

640-Gb/s OTDM RZ-DQPSK Signal Enabling 2.4-bit/s/Hz Spectral Efficiency and Its Detection with an EAM-based Receiver

Lothar Möller, Yikai Su*, Chongjin Xie, Jurgen Gripp, Xiang Liu, Roland Ryf

Bell Labs, Lucent Technologies, 791 Holmdel-Keyport RD, Holmdel, NJ 07733, USA, lmoeller@lucent.com

*State Key Lab of Advanced Optical Communication Systems and Networks, Shanghai Jiao Tong University, 200030, China, yikaisu@sjtu.edu.cn

Abstract: We demonstrate for the first time 640-Gb/s single-channel OTDM RZ-DQPSK signaling with record spectral efficiencies of 2.4 bit/s/Hz and up to 3.2 bit/s/Hz. The demonstrated data rate is the highest to date detected with an electro-absorption modulator (EAM) based receiver.

OCIS codes: (060.2330) Fiber optics communications, 060.4080 Modulation

1. Introduction

Ultra high-speed signaling has been attractive ever since the beginning of optical fiber communications. Historically the development of new optical transmission systems towards increased data rates per channel have brought advantages such as higher spectral efficiency, lower hardware costs, smaller equipment footprint, and reduced power consumption per transmitted bit. This paradigm will hold in the future only if integrated devices in the receivers and transmitters can be applied at the next higher data rate levels. Indeed, single-channel signals with up to 2.56-Tb/s data rate have been demonstrated^{i,iii,iii}, however their detection requires nonlinear fiber devices i.e. nonlinear optical loop mirror (NOLM) that are high cost and difficult to handle due to their relatively low stability.

Differential quadrature phase-shift keying (DQPSK) modulation is a convenient method to double the data rate of a channel for a given symbol rate and therefore it relaxes the electronic receiver bandwidth requirement. Thus, by combining DQPSK modulation and polarization multiplexing, an ultra high-speed 640-Gb/s signal can be obtained that is still recoverable with EAM based receivers. EAMs, driven in the reverse-bias regime, are preferred de-multiplexers for ultra high-speed signals since they enable simple operation, polarization-insensitive detection, and compact integration in line cards due to their small form factor. Besides, the narrow spectra of DQPSK signals allow for high spectral-efficiency transmission and a better tolerance of dispersion-compensation mismatch.

Ultra high-speed ETDM DQPSK signals have been experimentally investigated at data rates of 85 and 160 Gb/s^{iv,v,vi}. Here we report on our early 640-Gb/s OTDM DQPSK experiment^{vii} with semiconductor-based transmitter and receiver pairs, analyze the signal's performance, demonstrate its potential for achieving ultra-high spectral efficiency of up to 3.2 bit/s/Hz, and show its transmission with dispersion compensation using a tunable fiber Bragg grating (FBG).

2. Experimental setup and performance analysis of the modulation technique

In the transmitter (Fig.1) we used a commercially available semiconductor based mode-locked laser^{viii} as the pulse source, which periodically outputs phase-coherent pulses with 10-GHz repetition rate and 1.5-ps width (FWHM) at -5 dBm average power. After amplification, the pulse train is 0 and π phase modulated in a Mach-Zehnder (MZ) modulator that is biased at the null of its transfer function and driven with a 2^9-1 PRBS. A following phase modulator imprints phase shifts of 0 and $\pi/2$ and converts the 10-Gb/s DPSK signal to a 20-Gb/s RZ-DQPSK signal. This second modulator is driven with the inverted PRBS that is delayed by 538 bits with respect to the first modulation, as determined by its fiber jumper length, to de-correlate the data streams. The signal then enters an OTDM unit where its data rate is up converted to 320 Gb/s. A

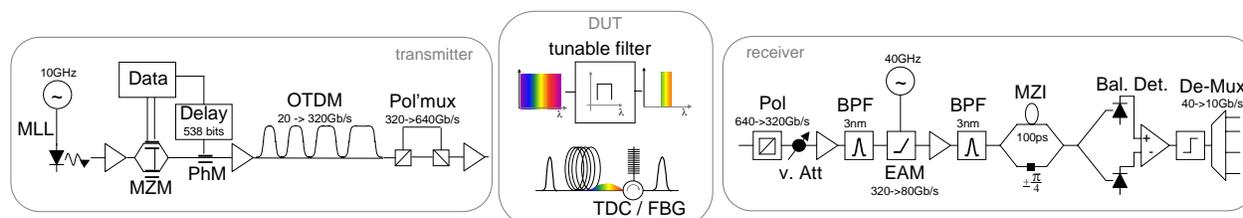


Fig.1: Schematic of the experimental setup. Transmitter and receiver architecture, narrow bandwidth filtering and dispersion compensation as test procedures (TDC tunable dispersion compensator; PhM phase modulator; Pol polarizer; MLL mode locked laser).

following pol'mux unit forms the 640-Gb/s RZ-DQPSK signal by combing two orthogonally polarized 320-Gb/s replicas delayed with respect to each other. After passing a device under test the 640-Gb/s RZ-DQPSK signal is polarization demultiplexed before entering the optical front-end of the receiver that consists of an optical pre-amplifier with a 3.3-dB noise figure and a variable attenuator. A bandpass filter with a 3-nm FWHM bandwidth blocks ASE noise at the output of the pre-amplifier before the signal enters an EAM. The EAM is reverse biased and driven by a 40-GHz sinusoidal clock (derived from the 10-GHz transmitter tone) resulting in a short switching window (~ 3.5 ps FWHM). The de-multiplexed signal at 40-Gsymbols/s enters another EDFA and subsequently a decoder via a second 3-nm bandpass filter. The decoder consists of a MZ interferometer that has a 100-ps delay in one arm and is connected to a balanced receiver with ~ 30 -GHz

bandwidth whose electrical output is sampled by a 40-Gb/s decision gate and de-multiplexed to 10 Gb/s where the bit-error-rate (BER) measurement is performed.

By switching the phase offset in both arms of the MZ interferometer between $\pm \pi/4$ the real (in-phase) and the imaginary (quadrature) component of the signal can be selected. During the modulation process the original PRBS characteristic of the pattern vanishes and the pattern detector has to be programmed with the anticipated sequences enabling it to correctly analyze the incoming data.

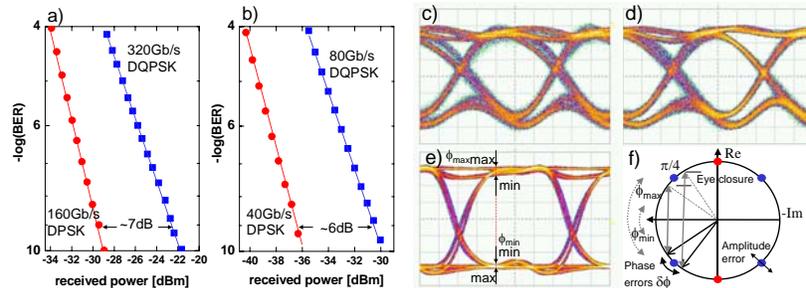


Fig.2: a, b) BER curves for RZ-DQPSK and RZ-DPSK, respectively. Eye diagrams of the 40G symbol rate signals: c) RZ-DQPSK and d) RZ-DPSK, respectively (5ps/div). e) Electrical eye at the modulator driver output (16.6 ps/div) (wide bandwidth scope, 60GHz). f) Visualization of the eye closure.

could originate from non-perfectly adjusted OTDM units. The average performance of in-phase and quadrature tributaries was similar. Pol' muxing of the signal did not cause any degradation (polarization extinction ratio >37 dB over the entire signal bandwidth). By switching off the $0-\pi/2$ phase modulation a RZ-DPSK signal was obtained (Fig.2a). The performance of its tributaries was even more similar (~ 0.2 -dB difference). At the receiver sensitivity level (BER = 1×10^{-9}) we measured ~ 7 -dB difference between the 320-Gb/s RZ-DQPSK and the 160-Gb/s RZ-DPSK signals. The absolute sensitivity values were -22.5 dBm and -29.6 dBm, respectively. Theory predicts the difference to be at least 5 dB^{ix,x} and we could identify experimentally the deviations from an ideal $0-\pi/2$ phase modulation and inter-symbol interference (ISI) as two main imperfections causing the remaining 2-dB difference in receiver sensitivity. Figs. 2c/d show eye diagrams of the de-multiplexed RZ-D(Q)PSK signals from the output of the balanced detectors at 40-G symbol rate. Pattern-dependent effects are more clearly visible in the RZ-DQPSK eye. The trace spreading appears wider, which is likely an effect caused by the non-ideal $0-\pi/2$ phase modulation. The eye diagram of the driving signal, detected at the input of the phase modulator, shows certain pattern dependence (Fig.2e). The electrical eye closure relative to the average opening is $\sim \pm 5\%$. Assuming a linear relation between the driving signal amplitude and the resulting phase shift, we expect a maximal optical phase noise of 9 degrees. The phasor diagram in Fig.2f allows an easy visualization of the eye-closure effect caused by small phase fluctuations $\delta\phi$, which can reduce the spacing between two phasors. In this situation the signal degradation can be estimated with a formalism equivalent to the one described in^{xi}. Thus a penalty of $20 \log(1 - 2/\pi \delta\phi) = 0.9$ dB is expected with a phase deviation of 9 degrees.

The ISI impact can be isolated by bypassing the pol' mux and the last two OTDM units, thus an 80Gb/s RZ-DQPSK signal and a 40-Gb/s DPSK signal with short duty cycles ($\sim 7\%$, no ISI) are launched into the RX. From receiver sensitivities of -36.5 dBm and -30.5 dBm read for the RZ-DPSK and RZ-DQPSK formats, respectively (fig.2b), we can conclude that ISI causes an additional penalty of ~ 1 dB in the 640Gb/s RZ-DQPSK signal compared to the corresponding DPSK signal.

3. Ultra-high spectral efficiency by narrow bandwidth filtering

To enhance the spectral efficiency of the 640-Gb/s OTDM RZ-DQPSK signal, we limited its spectrum with a continuously tunable bandwidth filter (Fig.3b). The signal is launched via an optical circulator into free space, where the light is collimated by a multi element lens with a focal length $f = 100$ mm on a grating. The grating arranged near Littrow geometry is an echelle with 52.67 lines/mm operated in the 22nd order and diffracts the spectral components of the signal under different angles depending on their wavelengths. The spectral components are then refocused by the same lens and selected by parallel razor blades before a mirror reflects them back following the inverse path. By adjusting the spacing between the two razor blades the spectrum of the signal can be bandwidth limited and the square-like filter passband allows for an out-of-band suppressing ratio of >30 dB. We set the filter bandwidth to 3.2 nm, 2.4 nm, and 1.6 nm, which enabled spectral efficiencies of 1.6 bit/s/Hz, 2.4 bit/s/Hz, and 3.2 bit/s/Hz, respectively (Fig. 3a). Note that to optimize the BER performance under tight filtering conditions, a certain filter-offset was applied to reduce ISI, known as vestigial sideband (VSB) filtering. The b-to-b sensitivity of the 640-Gb/s signal (Fig.3c) was ~ -23 dBm, which is slightly better than reported in Fig.2a due to receiver optimization, the 3-nm filter was substituted with a 5.2-nm filter to reduce ISI effects. Less than 1-dB penalties were observed when the tunable filter was applied with its bandwidth set to 3.2 nm, this already corresponds to a spectral efficiency of

1.6 bit/s/Hz. When the filter bandwidth was reduced to 2.1 nm resulting in a spectral efficiency of 2.4 bit/s/Hz, the penalty increased to ~ 2 dB for the worst tributary. Even with 1.6-nm bandwidth (corresponding to 3.2 bit/s/Hz spectral efficiency[§]) error-free operation was achieved but with a penalty of around 10 dB compared to b-to-b performance of the best tributary (inset in Fig.3c). The BER-curve kink indicates that ISI causes significant horizontal eye closure thus timing jitter becomes a dominant impairment. The performance variance of 0.8 dB between best and worst tributary can be reduced by fine-tuning the OTDM units. Better BER performance could be obtained by employing forward-error-correction techniques.

4. Dispersion compensation using a bandwidth-matched TDC after transmission

A tunable dispersion compensator (TDC) was used after the transmission of the 640-Gb/s OTDM RZ-DQPSK signal over a short SSMF link (13.5 km, CD~ 238 ps/nm, low PMD, linear propagation). The TDC with signal-spectrum matched

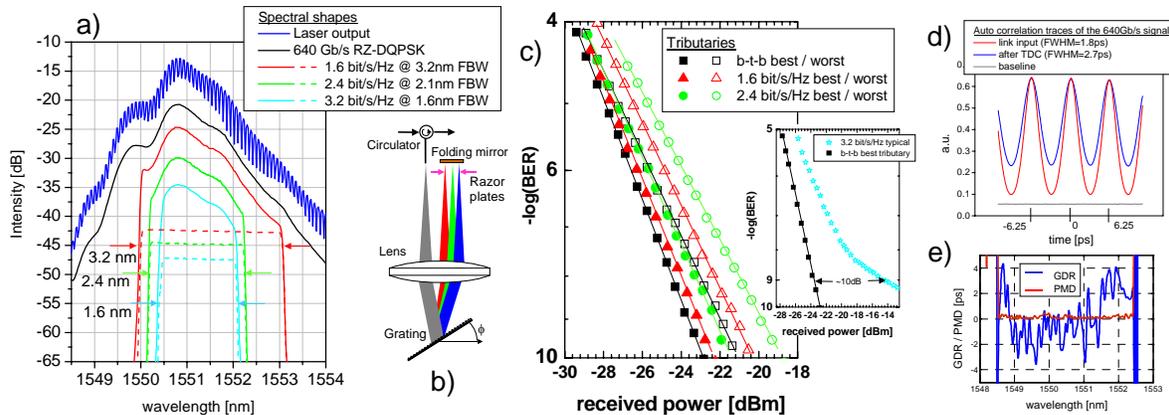


Fig. 3: a) Optical spectra of the MLL output, the 640-Gb/s DQPSK signal, the filtered signals, and the filter passband shapes, respectively (0.1nm res). b) Design of the bandwidth tunable filter. c) Measured BER curves at different filter bandwidth conditions. d) Auto correlation traces of the 640Gb/s at link input and after TDC, e) Group delay ripple (GDR) and PMD (DGD) of the TDC.

bandwidth (~3.6 nm) comprises a thermally tunable chirped fiber grating (tuning range -200 to -275 ps/nm) and is connected via an optical circulator to the link and receiver input. The signal's pulse widths at the link input and after the adjusted TDC were determined by auto correlation trace measurement (Fig.3d) to be 1.8 ps and 2.7 ps, respectively. The residual pulse broadening could be caused by the grating's intrinsic group delay ripple (~2 ps, Fig.3e) contributing mainly to a transmission penalty of ~2 dB. PMD effects were minimized by adjustment of the signal's launch polarization state.

5. Discussion

Compact spectra are not only beneficial for single channel systems where components with limited bandwidth such as equalizer are implemented but also in WDM systems. There, the general purpose behind striving for high spectral efficiency is to enhance the capacity without having the need for extending the amplifier gain bandwidth. Mainly two kinds of sophisticated techniques are required to exceed spectral efficiency values above the usual 0.4 bits/s/Hz. The WDM channels have to be (de)-muxed using components that minimize linear cross talk and modulation formats suitable for tight filtering have to be applied. In our method the almost rectangular-shaped passband of the filter, shown as the dashed lines in Fig. 3a, limits the spectral width. Extending this scheme to WDM applications would require to take small guard bands between channels for the (De)-Mux into account, that could slightly reduce the spectral efficiency. On the other hand we conservatively define the signal's spectral width at -20dB of its peak power density, which leaves some margin for incorporating guard bands while keeping the effective spectral efficiency values.

Conclusion

We have demonstrated for the first time a 640-Gb/s OTDM RZ-DQPSK format, which enables spectral efficiency of 2.4 bit/s/Hz with ~ 2-dB penalty and pointed out its potential for even higher values up to 3.2 bit/s/Hz with increased penalty. We also demonstrated its dispersion compensation by using a tunable FBG. The reported signal belongs to the class of formats with the highest achieved data rates to date that can be detected with an EAM based receiver.

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[§] Equally high spectral efficiency using WDM signals is reported in ^{xii}.