Demonstration of RZ-OOK Modulation Scheme for High Speed Optical Data Transmission

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***Abstract*—The optical communication has gained enormous popularity as an effective means of transferring data at high rates because of extremely high bandwidth access and cost effectiveness. On-Off keying (OOK) modulation scheme with direct detection is the most widely used intensity modulation scheme for optical communication. OOK can use either non-return-to-zero (NRZ) or return-to-zero (RZ) pulse formats for communication. RZ modulation format is becoming increasingly popular for high speed data transmission due to its superior performance over conventional NRZ format. In this paper, we demonstrate the design and implementation details for RZ-OOK modulation scheme for various duty cycles. The experimental setup and test results for 1 *Gbps* RZ-OOK transmitter has also been presented. This RZ-OOK transmitter consists of a laser diode followed by two Mach-Zehnder (MZ) modulators connected in cascade. We also present analysis and simulation results such as eye diagram, optical spectrum etc. for RZ-OOK as well as NRZ-OOK modulation schemes for data rates upto 10 *Gbps*.**

***Keywords*: Mach-Zehnder (MZ) modulator, nonreturn-to-zero (NRZ), on-off keying (OOK), return-to-zero (RZ)**

I. Introduction

Optical communication, whether it is fiber based or free space, have revolutionized the telecom industry. Optical fiber forms the backbone of the global telecommunications system. There are several amplitude and phase modulations schemes that are suitable for optical communication systems but OOK is undoubtedly the widely adopted modulation scheme used for optical communication because of ease in implementation, bandwidth efficiency, cost effectiveness and above all it facilitates direction detection too. Also, OOK systems are more robust with regard to atmospheric distortion than a coherently modulated system [1]. The NRZ and RZ signal formats are the two most popular formats for the implementation of OOK modulation technique.

The primary advantage of RZ-OOK over NRZ-OOK is the higher peak power together with the stronger confinement of pulses to the bit slot, results in an increased robustness to ISI generated within the transmitter or within the receiver. In addition, RZ formats are comparatively more robust to many nonlinear propagation distortions [2] [3]. Typically, a gain of $1 - 3dB$ for receiver sensitivity is observed in case of direct detection using RZ coding compared to the NRZ coding for the same average power at the receiver even if the receiver bandwidth is left unchanged [4]$-$[6]. This implies that for a required receiver sensitivity, the transmitted power can be lowered by employing the RZ-OOK modulation scheme rather than the NRZ-OOK. The better receiver sensitivity in the case of RZ-OOK scheme also suggests that the transmission distance can be increased compared with the NRZ-OOK scheme while keeping the transmitted power constant. The analysis of optically preamplified direct detection receivers show that the bit error probability can be reduced if RZ coding is employed instead of NRZ even for the same average optical power and same receiver bandwidth [6] [7]. In case of NRZ signal format, long strings of $1's$ or $0's$ will result in a total absence of any transitions, which makes it difficult for the receiver to recover the clock signal. The RZ format mitigates this problem to some extent since long strings of $1's$ will still produce transitions. In [8], analytical formulas for the power spectra of various RZ optical signals generated by MZ modulators are derived for pulse duty cycles of 33%, 50% and 67%, in conjunction with several modulation techniques including OOK. So, the aforesaid advantages and qualities of the RZ format justifies the requirement of a slightly more complex transmitter structure and bandwidth over NRZ format for OOK modulation scheme.

In this paper, we present the design and implementation details for the RZ-OOK modulation scheme for various duty cycles. The test results for this scheme for the data rate of 1 $Gbps$ have also been presented. The analysis and simulations of the main characteristics of RZ along with NRZ signal format for OOK modulation scheme, such as eye pattern, optical spectrum etc., have also been carried out for data rates upto 10 $Gbps$

This paper is organised as follows. Section II briefly summarizes the RZ-OOK modulation format. In section III, methods for the generation of this modulation scheme for different duty cycles are illustrated. Section IV presents the analysis and simulation results of RZ along with NRZ signal formats for OOK scheme for the data rates of upto 10 $Gbps$. Section V describes the experimental setup and test results. Finally, we conclude the paper in section VI.

II. The RZ-OOK Signal Format

The most common signal formats for OOK modulation scheme are NRZ and RZ. These formats are illustrated in Fig.1. For NRZ, the optical intensity does not return to zero between successive $'1'$ bit i.e. the pulse for a $'1'$ bit occupies the entire bit interval, and no pulse is used for $'0'$ bit. In the RZ format the pulse for a $'1'$ bit occupies only a fraction of the bit interval and no pulse is used for $'0'$ bit. The pulsed nature of RZ always lets the intensity return to zero between two successive $'1'$ bit.

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Due to its basic pulse nature, an RZ signal has many more transitions compared to NRZ and less DC content. There are several variations of RZ format based on the duration of the pulse such as 30%, 50% and 67%. RZ signals require more bandwidth than NRZ signals as the RZ signal switches twice as often as the NRZ signal. The general shape of the spectrum is $\sin x/x$ function for both the schemes.

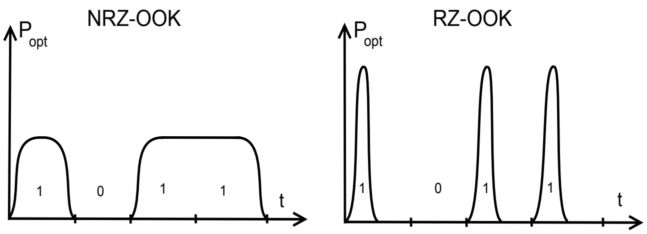

Fig. 1. Optical intensity waveforms for NRZ and RZ signal formats

III. THE RZ-OOK TRANSMITTER

The block diagram depicting the RZ-OOK transmitter is shown in Fig.2. The transmitter consists of a continuous wave (CW) laser followed by two external intensity MZ modulators connected in cascade. The first modulator, acts as a pulse carver, is driven by a microwave signal source, $X_1(t)$. The NRZ data, $X_2(t)$, generated by a pseudo random binary sequence (PRBS) data generator is used to drive the second modulator. Here $E(t)$ denotes the optical field intensity at the input and output port of each MZ modulator.

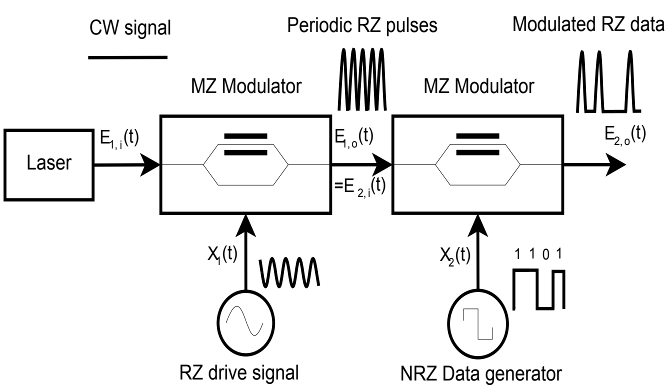

Fig. 2. RZ-OOK signal generation using cascaded MZ modulators

The MZ modulator is based on the principle of interference, controlled by modulating the optical phase. It is made up of a material showing strong electro-optic effect such as lithium niobate $(LiNbO_3)$. The electro-optic effect is the modification of the refractive index of a medium, caused by an electric field. The MZ modulator structure is shown in the block diagram of Fig.2. The input coupler is used to split the incoming optical signal into two paths. By applying a voltage to one (or both) the arms optical signal in each path is phase modulated as the optical path length is altered by the electric field. The applied voltage V modulates the refractive index of the waveguide material and hence phase shift is experienced by a optical signal propagating along the waveguide. Finally, an output coupler combines the two paths exhibiting different phase modulation leads to interference variation from destructive to constructive and thereby converting the phase modulation into intensity modulation.

The optical field transfer function $T_E(V_1, V_2)$ of the MZ modulator is given as [2]

$$\begin{aligned} T_E(V_1, V_2) &= \frac{1}{2}\{e^{i\phi(V_1)} + e^{i\phi(V_1)+i\xi}\} \\ &= e^{\frac{i(\phi(V_1)+\phi(V_2)+\xi)}{2}} \cos\{\frac{(\phi(V_1)-\phi(V_2))}{2} - \frac{\xi}{2}\} \end{aligned} \tag{1}$$

where $\phi(V_i); i = 1, 2$ is the voltage modulated optical phase of the MZ modulator arm, ξ is an additional temporally constant phase shift in one of the arms, referred to as the modulator bias. If the phase modulation varies linearly with the drive voltage i.e. $\phi = kV$, which is true for most materials used for MZ modulators, the MZ modulator power transfer function depends only on the drive voltage difference ΔV

$$T_P(V_1, V_2) = |T_E(V_1, V_2)|^2 = T_P(\Delta V) \tag{2}$$

$$= \cos^2(k\Delta V/2 + kV_b/2) \tag{3}$$

The characteristic sinusoidal MZ modulator power transfer function is shown in Fig.3. The modulation voltage that is required to change the phase in one modulator arm by π, thereby letting the MZ modulator switch from full transmission to full extinction, is called switching voltage V_π. The desired operating point, such as maxima, minima or quadrature point, over the optical transfer characteristics of the modulator is selected by the bias voltage applied to the DC electrodes.

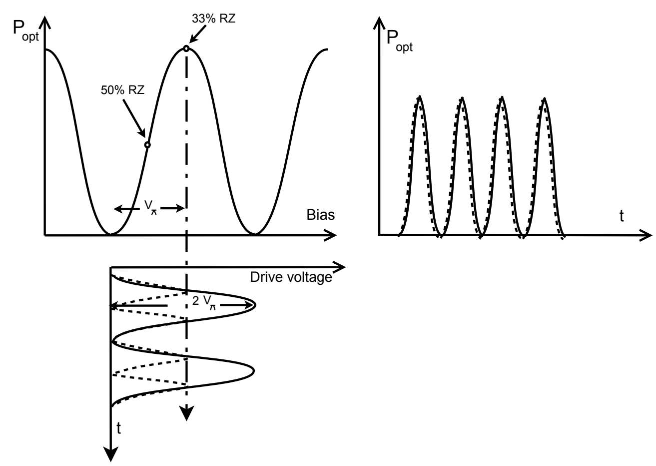

Fig. 3. MZ modulator as a pulse carver for 33% and 50% (dashed) duty cycle RZ waveform

The MZ modulator is the heart of the RZ-OOK transmitter. The beauty of the MZ modulator is that, it can be used to perform variety of operations by driving it in different ways. In this experiment it is used to generate RZ optical pulses as well as for data modulation. Depending on the drive waveform amplitude and DC bias to the MZ modulator, RZ pulses can have duty cycles of 33%, 50%, and 67%. The RZ optical pulses for different duty cycles are usually generated by three different methods.

- 33% duty cycle RZ pulses as shown in Fig.3. can be generated by sinusoidally driving MZ modulator with an amplitude of V_π between its transmission minima at half of the RZ pulse frequency.

- 50% duty cycle RZ pulses can be generated by sinusoidally driving MZ modulator with an amplitude of V_π between minimum and maximum transmission i.e. in the linear region at the same RZ pulse frequency as shown in Fig.3.
- 67% duty cycle RZ pulses can be generated by sinusoidally driving MZ modulator with an amplitude of $2V_\pi$ between its transmission maxima at half of the RZ pulse frequency. This pulse format is often referred to as carrier suppressed RZ (CSRZ).

The NRZ-OOK signal can also be generated using MZ modulator by biasing at quadrature point i.e. 50% transmission and driving it from minimum to maximum transmission with a voltage swing of V_π.

IV. Analysis and Simulation

The simulation has been carried out using the Optisystem software tool to study the performance of RZ as well as NRZ modulation schemes in optical domain. The eye diagram for NRZ and RZ modulated optical data is presented in Fig.4. It is a composition of several transmitted $1's$ and $0's$ overlaid on top of each other in a single display. The RZ signal transmission of logic $'1'$ will always begin at zero and end at zero. It can be seen that all $'1'$ pulses, whether they are preceded by and followed by a $'1'$ or a $'0'$, start and end at the low power state and hence there are no crossover points. In contrast, the NRZ diagram shows how a $'1'$ will stay at the high level if the preceding bit is a $'1'$.

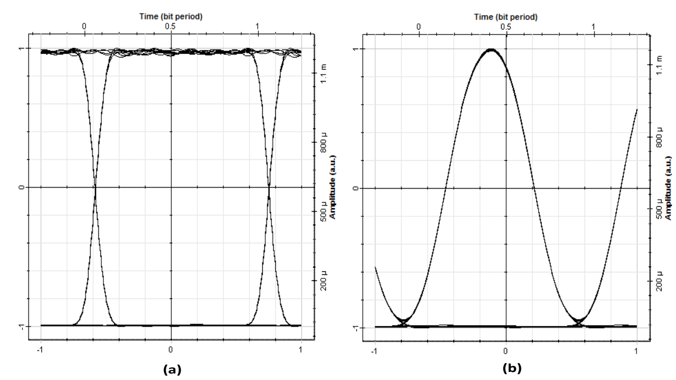

Fig. 4. Eye diagram of (a) NRZ signal (b) RZ signal for OOK modulation scheme

Fourier transform theory indicates that the signals of short duration have wide spectral width and vice versa. Fig.5 shows the optical spectrum of NRZ signal for 1 and 10 $Gbps$ data rate. We have presented the spectrum plots for 10 $Gbps$ data rate along with the 1 $Gbps$, as the qualitative information about main lobe, side lobes, peaks etc. can be seen explicitly in case of 10 $Gbps$ spectrum. The optical spectrum of 33% RZ-OOK, 50% RZ-OOK and 67% RZ-OOK signals is shown in Fig.6, Fig.7 and Fig.8 respectively. A comparison of the main lobes from Fig.6 to Fig.8 show that the 33% RZ pulse that has the shortest time duration has the widest main lobe, whereas the

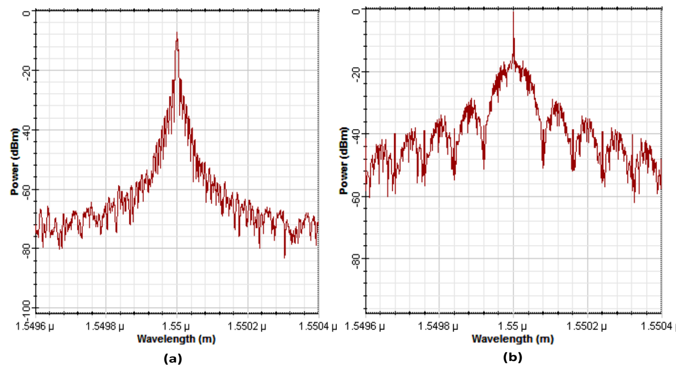

Fig. 5. Optical spectrum of NRZ-OOK signal for (a) 1 Gbps (b) 10 Gbps data rate

67% RZ pulse with the longest time duration has the narrowest main lobe. The heights of the side lobes are also very important when computing signal bandwidths based on the containment of a given percentage of total power. There is a monotonic decrease in the bandwidth, considering 90% of the total power, as the duty cycle progresses from 33% (Fig.6) to 67% (Fig.8). In [7], it is shown that as the duty cycle is decreased, significant gain in terms of receiver sensitivity is achieved.

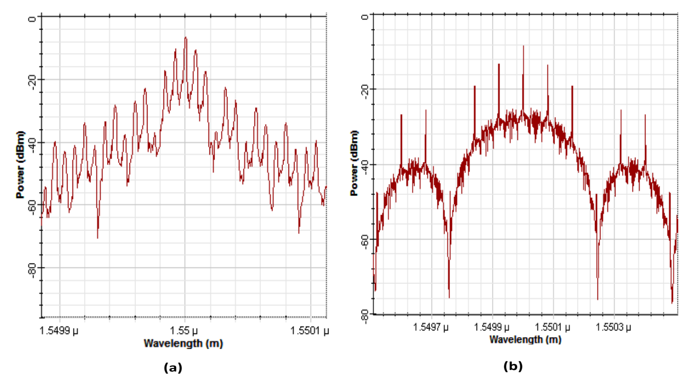

Fig. 6. Optical spectrum of 33% RZ-OOK signal for (a) 1 Gbps (b) 10 Gbps data rate

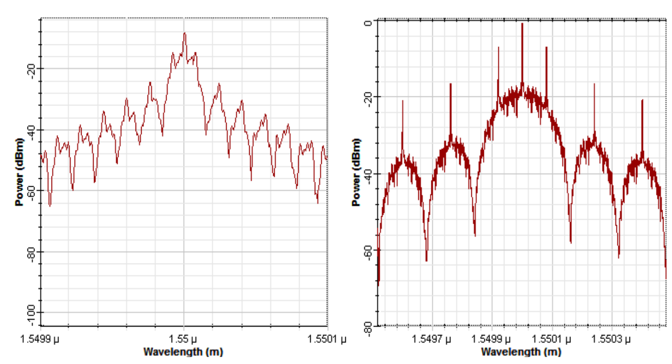

Fig. 7. Optical spectrum of 50% RZ-OOK signal for (a) 1 Gbps (b) 10 Gbps data rate

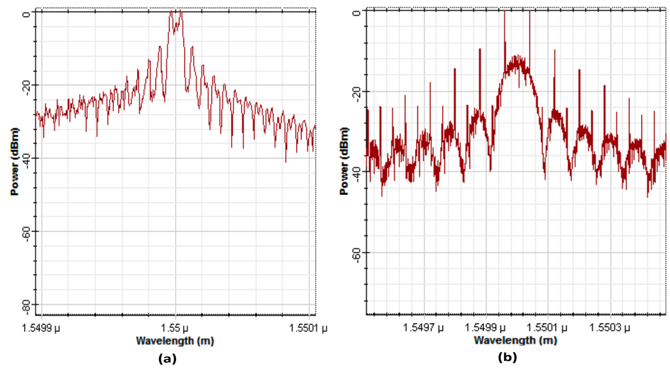

Fig. 8. Optical spectrum of 67% RZ-OOK (CSRZ) signal for (a) 1 Gbps (b) 10 Gbps data rate

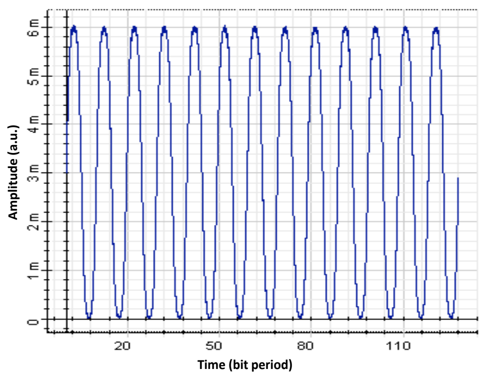

Fig. 9. Simulated RZ pulses after detection for OOK modulation scheme

V. Experimental Setup and Results

The experimental setup for the generation and reception of the RZ-OOK modulation scheme is shown in Fig.10, consists of a transmitter and a receiver separated by the channel. The RZ-OOK transmitter uses a CW laser source, two external intensity modulators connected in cascade, a microwave signal generator and a PRBS data generator. The CW laser source is made up of a semiconductor distributed-feedback (DFB) laser diode of wavelength $1550nm$ with a maximum output power of $+10dBm$. External intensity modulators are $LiNbO_3$ based MZ modulators. One of the MZ modulator is fed by a microwave signal source to produce the RZ optical pulses. The other one is used as modulating the PRBS data sequence generated from a data generator. The main parameters of the components used in the experiment are tabulated in Table.I. Fig.11 shows the detected 1 $Gbps$ RZ and NRZ data sequence for OOK modulation scheme. It can be seen that for RZ signal format the transmission of $'1'$ is always returns to low power state ($'0'$) within that bit period. The eye diagram for 1 $Gbps$ NRZ-OOK data is presented in Fig.12 and is perfectly matches with the simulated results of Fig.4.

The optical receiver consists of a photodetector and a transimpedence amplifier. The electrical signal at the output of the photodetector is amplified using transimpedence amplifier. The demodulated signal is then fed directly to an oscilloscope for waveform visualization. The detected 1 GHz RZ pulses, with 50% duty cycle, after the first MZ modulator is shown in Fig.13, perfectly matches with the simulated result of

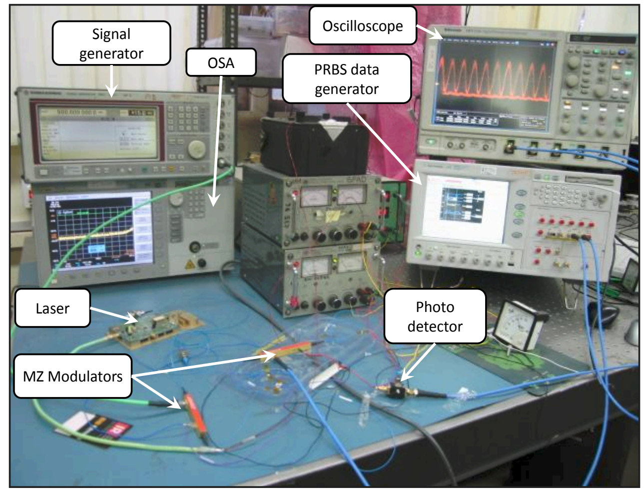

Fig. 10. Experimental setup for RZ-OOK modulation scheme

TABLE I. Main parameters of the components used in experiment

Component	*Parameters*	*Value*
Laser Diode	Type	DFB
	Peak wavelength	1550 nm
	max. optical power	+10 dBm
	max. modulation freq.	2.5 $Gbps$
	BW	DC to 10 GHz
MZ Modulator	operating wavelength	C & L band (1530-1625 nm)
	Vπ	∼4V
	Insertion Loss	∼5 dB
PIN Photodetector	operating wavelength	1100 - 1650 nm
	Sensitivity	-20 dBm
	speed	2.5 GHz
	responsivity	2.5 $mV/\mu W$

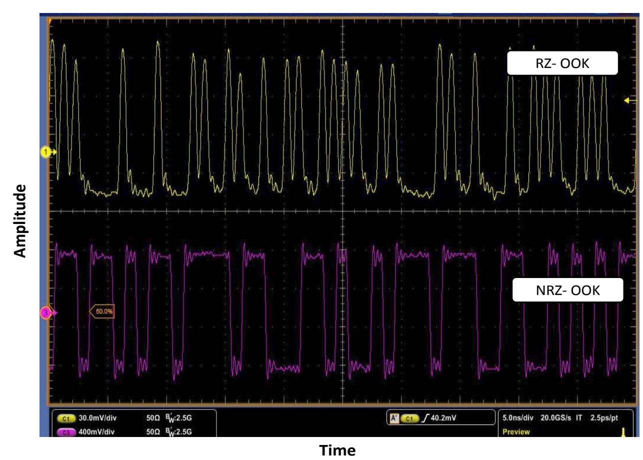

Fig. 11. 1 Gbps RZ and NRZ data waveforms for OOK scheme

TABLE II. Measured parameters for RZ transmitter

Parameters	*Simulated values*	*Measured values*
Signal power @1550nm	-3dBm	-4dBm
Extinction ratio	18 dB	∼12 dB
Duty cycle	50%	∼50%

Fig.9. A Microwave signal generator with the frequency of 1 GHz and power output of $+15dBm$ is used to drive this modulator. These RZ pulses are used to modulate the NRZ data sequence using second MZ modulator. The resulted RZ-OOK modulated signal is transmitted over fiber and then

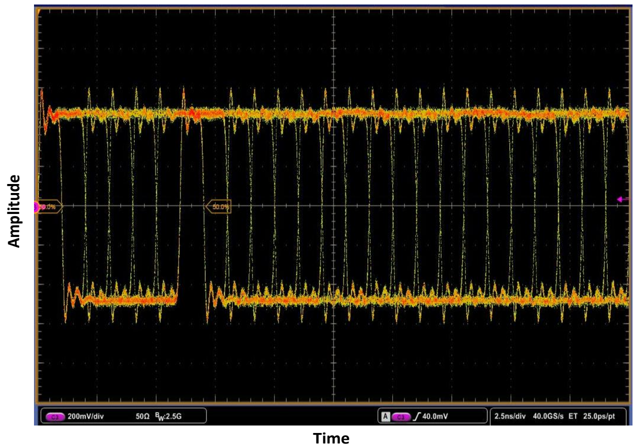

Fig. 12. Eye diagram for 1 Gbps NRZ-OOK data

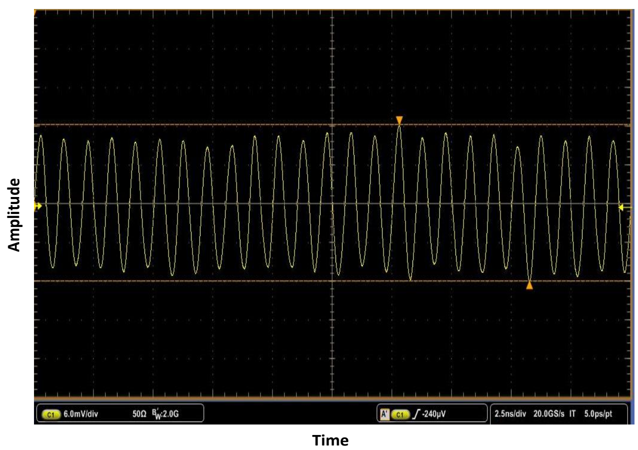

Fig. 13. 1 GHz detected RZ pulse

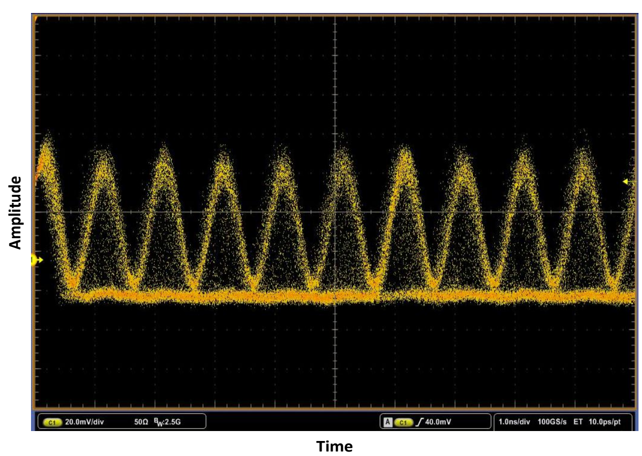

Fig. 14. Eye diagram for 1 Gbps RZ-OOK data

detected using photodiode. The measured eye diagram for 1 *Gbps* RZ-OOK demodulated data with 50% duty cycle is shown in Fig.14 which closely matches with the simulated result of Fig.4. Because of the limitation of the photodiode bandwidth, we could test it upto the data rate of 1 *Gbps* only. We have presented only time domain measurements as it is not possible to differentiate between different modulation formats over the frequency spectrum because of the low resolution of the optical spectrum analyzer. A comparison of the simulated and measured results is tabulated in Table.II. The measured extinction ratio of the RZ-OOK signal is lower because of the associated jitter with the signal.

VI. Conclusion

We have presented the design and implementation details for RZ-OOK modulation scheme for different duty cycles using two cascaded external intensity MZ modulators and demonstrated this scheme experimentally for the data rate of 1 *Gbps*. The simulations and analysis, including eye pattern, optical spectrum etc., of the OOK modulation scheme for RZ along with NRZ signal format have also been presented. The measured results show that a good quality RZ modulated waveform for OOK scheme can be generated using this technique.

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