Rayleigh Scattering Robust Access Network by λ-Shifting through Extraction of Suppressed RZ Clock Harmonic

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Abstract: Wavelength shifting based on the all-optical clock recovery of a RZ-downstream with suppressed clock harmonic is presented, avoiding in-band Rayleigh backscattering for choosing this particular harmonic as upstream carrier, even for a low OSRR <10dB.

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1. Introduction

As cornerstone for cost-effective passive optical networks (PON), wavelength reuse for the upstream transmission with reflective optical network units (ONU) has become an attractive field of research since it avoids the use of extra light sources at the optical line terminal (OLT) and the ONU. Such techniques have been recently demonstrated with all-optical implementations, using the simple intensity modulation without introducing large penalties for down- and upstream transmission [1,2]. However, the transmission in loopback PON configurations is vulnerable to distributed backscattering effects at fiber-based light paths or concentrated reflections. Rayleigh backscattering (RB) can impose a stringent impediment once the loss budget increases [3]. Means of RB mitigation have been proposed in earlier works, indicating that robustness of the upstream against RB can be achieved once the upstream wavelength is spectrally displaced from the optical downstream carrier. However, such techniques of wavelength shifting often need extra active elements or electro-optical modulators to obtain this desired frequency shift for the upstream [4,5].

In this work, advantage is taken from an all-optical clock recovery technique that is used for wavelength reuse, to displace the optical upstream carrier from the downstream signal with the help of selective optical filtering. An optical clock recovery at the ONU not only provides a method for downstream remodulation [2]; With its ability to recover an initially suppressed harmonic of the return-to-zero (RZ) downstream signal, it allows, together with the extraction of the same, recovered clock harmonic to immunize the upstream against RB from the downstream.

2. Wavelength Shifting based on Passive Optical Filtering

The proposed approach for RB mitigation is shown in Fig. 1. The RZ downstream passes through a narrowband notch-filter to remove one of its clock harmonics. Due to that, RB that derives at the bidirectional fiber link does not contain any spectral component at this suppressed tone. Consequently, if the upstream is transmitted at exactly this frequency, no RB degradation arises. To generate the optical upstream carrier at the desired wavelength, an all-optical clock recovery is used together with a narrow optical passband filter so that just a single optical carrier remains as seed of the upstream modulator. Depending on which clock harmonic the upstream is modulated at, a wavelength shift of up to a multiple of the downstream rate R_{DS} is provided. At the upstream receiver, the RB contribution, which is now out-of-band with the data, can be filtered with a filter that is centered at the upstream.

The concept was evaluated for a PON-like scenario and the case of asymmetrical data rates of 10 and 1 Gb/s for down- and upstream. Several optical filters for clock recovery and narrow-band filtering were realized by fiber-based Fabry-Pérot filters (FPF). The FPFs for the RZ tone rejection at the OLT and the tone extraction after the clock recovery at the ONU had a bandwidth of 0.55 and 0.29 GHz, respectively. The clock recovery comprised a semiconductor optical amplifier (SOA) and a FPF with a free spectral range of 10 GHz and a finesse of 40. An Erbium-doped fiber amplifier (EDFA) with a gain of 10 dB was included to compensate for the low SOA gain. At the OLT receiver, a 5 GHz broad FPF was placed inside a dual-stage EDFA preamplifier to filter the RB.

The RZ downstream was generated by using an electro-absorption modulator (EAM) for pulse carving and a Mach-Zehnder modulator (MZM) for bit-synchronized data modulation. The RB was generated at a 25 km long standard single-mode fiber (SMF), whose backscattered light was added to the upstream signal with worst-case polarization state. The attenuators A_D and A_U were fixed to a loss budget of 20 dB between OLT and ONU, meaning with the downstream launch of 10 dBm from the OLT transmitter an ONU input of -10 dBm. The third attenuator A_{RB} was used to adjust the upstream optical signal-to-RB ratio (OSRR). Two 3 nm broad bandpass filters were included in the distribution network to emulate the multiplexer of wavelength division multiplexed PONs.

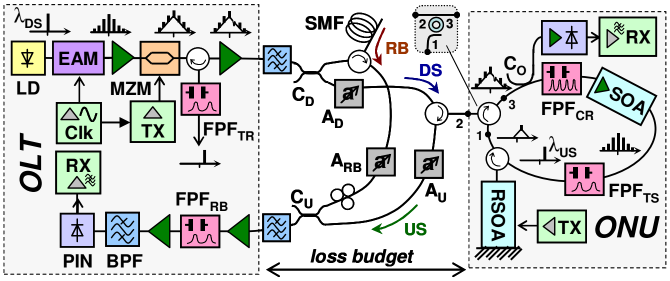

Fig. 1. Experimental proof-of-concept setup for the wavelength shifting scheme, based on passive optical filtering.

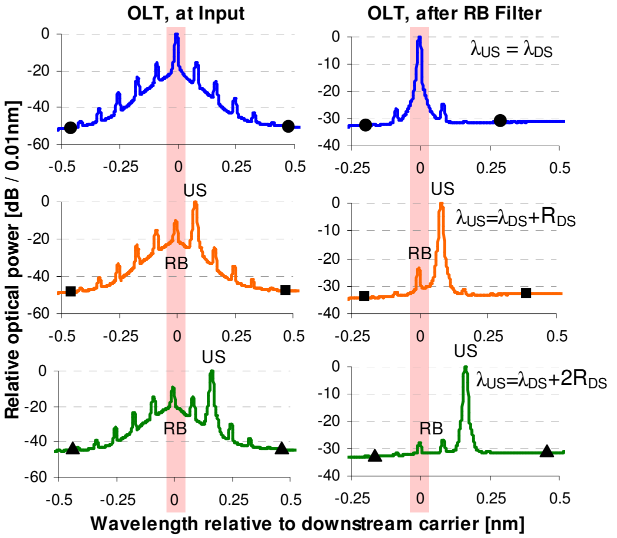

Fig. 3. Impact of the RB filter at the OLT receiver on upstream signals with different wavelength shifts corresponding to transmission at the downstream carrier wavelength, the +1 and +2 harmonic.

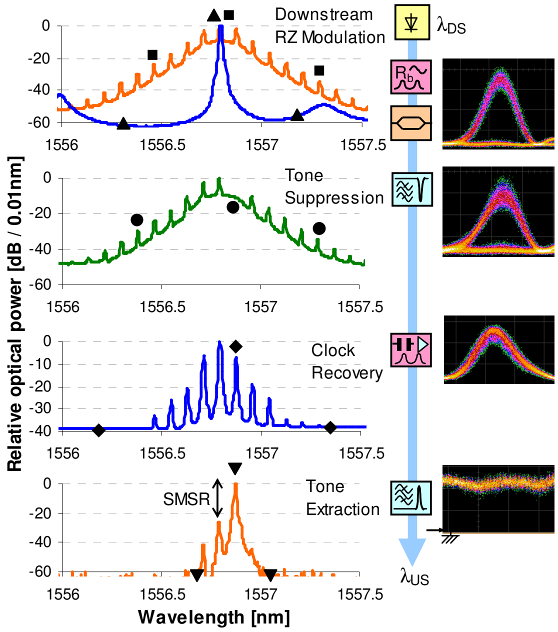

Fig. 2. Optical spectra illustrating the evolution of the RZ downstream towards a shifted upstream and corresponding eyes diagrams.

A 50/50 coupler (C_O) at the ONU splits the incident downstream for the purpose of remodulation and detection. For the latter, a combination of PIN diode and transimpedance amplifier was used. A low-cost reflective SOA (RSOA) with a small-signal gain of 21 dB constituted the upstream transmitter and was fed by a PRBS of length 2^{31}-1. With the upstream launch of 2.5 dBm, the net gain of the ONU is 12.5 dB. Note that in case of using an inline SOA, the circulator for the RSOA can be removed and the second circulator at the ONU input can be replaced by a ring resonator as shown in Fig. 1, having its drop port towards the upstream transmitter (i.e. SOA) while its express port relays the downstream to the clock recovery. Thus, a photonically integrable ONU can be obtained.

3. Signal Evolution and Performance Characterization

The spectral evolution of the downstream is presented in Fig. 2, where the optical power is normalized to the strongest spectral component. The downstream carrier (▲) was located at λ_{DS} = 1556.8 nm and shows solely the side-modes of the distributed feedback laser diode. After RZ modulation (■) with a PRBS 2^7-1 and clock tone suppression with the FPF (●), the first order (+1) harmonic (adjacent to the carrier) is rejected by ~10 dB. This value can be further increased with non-reflective filters such as ring resonators. The suppressed harmonic is again established after the clock recovery at the ONU (♦). Besides the obtained wavelength shift of 1•R_{DS} with respect to the downstream carrier, the SMSR after the tone extraction FPF (▼) is already in the range of 25 dB. Note that the separation between the strongest side peak, which derives from the downstream carrier at λ_{DS}, corresponds to the downstream rate R_{DS} and is wider than the FPF bandwidth at the OLT receiver, so that this SMSR is further improved before upstream detection.

This is obvious from the spectra in Fig. 3, showing the received upstream after RB addition at the OLT input and after the FPF that rejects the RB. Though the SMSR is high for the upstream without wavelength shift (●), there is significant in-band RB noise. On the contrary no in-band RB contribution exists for the shifted upstream thanks to the suppression of the clock harmonic at the OLT transmitter. For the upstream that is located at the +1 (■) and +2 harmonics (▲), the SMSR is thus determining the reception performance. As can be seen, this SMSR is ~25 dB.

The high SMSR, defined as indicated in Fig. 2, stems from the sufficient suppression of the other clock harmonics by the FPF during extraction of the upstream carrier. This SMSR for the upstream carrier is >27 dB even

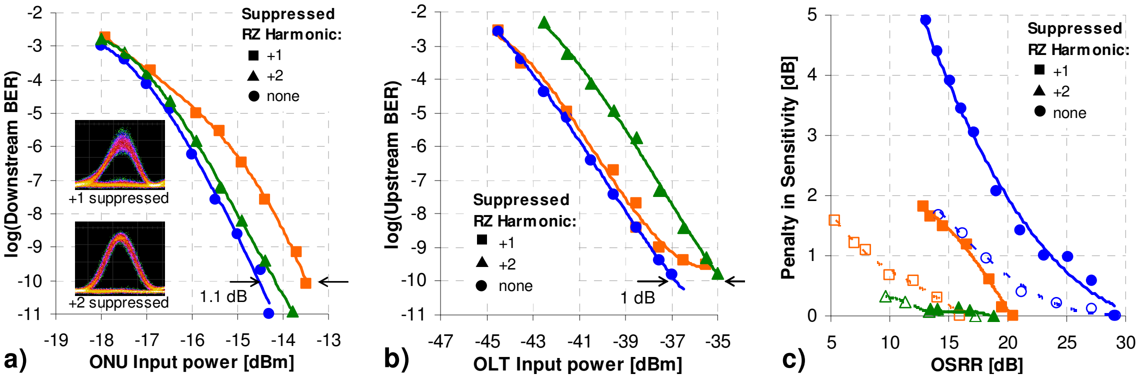

Fig. 4. BER performance for (a) the RZ downstream with tone suppression, and (b) the upstream at the recovered harmonic. (c) Penalty in sensitivity as function of the OSRR for the received upstream. Filled markers indicate a low BER of 10^{-9}, while hollow markers correspond to a higher BER level of 10^{-4}.

for transmission at farther harmonics, e.g. the +3 or -3 clock component. The induced excess filtering loss in respect to transmission at the optical carrier of the downstream is in the order of 5 dB for the +1 and +2 RZ harmonics and raises to 13 dB for the +3 clock component, while the filtering loss for transmission at the corresponding negative clock harmonics is slightly higher since the chirp of the SOAs acts beneficial for positive detuning.

As can be deduced from the eyes in Fig. 2, there is no strong distortion in the downstream once the +1 harmonic is suppressed, while it improves for rejecting higher-order harmonics that carry less power. The recovered upstream carrier at the initially rejected harmonic does not show significant patterning from the clock recovery. Note that for a longer downstream PRBS the finesse of the FPF used at the clock recovery has to be increased accordingly.

4. Transmission Performance in Loopback-PONs

The transmission performance for both data streams was assessed in terms of bit error ratio (BER) measurements. While for the suppression of the +1 harmonic of the RZ downstream a penalty of 1.1 dB arises at a BER of 10^{-10} compared to the RZ downstream containing all initial clock tones (Fig. 4(a)), this penalty reduces to <0.5 dB for rejecting the +2 harmonic. A power margin of 3.8 dB was found, considering the targeted loss budget of 20 dB.

In case of the upstream reception without added RB, shown in Fig. 4(b), the penalty that is attributed to the filtering loss of the wavelength shifting technique is 1 dB for a BER of 10^{-10} and the worse case of extracting the +2 tone as upstream carrier. This proves that with a reasonable amount of amplification inside the ONU, the inherent filtering losses can be overcome without being penalized. A budget of >38 dB is compatible for the upstream.

When adding the RB deriving from the downstream, the beneficial effect of wavelength shifting is obvious and dominates over the rather small impact of the filtering loss at the ONU. Fig. 4(c) shows the extra amount of optical power that is required to obtain a certain BER level when degrading the upstream OSRR. While the original, without tone suppression remodulated RZ downstream is penalized quickly and already at high OSRR values, the shifted upstream shows higher robustness against RB. Especially the upstream that is transmitted at the +2 RZ harmonic experiences penalties that remain below 0.5 dB even for a low OSRR of ~10 dB.

With a 1-dB reception penalty as reference, the compatible minimum OSRR values for a low (high) BER level of 10^{-9} (10^{-4}) are 23.5 (17.7) dB without wavelength shifting, 18.7 (8.2) dB for a shifted upstream at the +1 harmonic and <13 (<9.5) dB for a shifted upstream at the +2 harmonic, respectively.

5. Conclusion

A simple wavelength shifting technique for optical loopback networks, suitable for photonic integration due to its mostly passive nature, has been presented. Robust upstream transmission compatible with a loss budget of 20 dB has been obtained at the second harmonic of the RZ downstream, despite a low OSRR of <10 dB and filtering losses.

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6. References

[1] 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 10Gbps WDM-PONs," Proc. OFC'10, San Diego, USA, OWG4, 2010.
[2] M. Matsuura et al, "Optical Carrier Regeneration for Carrier Wavelength Reuse in a Multicarrier Distributed Network," PTL **20**, 808, 2010.
[3] R. Staubli et al, "Crosstalk Penalties Due to Coherent Rayleigh Noise in Bidirectional Optical Communication Systems", JLT **9**, 375, 1991.
[4] B. Schrenk et al, "Rayleigh Scattering Tolerant PON Assisted by Four-Wave Mixing in SOA-based ONUs," JLT **28**, 3364, 2010.
[5] M. Omella et al, "Driving Requirements for Wavelength Shifting in Colorless ONU With Dual-Arm Modulator," JLT **27**, 3912, 2009.