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

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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)
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 on each wavelength
  - For instance: PM-PAM4 at 56Gbaud would give 200 Gbit/s per wavelength
  - This in turn would mean only two wavelengths for 400G Ethernet
- … but due to the data-center scenario low-cost requirements:
  - Avoid coherent receivers
  - Avoid full Stokes DD receivers
  - They still require 3-4 DACs at the receiver depending on the implementation
  - Avoid Kramers-Kroning 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

TX

Laser $\lambda_1$ → 1x2 split → Modulator “X” → Polarizing combiner → Modulator “Y” → PAM-M amplitude modulation → SMF fiber → Polarization splitter → Waveguide “X” → Polarization rotator → Waveguide “Y” → Direct detection receiver

RX

Direct detection receiver
This is not in itself a new idea

But focus of this work is on:

1) Implementation of the polarization rotator on a Silicon Photonics platform

2) DSP-assisted polarization tracking running at low-speed sampling rate

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

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

Available bandwidth for each phase shifter \(\approx 30 \text{ kHz}\)

Phase Shifter Frequency response

Frequency (Hz)

Available bandwidth for each phase shifter

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>(10^3)</td>
<td>-1</td>
</tr>
<tr>
<td>(10^4)</td>
<td>-2</td>
</tr>
<tr>
<td>(10^5)</td>
<td>-3</td>
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<tr>
<td>(10^6)</td>
<td>-4</td>
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<tr>
<td>(10^7)</td>
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<tr>
<td>(10^9)</td>
<td>-7</td>
</tr>
<tr>
<td>(10^{10})</td>
<td>-8</td>
</tr>
</tbody>
</table>

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

Sean P. Anderson, Member, IEEE, and Mark Webster, Member, IEEE
EXPERIMENTAL DEMONSTRATION OF A POLARIZATION CONTROL ALGORITHM ON PM-PAM2
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 $2\pi$ 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

“Large signal” polarization tracking transient is 12 ms

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

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

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

![DAC voltage evolution](image)

![Short term BER measurement (20 seconds)](image)
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

![Input Polarization](image)

![BER vs Time](image)
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
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

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

- 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
Numerical results as a function of the angle $\theta$

- 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. $\pm 4$ degrees for a SISO approach
Approx. $\pm 8$ degrees for a 2x2 MIMO approach

$\theta$ (degrees)

Power penalty (dB)

These angles are defined in the Jones space (where for instance $\vartheta=90^\circ$ means orthogonal polarizations). Error tolerance in Stokes space will be twice as much.
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
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PhD and Post-doc positions available at our new PhotoNext Center@POLITO
For further information: please contact roberto.gaudino@polito.it
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

Fraction of dB more loss than a standard single polarization waveguide to fiber coupler

Around 6 dB extra-loss, to be recovered in improved TX laser power OR RX sensitivity