Robust Multi-level Phase Shift Modulation in High-speed WDM Transmission

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ABSTRACT

In this paper, an overview of promising solutions for multi-level modulation formats, primarily based on phase shift keying (PSK), in optical WDM-transmission is presented and some recent results are summarized. With PSK modulation the option of multi-level signalling is offered which means that more than one bit is mapped on one transmitted symbol and thus offering bandwidth reduction for increased spectral efficiency. We investigate the performance with respect to receiver sensitivity, non-linear fibre impairments, chromatic and polarization mode dispersion. Last but not least the implementation-effort at high speed must comply with economic constraints.

Keywords: Modulation, optical communications, WDM-transmission, optical channel model

1. INTRODUCTION

The constantly growing data and internet traffic has led to a dramatic increase in demand for transmission capacity, imposing an immediate requirement for broadband telecommunications networks, that will accommodate the growing size of data files and multimedia services. Video, pictures and other broadband services have to be transported over global distances. In order to address these requirements, telecommunications networks currently widely employ wavelength division multiplexing (WDM) for efficiently utilizing the capabilities of the installed optical fiber network and offer high transmission capacity and long reach.

Therefore in future high capacity optical networks it is necessary to optimise the transmission equipment with respect to performance efficiency and cost effectiveness as well as robustness towards parameter variations. The field installation should work according to a “plug-and-play” approach. Recently, a variety of possible modulation schemes have been investigated. Among the candidates are carrier suppressed formats, partial-response line-coding, single- and vestigial-sideband-modulation and multi-level phase shift keying. These formats were developed as a replacement for the standard on-off keying intensity modulation using NRZ (non-return-to zero) or RZ (return-to-zero) pulse shapes. They should require a moderate amount of new components in an optical transmission system. Therefore it is preferred to avoid carrier synchronization for recovering the phase of the received carrier signal and most of the discussed PSK modulation formats use differential encoding at the transmitter side to achieve this goal. However with the availability of stable and low phase noise lasers and with new concepts for the synchronization requirements the full variety of modulation schemes as multilevel QAM are under discussion for future optical systems.

2. MULTILEVEL MODULATION OF OPTICAL CARRIERS

Digital modulation formats are generally characterized by a so called constellation which is a graphical representation of the real and imaginary part of the complex envelope of the modulated carrier. In optical communications we have for the representation of the modulated carrier:

$$E(t) = \mathrm{Re}\left\{ a(t) e^{j\phi(t)} \cdot e^{j\omega_c t} \right\} \tag{1}$$

where

$$A(t) = A_R(t) + jA_I(t) = a(t)e^{j\phi(t)} \tag{2}$$

is the complex envelope or equivalent base-band representation, which contains both, amplitude modulation $a(t)$ and/or phase modulation $\phi(t)$ and is a complex signal with real part A_R and imaginary part A_I. Thus the complex envelope is the signal which carries the information in the considered transmission scheme, allowing phase (or frequency) as well as amplitude modulation. The optical carrier frequency is determined by the laser wavelength and is denoted as ω_c.

In digital transmission we transmit bits *b* with a bit rate of $r = 1/T_b$ bps, where T_b is the bit duration. In multilevel modulation several bits are collected and mapped to digital symbols which are chosen from an alphabet

$$d(k) \in \{d_0, d_1, \ldots, d_{M-1}\}, \quad M = 2^m \tag{3}$$

of *M* complex symbols at each symbol interval $T_s = mT_b$ numbered by integer *k*. For quaternary transmission with 4-level ASK (amplitude shift keying) and for QPSK (quaternary phase shift keying) we have e.g.

$d_0 = 0, \quad d_1 = 1, \quad d_2 = 2, \quad d_3 = 3$ 4 level ASK

$d_0 = 1, \quad d_1 = j, \quad d_2 = -1, \quad d_3 = -j$ quaternary PSK

In fig.1 we give some examples for useful constellations, which is the graphical representation of the complex symbols in the complex plane.

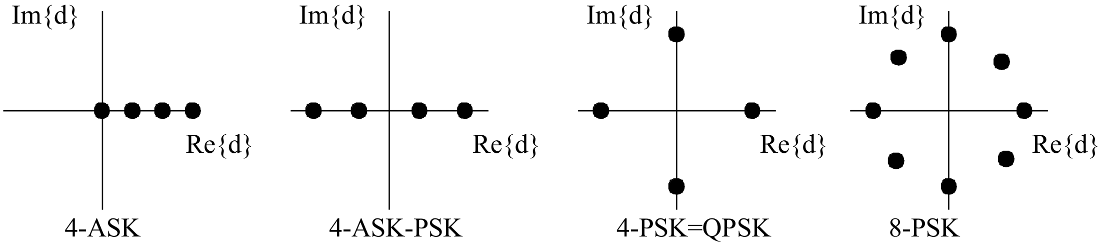

Fig. 1: Some example constellations for multilevel modulation formats

Using the symbols *d*, we rewrite (2) as

$$A(t) = \sum_k d(k) \cdot h(t - kT_s) \tag{4}$$

here $h(t)$ is the pulse shape given at the transmitter. Together with (1) we find the quadrature representation of a general linear modulation format

$$E(t) = \left[\sum_k d_R(k)h(t-kT_s)\right]\cos(\omega_c t) - \left[\sum_k d_I(k)h(t-kT_s)\right]\sin(\omega_c t) \tag{5}$$

which describes two symbol streams that are modulated onto orthogonal carriers.

A Mach-Zehnder interferometer structure may be used as device for producing nearly arbitrary phase and/or amplitude modulation onto an optical carrier. If we consider the usual two arm structure we find for the output complex envelope:

$$E_{out}(t) = E_{in}(t)\frac{1}{2}\left[e^{-j\Delta\phi_1} + e^{-j\Delta\phi_2}\right] = E_{in}(t)\cdot H \tag{6}$$

where $\Delta\phi_1$ and $\Delta\phi_2$ is proportional to the driving voltage in the upper and lower arm respectively and *H* is a complex transmission factor which is graphically represented as a phasor diagram in fig. 2. Thus it is clear that by a proper choice of the two driving voltages a variety of constellations can be achieved.

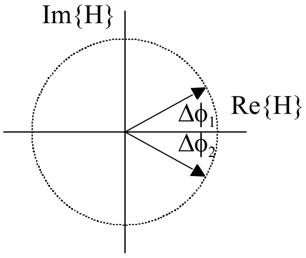

Fig. 2: Phasor diagram of Mach-Zehnder modulator, showing that by proper choice of the phase shift in each arm, arbitrary amplitude- and phase-modulation is achievable

3. DISCUSSION OF MULTILEVEL MODULATION FORMATS

4-ASK

A natural extension from 2-level to 4-level signaling in optical transmission is the 4-ASK format, where $m=2$ bits each are encoded in $M=4$ real valued symbols (see fig. 1) [6]-[8]. The general principle can be extended to a higher number of levels, resulting in M-ASK. With increasing number of signaling levels the bandwidth of the optical signal reduces by a factor of

$$FB_M = m = ld(M) \tag{7}$$

This advantage in bandwidth occupancy is however related to a penalty in receiver sensitivity according to

$$FP_M = \left(\frac{M-1}{\sqrt{ld(M)}}\right) = \left(\frac{2^m - 1}{\sqrt{m}}\right) \tag{8}$$

Thus for a large number of levels the power penalty is much more severe compared to the gain in bandwidth. This probably excludes the case M>4 from practical considerations.

An implementation principle of an 4-ASK transmitter is shown in fig. 3. Due to the signal dependent noise in optical communication, the level spacing should increase at the higher amplitude levels. At the receiver side three comparators are necessary, which produce two bitstreams (even and odd bits) after a decoding logic.

In summary the real valued multilevel ASK format requires a moderate increase in complexity. On the other hand the expected benefit in bandwidth efficiency is overcompensated by an increased noise sensitivity with increased levels. Compared to e.g. duobinary transmission, where a significant bandwidth reduction comes without receiver sensitivity penalty, the advantage is limited.

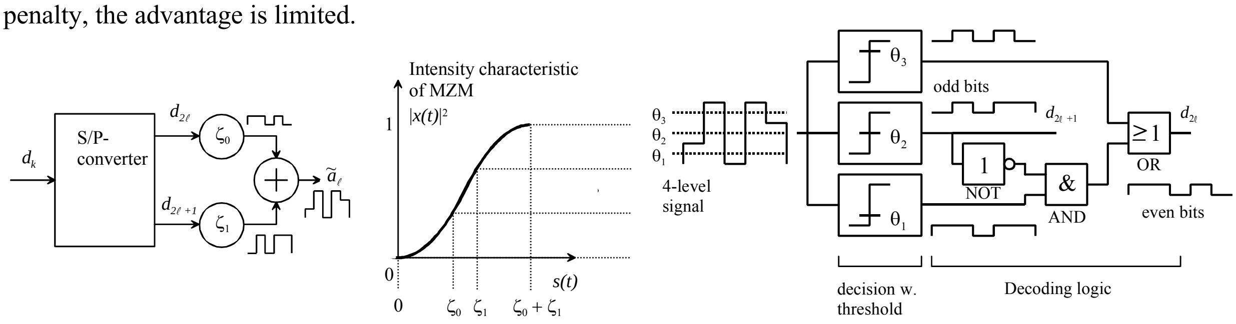

Fig. 3: Principle of optical 4-ASK transmission, left transmitter, right receiver

Differential Quaternary Phase Shift Keying (DQPSK)

Binary PSK with differential encoding has recently used not only in various laboratory experiments but also in record transmission experiments [1]-[5]. Most experiments use an additional clock driven MZM as a pulse carver in order to produce the RZ-DPSK rather than the NRZ-DPSK format. The major advantage over on-off keying (Amplitude Shift Keying, ASK) is the improved receiver sensitivity and the improved tolerance against nonlinear fiber impairments [4]. There is some additional implementation effort, as a differential encoder and a high voltage MZM driver amplifier is required at the transmitter side and a dual pin-diode configuration in a balanced detector and a differential demodulator usually implemented as Mach-Zehnder delay interferometer is necessary at the receiver. Moreover the spectral efficiency and the dispersion tolerance is basically not improved in comparison to conventional ASK.

The constellation of binary PSK has the two values +1 and –1 on the real axis (see fig. 1). If we use two different amplitude levels we end up with a 4-ASK-PSK format with a real valued constellation which was investigated recently e.g. in [9]-[11].

The DQPSK-format [12]-[26] is a multilevel format with a complex constellation (see fig. 1). The functional block diagram is shown in fig. 4. Again we can use RZ (including pulse carving MZM) or NRZ pulse shapes. According to (5), we need an optical carrier in quadrature (i.e. a sin and a cos output) where the real and the imaginary part of the symbols have to be modulated on. For our 4 symbol constellation this means that every other incoming bit is shifted to one of the quadrature carriers. This parallel structure is e.g. realized in [12]. We have implemented the serial transmitter in fig.4 [13]. Here we first produce a DPSK signal with the real data stream, resulting in the values {+1,-1} in the constellation. The imaginary data stream produces a phase swing of 90° and therefore the imaginary points {+j,-j} in the constellation. Thus the exact quadrature carrier is avoided for simplicity of the transmitter.

In both implementations the data stream is split up into two streams with half the speed each. If we consider a given data rate, e.g. 40Gb/s, we transmit with only half of the bandwidth and equipment with only half of the speed requirements compared to a binary transmission is needed.

For differential detection, at the receiver side a parallel delay interferometer demodulator with balanced detection is required. In the upper branch the real part and in the lower part the imaginary part of the data stream is detected. Both streams can be multiplexed together to deliver the double rate data signal.

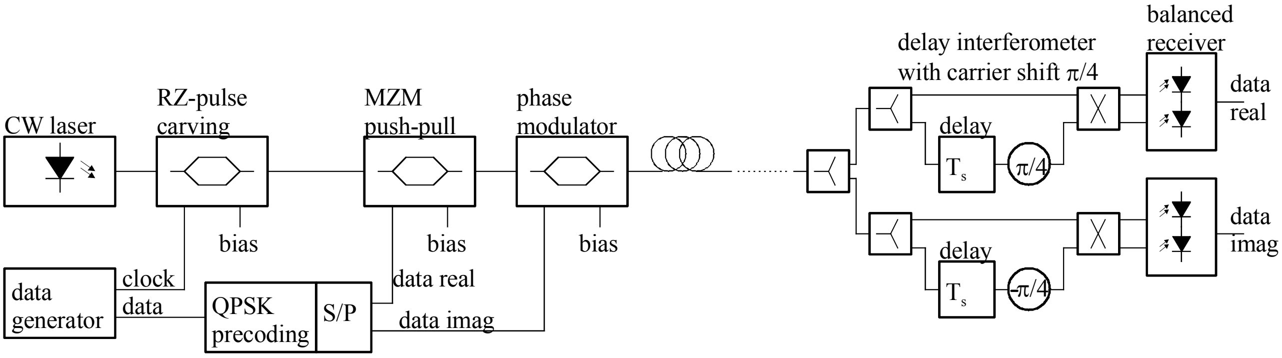

Fig. 4: DQPSK transmission using a serial transmitter configuration and double balanced detection

Fig. 5 shows the measured BER values for RZ-DQPSK in comparison to RZ-DPSK for both single ended and balanced reception, respectively. The measured eye diagrams for the imaginary channel of RZ-DQPSK single ended and balanced detection are given in fig. 6. To measure these eye diagrams the received power at the preamplifier at the receiving end was set to –10dBm to reduce the noise sufficiently.

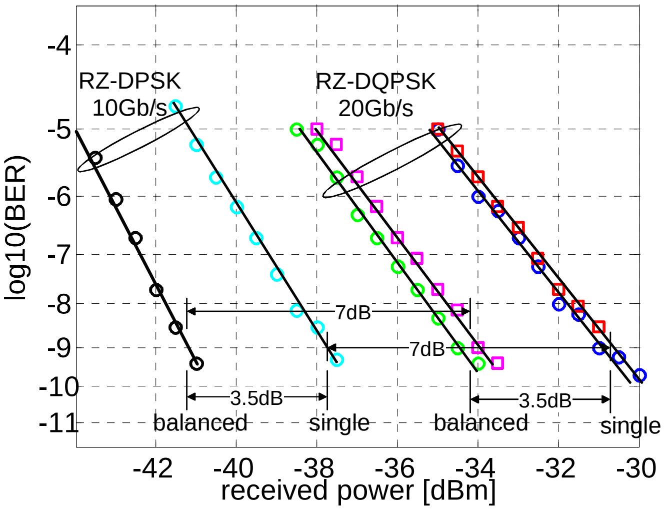

Fig. 5: Measured BER values for RZ-DPSK format at 10Gb/s and RZ-DQPSK at 20Gb/s (real (○) and imaginary (□) component) for balanced and single ended-detection, respectively

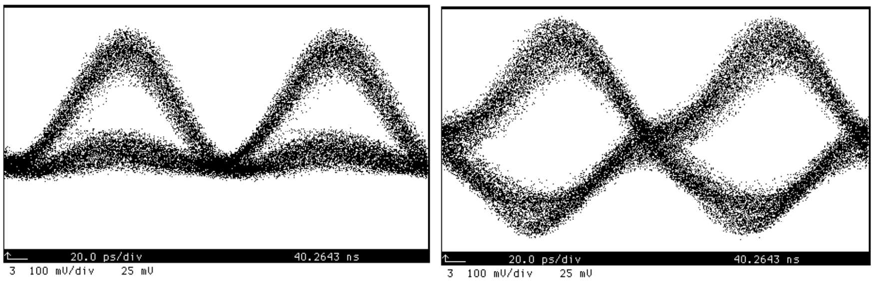

Fig. 6: Measured eye diagrams for imaginary channel of RZ-DQPSK at 20Gb/s for single ended detection (left) and balanced (right)

For both RZ-DPSK and RZ-DQPSK transmission, the balanced detector performs 3.5dB better compared to the single-ended detector. 0.5dB are attributed to the better thermal noise properties of the balanced detector, which is confirmed by the fact, that for high BERs where the thermal noise is completely negligible compared to the ASE noise, there is only a difference of 3dB. This is known to be equal to the maximum performance improvement achievable for balanced detection with sufficiently narrowband filtering in front of the MZI.

Moreover, if we compare RZ-DPSK and RZ-DQPSK, for both detection strategies (i.e. balanced/single-ended) RZ-DQPSK (20Gb/s) performs approximately 7dB worse than RZ-DPSK (10Gb/s). This is explained as follows: Taking the step from binary to quaternary transmission (doubling the transmission bit rate) using the same signal power, the minimum distance between the transmitted symbols in the complex plane is reduced by a factor of $\sqrt{2}$. Thus, to achieve the same minimum symbol distance for DQPSK the power has to be increased by 3dB. In addition autocorrelation (differential) detection compared to coherent detection induces an additional penalty. For binary DPSK, this additional penalty is negligible (<0.5dB) for good values of the BER, while for quaternary transmission a penalty of approximately 2dB is obtained as can be shown theoretically [31]. As a result, a sensitivity difference of at least 5dB is expected. We measure 7dB and attribute the remaining difference of 2dB to the accumulation of several minor impairments. For example, for the transmitter phase modulator the amplitude of the driving voltage must be set carefully to ensure exact orthogonality of real and imaginary part to avoid ISI. In the same way, for the receiver MZI any derivation from the phase shift of +45° and –45° introduces ISI as well. It should be considered however, that with the transition from RZ-DPSK towards RZ-DQPSK the data rate doubles.

Offset DQPSK

In [25] an implementation for Offset-DQPSK (O-DQPSK) is proposed. In contrast to DQPSK, which requires detection on the symbol rate, the demodulation of O-DQPSK can be achieved on the bit rate. Thus, this concept allows to detect the O-DQPSK signal with only one set of Mach-Zehnder delay interferometer and balanced photo-detector. Also O-DQPSK and DQPSK offer the same improved spectral efficiency. O-DQPSK has applications e.g. in transmission over the nonlinear satellite channel because it exhibits smooth phase transitions and avoids 180° phase jumps. It is therefore worth to investigate this format in the optical environment. An experimental verification at 10Gb/s was conducted. Even though the experimental setup exhibits fundamental stability problems that can only be overcome by a currently not available integrated solution, first results are shown and compared with the corresponding simulation results.

An optical 40Gb/s O-DQPSK signal can be generated by two binary RZ-DPSK signals operated at half the bit rate (20Gb/s) which are merged by a 3dB coupler with a delay of one bit duration T_B (25ps) to each other (see fig. 7b). As in non-Offset-DQPSK, a carrier phase difference of $\pi/2$ has to be guaranteed between the two parallel signals. This ensures four complex symbols $(0,+/-\pi/2,\pi)$ as shown in the inset of fig. 7a). From classical communications, it is known that for Offset-DQPSK with cosine pulse shape of the binary input signals, O-DQPSK corresponds to minimum-shift keying (MSK). MSK is a binary continuous phase modulation (CPM) with a phase swing of $\pi/2$. The conventional RZ pulse shape (duty cycle of 50%) used for fiber optical transmission is a rough approximation of the cosine pulse form. As indicated by the complex signal constellation shown in the inset of fig. 7a), the phasor of the O-DQPSK signal always has the same magnitude. During one bit duration, the phase of the phasor changes by either plus or minus 90°. Thus, O-DQPSK has a pure constant back-to-back intensity and very smooth phase transitions. In contrast to DQPSK where the symbols change according to half the bit rate, for ODQSK the symbol transitions take place bit-wise.

O-DQPSK can be differentially detected on a binary level with a Mach-Zehnder delay interferometer (MZDI) incorporating a differential delay of one bit duration (25ps) in conjunction with a balanced photo detector. This is the same receiver as is used for binary 40Gb/s DPSK. Only the internal phase difference within the MZDI has to be adjusted to $-\pi/2$ [25]. It is also possible to use a differential delay of two bit durations (50ps) within the MZDI which results in small changes of the demodulated eye diagram [25]. In the following, we restrict ourselves to the MZDI incorporating one bit duration. In contrast to DQPSK detection, where two sets of balanced receivers operating at the symbol rate (20GSymb/s) are needed, this concept requires only a single one at 40Gb/s. Like for binary DPSK, the concept of O-DQPSK requires a differential binary precoder which is easier to implement than a quaternary differential precoder as required for DQPSK.

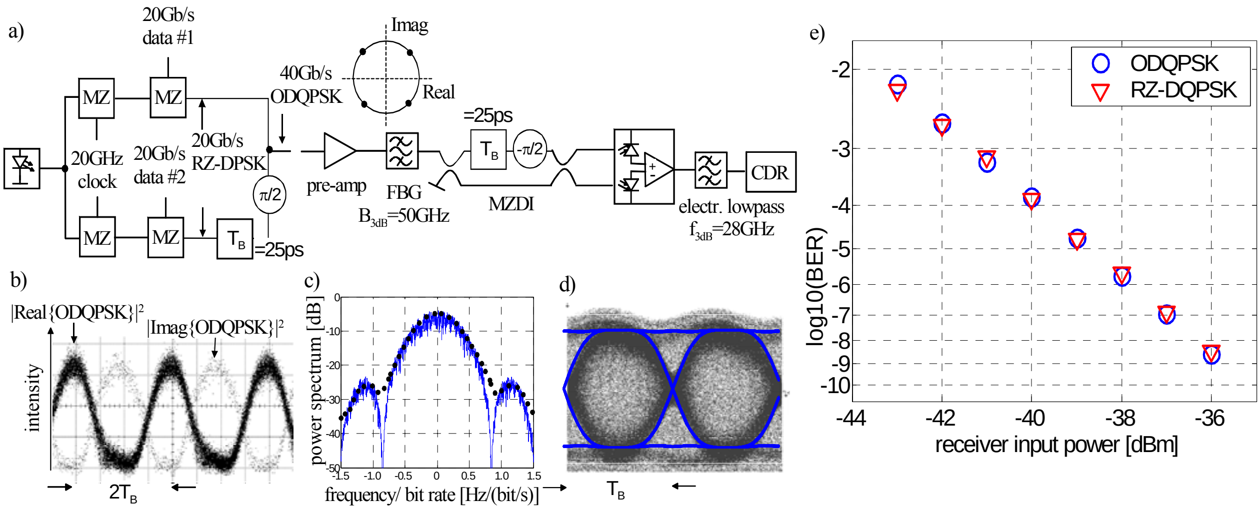

Fig. 7: a) Proposed transmitter and receiver setup to implement O-DQPSK transmission at 40Gb/s data rate; b) measured intensity of the two parallel input signals; c) measured (dotted) and simulated (solid) data spectrum; d) measured and simulated (solid) eye diagrams after the balanced receiver; e) BER values determined by 40Gb/s Monte Carlo simulations for ODPSK (circles) and RZ-DQPSK (triangle)

To investigate the impact of noise on O-DQPSK, a 40Gb/s Monte Carlo simulation with the set-up of fig. 7a) was carried out and compared to 40Gb/s RZ-DQPSK. By sophisticated programming, we were able to measure BER values down to 10^{-9}. In fig. 7e) both formats show the same receiver sensitivity of –35.6dBm at a bit error ratio of 10^{-9}. This is explained by taking into account that both formats exhibit the same minimum symbol distance. Moreover, both formats are detected by an autocorrelated (differential) reception.

To investigate the impact of fiber nonlinear effects, WDM simulations according to fig. 8a) were conducted. The WDM signal consists of 8 multiplexed 40Gb/s channels in O-DQPSK and RZ-DQPSK format, respectively, with a channel spacing of 50GHz. The optical multiplexer is modeled as an Arrayed-Waveguide Grating with first order Gaussian characteristic for each channel with the bandwidth optimized for each format (B_{3dB}=34GHz and 26GHz for O-DQPSK and RZ-DQPSK, respectively) by minimizing the combined effect of ISI and linear crosstalk. The 8-channel WDM signal (PRBS length 2^{10}-1) passes through 4 fiber spans. After the last span an additional dispersion element is provided which is designed to optimize the residual dispersion in order to obtain an optimum eye opening. After selecting the channel at 193.4THz, the O-DQPSK and RZ-DQPSK signal is detected.

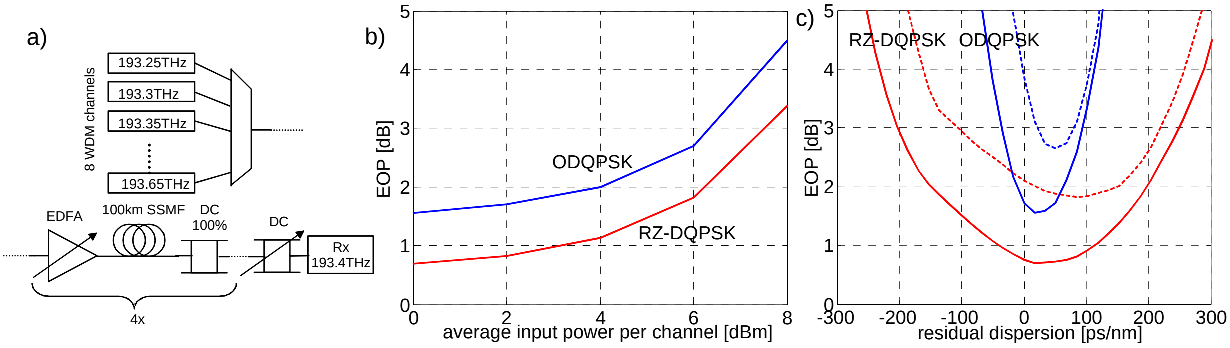

Fig. 8: a) WDM setup for 8x40Gb/s transmission over 4x100km SSMF; b) EOP of fourth channel versus average fiber input power; c) EOP as a function of residual dispersion for 0dBm and 6dBm input power

In fig. 8b) the eye opening penalty (EOP) is plotted versus the fiber input power per channel, indicating the increasing impact of fiber nonlinearities. Both formats exhibit a similar increase of the EOP with increasing input power. However, the results for low input power indicate that the impact of band limitation and linear crosstalk is stronger for O-DQPSK than for RZ-DQPSK. This can be understood by recalling that the O-DQPSK signal after detection is of NRZ pulse shape with a width of 25ps whereas RZ-DQPSK exhibits a RZ pulse shape of 50ps width. Thus, the binary NRZ type O-DQPSK signal suffers more from ISI by optical filtering with smooth gaussian filters than a quaternary RZ format.

The dispersion tolerance of O-DQPSK and RZ-DQPSK is shown in fig. 8c) after the transmission over 400km of SSMF at 0dBm and 6dBm input power, respectively. Even though both formats exhibit the same spectral width, the dispersion tolerance of RZ-DQPSK is more than three times higher than for O-DQPSK. For O-DQPSK the phase transitions that change bit-wise along the unit circle can be considered as chirp. This causes a stronger interaction with chromatic dispersion than for RZ-DQPSK where the phase transitions occur with significantly reduced power every two bits.

In summary, O-DQPSK exhibits a good receiver sensitivity and the format has a truly constant back-to-back envelope. At 0.8b/s/Hz spectral efficiency, O-DQPSK shows the same robustness towards fiber nonlinear effects as RZ-DQPSK. However, it suffers more from optical filtering which is necessary to reduce the WDM linear crosstalk. Because O-DQPSK must be considered as a binary format its dispersion tolerance cannot compete with quaternary DQPSK. On the other hand, this fact simplifies the implementation of the differential precoder and allows to detect the signal with only one differential receiver.

DQPSK with polmux

With DQPSK spectral efficiencies of 0.8b/s/Hz can be achieved in optical dense WDM systems [23]. This efficiency can be doubled by using orthogonal polarizations. In [21,26] a spectral efficiency of 1.6b/s/Hz by combining DQPSK and polarization multiplexing (PolMUX) has been shown experimentally. The combination of DQPSK and PolMUX is very promising, because the resulting, single wavelength, e.g. 40Gb/s bit rate can be transmitted at a quarter symbol rate of e.g. 10GSymbol/s. Not only does this imply that inexpensive standard 10Gb/s components can be used, but also that this 40Gb/s transmission format is more tolerant to impairments like PMD, chromatic dispersion and nonlinear effects and is comparable to standard 10Gb/s on-off keying transmission.

To measure the performance of this proposed technique, the setup shown in fig. 9 was implemented in [26]. Output from eight distributed feedback lasers (DFB) with carrier frequencies from 192.375THz to 192.550THz with a 25GHz grid were multiplexed by a 8:1 star coupler. A serial RZ-DQPSK set-up, with two MZMs for pulse carving and PSK-modulation and an PM for the phase shift of +45° and –45° was used.

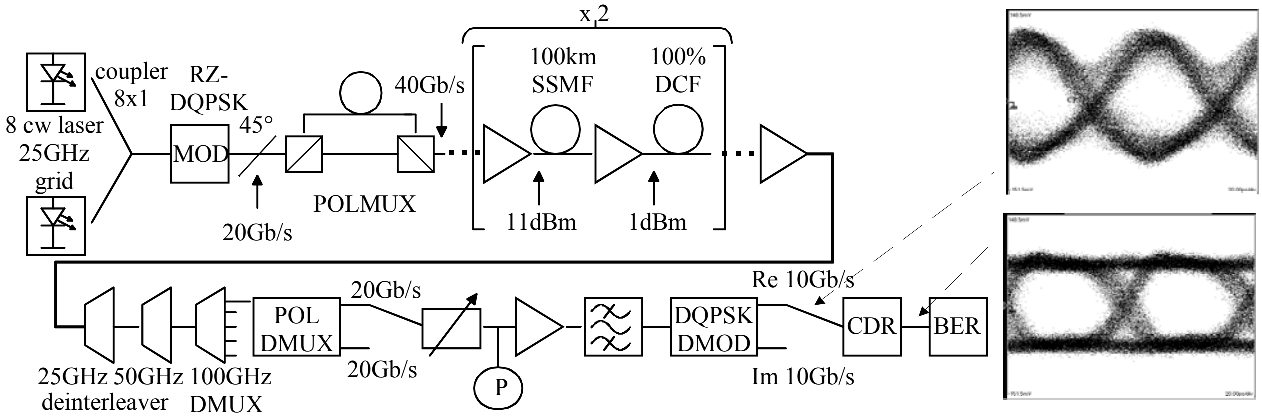

Fig. 9: Experimental setup of 4x10Gb/s with 8 wavelengths over 200km SSMF and the eye diagrams before and after CDR module

After RZ-DQPSK modulation the wavelength channels were polarization multiplexed so that each wavelength channel was comprised of two orthogonal polarization signals. A 10kHz phase modulation was added to one of the signals which was used for polarization control at the receiver. In [26] the WDM signal was transmitted over two spans. Each span consisted of 100km of SSMF fully compensated by DCF. The average fiber input power for SSMF and DCF were 11dBm and 1dBm, respectively.

At the receiver side, the WDM signal was amplified and wavelength demultiplexed by a 25GHz deinterleaver followed by a 50GHz deinterleaver and a 100GHz standard dielectric filter demultiplexer. After wavelength demultiplexing, polarization demultiplexing was performed. The real (in-phase) and imaginary (quadrature) part of the DQPSK signal were detected by a Mach-Zehnder interferometer (MZI) that incorporated a delay of one symbol duration of 100ps. The outputs from the MZI were fed to a commercially available, low-noise balanced receiver followed by an electrical 7.5GHz low-pass filter. After clock- and data recovery (CDR), the bit error rate (BER) was measured. For these measurements no differential quaternary precoder was available. While a precoder is necessary for true data transmission, for experimental purposes this problem can be bypassed by providing the BER tester with the expected data sequences (length 2^{15}-1).

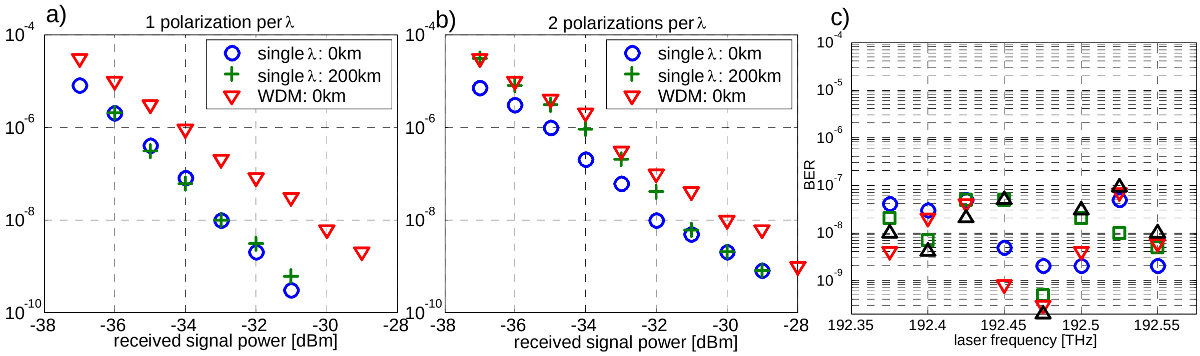

Fig. 10: a) BER versus signal power without PolMUX for one wavelength B2B (circles) and after 200km (crosses) and for WDM B2B (triangles); b) BER versus signal power with PolMUX for one wavelength B2B (circles) and after 200km (crosses) and WDM B2B (triangles); c) 4x10Gb/s with 8 wavelengths at 25GHz grid over 200km: measured BER values (uncorrected) for 8 wavelengths (4 tributaries each)

To understand the influence of the various degrading effects (linear crosstalk, non-ideal PolMUX and DQPSK implementation losses), sensitivity measurements with and without PolMUX were carried out. First, a single channel at a single wavelength without PolMUX was transmitted to investigate the performance of RZ-DQPSK at 20Gb/s back-to-back (B2B) and over 200km. In addition, WDM transmission was conducted B2B to measure the influence of linear crosstalk. The results are shown in fig. 10a). Further sensitivity measurements were made with both polarizations at 192.5THz. Results of this transmission at 4x10Gb/s at single wavelength B2B and over 200km as well as the results of a WDM B2B transmission are shown in fig 10b). Finally, the WDM signal was transmitted over 200km. For each wavelength the BER of each of the four tributaries was measured. The results are depicted in fig. 10c). BERs between 2x10^{-10} to 9x10^{-8} were measured. If standard for ward error correction is applied, we expect error free transmission.

Higher-level constellations

With quaternary (4-level) formats, a bandwidth reduction by a factor of two (without PolMUX) is associated, or equivalently the data rate can be doubled without doubling the speed requirement of the transceiver's optoelectronic and electronic components. Further enhancement of this principle would require a 16-level constellation in order to achieve the fourfold increase which is required for the next step in the SDH/Sonet hierarchy.

In wireless or high-speed wire line transmission such high level constellations are widely used [27]. In optical communications however mainly speed requirements and noise immunity make such constellations difficult to implement. However various approaches are currently under investigation. The first demonstration of a 16-ary PASK system has been published recently in [30].

Another approach is to increase the number of phase levels in M-PSK. An approach with 8-DPSK with RZ as well as with NRZ pulse shapes is investigated in [29]. The proposed transmitter and receiver design is shown in the figs. 11 and 12 below. A bandwidth reduction by a factor of 3 is achieved and thus the dispersion tolerance (at least in the linear low-power range of fiber cannel model) is expected to increase as compared to DQPSK. The improvement holds also in the nonlinear regime as is shown in fig. 13 [29]

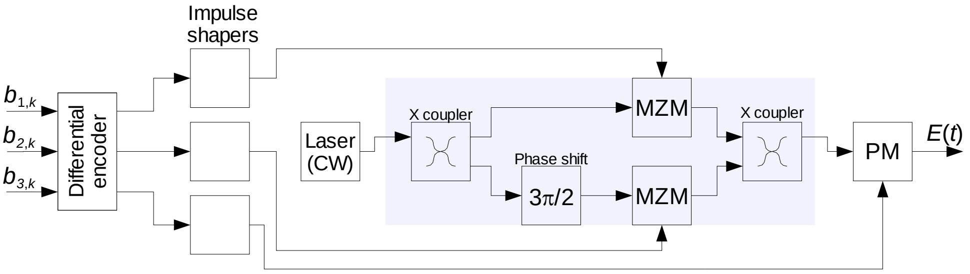

Fig. 11: 8-DPSK transmitter based on DQPSK modulator with an additional phase modulator (from[29])

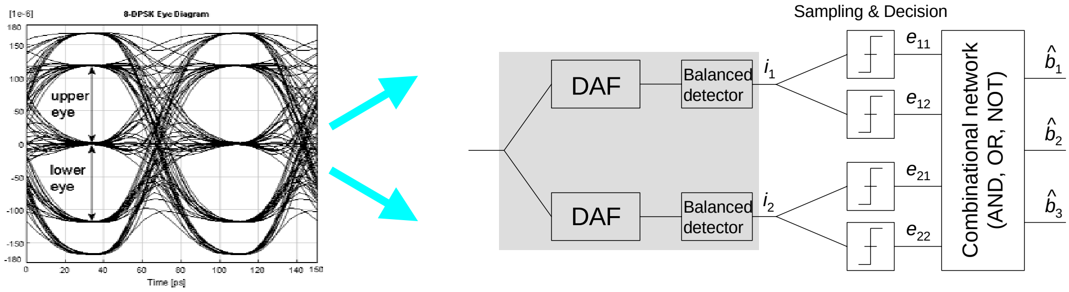

Fig 12: 8-DPSK receiver and multi-level eye diagram (from[29])

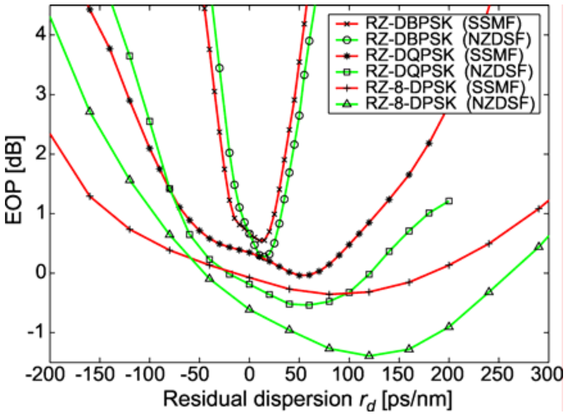

Fig. 13: Dispersion tolerance for 2-,4-, and 8-level DPSK modulation for SSMF and NZDSF in the nonlinear regime with fiber input power of 15dBm (from[29]).

4. CONCLUSIONS

We have discussed several innovative optical multi-level modulation formats. Emphasis was taken on those formats which were extensively investigated both experimentally and by simulation within the last few years. Multi-level formats are required for further increasing the spectral efficiency of fiber optic WDM transmission systems. Thus applications in future wide area as well as metropolitan area networks are expected. Due to the spectral compression there are major advantages in dispersion sensitivity achievable. PSK modulation offers also improved performance in a non-linear WDM environment and an improvement in receiver sensitivity. However additional optoelectronic devices are required and the noise performance is generally reduced with increasing number of levels. Probably the most attractive feature of multi-level modulation is the relaxed speed requirement of the associated electronics in the transceivers. Thus very high data rates through massive serial/parallel conversion, especially over short distances where noise is less destructive, could be achieved.

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