A Novel All-Optical ASK/DPSK Label Swapping Technique Based on Pump Depletion Effects in Parametric Amplifiers

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Abstract

An all-optical amplitude shift keying/differential phase shift-keying (ASK/DPSK) label swapping scheme based on the pump-depleted parametric process in optical fibers is numerically demonstrated. In contrast with the usual four-wave mixing (FWM) approaches, the proposed technique takes advantage of the depleted pump wave, which after the parametric process, carries both the payload and the new label. The feasibility of the proposed scheme is verified in a transmission system where 40Gb/s ASK packets along with 2.5Gb/s DPSK labels are efficiently transmitted over five 60Km-spaced hops.

Keywords: all-optical label swapping, parametric amplification, four-wave mixing, pump-depletion

1. Introduction

The next generation ultra-high speed all-optical networking approaches are evolving into an Internet protocol (IP) network upon a wavelength division multiplexing (WDM) physical infrastructure. In order to overcome the electronics bottlenecks, Blumenthal et. al [Blumenthal et. al, (2000)] have proposed the use of optical labels to route and forward IP data, thus avoiding to detect the payload. Generalized multiprotocol label switching (GMPLS) technology has been introduced as a solution for packet routing and forwarding functions, where λ serves as an optical label. Apart from λ labeling, a second level of optical label is essential for maintaining and restoring switched light-paths, supporting advance quality of service (QoS), routing and traffic engineering [Koonen et. al, (2001)]. The structure and performance of the optical core node (router) is determined by the all-optical label swapping (AOLS) technique adopted, which is the method of coding the label onto the packet after having removed the old one, for the implementation of all-optical packet routing and forwarding. Several techniques for the implementation of all-optical label swapping have been proposed in the literature, such as optical subcarrier multiplexed (SCM) header, bit serial header, wavelength labeled WDM and orthogonally modulated packet. The latter approximation has concentrated the interest of many research groups as such a two-level labeling allows more comprehensive network architectures requiring multiple addressing levels [Koonen et. al, (2001)]. The orthogonal label encoding has been initially demonstrated either combining amplitude shift keying (ASK) payload packets with differential phase shift keying (DPSK) or frequency shift keying (FSK) header packets [Koonen et. al, (2001), Chi et. al. (2003), Xu et. al. (2003), Lallas et. al, (2002)], while lately the opposite scheme utilizing balanced detection for DPSK payload has been proposed [Liu et. al. (2003)]-[Liu et. al. (2004)]. The latter approach offers certain advantages. The usage of the balanced receiver increases the receiver sensitivity not only for the DPSK payload, but also for the ASK label as higher extinction ratios (ER) can be supported. Moreover, the intensity modulated label is easily removed and inserted by utilizing the gain saturation in semiconductor optical amplifiers. However, the ASK/DPSK or ASK/FSK format to carry payload/label is better adapted to the present networks and it can be preferred if a simplified swapping technique operating at very high bit-rates of the payload ASK format is practicable. The usage of an electro-absorption modulator is possible to relax the above requirements up to 10Gb/s, when non-return to zero (NRZ) intensity modulation (IM) is utilized for the payload, as already reported in [Xu et. al, (2003)]. To extend the operation of label swapping up to 40Gb/s for the NRZ-IM payload, a fiber device must be utilized.

In this paper we numerically demonstrate an efficient method for the removal and insertion of DPSK modulated labels, which relies on the pump-depletion effect in fiber-optic parametric amplifiers (FOPAs). It is shown that through the depleted parametric process between the pump wave and the signal carrying the orthogonal ASK/DPSK modulation, the payload is inversely duplicated on the pump wavelength, which in advance has been phase-modulated with a new DPSK label. Finally, at the output of the FOPA, the pump wave carries both the payload and the new label, while the signal is filtered out, and hence the old wavelength and DPSK labels are completely dropped off. In the proposed scheme a balanced DPSK receiver is also utilized for performance optimization.

FOPAs are high-speed all-optical processors which provide a number of useful applications as high-gain optical amplification, efficient wavelength conversion, phase conjugation for dispersion compensation, all-optical regeneration, all-optical sampling and switching [Hansryd et. al. (2002)]. Their main advantage is related to the almost immediate time-response of the Kerr effect, which makes them suitable for high-bit rate all-optical processing applications. Furthermore, the design of short-fibers with enhanced non-linear features provides improved bandwidth and gain performance. The proposed AOLS method is another all-optical signal processing application of parametric amplification, which, to the best of our knowledge, has not been addressed before.

This paper is organized as follows. The description of a system utilizing the label swapping technique and the principle of operation of the proposed technique are comprehensively discussed in Section II. The performance of the parametric swapper is numerically assessed for 40Gb/s payload packets with 2.5Gb/s labels in a network consisting of 60Km spaced nodes in Section III. Finally, conclusions on the characteristics of the proposed AOLS technique are given in Section IV.

2. System description and principle of operation of the proposed scheme

A detailed schematic representation of a transmission system consisting of nodes utilizing the proposed technique is given in fig. 1, where the starting, end and intermediate nodes are shown as functional blocks. The ASK/DPSK orthogonally modulated packet can be generated by cascading an intensity modulator (IM) and a phase modulator (PM) in the source node. Although polarization controllers do not appear in the figure, they are required before and after each modulator in order to adjust the extinction ratio of the ASK payload before it is driven into the PM [Chi et. al. (2003)], and other characteristics as the transmitted power. The end node simultaneously detects both ASK payload and DPSK label, utilizing a balanced detector for the latter.

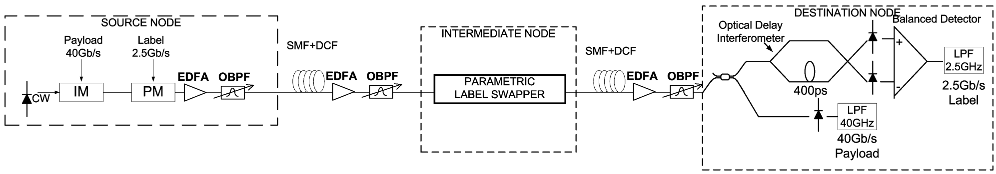

Figure 1. *Schematic representation of a network consisting of nodes performing parametric label swapping. IM: Intensity Modulator, PM: Phase Modulator, EDFA: Erbium Doped Fiber Amplifier, OBPF: Optical BandPass Filer, SMF: Single Mode Fiber, DCF: Dispersion Compensating Fiber, LPF: Low Pass Filter*

The intermediate nodes are responsible for the packet forwarding to the next nodes through the AOLS based on parametric amplification. The conceptual scheme of the proposed AOLS technique is illustrated in fig. 2. Part of the ASK/DPSK modulated input is driven to the label processor for extraction of the label information and generation of the new label. For this purpose, a balanced DPSK detector as the one depicted in the end node of fig. 1, must be employed in the label processing stage. The other part of the input is driven to the FOPA, where through the parametric process the two waves (pump and signal) interact providing new four-wave mixing (FWM) products. If the process is depleted, the pump power will vary inverse proportionally with respect to the input signal power [Marhic et. al. (2001)]. Thus, with proper adjustment of the signal power, the payload can be inversely transferred to the initially CW pump. Key point in the implementation of the proposed AOLS method is the loading of the new label on the pump wave (fig. 2). This is accomplished by utilizing a phase modulator (PM) which is also necessary for the suppression of the stimulated Brillouin scattering. According to FWM theory, the signal phase characteristics are transferred to the idler and the other products, but not to the pump wave. Hence, the new label loaded on the pump will not be affected by the old label of the signal through the FWM process. Finally, at the output of the swapper, the pump wave carries both the payload information (inverted with respect to the input signal payload), and the new DPSK label inserted by the PM, while the old DPSK label is completely dropped-off utilizing optical filtering. The attenuator positioned at the output of the device is necessary to adjust the power level of the output pump that will be launched in the transmission line. The new label is mainly impaired by the cross-phase modulation (XPM) and self-phase modulation (SPM) occurring in the FOPA and their effect will be studied in a subsequent paragraph. It is pointed out that the output wavelength is also changed from λ_s to λ_p, thus providing two-level all-optical label swapping.

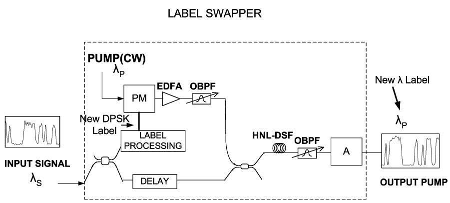

Figure 2. *Schematic representation of the FOPA-based AOLS technique. HNL-DSF: Highly Non-Linear Dispersion Shifted Fiber, A: Attenuator.*

3. Numerical results and discussion

The performance of the specific AOLS technique has been evaluated carrying out a twofold analysis. On one hand, the investigation on the swapping properties of the specific scheme assessing the influence of FOPA parasitic effects is carried out. On the other hand, the applicability of this method is evaluated in a transmission system as the one depicted in figure 1, where the network nodes are connected to each other with transmission fiber spans consisting of single mode and dispersion compensating fibers. Before focusing on the special characteristics of the proposed swapping technique, it is necessary to describe the features of the orthogonal ASK/DPSK modulation scheme and perform a trade-off analysis for the choice of the appropriate extinction ratio value that offers a robust performance for both modulation formats.

3.1 Orthogonal modulation characteristics

As already mentioned in section II, the orthogonally modulated packet consists of a 40Gb/s ASK non-return to zero (NRZ) payload and a 2.5Gb/s DPSK label. Both payload and label receivers are followed by third-order Butterworth filters having 3dB-bandwidth equal to 40GHz and 2.5GHz respectively (fig. 1). As the DPSK receiver employs balanced detection, the sensitivity is almost 3dB improved [Xu et. al. (2004)], and thus a higher extinction ratio is allowed for the ASK payload. The interplay between the extinction ratio limits of both modulation formats has been thoroughly investigated. The quality of the payload is evaluated in terms of the Q-factor, which is a reliable figure of merit for ASK modulated data, as for low intersymbol interference, it can be directly related to the bit-error rate (BER) based on the Gaussian assumption, in most cases [Humblet et. al. (1991)]. For the label, the alternative Q-factor that measures both phase and amplitude fluctuations introduced in [Xu et. al. (2004)] has been calculated, as it provides more accurate estimate of BER when balanced detection is utilized. In the context of this work, Q>6 is the criterion for acceptable system performance for both formats since, according to the Gaussian approximation, Q>6 corresponds to BER<10^{-9}. The Q-factor values calculated for both modulation formats as a function of the payload extinction ratio are depicted in fig. 3. The extinction ratio value is adjusted by assuming a constant power level at the spaces level (P_0=0dBm) and varying the power at marks (P_1) properly. As it can be seen in the figure, both formats provide similar performance (Q=12.5) at ER=3.3dB and can provide acceptable performance for ER values within the 2dB-7dB range. In a real system, the labeled payload undergoes the transmission impairments, and the high bit-rate ASK is expected to experience higher degradation than the DPSK label. On the other hand, the DPSK performance must be kept at high levels, as errors during the label extraction in an intermediate node, (fig. 2) will cause routing problems. In order to compromise the two requirements, an extinction ratio value equal to ER=5dB is selected for the numerical simulations carried out in the specific work. In the next paragraph, a first characterization of the parametric swapper is presented.

3.2 Parametric Swapper Properties

The parametric swapper has been simulated by numerically integrating the non-linear Schrödinger equation by means of the split-step Fourier method accounting for up to the third order dispersion. The highly non-linear dispersion-shifted fiber (HNL-DSF) of the FOPA is 1Km-long, with fiber losses equal to α=0.7dB/Km, nonlinear parameter γ=12W^{-1}Km^{-1}, zero dispersion at λ_0=1567nm, and dispersion slope dD/dλ=0.02 ps/nm^2/km. The simulation step is 5m. The polarization mode dispersion (PMD), the Raman effect and the longitudinal dispersion fluctuations have been ignored in the numerical description of the FOPA. The pump wave is noise-impaired, as in practice, EDFAs are employed in order to enhance the pump power up to several hundreds of mWatts. Thus, an OSNR value equal to 61dB (calculated within 0.1nm) is fixed for the pump wave, by adding white noise which corresponds to the amplified spontaneous emission of a 20dB gain EDFA, followed by an OBPF. In that way, the noise characteristics of the FOPAs are also accounted for.

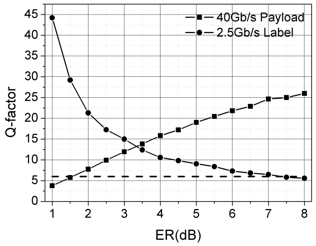

Figure 3. *Q-factor calculated for both payload and label in terms of the payload extinction ratio*

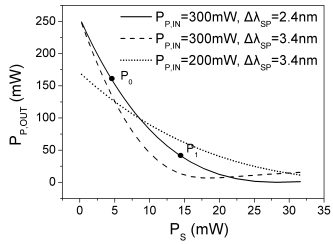

Figure 4. *Pump power PP,OUT at the output of the FOPA in terms of the input signal power PS for two signal-pump wavelength spacings* $\Delta\lambda_{SP}=\lambda_S-\lambda_P$

As already discussed in the previous section, the intensity modulation of the input packet is inverse proportionally transferred to the pump wave via the pump depletion effect. Hence, it is critical to investigate the degree of pump depletion in terms of various operating parameters of the FOPA. This analysis has been performed statically, varying the input signal power and calculating the pump power at the output of the FOPA. In fig. 4, the pump power PP-OUT at the FOPA output as a function of the input signal power P_S is plotted for two different signal-pump wavelength spacings $\Delta\lambda_{SP}=\lambda_S-\lambda_P$ and two different initial pump powers. The pump wavelength is equal to 1572.1nm. As it is seen in fig. 4, steeper responses can be achieved by increasing the spectral spacing between pump and signal, and the pump power. This behavior originates from the exponential dependence of parametric gain upon the pump power. On one hand, as the spectral distance increases, the phase-matching condition is better satisfied, the parametric process approaches its maximum efficiency, resulting thus in higher parametric gain. On the other hand, higher input pump power can provide higher parametric gain. According to the literature [Kylemark et. al. (2004)], as parametric gain increases, less input power is needed to saturate the gain and thus to deplete the pump power. It should be mentioned that the strong pump depletion observed in fig.4 is practically feasible, as it has been already experimentally shown in [Marhic et. al. (2001)] with 92% efficiency.

In the previous paragraph, an extinction ratio value equal to 5dB has been selected in order to keep the performance of both ASK and DPSK in high levels. This implies that the swapper should preserve the extinction ratio value of the payload so as not to disturb the performance of either modulation formats. Such a requirement can be more or less satisfied for any of the curves of fig. 4, if the power of the input signal is properly adjusted. For instance, for the parametric swapper corresponding to the solid curve of fig. 4, the input signal power at marks and spaces is chosen to be P_{S1}=14.7mW and P_{S0}=4.63mW (ER_S=5dB) resulting in output pump powers equal to 45.72mW and 161.2mW respectively (ER_P=5.5dB). The pump power at the output of the FOPA is extremely high and it must be attenuated before launched into a transmission fiber span. Hence, the attenuator depicted in fig. 2 serves as a pump power controller. In the rest of this analysis, a parametric swapper with operating conditions corresponding to the solid line of fig. 4 will be assumed.

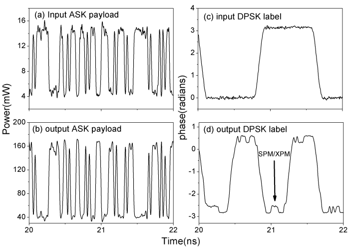

Figure 5. *The amplitude and phase characteristics of the input (a), (c) and the output (b), (d) packet. In the parametric process, the input packet corresponds to the signal and the output packet appears in the depleted pump.*

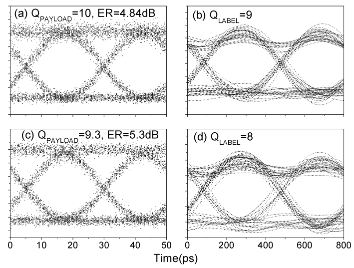

Figure 6. *Eye diagrams and Q-factor values of the input (a), (b) and output (c), (d) 40Gb/s payload and 2.5Gb/s label data.*

The parametric swapper suffers from two main detrimental effects. On one hand, through the parametric process, the signal intensity modulation affects the pump phase characteristics by means of XPM. Furthermore, the SPM effect also induces pump phase variations. These effects may distort the label loaded onto the pump wave (fig. 2). On the other hand, the excess pump noise causes parametric gain instabilities [Kylemark et. al. (2004)] which are experienced by the amplified signal and thus determine the depleted pump noise properties. The operation properties of the parametric swapper are depicted in fig. 5, for a 40Gb/s NRZ payload and a 2.5Gb/s DPSK label. In fig. 5, the payload and label time sequences are depicted for both the input and the output packet. It is clearly shown that the output payload (fig. 5(b)), which is the depleted pump wave, is the inverse replica of the input payload (fig. 5(a)) with the initial extinction ratio value being almost preserved. On the other hand, the pump label (fig. 5(d)) is affected by the high bit-rate XPM/SPM effects which appear in the form of short-pulses disturbing the 2.5Gb/s phase modulation. As the input signal increases, these short pulses become stronger degrading the phase modulation characteristics and thus the label decoding quality. For the input signal power levels considered in this work, the XPM does not seem to affect significantly the label according to the figure. Moreover, the high bit-rate XPM/SPM effects are filtered out in the 2.5Gb/s lowpass filter of the balanced detector. It is worth-mentioning that as it is seen in fig. 5(b), (d), the input label does not affect at all the pump label. This implies that phase distortion due to the parametric swapper non-linear effects is not accumulated in each swapping stage, as the input packet label is completely dropped off.

The performance of the parametric swapper is also impaired by the pump phase modulation. According to recent works [Mussot et. al. (2004)] the pump phase modulation can induce strong parametric gain modulation especially in the case of large pump-signal wavelength separation, where the gain is exponentially dependent on pump power. The strong parametric gain instability may cause pump depletion instability which is completely undesirable for the parametric swapper. However, for shorter wavelength spacings, the parametric gain is less sensitive in the phase-matching variations induced by the pump phase modulation, and thus the gain modulation is not noticeable. For example, for the FOPA length and dispersion slope parameters considered in this work, this phenomenon arises for wavelength spacings $\Delta\lambda_{SP}$>5nm. In this work, the $\Delta\lambda_{SP}$ value is 2.4nm, much lower than the 5nm limit.

In fig. 6, the swapping performance of the proposed AOLS technique is illustrated in terms of the eye diagrams and the corresponding *Q*-factor values of the payload and label at the input and the output of the device. It is clearly shown that the *Q*-factor performance of both modulation formats after the swapping process is slightly degraded compared to that of the input packet, thus confirming the applicability of this technique. The lower *Q*-factor observed for the DPSK output label is mainly attributed to the higher extinction ratio of the output payload. The *Q*-factor value of the pump payload is slightly decreased compared to the signal payload, mainly due to the excess pump noise which is responsible for parametric gain fluctuations.

3.3 Performance Characterization of a Transmission System utilizing the Parametric Swapping Technique

In this paragraph, the feasibility of the AOLS technique is investigated in a transmission system consisting of nodes employing the proposed swapping technique. The transmission segments have been simulated by numerically integrating the NLSE, utilizing the split-step Fourier method. The nodes are connected through a typical 60km-long single mode fiber (SMF) followed by a 7Km-long dispersion compensating fiber (DCF) utilized for the chromatic dispersion mitigation. Each SMF has chromatic dispersion coefficient D=16.6ps/nm/km, α=0.21dB/Km and γ=1.06W^{-1}Km^{-1}. Each DCF has D=-142.5ps/nm/km, α=0.549dB/Km and γ=5.07W^{-1}Km^{-1}. An EDFA module followed by an OBPF having 3dB-bandwidth equal to 1nm is placed at the end of each transmission segment (fig. 1) providing a twofold action. On one hand, it compensates for the losses of both SMF and DCF. On the other hand, it adjusts the input signal optical power level for the required pump depletion in the swapper. The amplified spontaneous emission noise of the EDFA is taken into account.

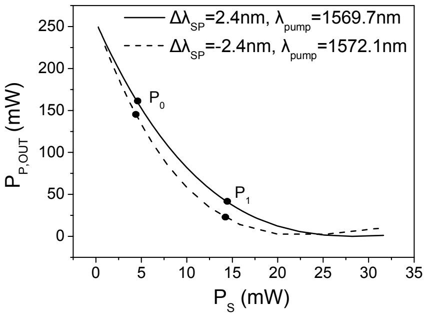

Figure 7. *Power characteristics of the even-numbered (solid line) and odd-numbered (dashed-line) nodes of the transmission system. The dots indicate the points where the average mark and space of the input signal are adjusted for the preservation of the 5dB extinction ratio.*

The spectral density of the Gaussian ASE noise generated by each EDFA stage per polarization axis is given by the following well known expression:

$$S_{ASE} = n_{sp} hf \left(G_{EDFA} - 1 \right) \qquad \textbf{(1),}$$

where n_{sp} is the EDFA population inversion factor, h is the Planck's constant, f the central frequency and G_{EDFA} is the amplifier gain. The proposed device is possible to operate for any combination of λ label values. In order to simplify the simulation process, the ASK/DPSK signal is initially placed at 1572.1nm and in each node, the λ label is periodically converted from 1569.7nm to 1572.1nm. Specifically, the source transmits an orthogonally modulated packet at 1572.1nm. Hence, for the nodes with even number, the incoming signal lies at 1572.1nm, and the pump lies at 1569.7nm. The depleted pump of each of these nodes is forwarded through the fiber span to the next odd-numbered node, where it plays the role of the signal in the parametric swapping process. Thus, for the nodes with odd number, the pump lies at 1572.1nm and the signal lies at 1569.7nm. For the first case, the pump power in terms of the input signal power has been already depicted in fig. 4 (solid line). In this line, the points where the signal mark and space level must be placed for the preservation of the initial extinction ratio are also shown. The power characteristics which correspond to both pump-signal wavelength settings are illustrated in fig. 7. For both swapper configurations, the initial pump power is equal to P_P=300mW. It is worth-mentioning that the initial payload shape is inverted at the even-numbered nodes and restored at the odd-numbered nodes.

The detrimental effect of PMD has been taken into account in the numerical model of fiber propagation in SMFs and DCFs. The high bitrate payload is unavoidably affected by this deleterious effect, and thus a complete transmission model should include it. The PMD effect has been simulated based on the well-known coarse step method [Marcuse et. al. (1997)] and assuming a typical PMD coefficient equal to $D_{PMD}=0.2ps/Km^{1/2}$. The inclusion of PMD introduces polarization variations which affect the performance of the polarization-dependent FOPA. Specifically, the FOPA requires that both waves (signal and pump) have identical state of polarization (SOP) for the maximization of the parametric interaction. For this reason, a polarization tracking device is considered before each node. This device is numerically approached by calculating the Stokes parameters of the incoming signal, and then adjusting the SOP of the polarized part to be parallel with that of the pump participating in the parametric process. Due to the stochastic nature of PMD, a number of 300 different numerical realizations of the whole transmission system have been carried out. The transmission system consists of five nodes, with the three intermediate nodes performing the proposed label swapping technique. At each node, the *Q*-factor of the detected payload and label is calculated after being transmitted in the fiber span. In the same figure, the *Q*-factor performance of both modulation formats in the case that the intermediate nodes do not perform any kind of signal processing, is also given. In the latter case the signal is transmitted over the fiber without being affected by the intermediate nodes. The comparison between the results extracted for the two cases provides the possibility to characterize the influence of the swapping process on the transmission performance of the ASK/DPSK packet. The *Q*-factor performance for both modulation formats corresponding to either of the two cases is illustrated in fig. 8(a). According to the figure, many interesting observations can be made. First, the payload performance degrades rapidly in terms of distance compared to the label performance. This behavior originates from the fact that the 40Gb/s payload is much more sensitive in transmission impairments than the 2.5Gb/s label. The payload performance is degraded by the parametric swapping process, as the detrimental SPM/XPM effect and the excess pump noise effect induce noisy fluctuations in the intensity modulation. Their impact justifies why the *Q*-factor is lower in the case that label swapping is performed. However, after four hops with 60Km distance and three adjacent nodes performing label swapping, the *Q*-factor is equal to 5.6, close to the limit of acceptable performance ($Q > 6$). The DPSK label quality is also impaired by the swapping process. While in the case that no intermediate swapping is performed, the label Q-factor seems to be constant over the transmission distance, in the case that the parametric swapper is utilized, its value gradually reduces, resulting in a 2 units difference at the final node. The label *Q*-factor reduction is mainly attributed to the fact that the extinction ratio slightly increases due to the parametric swapping process, thus disturbing the DPSK decoding. This ER increase is clearly shown in fig. 8(b). The XPM/SPM effects contribute in a less extent to the quality degradation. The eye-diagrams of both payload and label at the receivers of the second node and the last node are depicted in fig. 9.

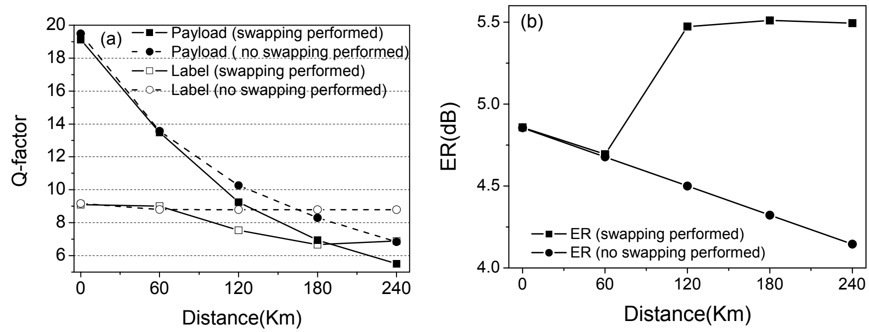

Figure 8. *Q-factor performance for both payload and label (a) and the payload extinction ratio (b) in terms of transmission distance. The squares correspond to the case that the intermediate nodes perform swapping, while the circles correspond to the case that no processing is applied at the intermediate stages.*

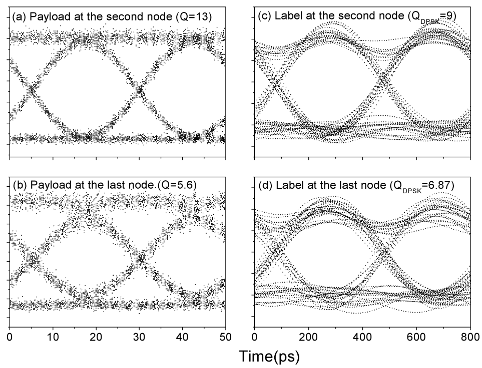

Figure 9. *Eye diagrams of both payload and label at the receiver side of the second (a), (b) and the last node (c), (d).*

According to the figure, the degradation of the payload is more evident. However, both modulation formats are quite acceptably detected at the last node, showing that the proposed method offers the possibility of cascading five 60Km-spaced nodes.

4. Conclusions

A novel all-optical label swapping technique based on the orthogonal ASK/DPSK packet modulation has been presented. The specific technique takes advantage of the pump depletion effect in fiber optic parametric amplifiers. It has been shown that the pump wave at the output of the FOPA is an inverse replica of the input ASK payload, carrying also a new DPSK label, while the old λ and DPSK labels are removed by optical filtering. The robustness of the parametric swapper is slightly impaired by the XPM/SPM effects and the excess pump noise. The pump phase modulation can be also a detrimental effect for large pump-signal wavelength detuning. The numerical analysis carried out has shown that the parametric device is a promising swapper for 40Gb/s ASK signals, providing almost error-free detection for both ASK payload and DPSK label in a transmission system consisting of five 60Km-spaced nodes, where the three intermediate nodes perform label swapping. The operation of the above technique can be easily extended to higher bit rates thanks to the ultra-fast fiber nonlinearity.

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