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Simultaneous Monitoring of In-Band Optical Noise for WDM Signals using Stimulated Brillouin Scattering

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Abstract: We demonstrate simultaneous monitoring of the optical signal to noise ratio (OSNR) for wavelength-division multiplexed 40 Gb/s signals using the back-reflected Stokes wave from Stimulated Brillouin Scattering. A highly sensitive OSNR range of 5-25 dB is observed.
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1. Introduction

Optical performance monitoring has an important role in optical communication networks for quantifying the signal quality in transmission. A crucial measurement is the optical signal to noise ratio (OSNR), which has been traditionally performed using an optical spectrum analyser (OSA) to extrapolate the in-band noise of the signal from the out of band noise floor. While this is adequate for simple communication links, it becomes more prone to errors for transmission of wavelength division multiplexed (WDM) signals through more complex network architectures, where the out of band noise level can be filtered by add drop multiplexes for example. To resolve this, a variety of different approaches have been explored for enabling direct measurement of the in-band OSNR. These include polarization nulling [1], electro-optic phase modulation [2] and a variety of nonlinear optic schemes [3], [4] to name a few. These techniques generally operate on a per channel basis. Monitoring the in-band noise of a WDM signal therefore requires a parallel bank of devices or a tunable optical filter to select a particular channel to test. Thus, a scheme that can simultaneously monitor WDM signals is of interest to reduce measurement latency, while providing a more scalable solution. Achieving this without compromising the measurement sensitivity is also important.

In this paper, we demonstrate the simultaneous monitoring of the in-band noise of WDM signals using Stimulated Brillouin Scattering (SBS) in an optical fiber. In contrast to other nonlinear schemes using the optical Kerr effect, which depends on the instantaneous optical intensity, SBS can be simultaneously excited for multiple channels of a WDM signal when the spectral power density exceeds a certain threshold. The back-reflected Stokes wave power for each channel are shown to vary in proportion to their OSNR, with a large dynamic range (>25 dB), that enables a highly sensitive measurement, while being insensitive to the input signal polarization to the fiber. We demonstrate the capability to monitor OSNRs between 5-25 dB for multiple channels of a WDM (3×40 Gb/s) signal.

2. Operating principle

Fig. 1(a) shows the schematic for the SBS based OSNR monitor. A portion of the signal is tapped from the network, and launched into an optical fiber with sufficient power to pump the nonlinear SBS process. The SBS arises from spontaneous inelastic scattering, which creates an acoustic wave in the fiber [5]. The pressure from this wave causes a periodic modulation of the fiber's density, and therefore its optical susceptibility, to create a moving refractive index grating. This in turn stimulates further scattering of the pump light by Bragg reflection, causing a back reflected Stokes wave, which is downshifted in frequency, typically by 10 GHz, due to the Doppler effect associated with the grating moving at the velocity of the acoustic wave. An equation for roughly estimating the SBS threshold is $g_B{\cdot}P_{th}{\cdot}L_{eff}/A_{eff} \approx 21$ where P_{th} is the critical pump power, g_B is the peak value of the Brillouin gain, and L_{eff} and A_{eff} are the fiber's effective length (accounting for loss) and effective mode area respectively [5]. In practice, the actual P_{th} depends on the spectral width of the signal with respect to the Brillouin gain spectrum, whose bandwidth is typically narrow (on the order of 10 MHz). Consequently, P_{th} is lowest for a narrow linewidth CW laser. Although typical high-speed optical communication signals have spectral widths much broader than that of the Brillouin-gain spectrum, signals encoded by on-off keying for example, have prominent, and narrow spectral peaks (in case of non-return to zero (NRZ), a strong peak at its carrier wavelength), that can promote SBS at just a moderately higher P_{th}.

The basis for OSNR monitoring by SBS is the nonlinear power transfer function given by $P_b = T(P_s)$ where P_s and P_b are the powers of the input signal (pump) and back-reflected Stokes wave from the fiber, respectively. The characteristic feature of SBS is a steep increase in P_b for $P_s > P_{th}$. By operating the OSNR monitor with a fixed total input optical power (P_i) of $P_i = P_s + P_n$ for noise power, P_n, while satisfying $P_i > P_{th}$, then P_b is maximum for a noiseless signal i.e. $P_i = P_s$, and decreases with increasing P_n, as $P_b \approx T(P_i - P_n)$. The same principle applies to a multi-channel signal, in which case the monitor requires $P_i\,(j) > P_{th}(j)$ for the respective powers of each channel, j. Simultaneous OSNR monitoring can then be performed by using the scheme as a nonlinear signal processing front end on either an OSA, or WDM demultiplexer with an array of photodetectors to simultaneously measure each $P_b(j)$.

3. Experimental results and discussion

Fig. 1(b) shows the OSNR monitoring experimental set-up. A 3 channel 40 Gb/s NRZ signal was generated using a WDM multiplexer (MUX) to combine three CW lasers, of specified spectral width < 30 MHz. These were separated by 200 GHz on the ITU grid at wavelengths 1549.32 nm, 1550.92 nm, and 1552.52 nm, denoted channels 1, 2 and 3 respectively. All 3 were simultaneously amplitude modulated by a $LiNbO_3$ Mach-Zehnder (MZ) modulator to encode a 40 Gb/s NRZ, pseudo random bit sequence (PRBS) of $2^{31}-1$ pattern length. The channels were then temporally decorrelated by propagation through 4 km of standard single mode fiber (SSMF). To vary the OSNR, noise was added from a cascade of two amplified spontaneous emission (ASE) sources with intermediate filtering by a tunable bandpass optical filter (BPF). The noise power was set by a variable optical attenuator (VOA), before being combined with the signal. Both were then amplified in an EDFA and launched into the optical fiber via a 99:1 coupler and optical circulator which enabled $P_i(j)$ and $P_b(j)$ to be measured by OSAs (on 1.0 nm RBW) respectively.

A nonlinear fiber with high L_{eff}/A_{eff} was chosen to minimize the launch power needed to satisfy $P_i(j) > P_{th}(j)$. A non-zero dispersion parameter was also desired to reduce four-wave mixing (FWM) between the WDM channels from the optical Kerr effect. In consideration of these factors, our experiment used a 1 km length of highly nonlinear fiber (HNLF) with a nonlinearity coefficient of 11.5 $W^{-1}km^{-1}$ ($A_{eff} \approx 12\ \mu m^2$) and a normal sign dispersion equal to −2.47 ps/nm.km at 1550 nm with slope of 0.02 ps/nm^2.km. SBS generation in the fiber was investigated for various sources including an un-modulated CW laser, and single and multi-channel 40 Gb/s NRZ and CS-RZ format signals. Fig. 1(c) plots the measured $T(P_s)$ in each case without noise added. It shows that P_{th} is lowest for the CW laser, and increases for the NRZ and CS-RZ signals. A further increase in P_{th} was also observed for each multi-channel case.

The fiber was then applied to the OSNR monitoring of the WDM 3×40 Gb/s NRZ signal. The initial experiment considered noise applied to only the central channel by using a 0.5 nm bandwidth BPF in the noise circuit with the center wavelength tuned to Ch. 2. To test the wavelength independency of the monitor, all three WDM channels were set at equal powers of $P_i(j)$ = 59 mW, which also satisfied $P_i(j) > P_{th}(j)$. The OSNR for Ch. 2 was determined by measuring the individual noise and signal powers at the input to the EDFA using an OSA. The input power to the EDFA was 0.2 mW, which ensured the EDFA added minimal noise. The OSNR was varied by adjusting the VOA in the noise circuit of Fig. 1(b). For each setting, the power of the Ch. 2 CW laser was adjusted to keep P_i constant.

Fig. 2(a) shows the optical spectra traces of the input, throughput and back reflected emission from the HNLF for a 15 dB OSNR (Ch. 2). Note, all OSNR values stated in this paper are with respect to a 0.1 nm noise bandwidth. The throughput spectrum in Fig. 2(b) showed that FWM in the HNLF remained small. Comparison of the input and reflected emission spectra shows that although $P_i(j)$ was equal for all 3 channels, a drop in P_b was observed only for Ch. 2. This is explained by the corresponding change in $T(P_i-P_n)$ for decreasing P_s at lower OSNR. Fig. 2(b) plots the measured P_b versus OSNR for Ch. 2, highlighting the large dynamic range (exceeding 25 dB) in P_b, as the OSNR varied between 5-25 dB, which is an important range of interest for practical application. In contrast, P_b for the noise-free channels 1 and 3 remained unchanged. The dynamic range is notably larger than reported for other

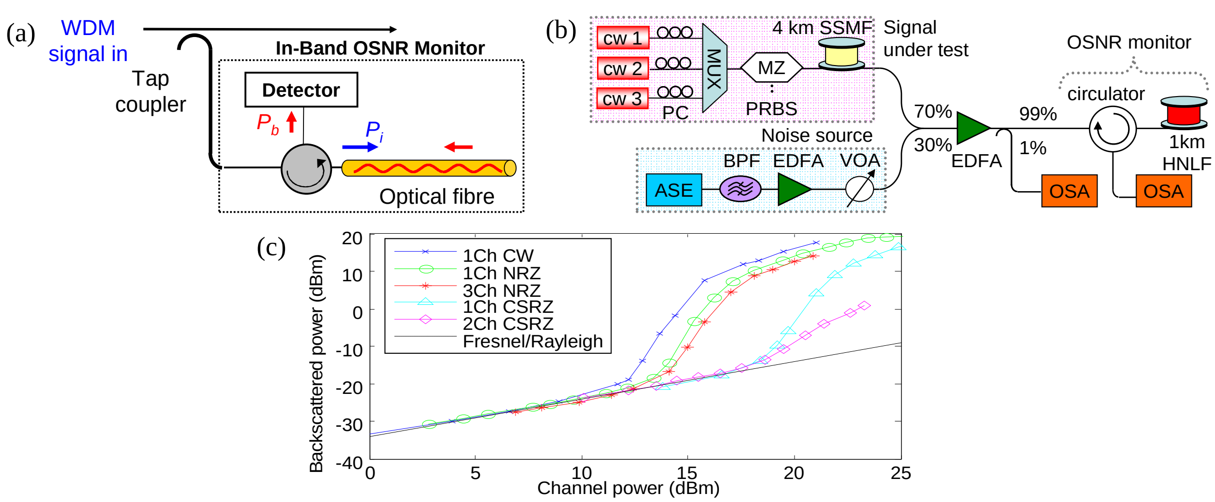

Fig. 1. (a) Schematic of a multi-channel OSNR monitor based on the SBS effect in an optical fiber. (b) Experimental set-up for OSNR monitoring of a WDM (3×40 Gb/s) NRZ signal. (c) Measured SBS power transfer function for various signal formats in the 1 km HNLF.

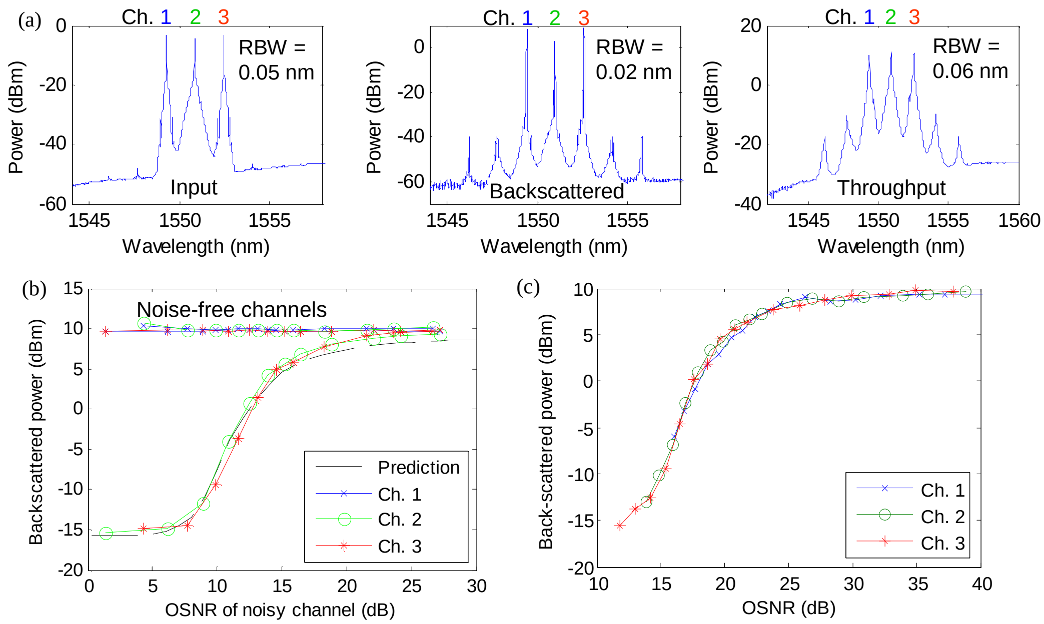

Fig. 2. Simultaneous OSNR monitoring of a WDM (3×40 Gb/s) NRZ signal using SBS effect. (a) Optical spectra at input, throughput and back-scattered from fiber for Ch. 2 OSNR = 15 dB, and Ch. 1 and 3 noise-free. (b) Measured back-scattered power for each channel, in case of OSNR varied for only either Ch. 2 or Ch. 3 while other channels remain noise-free. Also shown is predicted curve mapped from the power transfer function in Fig. 1 for 3 Ch. NRZ. (c) Measured back-scattered power for broadband noise applied to all channels.

nonlinear methods based on the optical Kerr effect [3], [4]. Fig. 2 also plots the expected P_b variation with varying OSNR mapped from the measured $T(P_s)$ in Fig. 1(c) (for 3 Ch. NRZ), by scaling P_s to the theoretical OSNR for a fixed P_i = 59 mW. A close fit to the measured curve was seen. Similar results were also obtained with the 0.5 nm bandwidth noise tuned to Ch. 3, (leaving channels 1 and 2 noise-free), as plotted in Fig. 2(b). The wavelength dependence for the SBS process was minimal, as expected given the small channel wavelength separation.

We also investigated the case of unequal broadband noise applied to all three WDM channels simultaneously. This was performed by swapping an 8 nm bandwidth BPF into the noise circuit. Again $P_i(j)$ = 59 mW was used for each channel. As the proportion of noise power was increased by varying the VOA, $P_i(j)$ was equalized by adjusting each CW laser power, and tweaking the EDFA gain. The OSNR of each channel was determined by comparing the signal and noise powers at the input to the EDFA. Fig. 2(c) shows the curves of P_b versus OSNR closely overlap for all channels, with a dynamic range and OSNR sensitivity similar to the 0.5 nm bandwidth noise result in Fig. 2(b).

Importantly, input signal polarization had little effect on P_b for all results. Scaling the technique to monitor more WDM channels or alternate data modulation formats such as CS-RZ, amongst others, would require a commensurate increase in launch power to satisfy $P_i(j) > P_{th}(j)$ for all channels. This was limited in our experiment by the available optical amplifiers. Its practical application would therefore benefit from further progress in the development of highly nonlinear glasses such as Chalcogenides [6], and waveguides with larger L_{eff}/A_{eff} to further reduce $P_{th}(j)$.

4. Conclusions

Simultaneous multi-channel OSNR monitoring of a WDM signal was demonstrated using the nonlinear SBS effect in an optical fiber. A proof of principle experiment showed the capability to distinguish the OSNR of each WDM channel in a 200 GHz spaced 3x40 Gb/s NRZ signal. A high dynamic range of >25 dB was observed for the back-reflected Stokes wave power in monitoring the OSNR over a 5-25 dB range, with insensitivity to input polarization.

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