OSNR monitoring of a 1.28 Tbit/s signal using a reconfigurable Wavelength Selective Switch

Jochen Schröder*[,1], Owen Brasier[1], Jürgen Van Erps[1,2], Michaël A. F. Roelens[3], Steve Frisken[3] and Benjamin J. Eggleton[1]

[1]*Centre for Ultrahigh bandwidth Devices for Optical Systems (CUDOS), Institute for Photonics and Optical Sciences (IPOS), School of Physics A28, The University of Sydney, NSW 2006 Australia*
[2] *Vrije Universiteit Brussel, Brussels Photonics Team, Dept. of Applied Physics and Photonics Pleinlaan 2, 1050 Brussel, Belgium*
[3] *Finisar Australia, Waterloo NSW 2017 Australia*
**j.schroeder@physics.usyd.edu.au*

Abstract: We demonstrate in-band optical signal to noise monitoring of an 1.28 Tbit/s signal by implementing an interferometer inside a reconfigurable wavelength selective switch based on liquid crystal on silicon technology.

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1. Introduction

Optical performance monitoring techniques are a key technology for maintenance and diagnostics optical communications networks [1] and the optical signal to noise ratio (OSNR) is arguably the major performance indicator for the signal quality of a transmission link. With the advent of reconfigurable or wavelength-routed networks, it has become highly desired to monitor the OSNR at various points of the network, to enable fault-localization and efficient rerouting. However the traditional method of interpolating the in-channel noise from the intra-channel noise level fails in reconfigurable networks, because the in-channel noise can differ significantly from out-of-channel noise, thus new in-band measurement techniques have to be developed.

One very promising method is based on interferometry, taking advantage of the different coherence properties of signal and noise to determine the in-band OSNR. This technique is particularly advantageous due to its robustness against other impairments such as chromatic dispersion or polarization mode dispersion [2] and because it is modulation format independent. A number of publications have shown OSNR measurements by this technique with various interferometer configurations [2–4]. However for integration into future wavelength-routed networks, novel OSNR monitoring techniques should be easily reconfigurable, e.g. to adapt to new network plans and be applicable to various modulation formats and be scalable to high bit-rates.

We recently demonstrated an interferometry-based OSNR-monitor by implementing a delay-line interferometer (DLI) using the liquid crystal on silicon (LCoS) array inside a wavelength selective switch (WSS) [5]. The advantage of this approach is its reconfigurability to different network plans and channel bandwidths and the ability to measure multiple channels simultaneously as well as the fact that it could be readily integrated into existing networks without significant infrastructure investments and the need for complicated stabilisation. In this paper we demonstrate the resilience of our approach to other impairments and its scalability to ultra-high bandwidth signals. In particular we show the OSNR monitoring of a 1.28 Tbit/s optical time-division multiplexed signal with a monitoring error below 1 dB over a monitoring range of 5 to 25 dB OSNR. This is to the best of our knowledge the first time that the OSNR of such a high symbol rate signal as been measured with this accuracy.

2. Method

The OSNR monitoring technique is based on the different coherence properties of a modulated signal and the amplified spontaneous emission (ASE) noise stemming from amplifiers in the network, which is the main cause of OSNR degradation [1, 2]. A signal, even if modulated by a random bit pattern, remains partially coherent over several bit-periods. The coherence time of ASE noise on the other hand is in general significantly shorter and is mainly determined by the channel-bandwidth. If the coherence function of the signal-only and noise-only are known (i.e. through configuration measurements), one can calculate the OSNR of a noisy signal from a measurement of its coherence, e.g. with an interferometer. Here we set the DLI to a specific delay and measure the power ratio of constructive over destructive interference R. The OSNR of the signal under test (SUT) can then be determined using the following equation [2]:

$$OSNR(dB) = 10 \cdot \log_{10}\left(\frac{1}{\frac{(n+1)(s-n)}{(R-n)(s+1)} - \frac{n+1}{s+1}} \times \frac{\Delta\nu}{12.5\ \text{GHz}}\right) \tag{1}$$

where n and s are the power ratio of constructive over destructive interference of the noise- and signal-only and $\Delta\nu$ is the noise equivalent bandwidth (the channel bandwidth). It should be noted that s and n are configuration measurements to determine the signal and noise coherence function. These measurements only have to be taken once. In an actual implementation, s would be determined at the point where the signal joins the network, and n would be acquired by a short measurement-run of the network running without signal but the amplifiers turned on.

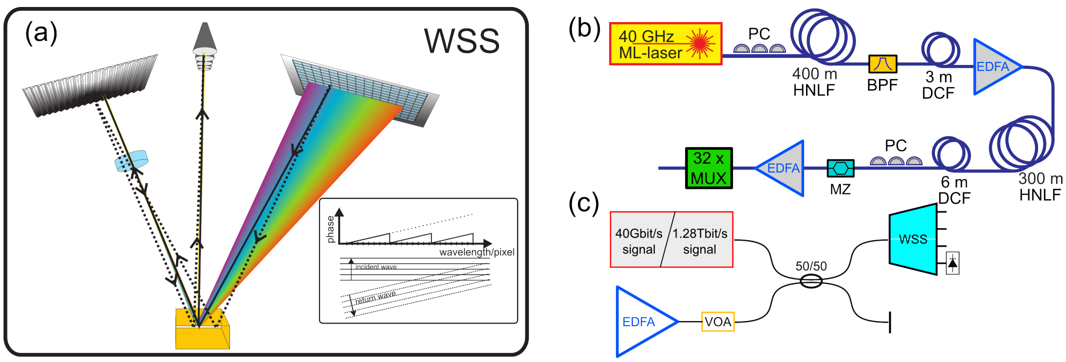

Fig. 1: (a) Operating principle of the WSS (Inset: principle of wave retardation) [6]. (b) Tbit/s generation, ML: mode-locked, HNLF: highly nonlinear fiber, PC: polarization controller, DCF: dispersion compensating fiber, MZ: Mach-Zehnder modulator, EDFA: Erbium-doped fiber amplifier. (c) Monitoring setup, VOA: variable optical attenuator.

The principle of our monitoring scheme is based on the flexible dispersion-trimming and phase-control capabilities of our LCoS-based WSS, enabling us to implement the DLI with the device itself. As WSSs are the key elements of reconfigurable add-drop multiplexers (ROADMs) which are already present at the nodes of the network, integration of the OSNR monitoring into current networks is greatly facilitated. A schematic of the WSS operating principle is depicted in figure 1(a). The active element of the switch is a two-dimensional LCoS pixel array. Light coming from an input fiber array is sent onto a diffraction grating which disperses the light onto the horizontal axis of the LCoS array, such that the C-band is mapped onto the whole array. Spectral filtering operations can be performed by applying a calculated phase front image to the LCoS array, while setting arbitrary filters by choosing the spatial extent of the phase front. This enables optical add/drop operations using different vertical phase ramps to redirect the light to different output fibers. Similarly one can apply a phase ramp along the horizontal axis of the LCoS causing the light to propagate along a slightly different path and resulting in a temporal delay [figure 1(b) (exaggerated)]. If we apply a different phase slope to the upper and lower half of the LCoS, we cause the light reflected from the lower half of the LCoS to follow a different path than the light reflected from the upper half. When the light interferes at the output fiber the two light paths will have acquired a phase delay with respect to each other and we have thus created an interferometer. The DLI is reconfigurable up to 50 ps of delay (limited by delay-dependent loss), furthermore by changing the relative phase between the phase gradients on the two parts of the LCoS it it possible to change between constructive and destructive interference.

3. Experiment

The experimental setup is depicted in figure 1. The 1.28 Tbit/s signal is created [figure 1(b)] by optical time-division multiplexing (OTDM). A 40 GHz optical clock emitting 1.4 ps pulses is compressed to approximately 275 fs via a two stage compression scheme using highly nonlinear fiber and data-encoded with a $2^{31}-1$ pseudo random bit sequence by a Mach-Zehnder modulator. After amplification with a low noise Erbium-doped fiber amplifier (EDFA), this 40 Gbit/s signal is time interleaved to 1.28 Tbit/s with five 2^7-1 multiplexing stages.

The generated signal is then combined with a controlled amount of amplified spontaneous emission (ASE) noise from a second EDFA via a 50/50 fiber coupler, before entering the WSS device [figure 1(c)]. Inside the device the DLI operation is performed and the light is directed to a slow photodiode connected to one of the output ports of the WSS. The reference OSNR is obtained by measuring the signal- and noise-only powers using the same photodiode without the DLI function of the WSS. The DLI was set to a delay of 4 ps in the low bit-rate case and 0.1 ps for the 1.28 Tbit/s signal. The average input power of the signal-only was between -10 and -15 dBm in all cases.

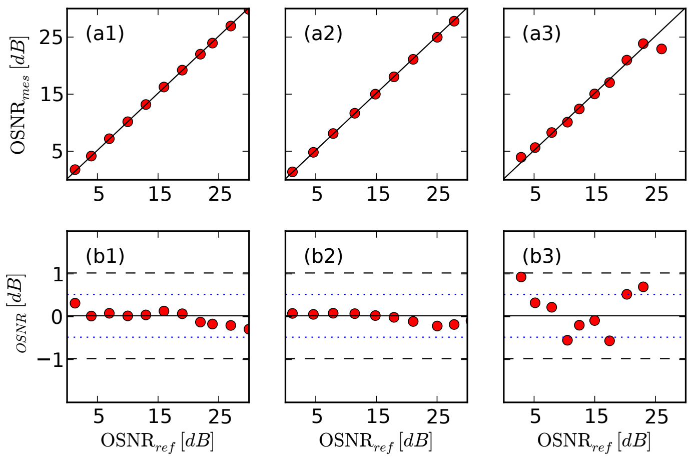

Fig. 2: Measured OSNR as a function of reference OSNR for a (a1) 40 Gbit/s NRZ-DPSK signal (a2) 40 Gbit/s NRZ-OOK signal with 10 km of standard SMF fiber dispersion and 10 ps DGD and (a3) 1.28 Tbit/s OTDM RZ-OOK signal. (b1)–(b3) The corresponding measurement errors.

Figure 2 depicts the measured OSNR as a function of reference OSNR for a (a1) 40 Gbit/s NRZ-DPSK signal, (a2) a 40 Gbit/s NRZ-OOK signal after propagation through 10 km of standard SMF fiber and with 10 ps of added differential group delay (DGD) and (a3) for the 1.28 Tbit/s OTDM signal. The measured OSNR closely follows the reference OSNR. The accuracy of our measurements is further confirmed by figures 2(b1)–(b3), depicting the measurement errors. For the low bit-rate signals the measurement error is below 0.5 dB over a range of 0-30 dB of OSNR. While the error is higher in the case of the 1.28 Tbit/s signal it is still below 1 dB over a range of 0 to 25 dB OSNR and only degrades above 25 dB.

4. Conclusion

We have demonstrated in-band OSNR monitoring by interferometry using a WSS. Our implementation is very accurate, reconfigurable and scalable up to 1.28 Tbit/s, where we achieved a measurement error of below 1 dB for a measurement range of 0–25 dB OSNR. This is to the best of our knowledge the most accurate OSNR measurement of such a high bandwidth signal to date.

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