On an ONU for Full-Duplex 10.5 Gbps/λ with Shared Delay Interferometer for Format Conversion and Chirp Filtering

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Abstract: Chirped IRZ downstream is used together with a delay interferometer and a RSOA at a low complexity ONU for full-duplex 10.5Gbps transmission on a single wavelength, supported by modulation format conversion and optical offset filtering.

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1. Introduction

Simplicity, energy-efficiency and low capital and operating expenditures are demanded from next generation access solutions, despite the concurrently growing need for data transmission with symmetrical, high data rates. The wavelength division multiplexed passive optical network (WDM-PON) with colorless optical network units (ONU) can suit to these requirements since its fully passive infrastructure that offers a high guaranteed bandwidth per user is free of electrically powered components and further shared among a higher number of customers. The latter is typically destined to be equipped with a low-cost upstream modulator such as the reflective semiconductor optical amplifier (RSOA), which has been already proven for 10 Gbps modulation [1].

The impressive strides that have been made for optical signal processing in core networks can be used advantageously and infiltrate the access segment to offer its techniques for functionalities such as re-utilization of optical carriers for bidirectional transmission with the simple amplitude shift keyed (ASK) modulation format [2].

In this work, we introduce another technique deriving from optical wavelength conversion [3] to support wavelength reuse by modulation format conversion and at the same time chirp managed full-duplex transmission at 10.5 Gbps, by sharing a delay interferometer (DI) between down- and upstream at a low-cost RSOA-based ONU design that is fully compatible with photonic integration.

2. Wavelength Re-Cycling through Shared DI for Format Conversion and Offset Filtering

Though the re-use of an optical carrier can be based on orthogonal modulation formats, which include differential phase shift keying (DPSK) or frequency modulation for the downstream while the upstream is modulated in its intensity [4], the complexity that is introduced for the demodulation of the downstream, such as the DI for PSK-to-ASK conversion, cannot be further utilized to support the upstream transmission due to the unfavorable seed that the demodulated signal imposes for the reflective modulator. On the other hand, the modulation bandwidth of an RSOA can be significantly enhanced by optical filtering due to the conversion of the introduced chirp into supportive amplitude modulation, for which a DI apparently provides a colorless solution [5]. The simultaneous use of the two DI arms for DPSK demodulation and offset filtering of a chirped upstream signal would require a reduced contrast for the phase modulation and, most important, costly and bulky phase modulators at the optical line terminal (OLT).

Instead, the use of ASK and a shared DI as detuned optical filter and format-converting element improves both, the converted downstream and the modulated upstream data (Fig. 1). In case of the downstream, the DI acts as inverse return-to-zero (IRZ) to RZ converter for the chirped IRZ-ASK downstream. The reception sensitivity can be thereby improved thanks to the polarity inversion property between the two output ports of the DI that translates into a better contrast in the converted RZ bit pattern [3]. Consequently, the downstream can be imprinted with a reduced IRZ extinction ratio (ER). In addition, the IRZ format makes the downstream suitable as optical seed for the RSOA-based non-return-to-zero (NRZ) ASK upstream modulator [6], however, in the case of a shared DI at the ONU the upstream bit slot is not halved. Note that the functionality of the power splitter that is typically placed between the downstream receiver and upstream transmitter is inherently provided by the DI.

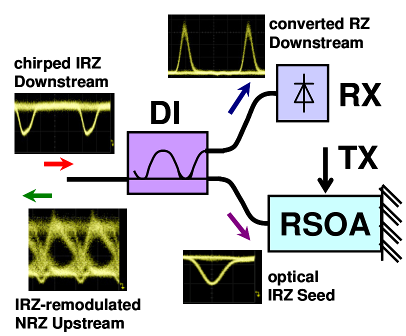


Fig. 1. Down-/Upstream modulation formats and ONU design for full-duplex data transmission.

3. Experimental Proof for Asymmetrical 10.5/5.25 Gbps and Symmetrical 10.5 Gbps Transmission

The proposed ONU design was proven in a simple WDM-PON configuration (Fig. 2), whereby its performance was assessed in a back-to-back environment to exclude dispersive effects that would require additional means of dispersion compensation. The arrayed waveguide grating was emulated by a broad optical bandpass filter.

At the OLT, the chirped IRZ downstream is generated via all-optical wavelength conversion in a SOA. For this reason, the pulse train of a mode-locked laser (MLL) that is operated at a repetition rate of 10.5 GHz is modulated with a MZM using a pseudo-random bit sequence of length 2^7-1 to avoid additional penalties from the gain dynamics of several SOA elements. This RZ data signal at λ_{MLL} = 1545 nm, having a pulse width of 8 ps, and a continuous-wave carrier at λ_{DS} = 1551.51 nm are combined with a coupler (C_S) and fed into a nonlinear SOA, where the carrier at λ_{DS} is imprinted with IRZ data due to cross-gain modulation (XGM). In addition, the IRZ signal experiences chirp due to the carrier density variation in the SOA that is caused by the optical swing in the RZ data signal at λ_{MLL}. The contrast in the converted IRZ signal was adjusted with variable attenuators and optimized in compromise with its later remodulation with upstream data at the ONU. The RZ data signal at λ_{MLL} is filtered by an 0.6 nm optical bandpass filter that can be also used to enhance the XGM speed, while the IRZ downstream at λ_{DS} is boosted with an Erbium-doped amplifier (EDFA) and launched with 13 dBm into the WDM-PON (point A in Fig. 2). The reduced IRZ ER for the transmitted downstream was 2.6 dB for injected power levels of -13 and -4 dBm for λ_{MLL} and λ_{DS} into the SOA, while it is 6.3 dB if the XGM effect in the SOA is fully exploited.

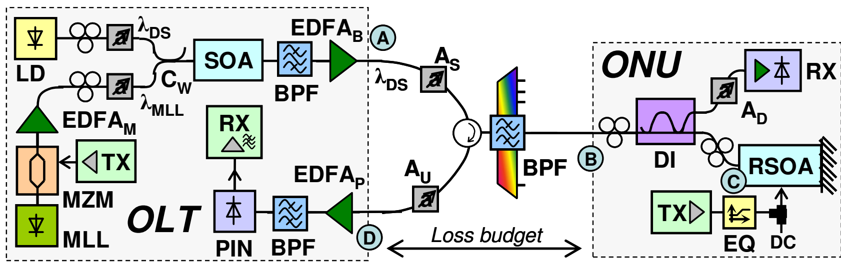


Fig. 2. Experimental setup for the back-to-back proof of concept in a WDM-PON environment.

At the ONU, the high-gain RSOA from [7] modulates the upstream onto the IRZ downstream that is re-used as optical seed. The intrinsic e/o modulation response of the RSOA, whose optical input was fixed to -20 dBm (point B) with a variable attenuator (A_S), was ~2.5 GHz and extended with a passive electrical RLC-equalizer and optical offset filtering with the DI. The chosen upstream data rate was 5.25 and 10.5 Gbps in accordance with a more symmetrical rate towards the 10.5 Gbps downstream, whose line rate was limited by the repetition rate of the MLL.

The DI had a differential delay of 12.5 ps, an extinction of 18 dB and a fiber-to-fiber loss of 13.5 dB. Due to the residual polarization sensitivity of the DI, controllers were added at the input and the bidirectional output port. However, DIs with low polarization dependent loss have been already demonstrated [8]. While the RSOA is connected to the non-inverting port of the DI, the downstream receiver (RX), which is comprised by a combination of EDFA and PIN diode since no avalanche photo diode (APD) was available, receives the format-converted RZ downstream signal at the inverting port of the DI. As it is also the case in the EDFA+PIN -based upstream receiver at the OLT, the PIN diodes had an electrical reception bandwidth of 10.6 GHz and a sensitivity of -19 dBm.

4. Results and Discussion

The spectra of the different signals at the ONU are shown in Fig. 3 for a downstream with reduced IRZ ER. The optical power level is normalized so that the peak power of the optical carrier relates to 0 dB. With the dip of the inverting DI port spectrally aligned at downstream wavelength λ_{DS}, the carrier is suppressed for the detected downstream, while the RSOA seed light appears as favorable for upstream modulation. Note that the DI is not fully optimized in its spectral periodicity for the chosen data rates.

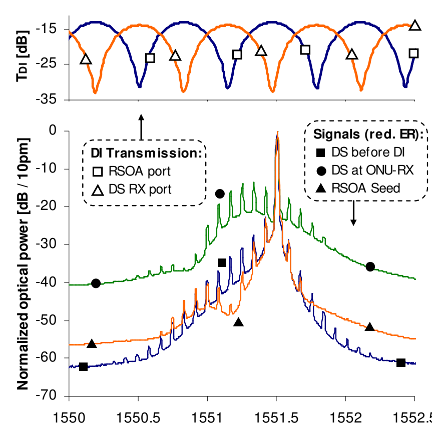
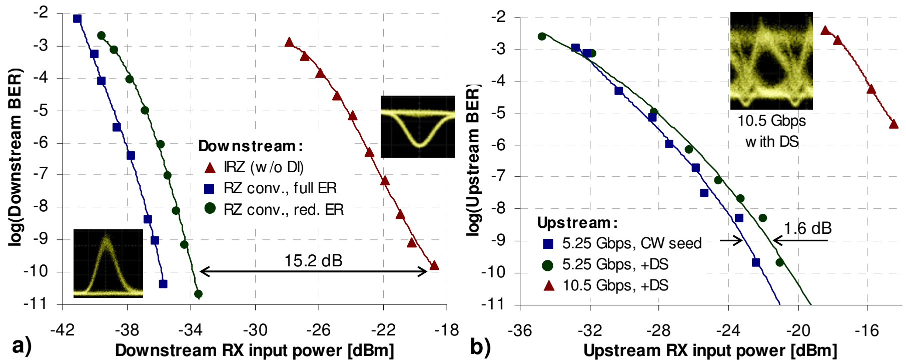


Fig. 3. Transmission function T_{DI} of the DI and spectra for a chirped IRZ downstream (DS) with reduced ER. The optical power is normalized to the carrier level and the resolution BW is 10 pm.

The performance of the ONU was assessed with bit error ratio (BER) measurements (Fig. 4), for which variable attenuators (A_D, A_U) were placed in front of the downstream and upstream receiver. The sensitivity for the downstream was referenced to the input of the receiver itself to exclude the losses of the DI for a later comparison of different parameters such as received modulation format and optical excess losses for the DI.

The reception sensitivity of the RZ-converted downstream with initially reduced IRZ ER is -33.8 dBm at a BER of 10^{-10} (● curve), having a penalty of 2 dB compared to the case where the ER and chirp is enhanced (■) through different optical levels for λ_{MLL} and λ_{DS} for the exploitation of XGM in the SOA (Fig. 4a). For the case that no DI is used (▲) and the IRZ signal is detected without format conversion, a penalty of



Compatible loss budget [dB] for line rates [Gbps] of down-/upstream.

Rate / Budget	10.5 / 5.25	10.5 / 10.5
DS (+FEC)	20.3 (24.5)	
Seed	29	
US (+FEC)	17.6 (28.3)	- (13.6)

Fig. 4. BER measurements. a) 10.5 Gbps Downstream in IRZ and converted RZ format with full and reduced IRZ extinction ratio (ER) at the OLT transmitter, b) Upstream (US) for 5.25 Gbps and 10.5 Gbps with present downstream and continuous wave (CW) light seed for the RSOA.

15.2 dB is suffered, mostly due to the optical power that resides in the IRZ carrier. With the given RZ data signal, a penalty of 3.3 dB remains if the modulation format specific power penalty from RZ-IRZ of 11.9 dB is subtracted.

With reasonable transmission losses of 4 dB for the DI [7], meaning a re-allocation of ~9.5 dB of excess loss towards the loss budget of the PON, an optical budget of 30.9 dB can be covered with the given EDFA+PIN receiver, considering that the sensitivity is referenced to the ONU input to which an IRZ downstream with optical power in the carrier is delivered. With a sensitivity of -37.6 dBm at a BER of 10^{-10} for a 10.5 Gbps NRZ data signal and the EDFA+PIN -based receiver, this penalty translates to a budget of 20.3 dB in case an APD with a sensitivity of -27 dBm as downstream receiver. With the inclusion of a Reed-Solomon (255, 239) forward error correction (FEC) that allows a BER level of 2.10^{-4} for the downstream reception, the loss budget can be extended to 24.5 dB.

The input power of the RSOA was fixed to -20 dBm for the upstream measurements, which would correspond to a seed budget of 29 dB if the excess losses of the DI are excluded from the ONU. With an upstream data rate of 5.25 Gbps, a small penalty of 1.6 dB is introduced at a BER of 10^{-10} by the simultaneously present downstream modulation (see ■ and ● curves in Fig. 4b). This penalty is attributed to the residual downstream pattern, which is just partially suppressed by the RSOA gain saturation. Note that the present chirp of the seeding downstream signal due to the XGM in the SOA does not significantly affect the upstream signal, which is chirped due to electro-optical gain-modulation of the RSOA. With a reception sensitivity of -20.4 dBm at a BER of 10^{-10} and the given launch of 1.2 dBm from the RSOA (point C), meaning an upstream launch of -2.8 dBm without excess loss of the DI, a loss budget of 17.6 dB is compatible. With FEC, the loss budget can be extended to 28.3 dB.

In case of a higher data rate of 10.5 Gbps for the upstream (▲), low BER values cannot be reached anymore due to the limited delivered optical power (at point D), which is bound by the high intrinsic loss of the DI that are also present in the upstream light path. However, even in this case of having full-duplex 10.5 Gbps transmission on a single wavelength, reception at the FEC threshold is possible and compatible with a loss budget of 13.6 dB.

5. Conclusion

An ONU design fully compatible with photonic integration has been proven for full-duplex ASK transmission on a single wavelength. Only a delay interferometer and a RSOA are required at the ONU, to support format conversion and chirp filtering. Loss budgets of 24.5 and 13.6 dB are compatible for 5.25 and 10.5 Gbps upstream line rate.

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