Enhanced 10 Gb/s operations of directly modulated reflective semiconductor optical amplifiers without electronic equalization

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Abstract: We report enhanced 10 Gb/s operation of directly modulated bandwidth-limited reflective semiconductor optical amplifiers. By using a single suitable arrayed waveguide grating we achieve simultaneously WDM demultiplexing and optical equalization. Compared to previous approaches, the proposed system results significantly more tolerant to seeding wavelength drifts. This removes the need for wavelength lockers, additional electronic equalization or complex digital signal processing. Uniform C-band operations are obtained experimentally with $<$ 2 dB power penalty within a wavelength drift of 10 GHz (which doubles the ITU-T standard recommendations).

OCIS codes: (060.4510) Optical Communications; (060.4080) Modulation.

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1. Introduction

The wavelength-division-multiplexed passive optical network (WDM-PON) is considered to be the next evolutionary solution for a simplified and future-proofed access system that can accommodate exponential traffic growth and bandwidth-hungry new applications. WDM-PON mitigates the complicated time-sharing and power budget issues in time-division-multiplexed PON (TDM-PON) by providing virtual point-to-point optical connectivity to multiple end users. Cost efficiency in WDM PON can be achieved by adopting colorless transmitters at the Optical Network Units (ONU) that remove the need for stock spare wavelength-defined transmitters.

R-SOAs fulfill most of the requirements to realize a low-cost colorless transceiver for WDM-PONs: they can be operated at any wavelength supplied by the Optical Line Terminal (OLT) across the C and L-bands, exhibit very low polarization dependency and can be directly modulated. Uncooled operation of those devices has been also demonstrated [1]. A major drawback of R-SOAs is their limited modulation bandwidth, which typically allows operations up to 2.5 Gb/s. However 10 Gb/s operation of bandwidth-limited R-SOAs can still be achieved by various means, such as electronic equalization and Forward Error Correction (FEC) [2–4], multilevel signaling, e.g. OFDM or duobinary coding [5,6]. Furthermore equalization achieved by optical off-set filtering could also be exploited to obtain 10 Gb/s. Demonstrations of this technique have been reported either aided by electronic equalization [7] or by detuned suitable delay interferometers [8,9]. However, in all previous off-set filtering demonstrations electronic equalization or FEC were anyway needed to achieve error-free operations or to increase the system tolerance to wavelength drifts.

In [10] we presented an improved off-set filtering technique suitable for WDM-PON applications. It is highly tolerant to the wavelength detuning (no wavelength locker is required) and does not require any pre-emphasis (adaptation of the R-SOA bandwidth) nor any post-detection equalization. Furthermore the proposed off-set filtering is realized directly by a common WDM demultiplexer with a suitable bandwidth. Thus, a single network element provides simultaneously WDM demultiplexing and bandwidth enhancement by off-set filtering for all the channels. System is greatly simplified and 10 Gb/s direct detection is feasible, yet providing superior performance. Here we present an extended characterization of this technique, including assessment of WDM performance and a study on the optimal filter bandwidth.

2. Operating principle

Direct modulation of a R-SOA produces optical signals modulated both in amplitude and phase [11]. The amplitude modulation is received by direct detection. In this case the effective modulation bandwidth is limited by the frequency response of the R-SOA which typically does not exceed 2 GHz. On the other hand, phase modulation can be converted in amplitude modulation by using suitable optical filters. As explained in [7], an optical filter of a suitable

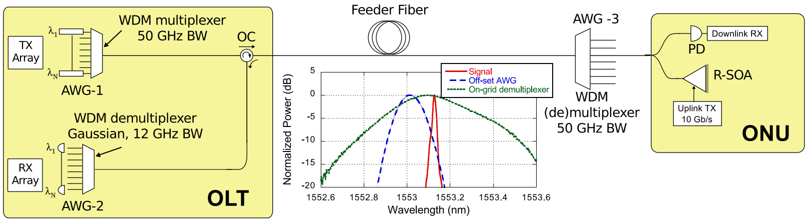

Fig. 1. WDM-PON architecture. A single Arrayed Waveguide Grating (AWG-2) operates simultaneously as off-set filter and WDM demultiplexer. AWG-2 has a 12 GHz bandwidth in order to relax constraints due to the chirp and the wavelength drift. Inset shows the relative position of on-grid AWG1 and AWG2, offset AWG-2 and optical signal

slope provides such phase-to-amplitude conversion. This is realized by using an optical filter detuned respect the carrier frequency of the optical signal (off-set filtering). Furthermore the off-set filter behaves like an high-pass filter. This therefore compensates for the low modulation bandwidth associated to the amplitude modulation and effectively extends the overall frequency response of the system.

In a typical WDM-PON architecture (see figure 1), the proposed offset filtering can be implemented at the receiver side by a commercially available Gaussian shaped Array Waveguide Grating (AWG2, in figure) having an optimized channel bandwidth. Such device provides simultaneously two functionalities, i.e. off-set filtering and WDM demultiplexing. In previous off-set filtering demonstration, filters ranging from 16 to 30 GHz where used [7–9, 12]. In the proposed implementation the bandwidth of the AWG2 is chosen to be narrower (12 GHz). By this choice we obtain a steeper slope that, combined with the R-SOA chirp provides a wide tolerance to the wavelength detuning; this removes the need for electronic equalization required in [7]. At the same time, the 12 GHz bandwidth provides a good compromise between extra losses induced by the off-set filtering and the need for a steep slope. Error-free operation is observed without Forward Error Correction, which was needed in the previous off-set filtering demonstrations [8]. In a WDM-PON scenario, all other AWGs implemented at the transmitter and the remote node are not offset so that they perform MUX/DeMUX without introducing extra losses.

3. Experiments

The experimental setup is reported in figure 2-a. We used a tunable laser ($\lambda = 1554$ nm) to feed a R-SOA. The seeding light was coupled into the R-SOA by an optical circulator (OC) providing an injection power of -10 dBm. An AWG (AWG-1) having 50 GHz bandwidth was placed in front of the R-SOA to emulate the remote node demultiplexer. The R-SOA was a butterfly packaged commercial device, having 0 dBm output saturation power, 28 dB small signal gain and < 1 dB polarization dependent gain when biased at 50 mA. Its α factor was experimentally measured (by using the technique proposed in [13]) to be around 5. For 10 Gb/s operation the R-SOA was biased at 86 mA and directly modulated by a $2^{31}-1$ long Pseudo Random Bit Sequence (PRBS) by means of a 2 Volt peak-to-peak electrical data signal. At the receiver side we implemented either the off-set AWG-2 ($3-$dB bandwidth of 12 GHz over a 50 GHz grid) or a programmable optical filter (POF). Shapes of both the AWG-2 and the POF Gaussian filter are shown in Figure 2-b. AWG-2 was thermally detuned by about 10 GHz in respect of the on-grid AWG-1. The detuning between AWG-2 and the optical signal was adjusted by setting the tunable laser emission wavelength accordingly. A 10 GHz Avalanche Photo-Diode (APD) was used as detector and the received signal was directly sent to a BER

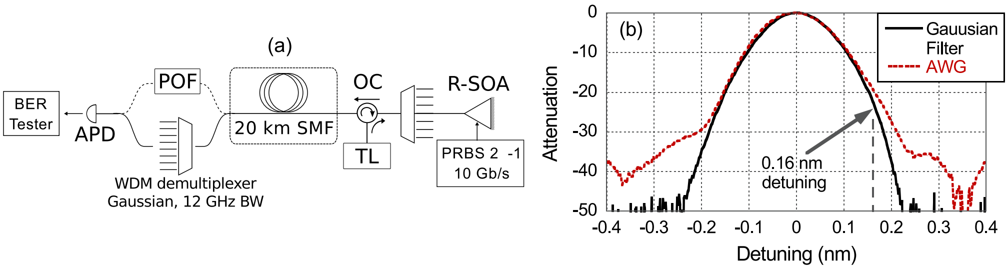

Fig. 2. a): Experimental setup. R-SOA: Reflective SOA; OC: Optical Circulator; TL: Tunable Laser; SMF: Single Mode Fiber; POF: Programmable Optical Filter; APD: Avalanche Photo Diode. b): Comparison of AWG-2 and ideal Gaussian filter obtained by the programmable optical filter.

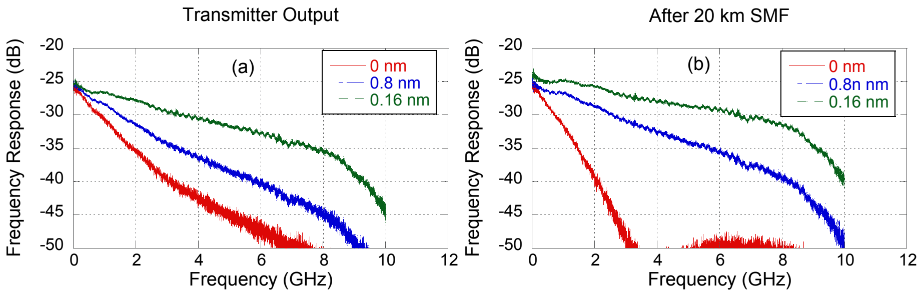

Fig. 3. Frequency response measured as a function of the detuning at the transmitter output (a) and after 20 km propagation (b).

tester, with no further electrical filtering or processing. A 20 km Single Mode Fibre (G.652) was also implemented for some measurements.

We first characterized experimentally the increase of the effective modulation bandwidth as a function of the detuning between the AWG2 and the optical signal. We report in figure 3-(a) three significant detuning cases: $0, 0.08, 0.16$ nm. Those detuning values range from no off-set detuning (pure low-pass E/O response of the R-SOA used in the experiment) to the maximum allowed detuning 0.16 nm (high-pass response added by the phase modulation). Further detuning would result in excessive insertion losses. As expected, the detuning increases the E/O modulation bandwidth. We repeated the same measurement after transmission over 20 km of SMF fiber (corresponding to 340 ps/nm): as can be seen in figure 3-(b), the low-pass response at 0 nm detuning is reduced by the combined effect of chirp and chromatic dispersion. However, when the high-pass filter due to phase modulation is added by increasing the detuning, the resulting E/O bandwidth results even enhanced. We also investigated the resilience of this scheme to the detuning between the AWG2 transmission peak and the seeding wavelength. To this aim we measured the Q-factor of the received signal as a function of the detuning (in back-to-back), as shown in figure 4-a. This measurement was performed by using a built-in function of the sampling oscilloscope (it gives a pessimistic estimation of the Q-factor as it includes the electrical noise added by the equipment). As can be seen, the Q-factor increases monotonically as the relative detuning between signal wavelength and filter center is increased. However it should be also noted that the detuning also increases the losses (which are indicated on top x-axis in figure 4-a). Therefore, a trade-off must be found between optimal performance and extra losses. Nevertheless, we obtained good performance (Q-factor $>$ 6, which corre-

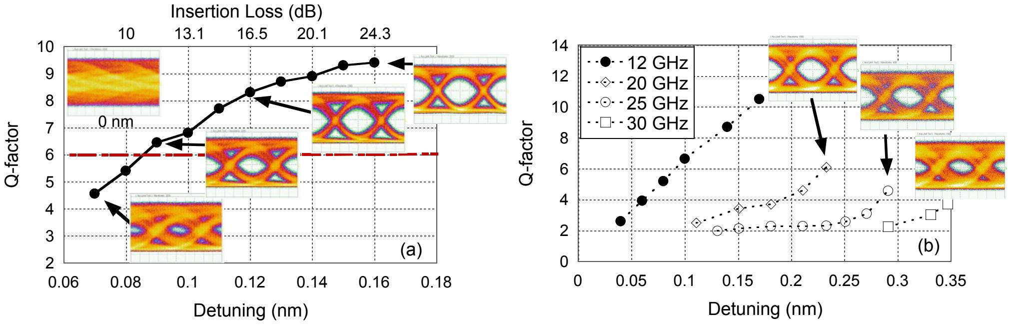

Fig. 4. a) Q-factor improvement as a function of the AWG detuning. For selected detuning, corresponding eye-diagrams are reported in the insets. On the left, the first eye diagram was recorded without offset between the AWG and the signal. Insertion losses for the various detuning are reported on top x-axis. b) Q-factor improvement obtained with Gaussian filters of different bandwidths. All measurements are performed in back-to-back and eye-diagrams have been recorded over 1 minute time persistence. Time scale is 20 ps/div.

spond to a BER lower than 10^{-9}) over a wide detuning range where the AWG2 slope increases linearly between 0.4 and 0.8 dB/GHz: this represents a significant improvement in respect to previous implementations [7–9] that required electronic equalization or wavelength lockers to compensate for the low tolerance to detuning. The proposed approach is therefore compliant with WDM standards, which specify tolerances of 6 GHz in respect to the nominal frequencies. The signal quality improvement can be clearly seen in figure 4-a. All the eye diagrams were recorded over the same persistence time (1 min.). We also report in the same figure (upper-left corner) an eye diagram recorded without applying the offset filtering: it was so closed that BER measurement or Q-factor estimation were not feasible.

In order to better understand the benefits added by the narrow off-set filtering, we compared the performance obtained by using Gaussian filters of different bandwidths. To this aim we used a programmable optical filter with 1 GHz resolution, set to provide a Gaussian shape with bandwidths between 12 and 30 GHz. We measured the Q-factor (in back-to-back) as a function of the detuning as reported in figure 4-b. The Q-factor was measured by keeping a constant optical power to the receiver (−17 dBm) for all the measured points. As can be seen, Q-factor exceeds the value of 6 only in the case of the 12 GHz filter. It could be noted that in the case of the 12 GHz filter at 0.16 nm detuning shows an even better value in respect to the result reported in figure 4-a. We attribute this behavior to the fact that the AWG has a non-exact Gaussian shape at large detuning: this is clearly visible in figure 2-b where we compare the shape of the Gaussian AWG and the synthesized Gaussian optical filter. The AWG shape starts differing from the ideal Gaussian one at 0.16 nm detuning where we found a saturation behavior of the Q-factor improvement (see figure 4-a.

Finally, we investigated the system performance by BER measurements taken for different values of the detuning. For both back-to-back, figure 5-(a), and propagation over 20 km, figure 5-(b), we obtained uniform performance (less than 2 dB power penalty) over a 10 GHz detuning range (from 0.08 to 0.16 nm detuning). Despite the link bandwidth is further enhanced after 20 km transmission (see figure3) we found about 1 dB additional power penalty after propagation, which is attributed to the accumulated chromatic dispersion. It can be noted that in both cases the sensitivity values were about −19 dBm, quite higher than the typical value of −28 dBm of 10 Gb/s IMDD system. This is due mostly to the reduced extinction ratio (ER) obtained by this technique. We experimentally measured ER values ranging from 1.8 to 2.8 dB in the considered detuning range.

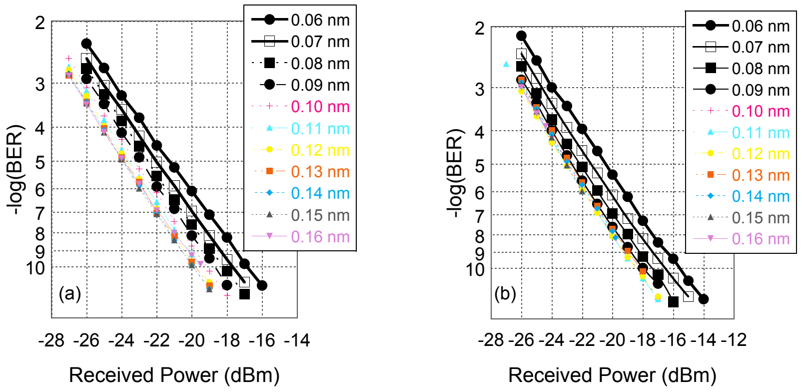

Fig. 5. BER measurements as function of the received optical power. a) Transmitter Output (Back-to-Back). b) After 20 km propagation

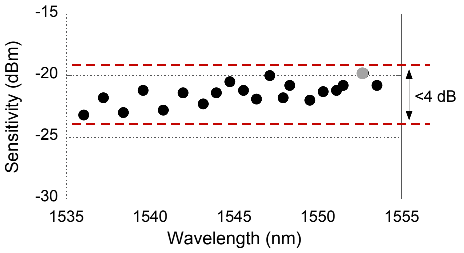

Fig. 6. Sensitivity of selected channels across the C-band. These measurements were performed by using the receiver of an OC-192 XFP transceiver. Light-gray point indicates the channel used for the extended characterization.

As the R-SOA chirp is not constant along its emission spectrum it is important to verify the system performance across the whole C-band. We verified this by measuring the sensitivity (in back-to-back) on selected channels in the 1535 $-$ 1555 nm range. In order to verify the compatibility of the proposed off-set filtering with commercial receivers, we replaced the optical receiver and used the one integrated within a XFP transceiver, which is designed for standard OC-192 WDM links and has a fixed built-in decision threshold. Results are shown in figure 6. As can be seen, on the selected channels, the sensitivities are within a range of 4 dB. This is due both to chirp variations and non optimized offset filtering (set at 0.14 nm). An optimized R-SOA design (aimed at increasing the chirp value and its uniformity) could help in reducing such spread.

4. Conclusion

We experimentally demonstrated an improved off-set filtering approach to extend the effective modulation bandwidth of a common R-SOA for WDM-PON applications. The proposed approach is based on the use of a single narrow bandwidth AWG detuned in respect to the WDM grid which acts simultaneously both as WDM-demultiplexer and bandwidth enhancer filter. This allows to obtain 10 Gb/s IMDD links by using a directly-modulated Reflective SOA of $<$ 1 GHz bandwidth with enhanced tolerance to the wavelength detuning (up to 10 GHz). The proposed filtering is effective across the C-band. Error-free operation was obtained after a 20 km fiber without the use of electronic equalization, pre-emphasis or Forward Error Correction, in favor of much simpler direct detection.