Wavelength Reuse in a Colorless ONU with All-Optical Clock Recovery for Full-Duplex Dense WDM PONs

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ABSTRACT
In this paper, an approach of a colorless ONU comprised by a Fabry-Pérot filter and a Semiconductor Optical Amplifier for all-optical clock recovery of the downstream signal, followed by a Mach-Zehnder modulator as the upstream modulator is experimentally demonstrated. The all-optical clock recovery performs data erasure allowing for efficient wavelength reuse of the downstream signal for upstream remodulation. Operation at a full-duplex 10Gb/s symmetrical data rate and 20 dB loss budget is demonstrated over fiber spans of 50 km with achieved power margin of ~8 dB.
Keywords: passive optical networks, wavelength reuse, WDM, clock recovery

1. INTRODUCTION

Residential access networks are urging for more bandwidth, driven by new applications like three-dimensional TV that cause localized traffic to surge near the end-user. In this extremely cost-sensitive network segment, Wavelength Division Multiplexing (WDM) Passive Optical Network (PON) architectures offer a scalable solution for accommodating the exponential growth of users distributed in different topology deployments without compromising the granted bandwidth [1]. To further cope with the limited margins for carrier revenues, colorless ONU designs have been proposed as a cheap solution for mass deployment. Such wavelength-agnostic ONUs based on reflective components allow efficient reuse of the downstream signal for upstream modulation [2-4]. To further simplify the system, intensity modulation formats are favored for both down- and up-stream transmission. However, for full-duplex operation on a single wavelength, this simplicity comes with a serious flaw: To achieve upstream modulation without severe degradation due to crosstalk from the downstream data, the downstream is typically transmitted with reduced modulation extinction ratio (ER) [5]. This effectively leads to a compromise between downstream and upstream performance and restricts the overall loss budget of the PON.

The reduced ER requirement for upstream remodulation can be overcome with suitable encoding such as Manchester or Inverse Return-to-Zero, using higher bandwidth electronics at the OLT. However, limitations have been experienced with this technique for remodulation at symmetrical data rates [6]. Alternatively, cancellation of the downstream modulation can be applied at the ONU to recover the optical carrier of the downstream. Recently, we demonstrated an all-optical scheme for carrier recovery that achieves data suppression at high downstream ERs of up to 9 dB by optical filtering [7]. Besides, a technique for all-optical clock recovery has been presented in [8] for regenerative purposes with application in transport networks. The scheme relies on simple photonic components such as periodic filters and semiconductor optical amplifiers (SOA) with the potential for on-chip integration.

In this paper we present a colorless ONU design that relies on an all-optical clock recovery circuit to achieve cancellation of the downstream modulation. The circuit generates a high-quality clock signal at the downstream wavelength [9,10] which is subsequently used for upstream transmission. In the following sections we provide an extensive study of full-duplex return-to-zero on-off-keying (RZ-OOK) transmission at 10 Gb/s with an extended reach up to 50 km. The transmission performance is investigated with respect to the word length of the data traffic and the accumulated dispersion of the optical distribution network (ODN). Finally, the wavelength transparency of the proposed ONU is elaborated.

2. ONU Design for Wavelength Reuse by Clock Recovery and Experimental Setup

The fundamental building blocks of the ONU are illustrated in Fig. 1(a). The all-optical clock recovery scheme comprises a Fabry-Pérot filter (FPF) for the generation of a clock-resembling signal followed by a SOA operated in deep saturation for peak pulse power equalization [9,10]. The extracted clock information of the downstream data is remodulated at the respective WDM channel by a Mach-Zehnder modulator (MZM) with upstream data, bit-synchronized with the recovered clock. The all-optical clock recovery circuit is capable of operating with arbitrary WDM channels within the C-band upon tuning the filter passband to a given wavelength grid for the downstream data signal due to the periodic transfer function of the FPF, hence offering a colorless ONU solution.

Fig. 1(b) shows the experimental setup. The downstream transmitter at the OLT comprises a laser diode emitting at 1556.55 nm, an EAM for pulse carving and a MZM for generating the return-to-zero on-off keying (RZ-OOK) downstream data signal at 10 Gb/s, electrically fed by an arbitrary pseudo-random binary sequence (PRBS) pattern.

The OLT receiver comprises a 10 GHz PIN photodiode and an Erbium-doped fiber amplifier (EDFA) as optical preamplifier. At the ONU, the downstream signal is split by a 50/50 coupler (CO) for signal detection and remodulation. Since no avalanche photodiode was available, a combination of EDFA, attenuator and PIN diode was used and calibrated to a reception sensitivity of -28 dBm for a 10 Gb/s non-return-to-zero (NRZ) data signal. The FPF has a free-spectral range 10.2289 GHz that is equal to the downstream bit rate, and a low-finesse of 47. The SOA is a 1.5mm long device with 3-dB gain bandwidth of 50 nm and 16 ps 1/e gain recovery time. An EDFA was used prior to the SOA to ensure that it is operated in the saturation region. The recovered clock is subsequently fed into a $LiNbO_3$ MZM with an ER of >13 dB driven by a 10.2289 Gb/s PRBS pattern for upstream transmission. An electrical delay line ($\Delta\tau$) is used for aligning the clock and data pulses at the MZM input.

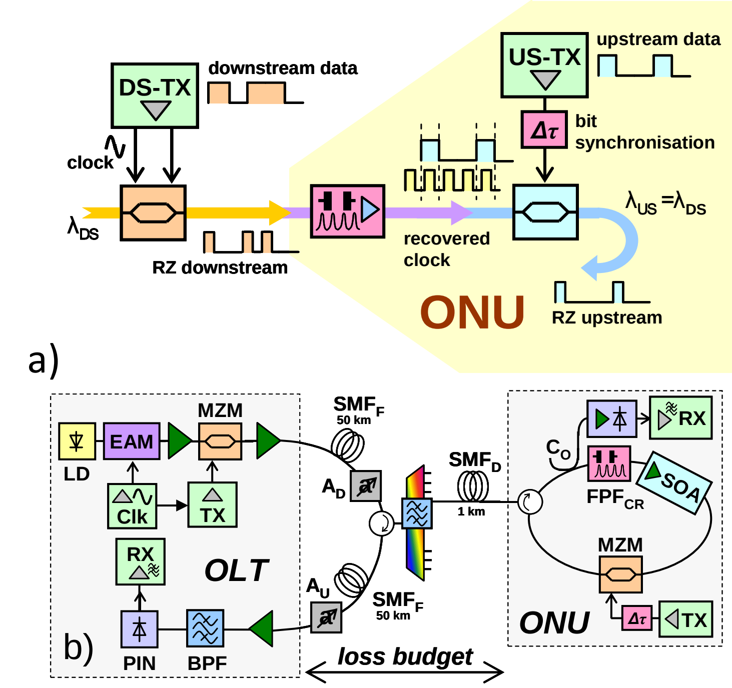

Fig. 1. (a) Colorless ONU design based on remodulation of the recovered clock from downstream transmission, (b) experimental setup.

The ODN of the PON is composed of a dual feeder fiber with a link length of up to 50 km of standard single mode fiber (SSMF), avoiding Rayleigh backscattering effects between the down- and up-stream, and a short drop fiber of 1 km length. The wavelength distributing element of the PON was emulated by a tunable optical filter. The loss budget of the PON, defined between the OLT and the ONU, was fixed with the attenuators A_D and A_U to 20 dB for both transmission directions. The transmitted power from the OLT was fixed to 10 dBm, while the upstream was launched with -0.5 dBm from the ONU. The optical signal-to-noise ratios, acquired with a resolution bandwidth of 0.1 nm, were 40.7 and 29.6 dB at the OLT and ONU output, respectively.

3. Results and Discussion

The spectra of different ONU signals are shown in Fig. 2 after transmission of 50 km. The optical power level at each spectrum is normalized so that the peak power relates to 0 dBm. From left to right, Fig. 2 depicts the downstream, the clock resembling signal after the FPF, the recovered clock after the SOA, and finally the remodulated upstream.

Fig. 3(a) presents measurements performed for 10 Gb/s NRZ-OOK upstream modulation with a continuous-wave light seed (i.e. ER = 0 dB) of the ONU, while Fig. 3(b) presents comparative measurements of the back-to-back 10 Gb/s upstream bit error ratio (BER) measurements after RZ-OOK data remodulation at the ONU for various PRBS word lengths. As can be seen, the penalty due to the slightly increased amplitude variation after clock extraction does not exceed 1.1 dB at a BER of 10^{-10} when increasing the word length of the downstream bit pattern. For the performance comparison between continuous-wave light injection (Fig. 3(a)) and downstream remodulation (Fig. 3(b)) a power conversion factor of 5.61 dB between the NRZ-OOK and the RZ-OOK format has to be taken into account for the given RZ duty cycle of 1:3.65, the latter defined as the ratio between pulse duration and bit period. With this, the remodulation technique suffers from a penalty of 3.9 dB for a PRBS of length 2^{31}-1 at a BER of 10^{-10}. This penalty is attributed to the residual amplitude variation of the recovered clock and can be further reduced by using a FPF with higher finesse [11]. Besides, this penalty has to be seen as

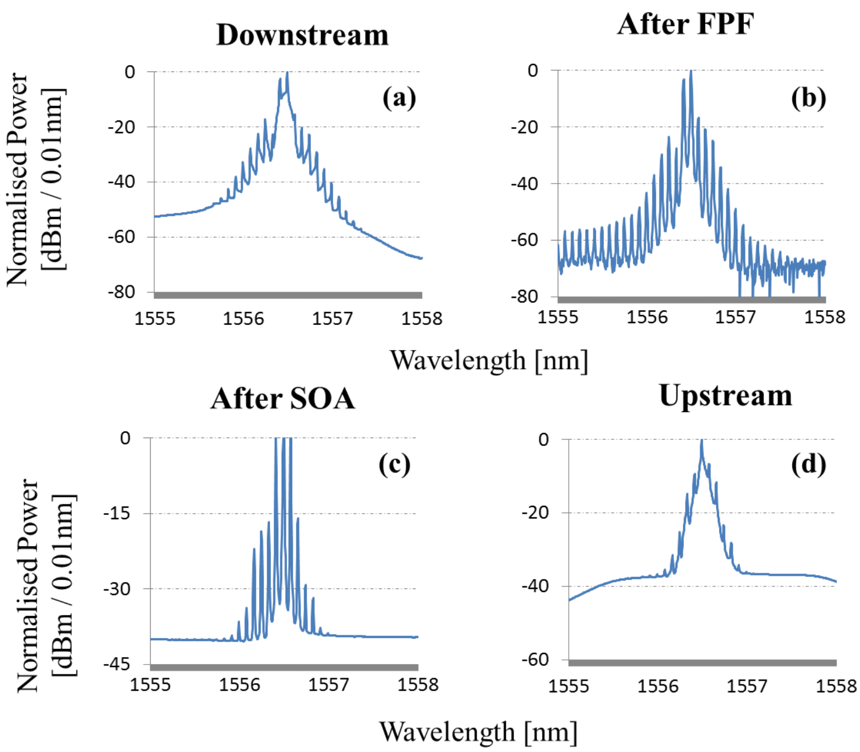

Fig. 2. Spectra of different ONU signals after 50 km transmission. a) Downstream, b) after the FPF, c) after passing through the SOA and d) upstream.

a compromise for having a downstream with infinite ER and, consequently, no reception penalty due to a reduced modulation index as in [7].

The transmission performance for the 10 Gb/s down- and up- stream signal, respectively, over fiber spans of 25 and 50 km for different PRBS lengths is depicted in Fig. 4. For the downstream (Fig 4(a)), a fiber length of 25 km causes a reception penalty of ~5 dB; however, a BER of 10^{-10} can be still obtained. A high power margin of 15 dB, found as the difference between the delivered optical power and the reception sensitivity – in case of the downstream referenced to the ONU input, is compatible in conjunction with the nominal loss budget of 20 dB for the PON. When the length of the transmission link is further increased to 50 km, the standard Reed-Solomon (255,239) FEC code can be employed at the BER level of 2.10^{-4} to achieve a BER level of 10^{-10}, suffering from a penalty of ~9dB compared to the corresponding back-to-back case.

Concerning the upstream that re-cycles the downstream signal with dispersion-induced pulse broadening as seed for the all-optical clock recovery, dispersive effects are pronounced due to the bidirectional transmission link. As can be seen in Fig. 4(b), the PRBS penalty increases. This stems from the degraded clock signal and causes already an error floor for a long PRBS of 2^{31}-1 in conjunction with a 25 km long span. For shorter PRBS lengths of 2^{7}-1 and 2^{11}-1, the reception penalties at the BER level of 10^{-10} are 5 and 9 dB, respectively, compared to the back-to-back case. The power margin for the PRBS 2^{11}-1 is then 8.3 dB and would be sufficiently large to accommodate extra end-of-life losses for components situated in an outside fiber plant. As it is the case for the

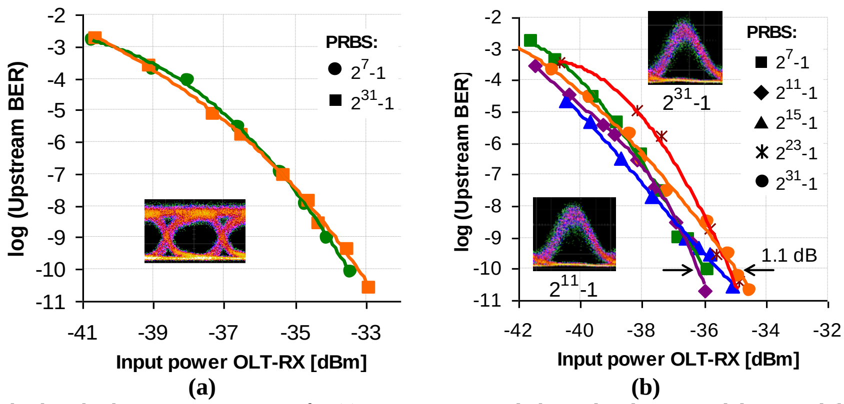

Fig. 3. Upstream back-to-back BER measurements for (a) continuous-wave light seed and NRZ modulation and (b) concurrent RZ downstream clock extraction.

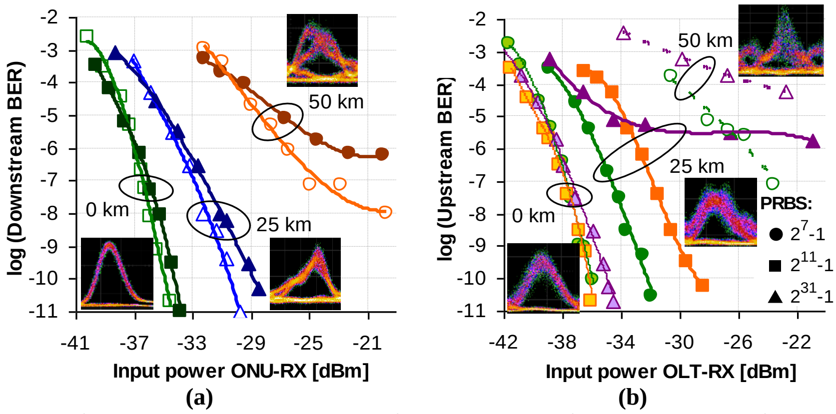

Fig. 4. BER performance for transmission over 25 and 50 km fiber spans in case of (a) the downstream (filled and hollow markers indicate a PRBS 2^{31}-1 and 2^{7}-1, respectively), and (b) the upstream that uses the recovered downstream clock as optical seed.

downstream, upstream reception can be obtained at the FEC level at an extended 50 km reach. However, margin reduction in excess of 10 dB was observed. Finally, we evaluated the clock remodulation method for different downstream wavelengths. The maximum divergence in the upstream sensitivity spectrum for the back-to-back case and a downstream PRBS of 2^{11}-1 is 1.5 dB in a frequency range of 1.25 THz in the C-band, proving in principle the colorless operation of the ONU.

4. CONCLUSIONS

A remodulation technique for optical access supported by an all-optical FPF-based clock recovery circuit was demonstrated over a PON with 50 km reach and 20 dB loss budget. A power margin of 8 dB has been achieved for full-duplex data rates of 10 Gb/s on a single wavelength.

ACKNOWLEDGEMENTS

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