20-Gb/s Quaternary Intensity Modulation Based on Duobinary Modulation With Unequal Amplitude in Two Polarizations

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***Abstract*—Two 10-Gb/s duobinary data streams are combined with unequal amplitudes and two orthogonal polarizations to generate a narrowband 20-Gb/s (10-Gbaud) quaternary intensity modulation. Sensitivity and chromatic dispersion tolerance of this modulation format, measured with a pseudorandom binary sequence 2^7-1, are -18.6 dBm and 530 ps/nm, respectively.**

***Index Terms*—Optical communication, optical modulation, polarization.**

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]. Higher spectral efficiency can be achieved by doubling the transmission capacity, by transmitting more information either in the amplitude, phase, polarization, or a combination thereof [2]–[10]. Differential quadrature phase-shift keying (DQPSK) is a promising modulation format that can be used to increase the spectral efficiency and the chromatic dispersion (CD) tolerance, but considerable technical effort at the receiver end is needed for its implementation, which reverberates in the cost budget [6], [7]. On the other hand, M-ary amplitude shift keying such as quaternary (four-level) intensity modulation (4-IM) [8], [9] is easy to detect using a direct detection receiver with a single photodiode, but has a relatively large power penalty. The spectral efficiency for quaternary intensity modulation signals can be further improved by duobinary modulation in two quadratures with unequal amplitudes to generate a nine-constellation point (9-QAM) quaternary intensity modulated signal [10].

In this letter, we generate a 20-Gb/s 9-QAM polarization-division-multiplexed (PolDM) signal by using two duobinary data streams with unequal amplitudes and orthogonal polarizations. The proposed 9-QAM PolDM signal can be detected as a 4-IM signal using a single photodiode and a suitable decoder. This modulation format is highly spectrally efficient and has a better CD tolerance than standard 20-Gb/s nonreturn-to-zero modulation. The generation scheme, receiver sensitivity, and CD tolerance of the proposed modulation format will be discussed in the following sections.

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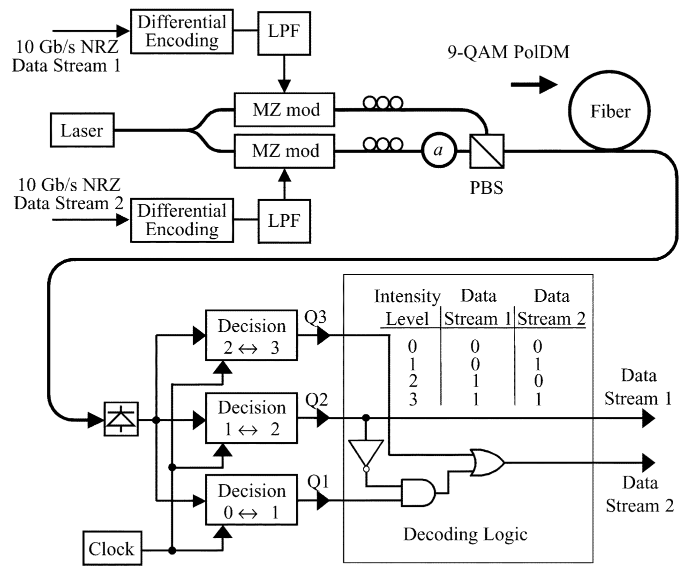

Fig. 1. Schematic of the optical 9-QAM PolDM signal generation and detection scheme ($a = 1/\sqrt{2}$).

II. Generation and Detection of 9-QAM PolDM Signal

The schematic shown in the upper part of Fig. 1 can be used to generate a 20-Gb/s 9-QAM PolDM signal. The 9-QAM PolDM transmitter consists of two Mach–Zehnder modulators (MZM) driven by electrical duobinary signals.

Duobinary modulation requires differential encoding at the transmitter side followed by subsequent filtering by a suitable low-pass filter (LPF). One of the modulated signals is optically attenuated by 3 dB ($a = 1/\sqrt{2}$) in order to obtain equal eye openings in the intensity domain, before they are recombined with orthogonal polarizations in a polarization beam splitter. The 9-QAM PolDM signal represents a 4-IM signal. This 4-IM signal contains three eye openings corresponding to three different patterns $\{Q1, Q2, Q3\}$. These patterns are detected at the receiver side in a single photodiode and are discriminated using three decision circuits (delay flip-flops). A suitable decoder, as shown in Fig. 1, is needed to recover the original data streams from the three detected patterns. Gray encoding could slightly improve the performance, but was not considered here.

III. Experimental Setup

Fig. 2 shows the experimental setup that was implemented to generate the 20-Gb/s (10-Gbaud) 9-QAM PolDM signal. The distributed-feedback transmitter laser has a frequency of

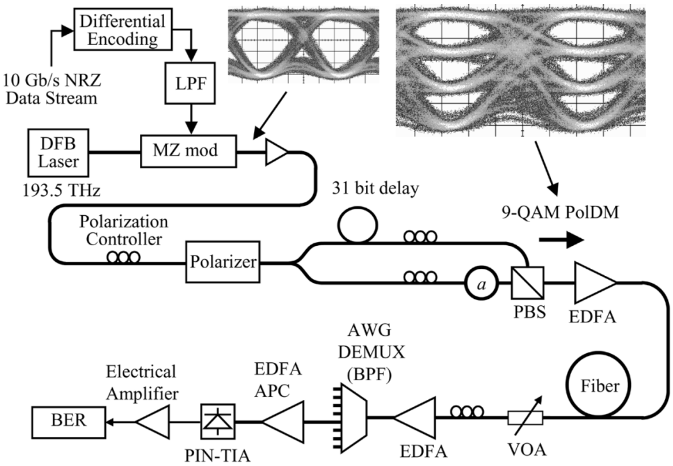

Fig. 2. Experimental setup to generate optical 10-Gbaud (20-Gb/s) 9-QAM PolDM ($a = 1/\sqrt{2}$). Detected intensity eye diagrams of the 10-Gb/s optical duobinary signal (left) and the 2 × 10 Gb/s 9-QAM PolDM signal (right) are also shown. (Color version available online at http://ieeexplore.ieee.org.)

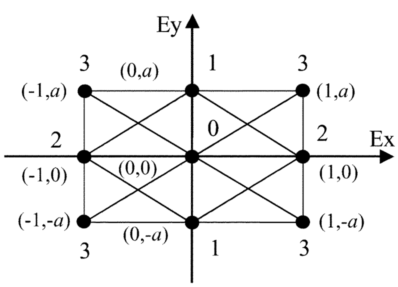

Fig. 3. Electrical field modulation constellation ($a = 1/\sqrt{2}$) of 9-QAM PolDM signal.

193.5 THz. For simplicity, only one optical duobinary signal was generated using an LPF. This LPF was realized using an open stub. It had a −35-dB dip in the frequency response at 6 GHz. The differential encoding was neither implemented nor needed because $2^7 - 1$ pseudorandom binary sequence (PRBS) data streams were transmitted. The electrical duobinary signal which drives the MZM has peak-to-peak amplitude of $2V_\pi$. The left eye diagram in Fig. 2 shows the intensity of the optical duobinary signal.

The optical duobinary signal passes through an optical amplifier, a polarization controller, and a polarizer. The output signal of the polarizer is split by a coupler into two branches. One of the signals, carrying a field with the amplitudes E_x equal to $\{-1, 0, +1\}$, is delayed by 31 symbol durations in an extra length of standard single-mode fiber (SSMF) to decorrelate the two PRBS patterns. The signal E_y in the other branch is optically attenuated by 3 dB ($a = 1/\sqrt{2}$) and has the field amplitudes $\{-a, 0, +a\}$. The two electric fields E_x and E_y are orthogonally recombined in a subsequent PBS. Due to the uncertain phase relationship between the two polarizations, the Jones vector of this 9-QAM PolDM signal is$\mathbf{E} = [\begin{smallmatrix} E_x \\ e^{j\varphi} E_y \end{smallmatrix}]$, where φ is the unknown phase difference. The constellation diagram of this modulation format is shown in Fig. 3. The signal can be detected as a 4-IM signal with intensities $\{0, a^2, 1, 1 + a^2\}$ with the levels labeled as "0", "1", "2", and "3". The right eye diagram in Fig. 2 shows the intensity of the 9-QAM PolDM signal. The electrical heterodyned spectrum shown in Fig. 4 has a 3-dB

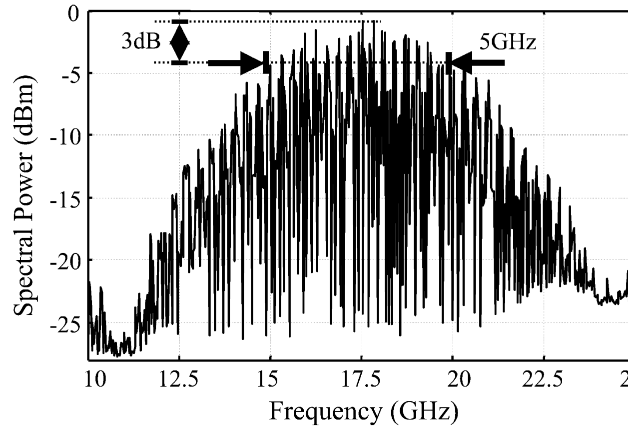

Fig. 4. Heterodyned electrical spectrum of the 2 × 10 Gb/s 9-QAM PolDM signal.

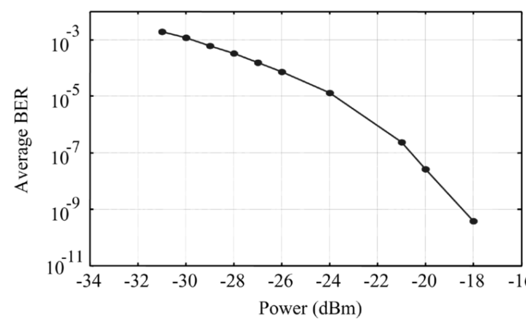

Fig. 5. Back-to-back receiver sensitivity for 9-QAM PolDM signal. (Color version available online at http://ieeexplore.ieee.org.)

(full-width at half-maximum) bandwidth of ~5 GHz, no carrier component, and is just as broad as for duobinary modulation, although the capacity is doubled.

The receiver employs an optical preamplifier followed by a 100-GHz-spaced 40-channel C-band DWDM demultiplexer (DeMux). This DeMux is of the Gaussian type and acts as a narrow bandpass optical filter. A variable optical attenuator followed by a polarization controller placed before the optical preamplifier is used to vary the optical signal-to-noise ratio (OSNR) for sensitivity and CD tolerance measurements. The polarization controller was used to compensate the polarization-dependent loss (PDL) of the optical preamplifier. For an automatic power control, the detected photocurrent of an optical front end, a PIN photodiode integrated with a transimpedance amplifier, is stabilized by a feedback loop (not shown) that controls the pump current of the last erbium-doped fiber amplifier. An electrical amplifier is used to amplify the received signal before it feeds an oscilloscope or an error detector. The error detector is programmed with three different expected patterns corresponding to the top, middle, and bottom eye diagrams. To detect these patterns, different decision threshold settings of the error detector are used. Proper bit-error-rate (BER) averaging is performed to represent the mean BER of the received patterns.

IV. Results

The measured receiver sensitivity for the 9-QAM PolDM signal with a PRBS $2^7 - 1$ at a BER of 10^{-9} is −18.6 dBm. The BER versus the received power measured at the optical preamplifier input is shown in Fig. 5. Fig. 6 shows the OSNR

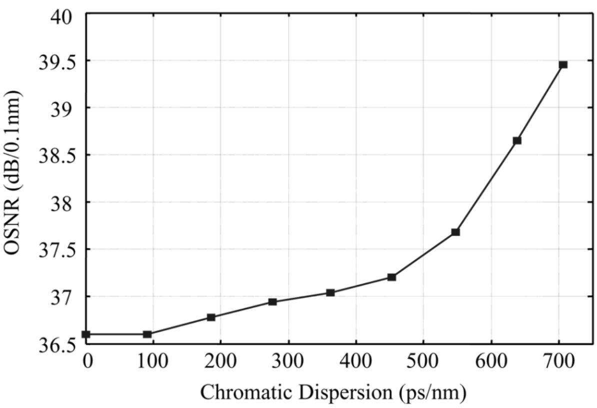

Fig. 6. OSNR needed for a BER of 10^{-9} versus CD in ps/nm. (Color version available online at http://ieeexplore.ieee.org.)

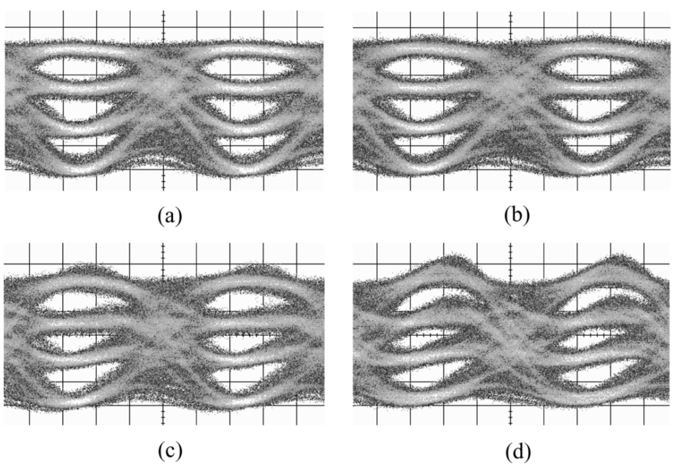

Fig. 7. Eye diagrams of the 9-QAM PolDM signal measured at the sensitivity edge after transmission over (a) 0 km (back-to-back), (b) 10.9 km, (c) 21.3 km, and (d) 41.5 km of SSMF. (Color version available online at http://ieeexplore.ieee.org.)

after the optical preamplifier needed for a BER of 10^{-9} versus CD. A 1-dB OSNR penalty at a BER of 10^{-9} was measured for 530 ps/nm. Fig. 7 shows the intensity eye diagrams at the sensitivity edge for 9-QAM PolDM signal for the back-to-back case (a) and after transmission over 10.9, 21.3, and 41.5 km of SSMF (dispersion:17 ps/nm/km) [(b), (c), and (d)], respectively.

V. Discussion

For comparison purposes, we have also generated a 20-Gb/s optical quaternary intensity modulated (4-IM) signal using a 4-ary electrical signal driving a single MZM similar to [8]. Two $2^7 - 1$ PRBS electrical data streams mutually delayed by 31 bits were transmitted. A sensitivity measurement setup similar to Fig. 2 was used. Even though the relative amplitudes of the two superimposed electrical signals as well as the modulator bias point were set for optimum sensitivity, the measured sensitivity was only -12.8 dBm, which is worse than for the 9-QAM PolDM method. Due to this poor receiver sensitivity, it was not possible to measure the CD tolerance. Later on, we generated a return-to-zero DQPSK (RZ-DQPSK) signal using a DQPSK modulator [6] and a subsequent RZ modulator driven by a 10-GHz signal. Here the receiver sensitivity and the CD tolerance, measured with an interferometer-based balanced (two photodiodes) optical receiver, were -35 dBm and 360 ps/nm, respectively. Due to the bandwith reduction characteristics of the duobinary modulation, the 9-QAM PolDM scheme has better spectral efficiency than RZ-DQPSK and 4-IM schemes. The 9-QAM PolDM scheme gave a better CD tolerance than RZ-DQPSK, but worse receiver sensitivity. The sensitivity advantage of the DQPSK signals comes at the cost, complexity, and extra component effort at the receiver side. The 9-QAM PolDM modulation format is affected by the PDL introduced in the system, since unbalanced optical powers in the orthogonal polarizations result in unequal eye openings at the receiver side. The effect of polarization-mode dispersion on the signal has not been yet assessed. The effects of very long PRBS ($\geqslant 2^{23}-1$) could not be assessed since the expected patterns could not be uploaded to the BER detector with the available software and memory size. But we were able to generate and detect the 9-QAM PolDM signal with PRBS lengths of $2^{10} - 1$ and $2^{15} - 1$. The sensitivity was degraded to -18 and -13 dBm, respectively, due to the duobinary modulation which has worse sensitivity at longer PRBS lengths [11].

VI. Conclusion

The proposed duobinary 9-QAM PolDM modulation scheme doubles the transmission capacity and is detected by a simple receiver with a back-to-back sensitivity of -18.6 dBm, measured with a PRBS $2^7 - 1$. It is believed to feature the largest reported CD tolerance (530 ps/nm) for 20-Gb/s intensity modulation with such a narrow spectrum, which makes it attractive for metro applications.

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