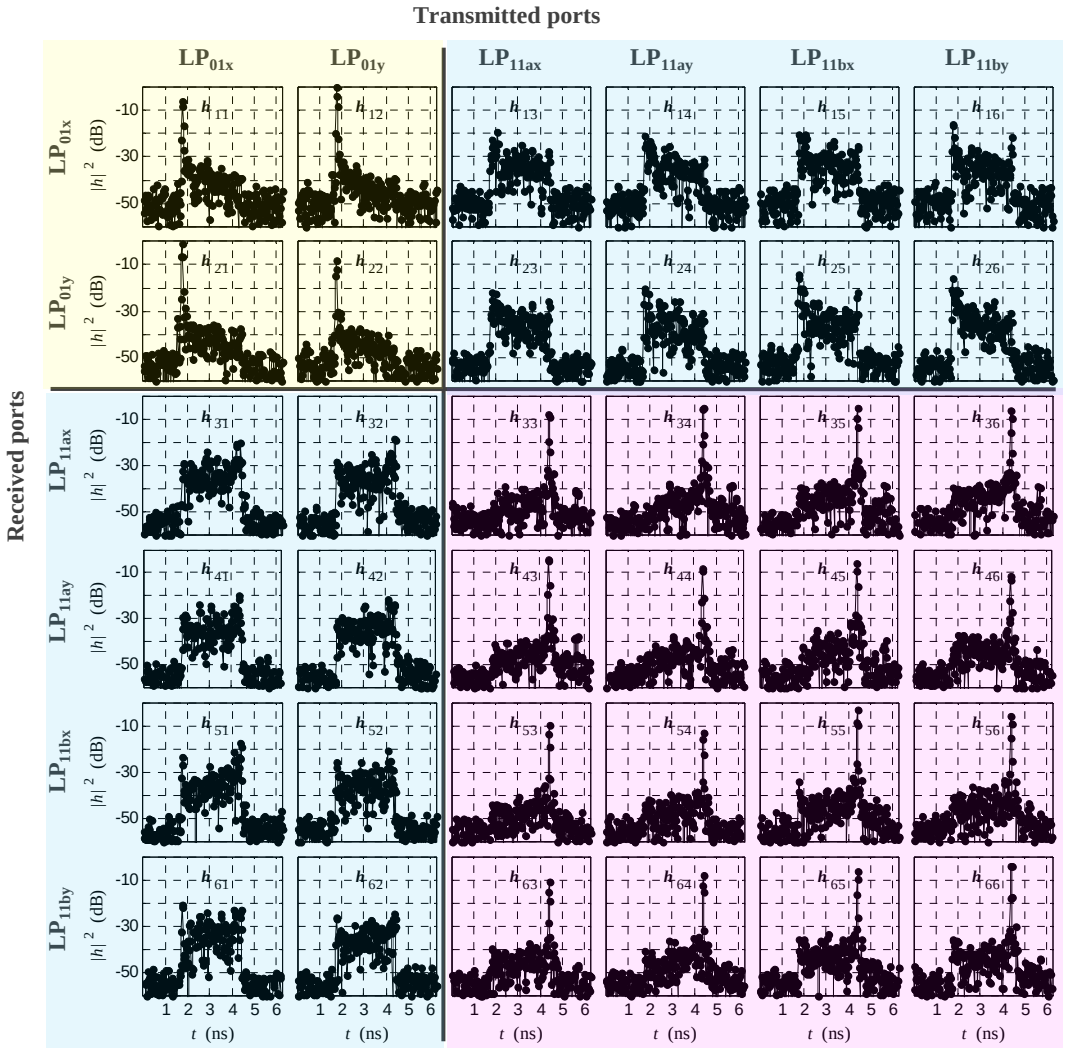
- Data aided least-mean square estimator (LMS) for first 500,000 symbols
- Switching to decision directed LMS
- Bit-error ratio evaluated for last 1 Million bits
- Low penalty < 2 dB observed for all 6 transmitted channels
- Best performance obtained for 120 taps



Randel et. al., Opt. Exp., V. 19, N. 17, 2011

IMPULSE RESPONSE MATRIX
FOR 96-km 6-MODE FEW-MODE FIBER

- The impulse response was characterized for all 6 outputs as function of all 6 inputs
- Strong coupling is observed within the LP_{01} and the LP_{11} mode
- Weaker coupling is observed between the LP_{01} and LP_{11} mode

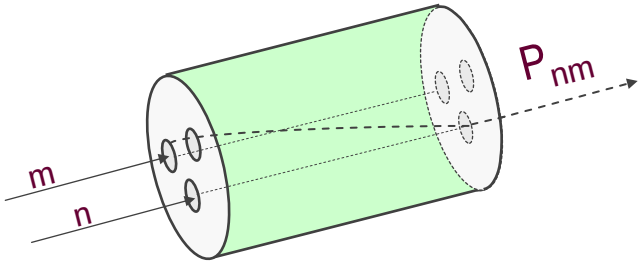


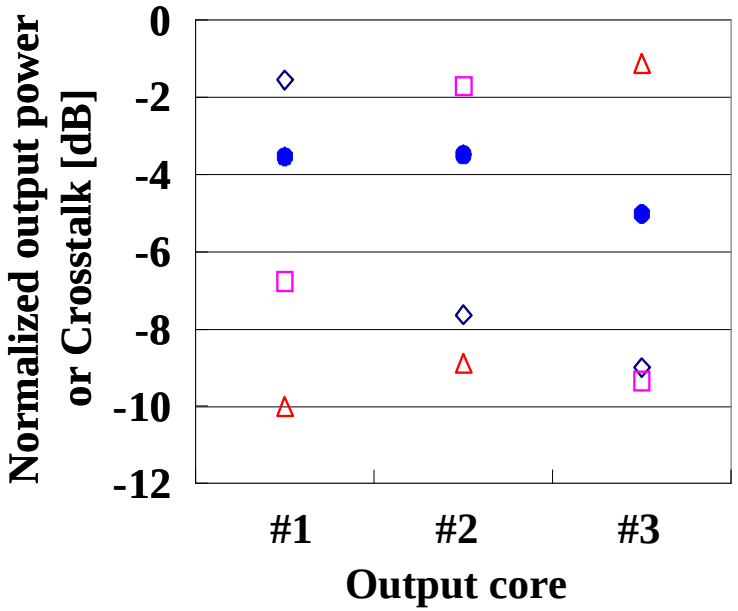
Ryf et. al., submitted to JLT, 2011

MULTI-MODE TRANSMISSION IN COUPLED CORE FIBERS

CHARACTERISTICS OF A 24 km 3-CORE COUPLED-CORE FIBER

- Number of cores 3
- Core diameter is 11.2 μm
- Refractive Index step Δ = 0.32%
- Distance between cores 38 μm
- Effective core area 104±1 μm^2
- Attenuation 0.177 dB/km
- Dispersion 20 ps/nm/km
- Dispersion slope 0.06 ps/nm^2/km

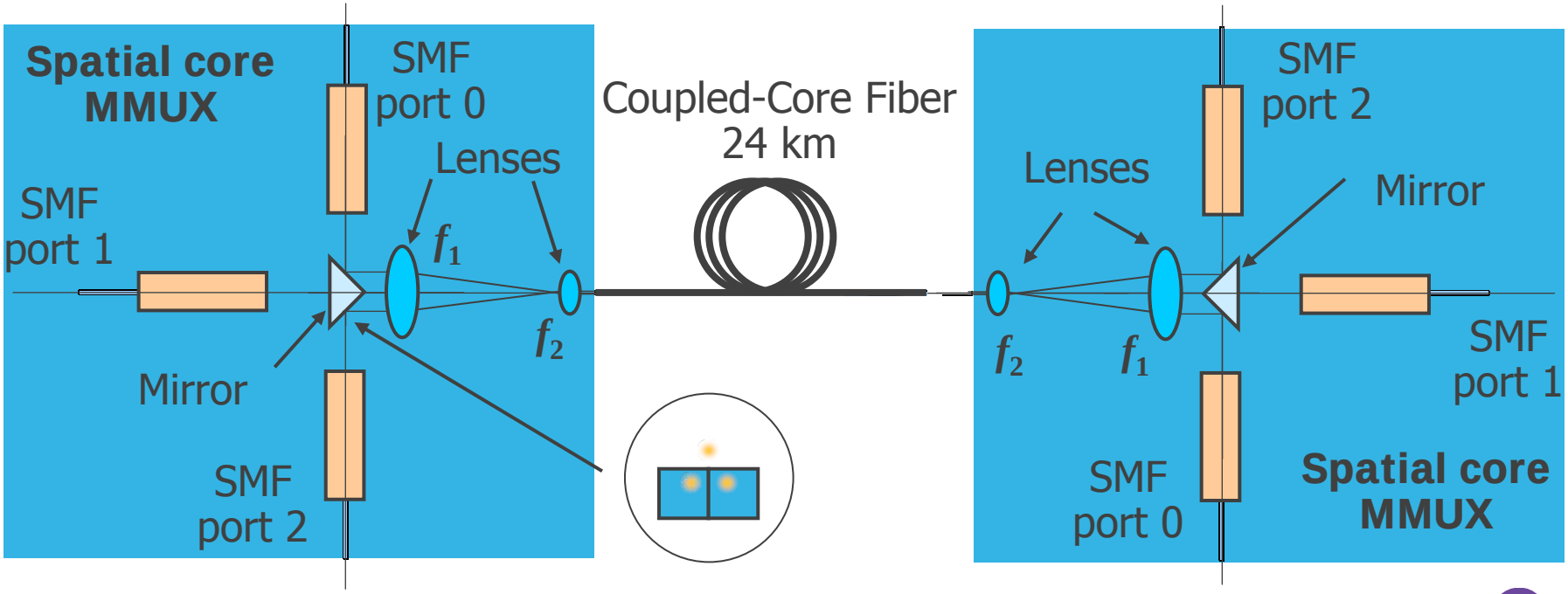




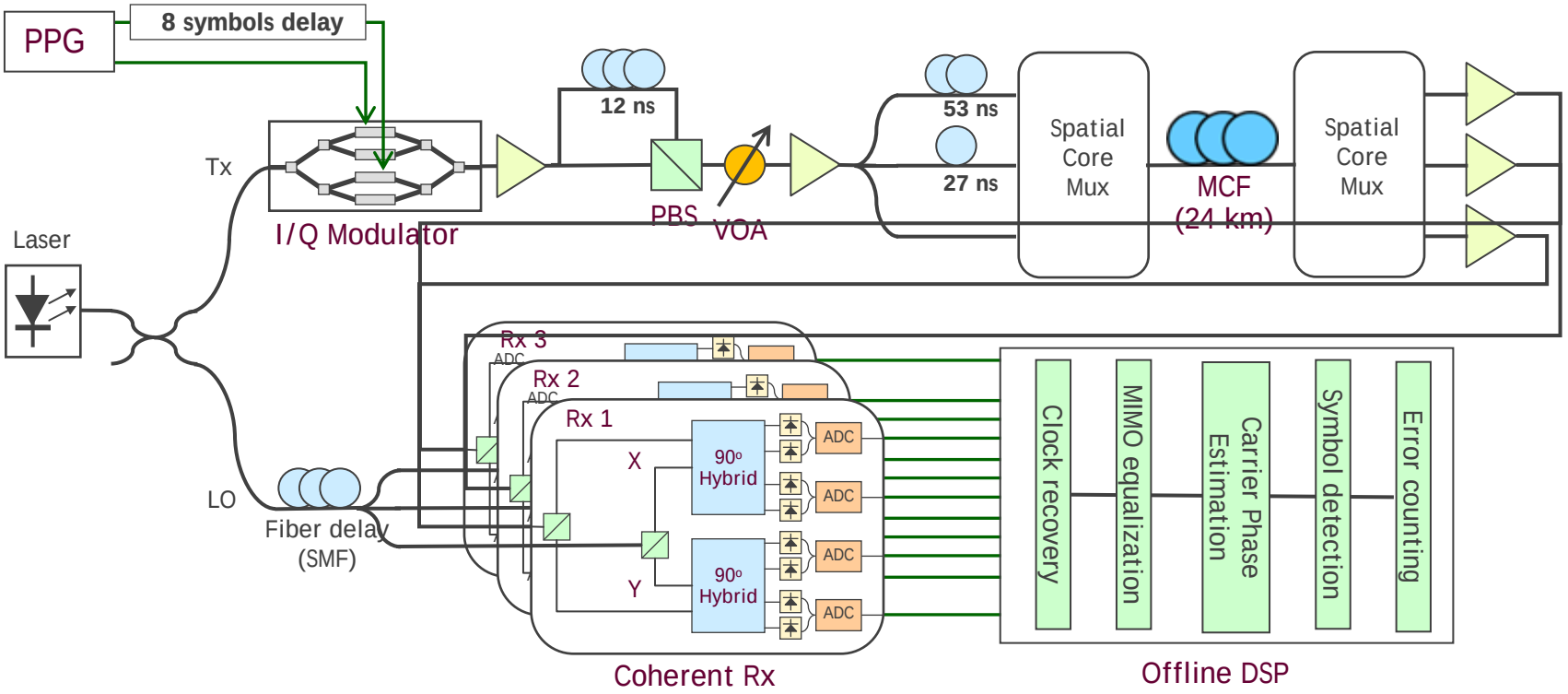
Ryf et. al., PTL, n. 99, 2011 (early access)

SPATIAL CORE MULTIPLEXER
FOR COUPLE-CORE FIBER

- Insertion loss < 2 dB
- Crosstalk suppression > 40 dB

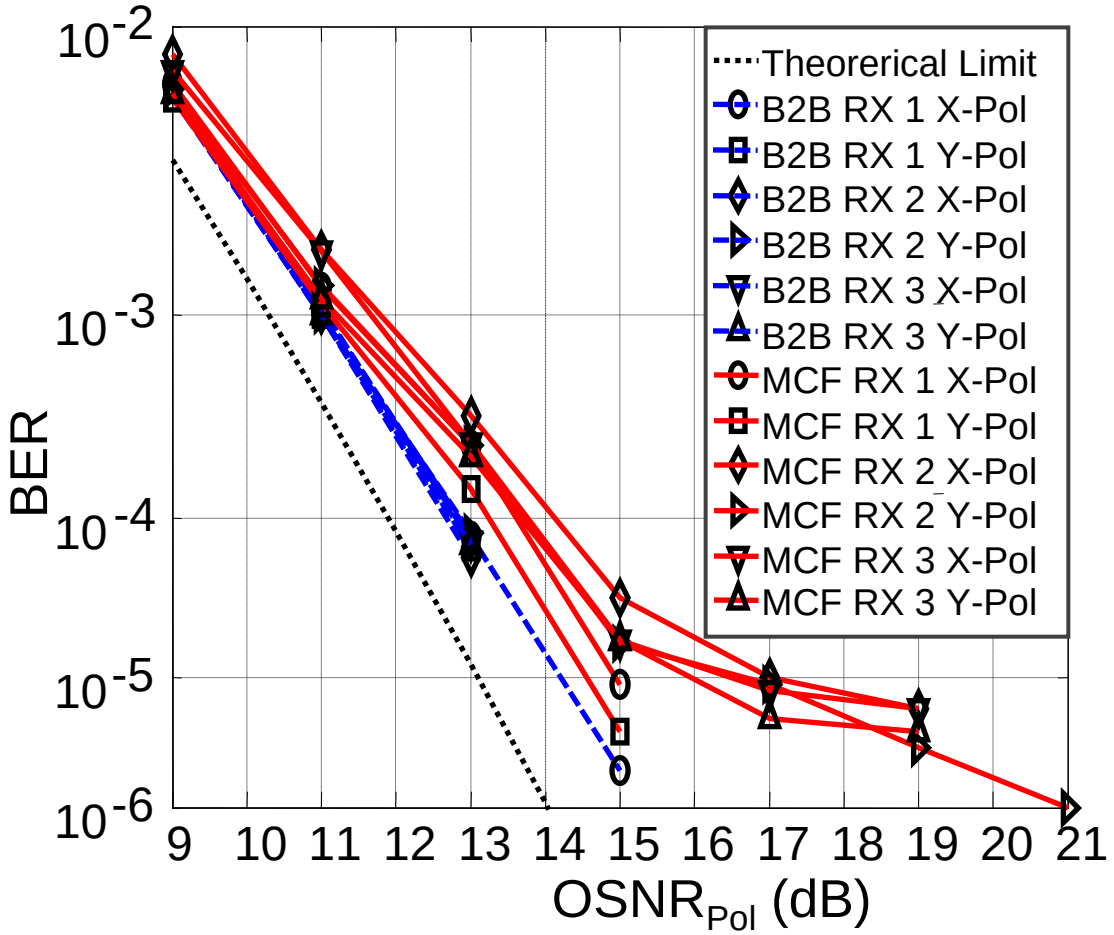


EXPERIMENTAL SETUP FOR MODE-MULTIPLEXING
OVER COUPLED-CORE FIBER



BER FOR 6 x 6 MIMO TRANSMISSION OVER CCF
WITH 24 km LENGTH AND 6 x 14-Gbaud QPSK SIGNALS

- Data aided least-mean square estimator (LMS) for first 500,000 symbols
- Switching to decision directed LMS
- Bit-error ratio evaluated for last 1 Million bits
- Low penalty < 2 dB observed for all 6 transmitted channels
- Best performance obtained for 100 taps



Ryf et. al., PTL, n. 99, 2011 (early access)

CONCLUSION

- We have experimentally confirmed that MIMO based crosstalk suppression is possible even in the presence of large crosstalk
- We have demonstrated mode-multiplexed transmission of 6 channels in 33 km few-mode fiber and 24 km coupled-core fiber
- We experimentally determined the impulse response matrix of the multi-mode fiber, which gives a complete instantaneous characterization of the fiber
- This clearly indicate the coherent MIMO applied over a full set of modes allow to reach maximum capacity gains
- Further technological development are required to improve the fiber characteristics and to perform MIMO DSP in real time

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