40 Gbit/s on-off-keyed system with 5.71 GHz clock recovery circuit using duty cycle division multiplexing

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ABSTRACT

Principle of 7 × 5.71 Gbit/s on-off-keyed (OOK) over duty cycle division multiplexing (DCDM) technique is presented. The 40 Gbit/s DCDM signals are then recovered with a receiver operates at 5.71 GHz clock using seven sampling circuits. With seven-user DCDM we show that spectral width of return-to-zero signal can be reduced around 42.8 %. The 40 Gbit/s OOK using DCDM required an optical signal-to-noise ratio of around 31.6 dB and tolerate around 50 ps/nm of chromatic dispersion. In addition, performance of the system is compared against other multiplexing techniques and modulation formats.

Keywords: Fiber optics communications, multiplexing, clock recovery, RZ duty cycle

1. INTRODUCTION

Multiplexing and modulation play an important role in communication systems. Different multiplexing techniques and modulation formats are proposed to improve channel utilization of communication systems. The invention of wavelength division multiplexing (WDM) [1] greatly improved channel utilization of the optical communication systems especially after the introduction of Erbium-doped fiber amplifier (EDFA) [2-4]. Using WDM, about forty channels can be multiplexed in the C-band at 100 GHz (0.8 nm) channel spacing [1]. The higher capacity can be supported by using dense WDM [5-8]. Using such structures, 2.5 Tbit/s transmission is experimentally reported in [5] by multiplexing 256 × 12.5 Gb/s and 12.5 GHz spacing. However, the costs of such systems are tremendously high due to requiring laser and optical filters for each individual channel. The cost of WDM system can be significantly reduced by transmitting higher bit rate per WDM channel. Time division multiplexing (TDM) is the most commonly used technique for such purpose. For example, 40 Gbit/s data stream can be achieved by multiplexing four 10 Gbit/s data using electrical TDM (ETDM) [9, 10]. Using such system, 3.2 Tbit/s (80 × 40 Gbit/s) WDM/ETDM transmission is experimentally reported [11]. In ETDM, both multiplexer and demultiplexer are required to operate at the speed equal to the channel aggregate bit rate. Thus, the maximum bit rate per WDM using ETDM is limited by the speed of electronic components.

On the other hand, increasing the bit rate per WDM channel caused to shorter pulse width and therefore more complicated clock and data recovery process is needed. Using return-to-zero (RZ) line coding, the bit level synchronization is improved with the cost of requiring higher spectral width.

Polarization division multiplexing (PDM) [12, 13], differential quadrature phase-shift keying (DQPSK) [14-17], and duobinary (DB) [18, 19] are the techniques that can be used to increase the bit rate per WDM channel by requiring transmitter and receiver operate at channel baud rate or symbol bit rate. However, they are limited to support only two users per WDM channel.

Duty-cycle division multiplexing (DCDM) is another technique that is able to increase the channel utilization of WDM system [20, 21]. This technique is implemented based on RZ duty cycle, in which different users are assigned specific RZ duty cycle values. This technique offers a good clock transition, which allows the receiver to operate at the speed equal to symbol rate for clock and data recovery. In comparison to conventional RZ (RZ-TDM), DCDM does not required symbol synchronization and has smaller spectral width. The multiplexing process of DCDM can be performed

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either in the electrical domain or in the optical domain. The focus of this paper is on the DCDM that is multiplexed in the optical domain. Performance of three 10 Gbit/s OOK channels multiplexed using DCDM and transmitted over single WDM channel was reported in [22, 23]. In this paper, we analyze the performance of 7 × 5.71 Gbit/s OOK using DCDM. We evaluate performance of the system in terms of optical signal-to-noise ratio (OSNR), chromatic dispersion tolerance, spectral width, and clock and data recovery speed.

2. SIMULATION SETUP

Fig. 1 (a) shows the simulation setup of seven-user DCDM. Data of user 1 (U1) to user 7 (U7), each with 5.71 Gbit/s pulse at pseudo random binary signal (PRBS) 2^{10}–1, are carved using seven RZ (RZ1 to 7) pulse generators each with different duty cycles (DCs). For simplicity, in this study, the RZ DCs are uniformly distributed. DC of the i^{th} RZ pulse generator, T_i, calculated as

$$T_i = \frac{i \times T_s}{n+1} \tag{1}$$

where T_s represents the multiplexed symbol duration as shown in Fig. 1 (b) and n is the number of multiplexed user. Output of the RZ signals are modulated onto a laser diode (LD) signal operated at 1550 nm optical carrier using seven Mach-Zehnder modulators (MZMs) (M1 to 7). The MZMs used in this simulation have a fixed extinction ratio of 30 dB. Output of the LD is divided into seven branches with equal power using a splitter and launched into seven MZMs. Then the modulated signals output from the MZMs are synchronously multiplexed using an optical power combiner. To avoid phase difference between the signals at the seven branches, the branches are assumed to have the same fiber lengths. Output of the multiplexer (or the optical power combiner) is a step down shape signal with $n + 1$ levels and also $n + 1$ slots. The last slot is used as the guard slot for improving the self-symbol synchronization properties of the DCDM technique. Fig. 1 (b) shows a back-to-back eye diagram for the seven multiplexed channels. Fig. 2 shows example of a multiplexing process in detail for multiplexing four users using DCDM technique, where Fig. 2 (a) shows the 16 ($2^n = 2^4$) possible combinations of bits for multiplexing four users. Based on the binary values shown in Fig. 2 (a), Figs. 2 (b) to (e) show a schematic signal of the U1 to U4 outputted from four RZ pulse generators (RZ1 to RZ4) respectively. Fig. 2 (f) shows the DCDM multiplexed signals.

At the receiver side, the optical signal is detected by a p-i-n photodiode and passed through a low-pass filter (LPF) followed by the DCDM demultiplexer. The Gaussian electrical LPF is used to minimize system noises with a cut-off frequency of 34.3 GHz (0.75 of the null-to-null bandwidth).

In the demultiplexer (Fig. 1 (c)), a clock recovery circuit (CRC) and an edge detecting circuit (EDC) are used to recover 5.71 GHz clock and detect the beginning of each multiplexed symbol [24]. The 5.71 GHz clock recovered referring to the impulse transition in the DCDM signal spectrum. The signal spectrum is shown in Fig. 3 (a). On the other hand, the beginning of each multiplexing symbol is detected using the EDC, since there is one and only one rising edge transition per multiplexed symbol, which appears at the beginning of the symbol as highlighted in Fig. 2 (f). Then, by detecting this rising edges, the beginning of each symbol is determined. Seven sampling circuits are synchronized with the edge detected signals. By putting an appropriate delay lines [25] for each of the sampler as shown in Fig. 1 (c), the first, second, …, and seventh sampler (S1, S2, …, and S7) take samples at $T_s/16$, $3T_s/16$, …, and $13T_s/16$ s per symbol respectively. The frequency of all samplers is equal to the symbol rate ($1/T_s$), which is equal to 5.71 GHz. Outputs of the samplers are fed into the decision and regeneration unit. In this unit, the sampled values are compared against seven threshold values, thr_1 to thr_7. For U1, the decision is made based on the information taken from the two consecutive sampling points, S1 and S2. If amplitudes of those two adjacent sampling points are equal, bit 0 is regenerated. On the other hand, when the amplitude at S1 is one level greater than S2, bit 1 is regenerated. The same method is used for U2, which utilizes information extracted from S2 and S3. The same pattern is applied to the other users. Only the last user, U7, is recovered by comparing amplitude of S7 against thr_1. Decision rules for data recovery are designed for each individual user, which is not presented in this paper. Bit error rate (BER) in this paper is calculated based on the probability of error method [21].

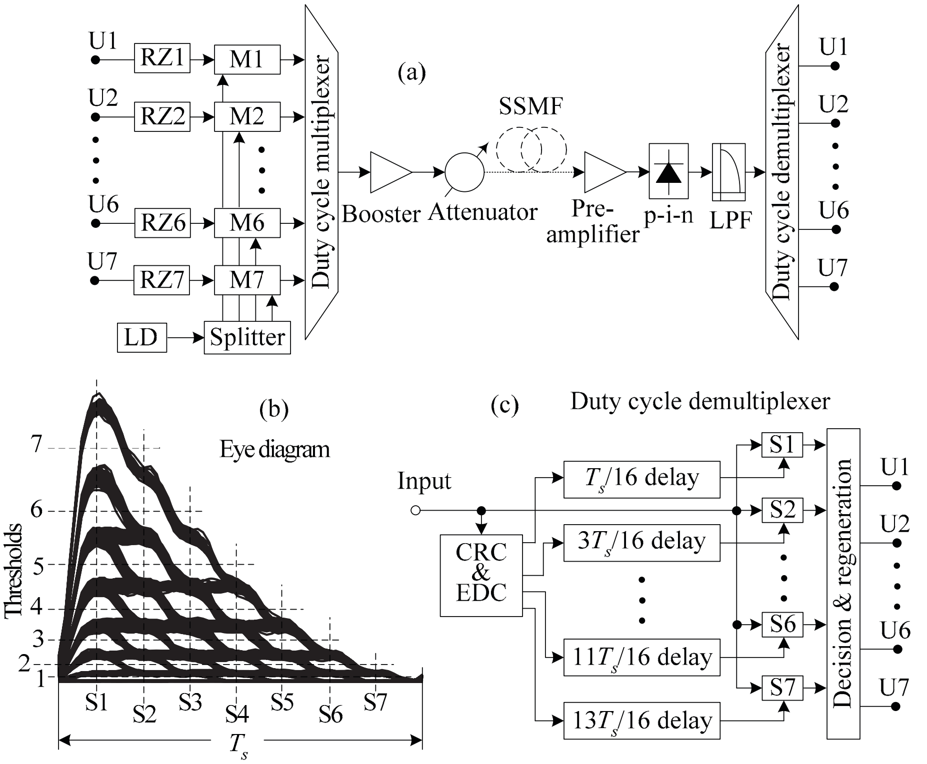

Fig. 1. (a) DCDM simulation setup for multiplexing 7 channels, (b) eye diagram, and (c) demultiplexer.

(a)

Cases	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
U1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1
U2	0	0	1	1	0	0	1	1	0	0	1	1	0	0	1	1
U3	0	0	0	0	1	1	1	1	0	0	0	0	1	1	1	1
U4	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1

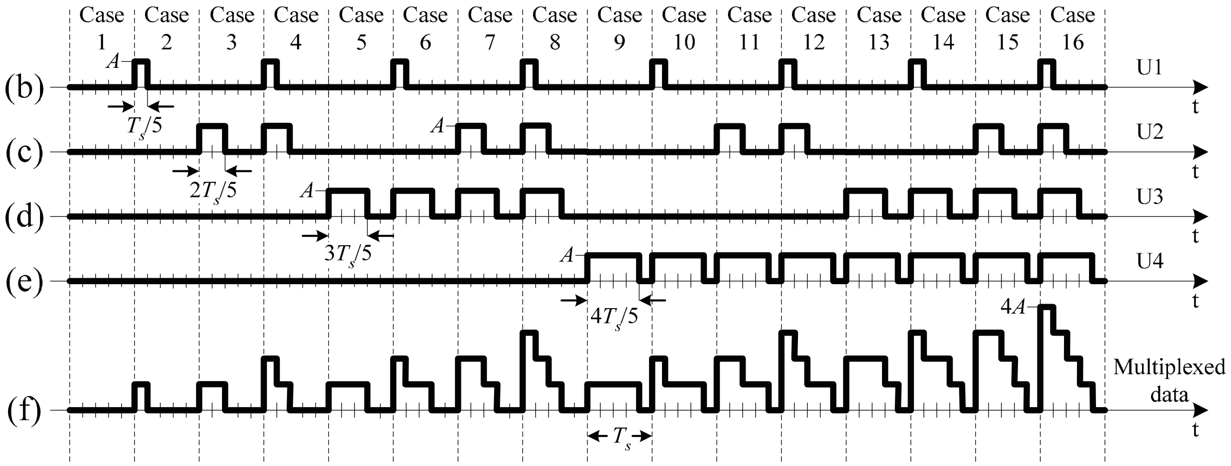

Figure 2. (a) 16 possible combinations of bits for four users, (b), (c), (d) and (e) signals for U1, U2, U3 and U4 respectively, and (f) DCDM multiplexed signals.

3. RESULTS AND DISCUSSION

Fig. 3 (a) shows spectrum of 40 Gbit/s (7 × 5.71 Gbit/s) DCDM system. For comparison purpose, spectrum of 40 Gbit/s RZ-OOK is shown in Fig. 3 (b). The seven-user DCDM has a null-to-null modulated spectral width of 91.43 GHz, which is around 42.8 % shorter than RZ spectral width. Seven-user DCDM system provides seven impulse transitions in its spectrum. As shown in the figure, the first impulse transition located at frequency 5.71 GHz, which is equal to the multiplexed signal symbol rate ($1/T_s$). The other impulses are repeated with a frequency range of 5.71 GHz away form the first impulse. By detecting the first impulse at 5.71 GHz, a clock of 5.71 GHz can be recovered from the received signals. As explained in Section 2, utilizing seven sampling circuits all operating at the same frequency of 5.71 GHz, and appropriate delay lines, the original data can be recovered at the symbol rate without requiring extra information for symbol level synchronization. Whereas, conventional RZ provides only one impulse transition with frequency of 40 GHz, which requires a 40 GHz receiver for clock and data recovery process. In addition to that, DCDM is a self-synchronized multiplexing system whereas TDM required for extra symbol synchronization scheme.

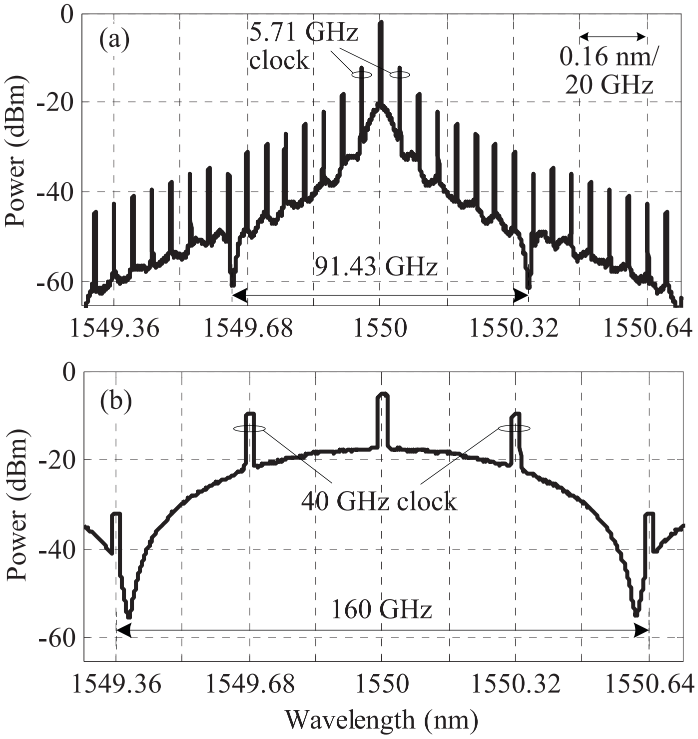

Fig. 3. (a) Spectra of 7 × 5.71 Gbit/s DCDM system and (b) spectra of 40 Gbit/s RZ.

Figs. 4 (a) and (b) show back-to-back pre-amplified receiver sensitivity and OSNR of 7 × 5.71 Gbit/s DCDM system respectively. In general, in both figures, all the seven users show almost similar performance. Referring to BER 10^{-9}, the worst user in this system required a receiver sensitivity of around –21.9 dBm and an OSNR of around 31.6 dB.

Fig. 5 shows the effect of chromatic dispersion on the seven-user DCDM system. All the seven users tolerate almost the same amount of chromatic dispersion. The worst user in the system can tolerate chromatic dispersion of around ±51 ps/nm.

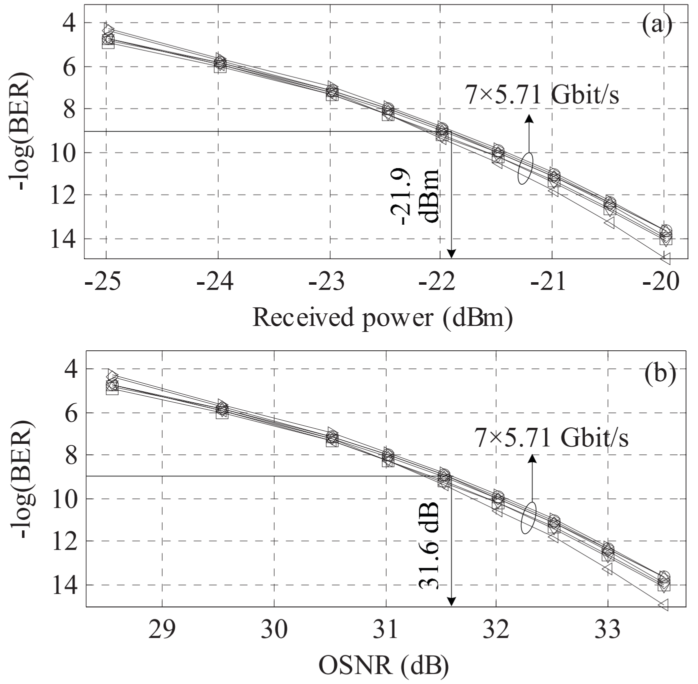

Fig. 4. Performance of 7 × 5.71 Gbit/s DCDM system, (a) Pre-amplified receiver sensitivity and (b) OSNR.

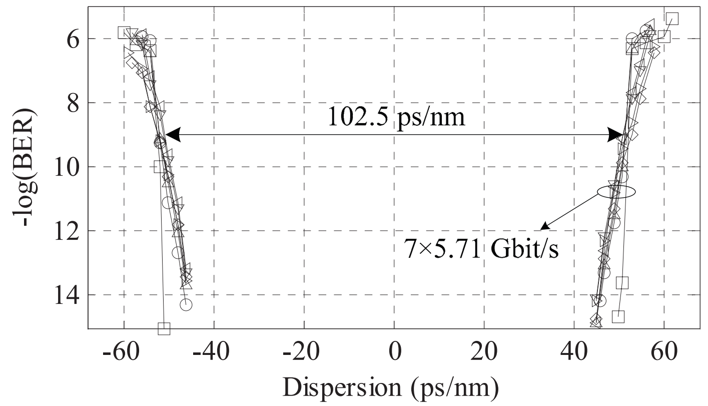

Fig. 5. Chromatic dispersion tolerance of 7 × 5.71 Gbit/s DCDM system.

For comparing DCDM with other techniques, Table 1 shows a comparison between DCDM and some other available multiplexing and modulation techniques based on simulation and/or experimental (Exp) reports. The comparison in this table is made based on the transmitter (Tx) and receiver (Rx) complexity, OSNR, chromatic dispersion (CD) tolerance, null-to-null modulated spectral bandwidth (BW), and clock recovery frequency. In terms of Tx complexity, DCDM has a costly Tx due to requiring one optical modulator for each multiplexing user. Instead it has a low cost receiver due to requiring only one PD, similar to the binary signaling. In terms of system performance, DCDM suffers from sensitivity penalty in compare to the other techniques. In terms of CD, it is comparable to the binary signaling but much less than DB and DQPSK. In terms of bandwidth requirement, DCDM has much smaller bandwidth as compared to the RZ binary signaling but it required higher bandwidth than the NRZ signaling, DB and DQPSK. In terms of CRF, DCDM required very low speed clock recovery system in comparison to the all other techniques.

Table 1. Comparison amongst different multiplexing techniques and modulation formats.

40 Gb/s	Complexity		OSNR (dB) at BER 10^{-9}	CD (ps/nm)	BW (GHz)	CRF (GHz)
Modulation format	Tx	Rx				
NRZ-OOK	1 M	1 PD	~23.3 (Exp) [6] 19.8 [26]	54	80	40
RZ-OOK	1 RZ-PG, 1 M	1 PD	~21 (Exp) [6] 18.3 [26]	48	160	40
CS-RZ-OOK	1 RZ-PG, 1 M	1 PD	18.8 [26]	42	120	40
NRZ-DPSK	1 M	1 DI + 2 PDs	18.5 [27] ~20 (Exp) [6]	74	80	40
RZ-DPSK	2 Ms	1 DI + 2 PDs	~18 (Exp) [6]	50	160	40
DB	1 M	1 PD	22.4 [26]	211	40 [28]	
NRZ-DQPSK	2 nested Ms	2 DIs + 4 PDs	20.5 [27] ~24.5 (Exp) [6]	168	40	20
RZ-DQPSK	2 nested Ms, 1 PC	2 DIs + 4 PDs	17.7 [26] 20.2 [27] ~23.3 (Exp) [6]	161	80	20
RZ-DQPSK PDM [29]	3 PCs, 2 Ms, 1 PM, 1 RZ-PG, 2 PBSs, 1 PBC [30]	1 PS, 1 PBS, 2 DIs, 4 PDs, PC [31]	13.7 (Exp) [30]		40	10
NRZ-16-QAM	3 PCs, 1 M [32]	2 PDs, 3 PCs, 1 Pol, 1 TFL [32]	20.9 [26]			
7-user DCDM	**7 RZ-PG, 7 Ms**	**1 PD**	**31.6**	**50**	**91.43**	**5.71**

WDM: Wavelength division multiplexing
DQPSK: Differential quadrature phase-shift keying
QAM: Quadrature amplitude modulation
PDM: Polarization division multiplexing
CRF: Clock recovery frequency
PBC: Polarization beam combiner
PBS: Polarization beam splitter
NRZ: Non return-to-zero
CD: Chromatic dispersion
OOK: On-off keying
PS: Polarization stabilizer
DI: Delay interferometer
PC: Polarization controller
TFL: Tunable fiber laser
RZ: Return-to-zero
BW: Bandwidth
Tx: Transmitter
Exp: Experimental
PD: Photodetector
PG: Pulse generator
M: Modulator
Pol: Polarizer
Rx: Receiver
DB: Duobinary

4. CONCLUSION

DCDM technique with the capacity of 40 Gbit/s is reported. Performance of DCDM was assessed in terms of OSNR and chromatic dispersion tolerance. Null-to-null spectral width for the aggregated bit rate of 40 Gbit/s is presented and compared with RZ-OOK. Seven-user DCDM with 91.43 GHz spectral width has around 42.8 % smaller spectral width in comparison to the conventional RZ-OOK. Due to the self-symbol synchronization property DCDM technique allows the aggregated capacity of 40 Gbit/s to be recovered by 5.71 GHz receiver and clock recovery system. This results in the usage of lower speed electronic component thus reduces the cost as compared to RZ-TDM, which required 40 GHz receiver.

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