100Gb/s dual-carrier DP-QPSK performance after WDM transmission including 50GHz Wavelength Selective Switches

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Abstract: Using a real-time intradyne receiver, we characterize the tolerance of a 100Gb/s dual-carrier dual-polarization-QPSK signal to carrier frequency separation and frequency offset after WDM transmission over 9×100km standard single-mode fiber and ten wavelength selective switches.

OCIS codes: (060.2330) Fiber optics communications, (060.4250) Fiber optics components, (060.1660) Coherent communications.

1. Introduction

Reconfigurable Optical Add/Drop Multiplexers (ROADMs) are being widely deployed in metro, regional, and long-haul optical networks. ROADMs afford carriers the advantages of reconfigurable optical networks, including the ability to remotely rearrange wavelength connections at intermediate sites to meet new traffic demands quickly and efficiently. In the near future, ROADMs will be deployed in networks carrying 100Gb/s channels on the 50GHz ITU grid. Therefore, the tolerance of 100Gb/s channels to the filtering from 50GHz wavelength-selective switches (WSS), the optical switch "building block" of a ROADM, is important. Several studies of the filtering penalties of 100Gb/s single-carrier dual-polarization quaternary-phase-shift-keyed (DP-QPSK) signals have been reported using offline processing [1-3]. Using a filter with near rectangular passband, reference [1] reported no significant penalty of the 27.75-Gbaud return-to-zero (RZ) DP-QPSK signal until the 3-dB bandwidth dropped below ~30GHz. In [2], a 127Gb/s single-carrier RZ DP-QPSK signal was passed through ten liquid-crystal-based WSSs with concatenated bandwidth of 36GHz FWHM, where each WSS had fourth-order super-Gaussian shape and ~45GHz FWHM.

In this paper, we used a 115.2Gb/s signal comprised of two 57.6Gb/s DP-QPSK carriers (each at 14.4 Gbaud) separated by approximately 20GHz and studied its tolerance to cascaded filtering. Multi-carrier transmission has the advantage of operating at a lower baud rate, without the complexity of optical OFDM or the optical-signal-to-noise (OSNR) requirements of higher-order modulation formats. This may become increasingly important as channel rates increase to 400Gbps and beyond. For the 115.2Gb/s dual-carrier signal, the tolerance to the carrier frequency separation as well as the offset of the center of the two carriers relative to the filter center was measured, for back-to-back and after transmission through two and ten micro-electromechanical (MEMs)-mirror-based WSSs. In addition, the 115.2Gb/s signal was transmitted, along with 112Gb/s dual-carrier neighbors, through 9×100km standard single-mode fiber (SSMF) and ten WSSs to understand its performance in a WDM environment. The measurements showed less than 1dB difference in required OSNR for carrier frequency separations between 17 and 26GHz, and that for 20GHz carrier separation, the center of the dual-carriers could be detuned by ±3GHz.

2. Experimental Setup

The experimental configuration for WDM transmission through fiber spans and WSSs is shown in Fig. 1. The signal under test (at 193.40THz, denoted channel 51) was generated and received using two pre-production grade Ciena eDC100G-LH transceivers, previously described in [4]. Two 57.6Gb/s DP-QPSK carriers, nominally spaced by 20GHz, are combined in a 3dB coupler, resulting in a dual-carrier 115.2GHz channel having a sufficiently compact spectrum to allow placement in the 50GHz ITU grid. For these experiments a PRBS of length 2^{31}-1 was used as the test data, and the modulators' bias voltages and RF drive levels are optimized automatically. In the receiver, a 3dB coupler splits the incoming signal and sends it to two coherent receivers utilizing different LO frequencies. Coherent detection can receive a single carrier from within a multi-carrier signal by tuning the local oscillator (LO) near the desired carrier and filtering the resulting signal electronically, enabling reception of the desired carrier without optical filtering [4]. Each coherent receiver uses four single-ended detectors to receive the four signal components that are orthogonal in optical phase and polarization. The signals are digitized and then processed in real-time using a custom ASIC, as described in [4,5]. As shown in Fig. 1, the system set-up also included 79 loading channels on the 50GHz grid to fill the C-band, including four 112Gb/s dual-carrier DP-QPSK loading signals on both sides of the channel-under-test, and seventy-one 56Gb/s DP-QPSK channels at wavelengths above and below the group of nine 100Gbps channels (see Fig. 2a). The loading wavelengths were combined and modulated such that adjacent channels and adjacent carriers passed through different modulators as a means of decorrelation. In addition, loading channels were transmitted through decorrelating fiber before being combined together and, thereafter, combined with the signal channel in WSS-1. Noise loading (to vary the received OSNR) was provided by the filtered amplified spontaneous emission from an optical amplifier. WSS-10 was used for demultiplexing the channel-under-test before the receiver input of tunable transceiver #2.

The transmission line consisted of nine 100-km spans of SSMF (average 20.5dB loss and PMD < 0.1ps/√km) and two-stage erbium-doped fiber amplifiers (EDFA), launching +18dBm into the spans (-1dBm/channel). The WSSs were arranged and configured to emulate a link in which the channel-under-test would undergo maximum filtering by ten WSSs and yet would be transmitted with 50GHz spaced neighbors in all nine fiber spans for maximum inter-channel nonlinearities. At the EDFA mid-stage after span 1, WSS-2 dropped a pair of 100Gbps channels from each side adjacent to the channel-under-test. These four dropped channels were amplified, passed through a 1×8 passive splitter, and then added to the express signals using a 3dB coupler before span 2 and using WSS-3 to WSS-9 before spans 3 to 9, respectively. The ten WSSs were 1×5, C-band, commercially available modules; the measured passbands and group delays (GD) were quite uniform across all ten WSSs, as shown in Fig. 3. For the concatenation of WSS1-10, the bandwidths at -3, -10, and -20dB were 35.7, 39.6, and 42.2GHz, respectively. Measured PDLs of each individual WSS (for the channel-under-test at 193.4THz) were less than 0.05dB.

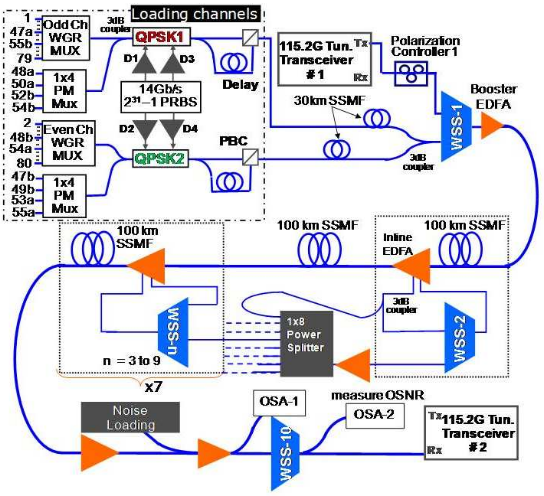

Fig. 1: Set-up for WDM transmission experiments. Lasers labeled with “a” (“b”) are shifted up (down) from the ITU channel frequency by one-half of the carrier separation.

3. Results

The frequencies of the 57.6Gb/s DP-QPSK carriers of the channel-under-test could be controlled, allowing investigation of the performance of the 115.2Gb/s channel relative to the carrier separation and carrier offsets. Measurements of bit-error-ratio (BER) versus OSNR were made for both carriers, both with and without the transmission fiber and WSS 2-9, as the carrier separation was varied. From these BER curves the required OSNRs

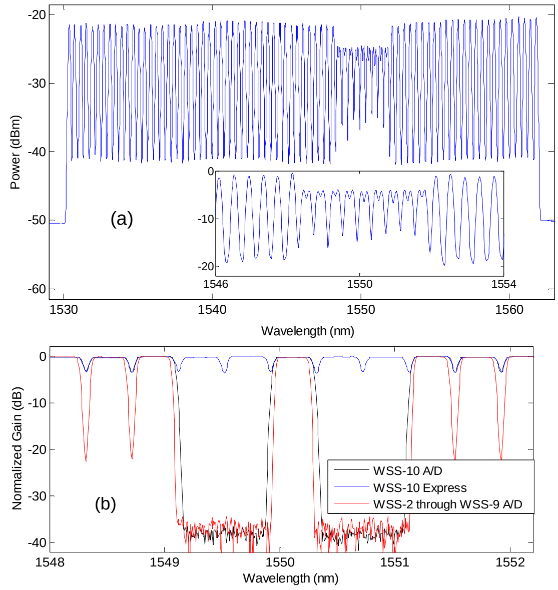

Fig. 2: (a) Optical Spectrum at span 9 output. Inset: expanded view of 100Gb/s channels at booster output. (0.1nm RBW) (b) Normalized gain of WSS-10 in Add/drop and Express modes and of WSS-2 through WSS-9 in Add/drop mode.

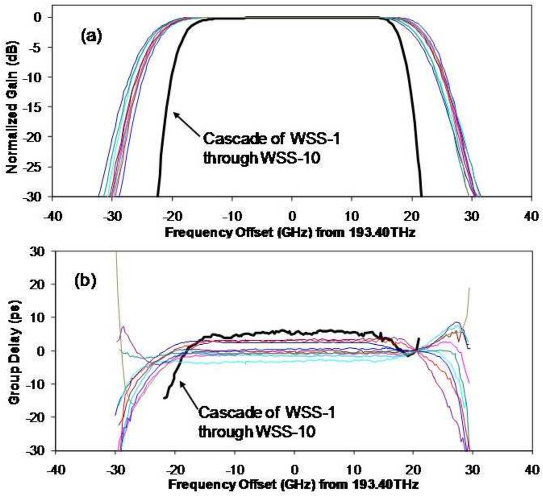

Fig. 3: (a) Measured passbands and (b) GD of the ten individual WSSs and for the cascade of WSS-1 through WSS-10, when in Add/drop mode. GD’s shown where normalized gain is > -30dB. The averages over the 10 WSS of the bandwidths at -3, -10, and -20dB were 45.1GHz, 50.8GHz, and 56.2GHz, respectively. The average center wavelength was 1550.119nm (defined as the average of the wavelengths at -3dB) with standard deviation of 0.006nm.

(ROSNRs) necessary to achieve a pre-FEC BER of 10^{-3} for each carrier were calculated and then averaged to obtain the ROSNR for the 115.2Gb/s channel. Figure 4 shows the ROSNR as a function of the frequency separation of the two carriers, with the dual carrier signal centered on the ITU channel (the average frequency of the two carriers was 193.40THz). Simulation results also are included in Fig. 4 and show good agreement with measurements. Simulations transmit random data of length greater than 2000 baud on each sub-carrier at the specified carrier spacing and channel offset through measured optical filter transfer functions. System optical noise is injected before the last WSS and the received pre-FEC BER is obtained by direct error counting on approximately 80,000 baud. In addition to measurement results when the WSSs were in add/drop mode, Fig. 4 also shows measurement results when all channels used the express path through WSS 2-9 (see Fig. 2b). After transmission through 900km and the ten WSSs there was no difference between the measured ROSNR for these two different configurations of WSS 2-9, as could be expected based on Fig. 2b.

Measurements and simulations were also performed as the dual carriers' center frequency (the average frequency of the two optical subcarriers) was offset from the ITU grid (i.e. 193.40THz), with a fixed 20 GHz separation between the two carriers. Curves labeled "full channel" in Fig. 5 show how the ROSNR (average of the two sub-carriers' ROSNRs when the full channel's BER is 10^{-3}) varies as the center frequency of the channel is detuned (for fixed 20GHz separation) for transmission through two and ten WSSs in add/drop mode (and no fiber) and for transmission over 900km and 10 WSSs in add/drop mode. Using the same BER data, Fig. 5 also shows the measured OSNR of the full channel when each subcarrier had a BER of 10^{-3}, plotted against that subcarrier's frequency. For example, the circled point in Fig. 5 was computed using the same raw data as was used to compute the two points denoted with arrows. Close agreement between measurements and simulation was found. As expected, when the two carriers are detuned so that their optical frequency is high, then errors due to carrier 1 (the higher frequency subcarrier) dominate. When the carriers are detuned in the opposite direction, then the errors on the lower-frequency carrier dominate. The results show that for this case of 20GHz carrier separation, there is less than 1dB ROSNR difference for ±3GHz detuning of the center of the dual-carriers from the center of the cascaded filters' passband.

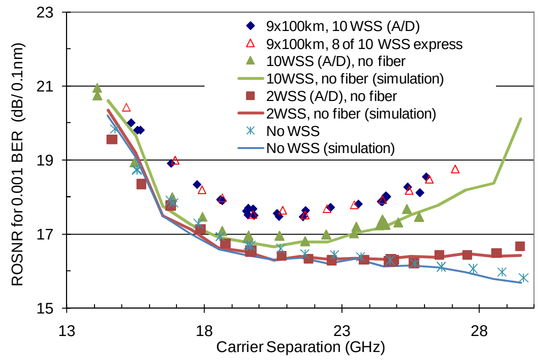

Fig. 4: The ROSNR of the dual-carrier 115.2 Gb/s channel to achieve a BER of 10^{-3} as the separation between the carriers was varied.

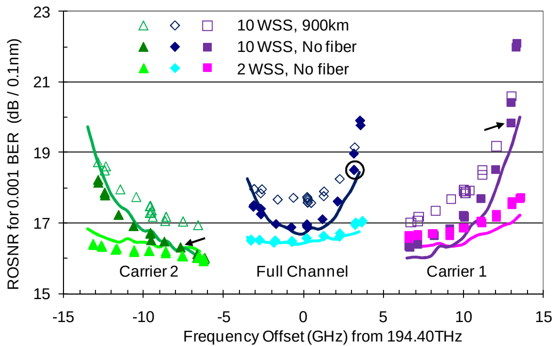

Fig. 5: ROSNR of the dual-carrier 115.2Gb/s channel for 10^{-3} BER as the signal was detuned from the ITU grid while maintaining 20GHz carrier separation. Also shown is the ROSNR when each of the two carriers has 10^{-3} BER. Markers: measurements; solid curves: simulations without fiber.

4. Conclusions

We have characterized the tolerance of a 115.2Gb/s dual-carrier DP-QPSK signal to carrier frequency separation and frequency offset after transmission through ten 50GHz WSSs, including with 900km SSMF transmission with 100Gbps dual-carrier neighbors. For carrier frequency separations between 17 and 26GHz, there was less than 1dB difference in ROSNR. For a fixed 20GHz carrier separation, the center of the dual-carriers could be detuned by ±3GHz, where as expected, the increase in the ROSNR can be attributed to filtering penalties imposed on the carrier closest to the band edge. Simulations of the performance without fiber transmission are in close agreement with measurements results.

References

1. C. Fludger et al., *J. Lightwave Technol.* **26**, 64 (2008).
2. B. Zhang et al., *OFC-NFOEC 2010*, paper NTuC5.
3. M. Birk et al., "Real-time, Single-carrier Coherent 100 Gbps PM-QPSK Field Trial," to appear in *J. Lightwave Technol.*
4. F. Ruhl et al., *OFC-NFOEC 2010*, paper NTuC4.
5. K. Roberts et al., *J. Lightwave Technol.* **27**, 3546 (2009).