Wavelength-space permutation switch with coherent PDM QPSK transmission for supercomputer optical interconnects

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Abstract: We experimentally study the performance of an economically-viable, high-capacity supercomputer optical interconnect employing wavelength-space optical packet switching, polarization division multiplexed (PDM) quadrature phase shift keying (QPSK) modulation and coherent detection.
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1. Introduction

Several low-cost, low-latency, high throughput optical interconnect architectures have been proposed in the past for supercomputer applications [1]-[3]. However, the future viability of optical interconnects depends critically on the drastic reduction of the cost per input/output port. In [4], we proposed an economically-viable design of a $N \times N$ all-optical, wavelength-space permutation switch fabric for supercomputer optical interconnects, which is a variant of the configuration proposed initially for the Optical Shared MemOry Supercomputer Interconnect System (OSMOSIS) project [2], [3]. It is based on a broadcast-and-select architecture, with fixed-wavelength transmitters and discretely-tunable receivers. The latter use optimized multi-stage wavelength selectors, composed of multiplexers-demultiplexers (MUX/DMUXs) with periodic transfer functions and a minimum number of semiconductor optical amplifiers (SOAs) as on-off gates.

One of the drawbacks of the proposed architecture is that optical signals propagate through a concatenation of several SOAs in the multi-stage wavelength selectors of the discretely-tunable receivers. This results in the accumulation of amplified spontaneous emission (ASE) noise and, most importantly, in distortion due to nonlinear effects, esp. self-gain and cross-gain modulation, in SOAs [5], [6]. These effects limit the maximum number of channel selection stages and, eventually, the size of the optical interconnect.

In order to overcome the aforementioned limiting factors, polarization division multiplexed (PDM) quadrature phase shift keying (QPSK) coherent optical transmission can be used. PDM QPSK is currently considered for high-capacity long-haul optical communications systems in order to achieve an effective bit rate of 40 Gb/s by using a symbol rate of only 10 GBd. Its use in high-throughput supercomputer optical interconnects requiring 40 Gb/s optical signals [2] is beneficial for several reasons. First it leads to a dramatic reduction in equipment cost, since off-the-shelf, commercially-available, optoelectronic and electronic components with 10 GHz bandwidth can be used instead of their expensive, 40 GHz bandwidth counterparts. In addition, due to its envelope constancy, the resilience to self-gain and cross-gain modulation is greatly enhanced. Moreover, the use of practical, all-digital, coherent homodyne synchronous receivers enable electronic equalization of these effects. Finally, the increased sensitivity of PDM-QPSK with coherent detection compared to intensity modulation/direct detection allows for the reduction of the launched optical power per channel. This enables the operation of SOAs in the quasi-linear regime to avoid excessive distortion and to increase the number of concatenated SOAs.

The present experimental feasibility study investigates the impact of various transmission impairments in the performance of a 64×64 supercomputer optical interconnect when PDM-QPSK modulation is employed. It is an extension of the study reported in [3], which was performed using a non-optimal 64×64 interconnect architecture.

2. Optical interconnect architecture

In [4], it was shown that the most economical implementation of a 64×64 supercomputer optical interconnect, in terms of the number of on-off gates, can be achieved using a three-stage multiplexing/demultiplexing hierarchy at the transmitter/receiver cards, respectively (Fig. 1). The 64 transmitters are grouped into four identical sets of 16 wavelengths transmitted into four separate fibers. The 16 wavelengths are organized into four wavebands of four wavelengths each. The 16-wavelength plan is shown in Fig. 2. Wavelengths within each waveband and successive wavebands have equal spacing. However, there is a guardband between adjacent wavebands, in order to facilitate their discrimination by commercially-available waveband demultiplexers in the discretely-tunable receivers.

All signals from all four fibers are broadcasted to all 64 receiver cards using 1:64 star couplers. The receiver cards (Fig. 1) consist of three selection stages, each one of which separates a subset of channels from the ones

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received at its input, until one wavelength is obtained finally. At the 1st stage (fiber selection stage), one out of the four fibers is selected by biasing one out of the four SOAs above the transparency level. At the second selection stage (waveband selection) of the channel selector, the four wavebands are spatially separated and one of the four wavebands is selected by appropriate biasing one out of the four SOAs. Finally, at the third stage (wavelength selection stage) of the channel selector, one of the four wavelengths of the waveband is selected by appropriate biasing one out of the four SOAs. The major advantage of the aforementioned multi-stage selection configuration is that the required number of SOAs scales proportionally to $N\ln N$ [4] as opposed to alternative configurations [7], [8], which are not scalable. To achieve this reduction in the number of SOAs, it is necessary to use periodic MUX/DMUXs at the wavelength selection stage, with free spectral range $FSR_{\lambda}=4\ \Delta f$, where Δf is the channel spacing within a waveband.

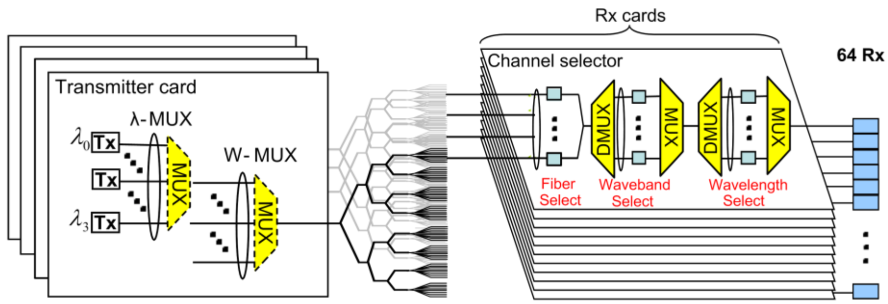

Fig. 1 Implementation of an optimal 64×64 optical interconnect with discretely-tunable receivers.

3. Experimental setup

Our experimental setup for a simplified, low-cost emulation of the aforementioned 64×64 optical interconnect is shown in Fig. 3. At the transmitter side, only three DFB lasers are used, each with ~20 MHz 3-dB linewidth, with appropriate optical powers and channel spacing to represent all 16 transmitted wavelengths. The first wavelength (λ_0=1547.725 nm), represents the channel under study that is finally detected at the receiver. The second one (λ_2=1549.325 nm), emulates the three neighboring channels in the same waveband as λ_0, and is therefore selected $2\Delta f$=200 GHz apart from λ_0 (Δf=100 GHz). Finally, the third wavelength (λ_{17}=1561.326 nm), emulates the twelve

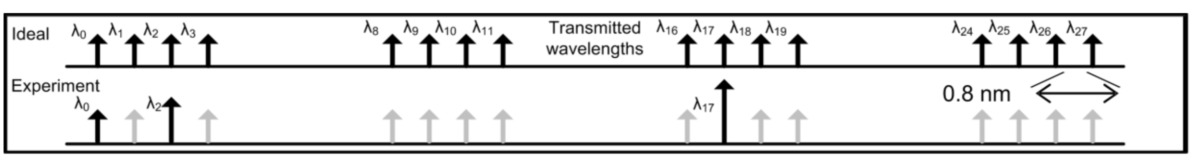

Fig. 2 Channel plan.

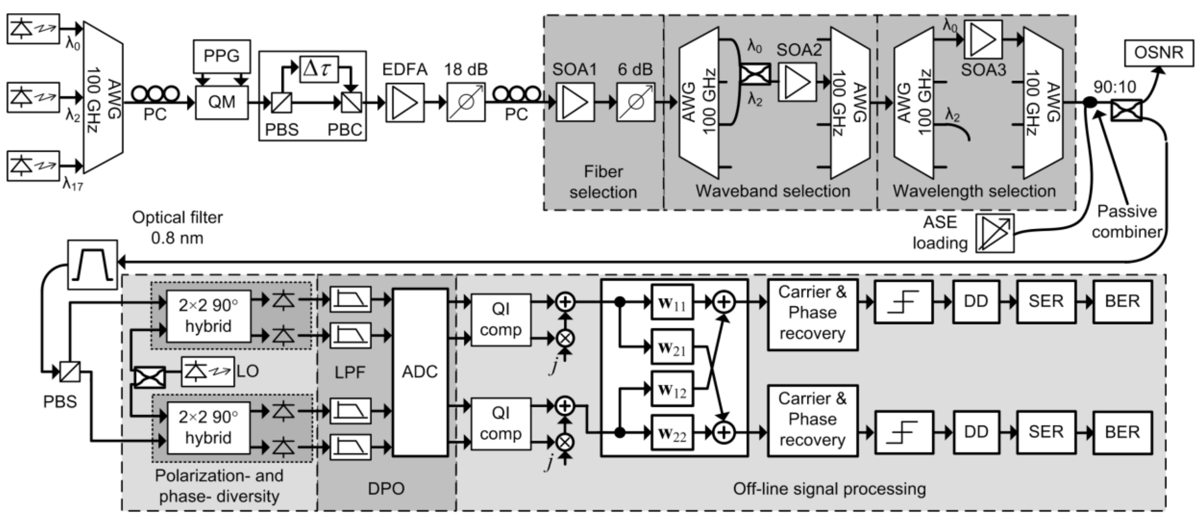

Fig. 3 Experimental setup and DSP algorithms.

wavelengths of the three adjacent wavebands. It is approximately placed in the middle of these wavebands so it is

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13.6 nm apart from λ_0. The launch powers are P_0, $3P_0$, and $12P_0$, respectively. The 3-stage multiplexing hierarchy at the transmitter is simplified by using a single AWG with 100 GHz channel spacing to combine all three wavelengths. Subsequently, the CW WDM optical signals are QPSK modulated using a quadrature modulator (QM). This is biased by two independent 2^7-1, 2.5 Gbps, pseudorandom binary sequences, generating a 2.5 GBd QPSK modulated signal. Polarization multiplexing is performed as shown in Fig. 3. The PDM-QPSK signal is amplified using a booster and then attenuated by 18 dB, representing the splitting ratio of the 1:64 star coupler in Fig. 1. The signal is then transmitted through a chain of SOAs. The 1st SOA represents the on-off gate of the fiber selection stage of the discretely-tunable receiver in Fig. 1. The 6 dB losses that follow represent the 4:1 combiner coupler losses after the fiber selection stage in Fig. 1. A flattened AWG DMUX with 100 GHz channel spacing and a 3 dB coupler that recombines λ_0 and λ_2 is then used to emulate the waveband demultiplexer in Fig.1. These wavelengths enter the 2nd SOA emulating the waveband on-off gate of the channel selector. Finally, the optical signal enters the wavelength selection stage, which consists of a pair of conventional AWG MUX/DMUX, with 100 GHz spacing, interconnected via a 3rd SOA. At this last stage, λ_2 is rejected and the selection of the desired wavelength channel λ_0 is performed. ASE noise is added to the signals at the link end to allow bit-error-rate (BER) measurements to be obtained as a function of OSNR. The PDM-QPSK signal is then filtered by a 0.8 nm optical filter and detected in a polarization- and phase- diversity coherent receiver, as shown in Fig. 3 [4]. The local oscillator is an external cavity laser (ECL) with 200 kHz linewidth. The outputs of photodetectors are sampled in a real-time digital oscilloscope (DPO) at a sampling rate of 5 GSa/s. The samples are then stored and processed off-line [9].

4. Results and Discussion

In order to evaluate the performance of the system, measurements of BER as a function of OSNR were carried out after each selection stage of the architecture. The results are summarized in Fig. 4. Comparing the BER curves we observe that the performance of the system degrades slightly as the number of selection stages increase. The high values of the required OSNR indicate a severe penalty due to the phase noise of the DFB laser and possibly due to imperfect QPSK modulation. Additional distortion in the phase of the signal might be due to SPM and XPM when the signal passes through the SOAs. In addition, deviation from orthogonality of the polarizations tributaries caused by the SOA polarization dependent gain (PDG) leads to cross-polarization interference. Nevertheless, the adaptive equalizer in the coherent receiver can compensate for these distortions to some extend. Despite the poor quality of the received signal, FEC can recover the initial data and warranty error free transmission. For qualitative comparison, constellation diagrams of one of the polarization components are shown on the right of Fig. 4 after the 1st, the 2nd and the 3rd selection stage, from left to right respectively, for OSNR=20dB.

In conclusion, we experimentally studied the performance of a 64x64 wavelength-space supercomputer optical interconnect based on on-off gates SOAs and showed the feasibility of the use of PDM-QPSK modulation and coherent detection for the first time.

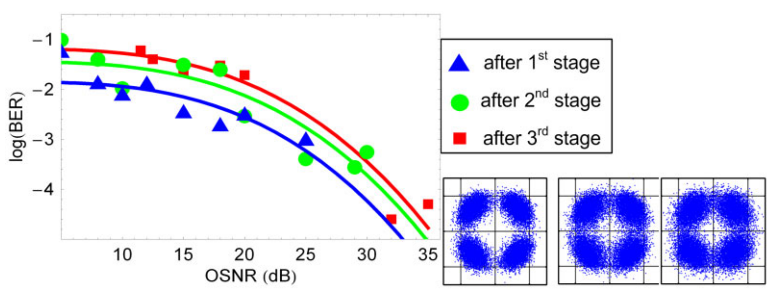

Fig. 4 BER vs. OSNR (measured at 0.07 nm Resolution Bandwidth) and representative constellation diagrams

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