REAL-TIME DEMONSTRATION OF POLARIZATION-MULTIPLEXED PAM USING A COMPACT SILICON PHOTONICS DEVICE

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POLITECNICO DI TORINO

OFC
San Diego Convention Center
13-15 March 2018

Outline

- The proposed solution: polarization-multiplexed (PM) PAM-M and direct detection in short reach data center interconnects (<2 km, SMF) to double capacity per wavelength/laser
- Silicon Photonic chip for endless polarization rotation
- Experimental demonstration of a polarization control algorithm on PM-PAM2
- Theoretical investigation on the impact of angular errors in PM-PAM4

THE PROPOSED ARCHITECTURE:

POLARIZATION-MULTIPLEXED (PM) PAM-M AND DIRECT DETECTION

IN SHORT REACH DATA-CENTER INTERCONNECTS (<2 KM)

Rationale of our work

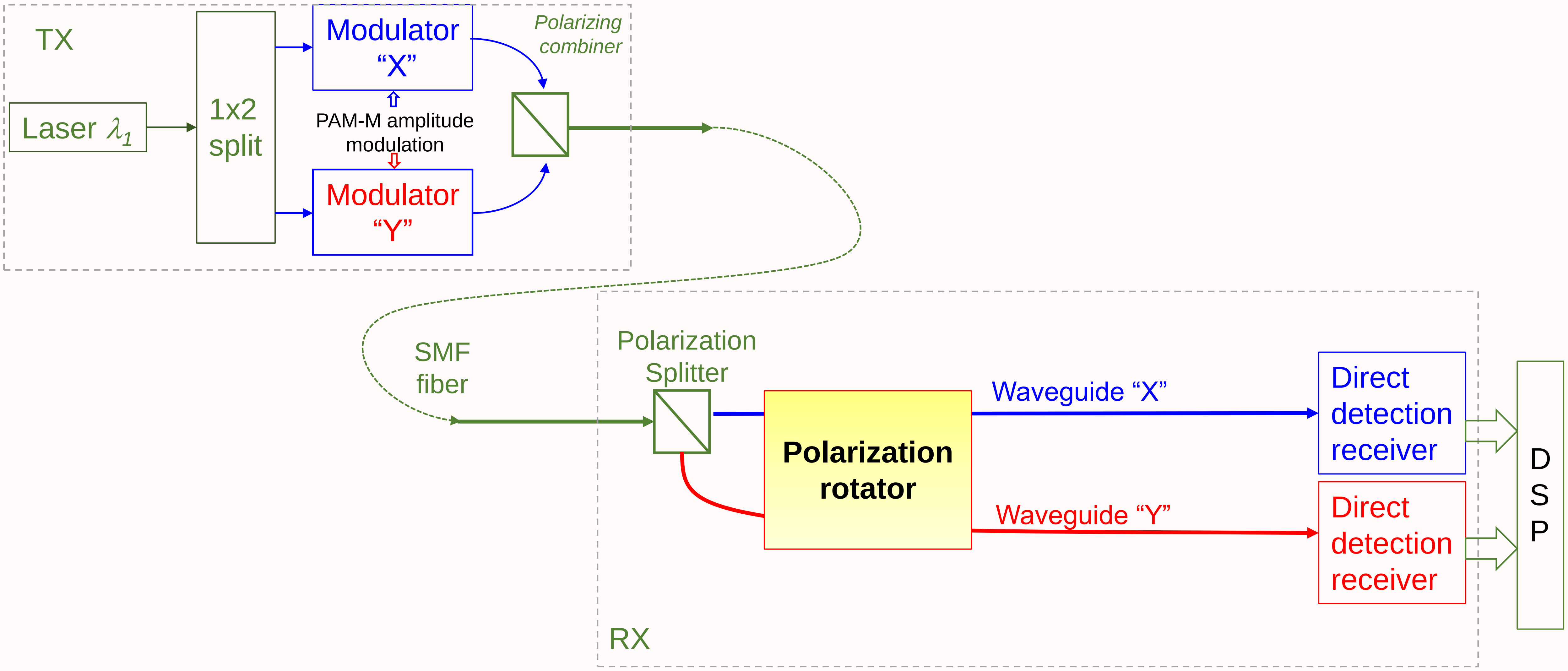
- **The proposed solution**:
  - **TX**: two independent PAM transmission over each polarization in SMF
  - **RX**: active polarization rotator to align the optical signals entering two separate direct detection receivers
- **Rationale**:
- Double bit rate (
  - For instance length
    - This in tur
- … but due to th
  - Avoid coher
  - Avoid full St
    - They still n
  - Avoid Kramers-Kronig DD receivers
    - They require one DAC but with 2x bandwidth (in KK basic implementation)

“Hands up” poll in OFC2018 Sunday Workshop:

S1A DSP for Short Reach and Client Optics - What Makes Sense?

- For <2km distance and 2023 time frame the majority of the audience voted for direct detection
- Rump-up session on this topic tonight

The proposed architecture

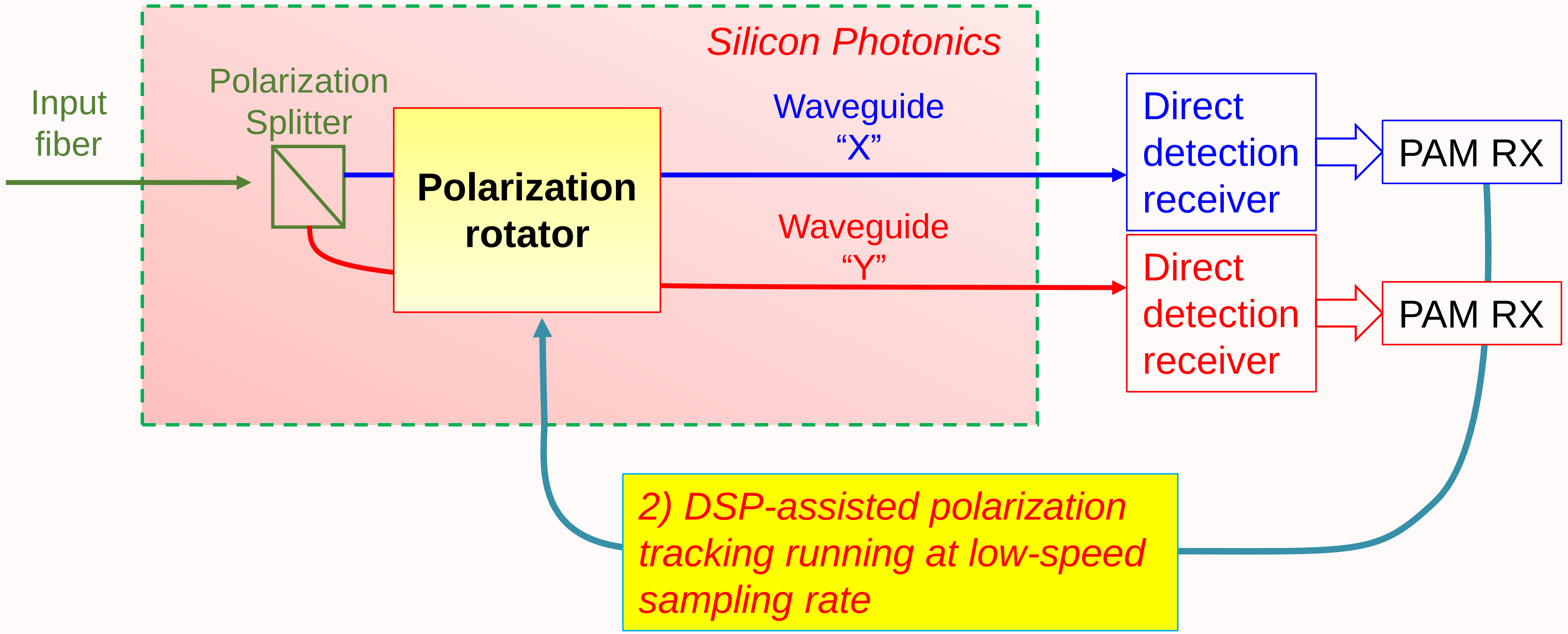


Polarization multiplexing – direct detection receiver

This is not in itself a new idea

But <u>focus of this work is on</u>:

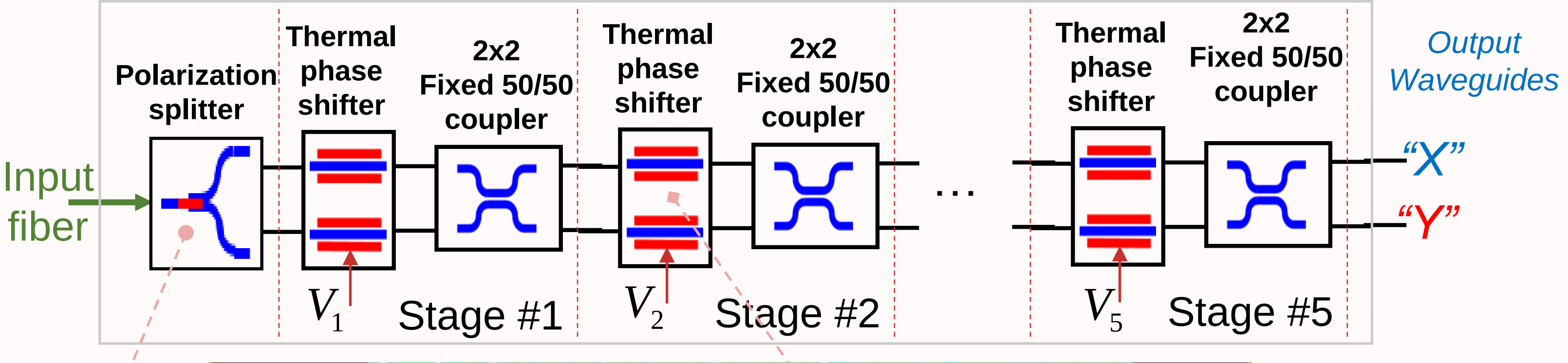
1) Implementation of the polarization rotator on a <u>Silicon Photonics platform</u>

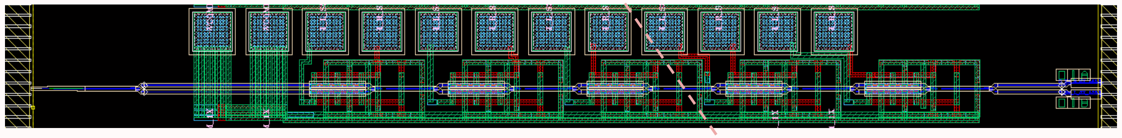


We target DSP algorithms running at around 30ksample/s
(thus much lower than system baud rate)

SILICON PHOTONIC CHIP FOR OPTICAL POLARIZATION CONTROL

Structure of the Silicon photonic chip





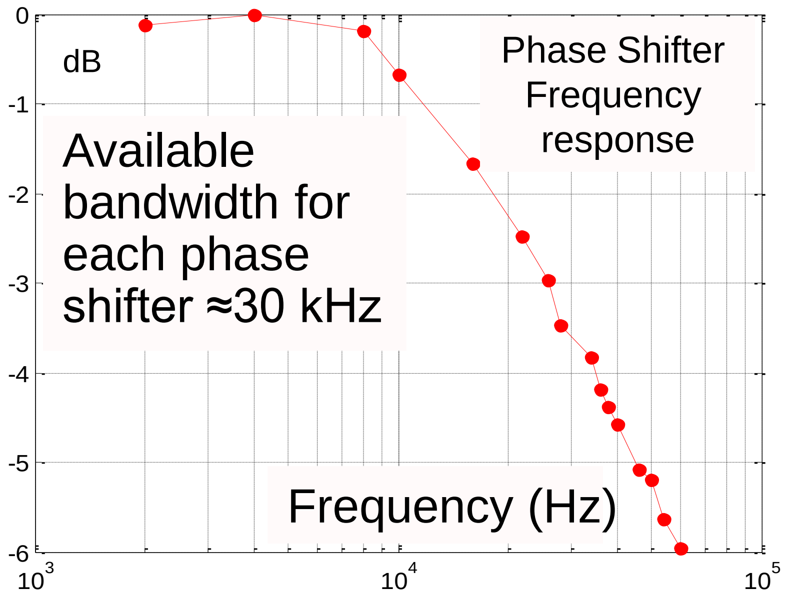
- Cascade of five sections, each made of a phase shifter and a 2x2 symmetric coupler
- It was demonstrated in the past (PMD compensator, 2001) that this structure can generate arbitrary polarization rotations

JOURNAL OF LIGHTWAVE TECHNOLOGY, VOL. 34, NO. 2, JANUARY 15, 2016

Silicon Photonic Polarization-Multiplexing Nanotaper for Chip-to-Fiber Coupling

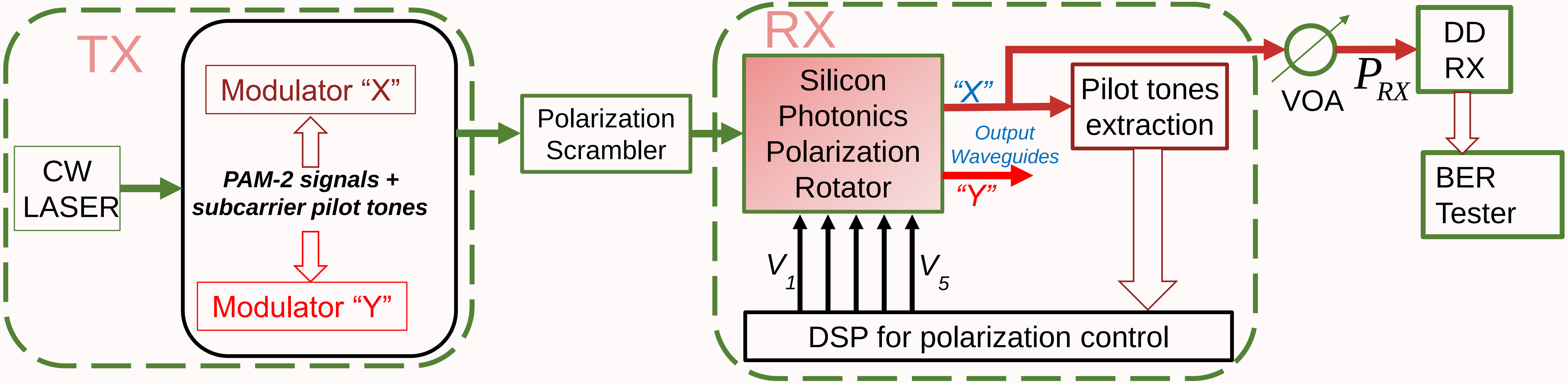
Sean P. Anderson, *Member, IEEE*, and Mark Webster, *Member, IEEE*

- Each of the five phase shifters has an independent control voltage



EXPERIMENTAL DEMONSTRATION OF A POLARIZATION CONTROL ALGORITHM ON PM-PAM2

Experimental setup



Transmitter characteristics:

- Two uncorrelated PAM-2 streams at 28 Gbps each
- Two low-frequency pilot tones at f_x=4 and f_y=7 MHz
  - To "label" the two polarizations

Receiver characteristics:

- Polarization recovery algorithm is implemented over a "low-speed" DSP microcontroller that uses as input the amplitudes of the two received pilot tones on one output waveguide. The five DACs update rate is 30 ksample/s
- BER is real-time measured on one output waveguide

Polarization rotator control algorithm

- Based on measurement of received pilot tones amplitudes A_x and A_y
- Feedback error signal is $C_e = A_x - A_y$ is used
- A gradient-based algorithm maximizes C_e over the five available degrees of freedom
  - i.e. the five available driving voltages for the five phase-shifters thermal heathers

- Endless polarization control must be achieved under the limited available range for the five voltages
  - In the current version of the chip, the available range corresponds to about 2π phase shift on each section

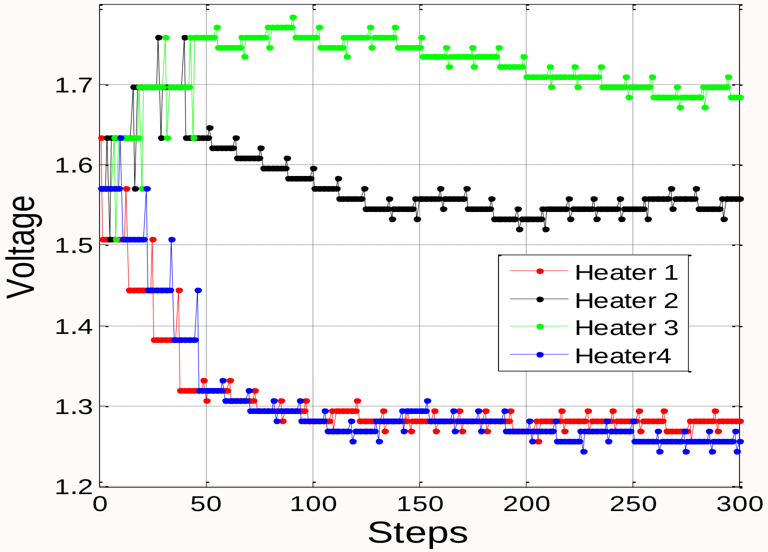
“Modified ±Δ algorithm”

FOR EACH AVAILABLE VOLTAGE:

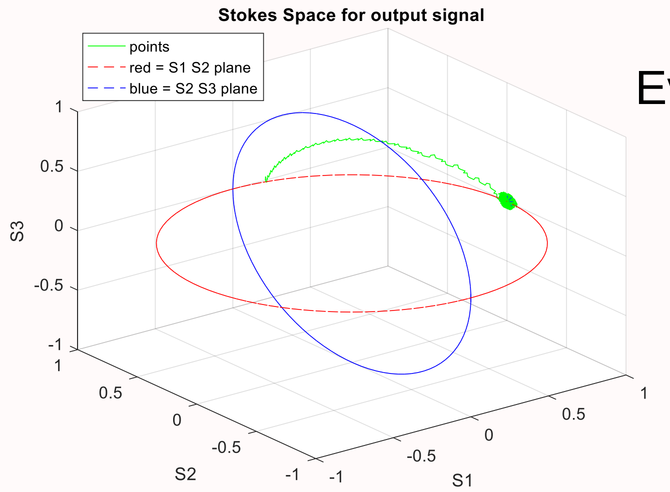
1) Try a +Δ step (if inside voltage range)

2) Try a -Δ step (if inside voltage range)

3) Set the sign (+Δ or –Δ) that gave an improvement on the target parameter C_e

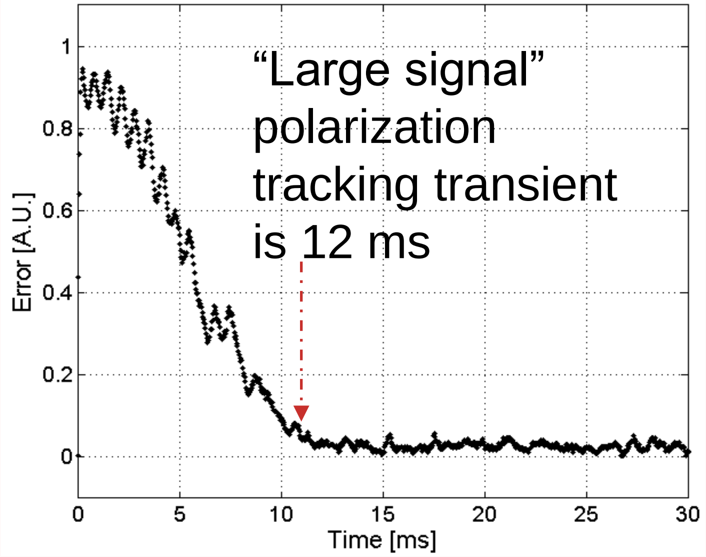


Initial transient in polarization control algorithm (Experiments)

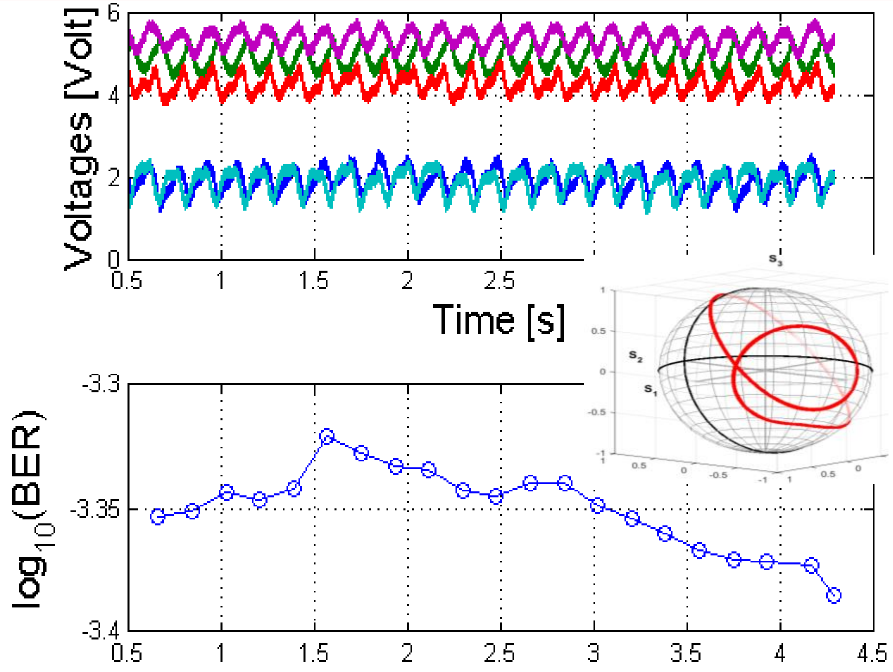


Evolution of output state of polarization in Stokes Space (simulations)

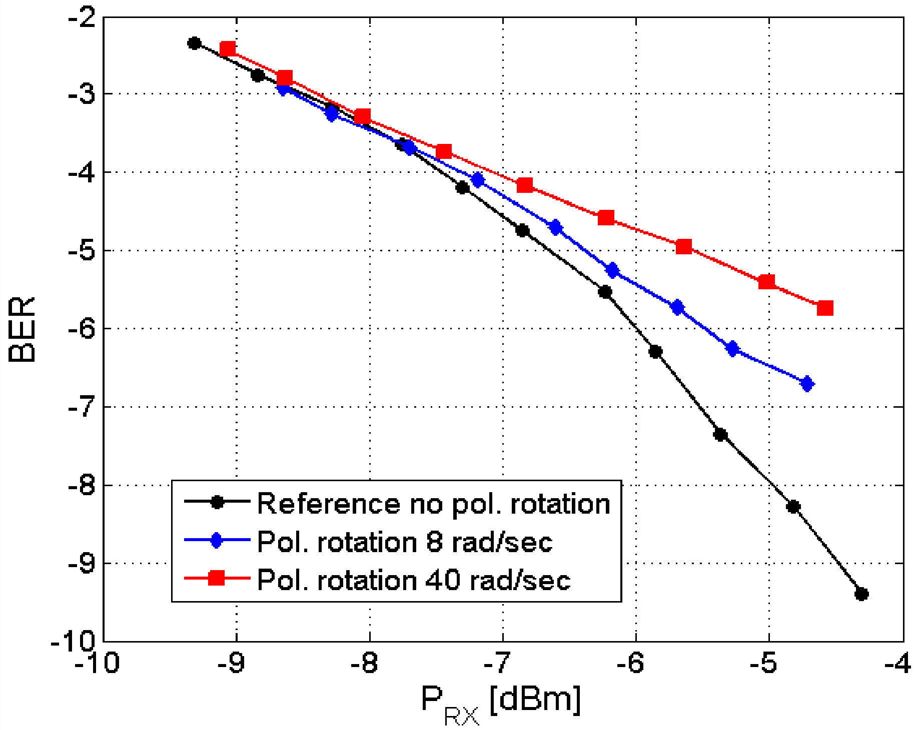
Experimental results



Pol-Ctrl 180° step response



Evolution of the five control voltages when input polarization is rotated at 40 rad/s and corresponding BER evolution



BER vs. P_{RX} at different scrambling speed

For completely random polarization scrambling, we observed unlocking events for simultaneous “out-of-bound” on more than 2 voltages

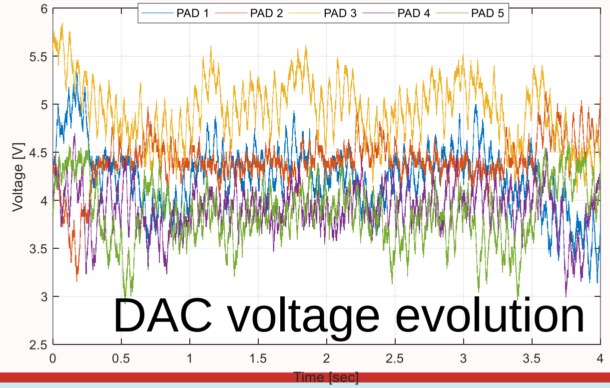
The power penalty at the target KP4 FEC threshold BER=$2 \cdot 10^{-4}$ is 0.6 dB at 40 rad/sec.

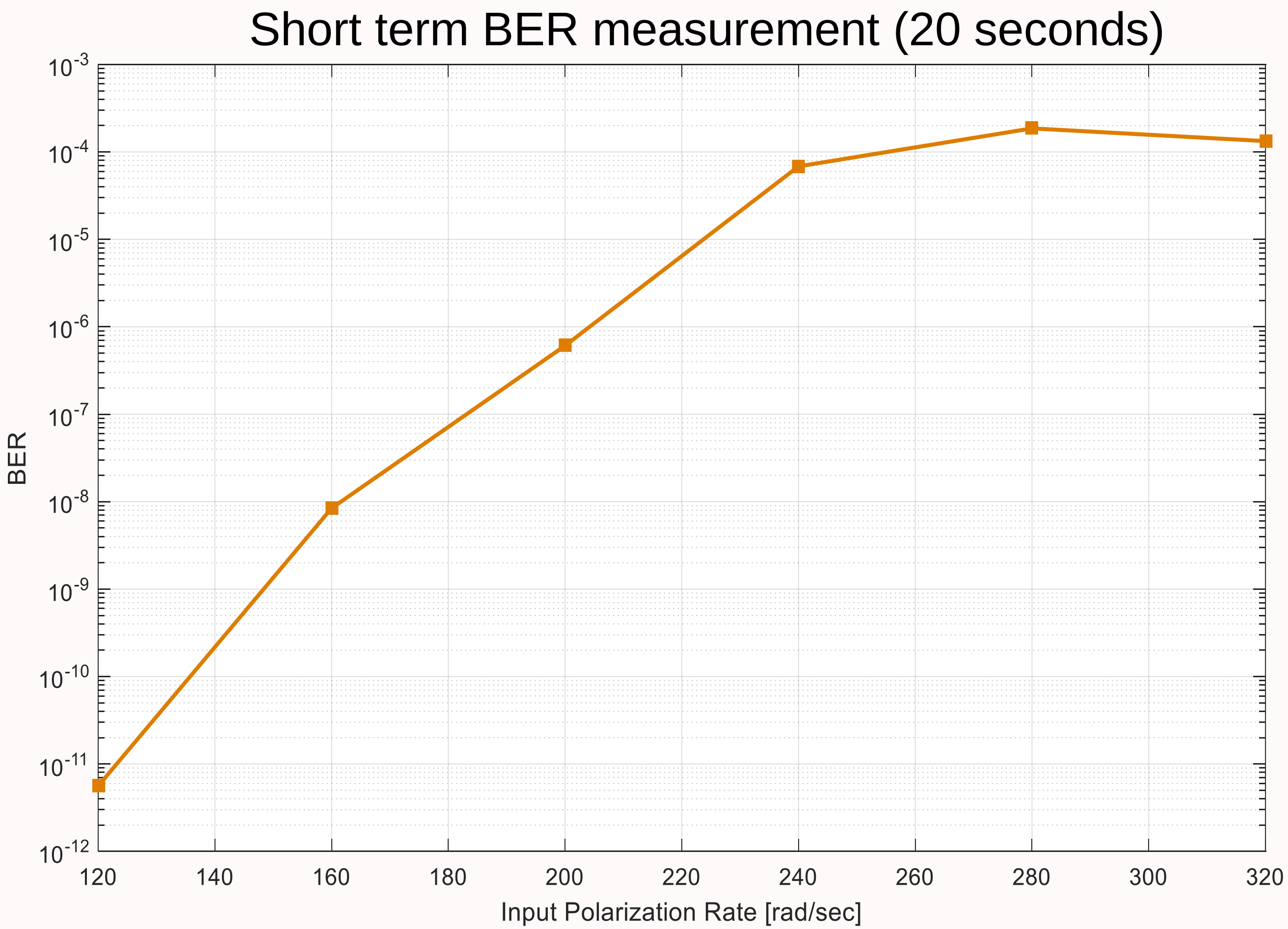
Newer experimental results

In the six months after the submission of the paper to OFC2018, we significantly improved results

1. Upgraded control software algorithm
2. Randomly scrambled input polarization

- We obtained polarization tracking speed higher than 100 rad/s





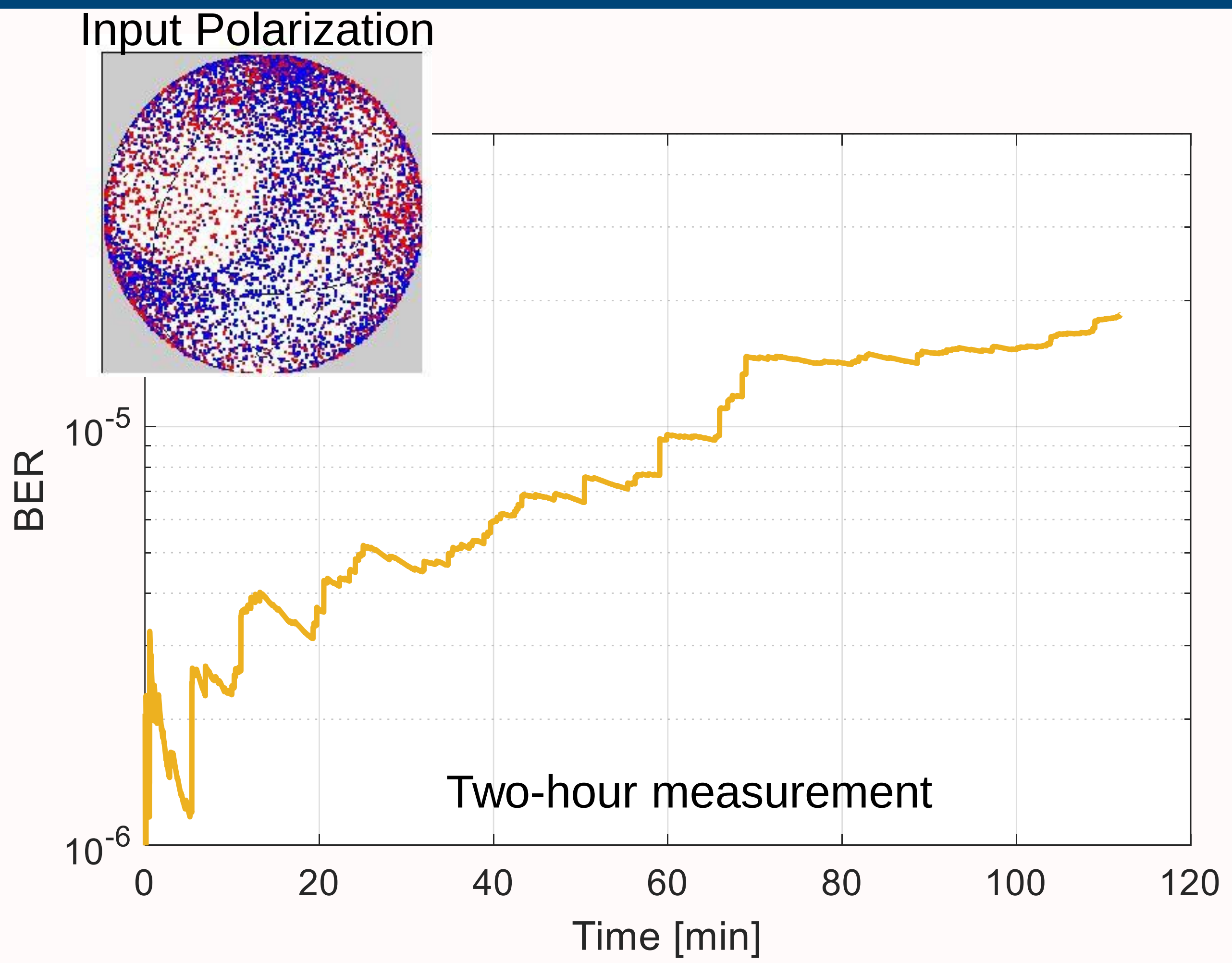
Long term measurements

INPUT

- Fully scrambled input polarization at 100 rad/s

OUTPUT

- Real-time accumulated BER measurement
- Relatively stable output, but:
  - Slight increase in accumulated BER over the two hours of measurements, showing that we still have some sporadic error bursts
  - Partial unlocking events?
    - Currently under investigation



Summary of experimental results

- Demostration of polarization control for 100 rad/s random scrambling on Poincarè sphere
- The limit is related to the phase shifter speed (30 kHz)
- But 100 rad/s should be sufficient to track actual polarization rotations on short reach links <2km

THEORETICAL INVESTIGATION ON THE IMPACT OF ANGULAR ERRORS IN

PM-PAM4

Assessing the impact of angular errors

We performed a realistic time domain simulation for PM-PAM4 including:

- 56 Gbaud PAM-4 (giving 200 Gbit/s per wavelength)
  - Electrical bandwidth = 20 GHz for all optoelectronics
- Overall Jones matrix (for fiber+polarization controller) with angular errors

$$\begin{bmatrix} E_x \\ E_y \end{bmatrix}_{out} = e^{i\varphi} \begin{bmatrix} e^{i\psi} & 0 \\ 0 & e^{-i\psi} \end{bmatrix} \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} e^{i\Delta} & 0 \\ 0 & e^{-i\Delta} \end{bmatrix} \begin{bmatrix} E_x \\ E_y \end{bmatrix}_{in}$$

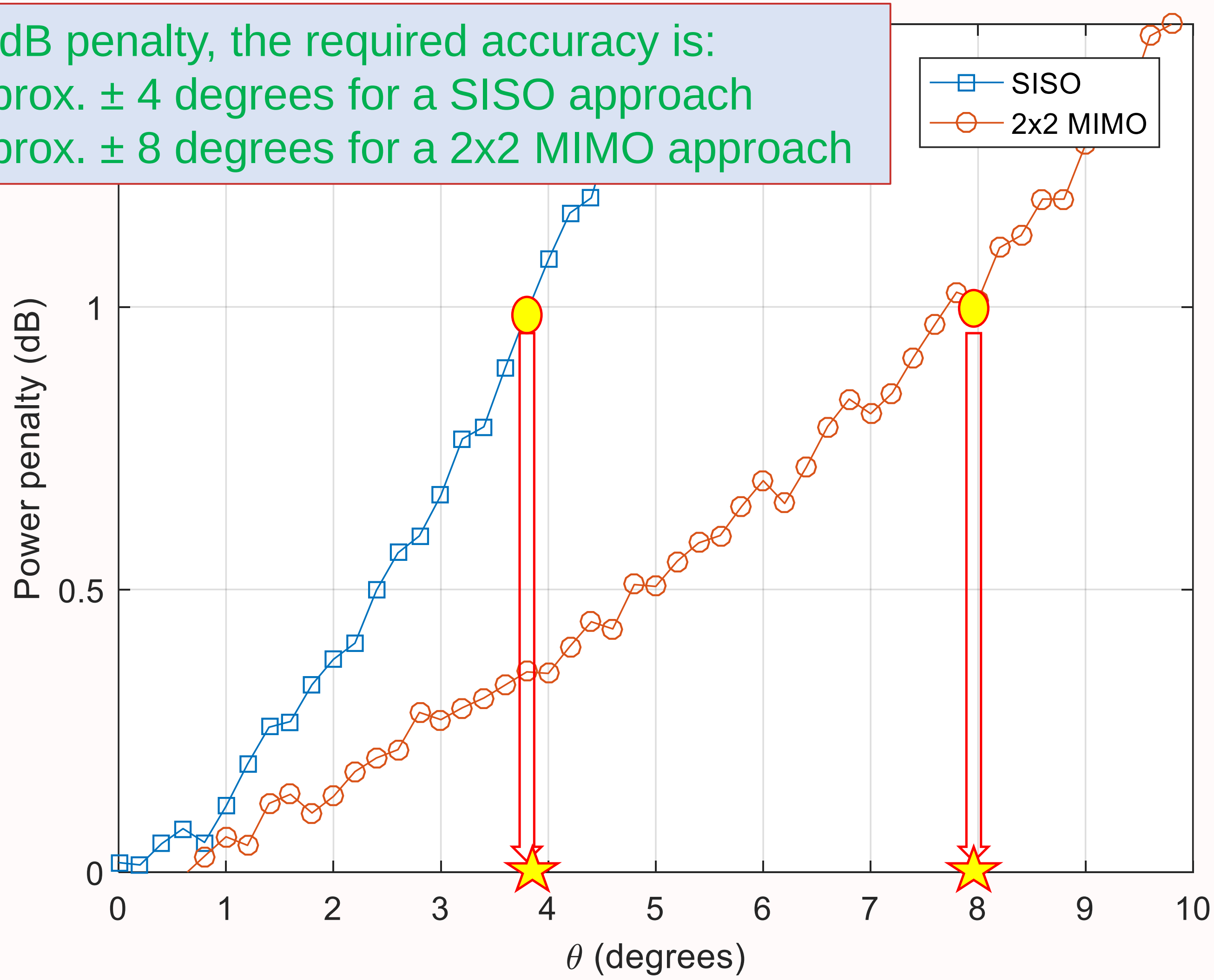
- We assumed Adaptive LMS-based FFE equalization at RX with two options:
  - A serial-in serial out "SISO" approach in which the two equalizers at the receivers acts independently
  - A "2x2 MIMO" approach
    - Using a 2x2 real MIMO algorithm, similar to the one required for 16-QAM

Full time domain simulations on PM-PAM4

- **Numerical results as a function of the angle θ**
  - The two other angles in previous formula below turned out to be irrelevant for penalty

$$e^{i\varphi}\begin{bmatrix} e^{i\psi} & 0 \\ 0 & e^{-i\psi}\end{bmatrix}\begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta\end{bmatrix}\begin{bmatrix} e^{i\Delta} & 0 \\ 0 & e^{-i\Delta}\end{bmatrix}$$

For a 1 dB penalty, the required accuracy is:
Approx. ± 4 degrees for a SISO approach
Approx. ± 8 degrees for a 2x2 MIMO approach



These angles are defined in the Jones space (where for instance θ=90° means orthogonal polarizations). Error tolerance in Stokes space will be twice as much

CONCLUSIONS

Conclusions

- We proposed and experimentally demonstrated a PM-PAM approach to double capacity per wavelength/laser for short-reach SMF links

- We showed in particular the feasibility of:
  - A silicon photonic chip for polarization rotation
  - A «low-speed» DSP-based algorithm to achieve endless polarization control
  - Experimental demonstration of tracking speed up to 100 rad/s

- Open issues
  - We still have to solve sporadic partial unlocking events under randomly scrambled input polarization, to be investigated

Thank you for your attention!

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BACK-UP SLIDES

Recent upgrades to the hardware and software

- Look-up table to compensate quadratic relation between applied voltage and resulting phase shift
  - Thermal effects are proportional to the voltage square

- Soft-bound approach
  - When a voltage approaches a bound, the “error signal” is artificially increased

- Optimized re-centering technique
  - Optimized threshold to decide when to re-center

- Hardware upgrade: accuracy of pilot tones amplitude estimation greatly increased

Why pilot tones?

- In our current implementation we didn’t have access to baud-rate DSP parameters
  - This is why we introduced pilot tones, that can be extracted with low rate ADC

- But in a full PAM4 implementation, the monitoring parameter can be extracted directly from the parameters of the baud-rate adaptive equalizer

The power budget issue: comparison to a traditional single channel PAM in DD