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An Optical Labeling Scheme with Novel DPSK/PPM Orthogonal Modulation *

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A novel differential-phase-shift-keying (DPSK)/pulse-position-modulation (PPM) orthogonal modulation is proposed for optical labeling applications, with PPM data as the high-speed payload and DPSK signal as the optical label. The systematic setup for the proposed scheme and research on bit-error rate is presented. The results show that at the bit-error rate of 10^{-9}, the power penalties for 70 km fiber transmission are in the range of 1–3 dB to DPSK label and 5–6 dB to PPM payload in our simulation system. This is under the condition that the large extinction ratio of 18–19 dB is used for the intensity modulators of the PPM payload, with a well received DPSK label. Thus the feasibility of the proposed scheme for all optical transmission networks is clearly verified.

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With the rapid development of optical fiber communication, all kinds of technologies and devices are emerging for optical transmitting such as fiber gratings and fiber lasers.[1−3] For optical networking, Optical label switching (OLS) technology, which uses encapsulated optical label containing information for packet routing and forwarding, has been considered as an attractive means of implementing high speed packet transmission in an all-optical domain. Different labeling approaches thereby were aroused to actualize the OLS network. Since the orthogonal modulation technique has been proposed,[4] many new schemes have been studied and demonstrated for the purpose of reaching higher transmission rate and achieving better spectral efficiency. These schemes basically involve two independent modulation formats representing either high-speed payload for various users and Internet services, or label information for payload routing and forwarding, while the two formats are orthogonally added on the same optical carrier and separated with respective detectors at user end. Some of the schemes most commonly used include frequency shift keying (FSK)/amplitude shift keying (ASK)[5] and differential phase shift keying (DPSK)/ASK,[6,7] together with others such as polarization-shift keying (PolSK)/ASK[8] and the newly proposed DPSK/FSK.[9]

In recent years, the DPSK format has been of particular research interest due to its 3 dB lower optical signal-to-noise ratio (OSNR) requirement to reach a given bit-error rate (BER) compared with ASK format, when balanced detection is employed,[10] and some other merits such as smaller bandwidth compared to FSK and the ability to reduce fiber nonlinearity which induces distortions like cross-phase-modulation (XPM).[11] Meanwhile, pulse position modulation (PPM) was introduced as an innovative format to carry optical payload and combined with FSK label, in order to solve the extinction ratio (ER) dilemma in traditional FSK/ASK systems.[12] In this Letter we propose the DPSK/PPM scheme as a novel orthogonal modulation for optical labeling application, investigating the feasibility and system performance through simulation. We elaborate on the generation and detecting mechanism of the combined signal, with analysis on BER performance versus optical power as well. We study system key parameters by comparing different ER values and their influence on receiver sensitivity. Simulation results verify that the proposed system is able to provide reasonable transmission performance, and the acceptable ER can be large for the good of payload detection, without deteriorating the label.

Pulse position modulation (PPM) has long since attracted considerable attention with respect to implementation over optical fiber channels.[12,13] In the PPM format, the information is represented using different positions of short pulses in each bit period. In the case of binary transmission, the pulse in the first half of a bit period denotes ‘1’ and the pulse in the second half denotes ‘0’, as shown in Fig. 1.

PPM has usually been used to exchange bandwidth for receiver sensitivity.[13] The short pulses with constant power benefit detection, and the fact that every time slot contains one optical pulse definitely facilitates the clock recovery process, compared with the case in traditional ASK systems where the possible long sequence of 1’s or 0’s makes it difficult for synchronization. Meanwhile, as an amplitude modulation format, PPM has kept the advantage of easy receiving as direct detection can be employed. Since data

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information is conveyed only by the temporal placement of pulses, the PPM signal can be combined with phase, frequency or polarization modulated formats for extensive use.

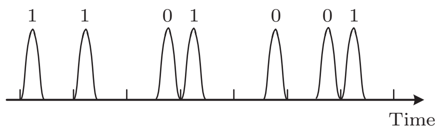

Fig. 1. PPM format.

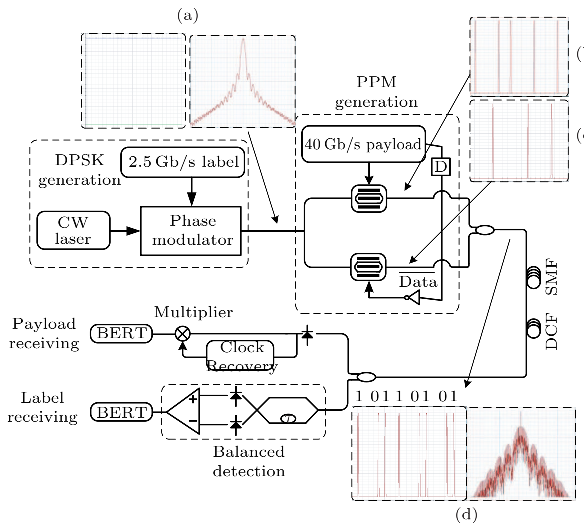

Fig. 2. DPSK/PPM scheme. Insets: (a) DPSK signal and spectrum, (b) pulse pattern "data", (c) complementary pulse pattern "$\overline{\text{data}}$", (d) DPSK/PPM signal pattern and spectrum.

We have established a systematic setup for the proposed DPSK/PPM scheme, as shown in Fig. 2. The system comprises two signal generation modules, a transmission span consists of 50 km single mode fiber (SMF) and 20 km dispersion compensation fiber (DCF), and respective receivers for DPSK and PPM. The cw laser is operated at 193.1 THz, with 1 MHz linewidth. A 2.5 Gb/s pattern generator generates $2^{23}-1$ pseudo-random bit sequence (PRBS) with a differentially encoded non-return-to-zero (NRZ) data stream, and drives a phase modulator biased at transmission null and twice the switching voltage. This provides a near-ideal π phase modulation that is critical in obtaining maximum receiver sensitivity. The phase modulator is driven in push-pull configuration to minimize chirp.[11] Then the DPSK modulated label is formed and forwarded to the PPM generation, which uses the same approach as in Ref. [12] as two 40 Gb/s complementary signals with PRBS length $2^{23}-1$. At each branch a Mach–Zehnder modulator (MZM) is used for intensity modulation, and a delay module is set in one of the branches. Then the signals are subsequently combined to form pulse-position modulated data. The pulse train generation here is accomplished by using the return-to-zero (RZ) pulses with low duty cycle, where the duty cycle is defined as the ratio between the pulse width T_p and the total bit interval T_b (duty cycle is T_p/T_b). The pulse width is 2 ps, and the time delay D in the $\overline{\text{data}}$ branch is set to 12.5 ps, which is half the payload bit period at 40 Gb/s. After that, the combined DPSK/PPM signal is sent to fiber transmission span, which consists of 50 km single mode fiber (SMF) with 0.19 dB/km attenuation, 0.08 ps$\cdot$nm^{-2}km^{-1} dispersion slope and D = 16 ps$\cdot$nm^{-1}km^{-1}, and 20 km dispersion compensation fiber (DCF) with 0.23dB/km attenuation, -0.28 ps$\cdot$nm^{-2}km^{-1} dispersion slope and D = -40 ps$\cdot$nm^{-1}km^{-1}. The insets in Fig. 2 depict the signal patterns and optical spectrums during DPSK/PPM combined modulation formation.

At the receiver end, the PPM payload and DPSK label are detected separately. In a real system the optical PPM signal can be decoded with an optical switch by selecting pulses at different positions, or to be differently polarized at PPM generation module with polarization control and de-polarized into intensity information at the receiver end.[12] However, high speed operation for 40 Gb/s all optical switches is difficult to implement. When electro-optical switches or micro electro mechanical systems (MEMS) are used, there are also serious problems like insertion loss and complicated setup, and the cost is considerable. Especially in wavelength division multiplexing (WDM) systems with multi-channels and multi-users, the system expanses will be largely expanded. On the other hand, proper polarization is unstable and hard to control. Here we take advantage of the easy timing extraction of PPM signal since a pulse is contained in every bit period, and use a clock recovery module to extract the 40 Gb/s clock signal from PPM data stream. The regenerated clock is in RZ form, and is electrically multiplied with the optical-electrical (OE) converted PPM stream. The pulse in the first half of each bit period denoting 1 is therefore kept while the pulse in the second half representing 0 is abandoned, reproducing the original bit sequence. The decoding process is demonstrated in Fig. 3.

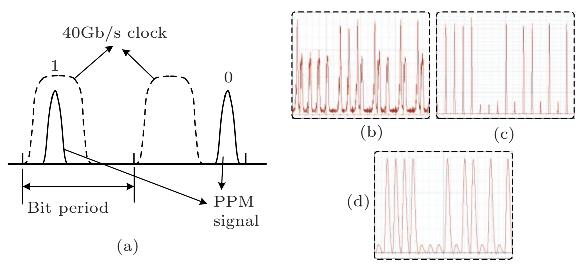

Fig. 3. PPM detection by 40 Gb/s RZ clock: (a) detection principle, (b) electrical PPM signal, (c) signal at multiplier output, and (d) after a low-pass-filter.

For DPSK demodulation, balanced detection is worth mentioning. The DPSK format carries information in optical phase changes between bits, and uses the phase of the preceding bit as a relative phase reference for demodulation due to the lack of an absolute phase reference.[11] The balanced detector in the system setup is explicitly depicted in Fig. 4. It is mainly composed of a Mach–Zehnder delay-interferometer (MZDI) with delay τ equal to the bit period (being 0.4 ns here for the 2.5 Gb/s label), a photodiode and a low-pass filter (LPF) at each branch from the MZDI output, and an electrical subtractor. In the one-bit MZDI, the input signal is first split into two branches, and interference occurs between two adjacent bits at the output port which leads to either the presence or the absence of optical power. The corresponding spectra in Fig. 4 reveal the constructive and destructive interference between the bits. The two output signals are carrying identical but logically conjugated information and either can be detected by themselves through a single detection scheme. However the single-ended receiver compares a single noisy signal against a deterministic (non-noisy) threshold to retrieve the digital data, while the balanced receiving essentially compares two noisy signals against each other and results in a 3 dB sensitivity improvement.[11]

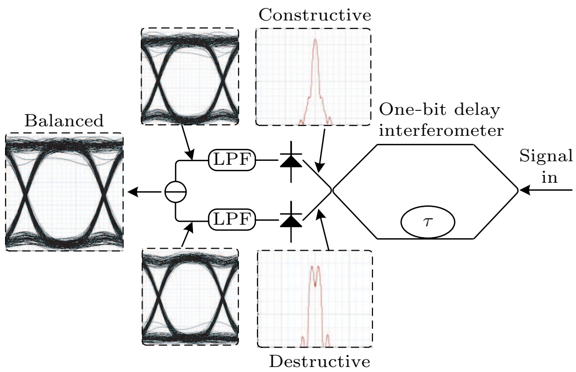

Fig. 4. Balanced detection for DPSK receiving.

In an orthogonal modulation system such as DPSK/ASK or FSK/ASK, the intensity modulated data (ASK) suffers from fiber nonlinearity which results in interference to the phase or frequency modulation and, in turn, the fiber chromatic dispersion will cause a phase-to-amplitude modulation conversion which certainly degrades the intensity modulation.[6,7] One of the major parameters affected by this interference is the extinction ratio (ER) of the intensity modulator, defined as the ratio between transmitted optical power of symbol '1' and that of symbol '0'. The difficulty in choosing an appropriate ER for orthogonal modulation has existed for a long time, and is mainly because the intensity modulation (IM) demands a high ER for better receiving while the phase and frequency modulation suffers from it due to the constant transmitted power in these formats. More specifically, the intensity modulation uses different optical power levels to represent 1 and 0 symbols, so a high ER is required to guarantee that the receiver successfully distinguishes 1 and 0 signals apart. However, DPSK or FSK format carries information in phase or frequency domain, and the same signal power is sent for 0's and 1's. Thus the reduced signal power of IM 0's causes receiving degradation of DPSK and FSK. Especially when long strings of IM 0's are sent, the high ER essential for IM leads to the fact that the transmitted signal power is always at a low level, which causes losing DPSK or FSK labeled information. Therefore, the ER value has to be decided on a compromise. Typical ER values in DPSK/ASK systems are about 3–4 dB.[6,7] With dc-null coding technique the acceptable ER can be increased up to 12 dB.[7]

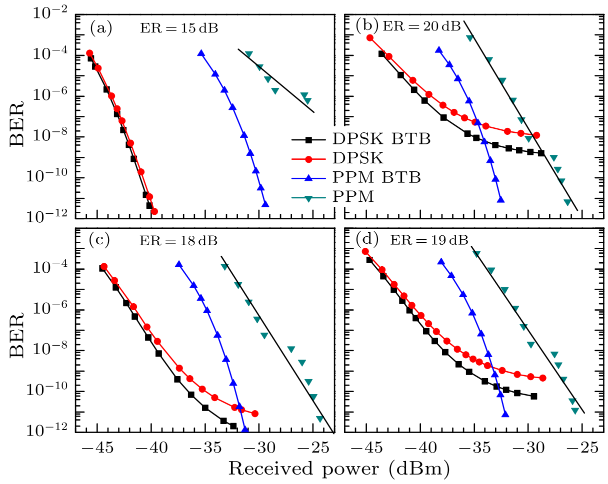

Fig. 5. Receiver power versus BER under different ER values: (a) and (b) inappropriate ER values, (c) and (d) adjusted ER values.

Since the importance of IM ER is acknowledged, we discuss the BER performance of label and payload under different ER values in Fig. 5. Both back-to-back (BTB) transmission and fiber transmission are tested. From Figs. 5(a) and 5(b) it is obvious that the ER plays a vital part in determining the receiver sensitivity. Although large ER (larger than 15 dB) can be employed in the system, inappropriate ER values severely deteriorate either label or payload performance and therefore affect the comprehensive system as a whole. This can be seen in Figs. 5(a) and 5(b) with ER = 15 dB and ER = 20 dB, respectively. For detailed analysis, Fig. 5(a) shows the case in which ER is relatively low for the system and, as can be expected, the 15 dB ER is of great benefit to the received DPSK signal for both BTB and fiber transmission but seriously degrades the PPM signal with fiber transmission as the minimum BER can only reach the level of 10^{-7}. On the contrary, when relatively large one (ER = 20 dB) is used as shown in Fig. 5(b), the PPM performance achieves a satisfactory outcome while the received DPSK is greatly distorted and can not reach 10^{-9} due to BER floor. These two figures demonstrate the extreme cases of how inappropriate ER values degrade system performance, and clearly reveal the fact that a trade-off is crucial for the proper detection of both label and payload. Hence we carefully adjusted the ER value to ensure a BER better than 10^{-9}, as can be seen in Figs. 5(c) and 5(d).

Figures 5(c) and 5(d) depict the cases when ER are 18 dB and 19 dB, respectively. In Fig. 5(c), the DPSK label with fiber transmission has a power penalty of about 1 dB at the BER of 10^{-9}, compared with BTB measurement. The PPM payload has a relatively large penalty of 6 dB. In Fig. 5(d) the power penalty is around 3 dB for the label and 5 dB for the payload. In spite of the performance better than previous ER cases, additional improvement is still needed. We choose the value of ER = 18.5 dB to make further amelioration on the imperfection, as shown in Fig. 6.

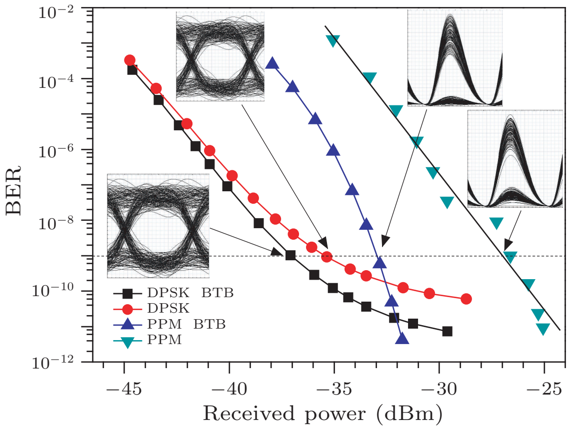

Fig. 6. Optimized ER = 18.5 dB. Eye diagrams are under the BER of 10^{-9}.

The eye diagrams in Fig. 6 indicate good receiving since large eye opening is obtained, with ER = 18.5 dB. The power penalty at BER of 10^{-9} is approximately 2 dB of DPSK label and 5 dB of PPM payload. It can be noticed that the power penalty induced by fiber transmission is much more serious in the PPM payload than that of DPSK label, and this is also the case that other ER values are used, as can be seen in Fig. 5. The reason for this is because the DPSK format modulates the optical phase in order to enhance robustness to dispersion and nonlinearities, while the short pulses under high-speed PPM modulation is easily affected by fiber chromatic dispersion. This can also be proofed by comparing the two eye diagrams of PPM in Fig. 6, where the eye of PPM signal with fiber transmission is distorted. Another critical thing in Figs. 5 and 6 is that over all speaking, the label performance should be better or at least not worse than the payload in order to ensure correct routing, which is of great importance in an optical transmitting network.

The ER value of 18.5 dB is chosen as the optimized parameter for the proposed DPSK/PPM system in our simulation. This value exhibits the great advantage of PPM over conventional ASK from one aspect, as we have pointed out that the maximum ER in DPSK/ASK can only reach 12 dB even by introducing line coding. The reason for this rests largely in the fact that PPM brings in optical pulses of constant amplitude and duration into every bit period, assuring equalized energy. Thus less damage appears in the DPSK detection when long sequences of IM 0's occur and the restriction on ER is thereby released, while with conventional ASK the DPSK signal would experience a long period of low power and suffers from poor detecting. Another benefit of PPM comes from the decoding process (determining which one of the two subintervals contains the pulse), which is performed by picking out 1 symbols with clock signal and therefore the noise in 0 symbols is greatly suppressed, while ASK signal goes directly to threshold tests with noise. In fact, it is unsurprising that large ER can be used since the ER in an FSK/PPM scheme can be larger than 15 dB.[12] Thus the PPM format shows itself as a promising candidate for carrying high-speed payload instead of ASK.

In conclusion, we have proposed a DPSK/PPM orthogonal modulation scheme for next-generation all optical label switching networks. Simulation setup has been organized, as we generated DPSK label with a phase modulator and used two complementary data to realize PPM payload. Detection details of both label and payload have been provided and systematic analysis has been conducted. The importance of crosstalk issue between label and the orthogonally modulated payload is discussed and given great attention, as we compared the system performance under several extinction ratio values. The results prove that in the DPSK/PPM scheme the ER of intensity modulators can be increased up to 18–19 dB compared to the 3–4 dB in the conventional DPSK/ASK, validating the significant advantage of PPM format over ASK. The discussion in this study has shown that with PPM modulated ultra-short pulses for data payload and DPSK modulated optical label for payload forwarding, reliable transmission can be achieved. Potential issues of the scheme are under further investigation, and it is envisaged that the proposed DPSK/PPM scheme will be a suitable candidate for next-generation all-optical switching networks.

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