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Optimizing 10 Gbps optical communication system with duty cycle selection of return to zero pulse

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Abstract

We have investigated the return-to-zero (RZ) pulse duty cycle for single-channel Standard Single mode fiber (SSMF), Non Zero Dispersion shifted fibers (normal NZDSF and anomalous NZDSF fiber) for 10 Gbps optical fiber communication system. We give a comprehensive look on the behavior of variable duty cycle optical RZ pulse indicating that lowest bit error rate for duty cycle 0.8 among the duty cycle values 0.2, 0.4, 0.6 and 0.8 investigated for the case of SSMF. The single repeaterless mode fiber length is increased from existing 55 km at duty cycle 0.2 to fiber length 85 km by keeping duty cycle at 0.8. The result is also emphasized through the 10 dB *Q* value improvement and corresponding improvement in average eye opening diagram. The normal NZDSF show similar improvement but at greater fiber length, it offers BER 10^{-9} at length 110 km with duty cycle 0.2. NZDSF operating length can further be increased to length 160 km by keeping duty cycle 0.8. The corresponding 8 dB *Q* value improvement and Average eye opening improvement also supports the result through its graphical variation. Thirdly Anomalous NZDSF for same optical communication system showed that 0.2 duty cycle value give operational length of 130 km which could be extended to 160 km if 0.8 duty cycle is kept. The corresponding 8 dB *Q* value improvement, average eye-opening improvement endorsed the fact in the graphs.

Keywords: RZ pulse width; Dispersion compensation length; Timing jitter; Bit error rate; *Q* value

1. Introduction

For intensity-modulated direct-detection (IM/DD) systems, there are two possible modulation formats, nonreturn-to-zero (NRZ), in which a constant power is transmitted during the entire bit period, and return-to-zero (RZ), in which power is transmitted only for a fraction of the bit period. The question of which format has better receiver sensitivity, although addressed more than 20 years ago by Personick [1], periodically resurfaces. This perennial debate was carried further by studying its transmission implications. Personick, and later Marcuse [2] for amplified systems, have considered the comparison of RZ and NRZ assuming an ideal transmission medium, and concentrating on receiver performance. The transmission impairments

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introduced by the optical fiber dispersion and nonlinear effects were considered for both modulation formats. It is shown that NRZ is in general more robust against degradations due to fiber propagation. This is the case for both deployed systems (in which case RZ and NRZ are compared for the same value of dispersion). For simplicity, RZ modulation with rectangular pulse shape was assumed. Furthermore, interaction among the propagation effects is neglected [2].

The dependence of the 10-Gb/s/ch long-distance transmission performance on the signal pulse duty factor is studied by numerical calculations and experiments [3]. The dependence of the 10-Gb/s/ch long-distance transmission performance on the signal pulse duty factor was investigated. It is clarified that the optimum duty factor depends on GVD compensation interval for single-channel transmission. Reducing the duty factor was effective in suppressing XPM induced waveform distortion in WDM transmission. Analysis of both single-channel and WDM transmission showed that duty factors 0.5 were suitable for a dispersion managed system with GVD compensation interval of 500 km and a fiber dispersion parameter of 1 ps/nm/km.

Going through the literature, a need was felt to have a performance details of optical RZ pulse in other fiber types especially dispersion shifted fibers of optical communication systems [4–17]. Here, issue of which is better duty cycle for RZ pulse, is addressed from a transmission point of view for single channel 10 Gbps optical communication system through the SSMF which is extended to the dispersion shifted regime. The results for variable duty cycle fraction for SSMF, normal NZDSF and anomalous NZDSF are not available as such in the literature, thus explored here to investigate performance contrast among above fiber types under variable duty cycle of RZ pulse.

2. Theory

When a channel is intensity modulated with bit rate $R = 1/T$, and the "one" symbols are transmitted using rectangular pulses with duration ρT. The parameter ρ, $0 < \rho \leqslant 1$, is the duty cycle. The peak power of each pulse is $Pp = P/\rho$, where P is the average power transmitted on a "one" bit. For NRZ, $P\rho = P$. In the following, a single span of an amplified system is considered for simplicity, with length L. The fiber has loss α, effective length $L_e = (1 - e^{-\alpha L A e})/\alpha$, and effective core area A_e. The chromatic dispersion D may vary along the link, according to a prescribed dispersion map.

It was shown by Personick [1] that the optimal input pulse for an IM/DD optical communication system is an impulse. For pin receivers the sensitivity is 2 dB better than for NRZ. Interestingly enough, a duty cycle of 0.5 is sufficient to obtain the bulk of this improvement [1]. For a pre-amplified receiver using an "integrate and dump" filter, Marcuse has shown that the sensitivity depends only on the average received power and not on the duty cycle [2]. However, if a more general electrical filter shape is allowed, Personick's considerations for pin receivers carry over to pre-amplified receivers. This has been verified using the simulator described in [6]. The reason is that with RZ the pulse energy is concentrated in a shorter time interval, providing a larger eye opening for the same filter bandwidth or the possibility of enhanced noise rejection for the same intersymbol interference. This 2-dB sensitivity improvement, although not negligible, is the only advantage that RZ offers over NRZ.

The effect of chromatic dispersion is to introduce a delay among the spectral components of the signal. Since the lower the duty cycle ρ, the larger the bandwidth, it is expected that the effect of dispersion is larger for smaller ρ. A good estimate of the dispersion length, here defined as the length at which the eye opening has a relevant penalty, can be obtained assuming that the pulse is composed of two overlapping pulses separated in frequency by R. Serious degradation results when the fiber dispersion separates the two pulses in time by, therefore

$$L_D = \frac{c}{\lambda^2}\frac{\rho}{R^2 D}, \tag{1}$$

where c is the light speed in free space and λ is the wavelength. Notice that for, (1) gives $L_D R^2 D/\rho = 1.2 \times 10^{20}\,\mathrm{m^{-1}s^{-1}}$, which for conventional fiber (16 ps/nm/km) and for a bit rate of 10 Gb/s results in 75 km.

3. System description

The block diagram of optical communication system considered is given in the Fig. 1 to examine the performance of RZ pulse of variable duty cycle through SSMF, normal NZDSF and anomalous NZDSF with length varied from 5 to 120 km. The data source is pseudo random having bit rate 10 Gbit/s with 31 samples per bit using polynomial of 7 degrees. The adjustable duty cycle RZ driver converts logical inputs to electrical outputs −2.5 V low level and 2.5 V high level with variable duty cycle 0.2, 0.4, 0.6, 0.8. The number of poles in low pass filter has been kept to 5 and uses the −3 dB cutoff frequency 8 GHz.

The modulator is a single-arm Mach-Zehnder amplitude modulator with $\sin^2$ electrical shaped Input–Output (P–V) characteristic. The typical transfer function is taken for a Mach-Zehnder external modulator based on the electro-optic effects in the $LiNbO_3$ devices. The level of extinction ratio (corresponding to the ratio between the maximum and minimum values of the input–output transmission characteristics) is kept ideal.

The input voltage is equal to maximum transmissivity offset voltage and the power of the optical signal is attenuated by the excess loss only so that the modulator attains the state of maximum transmission.

The fiber of length is varied from 5 to 120 km for each type of fiber considered whose typical characteristics are listed in the Table 1, in the presence of fiber non linearity, fiber PMD, fiber birefringence but without Raman crosstalk. The reference wavelength is 1550 nm at which loss is 0.2 dB/km, fiber non-linearity coefficient is 1.23, fiber PMD is 0.1 ps/km$^{0.5}$ and other respective parameters as per list provided in Table 1.

1. **For the case of simple system**

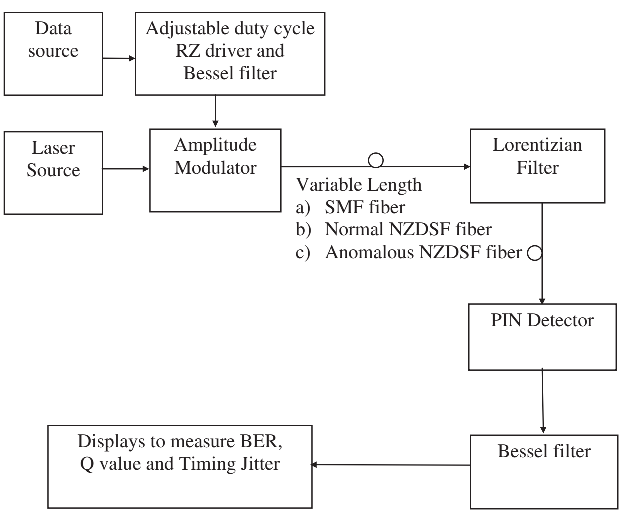

Fig. 1. Optical communication block diagram to examine performance of RZ pulse of variable duty cycle 0.2, 0.4, 0.6, 0.8 for single-mode fiber, normal DSF and anomalous DSF of variable length 5–20 km.

At receiver, optical signal is passed through three-stage Lorentzian filter of center wavelength 1550 nm. The detection is done with the use of PIN photodiode at 1550 nm wavelength of 0.7 quantum efficiency and 0.875 A/W responsivity and 0.1 nA dark current. Electrical filter of Low pass Bessel type with 5 poles & −3 dB bandwidth gives the electrical signal which is subsequently measured for BER, Q value, and average eye opening.

4. Observation and results

Optical communication system model block diagram to examine performance of RZ pulse of variable duty cycle for SSMF, normal NZDSF and anomalous NZDSF of variable length 5–120 km is shown in Fig. 1. Bit error rate (BER), Q value and Average eye opening versus single mode fiber length for variable duty cycle 0.2, 0.4, 0.6, 0.8 of RZ pulse are shown in the Figs. 2–4, respectively. BER graph shows that increasing the duty cycle value from 0.2

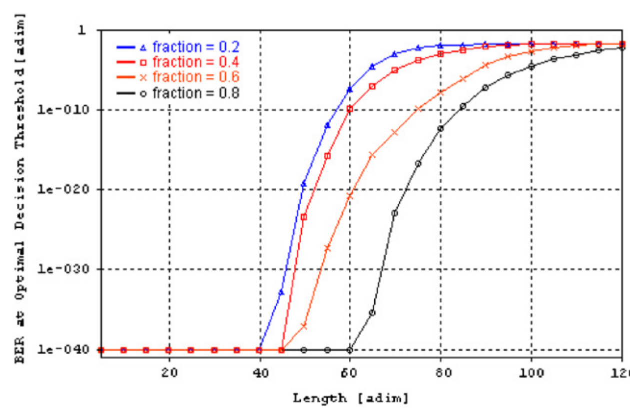

Fig. 2. Bit error rate (BER) versus single-mode fiber length for variable duty cycle 0.2, 0.4, 0.6, 0.8 of RZ pulse.

Table 1. List of fiber parameters considered in the set up

S. no.	Parameter	SSMF	Normal DSF	Anomalous DSF
1.	Core effective area (m^2)	80×10^{-12}	55×10^{-12}	55×10^{-12}
2.	Loss @ $\lambda = 1550$ nm (dB)	0.2	0.2	0.2
3.	Non-linearity refer. wavelength (nm)	1550	1550	1550
4.	Zero dispersion wavelength (nm)	1391.5	1580.24	1522.93
5.	Fiber non-linearity (1/W/km)	1.23	1.23	1.84
6.	Non-linearity refractive index	2.5×10^{-20}	2.5×10^{-20}	2.5×10^{-20}
7.	β_2 (ps^2/km)	−20.407	2.55089	−2.55
8.	β_3 (ps^3/km)	0.14745	0.1096	0.118
9.	Fiber birefringence	On	On	On
10.	First order dispersion-D (ps/nm/km)	16	−2	2
11.	Second order dispersion-D’ (ps/nm^2/km)	0.07	0.07	0.07
12.	Fiber average beat length (m)	5	5	5
13.	Fiber PMD (ps/$km^{0.5}$)	0.1	0.1	0.1

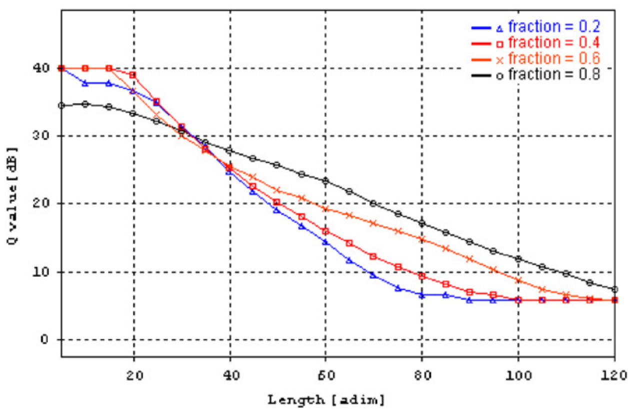

Fig. 3. Average eye opening versus single-mode fiber length for variable duty cycle 0.2, 0.4, 0.6, 0.8 of RZ pulse.

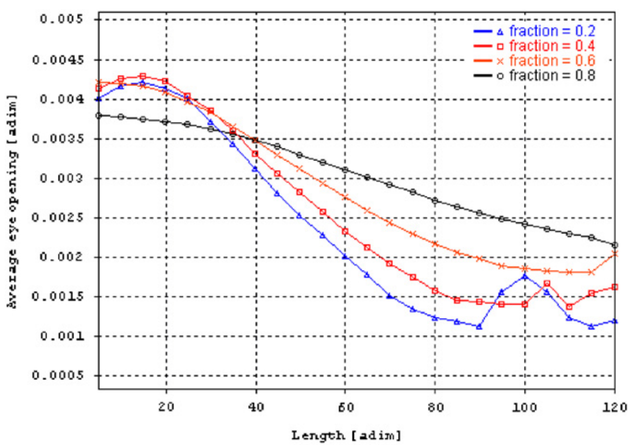

Fig. 4. Average eye opening versus single-mode fiber length for variable duty cycle 0.2, 0.4, 0.6, 0.8 of RZ pulse.

Table 2. List of dispersion length L_D

S. No.	Characteristics	SSMF
1.	First-order Dispersion-D (ps/nm/km)	16
2.	L_D (km) when $\rho = 1$	75
3.	L_D (km) when $\rho = 0.8$	60
4.	L_D (km) when $\rho = 0.6$	45
5.	L_D (km) when $\rho = 0.4$	30
6.	L_D (km) when $\rho = 0.2$	15

to 0.8 provides optical communication link in the range of 55–85 km for the SSMF. The result can be validated by substituting in the relation (1), the calculated values of dispersion length L_D are also shown in tabular form in Table 2.

Normal NZDSF is analyzed for variable duty cycle and shown in Figs. 5–7 represents in sequence BER, Jitter value and Q value average eye opening versus Normal Dispersion Shifted fiber length for variable duty cycle 0.2, 0.4, 0.6, 0.8 of RZ pulse.

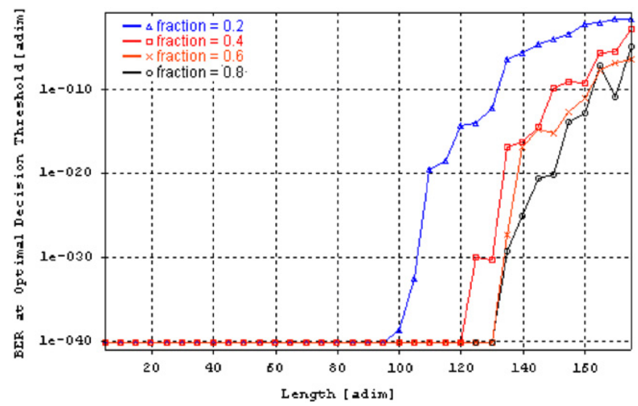

Fig. 5. Bit error rate (BER) versus normal non zero dispersion Shifted fiber length for variable duty cycle 0.2, 0.4, 0.6, 0.8 of RZ pulse.

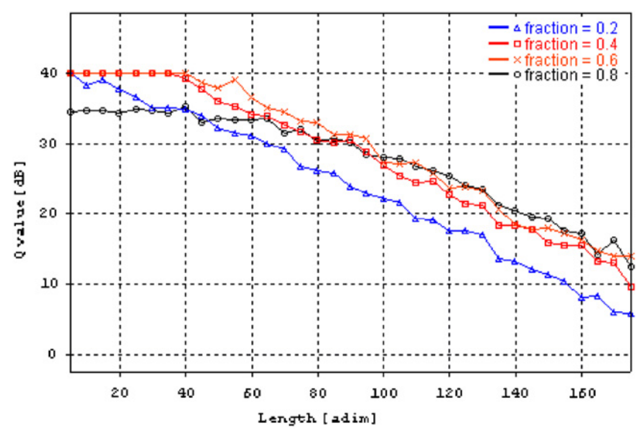

Fig. 6. Q value versus normal non zero dispersion Shifted fiber length for variable duty cycle 0.2, 0.4, 0.6, 0.8 of RZ pulse.

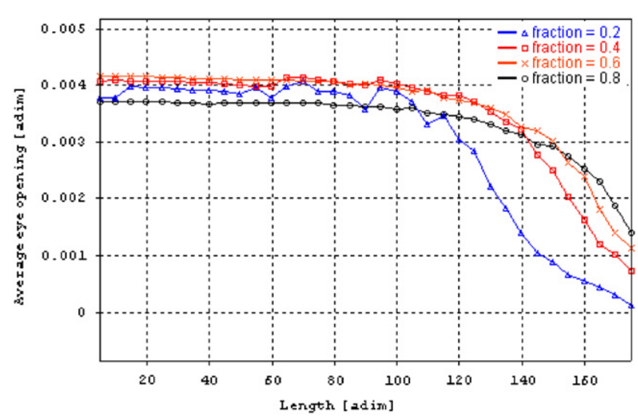

Fig. 7. Average eye opening versus normal non zero dispersion shifted fiber length for variable duty cycle 0.2, 0.4, 0.6, 0.8 of RZ pulse.

Figs. 8–10, indicates BER, Q value and Average Eye opening versus Anomalous dispersion shifted fiber length for variable duty cycle 0.2, 0.4, 0.6, 0.8 of RZ pulse.

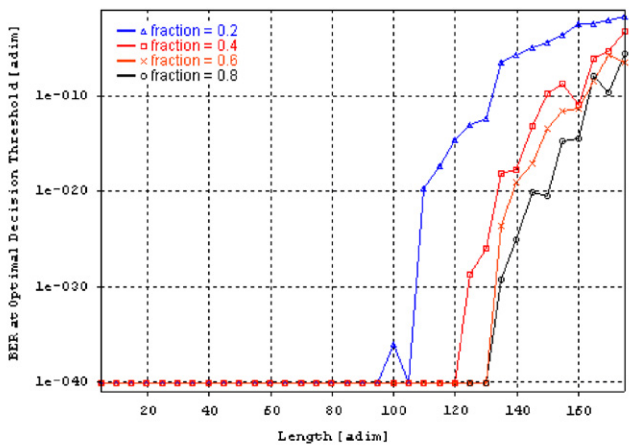

Fig. 8. Bit error rate (BER) value versus anomalous dispersion shifted fiber length for variable duty cycle 0.2, 0.4, 0.6, 0.8 of RZ pulse.

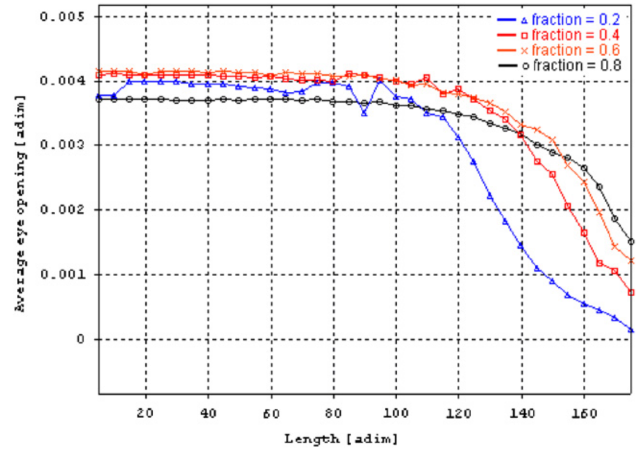

Fig. 10. Average eye opening value versus anomalous non zero dispersion shifted fiber length for variable duty cycle 0.2, 0.4, 0.6, 0.8 of RZ pulse.

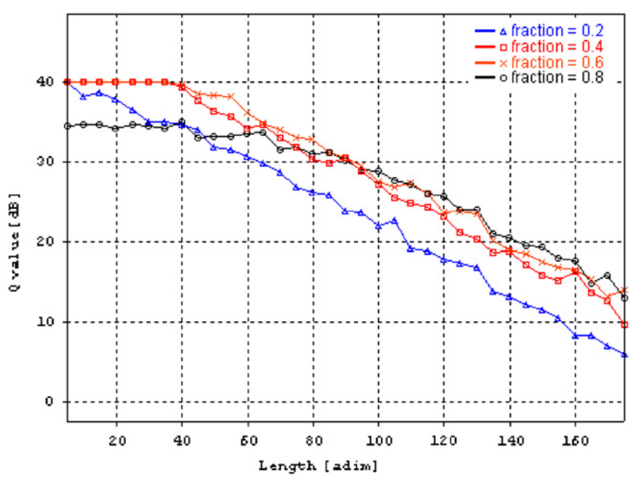

Fig. 9. *Q* value versus anomalous non zero dispersion shifted fiber length for variable duty cycle 0.2, 0.4, 0.6, 0.8 of RZ pulse.

Lowest jitter for duty cycle = 0.2, 0.4 jitter value irrespective of the duty cycle swing from 5 to 25 ps for fiber length increase from 35 to 45 km.

Duty cycle = 0.8 gives better BER up to length = 85 km.

5. Conclusion

With increase in the duty cycle of RZ optical pulse decreases the BER for standard SSMF in optical communication system. For 60 km SSMF drastic change is observed, BER $\ll 10^{-9}$ at 0.8 duty cycle while BER $> 10^{-9}$ is observed at 0.2 duty cycle. A similar trend is observed for *Q* value that showed that in general with every duty cycle, *Q* value decreases with increase in fiber length. At the same time, also observed that higher-duty cycle gives higher *Q* values for long distance greater than 30 km but lower length of fiber i.e. <30 km gives reverse trend. The overall phenomenon is shown through average eye opening diagram for SSMF.

Various duty cycles when seen under normal NZDSF, the similar trend is seen although the low BER length ($<10^{-9}$) is shifted to the length 100 km of fiber which had started deteriorating beyond length 40 km earlier for SSMF at 40 km. The BER trend when seen for each case of duty cycle under consideration, at higher duty cycle 0.8 the transmission viability is up to 150 km for duty cycle 0.2 it reduces to 130 km. Timing jitter figure showed that lesser width or duty cycle give lesser timing jitter. The normal NZDSF results are enforced in *Q* value and average eye opening diagrams.

The anomalous NZDSF when examined under the various duty cycles values, the RZ pulse behaves similarly and emphasize importance of higher duty cycle for lesser BER. The overall transmission viability is reduced to range 100–130 km in relation to duty cycle value. *Q* value, average eye opening indicate parallel variation.

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