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Optik 120 (2009) 704–709
Optik Optics
www.elsevier.de/ijleo

Impact of extinction ratio of single arm $\sin^2$ $LiNbO_3$ Mach–Zehnder modulator on the performance of 10 and 20 Gb/s NRZ optical communication system

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Received 20 September 2007; accepted 23 February 2008

Abstract

We investigate the impact of extinction ratio of single arm $\sin^2$ $LiNbO_3$ Mach–Zehnder (MZ) amplitude modulator on the performance of 10 and 20 Gb/s single-channel optical communication system. For different fiber lengths, the system performance has been analyzed with the increase in the extinction ratio. The effect of variation in dispersion parameter has also been illustrated. The impact of extinction ratio (ζ), dispersion parameter and length of the fiber has been further optimized with minimum bit error rate (BER) at optimal decision threshold (10^{-9}) for 10 and 20 Gb/s bit rate. It is found that the system gives optimum performance at extinction ratio (ζ) value 20 dB. The increase in the transmission distance from 468 km for 10 Gb/s to 532 km for 20 Gb/s has been reported, and 8 dB improvement in the Q value has been observed as the value of ζ is increased from 10 to 20 dB. At 20 Gb/s, the system gives optimum performance for dispersion parameter value only up to 4 ps/nm km; however, at 10 Gb/s the system can operate for dispersion values up to 14.3 ps/nm km. Further we investigate the self-phase modulation (SPM) effect for the increase in the input power. It is observed that the SPM effect is negligible below 3 dB m input power and it increases at higher power levels.

Keywords: Extinction ratio; BER; SPM

1. Introduction

At bit rates of 10 Gb/s or higher, the frequency chirp imposed by the direct modulation method become large enough that direct modulation of semiconductor lasers is rarely used. For such high-speed optical transmitters, external modulators are preferred. In these systems, intensity modulated pulse is distorted by fiber dispersion, fiber nonlinearity and transient chirping of transmitters [1]. Therefore, in order to estimate transmission performance, transmitter characteristics as well as waveform distortion such as dispersion and nonlinear effects must be considered. The important parameters to be considered in a transmitter are the input power, bit rate and the characteristics of the modulator, i.e. chirp and the extinction ratio. Extinction ratio is an important parameter included in the specifications of the modulator, which describes the content strength of the signal that the transmitter puts on the fiber.

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0030-4026/$ - see front matter
doi:10.1016/j.ijleo.2008.02.023

Martin Pauer et al. [2,3] showed that the finite extinction ratios can significantly reduce the achievable RZ coding gain. They quantitatively discussed the influence of the optical pulse shape on the achievable RZ coding gain and especially when the RZ signals are produced by direct-modulation methods. They further proved that the RZ gain drops considerably as the extinction ratio (ζ) decreases and the requirements on extinction ratio (ζ) are more severe if lower duty cycle is employed. Yonglin et al. [4] reported that in addition to the X talk level, the extinction ratio can also be used to characterize the suitability of a switch for optical networking applications and that the mechanical switches have extinction ratios of 40–50 dB and high-speed external modulators tend to have X ratios of 10–25 dB.

The effect of frequency response of receiver and chirping of transmitter on transmission performance of 10 Gb/s NRZ $LiNbO_3$ modulator-based lightwave systems had been investigated by Sung Kee Kim et al. [5,6]. By solving the nonlinear Schrodinger wave equation including chirping for the transmitters, they evaluated transmission performance by bit error rate (BER) and eye opening penalty. They further investigated [10,11] cost-effective and simple duobinary modulations with/without using low pass filters for the conventional duobinary modulation and analyzed the effects of the electrical bandwidth and the DC extinction ratio of Mach–Zehnder (MZ) modulators for transmission performances of the 10 Gb/s system. In another paper, Jeohoon Lee et al. [7] experimentally and theoretically investigated the electrical eye margin characteristics as the method of performance evaluation and prediction of high-speed optical transmission systems for single-channel 10 Gb/s optical transmission systems including chirp and extinction ratio. They showed that negative chirp can reduce the group velocity dispersion (GVD) than the positive chirp. Lima et al. [12] reported numerical studies of the propagation of ultra-short optical soliton pulses in a four-stage MZ interferometer (4SMZI), which is constructed with ordinary telecommunication fiber and dispersion decreasing fibers. They showed that crosstalk (X talk) level is dependent on the pump power and the dispersion of the fibers. Joon-Hak et al. [13] presented a technique for improving the input power dynamic range and extinction ratio of wavelength converters based on cross-gain modulation in a semiconductor optical amplifier.

However, the impact of extinction ratio of the modulator with dispersion and self-phase modulation (SPM) effect for 10 and 20 Gb/s system is not available as such in the literature, and thus is explored here to investigate the performance of the single-channel optical communication system for varying length and dispersion values. The system performance has also been investigated for different input powers to analyze the SPM effect.

2. System description and simulation

The optical communication system shown in Fig. 1 has been numerically simulated to investigate the effect of extinction ratio of the MZ $LiNbO_3$ external modulator on the system performance using the split step Fourier transform method. Here, the issue of extinction ratio of the modulator is addressed from the transmission point of view for a 10 and 20 Gb/s NRZ optical communication system.

The system transmitter consists of the pseudo random data source having random generating polynomial of 7°, the rectangular NRZ driver with -2.5 V low level and 2.5 V high level and the low pass Bessel filter with 5 poles and -3 dB cutoff frequency = 8 GHz. The CW laser source is taken with variable power, center emission frequency = 193THz, noise bandwidth = ideal, line width FWHM = 10 MHz.

The amplitude modulator model considered here implements a single arm MZ amplitude modulator with $\sin^2$ electrical shaped input–output *P–V* characteristic based on the electro-optic effects in the $LiNbO_3$ devices. As given in Refs. [6,9], for the input optical signal V_{in} applied to the MZ modulator, the output electric field is given as

$$\vec{E}_{out} = 10^{-(EL_{dB}/20)}\left\{\cos\phi_D - j\frac{1}{\varsigma_{lin}}\sin\phi_D\right\}e^{j\varepsilon}\vec{E}_{in} \qquad (1)$$

where $\vec{E}_{in}$ is the incoming electric field, EL_{dB} is the excess loss introduced by the modulator, phase difference ϕ_D is given as

$$\phi_D = \frac{\pi}{2}\left[\frac{V_{in} - V_{on}}{V_\pi}\right] \qquad (2)$$

where V_π is the switching voltage of the modulator and V_{on} is the maximum transmissivity offset voltage, i.e. the value of the electrical input corresponding to the maximum transmission state. Here, $V_{on} = 2.5$ V and

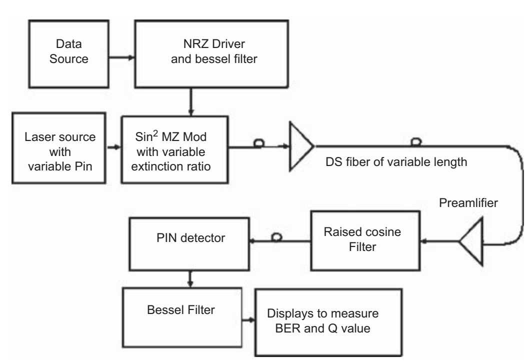

Fig. 1. Schematic of simulation setup to examine the performance of modulator with variable extinction ratio (10–20 dB) for varying fiber length (50–550 km).

$V_\pi = 5\,\mathrm{V}$. Average power reduction due to modulation is 3 dB.

Also, $\varepsilon = 0.5\,c \ln P_{out}$ where c is the chirp factor which has been taken as zero and P_{out} is the output power given by

$$P_{out} = \left|\vec{E}_{out}\right|^2 \quad (3)$$

when $V_{in} = V_{on}$, the power of the optical signal is attenuated by the excess loss only, so the modulator attains the state of maximum transmission. To switch over to the state of minimum transmission a V_π voltage must be applied in addition to the V_{on} one. Therefore, the linear extinction ratio ζ_{lin} is defined [8] as

$$\zeta_{lin} = \frac{\left|\vec{E}_{out}\right|_{max}}{\left|\vec{E}_{out}\right|_{min}} \quad (4)$$

The extinction ratio in decibels ζ_{dB} is the ratio between the output optical power corresponding to the maximum transmission value and the one corresponding to the minimum transmission value and given as

$$\zeta_{dB} = 10 \log [\zeta_{lin}]^2 \quad \text{or}$$

$$\zeta_{dB} = 10 \log \frac{\left|\vec{E}_{out}\right|^2_{max}}{\left|\vec{E}_{out}\right|^2_{min}} \quad (5)$$

In this model, the extinction ratio of the modulator has been varied from 10 to 20 dB. As given in Refs. [1,8], the Q value in terms of ζ is described as

$$Q = \frac{\rho P_{avg}}{\sigma_T} \left[\frac{\zeta - 1}{\zeta + 1}\right]$$

ρ is responsivity of the receiver, σ_T is the standard deviation of the thermal noise and P_{avg} is the average optical power at the receiver. Thus, with the increase in the extinction ratio, the Q value of the system increases, as the maximum transmission value increases [1].

The system has been simulated for varying length of the fiber and dispersion parameter D. The fiber length is ranging from 50 to 550 km. At reference wavelength 1550 nm the fiber loss is 0.25 dB/km and D is varied from 0 to 18 ps/nm km, the optical Kerr nonlinearity coefficient $\gamma = n_2\omega_0/cA_{eff} = 1.8\,\mathrm{W}^{-1}/\mathrm{km}$ for nonlinear refractive index $n_2 = 2.6 \times 10^{-20}\,\mathrm{m}^2/\mathrm{W}$, A_{eff} the core effective area $= 67.56 \times 10^{-12}\,\mathrm{m}^2$ and $\omega_0/c = 2\pi/\lambda = 2\pi/1.55 \times 10^{-6}\,\mathrm{m}^{-1}$, fiber PMD = 0.1 ps/km$^{0.5}$.

At the receiver, optical signal from raised cosine BP filter of center wavelength 1553.32 nm, raised cosine exponent = 1 and rolloff = 0.1 is passed through the sensitivity receiver using PIN photodiode at 1550 nm with 0.7 quantum efficiency and 0.1 nA dark current, the sensitivity reference error probability is 1×10^{-9}. Electrical filter of low pass Bessel type with 5 poles and −3 dB bandwidth gives the electrical signal which is subsequently measured for BER, Q value, eye opening and eye closure.

SPM-induced spectral broadening is a consequence of nonlinear phase shift $\phi_{NL} = \gamma P_{in} L_{eff}$ where P_{in} is the input power and L_{eff} is the effective interaction length, $L_{eff} = [1-\exp(-\alpha L)]/\alpha$. For long fiber lengths $\alpha L \gg 1$ and $L_{eff} \approx 1/\alpha$. To reduce the impact of SPM, it is necessary that $\phi_{NL} \ll 1$ and the input peak power should be very low limited to below 3 mW. Thus, as reported in Refs. [1,6], for low input powers the SPM effect is not very significant.

3. Results and discussion

To estimate the performance, the BER at optimal decision threshold and the Q value [dB] from the eye diagrams of electrical scope have been considered. For 10 Gb/s Fig. 2(a) and (b) shows BER and Q value, respectively, for the extinction ratio value ranging from 10 to 20 dB, $P_{in} = 6$ dB and $D = 0.4$ ps/nm km and the length of the fiber. Fig. 2(a) shows that the BER increases with the increase in the transmission distance because of pulse broadening due to GVD and also due to SPM; however, it decreases with the increase in extinction ratio ζ. The transmission distance can be increased from 329 km (BER $< 10^{-9}$) for $\zeta = 10$–468 km if the ζ value is increased to 20 dB. The result is also emphasized through 6 dB Q value improvement if the value of ζ is increased from 10 to 20 dB as shown in Fig. 2(b) and also the Q value decreases with the increase in length of the fiber. The results show consistency with the studies in Refs. [5,6]. For 20 Gb/s,

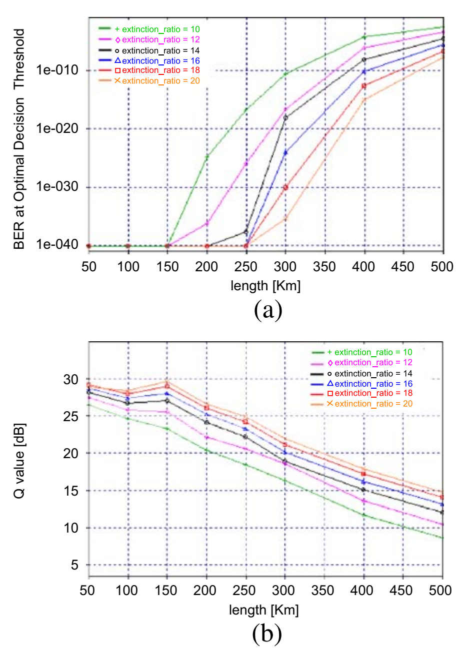

Fig. 2. 10 Gb/s system for variable extinction ratio ζ, $P_{in} = 6$ dB m and $D = 0.4$ ps/nm km. (a) BER vs fiber length, (b) Q value vs fiber length.

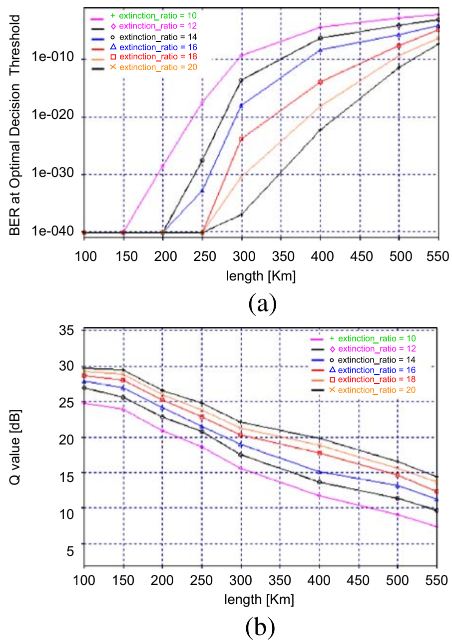

Fig. 3. 20 Gb/s system for variable extinction ratio ζ, $P_{in} = 6$ dB m and $D = 0.4$ ps/nm km. (a) BER vs fiber length, (b) Q value vs fiber length.

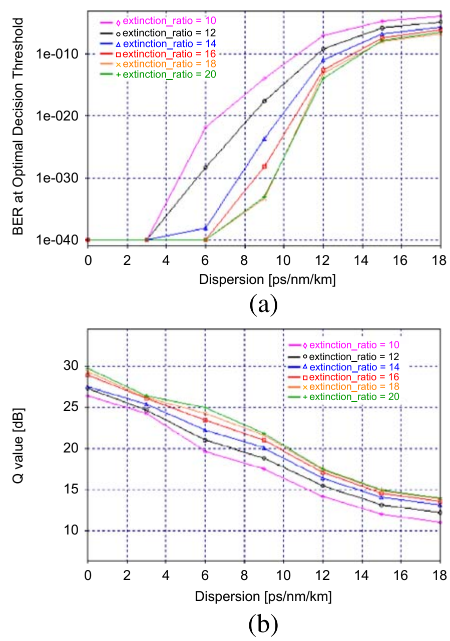

Fig. 4. 10 Gb/s system for variable extinction ratio ζ, $P_{in} = 6$ dB m and fiber length = 100 km. (a) BER vs dispersion (b) Q value vs dispersion.

Fig. 3(a) and (b) shows BER and Q value, respectively, for the variation in ζ of the modulator and the length of the fiber. The results for 20 Gb/s show similar trend as for 10 Gb/s. Fig. 3(a) shows that the transmission distance can be increased from 302 km to 532 km ζ 10 and 20 dB respectively. Enhancement of 8 dB in the Q value is observed at 400 km as shown in Fig. 3(b) as the value of ζ is increased from 10 to 20 dB.

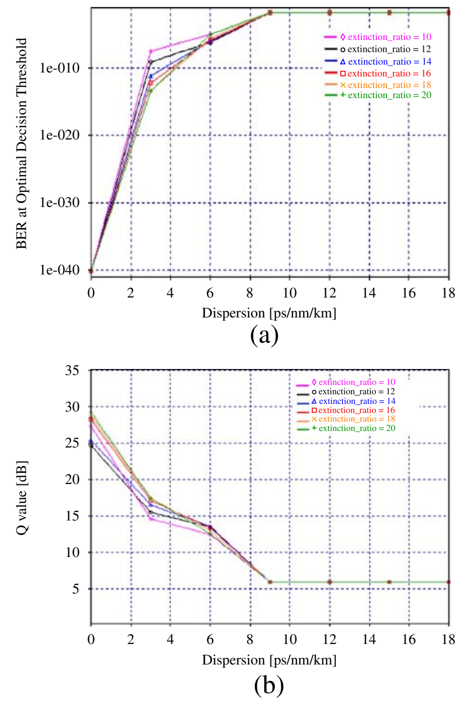

Fig. 5. 20 Gb/s system for variable extinction ratio ζ, $P_{in} = 6$ dB m and fiber length = 100 km. (a) BER vs dispersion (b) Q value vs dispersion.

Fig. 4(a) and (b) shows the effect of dispersion for varying ζ on the performance of the 10 Gb/s system with $P_{in} = 6$ dB and fiber length = 100 km. BER increases with the dispersion parameter D [ps/nm km] as seen in Fig. 4(a). For $\zeta = 10$, the dispersion value for which BER is $< 10^{-9}$ is $D = 11.6$ ps/nm km; however, on increasing the value of extinction ratio to $\zeta = 20$ the optical system can operate in more dispersive environment up to $D = 14.3$ ps/nm km. The result is also supported through 4 dB improvement in the Q value if ζ increases from 10 to 20 dB as can be observed in Fig. 4(b). For 20 Gb/s optical system Fig. 5(a) and (b) shows the effect of dispersion on the system performance. BER increases drastically after $D = 2$ ps/nm km as seen in Fig. 5(a), so 20 Gb/s system operates for very low value of dispersion. At higher bit rate, SPM-induced optical Kerr's effect increases as the effective nonlinear length is very large as compared to the dispersion length, so performance degradation with dispersion increases [6,7]. For $\zeta = 10$, $D = 2$ ps/nm km for which BER is $< 10^{-9}$ and for $\zeta = 20$ the optical system can operate up to $D = 4$ ps/nm km. Q value declines sharply with the increase in dispersion and falls below 14.8 dB after 4 ps/nm km as seen in Fig. 5(b).

The optical Kerr's effect due to SPM for 20 Gb/s system having length = 100 km, $D = 0.4$ ps/nm km can be clearly visualized in Figs. 6 and 7 with the input powers 2 and 14 dB m, respectively. The optical

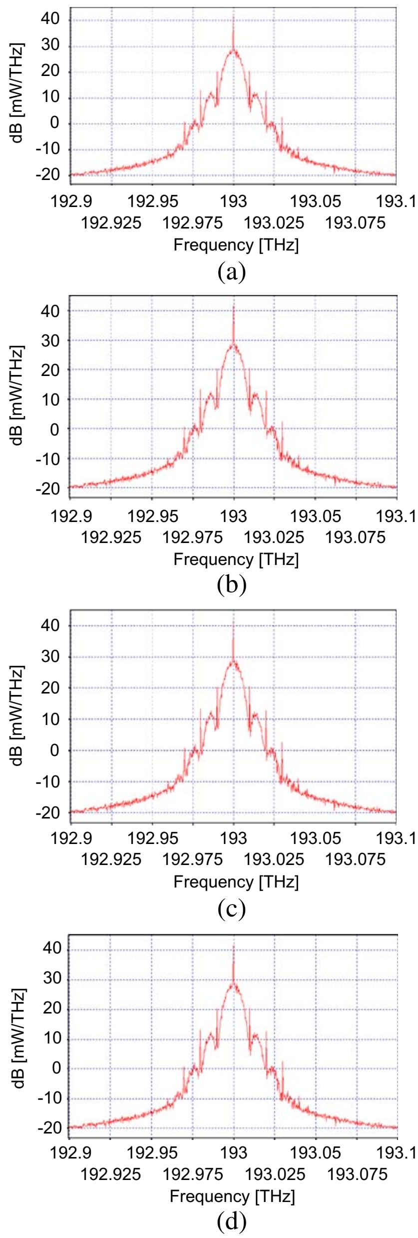

Fig. 6. Optical spectrum for $P_{in} = 2\,dBm$ and fiber length = 100 km. (a) $\zeta = 20$, (b) $\zeta = 16$, (c) $\zeta = 12$ and (d) $\zeta = 10\,dB$.

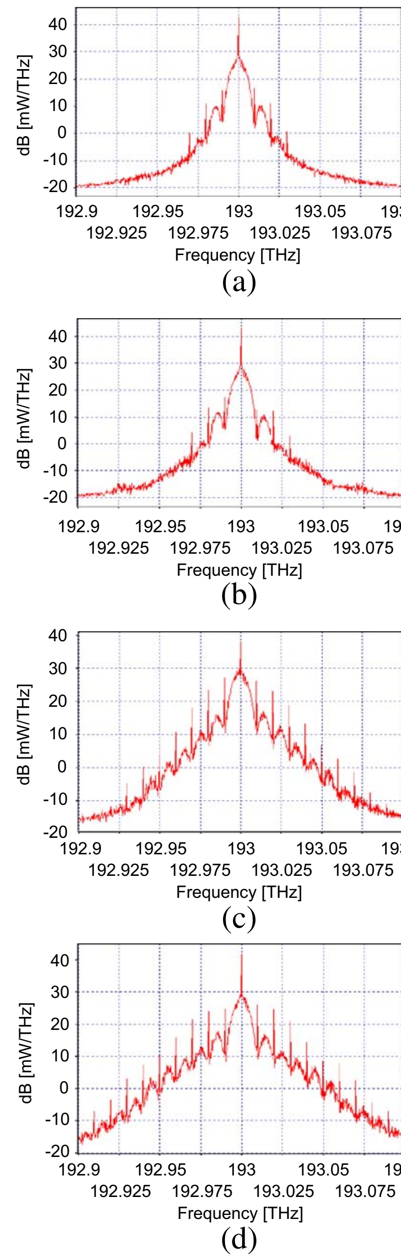

Fig. 7. Optical spectrum for $P_{in} = 12\,dBm$ and fiber length = 100 km. (a) $\zeta = 20$, (b) $\zeta = 16$, (c) $\zeta = 12$ and (d) $\zeta = 10\,dB$.

spectrum does not expand with the variation in the value of ζ for low power, i.e. 2 dB m, thus excluding the SPM effect. But for high input power, as shown in Fig. 7, the optical spectrum expands and the SPM effect grows with the decrease in the value of ζ. The results show good agreement with the work reported in Refs. [6,11].

4. Conclusions

It is concluded that with the increase in extinction ratio ζ of the modulator BER at decision threshold declines and Q value improves for an optical communication system. At 330 km fiber length, for 10 Gb/s system, drastic change has been observed, BER $\ll 10^{-9}$ for $\zeta = 10\,dB$ while BER $> 10^{-9}$ for $\zeta = 20\,dB$. The transmission viability is up to 468 km for higher extinction ratio $\zeta = 20\,dB$ and reduces to 329 km for extinction ratio $\zeta = 10\,dB$. A similar trend is observed for the system with bit rate 20 Gb/s. It has been found that maximum transmission distance can be increased from 468 km for 10 Gb/s to 532 km for 20 b/system. It is also quite evident from the results that the Q value decreases and BER at decision threshold increases with the increase in fiber length. Further it is seen that the system performance degrades with dispersion due to spectral broadening and SPM effect. At 10 Gb/s the system performs well up to $D = 11.6$ ps/nm km, whereas at 20 Gb/s the system can operate for very low values of dispersion up to only 4 ps/nm km. It is also reported that the SPM-induced spectral broadening reduces with the increase in extinction ratio, and the SPM effect is negligible for low input powers.

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