Performance of 20 Gb/s Quaternary Intensity Modulation Based on Binary or Duobinary Modulation in Two Quadratures With Unequal Amplitudes

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***Abstract*—2×10 Gb/s quaternary intensity modulation signals (4-IM) can be generated by combining two modulation signals with unequal amplitudes in quadrature phases or orthogonal polarizations. Two 10-Gb/s nonreturn-to-zero (NRZ) amplitude-shift keying (ASK) signals and a quadrature phase-shift keying (QPSK) modulator allow to generate 4-IM with the same bandwidth as an NRZ-ASK signal (QASK). Measured sensitivity at a bit error rate (BER) of 10^{-9} and chromatic dispersion (CD) tolerance are -21.6 dBm and $\sim +130$ ps/nm, respectively. Two duobinary 10-Gb/s data streams and a QPSK modulator allow to generate a 9-constellation point quaternary intensity signal (QDB), with the same bandwidth as a duobinary signal. A stub filter with frequency response dip at 5 GHz was used to generate the duobinary signals. Detected as a 4-IM, this scheme features a sensitivity and a CD tolerance of -21.2 dBm and $\sim +140$ ps/nm, respectively. By combining the two duobinary 10-Gb/s data streams with unequal amplitudes in orthogonal polarizations, a 9-constellation point quaternary intensity signal was also obtained (QPolDB). Sensitivity and CD tolerance were -20.5 dBm and $\sim +340$ ps/nm, respectively. They became -18.4 dBm and $\sim +530$ ps/nm, respectively, when the frequency response dip of the stub filter was changed to 6 GHz. A polarization and phase-insensitive direct detection receiver with a single photodiode has been used to detect all generated quaternary signals as 4-IM signals.**

***Index Terms*—Quadrature amplitude modulation (QAM), quadrature phase-shift keying (QPSK).**

I. Introduction

UPGRADING of existing dense wavelength-division-multiplexed (DWDM) systems to higher bit rates requires wider optical bandwidths per channel or advanced modulation formats with higher spectral efficiency or a combination of both [1]–[4]. Spectral efficiency is important in this context to keep long-term overall cost (including fiber infrastructure) favorable [4]. Some of the advanced modulation formats are not only useful because they are spectrally efficient but also because they have other features such as high resistance to chromatic dispersion (CD) [4], [5]. Duobinary modulation is an attractive candidate because it is spectrally efficient (~0.8 b/s/Hz), simple to implement, and also CD tolerant [6]–[12]. Higher spectral efficiency can be achieved by doubling the transmission capacity, by transmitting more information in the amplitude, phase, polarization domain, or a combination thereof [13]–[24]. So far, differential quadrature phase-shift keying (DQPSK) and/or polarization multiplex are needed to increase spectral efficiency beyond that of duobinary modulation, but considerable technical effort at the receive end is needed for their implementation (interferometer and its stabilization, polarization control, two independent photoreceivers to independently detect the two data streams), which reverberates in the cost budget [4], [18], [19], [25], [26]. On the other hand, M-ary amplitude shift keying such as quaternary (4-level) intensity modulation (4-IM) [4], [20]–[22] is easy to detect using a direct detection receiver with a single photodiode, but has a relatively large power penalty. The four levels can be discriminated in three D-flip-flops and processed to reconstruct the transmitted data. Although 4-IM doubles the transmission rate, it does not have the best spectral efficiency. The spectral efficiency for quaternary intensity modulation signals can be further improved by combining two duobinary modulation signals in two quadratures with unequal amplitudes to generate a 9-constellation point quaternary intensity modulated signal (QDB) [23]. Also, a high spectrally efficient modulation format with high CD tolerance can be obtained from a quaternary signal generated by combining two duobinary data streams with unequal amplitudes and orthogonal polarizations (QPolDB) [24].

In this paper we use an optical QPSK modulator, driven by two *binary* 10-Gb/s nonreturn to zero (NRZ) data streams with unequal amplitudes, to generate an optical 4-constellation-point 20-Gb/s quaternary intensity signal (QASK) [14]. To further increase the spectral efficiency we replace the binary by *duobinary* data streams to generate a 20-Gb/s QDB signal. Finally we used a polarization division multiplex setup with duobinary signals at 10 Gb/s to generate a 20-Gb/s QPolDB signal. Due to different amplitudes chosen for the two quadratures/polarizations, all three optical quaternary schemes allow direct detection as 4-IM signals. Their performance and CD tolerance will be discussed in the following sections.

II. Quaternary Intensity Modulation Generation

A. *Generation of a QASK Signal Using an Optical QPSK Modulator and Two 10-Gb/s NRZ-ASK Signals*

The optical QPSK modulator shown in Fig. 1 contains two Mach–Zehnder modulators (MZMs), placed in the two arms of another interferometer that forms a Mach–Zehnder

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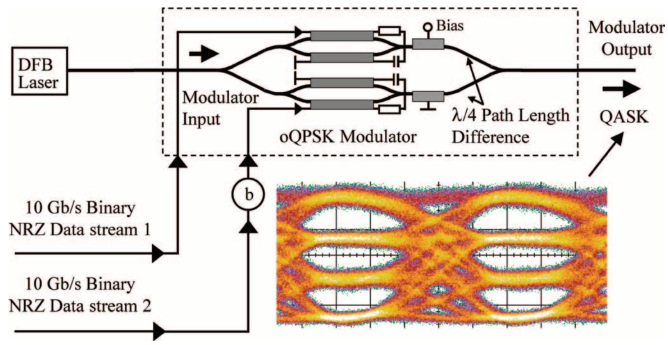

Fig. 1. Optical QASK (2×10 Gbit/s) generation in an optical QPSK modulator, and resulting quaternary intensity eye diagram for quaternary signal (electrical attenuator setting $b = 1/2$). (Color version available online at http://ieeexplore.ieee.org.)

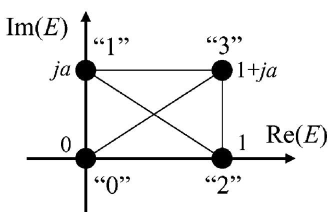

Fig. 2. Electrical field modulation constellation ($a = 1/\sqrt{2}$). A quaternary intensity modulation results from this QASK.

superstructure. The superstructure has quadrature control electrodes in both arms for phase trimming. Throughout the experiments of this paper, a fiber-pigtailed Bookham GaAs/AlGaAs DQPSK modulator [18] was used.

The two MZMs are driven by two binary electrical 10-Gb/s NRZ signals. The drive amplitude of the NRZ-ASK signal in one of the MZMs equals V_π. This generates an in-phase optical field $\mathrm{Re}(E)$ with normalized field amplitudes $\{0, +1\}$. The other MZM is driven by an NRZ-ASK signal with a $V_\pi/2$ amplitude. It generates a quadrature optical field $\mathrm{Im}(E)$ with normalized field amplitudes $\{0, +a\}$. The total output electric field is $E_o = \mathrm{Re}(E) + j\mathrm{Im}(E)$. The modulation constellation diagram is shown in Fig. 2. The generated fields are $\{0, +ja, +1, \text{and} +1 + ja\}$. The four different constellation points result in four different intensities $\{0, a^2, 1, 1 + a^2\}$. For $a = 1/\sqrt{2}$, corresponding to 6 dB of electrical attenuation $(b = 1/2)$, the intensities are equidistant and are now labeled as "0," "1," "2," "3."

Fig. 1 shows also the 4-level eye diagram of the quaternary intensity modulated signal, detected at the modulator output at 10 GBaud (20 Gb/s).

The QASK constellation represents a 4-IM and the spectrum is just as broad as for NRZ modulation although the capacity is doubled. Fig. 3 shows the heterodyned electrical spectrum of the 10 GBd optical QASK. The spectrum contains a carrier and it is equivalent to that of a 10-Gb/s NRZ-ASK signal. Suitable decoding is needed at the receiver side [20].

B. Generation of a QDB Signal Using an Optical QPSK Modulator and Two 10-Gb/s Duobinary Signals

We use the setup of Fig. 1, but replace the binary by duobinary data streams (Fig. 4). Since differential encoding was not

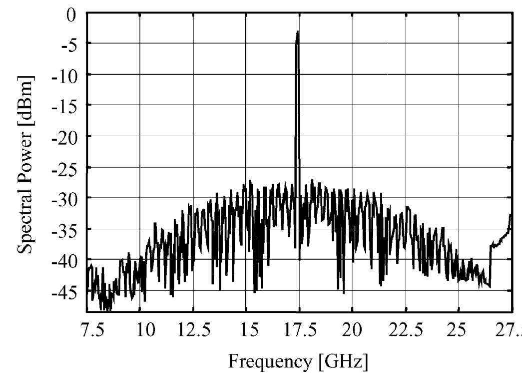

Fig. 3. Heterodyned electrical spectrum of the 2×10 Gb/s 4-point QASK = 4-IM signal.

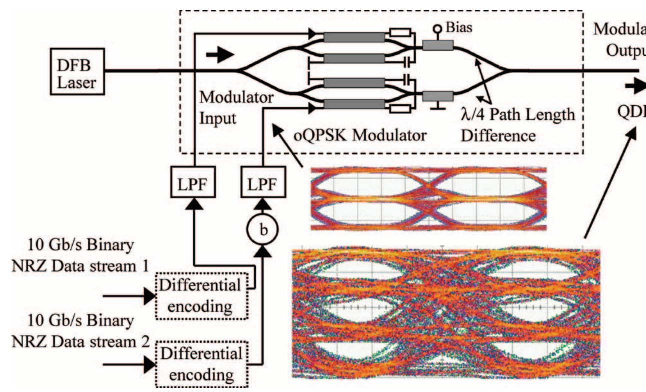

Fig. 4. Principle of optical QDB modulation using duobinary lowpass filtering (LPF) and a QPSK modulator (electrical attenuator setting $b = 1/2$). The resulting quaternary intensity eye diagram (bottom) and the electrical duobinary eye diagram (top) are also shown. (Color version available online at http://ieeexplore.ieee.org.)

available, two mutually delayed 10-Gb/s binary NRZ electrical signals were lowpass-filtered (LPF) to generate the duobinary signals. The lowpass filters are constructed using open stubs with single-path delays of 50 ps and 25-Ω characteristic impedance and are attached to each 50-Ω modulator drive cable.

Each stub filter (LPF) responds to an impulse by two impulses of equal height and 100-ps mutual delay, thereby forming an idealized duobinary one-bit-delay and add filter [6], [9], [12]. The simulated frequency response of the LPF stub used in this experiment had a $\sim$35-dB dip at the frequency 5 GHz.

A duobinary signal with a full $2V_\pi$ total swing generates in one MZM the in-phase optical field $\mathrm{Re}(E)$ with normalized field amplitudes $\{-1, 0, +1\}$. The other arm MZM is driven with a duobinary signal with a V_π total swing and generates the quadrature component $\mathrm{Im}(E)$ with normalized field amplitudes $\{-a, 0, +a\}$. The total output field is again $E_o = \mathrm{Re}(E) + j\mathrm{Im}(E)$. The modulation constellation is shown in Fig. 5. The generated fields are $\{0, \pm aj, \pm 1, \pm 1 \pm aj\}$, corresponding to four different intensities $\{0, a^2, 1, 1 + a^2\}$. Illustrating the case $a = 1/\sqrt{2}(b = 1/2)$, the intensities are again labeled "0," "1," "2," "3."

Fig. 4 also shows the 4-level 10-GBd (20 Gb/s) intensity eye diagram, detected at the modulator output. Not only differential encoding is needed at the transmitter side, but also 4-IM

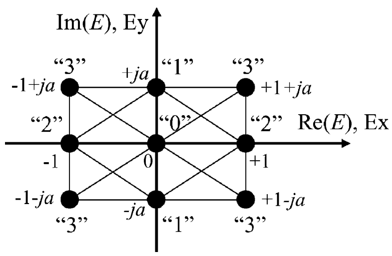

Fig. 5. Electrical field modulation constellation $(a = 1/\sqrt{2})$ of QDB. The two quadratures either have orthogonal phases in one polarization $(\mathrm{Re}(E), \mathrm{Im}(E))$ QDB, or have orthogonal polarizations (E_x, E_y) QPolDB. In both cases a quaternary intensity modulation results.

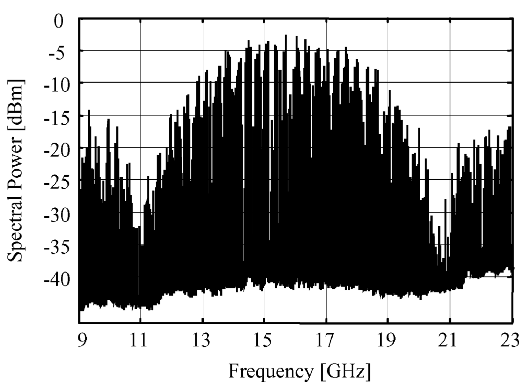

Fig. 6. Heterodyned electrical spectrum of the 2×10 Gb/s QDB = 4-IM signal using a QPSK modulator (QDB-5).

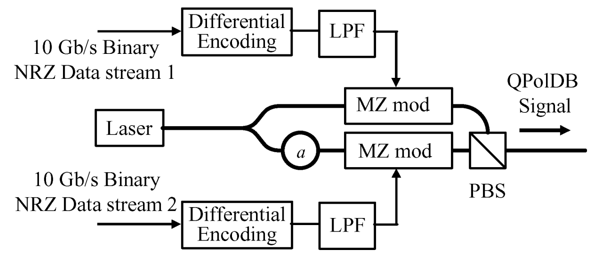

Fig. 7. Implementation of a QPolDB modulation with a duobinary low-pass filtering (LPF) and a polarization division multiplex setup $(a = 1/\sqrt{2})$.

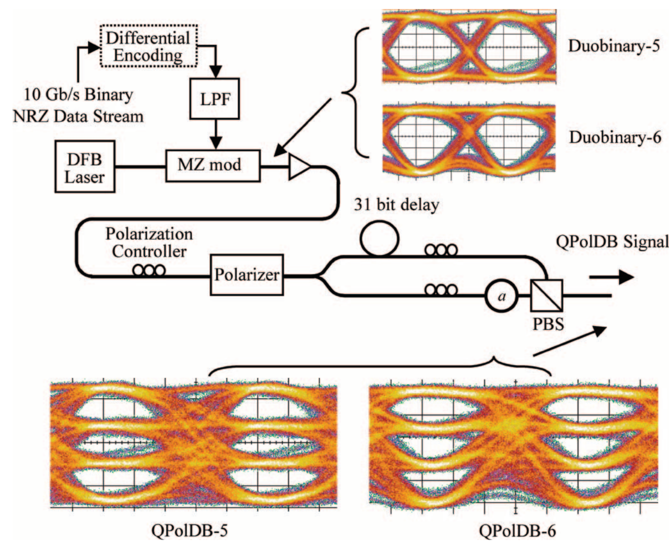

Fig. 8. Experimental setup to generate optical 10 Gbaud QPolDB using a duobinary lowpass filter (LPF), a Mach–Zehnder modulator, and polarization division multiplex (PolDM); $a = 1/\sqrt{2}$. Detected intensity eye diagrams of the 2×10 Gb/s QPolDB (quaternary intensity; bottom) and 10 Gbit/s duobinary signal (binary intensity; top) are also shown. (Color version available online at http://ieeexplore.ieee.org.)

decoding at the receiver side. The spectrum of the generated QDB (4-IM) is just as broad as for duobinary modulation although capacity is doubled. Fig. 6 shows the heterodyned electrical spectrum of the 10-GBd optical QDB signal. There is no carrier in the spectrum, and it is equivalent to the spectrum of a 10-Gb/s duobinary signal.

C. Generation of a QPolDB Signal by Two 10-Gb/s Duobinary Signals With Polarization Division Multiplex

If the two quadratures belong to the same polarization then they must be orthogonal in phase. But they may as well belong to two orthogonal polarizations (Fig. 7), and in this case their phase relationship does not matter. Other than in Fig. 4, the QPolDB transmitter consists of two Mach–Zehnder modulators driven by electrical duobinary signals. One of the modulated signals is optically attenuated by 3 dB $(a = 1/\sqrt{2})$, before they are combined together with orthogonal polarizations in a polarization beam splitter (PBS).

The experimental setup that was implemented to generate such a 10 GBd (20 Gb/s) QPolDB is shown in Fig. 8.

For simplicity, only one optical duobinary signal was generated, using one of the mentioned stub filters and no precoding. The electrical duobinary signal has a $2V_\pi$ total swing and drives one MZM. Right there, a photoreceiver (not shown) detects the intensity eye diagram shown topmost in Fig. 8 (duobinary-5). Another stub LPF, producing impulses spaced by 83 ps and having a frequency response dip at 6 GHz, was also used, and the corresponding eye diagram is also shown in Fig. 8 (duobinary-6) [7], [9], [12]. The duobinary optical signal passes through an optical amplifier, polarization controllers, and a polarizer. The output signal of the polarizer is split by a coupler into two branches. One of them, carrying a field E_x equal to $\{-1, 0, +1\}$, delays it by 31 symbol periods in an additional certain length of standard single-mode fiber (SSMF). The signal E_y in the other branch is optically attenuated by 3 dB$(a = 1/\sqrt{2})$ and the field amplitudes $\{-a, 0, +a\}$. The two electric fields Ex and Ey are orthogonally recombined in a subsequent PBS.

Due to the uncertain phase relationship of the two polarizations, the Jones vector of this QPolDB signal is $\mathbf{E} = \begin{bmatrix} E_x \\ e^{j\varphi} E_y \end{bmatrix}$, where φ is the unknown and unimportant phase difference. The modulation constellation diagram is again given by Fig. 5, and this can be detected as a 4-IM with intensities $\{0, a^2, 1, 1 + a^2\}$ and symbols "0," "1," "2," "3."

The eye diagrams of the QPolDB signal generated using the two stub filters are shown in Fig. 8 (bottom). The extension -5 or -6 of the modulation format acronym QPolDB denotes the dip frequency of the respective stub filter in GHz. Later, it will be seen that the QPolDB-5 signals yield better sensitivity but worse CD tolerance than the QPolDB-6 signals. Similar

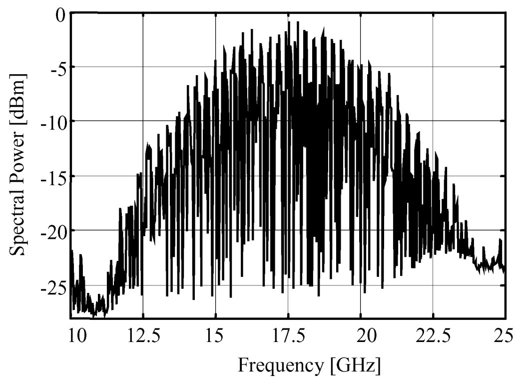

Fig. 9. Heterodyned electrical spectrum of the 2×10 Gb/s QPolDB-6 $=$ 4-IM signal using a polarization division multiplex setup with 6-GHz stubs.

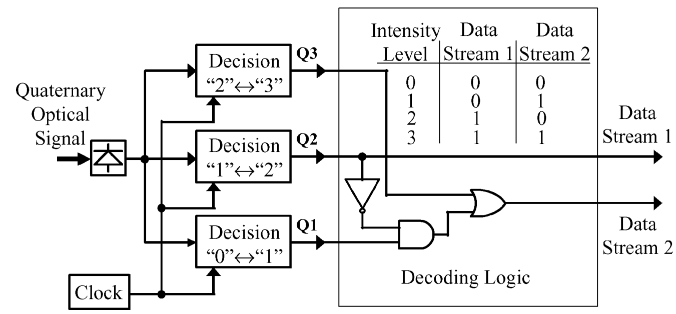

Fig. 10. 4-IM receiver with decoding logic diagram and corresponding truth table.

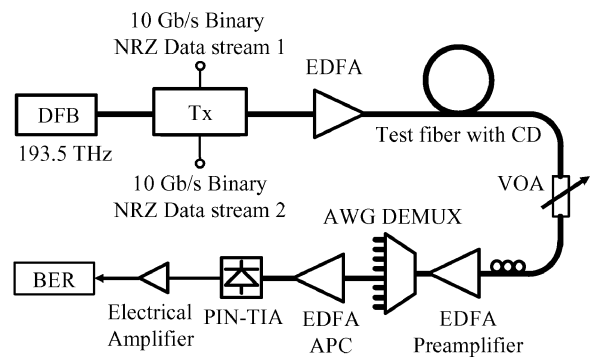

Fig. 11. 20-Gb/s quaternary (4-IM) transmission setup.

experience with differently shaped duobinary signals has been reported in [8], [9], [12]. The total bandwidth is only that of the duobinary modulation. Fig. 9 shows the heterodyned electrical spectrum of the QPolDB-6 signal. There is no carrier, and the bandwidth is equivalent to that of the electrical duobinary-6 signal. The spectrum of the QPolDB-5 signal looks the same and has the same bandwidth as the heterodyned QDB spectrum shown in Fig. 6.

III. Quaternary Intensity Modulation Detection

The two variants of QDB and the QASK each represent a 4-IM signal. The 4-IM signal contains three eye openings corresponding to three different patterns. These patterns $\{Q1, Q2, Q3\}$ can be detected at the receiver using a single photodiode (direct detection) and three decision circuits (D-flip-flops) as shown in Fig. 10. Suitable decoding is needed to recover the two data streams from the three detected patterns [20]. The schematic of the decoding logic circuit is shown in Fig. 10 in addition to its corresponding truth table.

IV. Transmission Setup

Fig. 11 shows an experimental 2×10 Gb/s transmission setup used for the schemes of Section II. The distributed-feedback laser (DFB) transmitter laser has a frequency of 193.5 THz. Two $2^7 - 1$ PRBS are transmitted. A mutual delay of 31-bit durations decorrelates the patterns.

The encoding function is not implemented for the duobinary case. The receiver employs an optical preamplifier followed by a dense wavelength division multiplexing (DWDM) Arrayed Waveguide Grating (AWG) Demultiplexer (DEMUX) of Gaussian type with 100-GHz spacing of its 40 channels, which acts as a narrow bandpass optical filter.

A variable optical attenuator (VOA) placed before the optical preamplifier is used for sensitivity and optical signal-to-noise ratio (OSNR) measurements. The detected photocurrent of an optical front-end PIN photodiode with transimpedance amplifier (PIN-TIA) is stabilized by a feedback loop (not shown) that controls the pump current of the last EDFA for automatic power control (APC). An electrical amplifier amplifies the received signal before it feeds an oscilloscope or an error detector. The error detector is programmed, using different thresholds, to receive all the three patterns, corresponding to the top, middle, and bottom eye diagram. Proper Bit Error Rate (BER) averaging is performed to represent the mean BER of the received patterns. A polarization controller was placed before the optical preamplifier when measurements were performed with QPolDB signals, in order to compensate for the polarization-dependent loss (PDL) of the optical preamplifier.

Fig. 12(a)–(c) shows the BER curves for the three received eyes (top, middle, and bottom) for QASK, QDB, and QPolDB-5, respectively. The top eye, which represents the intensity levels "2" and "3", dominates the overall BER in all three cases.

Assuming Gray encoding and neglecting the probability of decision errors larger than one quantization step, the true BER is (approximately) calculated as $1/2$ times the sum of the individual BERs obtained in the three decision processes. The sensitivities at an average BER of 10^{-9} for binary QASK, duobinary QDB with QPSK modulator using LPF stubs with 5-GHz dip (QDB-5), duobinary QPolDB with polarization division multiplex using LPF stubs with 5-GHz dip (QPolDB-5), and duobinary QPolDB with polarization division multiplex using LPF stubs with 6-GHz dip (QPolDB-6) are $-21.6, -21.2, -20.5$, and -18.4 dBm, respectively. These figures were obtained from the measured mean BERs which are plotted versus received power in Fig. 13.

Fig. 15 shows intensity eye diagrams at the sensitivity edge for QPolDB-5 (top) and -6 (bottom) after transmission over 21.3 km (left) and 37.5 km (right) of SSMF (a-right). The better CD resilience of the less bandlimited QPolDB-6 scheme is visible.

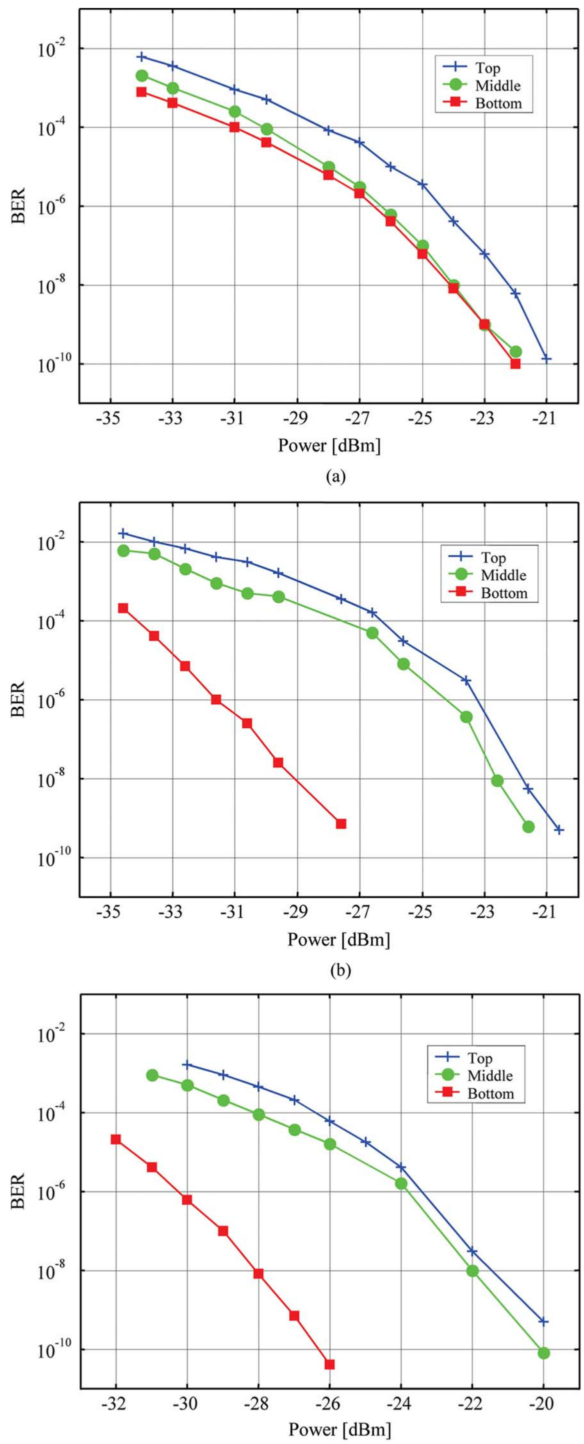

Fig. 12. BER curves for the three received eyes (top, middle, and bottom) for (a) QASK, (b) QDB, and (c) QPolDB-5. (Color version available online at http://ieeexplore.ieee.org.)

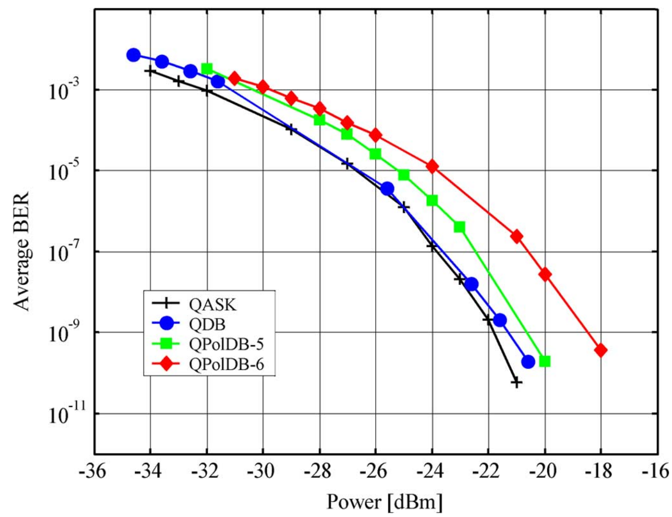

Fig. 13. Back-to-back receiver sensitivity for quaternary intensity modulation. (Color version available online at http://ieeexplore.ieee.org.)

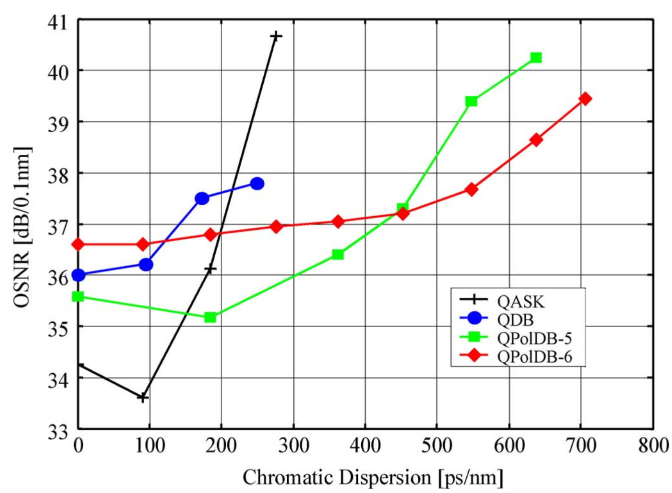

Fig. 14. OSNR needed for a BER of 10^{-9} versus CD in picoseconds per nanometer. (Color version available online at http://ieeexplore.ieee.org.)

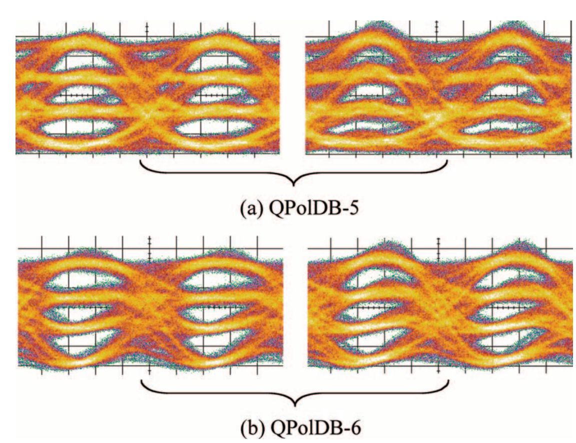

Fig. 15. (a) Eye diagram of the QPolDB-5 signal measured at the sensitivity edge after transmission over 21.3 km of SSMF (left) and 37.5 km of SSMF right), (b) Eye diagram of the QPolDB-6 signal measured at the sensitivity edge after transmission over 21.3 km of SSMF (left) and 37.5 km of SSMF (right). (Color version available online at http://ieeexplore.ieee.org.)

The CD tolerance was measured for all generated quaternary signals. Fig. 14 shows the OSNR after the optical preamplifier needed for a BER of 10^{-9} versus CD. An optical attenuator was used to vary the OSNR. The 1-dB tolerances at a BER of 10^{-9} are $\sim$130, $\sim$140, $\sim$340, and $\sim$530 ps/nm for QASK, QDB-5, QPolDB-5, and QPolDB-6, respectively.

V. Discussion

According to Fig. 14, the QDB schemes are superior to the QASK scheme, due to the reduced bandwith of their duobinary modulation. The QPolDB signal with polarization division multiplex based scheme gave the best CD-tolerance range, but worst sensitivity. The analog QDB signal with QPSK modulator-based scheme had a better sensitivity but a worse CD tolerance. The reduced CD tolerance of the QDB scheme may be understood from the fact that CD affects the phase. On the other hand, QPolDB is of course affected by polarization-dependent loss, since unbalanced optical powers in the orthogonal polarizations result in unequal eye openings at the receiver side. The QDB signal is affected by the fact that one of the Mach–Zehnder modulators is driven with a V_π voltage swing. In the presence of electrical intersymbol interference this results in a nonoptimal optical duobinary signal in that modulator. A solution to this problem is to place an optical attenuator in one of the QPSK modulator branches [14] and drive both Mach–Zehnder modulators with a full $2V_\pi$ voltage swing, where optical duobinary signal quality is best. The modulation amplitudes in all the quaternary generation schemes were chosen to optimize the three eye openings for the quaternary signal. Any change in the modulation amplitudes will cause unequal eye openings in the quaternary signal.

It was also found that the 5-GHz stub-generated QPolDB-5 signals have better sensitivity but worse CD tolerance than the QPolDB-6 signals generated by a 6-GHz stub. This is due to the fact that two different methods were used to generate the two duobinary signals. The QPolDB-5 signals were similar to the duobinary signals generated by the conventional one-bit-delay and add method [6], [9]. The QPolDB-6 signals were similar to the duobinary signals generated by the LPF method [7], [9]. It has been reported in [9], [12] that the LPF method better suppresses the optical spectrum sidelobes, tolerates more CD than the one-bit delay method, and has a worse back-to-back sensitivity than the one-bit-delay and add method.

It is of course also possible to generate QASK with polarization division multiplex (QPolASK) [15]. In principle, QPSK and PolDM could even be combined to generate 16-ary intensity modulation (16-IM) by binary (16-QASK) or duobinary (81-QPolDB) modulation in four quadratures with relative field amplitudes of 1, $\sqrt{2}$, 2, $2\sqrt{2}$.

For comparison, we have generated an electrical quaternary intensity-modulated signal at 10 GBd by superimposing two mutually delayed 10-Gb/s data streams. It was used to drive one Mach–Zehnder modulator. The thereby generated optical 4-IM signal was detected with the same receiver as for the quaternary schemes (Fig. 10). Even though the relative amplitudes of the two superimposed electrical signals as well as the modulator bias point were set for optimum sensitivity this sensitivity was only -12.8 dBm, worse than for the quaternary QAM, QDM, QPolDM methods. The CD- tolerance measurement was not possible for the 4-IM signal due to high noise and poor receiver sensitivity. We have also generated a return-to-zero DQPSK (RZ-DQPSK) signal using the QPSK modulator and a subsequent RZ modulator afterwards. The measured RZ-DQPSK receiver sensitivity was ~ -35 dB $\cdot$ m, using an interferometer-based balanced photoreceiver (with two photodiodes) and the CD tolerance was 360 ps/nm. The merits of the DQPSK signals come at the cost and complexity of the extra components at the receiver.

TABLE I
Comparison Between Different Modulation Formats at 20 Gb/s

Modulation Format	Sensitivity (dBm)	CD tolerance (ps/nm)	BW (GHz)	Ref.
NRZ-ASK	-31.6	~260ps/nm	40	[27]
Duobinary	-28.5	600ps/nm	20	[9]
4-IM	-12.8	-	20	-
DP-ASK	-30	-	20	[17]
RZ-DQPSK	-35	360ps/nm	>20	-
QASK	-21.6	130ps/nm	20	-
QDB	-21.2	140ps/nm	~10	[23]
QPolDB-5	-20.5	340ps/nm	~10	-
QPolDB-6	-18.4	530ps/nm	~12	[24]

The reason why the experiments in this paper were performed with PRBS length of $2^7 - 1$ was the impossibility to program the BER detector to receive the expected patterns at longer PRBS lengths with the available software. We believe that the sensitivity for the QDB and QPolDB signals would be degraded at higher PRBS lengths since they are based on duobinary modulation, as has been reported in [10]. Table I shows and compares different modulation formats at 20 Gb/s. For comparability, all quaternary modulation experiments in Table I and [14] refer to a PRBS length of $2^7 - 1$.

The sensitivity of standard NRZ binary 20-Gb/s modulation is better than that of the proposed quaternary formats, but it has worse CD tolerance than QPolDB and worse spectral efficiency than QASK, QDB, and QPolDB. The proposed formats can be used to double the capacity for distances on the order of 40 km (using QPolDB-6), which is typical for short metro applications without dispersion compensation. However, they are not meant to compete against RZ-DQPSK, which is a potential candidate for long or ultralong haul optical fiber transmission systems.

VI. Conclusion

The two duobinary QDB schemes which require only a simple receiver are believed to represent intensity modulation with the narrowest-reported spectrum reported to date. Also, the polarization division multiplex based duobinary QPolDB scheme exhibits a better CD tolerance than the other 4-IM formats.

Acknowledgment

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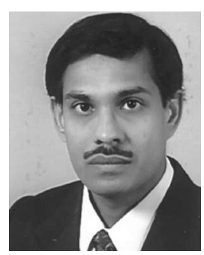

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