Penalty-Free Transmission of 127-Gb/s Coherent PM-QPSK over 1500-km of NDSF with 10 Cascaded 50-GHz ROADMs

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Abstract: We experimentally demonstrate penalty-free transmission of 127-Gb/s coherent PM-QPSK through a cascade of ten commercial 50-GHz WSS over 1500-km NDSF. Simulation results show that cascades of 40 such 50-GHz liquid-crystal based ROADMs is feasible.

OCIS codes: (060.1660) Coherent communications; (130.7408) Wavelength filtering devices

1. Introduction

In recent years, polarization-multiplexed quadrature phase shift keying (PM-QPSK) with coherent detection has emerged as the leading candidate for single-carrier 100-Gbit/s Ethernet (100-GE) metro and long-haul transport [1]. The factor of 4 reduction in the symbol rate suits well with state-of-the-art CMOS analog-to-digital converters (ADCs). The use of coherent detection and digital signal processing substantially enhances the tolerance of virtually any linear fiber impairments [1]. The demand for higher network capacity is driving the industry to retrofit existing networks with these 100-Gb/s channels operating at 50-GHz spacing. Adding to the challenge, modern networks are increasingly using ROADMs for reconfigurable networks. Cascades of ROADMs can lead to a significant reduction in the available optical bandwidth, which presents a major concern for high data rate (40G and beyond) systems.

While compatibility of various 40-Gb/s formats with cascades of ROADMs has been documented in literature [2-3], very few papers [1, 4] have touched on the filtering tolerance of 100-Gb/s formats and information regarding the dependence on filter shape and cascading limits is lacking. In this paper, we show, via simulation and experiments, the outstanding tolerance of coherent 100-Gb/s PM-QPSK to cascades of 50-GHz WSS. The WSS used in the experiments are based on liquid crystal technology [5], and provide a 4th order super-Gaussian shape with a nominal 3-dB bandwidth of 45 GHz. Concatenation of 10 such devices still leaves ~36-GHz bandwidth and thus results in no measureable penalty on the 100 Gb/s channel, in line with our modeling results. In addition, we investigate in simulation the impact of various practical filter shapes and bandwidths. We find that cascades of up to 40 ROADMs is possible using the same 4th order WSS modules. Finally, we demonstrate penalty-free transmission of 127-Gb/s PM-QPSK (representing a signal with 20% FEC overhead) over a distance of 1500-km NDSF with a cascade of ten 50-GHz WSS. Linear and nonlinear transmissions are compared with and without ROADM filtering.

2. Concept and Experimental Setup

The 127-Gb/s transmitter and receiver architectures are shown in Fig. 1 (a) and (b), respectively. The PM-QPSK Tx consists of a tunable laser source (TLS) with 100-kHz linewidth, an RZ carver, followed by two Mach- Zehnder

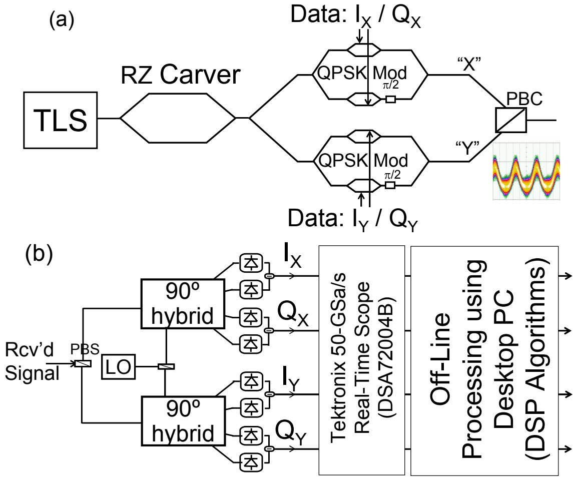

Fig. 1 (a). 127-Gb/s PM-QPSK transmitter structure; (b). 127-Gb/s PM-QPSK coherent receiver structure.

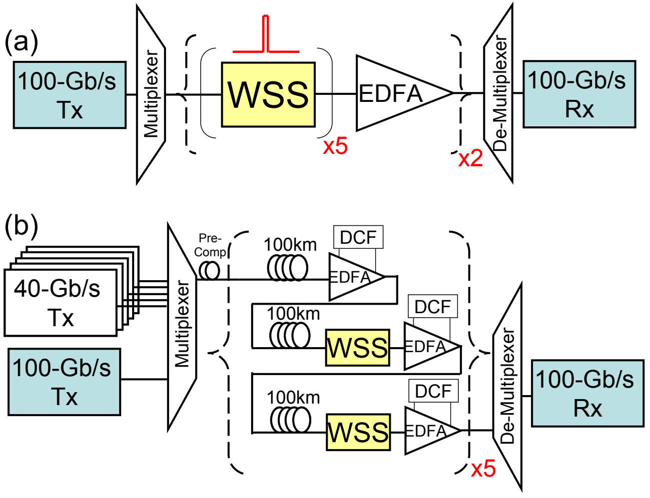

Fig. 2. Experimental setup of (a) back to back and (b) 1500-km transmission over a cascade of ten 50-GHz WSS using 127-Gb/s coherent PM-QPSK.

modulators and a polarization beam combiner (PBC) to combine the two arms into orthogonal polarizations. Each QPSK modulator is fed with independent PRBS 2^{21}-1 data patterns at 31.625-GSymbol/s, resulting in a total line rate of 127-Gbit/s. The inset in Fig. 1(a) shows a typical output from the PM-RZ-QPSK Tx. The receiver optical front-end is comprised of a local oscillator (LO) with a 100-kHz linewidth, a polarization beam splitter (PBS), two 90^o optical hybrids, and four balanced photodiodes. The beat terms, I_X, Q_X, I_Y, Q_Y, are digitized and stored using a Tektronix real-time scope (DSA72004B) running at 50-GSample/s. Care is taken to synchronize the four optical paths to the ADCs within 1ps. The stored data are then post-processed off-line on a PC using the following DSP algorithms: 1). Constant modulus (CMA) equalization; 2). Fine frequency correction (FFC); 3). LMS adaptation for linear equalization; 4). Viterbi-Viterbi carrier phase estimation (CPE), and 5). Detection and calculation of constellation SNR, which directly maps to Q^2 factor via BER when there is no cycle slip during CPE.

Fig. 2 shows the experimental setup of back-to-back and 1500-km fiber transmission with up to ten 50-GHz WSS concatenations. Two EDFAs are used to compensate the insertion loss of the 10 WSS in Fig. 2 (a). For Fig. 2 (b), the 1500-km transmission link consists of a pre-compensation of -500 ps/nm, 15 spans of 100-km Corning SMF-28 ultra-low loss (ULL) fiber (18 dB span loss) with 98% in-line dispersion compensating fiber (DCF). For every three fiber spans, 2 WSS's are inserted after the SMF-28 ULL, and a total of 10 WSS's are incorporated. The 127-Gb/s PM-RZ-QPSK signal at 1548.51 nm, together with an additional five 40-Gb/s DPSK signals, constitute the WDM channels. All the channels are multiplexed with sufficient channel spacing to allow us to only concentrate on single channel performance and, thus, the worst cascaded narrow-band filtering scenario.

The WSS modules are based on CoAdna's patented liquid crystal (LC) technology [5]. Controlling an LC's orientation via external electric fields controls the input beam polarization and provides a means for any wavelength to be directed to any port and attenuated or blocked as needed. The transition between adjacent channels occurs over a narrow and stable region thereby forming a wide, sharp and stable passband filter shape. This also provides low CD, PMD, PDL and group delay ripple (GDR), as shown in Fig. 3, which are desirable for coherent receivers.

3. Experimental and Simulation Results

Figure 4 shows the measured 127-Gbit/s PM-RZ-QPSK spectrum overlaid with the spectra of one and ten cascaded 50-GHz WSS. Thanks to the spectrally efficient multi-level format, the 100-Gb/s signal fits well into the 50-GHz channel grid. The 50 GHz WSS's have a fourth-order super-Gaussian shape with a nominal 3-dB bandwidth of 45 GHz. After concatenating ten such devices, the resultant bandwidth still exceeds 36 GHz, shown as the red curve in Fig. 4. The measured OSNR sensitivity of the filtered (50 GHz MUX) 127-Gb/s PM-QPSK signal with and without traversing the 10 WSS's is shown in Fig. 5. The large cascaded bandwidth, together with the powerful equalization techniques used in coherent detection, results in negligible penalty after 10 cascaded WSS, as shown in Fig. 5.

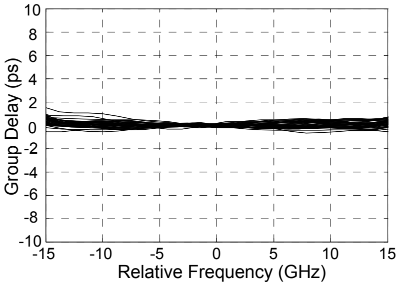

Fig. 3. Typical group delay of overlaid 96 channels from 50 GHz WSS. Less than 2-ps peak-peak GDR is observed on all channels.

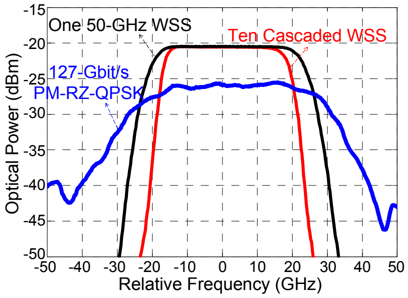

Fig. 4. Unfiltered 127-Gb/s PM-QPSK spectrum, together with the pass-band of a single and ten cascaded 50-GHz WSS.

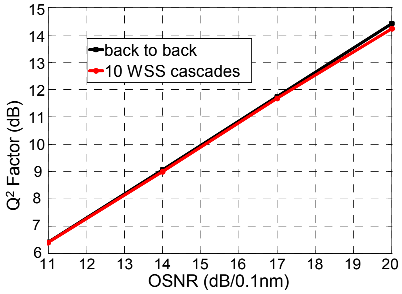

Fig. 5. OSNR sensitivity measurement with and without 10 cascaded WSS. No penalty is observed after ten concatenated devices.

We carried out numerical simulations to investigate the impact of the filter shape and bandwidth on the ROADM cascadability limit for 127-Gb/s coherent PM-QPSK signals. The 127-Gbit/s transmitter first goes through a 50 GHz MUX with a 2nd order super-Gaussian profile and a 3-dB bandwidth of 40 GHz. We then vary the 3-dB bandwidth and filter order of the DeMux filter to mimic the WSS-induced narrow-band filtering effects. For a fixed OSNR of 20 dB at the receiver, Fig. 6 shows the normalized Q^2 penalty versus the 3-dB bandwidth for four different WSS super-Gaussian order filters. Compared to the lower order super-Gaussian filters, the higher order ones have less absolute 3-dB bandwidth tolerance due to the steeper roll-offs and resultant loss of information. If we draw a Q^2 penalty line (0.5 dB in this case), we determine the cut-off bandwidths for order 1, 2, 3, and 4 super-Gaussian filters to be 17.8 GHz, 24.5 GHz, 27 GHz and 28.5 GHz, respectively. Plotting the experimental points (red stars) 1 to 10 cascaded 4th order WSS, we find an excellent match between experiment and simulation.

At first glance, the lower order filters seem to perform better, as judged by their better performance at lower 3-dB bandwidth shown in Fig. 6. However, when we consider cascading performance, the higher order filters substantially out-perform lower order ones, as shown in Fig. 7. Fourth order filters have a much slower cascaded bandwidth reduction compared to that of lower order filters, as can be confirmed from the following equation [6].

$$B_{cascaded} = \left(\frac{1}{N}\right)^{\frac{1}{2n}} B_0$$

where n is the order, N is the number of cascades, and B_0 is the 3-dB bandwidth of a single filter. If we plot the 0.5-dB penalty values obtained from Fig. 6 on Figure 7, we find the cascadability limits for order 1, 2, 3, and 4 super-Gaussian filters to be 6, 11, 21 and 41 modules, respectively, assuming a uniform 45-GHz single element bandwidth and no frequency offset. The measured results from 1 to 10 WSS cascades ("red star" symbols in Fig. 7) indicate that some modules have an order higher than 4 or exceed the 45-GHz nominal bandwidth.

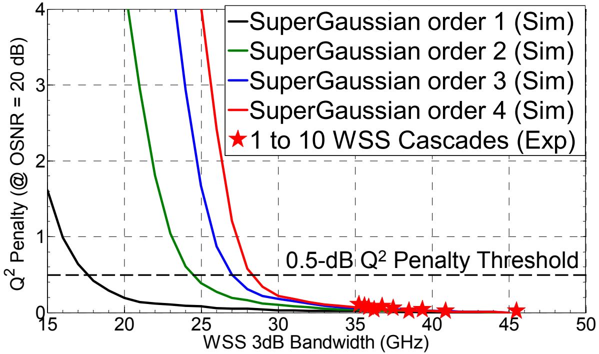

Fig. 6. Simulation results of Q^2 penalty versus 3-dB bandwidth for order-1 to order-4 super-Gaussian filter shape. 0.5-dB penalty line is drawn, showing the bandwidth tolerance for various filter shapes.

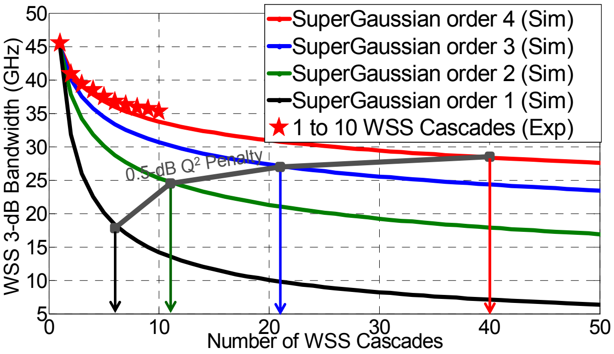

Fig. 7. Simulation curves showing the cascadability of various filter shapes based on the 0.5-dB Q-penalty line. This reveals that up to 40 cascades of 4th-order WSS are feasible with 127-Gb/s signals.

We next incorporate these 10 WSS modules into a fiber transmission environment to investigate the interaction between filtering and linear/nonlinear fiber impairments. The 1500 km link is as described in section 2, with the 10 WSS configured to have either of the two modes shown in Fig. 8. The "Drop Mode", in which the two adjacent 50 GHz channels are blocked, emulates the worst case filtering from the 10 cascaded WSS. Since near identical optical powers are passed through the cascaded WSS for these two WSS profiles, all 15 EDFAs are operating at the same condition, and thus the OSNRs after 1500 km transmission are the same for these two modes. For 0-dBm fiber launch power, the OSNR at the end of the link is 18.4 dB. Fig. 9 shows the transmission performance as a function of fiber launch power. At low launch power from – 4 dBm to -2 dBm, the "Express" and "Drop" modes perform identical, which is in line with the linear cascade results in Fig. 5. At 0 dBm optimal launch, only 0.3-dB additional penalty from the "Drop" mode is observed, which can be attributed to the filtering-induced pattern-dependent power fluctuations resulting in higher nonlinear penalty. At launch powers from 2 to 5 dBm, the difference gradually diminishes as intrinsic fiber nonlinear effects starts to dominate. This small additional penalty is due to the large effective bandwidth (36 GHz) after 10 cascaded ROADMs, as indicated by the near identical signal quality from the two inset QPSK constellations on one of the two polarizations. We expect the WSS-induced nonlinear penalty to increase if the number of cascades is increased or the order of the filter is reduced.

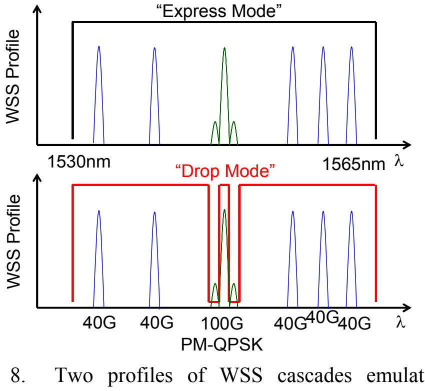

Fig. 8. Two profiles of WSS cascades emulating "express" and "drop" operation modes, which are compared in the 1500-km transmission experiment.

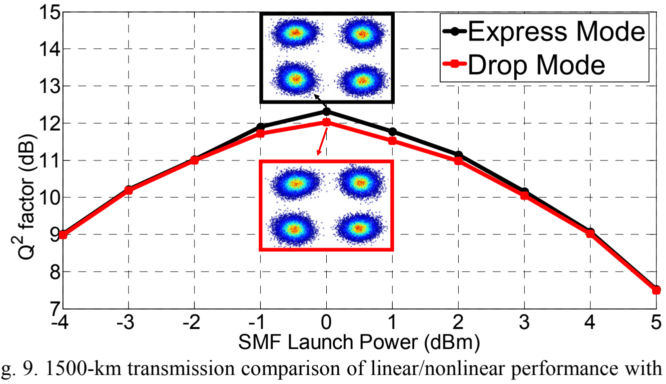

Fig. 9. 1500-km transmission comparison of linear/nonlinear performance with and without cascaded WSS filtering. < 0.3 dB penalty at optimal launch power shows the nonlinear robustness of 127-Gb/s PM-QPSK signals over ten 50-GHz WSS's.

4. References

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