An All-Optical Carrier Recovery Scheme for Access Networks With Simple ASK Modulation

Bernhard Schrenk, Paraskevas Bakopoulos, Efstratios Kehayas, Alexandros Maziotis, Jose A. Lazaro, Hercules Avramopoulos, and Josep Prat

***Abstract*—We theoretically investigate and experimentally demonstrate a scheme for all-optical carrier recovery in loopback access networks that avoids orthogonal or complex modulation formats for the downstream or upstream signals. The applied technique is based on a passive resonating circuit that is capable of recovering the optical carrier of the amplitude-shift-keyed downstream signal for remodulation with a reflective modulator as upstream transmitter enabling full-duplex 10 Gb/s operation. The scheme is compared with alternative pattern suppression techniques based on optical gain saturation and electro-optical feed-forward injection for the stringent requirements of next-generation access networks, namely, an extended loss budget and high upstream data rates. Operation at downstream modulation depths of ~3 dB is reported with the feed-forward approach, while higher modulation depths of up to 9 dB are demonstrated with the all-optical carrier recovery technique, for which the dependence on longer sequences of consecutive identical bits is investigated. Finally, the feasibility of the all-optical downstream cancelation technique for optical access networks is evaluated in a wavelength division multiplexed passive optical network, showing full-duplex transmission with margins of at least 9 dB.**

***Index Terms*—Optical access; Optical communication terminals; Optical resonators; Optical signal processing.**

I. Introduction

Energy efficiency, low cost and high data rates is a key combination for successful deployment of next-generation broadband access networks. The high customer density of these networks demands a simple and colorless optical network unit (ONU) that is suitable for mass deployment. Wavelength-dependent elements such as filters and optical sources can be avoided with reflective ONU designs [1], where the incident downstream signal is reused for upstream transmission [2–5]. In this context, the ASK/ASK modulation format with reduced downstream extinction ratio (ER) can provide low cost for the receiving and transmitting sub-systems, which are subject to increased complexity when orthogonal modulation formats are applied [6,7]. However, the simplicity at the downstream receiver comes with a penalty for the upstream transmission due to the crosstalk that derives from the remaining downstream pattern.

An initial proof-of-principle of the all-optical carrier recovery scheme for full-duplex ASK transmission was demonstrated in [5]. In this work, we perform an analytical study and evaluate its performance experimentally under various conditions for the input signal and circuit parameters. Further, we compare the all-optical scheme with different methods that can reduce the remodulation penalty for the upstream, based on optical gain saturation in a reflective semiconductor optical amplifier (RSOA) and on an electro-optical feed-forward injection of the detected downstream, under conditions of an extended loss budget and an advanced upstream transmission rate in conjunction with a commercial off-the-shelf modulator.

II. Carrier Recovery Schemes and Theoretical Basis

Wavelength reuse in transmission systems with ASK modulation in the downstream and upstream requires a reduced ER for the downstream as a trade-off between the penalties for the reception of both data streams [2]. The penalty ξ for the reception of the downstream, whose pattern is modulated with a certain extinction $\mathrm{ER_{DS}}$, corresponds to the extra amount of optical power needed to obtain the same Q-factor as would be given for an infinite downstream ER. Its logarithmic value is found with

$$\xi = 10\log\left(\frac{1+1/\mathrm{ER_{DS}}}{1-1/\mathrm{ER_{DS}}}\right). \quad (1)$$

Carrier recovery techniques at the ONU that aim at a suppression of the downstream pattern can reduce the penalty for upstream reception without the need of modifying the downstream ER and enhance therefore the overall system performance. Alternatively, these techniques allow one to operate with a higher downstream ER without introducing an extra penalty for the upstream reception.

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The simplest method for erasing a present downstream pattern before remodulation is to exploit the gain saturation of a SOA [2] (Fig. 1(a)). The compression of the modulation information is caused by the higher gain that the space bits experience over the marks. However, this technique obviously suffers from the relatively high input power levels required to reach the saturation regime of the SOA and is not always applicable.

A second approach where the pattern is actively suppressed by synchronized loss or gain modulation in the upstream modulator can provide higher efficiency [3,4] (Fig. 1(b)). The detected downstream is forwarded to the RSOA that is operated in its linear regime, where the output power p_{out} follows the input p_{in} according to the bias current I_{dc} and the modulation i_{mod} via a linear gain–current relation dG/dI:

$$p_{out}(t) = p_{in}(t)\left[G\left(I_{dc}\right) + \frac{dG}{dI} i_{mod}(t)\right]. \qquad (2)$$

The optical seed of the RSOA is composed from the downstream and is characterized by ER_{DS}, the average power P and the bit pattern π_{DS}. For pure carrier recovery without upstream transmission, the modulation current i_{mod} is determined by the inverted downstream signal that is fed forward with a certain magnitude I_{ff}:

$$p_{DS}(t) = \frac{2\bar{P}}{ER_{DS}+1}\left[1 + \left(ER_{DS}-1\right)\pi_{DS}(t)\right] \qquad (3)$$

$$p_{out}(t) = p_{DS}(t)\left[G\left(I_{dc}\right) + \frac{dG}{dI} I_{ff}\left(h_{e/o} * \bar{\pi}_{DS}\right)(t)\right]. \qquad (4)$$

The eventually limited electro-optical bandwidth of the upstream modulator is here accounted for by the convolution of its impulse response $h_{e/o}$ and the forwarded downstream data. With a proper adjustment of I_{ff} according to the conditions in [3], the recovered optical carrier at the output of the RSOA becomes

$$p_{out}(t) = G\left(I_{dc}\right)\frac{2\bar{P}}{ER_{DS}+1} \times \left[1 + \left(ER_{DS}-1\right)\left(\pi_{DS}(t) + \left(h_{e/o} * \bar{\pi}_{DS}\right)(t)\right)\right] \qquad (5)$$

and is mainly constrained by the electro-optical modulation bandwidth if patterning due to the finite gain recovery time of the RSOA [8] is not taken into consideration.

The third method used to effectively suppress a downstream pattern is an all-optical technique that relies on the use of a passive optical resonator tuned at the carrier wavelength [5] (Fig. 1(c)). Though this approach is known for the purpose of clock recovery [9,10], its applicability to carrier recovery for full-duplex transmission with the simple ASK/ASK modulation format has not been studied in depth so far. Acting as a filter, the resonator partially recovers the carrier wavelength by effectively suppressing the downstream data harmonics. An optical filter with a periodic frequency transfer function such as a Fabry–Pérot filter (FPF) is used to provide its functionality as an optical memory element and at the same time enables colorless operation due to its spectral periodicity, as shown in Fig. 1(d). To ensure immunity to possible wavelength variations of the downstream laser, the FPF is aligned with respect to the incident data signal by fine-tuning of its spectral transmission peaks inside the free spectral range (FSR) rather than over the full operating wavelength range. As is illustrated in Fig. 1(d), the FPF transmission is in principle designed to match with the downstream wavelength grid. While it may be aligned for the signal at λ_1, a wavelength drift of the downstream laser at λ_2 would require a further fine-tuning of the comb. However, this fine-tuning is required at the branch of the WDM network that is designated as λ_2, to spectrally co-locate a peak of the comb with the optical carrier frequency of the data signal at λ_2. In this sense, the FPFs used in different branches are adjusted to the incoming wavelength rather than to the whole WDM comb.

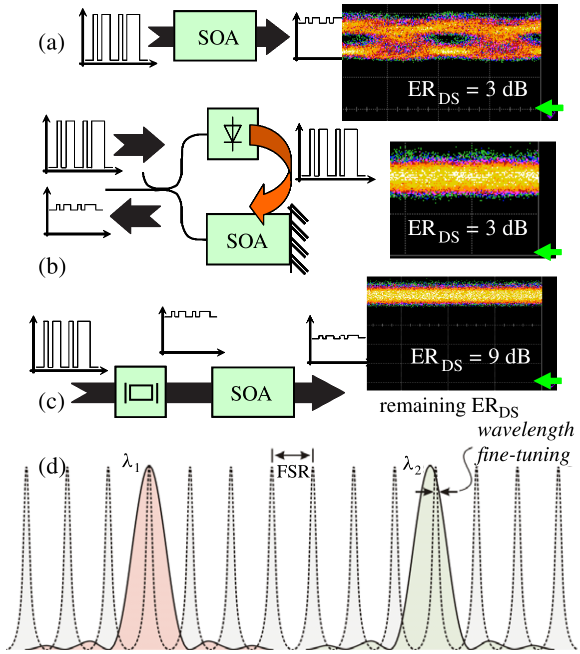

Fig. 1. (Color online) Pattern suppression techniques based on (a) optical gain saturation in a SOA, (b) feed-forward current injection and (c) passive optical resonating circuit. The insets on the right show the recovered optical carriers, for which the arrows indicate the reference levels. (d) WDM operation of the all-optical carrier recovery with FPF. Periodic filter peaks (dotted line) coincide with the downstream wavelength grid.

In the time domain representation, the cavity effect leads to a filling of the space bits with light. The output field E_{out} is related to the input E_{in} via the reflectivity R of the FPF facets and the round trip time T_{rtt} of the signal inside the cavity:

$$E_{out}(t) = (1-R)\sum_{k=0}^{\infty} E_{in}(t-kT_{rtt})R^k. \qquad (6)$$

The decay time τ for the light inside the cavity is given by the bandwidth δf of the filter and therefore by the filter finesse F and the optical path, which is defined by the refractive index n of the medium inside the cavity of length L:

$$\tau = \frac{1}{2\pi\delta f} = \frac{nLF}{\pi c} \approx \frac{nL}{c(1-R)}, \qquad (7)$$

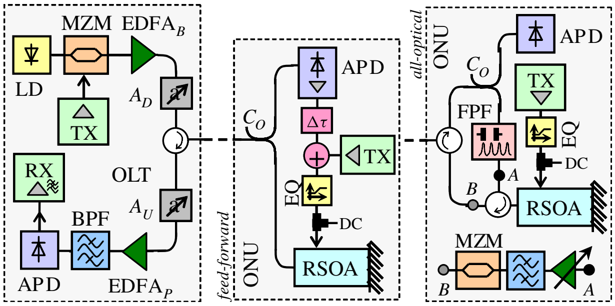

Fig. 2. (Color online) Experimental setup for the proof of the carrier recovery techniques.

where c is the speed of light in vacuum. The output power P_{out} fluctuates according to this exponential decay and depends on the downstream bit pattern. Critical are sequences with a large number of consecutive identical space bits that appear at a certain point of time t_0 and last for a time span δt. If these bit combinations are sufficiently long, they will "empty" the filter toward the residual power during the space bits. This residual power is determined by the maximum output power $P_{\max}$ at the FPF output and the downstream ER:

$$P_{\text{out}}(t_0+\delta t) = \Delta P \exp(-\delta t/\tau) + \frac{P_{\max}}{\text{ER}_{\text{DS}}}. \tag{8}$$

For the case where the FPF is filled with light by a previously received pattern with equally distributed mark and space bits, the maximum swing ΔP that characterizes the decay is determined by the difference between the average power level and the residual power during the space bits after transmission through the FPF, whose maximum transmission $T_{\max}$ is in turn defined by the facet reflectivities and an eventual cavity loss α:

$$\Delta P = \bar{P}_{\text{in}} T_{\max} - \frac{P_{\max}}{\text{ER}_{\text{DS}}}, \qquad P_{\max} = 2\bar{P}_{\text{in}} \frac{\text{ER}_{\text{DS}}}{\text{ER}_{\text{DS}}+1} T_{\max}, \tag{9}$$

$$T_{\max} = \frac{(1-R)^2 \alpha}{(1-R\alpha)^2}. \tag{10}$$

In a similar manner, consecutive mark bits will lead to a maximum output power for the FPF. The residual extinction ratio ER_{out} for a pseudo-random bit sequence (PRBS) of length $2^z - 1$ is then retrieved by the decay over z consecutive identical bits at the downstream data rate R_b and relates to the maximum and minimum power levels according to the fluctuations caused by these consecutive mark or space bits:

$$\text{ER}_{\text{out}} = \text{ER}_{\text{DS}} \frac{1 - \frac{1}{2\text{ER}_{\text{DS}}}\left(\text{ER}_{\text{DS}}-1\right)\exp\left(-z\pi c/nLFR_b\right)}{1+\frac{1}{2}\left(\text{ER}_{\text{DS}}-1\right)\exp\left(-z\pi c/nLFR_b\right)}. \tag{11}$$

With a finesse high enough to suppress the data pattern effectively, the in-band optical carrier is recovered and suitable for remodulation with upstream data.

Note that ER_{out} in Eq. (11) corresponds to a peak value for the remaining downstream ER, which is only given for the worst case of having z consecutive identical bits that appear with a probability of 2^{-z} inside the PRBS. An average ER_{out} value for the PRBS does not make sense, since the worst case ER_{out} has to be taken into account. This is the case where a few errors can be introduced, causing error floors at low bit error ratios (BERs), as will be discussed in Section IV.

III. Experimental Comparison With a Commercial Off-the-Shelf Modulator Under an Extended Loss Budget

The different cancelation techniques were evaluated in a simple setup (Fig. 2) in terms of their BER performance. The downstream is modulated on a wavelength at 1551.72 nm with a Mach–Zehnder modulator (MZM) at 10 Gb/s and a PRBS of length $2^7 - 1$. The latter ensures that no patterning effects due to the gain dynamics of the RSOA influence the transmission. An erbium-doped fiber amplifier (EDFA) was used to compensate the losses of the MZM and the ONU input was fixed to −7.5 dBm. This input power can be seen as feasible for an upper limit in access networks, meaning that with the given losses in the optical distribution network the optical power at the ONU input will not exceed this value. The receiver of the optical line terminal (OLT) consisted of an EDFA and an avalanche photodiode (APD).

The ONUs contain a commercial transistor-outline RSOA as the upstream transmitter. The RSOA had a small signal gain of 13 dB and a gain spectrum with a 3 dB gain bandwidth of 58 nm that is centered at 1550 nm. The noise figure was 9.2 dB. The electro-optical bandwidth was extended to 5.8 GHz by equalization with a passive filter (EQ) and a proper blueshifting of the optical 100 GHz bandpass filter at the OLT receiver [11]. An ER of 6.4 dB was obtained for the 10 Gb/s upstream. The ratio of the optical coupler (C_O) was chosen with 10/90 to favor the upstream branch for preventing noise degradation during remodulation.

According to the feed-forward cancelation, the detected downstream was forwarded from the APD with adjusted delay $\Delta\tau$ (of the order of a few ns for bit synchronization) and magnitude toward the RSOA. This feed-forward path was opened to compare the results also with the case of exploiting solely gain saturation in the RSOA for the purpose of downstream suppression.

The all-optical cancelation includes a fiber-based FPF with a FSR of 10 GHz, a finesse of 47 and an insertion loss of 2.7 dB. An integrated piezo-based circuit was used to fine-tune the FPF transfer function in order to align the filter peaks with the downstream carrier. This also allows one to follow minor wavelength drifts of the downstream laser (Fig. 1(d)). A polarization controller was included with the FPF to account for its polarization sensitivity. The latter could be avoided with an integrated design that uses suitable elements such as ring resonators [12].

A good downstream reception sensitivity is important since no optical preamplifiers can be used at the cost-sensitive ONU. The downstream ER has a big impact for the ASK/ASK-based modulation format where a reduced ER of 3 dB already causes a penalty of 5.8 dB at a BER of 10^{-10}. In contrast, the penalty is just 1.2 dB for an ER of 9 dB (Fig. 3(a)).

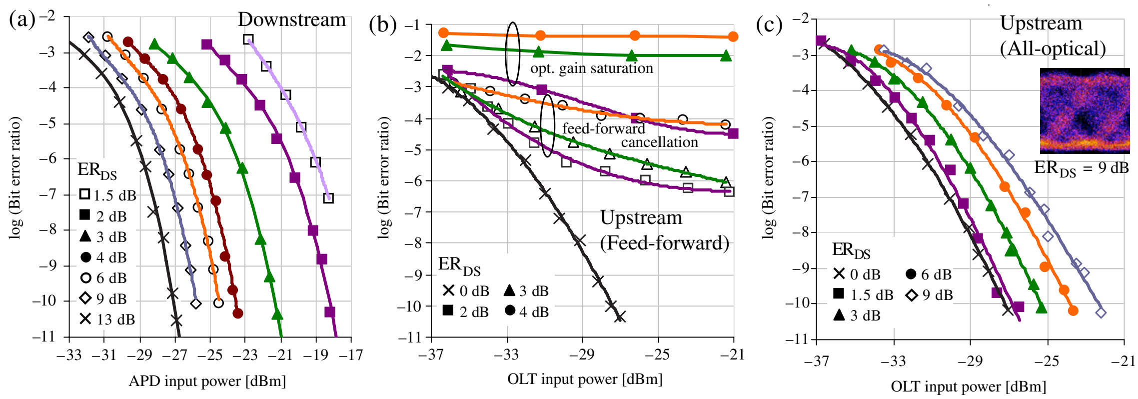

Fig. 3. (Color online) BER performance for (a) the downstream and the upstream including (b) a feed-forward and (c) an all-optical carrier recovery technique.

On the other hand, higher ERs cause stronger distortions in the upstream. For a downstream ER of 3 dB, the upstream already exhibits a residual amplitude variation due to the remaining downstream pattern. This variation is equal to ERs of 2.3 and 1.5 dB for the case of utilizing solely the optical gain saturation and the additional feed-forward cancelation, respectively (see Fig. 1). This high distortion in the upstream causes BER floors above 10^{-10} (Fig. 3(b)). Nevertheless, the feed-forward cancelation allows reception with a Reed–Solomon (255, 239) forward error correction (FEC) at a BER level of 10^{-4} while the optical gain saturation does not for downstream ERs that are >2 dB. Note that this comparison stands for the conditions mentioned. Each of these two techniques, or a combination of them, has already been demonstrated with superior performance in earlier works [2–4]. However, a good downstream cancelation was only achieved for having either an optical input signal strong enough to reach saturation or a more favorable ratio between the modulation bandwidth and upstream data rate.

In contrast to that, the all-optical suppression technique allows much higher downstream ERs of 9 dB, which survive the cancelation with only 0.85 dB. This low crosstalk allows us to reach a BER of 10^{-10} even for a downstream ER of 9 dB. The penalty is then just 4.9 dB compared to the ideal case of having an unmodulated downstream (Fig. 3(c)).

IV. Performance Investigation of All-Optical Carrier Recovery

To validate the performance of the all-optical carrier recovery and investigate its operating range, a further experimental characterization regarding the PRBS length and filter bandwidth of the FPF was carried out. For this investigation that considers the upstream reception penalty as the figure of merit, the RSOA at the ONU was replaced by a combination of MZM and EDFA (as indicated by points A and B in Fig. 2), to avoid additional patterning effects in the upstream modulator [8]. The driving conditions of the MZM and the EDFA input power and gain were adjusted to provide the same upstream ER, net ONU gain and optical signal-to-noise ratio (OSNR) at the ONU output. Note that for this following study the receiver at the OLT was replaced by a PIN diode since no detuned optical filter is required to achieve upstream transmission at 10 Gb/s thanks to the large inherent modulation bandwidth of the MZM, and hence no optical losses are introduced by the optical bandpass filter at the optical upstream receiver.

Figure 4(a) shows the upstream reception performance for the long PRBS length of $2^{31}-1$ for the downstream and upstream data patterns. Compared to the previously studied case with a PRBS of 2^7-1, the optical memory effect by the FPF is no longer strong enough to prevent amplitude fluctuations in the recovered optical carrier and, consequently, the longer sequence of consecutive identical bits causes an error floor slightly above 10^{-9} in the case of a downstream ER of 9 dB. As is also obvious from Eq. (11), the BER performance could be improved by choosing either a higher finesse F or, in the case where this is not possible for some reason as in the presented experimental case where no FPF with higher finesse was available, a lower ER_{DS}. The swing in the amplitude fluctuations is reduced once the downstream ER is, and for an ER of 7.5 dB a BER level of 10^{-9} can be obtained, leaving just a penalty of 2.3 dB compared to the remodulation of an optical carrier without the present downstream pattern. Note that this reduction of the ER leads to a theoretical increase in the reception penalty for the downstream of 0.46 dB.

The dependence of the upstream performance on the PRBS length for a fixed downstream ER of 9 dB is presented in Fig. 4(b). As is obvious, error floors appear for longer PRBS lengths of $2^{23}-1$ and $2^{31}-1$. Note that the sensitivity in Fig. 4(b) differs from that obtained in Fig. 3(c) since a less sensitive PIN-based upstream receiver was used at the OLT. Figure 4(c) shows the residual pattern of a downstream with an ER of 9 dB for consecutive identical mark bits in the case of the two PRBS lengths of 2^7-1 and $2^{11}-1$. The latter causes a slightly higher swing in the amplitude fluctuations of the recovered optical carrier.

Figure 5 shows the measured upstream reception sensitivity at a BER of 10^{-9} for various downstream ERs and PRBS lengths. For low and intermediate values of the downstream ERs, there is no significant penalty for a long PRBS since the finesse of the chosen FPF is sufficiently high to prevent error floors from raising above this reference BER level. Once the

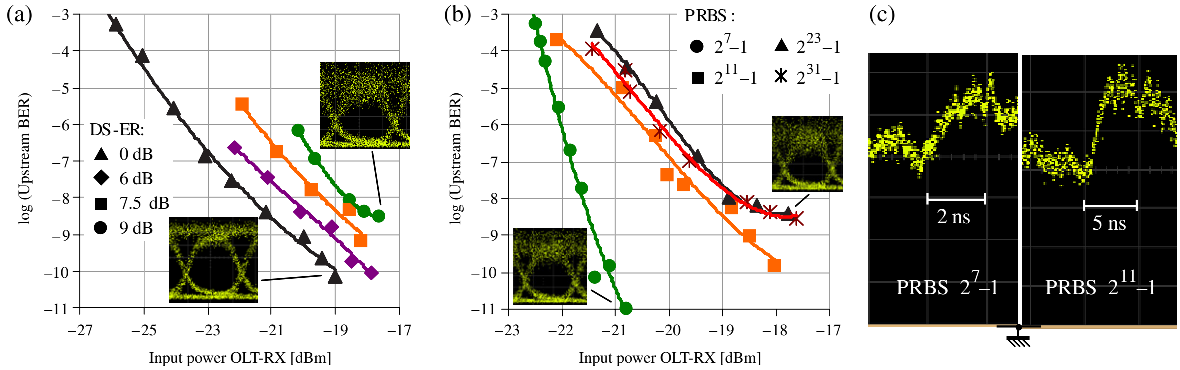

Fig. 4. (Color online) Upstream BER for (a) a PRBS of $2^{31}-1$ and different downstream ERs, and (b) a fixed downstream ER and different PRBS lengths. (c) Recovered optical carrier after the FPF for the case of experiencing the largest number of consecutive identical mark bits inside the PRBS.

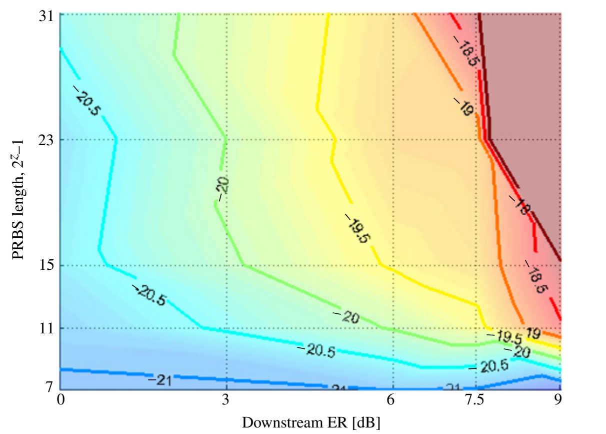

Fig. 5. (Color online) Upstream reception sensitivity for a BER of 10^{-9} as a function of the downstream ER and the PRBS length. The dark area top right indicates a BER floor above 10^{-9}.

downstream ER increases to 7.5 dB and above, penalties are introduced for longer PRBS lengths and even prevent reaching error-free operation for data patterns with lengths of $2^{23}-1$ or longer in the case of a high downstream ER of 9 dB.

The previously discussed effect of the finesse, which is related to a certain filter bandwidth δf, is addressed in Fig. 6(a), showing the upstream performance for a downstream ER of 9 dB. Since the highest finesse of the available FPFs was 47, results are shown for a PRBS of $2^{11}-1$ and the finesse is gradually reduced to investigate the impact on the error performance.

The reception sensitivity of the original FPF with δf = 0.21 GHz can be still kept with a slightly wider bandwidth of 0.55 GHz. However, with a further increase of the bandwidth, power penalties and error floors are introduced, since the effect of downstream cancelation is lost. As a result, a filter bandwidth of approximately half the data rate already prevents reaching the FEC level.

Note that the downstream cancelation effect with a spectrally narrow filter is bound to optical losses since the modulation information of the incident light signal is rejected on its way to the upstream modulator. These losses are presented in Fig. 6(b) for the two extreme cases of δf = 0.21 and 5.19 GHz. Although the filtering loss of the more appropriate narrow filter bandwidth is increased for higher modulation indices, this extra loss of 1.2 dB for a downstream ER of 9 dB is relatively small compared to the unavoidable FPF insertion loss that is experienced when passing an unmodulated optical carrier. The spectra of the incident downstream signal and the recovered optical carrier are presented in Fig. 6(c), where the rejection of the optical sidebands can be seen.

Being a component with a spectrally periodical transfer function, the FPF obviously provides a wavelength-agnostic solution that is compatible to WDM-based transmission systems. To demonstrate colorless operation of the all-optical downstream cancelation, upstream measurements have been performed for a downstream ER of 9 dB, a filter bandwidth of 0.21 GHz and a PRBS of $2^{11}-1$ for different wavelengths. As can be seen in Fig. 7, the reception sensitivity at a BER level of 10^{-9} differs by just 0.9 dB. The larger reception penalty of ~2 dB for the wavelength at 1560.61 nm is attributed to the roll-off of the C-band EDFA gain profile, which was already located at this upper border downstream wavelength.

V. Transmission Performance in a WDM-PON

For the sake of completeness, the ONU of Section III featuring the all-optical downstream cancelation was embedded in the WDM-PON [5] that is shown in Fig. 8. The PON aims at full-duplex 10 Gb/s transmission per wavelength and comprises a dual feeder and a drop standard single-mode fiber (SMF) span with lengths of 25 and 6 km, respectively. A 1 × 40 arrayed waveguide grating (AWG) was used as the distribution node inside the optical distribution network. Dispersion compensating fibers (DCFs) at the OLT cope with dispersive effects in the optical light path that are pronounced especially in the upstream direction due to the interplay of the RSOA chirp with the fiber dispersion. The losses of these DCFs are compensated by preceding EDFAs.

The downstream was launched with 6 dBm and an OSNR of 46.8 dB from the OLT. After remodulation with the low-gain RSOA, which is responsible for the ONU net gain

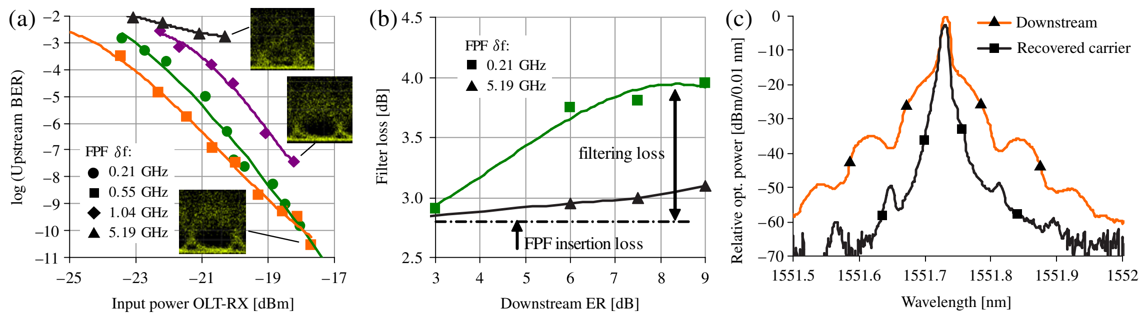

Fig. 6. (Color online) (a) Upstream BER for a PRBS of $2^{11}-1$ and a downstream ER of 9 dB for different FPF bandwidths, (b) the FPF loss and (c) the signal spectra for the incident downstream and the recovered carrier, whose optical power levels are referenced to that of the optical carrier wavelength at 1551.72 nm of the downstream.

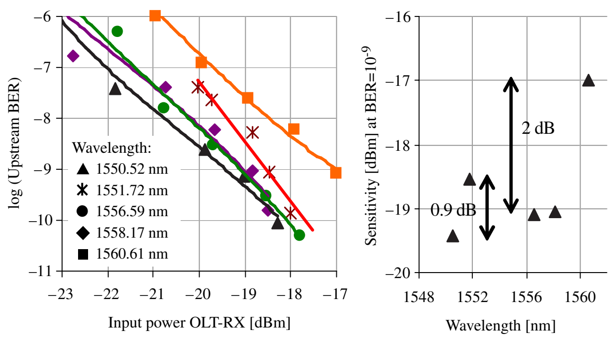

Fig. 7. (Color online) Upstream BER for different downstream wavelengths and the corresponding reception sensitivity spectrum for a BER of 10^{-9}.

of 5.8 dB, the OSNR is reduced to 38 dB. The upstream output power of the ONU is therefore −1.7 dBm. The optical signal-to-Rayleigh-backscattering ratio at the drop fiber span was >29 dB for the downstream and upstream and thus no degradation is expected to arise at this bidirectionally used fiber span.

The transmission performance for the PON was assessed in terms of downstream and upstream reception sensitivity at two representative BER levels: a BER of 10^{-10}, which is supposed to be low enough to allow error-free operation of end-user applications without additional data encoding, and a BER of 10^{-4} that enables transmission in conjunction with a Reed–Solomon (255, 239) FEC [13], as is proposed for gigabit PON systems [14].

As a figure of merit for the transmission, the power margin is thereby defined as the difference between the power delivered to the receiver and the reception sensitivity. The delivered power is in turn given by the launched power at the downstream and upstream transmitters and the loss budget of the PON, excluding the losses of the variable attenuators (A_D, A_U). The margins can then be improved in downstream and/or upstream transmission by applying FEC, at a magnitude that corresponds to the difference between the sensitivities at the BER levels of 10^{-10} and 10^{-4}.

The optimum ER for the downstream is then defined for the most balanced power margins for the downstream and upstream reception. Table I summarizes the optimum ER that has been found for different PRBS lengths and BER levels, and reports the margins that correspond to these cases.

To avoid the effects of patterning by the RSOA, the short PRBS length of 2^7-1 was chosen for this investigation though it does not emulate well the traffic of next-generation PON standards. However, when using a longer PRBS, the gain dynamics of the RSOA caused severe distortions in the upstream bit pattern that degraded the transmission performance far more negatively than was experienced

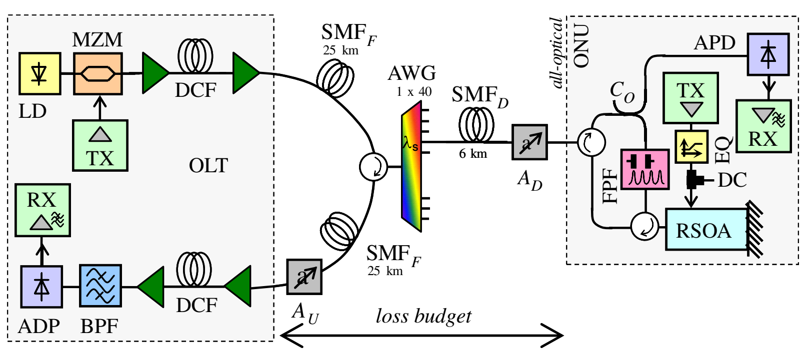

Fig. 8. (Color online) Experimental setup for evaluating the all-optical carrier recovery in a WDM-PON with bidirectional 10 Gb/s data transmission on a single wavelength.

TABLE I
OPTIMUM DOWNSTREAM ER AND CORRESPONDING POWER MARGINS

Configuration	No FEC	FEC for downstream	FEC also for upstream
Optimum ER [dB]	9	9	9
DS margin [dB]	5.0	9.0	9.0
US margin [dB]	7.1	7.1	15.0
Imbalance [dB]	2.1	1.9	6.0

previously, in Section IV, even in the case of continuous-wave light injection [15].

As can be seen in Figs. 9(a) and 9(b), the downstream and upstream BER performances are slightly worse than for the corresponding BER measurements in Section III. However, the penalties for fiber-based transmission are less than 1.5 dB. Note that the downstream reception sensitivity is referenced to the input of the APD, so a difference of 11.2 dB has to be accounted for when relating this sensitivity to the ONU input.

The downstream penalty, which is referenced to a downstream pattern with an ER of 13 dB, is ~4.3 dB for an ER of 3 dB (Fig. 9(c)). The corresponding FEC improvement is 3.7 dB (Fig. 9(d)). Thanks to the all-optical carrier recovery, the downstream ER of 9 dB lowers the penalty to just 1.7 dB, while the FEC improvement for this ER is slightly raised to 4 dB due to a less steep BER curve at this high downstream ER.

In the upstream direction, there is only a penalty of 3.4 dB at a BER of 10^{-10} for a downstream ER of 9 dB compared to a continuous-wave RSOA seed (i.e., a downstream ER of 0 dB). The FEC gain for the upstream is 7.5 and 7.9 dB for an ER of 0 and 9 dB, respectively.

The behaviors of the reception penalties (Fig. 9(c)) are also pronounced in the power margins (Fig. 9(d)). The pre-emission of high downstream ERs where neither the downstream nor the upstream penalty is large allows us to balance the margins in both transmission directions. Once FEC is included in the more critical downstream reception, the margins for a higher downstream ER of 9 dB are increased to 9 and 7.1 dB for the downstream and upstream, respectively. This leads to compatible PON loss budgets of 22.5 and 20.7 dB. The loss budgets can be calculated from the power launched from the transmitter and the reception sensitivity, e.g., in the case of the downstream the launched power was 6 dBm and the reception sensitivity referenced to the ONU input is −16.5 dBm, while for the upstream launch at the ONU was −1.7 dBm and the reception sensitivity at the OLT is −22.4 dBm. Note that alternatively to the inclusion of FEC, the coupling ratio of the power splitter C_O inside the ONU could be varied to balance the power margins. Compared to a typically chosen ER of 3 dB for conventional carrier recovery techniques [16], where the margins for downstream and upstream reception are 2.6 and 9.3 dB in the case of the already more efficient all-optical carrier recovery, additional improvement regarding the balanced margin is achieved with the higher optimal ER of 9 dB thanks to a significant reduction of the downstream reception penalty. The all-optical carrier recovery approximates therefore the performance of ideal orthogonal modulation formats that benefit from the intrinsically small remodulation penalty of frequency or phase modulated downstream signals up to 1 dB, as demonstrated in [17] or [18]. However, by using amplitude modulation for the downstream transmission, complex modulators at the OLT are avoided.

If FEC is also used for the upstream direction, its power margin raises to 15 dB for a downstream ER of 9 dB, leaving the downstream margin of 9 dB as the limiting factor.

Note that due to the loopback configuration of the WDM-PON, the seed budget of the RSOA has to be taken into account as well. In this case, the loss budget would be limited to 13.5 dB due to the chosen downstream launch and ONU input power that was compromised to a high value of −7.5 dBm by the low-gain RSOA. However, loopback configurations with high-gain RSOAs able to operate at optical power levels as low as −20 dBm have already been demonstrated [19].

VI. CONCLUSION

A colorless ONU design for full-duplex 10 Gb/s transmission with the simple ASK/ASK modulation format has been studied

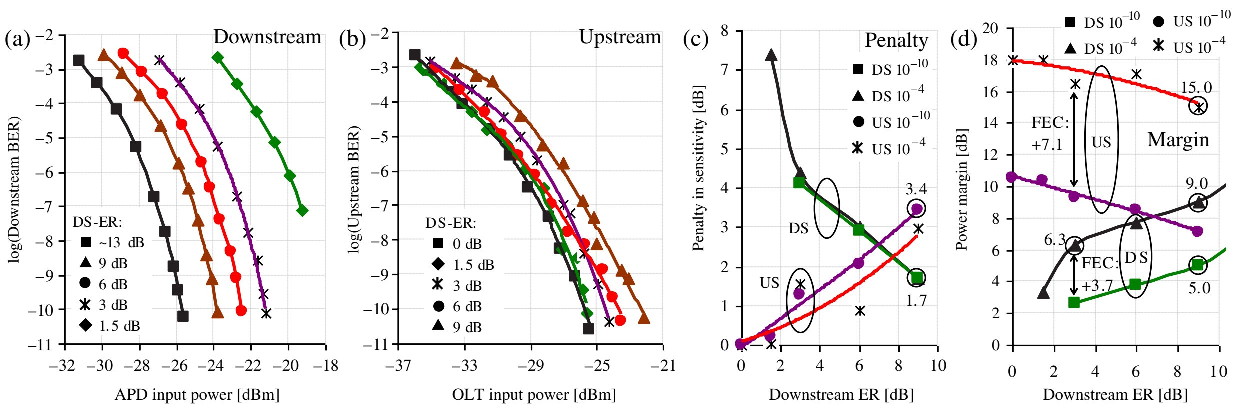

Fig. 9. (Color online) BER measurements for (a) the downstream and (b) the upstream. (c) Reception penalties, referenced to an ER of 13 dB for the downstream and to an ER of 0 dB for the upstream. (d) Power margins with and without FEC.

in detail. The performance of the all-optical carrier recovery technique employed has been investigated for different data patterns and shows that the filter design has to accommodate longer sequences of consecutive identical bits. Verification of the all-optical downstream cancelation in a simple WDM-PON environment with full-duplex 10 Gb/s transmission showed that power margins of at least 9 dB are available when FEC is applied for the more critical downstream reception.

A comparison with further downstream cancelation techniques has been performed under the conditions of next-generation optical access networks. While the electro-optical feed-forward carrier recovery allows full-duplex transmission with the help of FEC, the all-optical downstream suppression that employs a passive resonating circuit reduces the reception penalties significantly (i.e., allows higher loss budgets in the case of deployment in access networks) since it avoids problems with a reduced modulation bandwidth and, as a result, the mandatory use of FEC for the upstream reception.

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