Novel WDM-PON Architecture Based on a Spectrally Efficient IM-FSK Scheme Using DMLs and RSOAs

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***Abstract*—This paper proposes a wavelength-division-multiplexing passive optical network architecture with colorless user terminals based on the use of a different modulation scheme for each way of communication. Narrow-frequency-shift keying (FSK) modulation obtained by direct modulation of a distributed feedback laser has been used for the downstream channel, and intensity modulation has been used for the upstream channel. The performance of a link based on this scheme has been assessed, with particular emphasis on the description of the narrow-FSK modulation technique and its range of applicability in terms of bit rates and power levels. The operation of the architecture is demonstrated by simultaneously transmitting Ethernet frames at 1.25 Gb/s (gigabit Ethernet) in both the upstream and downstream channels. Error rates for downstream and upstream channels show excellent performance for distances up to 50 km.**

***Index Terms*—Colorless optical network units (ONUs), frequency-shift keying (FSK) modulation, optical Ethernet, passive optical networks (PONs).**

I. Introduction

PASSIVE optical networks (PONs) are receiving much interest because they represent the cheapest way to provide fiber to the home. They also remove the bandwidth bottleneck between subscribers and the core network. Wavelength-division-multiplexing (WDM) access systems have also been widely reported as a method for enhancing optical access network bandwidth [1]. The increased capacity of WDM-PON technology may also increase the number of users served in an access network. A different individual wavelength path could be assigned to each user or group of users sharing the optical fiber.

However, in a WDM PON, the user terminals or optical network units (ONUs) must have light sources at different and precisely tuned wavelengths, making the ONUs too expensive for commercial purposes. A key issue in the current research to solve this problem is to devise architectures with a colorless and uniform ONU design. A common method to achieve this objective is the optical loopback technique [2], where the ONU is wavelength seeded from the optical line terminal (OLT) that is located at the central office (CO). This is performed by spectral sliced sources or continuous-wave (CW) lasers that are amplified and modulated for the upstream channel by means of reflective semiconductor optical amplifiers (RSOAs) [3], [4] or similar devices. The optical loopback technique can also be combined with WDM access to increase the capacity and flexibility of the network [5]. In some of these proposals, both the upstream and downstream channels use the same wavelength path, so it is necessary to separate them by different modulation schemes to avoid crosstalk. Modulation formats reported include frequency-shift keying (FSK) [6], differential phase-shift keying (DPSK) [7], and inverse return-to-zero (RZ) [8] for the downstream channel, and intensity modulation (IM) for the upstream channel. However, there are some limitations in the use of these schemes: the DPSK modulation requires external modulation and has important insertion losses, which may be critical for the power budget; the FSK modulation using a grating-assisted coupler with sampled reflector (GCSR) laser has low bandwidth and is spectrally inefficient; and the inverse-RZ scheme requires dispersion compensation to achieve a good performance.

Recently, we proposed a new method for FSK modulation of the downstream channel in WDM PONs [9]. It is based on the frequency shift caused by chirp effects when directly modulating a distributed feedback (DFB) laser [10] that was termed narrow-FSK modulation. The main interest of this approach is its simplicity, combined with a high spectral efficiency compared to similar schemes based on DFB direct modulation. The cause of this increased efficiency is that, in our proposal, the spectrum of the modulated signal is only slightly wider than the CW signal. Moreover, the effective optical bandwidth increase of the downstream signal induced by the FSK modulation decreases the efficiency of nonlinear effects such as Brillouin and Rayleigh scattering [11], [12], whose penalty effect grows with increasing fiber optical power [13]. This fact allows us to transmit higher optical powers from the CO, which implies accomplishing lower bit error rates (BERs) and a more efficient feeding of the remote ONUs.

In this paper, we will assess the limits of applicability of this technique in terms of adequate bit rates and optical power budgets needed to implement it using commercially available devices.

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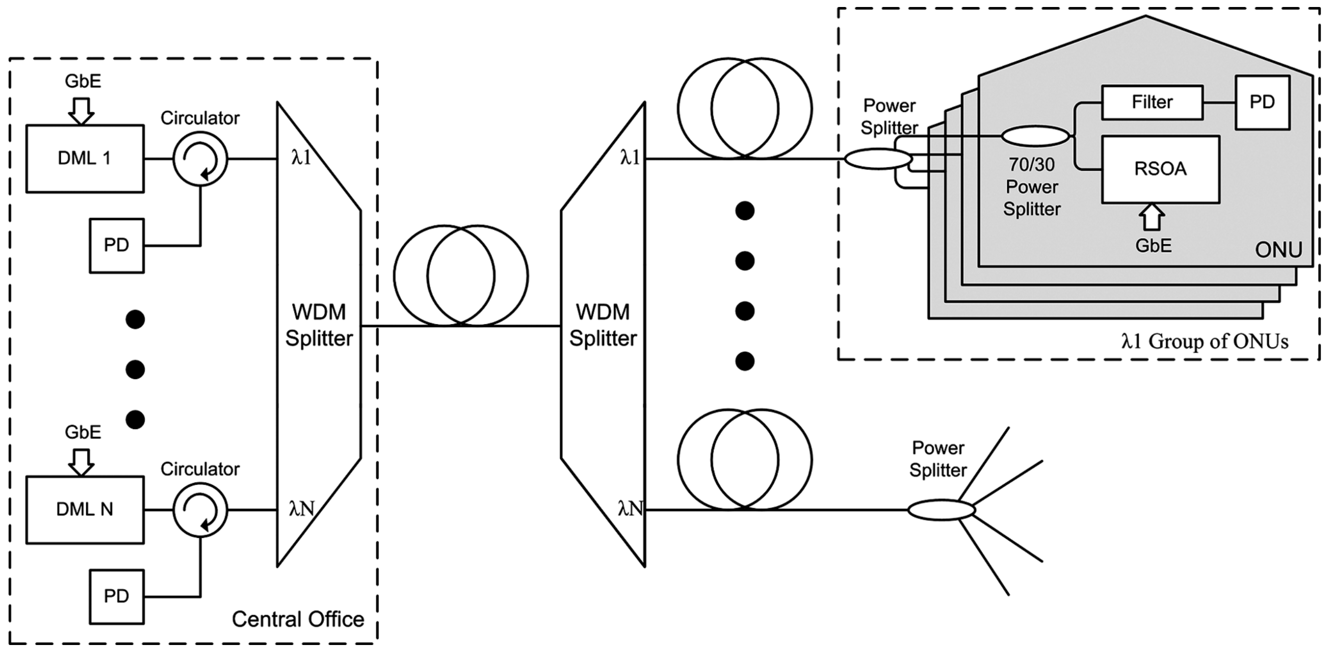

Fig. 1. Proposed WDM-PON architecture.

II. Network Architecture

The network architecture scheme that we propose is depicted in Fig. 1. It is based on a set of directly modulated DFB lasers (DML), all of them placed at the CO, and each one serving different groups of 32 to 64 users where every individual user is connected by a standard optic power splitter to the same fiber end. Each group of users shares the communication channel by means of a traditional dynamic time-division multiple access request/grant approach [as, for example, in Ethernet PON (EPON)], or any other suitable method to obtain collision avoidance. The different pairs of DML group of users can be seen as individual PONs.

For every different group of users, the downstream channel data are narrow-FSK modulated via direct modulation of the laser taking advantage of the laser adiabatic chirp in the frequency range where this is the dominant effect. Other chirp effects such as transient and thermal chirp [14], however, restrict the usable frequency range, as will be shown later. The laser modulation must be low enough to grant that the residual IM of the downstream signal is negligible compared to that of the upstream signal, but sufficient to ensure that the optical carrier frequency of the laser is slightly modulated by its own chirp. The frequency excursion in narrow-FSK depends on the power levels for '1' and '0', and thus, a low extinction ratio value is required. The downstream data are carried from the OLT to the ONUs, where the signal is divided. Part of the FSK signal is demodulated using an athermal filter, which filters out one of the peaks of the FSK modulation, and therefore, the signal can be directly detected. The other part of the signal is then intensity modulated and amplified in the ONU using an RSOA to carry the upstream data.

One of the main advantages of the proposed approach is that each link (upstream and downstream channels of a group of users) uses a unique wavelength for both ways of the communication. This fact enables a great increment of the number of users in already deployed PONS without any infrastructure modification, since the installed fiber that links the OLT and the ONUs remains unaltered. The only important modification from a time-division modulation-PON is the introduction of two wavelength mux/demux.

Another key factor is to enable the use of the same ONU design for all the users, thus reducing the cost and simplifying the installation and maintenance of the user terminal. Our ONU design, considering the broadband wavelength characteristics of all its components, accomplishes these desired features of colorlessness and uniformity.

III. Downstream Channel

We propose the use of two quasi-orthogonal modulation techniques for downstream and upstream channels. IM for the upstream channel is straightforward using an RSOA in the ONU. For the downstream channel, we believe that narrow-FSK modulation by the intrinsic laser chirp is a good choice to achieve good bandwidth, cost, spectral efficiency, and robustness to dispersion.

Any semiconductor laser under IM suffers a normally undesired frequency modulation called frequency chirping described by [15]

$$\begin{aligned}\Delta\nu(t) &= \frac{1}{2\pi}\frac{d\phi(t)}{dt}\\ &= \frac{\alpha}{4\pi}\left(\frac{1}{P(t)}\frac{dP(t)}{dt} + \kappa P(t)\right) + \Delta\nu(T,P) \qquad (1)\end{aligned}$$

where $\Delta\nu$ is the relative frequency deviation of the laser emission wavelength, α is the linewidth enhancement factor, and κ is the adiabatic chirp parameter. We can distinguish three different contributions to the frequency chirp. First, the transient chirp

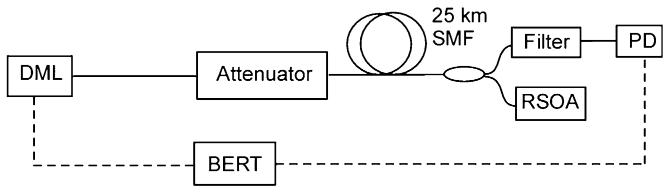

Fig. 2. Experimental setup for the measurement of narrow-FSK BER characteristics.

which is related to the sudden changes of the refractive index with carrier density, thus depending on the power derivative; this term is frequently the only one considered in intensity-modulated signals, as is the principal responsible for the dispersion penalty and the transmission reach. The second term is related to the static power dependence of the refractive index in the active cavity, and is called adiabatic chirp. A third term must be included for a complete description, covering the thermal dependence of the emission wavelength; it is the thermal chirp, and it has a decreasing exponential behavior with a slow time constant.

Of all these effects, the adiabatic chirp is the contribution needed to achieve FSK modulation. Modulating the bias current of the laser, a considerable frequency modulation can be obtained, depending on the current excursion and on the adiabatic chirp of the device. A residual IM is also added to the FSK modulation, which complicates the use of the same wavelength for an IM channel in the upstream channel. However, we will show that, if the residual IM is kept small, the same wavelength can be reused for the upstream channel.

First, the behavior of the downstream channel was evaluated using the experimental setup shown in Fig. 2. The purpose of this experiment was to analyze the bit rates supported by a DML with narrow-FSK modulation.

The DML we used was a 1544-nm standard DFB laser source emitting +7 dBm optical power with a linewidth enhancement factor of 3.6 and an adiabatic chirp of 3 GHz/mW. The electrical signal modulating in frequency of the laser source was obtained from a bit-error-rate tester (BERT 86130A from Agilent). The pattern used for all bit rates tested in this section is a $2^7 - 1$ order pseudorandom binary sequence (PRBS) signal, which was chosen to avoid thermal chirp effects in the DML. This signal was attenuated before being used to modulate the DFB, obtaining a ±4-mA excursion over the dc level of the bias current. The differences in the laser optical spectra with and without FSK modulation are shown in Fig. 3. The spectra were measured with a high-resolution optical spectrum analyzer (Aragon Photonics BOSA-C) that allows to precisely evaluate the optical frequency separation between the two peaks associated with the different bias currents for '1' and '0' bits. Furthermore, the different optical power levels for the '1' and '0' peaks can also be appreciated. The reason for this power difference is that each peak is driven by a slightly different bias current. As the figure shows, there is only a slight increase in spectral bandwidth compared to the CW spectrum because the modulation applied to the DFB laser was very small.

The downstream FSK signal from the DML was attenuated to produce different received optical powers and then transmitted over 25 km of optical fiber. At the reception end, the FSK signal was divided using a 30/70 power splitter. The 70% power end was directed to feed the RSOA for the upstream channel. Although in this experiment, the upstream channel was not evaluated, the RSOA was always actively modulating, amplifying, and reflecting the incoming signal, with an output optical power of +5 dBm. In this way, the reception in the downstream channel was in the same conditions as in the complete proposed scheme. At the 30% end of the power splitter, the downstream demodulation was performed using an athermal custom Mach–Zehnder delay interferometer filter from Optoplex Inc., with 2-dB insertion loss, 2.5-GHz free spectral range, and 0.3- GHz/°C thermal behavior. The filter's insertion loss as a function of the wavelength is also depicted in Fig. 3, where it can be seen how the filter is able to suppress one of the two peaks of the FSK signal without affecting the other. This filtering transforms the FSK modulation into a simple amplitude modulation that can be directly detected. It must be noted that the filter can be tuned to pass any of the two peaks of the FSK signal. Since, as previously seen in Fig. 3, one of the peaks has lower optical power than the other, a slightly better performance can be accomplished by filtering out this lowest peak. Finally, the demodulated signal is detected by means of a p-i-n photodiode with approximately −24-dBm sensitivity at 10^{-12} BER and sent to the BERT to test the quality of the link.

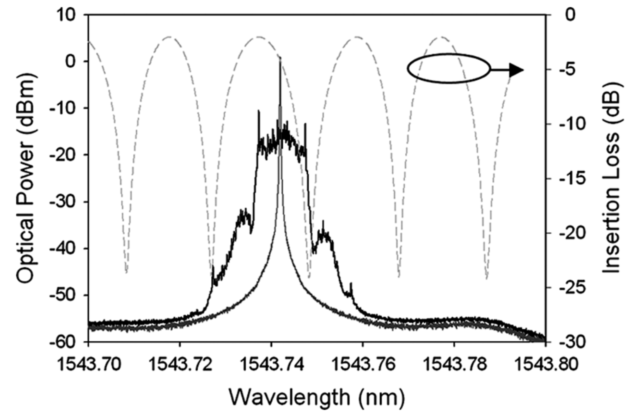

Fig. 3. Measured optical spectra of a (dark gray line) CW DFB, (black line) a narrow-FSK-modulated signal, and (dashed line) insertion loss of the demodulator.

The effect of the filtering is illustrated in the optical eye diagrams of the received downstream signals before and after the filter (Figs. 4 and 5, respectively). In the eye diagram of the downstream signal before the filter, the residual IM resulting from the direct modulation of the DFB can be clearly appreciated. The eye diagram of the demodulated signal in Fig. 5, where one of the peaks of the FSK signal was filtered out, is typical of an amplitude modulation.

Fig. 6 shows the measured BER versus the optical received power for different bit rates of the FSK signal. BER is similar for bit rates from 0.312 to 1.25 Gb/s because, in this range of frequencies, the main effect is the adiabatic chirp, which turns the power oscillations into frequency variations without any major drawbacks. However, a clear lower limit in the measured BER appears for the 155-Mb/s transmission, which does not improve

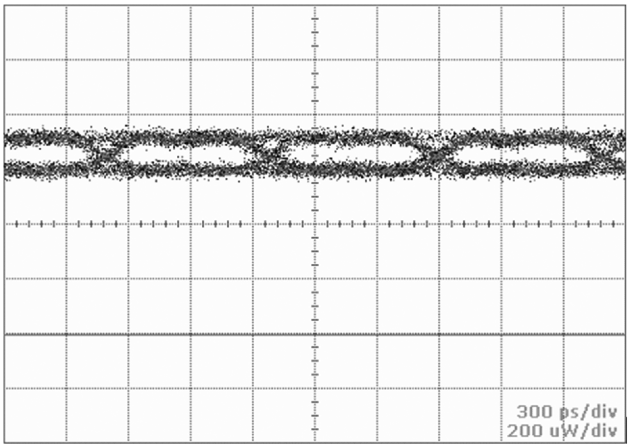

Fig. 4. Eye diagram of the downstream narrow-FSK signal before the filter.

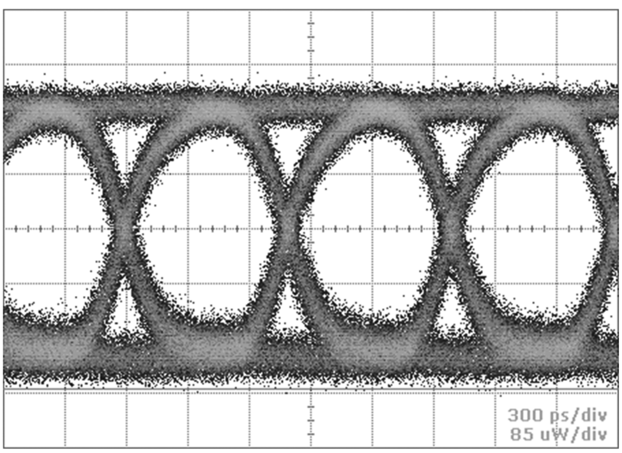

Fig. 5. Eye diagram of the downstream filtered narrow-FSK signal.

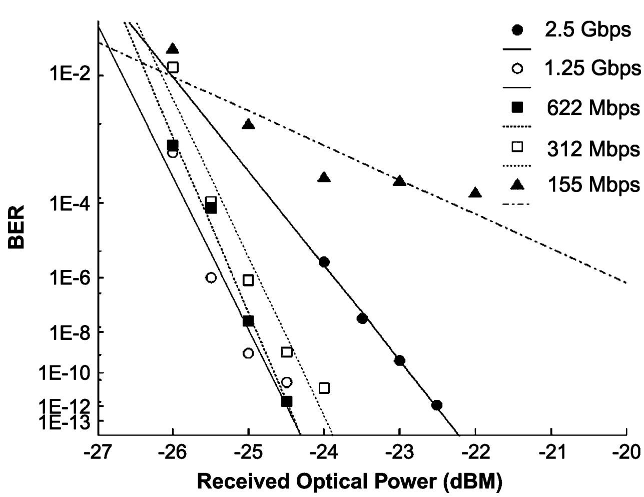

Fig. 6. Narrow-FSK BER curves as a function of received optical power measured for different bit rates using the setup shown in Fig. 2.

by increasing the received optical power. This limitation appears in the range where the thermal chirp of the laser has the strongest effect, which suggests that it can be the cause of this lower limit. The figure also shows a 2-dB power penalty for the 2.5-Gb/s transmission relative to its best values. However, these higher rates are still usable if this power penalty is compensated. This effect can be explained by the increase of the laser transient chirp, which poses the limits of applicability of the narrow-FSK scheme at higher bit rates.

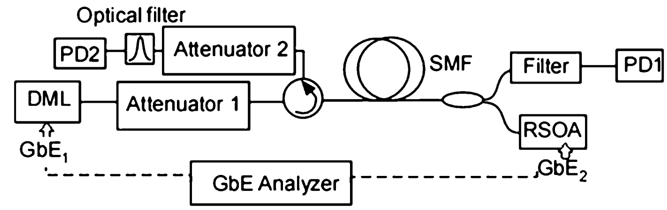

Fig. 7. Experimental setup for the characterization of the upstream channel and complete link using GbE (1.25 Gb/s) channels.

IV. Upstream Channel

Once narrow-FSK transmission for the downstream channel was evaluated, we analyzed some characteristics of the upstream channel. Fig. 7 shows the experimental setup used for this experiment, which is also used later to evaluate the complete architecture. We used an RSOA for the upstream transmission (SOA-RL-OEC-1550 from CIP), with a +5-dBm optical saturation power and a 20-dB optical gain at 500-mA bias current. Polarization dependence of the RSOA was lower than 1.5 dB. The BERT was replaced by a gigabit Ethernet (GbE) analyzer (Advisor J3446 from Agilent) as the electrical source for the modulations. The analyzer has two GbE ports, each with an output to simultaneously feed both upstream and downstream channels, and an input to independently analyze the received data in each channel. It should be noted at this point that the optical detector used in the following measurements is included in the own GbE analyzer and has a better sensitivity than the one used in the previous section. The data traffic obtained from the Analyzer is real Ethernet traffic at the maximum channel load, and the BER measurements presented from this experiment were obtained from the number of frame check sequence errors, provided that there was no loss of Ethernet frames. In this way, due to the codification of the Ethernet signal, we obtain a nearly pure random signal but without the low frequencies that would degrade transmission in the downstream channel due to the thermal chirp of the laser. In this sense, the signal has a spectrum similar to a low-order PRBS signal.

In the setup in Fig. 7, after the DML and the attenuator, an optical circulator was inserted at the OLT to separate the received upstream traffic from the emitted downstream traffic. The circulator end connected to the fiber represents the limit of the OLT. At the user end, the ONU was not modified from the previous setup. Since the RSOA operates better at higher input powers, and the upstream data have to be transmitted over twice the distance of the downstream data, the 70% end of the splitter remains connected to the RSOA. In the reception of the upstream data, a 1.2-nm full-width at half-maximum optical bandpass filter was used to evaluate the influence of the signal to amplified spontaneous emission (ASE) ratio in the upstream channel. Finally, a second attenuator similar to the one in the ONU was positioned before the detector to add flexibility and to avoid placing an attenuator in the fiber link, which can cause undesired reflections at the connectors.

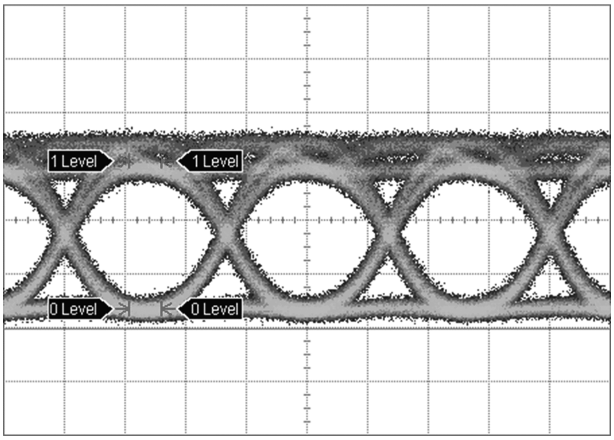

Fig. 8. Eye diagram of the upstream channel.

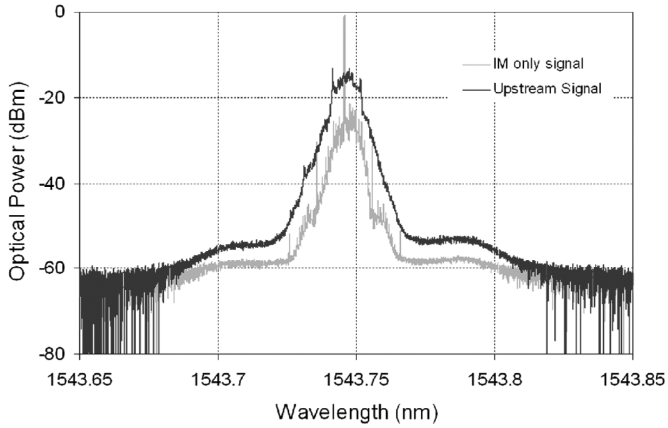

Fig. 9. Optical spectra of the upstream channel signal and of a pure-intensity-modulated signal.

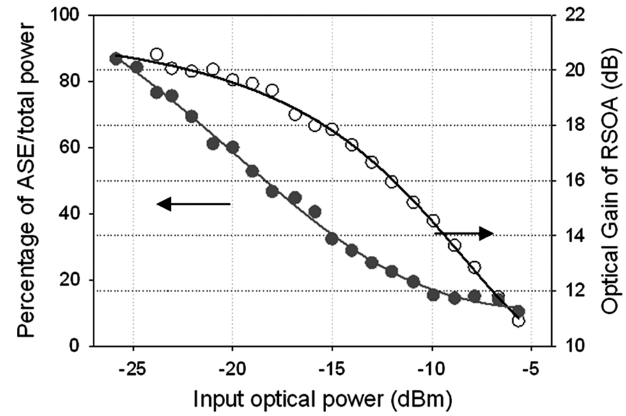

Fig. 10. (solid circles) Gain and (open circles) ASE/total power ratio of the RSOA versus input optical power.

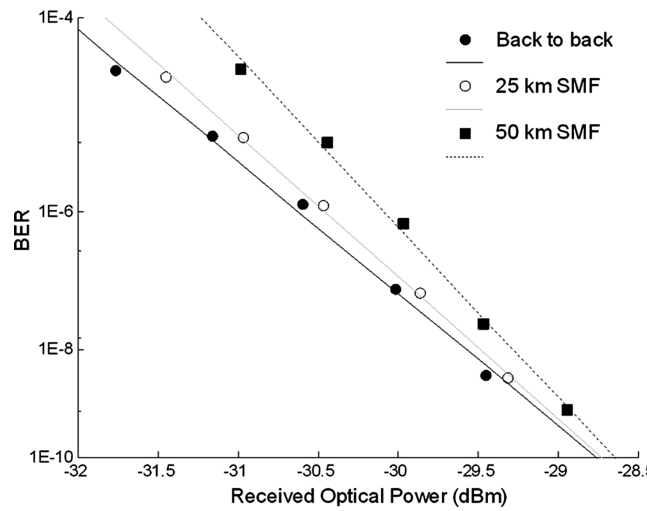

Fig. 11. BER for the downstream narrow-FSK signal (solid circles) back to back, with (open circles) 25 km, and (squares) 50 km of standard SMF obtained using the setup shown in Fig. 7.

The eye diagram of the upstream signal is depicted in Fig. 8. A small residual IM from the FSK downstream channel used to feed the RSOA can be appreciated over the top level of the modulation.

Fig. 9 shows the measured optical spectra of the real upstream signal and of the IM signal obtained when feeding the RSOA with a CW source. The narrow-FSK modulation superimposed to the upstream IM signal can be seen in the figure. The comparison of these spectra reveals a general broadening of the upstream channel signal when the FSK-modulated signal is used as a source. As expected, the carrier single peak was replaced by the two FSK peaks of the source downstream signal. However, as we show in this paper, the presence of the frequency modulation and the residual IM does not impair the direct detection of the upstream IM signal.

The characteristics of the RSOA have a great impact in the upstream channel, and thus, they have to be taken into account. In Fig. 10, the ratio of ASE to total power and the optical gain of the RSOA are shown as functions of the input power. As the power input to the RSOA increases, the optical gain of the device decreases until saturation is reached. Below saturation level, the ASE/total power ratio of the reflected amplified signal grows as a consequence of the reduction in the stimulated emission associated with the input power.

V. Complete Link

Finally, after independently testing both the downstream and upstream channels of the architecture, we present different results to assess the behavior of the complete scheme.

Fig. 11 shows the BER characteristics of the downstream channel versus the received optical power after transmission, over 50 km of single mode fiber (SMF), over 25 km, and in a back-to-back configuration. The results show that the power penalty associated with the chromatic dispersion of the fiber is negligible in the measurements with 25 km and only slightly higher with 50 km, which confirms our previous assertion that chromatic dispersion is not a critical factor as a result of the small spectral width of the narrow-FSK-modulated signal.

Fig. 12 shows the BER curves for the upstream signal in back-to-back measurements for different constant RSOA input powers, without the bandpass optical filter in the reception end of the OLT. The channel behavior only changes slightly at different input powers, although we found a high variation of the ASE at the RSOA output (Fig. 10). As an explanation, we suggest the combination of two facts: first, that the total optical reflected power (combination of ASE and signal) in the RSOA remains almost constant with independence of the

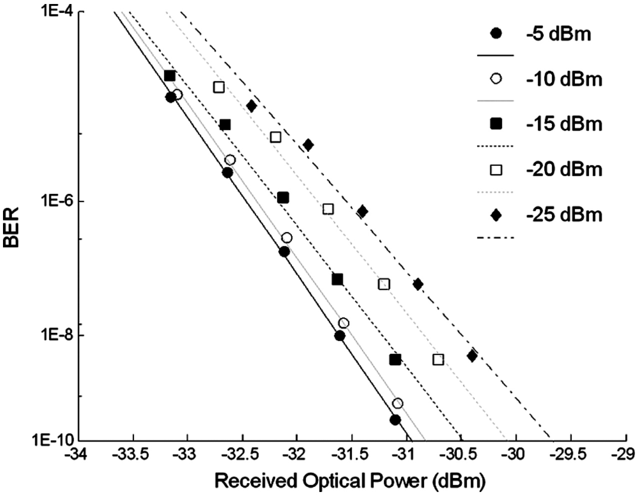

Fig. 12. Back-to-back BER for the upstream channel obtained with the setup in Fig. 7 without the optical filter in the OLT end for different RSOA input powers.

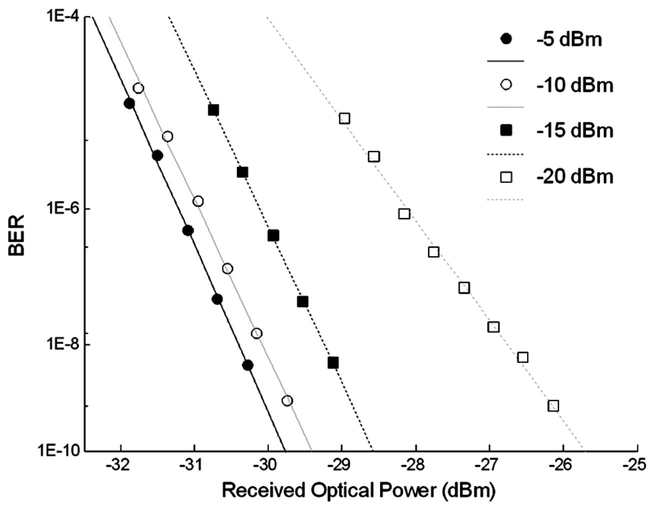

Fig. 13. Back-to-back BER for the upstream channel obtained with the setup in Fig. 7 with an optical filter in the OLT end for different RSOA input powers.

input power; and second, that the ASE is also modulated along with the signal by the GbE source that feeds the RSOA. As both modulated ASE and signal are detected at the end of the upstream channel, the total optical GbE-modulated power does not suffer strong variations, and the BER penalties are lower than expected, showing a maximum difference of 1 dB.

To confirm our explanation, the BER curves in Fig. 12 must be contrasted with the ones in Fig. 13, that also show the upstream channel behavior back-to-back for different optical RSOA input powers, but this time with a WDM filter at the reception. The presence of the filter increased the power penalty when decreasing the RSOA input power. For −5 and −10 dBm, the penalty relative to the case without filter is slightly above 1 dB, but for lower input powers (−15 and − 20 dBm), the penalty is even higher. This comparison confirms our previous assertion that ASE is also modulated along with the amplified signal in the RSOA. When the bandpass optical filter is used, out-of-band ASE is rejected, introducing a noticeable power penalty, which depends of the amount of ASE in the received signal. Signals with RSOA input powers of −5 and −10 dBm (less than 20% of ASE) suffer considerably less degradation than those with lower RSOA input power. This is one of the reasons that justify the use of a 70/30 splitter instead of a 50/50 splitter for a better performance of the RSOA. In a real WDM-PON design, the bandpass filter will be substituted by a wavelength demultiplexer with similar characteristics, and the effects of the filtering out of the RSOA-modulated ASE will have to be considered.

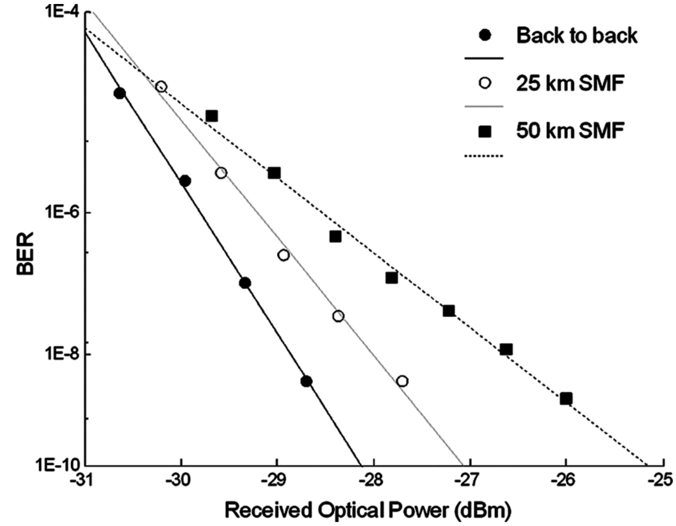

Fig. 14. BER (back-to-back, 25 km, and 50 km SMF) for the upstream channel with equal attenuations for the downstream and upstream links obtained using the setup shown in Fig. 7 including the WDM optical filtering, as in Fig. 13.

BER results for the upstream channel for different link distances are displayed in Fig. 14. These measurements were taken with the optical filter, and both attenuators were adjusted to obtain exactly the same attenuation in the upstream and downstream channels to simulate a more realistic situation; curves for three different conditions (back-to-back, 25, and 50 km of SMF) were measured. A comparison of Figs. 11 and 14 shows that, in the back-to-back configuration, the downstream channel has better performance than the upstream one due to the IM residual modulation. In addition, fiber transmission hardly affects the downstream FSK-modulated signal, whereas the upstream intensity-modulated signal suffers higher penalizations as we increase the length of the fiber link. This degradation can be explained by the joint effects of the ASE-to-signal ratio in the fiber and the reflections of the RSOA output optical power. However, the penalty from back-to-back transmission at a BER of 10^{-9} is only around 1 dB with 25 km of SMF, and less than 3 dB with 50 km, which confirms the robustness to dispersion of the proposed architecture.

VI. Conclusion

A bidirectional PON suitable for WDM networks based on narrow-FSK modulation for the downstream channel and IM of the same wavelength by an RSOA for the upstream channel has been demonstrated and evaluated for a 50-km link. We found that the chirp characteristics of the directly modulated laser set the limits to the modulation frequency for the downstream signal giving a satisfactory performance from 0.3 to 2.5 Gb/s. For the upstream channel, the performance was acceptable, but depends on the RSOA characteristics, the input optical power, and the signal-to-ASE ratio when using narrow optical filters in WDM architectures.

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