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Proof-of-Concept of Polarization-Multiplexed PAM using a Compact Si-Ph Device

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***Abstract* — We experimentally propose and demonstrate how to double the capacity per wavelength in short distance data center interconnect fiber links by polarization multiplexing two PAM streams and by using a very compact Silicon Photonic polarization rotator driven by an algorithm implemented in a low speed DSP platform, avoiding more complex coherent and/or Stokes receiver structures. Tackling up to 100 rad/sec, the system gives automatic stabilization against polarization fluctuations. We also report on the experimentally measured evolution of the state of polarization in an installed data center link.**

***Index Terms* — Short-Reach Optical Transmission, Polarization Multiplexing, Silicon Photonics.**

I. Introduction

The increasing requests in terms of bit rate for intra data center optical interconnection for distances below 2 km is today a hot topic, as demonstrated by the large number of recently published papers in this area. As outlined in [1], intra data center communications and data center interconnects (DCI) have very tight cost requirements, and the techno-economic analysis reveals that DCI transceivers with lower number of laser sources and higher baud rate exhibit an advantage in terms of scaling, cost and power consumption compared to dense-WDM solutions. Moreover, DCI for distances below 10km is one of the few areas where coherent transceivers are still perceived as too expensive, and thus direct-detection (DD) solutions are pursued as baud rates increase. In this paper, we explore increasing the bit rate without increasing the number of lasers and extending our preliminary results presented in [2], we propose to double capacity per wavelength by polarization multiplexing (PM) [3-5] two PAM streams on SMF fibers using the schematic shown in Fig. 1. Our focus is demonstrating the use of a very compact integrated Silicon Photonic (SiP) polarization rotator (Pol-Rot) device [2], [6] to perform active polarization recovery (Pol-Rec) followed by two standard DD receivers, and its real time Pol-Rec algorithm implemented in a low speed Digital Signal Processing (DSP) platform running at much slower update rate than the PAM baud rate. The idea, that we indicated in the following as DD PM-PAM, is obviously not new, since it was proposed by previous papers, usually for long-haul applications [3-5] before the "coherent revolution". However, the Pol-Rec devices used in these papers were exceedingly expensive for DCI, being based on Lithium-Niobate (LN) multi-section solutions [3-4]. These devices were required to track the very fast polarization changes that may sporadically happen in long-haul fibers. Applying PM-PAM for DCI would have anyway very different constraints: on one side, expensive optoelectronic devices are completely out of question, for cost and size reasons. At the same time, Pol-Rot speed in DCI is expected to be slower (by orders of magnitude, as we will show experimentally in a following Section) than in long-haul links, since the fiber is short (less than 2 km for all IEEE current standards for DCI) and it is deployed in a controlled environment from a temperature and mechanical viewpoint. In this paper, we propose to achieve polarization tracking using an integrated SiP chip that potentially has much lower cost and size than bulk LN solutions. The trackable Pol-Rot speed is lower than the LN solutions, but still suitable for DCI. The novelty of this paper compared to our previous results [2] is in the demonstration of improved achievable polarization tracking speed, from the previous 40 rad/s measured over a short-term period (few seconds) to more than 100 rad/s measured over a longer term (two hours), thanks to a new algorithm implemented and a faster real-time FPGA platform. Moreover, the long-term State of Polarization (SOP) measurements inside a real data center are completely new and we believe are highly interesting.

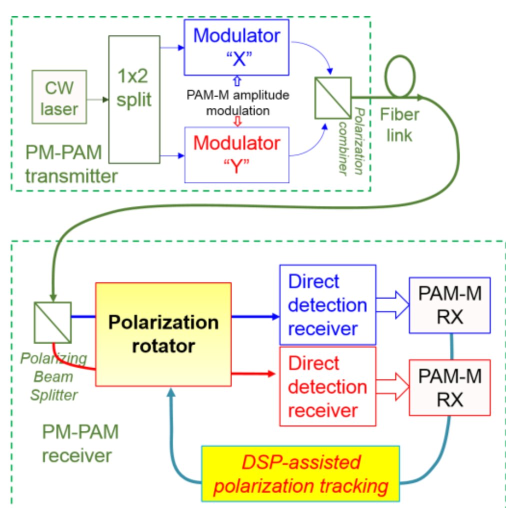

Fig. 1: general schematic of the proposed PM-PAM architecture.

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This paper is an extension of the paper [2] published for OFC2018. The experimental results presented here are anyway completely new.

The paper is organized as follows. In Sect. II we present measurements on SOP evolution taken in a real data center. In Sect. III we describe the proposed PM-PAM system in terms of hardware setup and DSP algorithms, and in the following Sect. IV we show experiments demonstrating the effectiveness of the proposed architecture, testing it on a PM-PAM-2 signal at 56 Gbps gross on a single λ (2 PAM-2 streams at 28 Gbps) with real time Pol-Rec using low frequency pilot tone signaling.

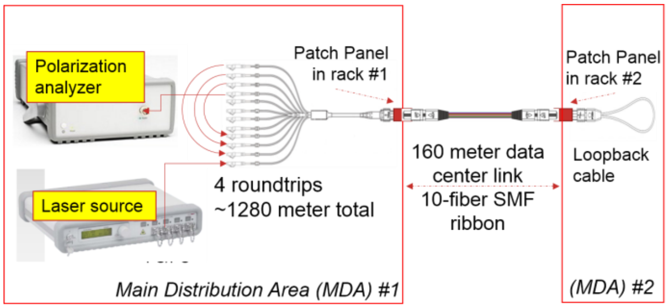

Fig. 2: Experimental setup for the polarization evolution measurement over an installed data center link (1280 meters total).

II. Data Center: Scenario and Polarization Evolution Measurements

A set of measurements was organized inside a fully-functional large data center, using the experimental setup shown in Fig. 2, to assess the typical SOP rotation speed in the scenario for which the transmission technique proposed in this paper is meant, that is short reach (<2km) ultra-high speed interconnect on SMF.We used an installed 10-fiber SMF ribbon cable connecting two Main Distribution Areas (MDA #1 and #2 in the figure) spaced by 160 meters and located at the two farthest ends of an operational data center. To reach a longer distance, we loop-backed 8 of the 10 fibers at both ends, resulting in an approximately 1280 meters link, which was then fed by a CW laser at 1300 nm. The link SOP evolution was continually measured by a high-performance polarization analyzer for 48 hours. The loopback configuration is expected to be a (strongly) worst-case situation for the given distance (1280 meters) since for instance any local mechanical vibration would impact the cables eight times in an approximately synchronous way. The results are presented in Fig. 3(a) in terms of Stokes parameter evolution over time (the corresponding traces on the Poincarè sphere are shown in the inset of the graph). This figure shows that, apart from a couple of sporadic events (see later), the evolution of the SOP was very smooth over time. In Fig. 3(b) we plot the resulting SOP changes in radians per second measured by the polarization analyzer (running at 1Msample/s). This graph shows that the SOP variation was very stable, typically below 0.01 rad/s (i.e. less than 1 degree per second) for most of the time. In the same graph, we zoomed in around the fastest of the two sporadic events, which we know was generated by a manual maintenance procedure in which a tool accidentally hit the cable. During this event, the polarization speed was about 110 rad/s as a peak speed. Reminding that our 1280 meters link was in a severely worst-case condition for polarization evolution due to the loopback condition, we can derive that, at least for our 48-hour long set of measurement, the maximum SOP speed of rotation inside a typical data center environment is normally very slow, and below about 100 rad/s even under accidental events.

III. The Proposed PM-PAM System: Experimental Setup and Control Algorithms

In this Section, we present the full experimental setup (shown in Fig. 4), including details on the SiP chip and on the DSP algorithms.

At the transmitter we generated a PM-PAM-2 signal using a pair of external modulators that were independently driven by two orthogonal PRBS11 pseudorandom streams, on top of which we also added two low-frequency pilot tones at f_x=2 and f_y=5 MHz, which were used for polarization tracking at the receiver, as outlined later. The transmitter was not the aim of this paper and was thus assembled using off-the-shelf LN modulators (the focus of the paper actually being the SiP receiver). The transmitter output was sent into a fast and programmable laboratory polarization scrambler (used to emulate fast polarization rotations) and then it entered the SiP Pol-Rot device, whose architecture is schematically represented in the bottom part of Fig. 4, together with its photo taken by a microscope.

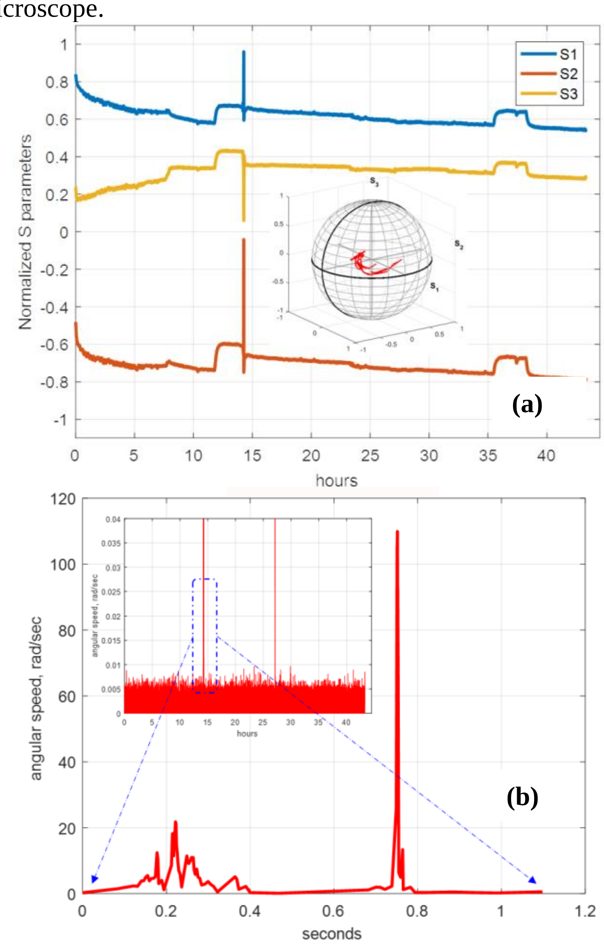

Fig. 3: (a) SOP evolution over the 2-day long term measurement in the data center. (b) Resulting angular speed vs. time on two different zoom representations: the inset allows to see the “normal” slow evolution, while the bigger graph zooms around the fastest polarization variations (due to an accidental event).

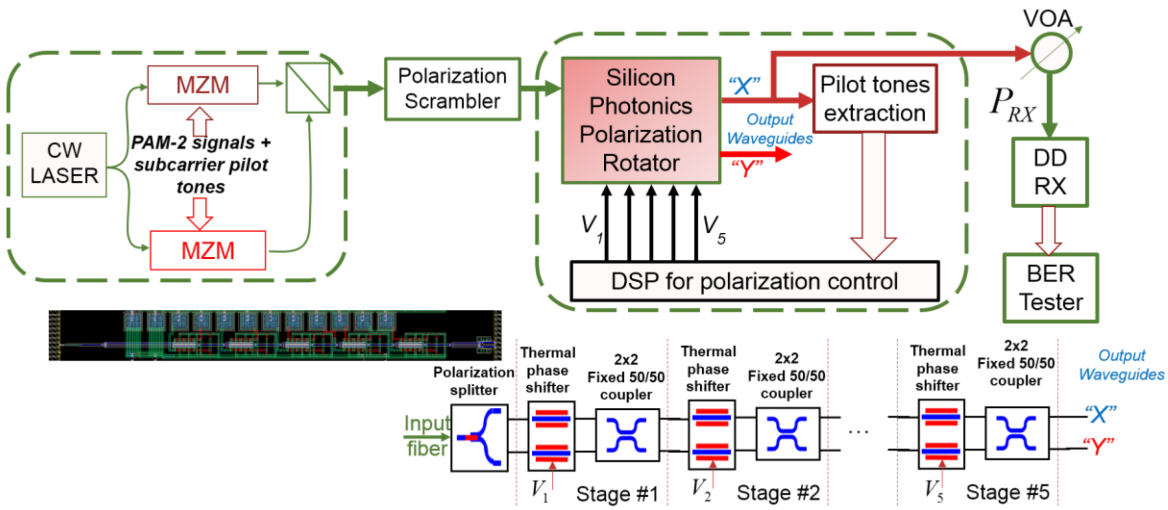

Fig. 4: Experimental setup for the PM-PAM2 polarization tracking and BER measurement demonstration

This Pol-Rot device has an input polarization demultiplexer [6] followed by a cascade of five stages, each composed by MZs whose phase shift can be thermally tuned by changing the voltage applied to the heater that is present over each section. The 3dB small-signal bandwidth of each phase section is around 25 kHz [2]. Our Pol-Rot architecture is like the one proposed in [5], being based on the cascade of variable phase shifters and fixed 2x2 symmetric couplers, but it is implemented in a very compact SiP chip. It was demonstrated in [5] that this polarization rotation can obtain endless polarization tracking when driven by a suitable controlling algorithm. For CW signals, it was tested to have more than 25 dB polarization extinction ratio capability. This SiP Pol-Rot is a prototype device, developed specifically for this set of experiments, and it requires free-space micro-optical alignment at its input and output waveguides, in fact giving a high fiber-to-fiber insertion loss around 20 dB. In our experiments, one waveguides was sent to a high-speed direct detection receiver which was then connected to a BER tester for continuous real-time BER measurement, thus avoiding any off-line processing A fraction of the output light, tapped from the same waveguide, was received by a dedicated electronic circuit to perform the estimation of the two pilot tones amplitudes A_x and A_y at f_x and f_y. The feedback error signal $C_e = A_y - A_x$ is used at the input of a Pol-Ctrl algorithm that runs on an FPGA platform equipped with five output DACs, whose voltages are then applied to the five sections of the chip. Our Pol-Ctrl algorithm minimizes in real-time the C_e error signal using a gradient algorithm and manages to demultiplex one of the two PAM-2 signals at the output of the considered waveguide. The upgraded version of our setup (compared to [2]) still update the DACs at 30 kSample/s, but internally runs a more sophisticated algorithm using a gradient algorithm with modifications that must handle the limited voltage (and thus phase rotation) excursion on each of the five stages. The algorithm that was programmed on our FPGA is based on the following steps: for each of the five sections (index i) and for each discrete time step (index n)

1. the phase of each of the five sections of the SiP Por-Rot is incremented by a small variation $\Phi_i(n) = \Phi_i(n-1) + \Delta$
2. the resulting new value of the monitoring signal $C_e(n)$ is acquired by the pilot tone receiver circuit. A modified monitoring signal is then obtained as $C_{e,bound}(n) = C_e(n) + f_{smooth}(\Phi_i(n))$ where $f_{smooth}(\cdot)$ is a smooth bath-tub curve that artificially increase the monitoring signal when the phase gets close to its bound, thus preventing it to go out of its range. We used the function $f_{smooth}(x) = erfc\left(2 \cdot \frac{x+\alpha}{\beta}\right) + erfc\left(-2 \cdot \frac{x-\alpha}{\beta}\right)$
3. the phase is then updated according to the following modified gradient algorithm
    a. $\Phi_i(n+1) = \Phi_i(n-1) + \mu \cdot (C_{e,bound}(n) - C_{e,bound}(n-1))/\Delta$
4. Given the value $\Phi_i(n+1)$, a new voltage $V_i(n+1)$ value is applied to section i electrodes. A look up table was used to consider the (approximately) quadratic relation between the applied voltage V_i and the corresponding phase rotation Φ_i, due to the fact that the device implements thermal tuning in each section, so that the phase rotation is approximately equal to the dissipated electrical power, which is then proportional to the voltage squared
5. The procedure is cyclically repeated over all the 5 sections of the Pol-Rot

The main upgrades of our current algorithms compared to [2] is in the new formulas used in points 2-4 of the previous list. The experimental results presented in the next section where taken after a heuristic optimization of the several free parameters of this algorithm (i.e. $\mu, \Delta, \alpha, \beta$) to obtain a best compromise between polarization tracking speed and accuracy.

IV. EXPERIMENTAL RESULTS

We transmitted PM-PAM-2 at 28 Gbaud, obtaining a gross baud rate of 56 Gbit/s using Fig. 4 setup. To test the effects of fast polarization variations, we used a commercial polarization scrambler. In a first set of experiments, to test the maximum polarization rotation speed that our system was able to sustain, we programmed the polarization scrambler to cyclically rotate one of its internal waveplates at speed gradually increased up to 350 rad/sec, generating different traces on the Poincarè sphere (two of them are shown in the inset of Fig. 5, which also report an example of the evolution of the five voltages applied to the Pol-Rot five sections).

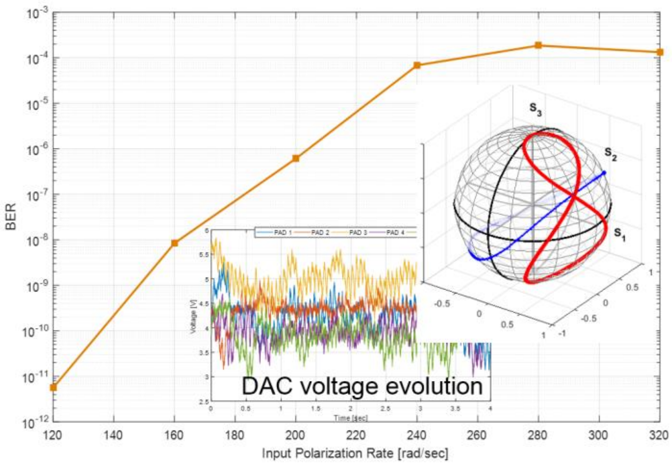

Fig. 5: BER vs. polarization rotation speed. The insets show two of the four generated paths on the Poincarè sphere at the input of the Pol-Rot, and an example of the evolution of the five voltages applied over the five sections of the Pol-Rot.

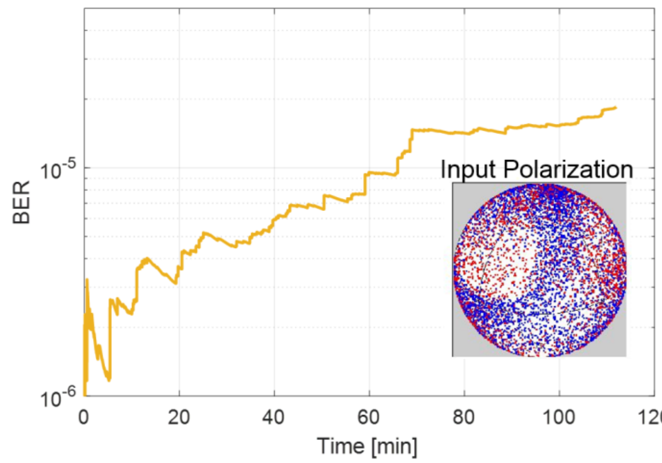

Fig. 6: Long term BER measurement (2 hours) at 100 rad/s random polarization rotations. The inset shows the resulting evolution on the Poincarè sphere at the input of the Pol-Rot.

Real-time BER values were then acquired, taking the worst case BER of 12 consecutive measurements (4 different paths on Poincarè sphere x 3 acquisitions). The results are shown in Fig. 5 as BER vs. rotation speed on the Poincarè sphere. The system was set to have BER=10^{-11} for null polarization rotation, then the polarization rotation speed was gradually increased. Fig. 5 shows that there is negligible penalty in the performance up to more than 100 rad/s input polarization rotations, while for values above 150 rad/s a BER degradation starts to be evident. In fact, when our tracker cannot follow anymore the fast input polarization variation, BER is degraded by the fact that a given output waveguide starts having significant crosstalk from the PAM-2 stream nominally meant for the other waveguide.

In a second set of experiments, shown in Fig. 6, we programmed the polarization scrambler to generate random polarization movements at 100 rad/s over the Poincarè sphere, then we continuously measured for two hours the resulting BER. Fig. 6 shows that the BER consistently remained well below the KP4 FEC threshold (BER<2e-4), typically used by IEEE standards in the DCI short reach sectors and demonstrate that polarization tracking was consistently achieved by our system for more than two hours. The insets of Fig. 6 shows the random evolution of the input polarization in a time window of 6 sec as measured by a polarization analyzer running at approx. 2Ksample/s. The increase in the measured BER over time is likely due to:

- long-term drifts in the free-space fiber-to-chip-to-fiber alignment system that, as previously explained, we have to implement to use our prototypal SiP chip
- some sporadic partial glitches in the polarization tracking, an effect we are still working on.

Due to some hardware limitation in our lab, we were limited to 28 Gbaud PM-PAM2, thus achieving a raw bit rate of 56 Gbit/s on a single wavelength. We are currently working on extending the experimental results to PM-PAM4 and to higher baud rates. We would anyway like to point out that the proposed polarization tracking algorithm is mostly independent on the PAM-M baud rate, since it works only on the information coming from the pilot tones. Thus, the achievable polarization tracking speed and the PAM-M speed are largely uncorrelated.

V. Discussion and Conclusion

We proposed and demonstrated how to double the capacity of DCI systems by using PM, but still sticking with direct-detection, showing achievable polarization tracking speed around 100 rad/s. The key results and novelty of our paper are: (i) use of a potentially very low cost receiver in SiP using only a direct-detection structure (no Stokes or coherent receivers needed); (ii) demonstration of an active real time polarization tracking algorithm based on simple and low-speed DSP processing and (iii) long-term measurement of SOP evolution in a commercial data center. From a techno-economic point of view, the proposed solution should be compared with a coherent-receiver one. While a detailed analysis is outside the scope of this paper, we point out anyway that from the DSP side, the required algorithms for pilot-tone handling and for polarization control run at relatively low rate (Msample/s) while the DSP required in coherent systems has to run (at least) at the baud rate, thus orders of magnitude faster. As a future work, longer term polarization rotation measurements in several types of real data centers would be needed to better address the maximum SOP rotation speed that can actually happen in a <2km data center link.

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