Direct DPSK modulation of chirp-managed laser as cost-effective downstream transmitter for symmetrical 10-Gbit/s WDM PONs

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Abstract: This paper proposes the use of chirp-managed lasers (CML) as cost-effective downstream (DS) transmitters for next generation access networks. As the laser bandwidth is as high as 10 GHz, the CML could be directly modulated at 10 Gbit/s for downstream transmission in future wavelength division multiplexing passive optical networks (WDM PON). The laser adiabatic chirp, which is the main drawback limiting the transmission performance of directly modulated lasers, is now utilized to generate phase-shift keying (PSK) modulation format by direct modulation. At the user premise, the wavelength reuse technique based on reflective colorless upstream transmitter is applied. The optical network unit (ONU) reflects and orthogonally remodulates the received light with upstream data. A full-duplex transmission with symmetrical 10-Gbit/s bandwidth is demonstrated. Bit-error-rate measurement showed that optical power budgets of 29 dB at BER of $10^{-9}$ or of 36 dB at BER of $10^{-3}$ could be obtained with direct phase-shift-keying modulation of CML which proves that the proposed solution is a viable candidate for future WDM-PONs.

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References and links

1. Introduction

Fiber to the Home (FTTH) or Building (FTTB) are access network methods that deliver the highest possible speed of Internet connection by using optical fiber that runs directly into the home, building or office. Deployment of FTTH/B access networks has already started in many countries. In Europe, the annual progress of optical access network deployment is 41%, with nearly 28 million homes passed at the end of 2011 [1]. With the continuous increase in bandwidth demand generated by consumer and business applications (high-definition TV, cloud computing, online gaming, videoconferencing, etc.), and the required high-speed mobile backhaul for Long Term Evolution (LTE) networks, the need for a new, higher capacity access architecture becomes clear.

Wavelength-division-multiplexed passive optical network (WDM-PON) is an efficient choice for future fiber access networks as it can provide a point-to-point connectivity to multiple remote locations sharing the major part of the fiber plan. In spite of the numerous advantages associated with WDM-PON, the high cost attributed to wavelength specific transmitters at the optical line termination (OLT) and within each optical network unit (ONU) has reduced the competitiveness of this technology [2]. Several network architectures have been proposed to achieve full-duplex transmission over a single fiber for implementation in WDM-PONs. Among them, phase [3] or frequency shift keyed [4] (PSK or FSK) modulation formats were proposed for the downstream (DS) transmission, which provided an almost continuous wave signal for colorless upstream (US) re-modulation in the ONU. However, most of the solutions that have been studied so far were limited by the use of high-cost and power-budget-consuming external modulators to generate differential PSK (DPSK) signals. Some directly modulated DPSK solutions were proposed by the use of high-bandwidth three-level driving signals [5].

Recently, the high performance transmission of directly modulated chirp-managed lasers (CML) have been demonstrated [6]. Generation of return-to-zero DPSK (RZ DPSK) signal by direct modulation of CML has also been shown. However, the use of external modulator as pulse carver [7], or high-bandwidth three-level driving signals are necessary [8]. In Ref [9], a summary of advanced modulation formats that could be generated by direct modulation of CML was presented. This reference has also proposed a WDM-PON configuration using 10-Gbit/s inverse RZ (IRZ) duobinary modulation for the downstream and remodulation at 2.5 Gbit/s for the upstream. However, with the use of high-extinction-ratio IRZ duobinary signal...
for the downstream, high crosstalk is present when remodulation technique is used for the upstream. Therefore, in this reference, the upstream data rate was only 2.5 Gbit/s and low pass filter was used to suppress the residual modulation at 10 Gbit/s.

Here, in this paper, we investigate the CML as a cost-effective DPSK downstream transmitter in a symmetrical 10-Gbit/s WDM-PON configuration [10]. The CML-based transmitter configuration is similar to the IRZ duobinary transmitter proposed in Ref [9]. However, instead of using the optical spectrum reshaper (OSR) integrated in the CML to increase the intensity extinction ratio, the OSR is now red-shifted in order to equalize the intensity fluctuations. As a consequence, pure DPSK signal with an intensity almost constant could be generated. This technique, to the best of our knowledge, has never been demonstrated before. Thanks to the low intensity fluctuations, the downstream DPSK signal can be re-modulated at the ONU for on-off keying (OOK) upstream transmission. A full-duplex transmission with symmetrical 10-Gbit/s bandwidth is demonstrated.

2. Principle of operation

Figure 1 shows the schematic of the CML 10-Gbit/s DPSK transmitter. A CML consists of a semiconductor laser (DFB - distributed feedback laser) followed by an optical filter (OSR - optical spectrum reshaper). The driving electrical signal is encoded in inverse return-to-zero (IRZ) format, via a commercial logic NAND gate, before being sent to the CML.

Figure 2 illustrates the operation principle through driving current/output intensity, frequency and phase characteristics of the output signal. By direct modulation, a corresponding frequency shift was generated due to the adiabatic chirp of the laser. In this application, the bias current is set far above the threshold. The transient chirp can therefore be neglected. As the optical phase is a time integral of the instantaneous frequency, a phase shift of \( \Delta \phi = 2\pi \int_0^T \Delta f(t)dt \) where \( \Delta f(t) \) is the optical frequency deviation, is generated during a pulse duration (T). If the pulse shape is correctly chosen, DPSK signal (the “1” value is coded by a constant phase, and the “0” is coded by a phase shift of \( \pi \)) could be directly generated. In this case, the driving voltage is adjusted to induce adiabatic chirp of \( \Delta f = 1/T \). The phase shift generated by the inverse pulses is thus \( \Delta \phi = 2\pi \int_0^T \Delta f(t)dt = 2\pi \times \frac{1}{T} \times \frac{1}{2} = \pi \). As a consequence, in order to obtain a phase shift of \( \pi \) with a 50%-duty-cycle IRZ signal, a maximum frequency shift of about 10 GHz is required. The resulting phase modulation is intrinsically differentially encoded, eliminating the need for a differential encoder. In order to achieve pure DPSK signal in which information is only carried by the optical phase, the optical spectrum reshaper integrated at the output of the laser is red-shifted to equalize the output intensity.
In order to assess the frequency modulation efficiency of the laser, the chirp characteristic of the laser is investigated. A commercial CML module (AZNA DM200-01) was used in this experiment. The input impedance and threshold current of the laser module were 50 Ohms, 25 mA, respectively. Wide-bandwidth time-resolved chirp measurement technique was used [11]. Figure 3 shows the laser adiabatic chirp versus driving voltage. The laser was biased at 80 mA, about three times above threshold in order to generate small residual intensity fluctuations, proper chirp (no transient chirp was observed). The resulting adiabatic chirp is almost linearly proportional with the driving voltage. In order to achieve a frequency shift of 10 GHz, a peak-to-peak driving voltage of 2 V is required, showing a frequency-modulation efficiency of 0.24 GHz/mA.

3. Network architecture

Figure 4 illustrates the schematic diagram of the considered WDM PON. Each downstream transmitter consists of a 10-Gbit/s DPSK directly modulated CML. Two identical arrayed waveguide gratings are used at the OLT and remote node to combine and separate downstream wavelength channels that carry signals from the OLT to the ONUs, as well as
upstream wavelength channels that carry signals from the ONUs to the OLT. The main advantage of the downstream DPSK format is that the laser power is preserved in half bit duration where the signal phase is stable. As a consequence, the demodulated signal at the receiver would not be degraded by residual intensity fluctuations. In addition, this stable phase and stable power slot could be used for symmetrical-rate colorless upstream based on remodulation technique. As a consequence, each ONU is assigned with one wavelength for both downstream and upstream. The upstream transmitters consist of reflective semiconductor modulators (RSOA) or reflective electro-absorption modulators (REAM).

Fig. 4. WDM PON architecture.

The colorless remodulation scheme at the ONU used in this experiment is shown in Fig. 5. The signal was split using a 3-dB coupler with one arm fed directly into a downstream receiver (DS Rx) which comprises a delay interferometer (DIL) and a single-ended receiver (APD-avalanche photodiode). The second arm of the 3-dB coupler in the ONU was fed into the colorless upstream remodulation transmitter (US Tx) which consists of an optical delay line (ODL), a semiconductor amplifier (SOA) and an electro-absorption modulator (EAM). The line coding for upstream signal was 50% RZ format that has exactly the same bit rate as the downstream signal. If the RZ modulation is interleaved by half-bit in respect to the incoming IRZ pattern, then RZ modulation could be performed over a stable and high-power slot [12]. This can eliminate the process of erasing the downstream data from the received optical carrier. As a consequence, the constraint on downstream signal power to saturate the SOA [13] in the ONU could be released. The synchronization between upstream and downstream is principally not an issue as the downstream clock is recovered at the downstream receiver. The synchronization delay is fix for each ONU which corresponds to the traveling time between OLT and ONU modulo the bit duration. The adjustment could be performed either in optical or electrical domain. In this work, this was manually done by optical delay line. Figure 6 shows the 10-Gbit/s RZ upstream eye patterns when the delay between DS and US signals is correctly adjusted (a) or mismatched (b).

Fig. 5. Proposed DS receiver and US transmitter.
In addition, as the DPSK modulation corresponding to the downstream data is still remained in the upstream signal, some adjacent upstream RZ pulses have a phase shift of $\pi$. The inter-symbol interference due to chromatic dispersion could be partly reduced thanks to destructive interference. In order to reduce the cost and complexity of the ONU, the circulator, SOA and the EAM would ideally be replaced by a reflective EAM-SOA [14].

4. Experimental results

The experimental setup is shown in Fig. 7, only one channel was considered in this work. For simplicity, in this experiment, we used different fibers for upstream and downstream transmission. Two attenuators (ATT) were used to emulate the upstream and downstream optical budgets. The downstream data was a 10-Gbit/s PRBS $2^{11}$-1 generated by a pulse pattern generator. The required frequency shift of 10 GHz was obtained by applying a peak-to-peak driving voltage of 2 V. The laser was biased at 80 mA and the output power was 4 dBm. The central wavelength of the signal was 1536.88 nm. The integrated OSR is a Fabry-Pérot filter with 3-dB bandwidth of 0.06 nm.

Figure 8(a) shows the eye pattern of the CML output during two bit durations, IRZ intensity modulation is equalized by the integrated OSR resulting in an almost constant intensity for upstream remodulation. The lowest residual intensity fluctuation parts are highlighted, where synchronous RZ remodualtion can be applied. Demodulated DPSK signals at the constructive port (b), and at the destructive port (c) are also shown with similar performance. Single-end detection was used in this work.
Figure 8. (a) Residual intensity fluctuations at the CML output, and demodulated signals at the DLI constructive port (b) and DLI destructive port (c).

Figure 9 shows the measured bit error ratio (BER) performance of DPSK signal generated by direct modulation of CML and external dual-drive Mach-Zehnder modulator (MZM). The back-to-back receiver power sensitivities at a BER of $10^{-9}$ for CML and MZM are $-26$ dBm and $-27$ dBm, respectively. The 1-dB penalty is mainly due to the residual intensity noise at the output of the directly modulated laser.

Figure 10 shows the BER of the 10-Gbit/s DPSK downstream signal in the case of back-to-back (B2B), after 10 km and 25 km of transmission in standard single-mode fiber (SMF), respectively. After propagating over 25 km, the power penalty compared to B2B scenario was only 0.5 dB, which proves once again the high tolerance to chromatic dispersion of directly modulated CML. Error-free (BER $< 10^{-9}$) transmission was achieved for the considered scenarios at receiver power of $-25$ dBm, which corresponds to a downstream optical budget of 29 dB. If we consider the BER of $10^{-3}$ which is the limit of forward error correction code (FEC), an optical budget of 36 dB was obtained. This achieved optical budget covers the losses of WDM MUX/DEMUX (2 × 4 dB), downstream/upstream separators (4 dB), and DLI (5 dB). An extra budget of 19 dB could be used for fiber transmission and an integration with the former deployed PON systems, as a smooth mitigation of infrastructure is one of the major requirements from operators for WDM PONs [15]. This extra optical budget could also be used to employ power splitters to share time division multiplexed 10-Gbit/s bandwidth to a number of users. For the upstream, an RZ encoder was used with PRBS of $2^{31}-1$. The SOA has a saturated power of 10 dBm at 1550 nm with 200-mA injection current. The SOA optical input power was set at $-10$ dBm. The EAM was modulated with 3-V peak-to-peak driving signal which provided an output extension ratio of 9 dB, its total loss was 15 dB.
Figure 11 shows the BER analysis of the 10-Gbit/s RZ upstream signal. The square-marked curve corresponds to the case of upstream back-to-back without downlink DPSK modulation. The rhombus-marked curve is for the case with downlink DPSK modulation and the remodulation delay is correctly adjusted. A power penalty of only 1 dB is observed due to the downlink residual intensity modulation. After transmission over 10 km (circle) and 25 km (triangle), the power penalties relative to B2B case are 2 dB and 2.5 dB, respectively. Although, error-free transmission was achieved at input power of −24 dBm, corresponding to an upstream optical budget of only 19 dB. With the use of FEC, the achieved upstream budget is 25 dB. Better performance could be obtained by the use of a reflective EAM-SOA with higher effective gain and output power.

5. Conclusion
We have investigated for the first time the performance of a cost-effective downstream transmitter for symmetrical 10-Gbit/s WDM-PONs chirp-managed laser. By using the inverse RZ driving signal, an optical DPSK signal was intrinsically obtained at the laser output. The
need for either high-bandwidth driving signal, differential encoder or high-cost and power budget consuming external modulator was eliminated. The integrated optical filter equalized the intensity levels, the residual intensity fluctuations were thus reduced. Excellent system performance was demonstrated for the phase encoded downstream signal. In back-to-back measurement, a power penalty of only 1 dB compared to the Mach-Zehnder-modulator-based DPSK signal was obtained. After the propagation over 10 km and 25 km of single mode fiber, the power penalty did not exceed 0.5 dB. The achieved downstream optical budget, 29 dB at BER of $10^{-9}$ or of 36 dB at BER of $10^{-3}$, proved that the proposed solution could be a strong candidate for future WDM PONs. This power budget could be drastically increased by the use of a DPSK-compatible PON extender called saturated collision amplifier [16, 17] for high-capacity TDM/WDM PON systems.

At the ONU, a reflective colorless upstream transmitter scheme based on EAM-SOA combination was used. Symmetrical-rate transmission was obtained by the use of synchronized remodulation of the high power slot in downstream signal with RZ modulation format. This can eliminate the process of erasing the downstream data from the received optical carrier. As a consequence, the constraint on downstream signal power to saturate the SOA in the ONU could be released. A power penalty of 2.5 dB was obtained for 10-Gbit/s upstream data transmission after 25 km. To reduce the complexity of the upstream transmitter, an integrated reflective EAM-SOA combination could be employed.