Optical Fiber Technology 20 (2014) 39–43

Contents lists available at ScienceDirect

Optical Fiber Technology

www.elsevier.com/locate/yofte

Experimental evaluation of prefiltering for 56 Gbaud DP-QPSK signal transmission in 75 GHz WDM grid ☆

Robert Borkowski [a,*], Luis Henrique H. de Carvalho [b], Edson Porto da Silva [b], Júlio César M. Diniz [b], Darko Zibar [a], Júlio César R.F. de Oliveira [b], Idelfonso Tafur Monroy [a]

[a] *DTU Fotonik – Department of Photonics Engineering, Technical University of Denmark, 2800 Kgs. Lyngby, Denmark*

[b] *CPqD – Centro de Pesquisa e Desenvolvimento em Telecomunicações, Campinas, SP, Brazil*

ARTICLE INFO

Article history:
Received 30 August 2013
Revised 17 November 2013
Available online 18 December 2013

Keywords:
Optical prefiltering
Optical modulation
Quaternary phase shift keying
Coherent detection
Optical transmission
Wavelength division multiplexing

ABSTRACT

We investigate optical prefiltering for 56 Gbaud (224 Gbit/s) electrical time-division multiplexed (ETDM) dual polarization (DP) quaternary phase shift keying (QPSK) transmission. Different transmitter-side optical filter shapes are tested and their bandwidths are varied. Comparison of studied filter shapes shows an advantage of a pre-emphasis filter. Subsequently, we perform a fiber transmission of the 56 Gbaud DP QPSK signal filtered with the 65 GHz pre-emphasis filter to fit the 75 GHz transmission grid. Bit error rate (BER) of the signal remains below forward error correction (FEC) limit after 300 km of fiber propagation.

1. Introduction

One of the possible solutions to temporarily postpone fiber bandwidth exhaustion is to increase transmission symbol rates and spectral efficiency. Moving to dual polarization (DP) quaternary phase shift keyed (QPSK) transmissions at symbol rates of 56 Gbaud and beyond obtained by electrical time-division multiplexing (ETDM) is very demanding. This is due to a wideband nature of the transmitted signals, which set very high bandwidth (BW) requirements towards electrical components. Due to this, reported QPSK [1–3] or 16-QAM [4,5] transmission experiments at these high symbol rates are sparse. The wide optical spectrum of high symbol rate signals is also facing increased penalties due to cascaded filtering in fixed-grid reconfigurable optical add-drop multiplexers (ROADMs) [6].

With the advent of programmable optical filters, such as the WaveShaper (WS), controlled filtering at the transmitter (prefiltering) has recently been used to reduce bandwidth of signals with broad spectral support. While only a marginal performance penalty is introduced [7], it allows for transport in narrow grids resulting in increased spectral efficiency, as well as enhances signal tolerance towards ROADMs filtering. Simultaneously, WS can be used to introduce pre-emphasis into the signal spectrum to combat BW limitation of electrical components as was recently reported for an 80 Gbaud system [3].

In this paper, we further investigate and compare different optical prefilters for 56 Gbaud DP-QPSK signal transmission. We analyze three different filter shapes (rectangular, Gaussian, pre-emphasis) and show that filtering can improve BER compared to unfiltered signal. We then analyze crosstalk from neighboring (interfering) channels and perform an experiment with five, 224 Gbit/s (DP QPSK and 16-QAM) 65 GHz-filtered channels aligned to 75 GHz grid, which leaves sufficient margin for propagation over at least 300 km of standard single-mode fiber (SSMF) with three ROADMs at 100 km spacing.

2. Experimental setup

Experimental setup is shown in Fig. 1. CW light at 1550.116 nm, being the channel under test (CUT), was originating from a 100 kHz-linewidth external cavity laser (ECL). The light source was followed by an optional pulse carver (PC). The PC was either clocked at 28 GHz which was resulting in a 67% duty cycle return-to-zero (67%RZ) pulse train or if no clock signal was present, the CW light was passing through without pulse carving, effectively removing PC from the setup. After the pulse carver, a 22 GHz BW in-phase/quadrature (I/Q) modulator was placed.

* Corresponding author. Fax: +45 4593 6581.
E-mail address: rbor@fotonik.dtu.dk (R. Borkowski).

1068-5200/$ - see front matter © 2013 The Authors. Published by Elsevier Inc. All rights reserved.
http://dx.doi.org/10.1016/j.yofte.2013.11.006

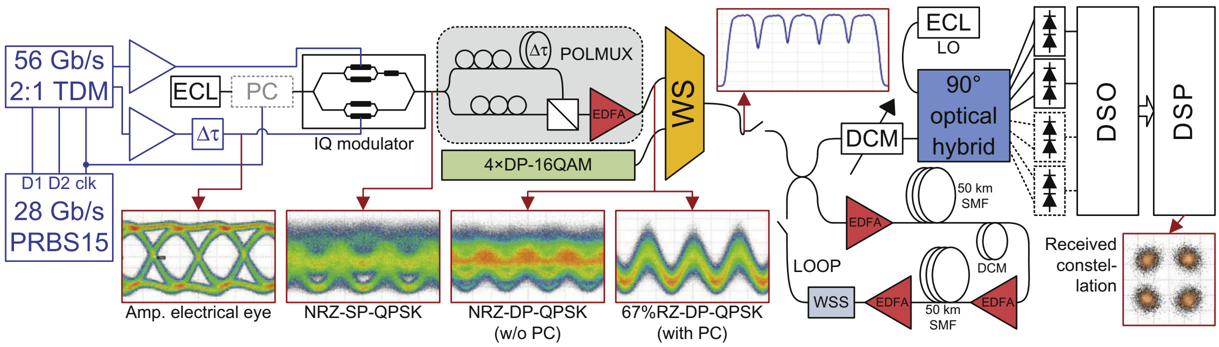

Fig. 1. Experimental setup, 56 Gbaud eye diagrams, optical spectrum (magnified in Fig. 3) and received constellation.

The electrical data signal, $2^{15}-1$ pseudo-random binary sequence (PRBS-15), for the I/Q modulator originated from a 28 Gbit/s pattern generator with two outputs. Both electrical outputs produced sequences offset by a quarter of their length and were subsequently time-division multiplexed (TDM) to obtain 56 Gbit/s two-level electrical signal by interleaving both 28 Gbit/s input signals. Normal and inverted outputs of the TDM device were amplified, each to 4.4 V_{pp} (eye diagram shown in inset in Fig. 1), decorrelated by cables of different lengths and a delay line, and provided to I and Q inputs of the modulator to result in 112 Gbit/s (56 Gbaud) single polarization (SP) QPSK optical signal. This modulated signal was then polarization-division multiplexed by combining it with its delayed copy in the orthogonal polarization state. The obtained 224 Gbit/s (56 Gbaud) DP signal was subsequently amplified with erbium-doped fiber amplifier (EDFA) to account for components' losses and connected to one of the ports of the WS.

For experiments involving wavelength-division multiplexing (WDM), a subsystem generating four 28 Gbaud (224 Gbit/s) RZ-DP-16QAM interfering channels tightly surrounding the CUT was connected to another WS input. The WS was used to apply spectral shaping to connected input signals, separately to the CUT and the interfering channels, and combine them into one output signal.

For transmission experiments, signal was connected to a 2×50 km SSMF loop with a dispersion compensating module (DCM) between both spans, a wavelength-selective switch (WSS) to emulate ROADM filtering and to equalize power, and EDFAs to compensate spans and WSSs losses. A variable DCM was connected at the loop output to fine-tune chromatic dispersion (CD) of the signal after propagation in the loop. The need for such accurate chromatic dispersion compensation was due to limited capabilities of the receiver, which are described further. For back-to-back experiments, the transmission loop was omitted and signal from the WS was directly connected to the receiver.

The receiver was built from discrete components as none of the available commercial 100G integrated coherent receivers exhibited sufficient performance with the CUT. The received signal was mixed with a local oscillator, CW signal from a 100 kHz-linewidth ECL spectrally separated from the CUT laser by a couple of hundreds of MHz, in a 90° optical hybrid. Four of the hybrid outputs, responsible for one of the polarizations, were supplied to two balanced photoreceivers (BPRXs) with 30 GHz BW. Since BPRXs were equipped with limiting transimpedance amplifiers (TIAs), their output amplitude was effectively limited to two levels. This, in turn, prevented digital signal processing-based (DSP-based) CD compensation and necessitated the use of DCM. One of the CUT polarizations was always aligned to the state of polarization received from the hybrid to assure minimum polarization mixing. Electrical signals from BPRXs were sampled at 80 GSa/s (≈1.43 Sa/symbol) with 30 GHz-BW oscilloscope. Traces were captured and subsequently processed with offline DSP [7] algorithms to equalize received constellation.

2.1. Optical prefiltering

Unfiltered signal spectra are shown for reference in Fig. 2(a). Due to RZ shaping, the spectral support of RZ signal is approximately twice that of NRZ signal. Amplitude responses of filters applied to the WS are shown in Fig. 2(b–d). Designed and measured 3 dB and 10 dB responses are listed in Table 1.

The pre-emphasis filter (Fig. 2(d)) is an inverse of the transmitted signal spectrum in the interval equal to the filter BW and zero elsewhere. Effectively, it attenuates low- and mid-frequency components and results in approximately rectangular optical spectrum. The filter attenuation, α_{Pre}, expressed in linear scale, where 1 corresponds to complete attenuation and 0 to no attenuation, is given by Eq. 1 as

$$\alpha_{Pre}(f)=\begin{cases}1-\frac{\min P(f)}{P(f)} & \text{for} \quad -\frac{BW}{2}\leqslant f\leqslant\frac{BW}{2}\\ 1 & \text{otherwise}\end{cases}, \tag{1}$$

where f is the optical frequency relative to the WDM channel center, $P(f)$ is the discrete optical power spectrum measured at the transmitter output, and BW is the filter 3 dB bandwidth. This filter a zero-forcing equalizer applied at the transmitter that helps to mitigate intersymbol interference (ISI). The optical spectrum processed with a set of those filters is shown in Fig. 3(a).

We compare it with two, simpler to implement filters. Rectangular (Fig. 2(b)) filter, as defined by Eq. 2 has a flat amplitude response across its BW and a sharp cutoff outside of its BW. Its attenuation, α_{Rect}, is specified as

$$\alpha_{Rect}(f)=\begin{cases}0 & \text{for} \quad -\frac{BW}{2}\leqslant f\leqslant\frac{BW}{2}\\ 1 & \text{otherwise}\end{cases}. \tag{2}$$

The specification of Gaussian filter is given by Eq. 3 (Fig. 2(c)). Its shape follows a Gaussian function with full width at half maximum equal to the filter BW. Spectral components outside of the WDM grid slot are cut off.

$$\alpha_{Gauss}(f)=\begin{cases}1-\exp\left(-\frac{f^2}{2[BW/(2\sqrt{2\ln 2})]^2}\right) & \text{for} \quad -37.5\,\text{GHz}\leqslant f\leqslant 37.5\,\text{GHz}\\ 1 & \text{otherwise}\end{cases}. \tag{3}$$

As measured from the spectrum of the rectangular filter, the WS has a 0.85 dB/GHz roll-off in the transition band and bandwidth setting resolution of approximately 1 GHz.