Wavelength Conversion Towards Rayleigh Backscattering Tolerant PONs via Four-Wave Mixing in SOA-based ONUs

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Abstract: Wavelength shifting in PONs with downstream signal remodulation is presented, allowing upstream transmission over trees with 25km feeder and 1:32 split with penalties <2dB, originally Rayleigh backscattering limited. Side-mode suppression is analyzed for hybrid PONs.

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1. Introduction

Fiber-to-the-Home solutions are gaining focus due to their capability of satisfying high bandwidth demands of the customers in access networks, especially in cost-efficient passive optical networks (PON). Due to the permanently increasing number of customers, a convergence between the access and the metro segment is expected, giving also rise to hybrid architectures that consider wavelength and time division multiplexing (WDM/TDM) to expand the number of served customers [1,2]. Such architectures can be comprised of a WDM metro ring and a TDM tree, interconnected at conjunction points referred to as the remote nodes (RN). The latter are supposed to provide remote amplification, to overcome the high losses of such a hybrid PON, which is typically subject of advanced power budgets due to extended reach and high split in the tree. Colorless optical network units (ONU), holding reflective modulators, ensure a cost efficient mass deployment of customer premises equipment across the whole PON.

The spectral efficiency has to be kept high in dense PONs, so that each tree can only acquire the use of a single wavelength, on which down- and also upstream data is imprinted for full-duplex transmission. In addition, a single fiber access is intended for each ONU. Due to the high splitting ratio required in the tree, the downstream has to be launched with high optical power from the RN to reach the ONUs with sufficient remaining power. The feeder fiber that is typically placed between the RN and the splitter causes strong Rayleigh backscattering (RB) and leads to degradation in the transmission performance of the upstream since the net gain of the ONU is limited while the splitter loss is high, therefore resulting in a low optical signal-to-RB ratio. Besides mitigation approaches like frequency dithering which suffer from reduced efficiency, means of wavelength shifting at the ONU can provide a solution as long as they are cost efficient.

In this work, advantage is taken out of the Sardana architecture [2], in which two wavelengths are dropped at each RN to obtain a more practical realization in terms of gain transient stabilization in its bidirectional, remotely pumped Erbium-doped fiber (EDF) based amplification stages for down- and upstream [3]. Inherently, the two dropped wavelengths can feed two trees that are connected to the RN, whereby each one of the trees is dedicated to one of the wavelengths. For the approach presented, we feed both wavelengths to both trees, and perform all-optical wavelength shifting in the ONU, obtained by four-wave mixing (FWM) in a semiconductor optical amplifier (SOA) [4]. We show that the influence of RB is drastically reduced while only a low reception penalty is introduced.

2. Scheme

The pumping scheme for the FWM process in the ONU is determined by the two tree wavelengths used for downstream transmission, located at the wavelengths λ_1 and λ_2. As these are lying close together, on neighboring channels of the ITU grid, no broad wavelength shift is asked for the FWM process, implying a reasonable efficiency for the generation of ghost wavelengths in the intended wavelength range that is dropped from the RN in the PON.

The transmission scheme is illustrated in Fig. 1 and shows the specific filtering used in the RN and the ONU. The two pumps at the downstream wavelengths (λ_1,λ_2), are sent from the OLT via the ring to the RN, where they are amplified and fed to the trees. For this reason, a 50/50 coupler would have to be inserted before the feeder fiber, as both trees have to be provided with both pumps. Once at the ONU, the pumps are directed with an interleaver to the SOA in which the FWM takes place, generating two ghost wavelengths (λ_3,λ_4). After remodulation (not shown), the interleaver is used a second time to reject the remaining pump signals so that only the modulated ghosts are passed back to the RN, where they are now amplified by in upstream direction and finally arrive via the ring at the OLT receiver, where the upstream signal of the appropriate tree is selected and other side channels are suppressed.

It has to be noted that the interleaver apparently maintains a colorless solution for the ONU, which is also suitable for photonic integration, e.g. by Mach-Zehnder structures or ring resonators.

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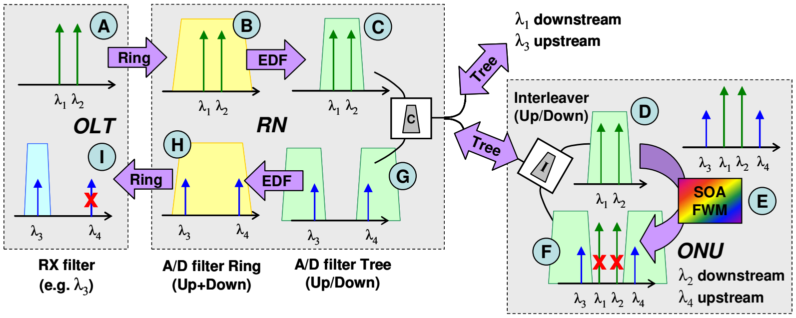

Fig. 1. Functional scheme of the PON. In compatibility with the Sardana architecture, two pumps are fed to each tree. The filters in the RN and the interleaver in the ONU are chosen to suppress unwanted spectral components after the FWM process in the SOA-based ONU.

3. Experimental Setup

Two wavelengths at λ_1 = 1552.47 nm and λ_2 = 1552.77 nm are multiplexed (M_T in Fig. 2a) and launched into the PON with a power of 3 dBm each. No downstream pattern was imprinted as this would cause additional errors when reusing the wavelength for the upstream, thus distorting the penalties deriving from RB, which are subject of investigation. The downstream ring span is emulated by 15 dB of loss, corresponding to a reach of about 75 km. No single-mode fiber (SMF) was placed to keep the penalties free of dispersive effects for this investigation.

Thin film add/drop filters in the RN, centered at 1552.53 nm with a bandwidth of 200 GHz, select two neighboring wavelengths (λ_1,λ_2) as the downstream signals. 50/50 couplers (C_R) are placed to accommodate for resiliency in the dual fiber ring, whereas the ring was not implemented for simplicity. The signals are then amplified by 15 m of HE980 EDF, locally pumped by a laser diode at 1480 nm with a power of 19 dBm. In a real scenario, this pump would have to be transmitted by the OLT along the ring. A 100 GHz add/drop filter, centered at the same wavelength as the add/drop filters from the ring, then feeds the signals into the tree. With this cascaded filter scheme, a four channel allocation with 50 GHz spacing is given, assigning the pumps (λ_1,λ_2) to the two inner channels and the ghosts (λ_3,λ_4) to the two outer channels. The filters rejected the adjacent channels with >25 dB.

The tree consists of a feeder SMF with a length from 0 to 25 km and a 1:32 splitter. The overall loss of the feeder was kept constant (i.e. parts of the fiber were replaced by equivalent attenuation). In this way, the input power for the ONU stays the same, and no additional optical signal-to-noise ratio (OSNR) degradation is suffered.

At the ONU, a first SOA (model Kamelian OPA-20) is used as preamplifier and booster. An interleaver (I_O), directs the incoming (pump) signals at λ_1 and λ_2 with -4.7 dBm into a SOA (model JDSU CQF871) that is intended to be used as booster. FWM products arise at the ghost wavelengths λ_3 and λ_4, intended to carry the upstream data. These new carriers are shifted by 50 GHz from the pump signals (λ_1,λ_2). As remodulator (RMD), a reflective SOA (RSOA) biased at 55 mA and modulated with 70 mA_{pp} was used, leading to an upstream extinction ratio of 8 dB. The RSOA had a noise figure of 9 dB and a small signal gain of 21.7 dB, with an optical 3 dB gain bandwidth of 54 nm centered at 1550 nm. Instead, also an inline EAM could be used in principle, best in combination with the preceding SOA in form of an integrated SOA/REAM, which would avoid the circulator that is not suitable for photonic integration so far. The upstream data was imprinted with 1.25 Gbps (arbitrary low for this proof of concept, to avoid dispersive effects in the feeder fiber) and a pseudo-random bit sequence with a length of 2^{31}-1. The interleaver then passes only the modulated ghost signals (λ_3,λ_4) to the output of the ONU, and rejects the still remaining pump signals. Due to the high gain provided by the RSOA, a small additional loss was placed between the output of the circulator and the interleaver, to avoid cross gain modulation between the ghost signals and the pump signals in the common SOA at the input of the ONU. The net ONU gain, defined by the incident pump and outgoing ghost signals, was 17.2 dB. For comparison, a standard ONU, containing only the RSOA, was also used.

The add/drop filter at the tree interface of the RN now routes the ghosts (λ_3,λ_4) to the upstream EDF amplifier. It shall be noted that this add/drop filter does not have to provide a spectral periodical transfer function like an

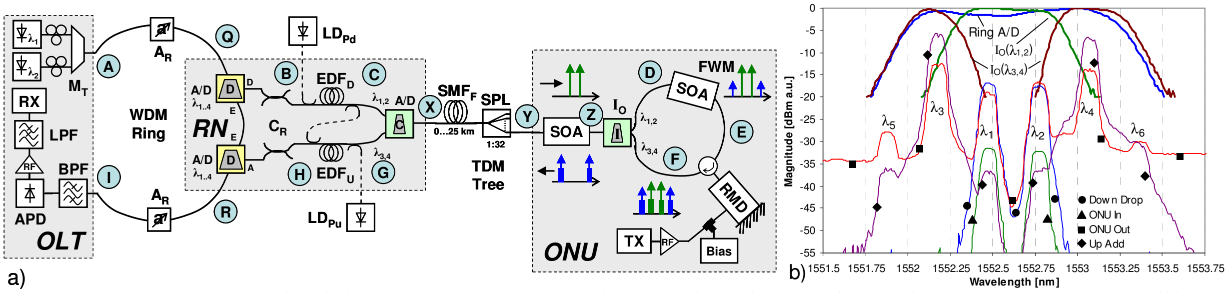

Fig. 2. (a) Experimental setup for a hybrid PON whose ONUs include means of wavelength shifting, and (b) optical spectra at the add/drop filters of the ring interface and at the ONU entrance, and the transfer functions of the ring add/drop filter and the interleaver (I_O) in the ONU.

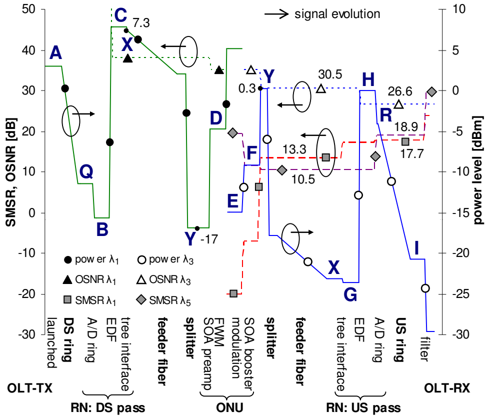

Fig. 3. Signal power levels, OSNR and SMSR along the PON.

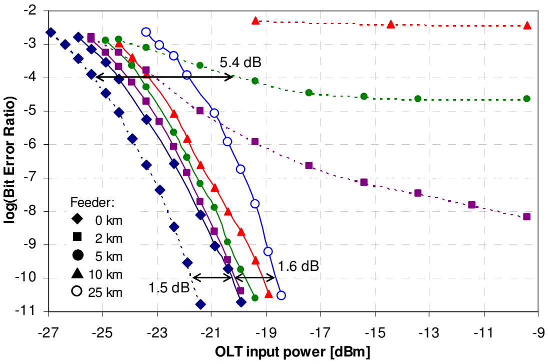

Fig. 4. BER measurements for the ONU without (dashed lines) and with wavelength shifting (solid lines) for different feeder lengths up to 25 km.

interleaver has, as the RN does not have to be colorless. It shall be noted that although the RN has a complex design, it is kept passive and does not have operating expenditures. The signals are finally injected into the ring, whose fiber is emulated by an attenuator with 15 dB of loss, taking another 75 km of reach into account. The optical OLT receiver holds a bandpass filter to select the appropriate signal wavelength (λ_3) and an avalanche photodiode (APD).

The process of shifting can be seen in the optical spectra in Fig. 2b. The incident (pump) signals at λ_1 and λ_2 pass the interleaver I_O in the ONU, whose transfer function is also shown in Fig. 2b together with its reflective port, which in turn selects only the ghost signals at λ_3 and λ_4. At the output of the ONU, there are also spectral components at λ_5 and λ_6, also caused by FWM in the modulator. These ghosts are also suppressed by the interleaver, due to the chosen spacing between the FWM products. The upstream that is added to the ring finally contains only components at λ_3 and λ_4, with a sufficient suppression of the pump signals (λ_1,λ_2) and the outer ghosts at λ_5 and λ_6.

4. Results and Discussion

A quantitative representation of the side-mode suppression ratio (SMSR) and the OSNR is given in Fig. 3, showing also the signal power levels along the PON, where the ONU input was kept at -17 dBm. While the OSNR is still quite high with 30.5 dB at the ONU output for the inner ghost at λ_3, carrying the upstream signal, the SMSR is here just 13.3 and 10.5 dB for the remaining pump (λ_1) and the outer ghost (λ_5). However, the latter are raised to 17.7 and 18.9 dB after the RN, while the OSNR is degraded to 26.6 dB, which is an acceptable noise background.

Transmission with the standard ONU, comprising just a RSOA, is penalized strongly by RB. A feeder fiber of 2 km makes transmission at a bit error ratio (BER) level of 10^{-10} impossible (Fig. 4) as there is an error floor. At the forward error correction (FEC) threshold with a BER of 10^{-4}, the penalty is already 2.2 and 5.4 dB for a feeder of 2 and 5 km, which correspond with the given splitting ratio to an optical signal-to-RB (OSRR) ratio of 7.0 and 5.4 dB. For the latter, an error floor is caused just below the FEC threshold, preventing the use of longer feeder segments.

When adding the FWM shifter, there is a penalty of 1.5 dB at a BER of 10^{-10} in the back-to-back case, compared to the standard ONU. This can be explained with the additional OSNR degradation and the crosstalk from the surrounding wavelengths. However, the penalties for having feeder lengths of 2, 5, 10 and 25 km (corresponding to an OSRR of 7.0, 5.4, 3.9 and 3.2 dB) are just 0.1, 0.5, 1.1 and 1.6 dB. This reflects that the shifted upstream signal at λ_3 is insensible to RB of the downstream at λ_1, which is also evident from the eye diagrams (Fig. 5).

5. Conclusion

Wavelength shifting by four-wave mixing between the downstream signals of the trees in a PON with wavelength reuse has been shown to enable upstream transmission, normally Rayleigh backscattering limited in its transmission. An acceptable penalty of 1.5 dB is introduced by the modified ONU design due to side mode crosstalk at the reception. The penalty caused by a feeder fiber of 25 km is then <2dB. Downstream operation is left for future work.

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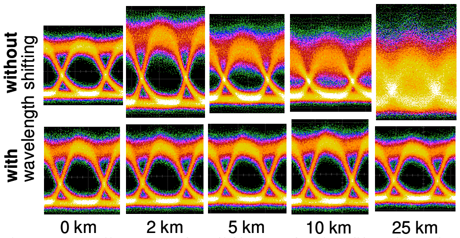

Fig. 5. Eye diagrams for different feeder fiber lengths.

6. References

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