Colorless ONU With All-Optical Clock Recovery for Full-Duplex Dense WDM PONs

Alexandros Maziotis, Bernhard Schrenk, Paraskevas Bakopoulos, Maria Spyropoulou, José Antonio Lázaro Villa, Josep Joan Prat Gomá, and Hercules Avramopoulos

***Abstract*—We propose a colorless optical network unit (ONU) comprised of a Fabry–Pérot filter (FPF) and a semiconductor optical amplifier (SOA) for all-optical clock recovery of the downstream signal, followed by a Mach–Zehnder modulator (MZM) as the upstream modulator. 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 10-Gb/s symmetrical data rate and 20-dB loss budget is demonstrated over fiber spans of 50 km.**

***Index Terms*—Optical communication terminals, optical fiber communication, optical modulation.**

I. Introduction

NEXT generation optical access networks require the use of novel photonic components able to handle the increasing traffic demands and number of users by relaxing cost and power consumption requirements. The ONU requires a simple and cost-effective design, as this will determine the expenditures due to its mass deployment. Wavelength division multiplexed (WDM) passive optical network (PON) architectures constitute a scalable solution for increasing the network capacity and for accommodating the exponential growth of number of users distributed in different topology deployments without compromising the granted bandwidth [1]. A colorless design for mass deployment and wavelength reuse for the upstream modulation ensure an efficient utilization of the available optical carriers in the transmission waveband. A reflective ONU architecture provides then an attractive and cheap solution keeping the ONU wavelength-agnostic [2].

Simplicity at the subsystems for the optical line terminal (OLT) and the ONU further requires simple modulation formats based on intensity modulation. For full-duplex transmission on a single wavelength however, the downstream is typically transmitted with reduced modulation extinction ratio (ER) to provide a possibility for upstream modulation without severe signal degradation due to crosstalk deriving from downstream data [3]. Alternatively, higher bandwidth electronics allow encoding the downstream in Manchester or inverse return-to-zero format; however, limitations have been experienced for remodulation at symmetrical data rates [4].

Manuscript received March 16, 2011; revised June 09, 2011; accepted June 18, 2011. Date of publication June 27, 2011; date of current version September 21, 2011. This work was supported by the EU project EURO-FOS.

A. Maziotis, B. Schrenk, P. Bakopoulos, M. Spyropoulou, and H. Avramopoulos are with the School of Electrical and Electronic Engineering, National Technical University of Athens, GR-15773, Zografou, Athens, Greece (e-mail: maziotis@mail.ntua.gr; schrenk@mail.ntua.gr; pbakop@mail.ntua.gr; mspy@mail.ntua.gr; hav@mail.ntua.gr).

J. A. Lázaro Villa and J. J. Prat Gomá are with the Department of Signal Theory and Communication, Technical University of Catalonia, Barcelona 08034, Spain (e-mail: jose.lazaro@tsc.upc.edu; jprat@tsc.upc.edu).

Color versions of one or more of the figures in this letter are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/LPT.2011.2160622

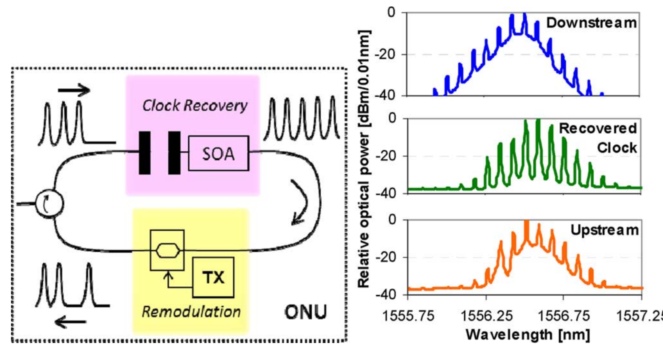

Fig. 1. Colorless ONU design based on remodulation of the recovered clock from downstream transmission in access networks and signal spectra at the ONU with their optical power normalized to the spectral peak component.

Recently, an all-optical approach for downstream cancellation in WDM-PONs by means of all-optical carrier recovery was demonstrated at high downstream ERs of up to 9 dB, employing all-optical data suppression by optical filtering [5]. Furthermore, an optical clock recovery scheme has been presented for regenerative purposes in transport networks, showing its ability for high signal quality remodulation [6]. The all-optical clock recovery circuit relies on simple photonic components such as periodic filters and SOAs with the potential for on-chip integration, which can also play a significant role towards reducing installation and operational expenditure in optical access.

In this letter, we present a colorless ONU design exploiting an all-optical clock recovery circuit to extract the clock information of the downstream. The circuit yields a high quality clock signal [7], [8], which is used as the optical seed for the subsequent upstream transmission. We perform an extensive investigation of full duplex return-to-zero on-off-keying (RZ-OOK) transmission at 10 Gb/s with extended reach. The transmission performance was analyzed with respect to the word length of the data traffic and the accumulated dispersion of the optical distribution network. Finally, we examine the wavelength transparency of this remodulation scheme.

II. ONU Design and Experimental Setup

Fig. 1 shows the fundamental building blocks of the ONU and the spectra of different ONU signals. At the right side, from top to bottom are depicted the downstream, the recovered clock

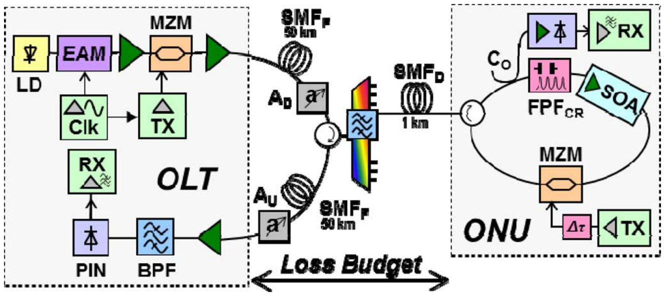

Fig. 2. Experimental setup with wavelength reuse by means of optical clock remodulation.

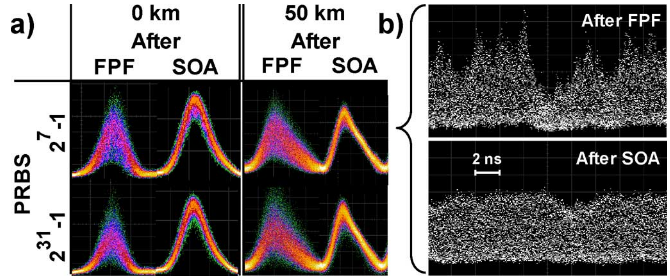

Fig. 3. (a) Eye diagrams at 10 Gb/s of the downstream clock-resembling and the recovered clock signals at the FPF and SOA outputs for PRBS $2^7 - 1$ and $2^{31} - 1$ in the back-to-back case and after 50 km. (b) Traces of the respective signals for PRBS $2^7 - 1$ after 50-km transmission.

after the FPF and the SOA, and finally the remodulated upstream; the optical power level at each spectrum is normalized so that the peak power relates to 0 dB. At the left side, the all-optical clock recovery circuit comprises a FPF for the generation of a clock resembling signal followed by a SOA operated in deep saturation for peak pulse power equalization [7], [8]. The extracted clock information of the downstream data is remodulated at the respective WDM channel by a MZM with upstream data, bit-synchronized with the recovered clock. A MZM modulator was used for this proof of principle in an access environment. For a more cost-effective ONU design with small form factor, a photonic integrable device such as an electroabsorption modulator (EAM) would be more suitable, being also insensitive to the input state of polarization. The all-optical clock recovery circuit is capable of operating for arbitrary WDM channels within the C-band upon tuning the filter passband around the central frequency of the downstream data signal due to the periodic transfer function of the FPF, hence offering a colorless ONU solution.

The experimental setup is shown in Fig. 2. 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 RZ-OOK downstream data signal at 10 Gb/s, electrically fed by an arbitrary pseudorandom binary sequence (PRBS) pattern. The OLT receiver comprises a 10 GHz PIN photodiode and an Erbium-doped fiber amplifier (EDFA) as optical preamplifier with a noise figure of 4.4 dB.

At the ONU, the downstream signal is split by a 50/50 coupler (C_O) 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 nonreturn-to-zero (NRZ) data signal. The FPF has a free-spectral range 10.2289 GHz that is equal the downstream bit rate and a low-finesse of 47. The SOA is a 1.5 mm long device with 3-dB gain bandwidth of 50 nm and a 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 ER > 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.

The optical distribution network 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 upstream, and a short drop fiber of 1 km length. The wavelength distributing element of the PON was emulated by a tunable optical filter with a bandwidth of 125 GHz. The loss budget of the PON, defined between the OLT and the ONU (see Fig. 2) was fixed by adjustment of 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.

III. Results and Discussion

Fig. 3 illustrates the eye diagrams and the respective traces of the clock resembling and the recovered clock signals at the output of the FPF and the SOA, respectively, for the back-to-back case and after downstream transmission over 50 km. The clock resembling signal after the FPF exhibits strong amplitude variation that equals 6.5 dB for PRBS $2^7 - 1$ and reaches 6.8 dB for PRBS $2^{31} - 1$. Significant suppression is achieved for both cases after passing through the SOA, yielding residual amplitude variation of 1.7 dB for PRBS $2^7 - 1$ and 1.9 dB for PRBS $2^{31} - 1$. In the case of transmission over 50 km, additional amplitude variation is expected due to the enhanced patterning effects of the SOA stemming from the induced pulse broadening. An excess of the residual amplitude variation for $2^7 - 1$ and $2^{31} - 1$ PRBS is 0.5 dB and 1.3 dB with respect to the back-to-back case is observed.

Fig. 4(a) presents comparative bit error ratio (BER) measurements performed between the back-to-back 10 Gb/s upstream after RZ-OOK data remodulation at the ONU for various PRBS word lengths and for 10 Gb/s NRZ-OOK upstream modulation for continuous-wave light seed of the ONU. As can be seen, the penalty due to remodulation, caused by 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.

It is noteworthy that for the performance comparison between continuous-wave light injection (case of NRZ upstream) and downstream remodulation (RZ) 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

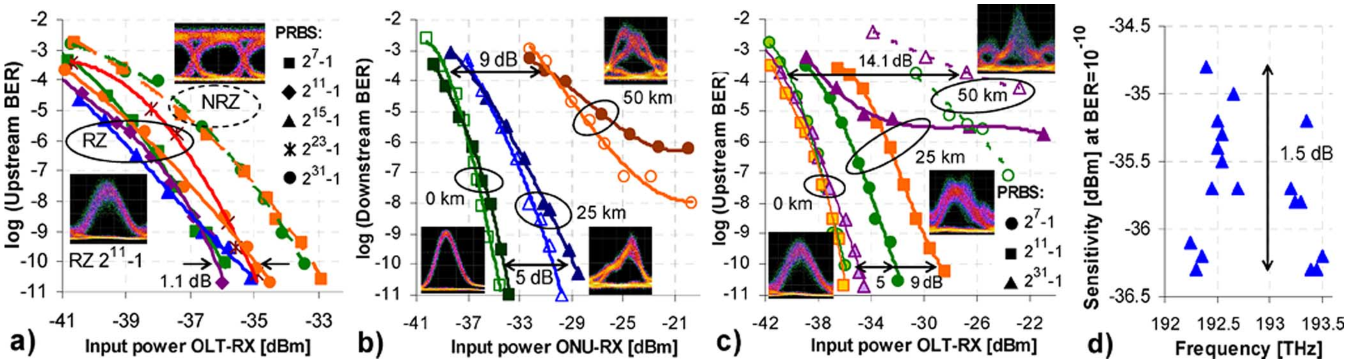

Fig. 4. Upstream back-to-back BER measurements for (a) concurrent RZ downstream clock extraction, and continuous-wave light seed with NRZ modulation. BER performance for transmission over 25- and 50-km fiber spans in case of (b) the downstream (filled and hollow markers indicate a PRBS $2^{31}-1$ and 2^7-1, respectively), (c) the upstream using the recovered downstream clock as optical seed. Finally, (d) back-to-back upstream sensitivity spectrum.

TABLE I
COMPATIBLE POWER MARGINS FOR DOWN- AND UPSTREAM RECEPTION

Fiber length:	Downstream PRBS: 2^7-1	Downstream 2^{31}-1	Upstream 2^7-1	Upstream 2^{31}-1
0 km	25.5 (29.2)	24.4 (29.6)	16.0 (20.3)	14.7 (20.4)
25 km	20.7 (27.1)	19.2 (28.3)	12.0 (18.4)	- (18.4)
50 km	- (10.9)	- (11.0)	- (10.0)	- (6.3)

Values for the margins are shown at a BER of 10^{-10}, and in brackets for the FEC threshold at a BER of 2.10^{-4}.

recovered clock and can be further reduced by using a FPF with higher finesse [9].

Fig. 4(b) and (c) depict 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. For the downstream, a fiber length of 25 km causes a reception penalty of $\sim$ 5 dB (Table I) due to dispersive effects; 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 targeted loss budget of 20 dB that was set between OLT and ONU. When the length of the transmission link is further increased to 50 km, there is still penalized reception possible with a Reed-Solomon (255, 239) Forward Error Correction (FEC) at a BER level of 2.10^{-4}, suffering from a penalty of $\sim$ 9 dB compared to the back-to-back case.

For the upstream that recycles 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(c), 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 a low BER 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 downstream, upstream reception can be obtained at the FEC level at an extended 50 km reach. However, the power margin is reduced in excess of 10 dB, proving the need for dispersion compensation.

Finally, the clock remodulation method was evaluated for different downstream wavelengths. Fig. 4(d) shows the upstream sensitivity spectrum for the back-to-back case and a downstream PRBS of $2^{11}-1$. The maximum divergence is 1.5 dB for a frequency range of 1.25 THz in the C-band, proving in principle the colorless operation of the ONU.

IV. CONCLUSION

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 6 dB has been achieved with FEC for a PRBS $2^{31}-1$ at full-duplex data rates of 10 Gb/s on a single wavelength.

REFERENCES

[1] N. J. Frigo *et al.*, "A wavelength-division multiplexed passive optical network with cost-shared components," *IEEE Photon. Technol. Lett.*, vol. 6, no. 11, pp. 1365–1367, Nov. 1994.

[2] M. D. Feuer *et al.*, "Single-port laser-amplifier modulators for local access," *IEEE Photon. Technol. Lett.*, vol. 8, no. 9, pp. 1175–1177, Sep. 1996.

[3] B. Schrenk, F. Bonada, J. A. Lazaro, and J. Prat, "Remotely pumped long-reach hybrid PON with wavelength reuse in RSOA-based ONUs," *J. Lightw. Technol.*, vol. 29, no. 5, pp. 635–641, Mar. 1, 2011.

[4] H. S. Chung, B. K. Kim, and K. Kim, "Performance comparison between Manchester and inverse-RZ coding in a wavelength re-modulated WDM-PON," in *Proc. OFC'08*, San Diego, CA, Feb. 2008, Paper JThA94.

[5] E. Kehayas *et al.*, "All-optical carrier recovery with periodic optical filtering for wavelength reuse in RSOA-based colorless optical network units in full-duplex 10 Gbps WDM-PONs," in *Proc. OFC'10*, San Diego, CA, Mar. 2010, Paper OWG4.

[6] M. Matsuura and E. Oki, "Optical carrier regeneration for carrier wavelength reuse in a multicarrier distributed WDM network," *IEEE Photon. Technol. Lett.*, vol. 20, no. 11, pp. 808–810, Jun. 1, 2010.

[7] C. Bintjas *et al.*, "Clock recovery circuit for optical packets," *IEEE Photon. Technol. Lett.*, vol. 14, no. 9, pp. 1363–1365, Sep. 2002.

[8] G. Contestabile, A. D'Errico, M. Presi, and E. Ciaramella, "40-GHz all-optical clock extraction using a semiconductor-assisted Fabry–Pérot filter," *IEEE Photon. Technol. Lett.*, vol. 16, no. 11, pp. 2523–2525, Nov. 2004.

[9] X. Zhou, C. Lu, P. Shum, H. H. M. Shalaby, T. H. Cheng, and P. Ye, "A performance analysis of an all-optical clock extraction circuit based on Fabry–Perot filter," *J. Lightw. Technol.*, vol. 19, no. 5, pp. 603–613, May 2001.