Effect of Transmitter Speed and Receiver Bandwidth on the Eye Margin Performance of a 10-Gb/s Optical Fiber Transmission System

R. J. Nuyts, L. D. Tzeng, O. Mizuhara, and P. Gallion

***Abstract*— We calculated the effect of the transmitter speed and receiver bandwidth on the electrical eye margin performance of a 10-Gb/s NRZ optical fiber transmission system. The transmitter under consideration used a 1.5 μm DFB-laser externally modulated by a zero-chirp $LiNbO_3$ modulator with NRZ, $2^7 - 1$, PRBS data. The receiver was a pin-diode based direct detection receiver. Main results are 1) near optimum system performance is achieved when the 10–90% rise/fall-time of the transmitter output is 40 ps, only small improvement is obtained by using faster speeds and, 2) the optimum bandwidth of the receiver is at 10 GHz (the baudrate) for both the back-to-back and the 120-km transmission configuration. Thus, the optimum receiver bandwidth is at the baudrate (10 GHz) which is in conflict with accepted practice which sugests approximately 0.6× baudrate (6 GHz). The reason for this discropancy is that we considered an optically amplified NRZ transmission system where the optical power level at the receiver input is well above the receiver sensitivity. Therefore, the impact of thermal noise is negligible and the system is dominated by ISI, which can be reduced by increasing the receiver bandwidth.**

***Index Terms*— Modeling, optical fiber communication, receivers, systems engineering, transmitters.**

I. Introduction

THE BANDWIDTH of the electrical circuitry in both the transmitter and receiver used in high speed optical fiber transmission systems have an important impact on the inter symbol interference (ISI) at the input of the decision circuit. The fiber Kerr nonlinearity which became important due to the use of high power erbium-doped fiber amplifiers (EDFA's) and the chromatic dispersion in the transmission fibers are a second source of ISI. Finally, the amplified spontaneous emission (ASE) noise of the EDFA's and the thermal noise of the receiver lead to a statistical variation of the received signal and, therefore, to additional eye closure at the input of the decision circuit. Increasing the receiver bandwidth will reduce the ISI but at the same time increase the noise level at the decision circuit input in the receiver. To investigate the effect of the transmitter speed and receiver bandwidth on the system performance, we calculated the electrical eye margin at a BER of 10^{-9} as a function of the transmitter rise/fall-time and the receiver bandwidth. To separate the contribution to the ISI from the bandwidth of the transmitter and the receiver from that of the SPM and dispersion in the fiber, we calculated the system performance in terms of the electrical eye margin for two different cases: 1) for the back-to-back configuration and, 2) after transmission through 120 km of standard (1.3 μm zero-dispersion) single-mode fiber (SMF) and concatenated dispersion compensating fiber (DCF) to compensate for the chromatic dispersion. We used fast Fourier transforms (FFT's) to include the impact of the receiver frequency response on the data signal. We used a model developed in [1], [2] to model the SPM, dispersion and loss in the transmission fiber.

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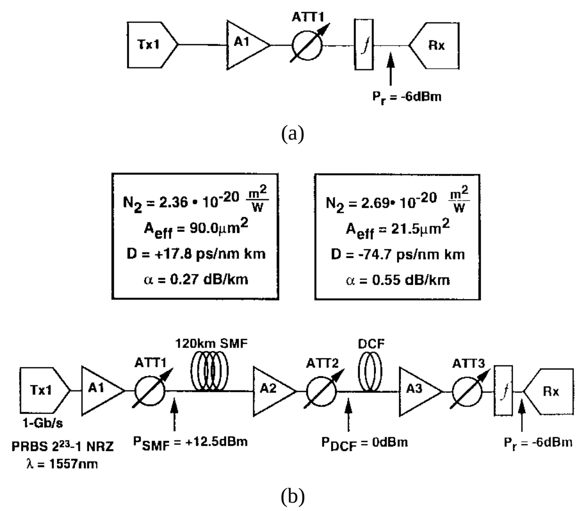

Fig. 1. (a) Back-to-back and (b) 120-km transmission system configuration.

II. Model Description

Fig. 1 shows the system configurations that we considered. The transmitter was a DFB laser operating at the 1557-nm wavelength externally modulated by a zero-chirp $LiNbO_3$ modulator with nonreturn to zero (NRZ), $2^7 - 1$ PRBS data. To model the initial electrical field at the input of the fiber we used a model first presented in [3] describing the slowly varying envelope of the electrical field $E_m(t)$ at the output of the external modulator as follows: $E_m(t) = E_0 \cos[\pi/2\{1 - f(t)\}]$, where $f(t)$ is the normalized electrical $2^7 - 1$ NRZ signal that drives the modulator. In the calculations we varied the 10%–90% rise/fall-time of the transmitter between 26 and 60 ps by changing the level of the driving voltage of the modulator. We calculated the optical SNR at the receiver input from the following formula to calculate the noise-to-signal ratio [4]: $[N/S] = \Sigma\ (2h\nu RN_{\rm sp}^j)/P_{\rm in}^j$, where h is Plancks' constant, ν is the optical frequency in Hz, R is the optical measurement bandwidth in Hz, $N_{\rm sp}^j$ is the spontaneous noise factor and $P_{\rm in}^j$ is the optical input power of the jth EDFA. In our calculations, we assumed an optical measurement bandwidth of 0.1 nm

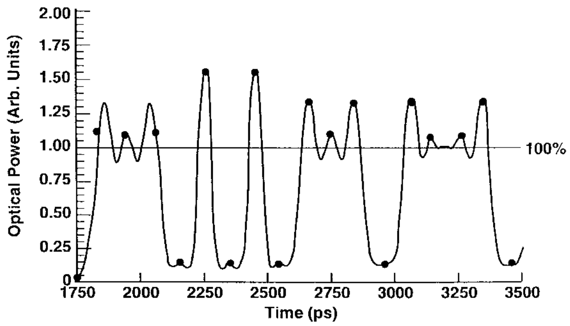

Fig. 2. Determination of the ISI at each mark, $C_{\rm ISI}^{+}$, and space, $C_{\rm ISI}^{-}$, of the 2^7-1 PRBS data signal.

corresponding to $R = 12.4$ GHz at 1557 nm. Typically, in the back-to-back configuration [Fig. 1(a)] using a power booster with an optical input power of -4.0 dBm and a noise figure (NF) of 7.0 dB, the calculated optical SNR at the receiver is 47 dB. Fig. 1(b) shows the fiber parameters and the optical power levels at the input of the standard fiber and the DCF that were used in the case of 120 km transmission. The optical amplifiers A_2 and A_3 compensate for the loss in the transmission fiber and the DCF, respectively, to prevent the degradation of the optical SNR and, therefore, the system performance. Using in-line EDFA's with optical input power levels of -19.0 dBm (corresponding to an absorption constant for the SMF of $\alpha_{\rm SMF} = 0.27$ dB/km) and -13 dBm ($\alpha_{\rm DCF} = 0.55$ dB/km) and NF's of 4.5 dB results in an optical SNR of 33 dB at the receiver end. We calculated the effect of SPM, dispersion and loss on the pulse shape at the input of the receiver by solving the nonlinear Schrödinger equation for both the standard fiber and the DCF. At the fiber output, first the optical eye closures $c_{\rm ISI}^{+}$ at the "1"-level and $c_{\rm ISI}^{-}$ at the "0"-level are determined at each individual bit of the 2^7-1 PRBS signal as shown in Fig. 2 for an example signal. The samples are indicated by dots on the trace. These eye closures are then used to calculate the variances of the noise sources at each sample. After detection at the receiver the electrical signal is filtered by the receiver frequency response to take into account the ISI caused by these electrical circuits. We assumed that the noise distribution on the sampling moments (at $t = 50$ ps, 150 ps $\ldots$ etc) is not changed by the filtering. The optical power level $P_{\rm rec}$ at the input of the receiver was -6 dBm to assure that the impact of the receiver thermal noise is negligible. Fig. 3 shows the measured frequency response of the receiver that we used in the calculations. The receiver had a 3-dB bandwidth of 11.6 GHz and a 20°-bandwidth of 10.0 GHz. We defined the phase bandwidth as the frequency where the normalized phase differs more than 20° from the dc value. In the calculations, we varied the receiver bandwidth from 5.0 to 25 GHz by scaling both the amplitude and phase frequency response.

The time-averaged signal and ASE photo currents can be determined from the average optical power $P_{\rm rec}$ and the optical SNR at the input of the receiver: $I_s = e/(h\nu)P_{\rm rec}$ and $I_{\rm sp} = (I_s B_0/\text{SNR } R)$. The ASE noise photocurrent $I_{\rm sp}$ is proportional to the bandwidth B_0 of the optical filter. The

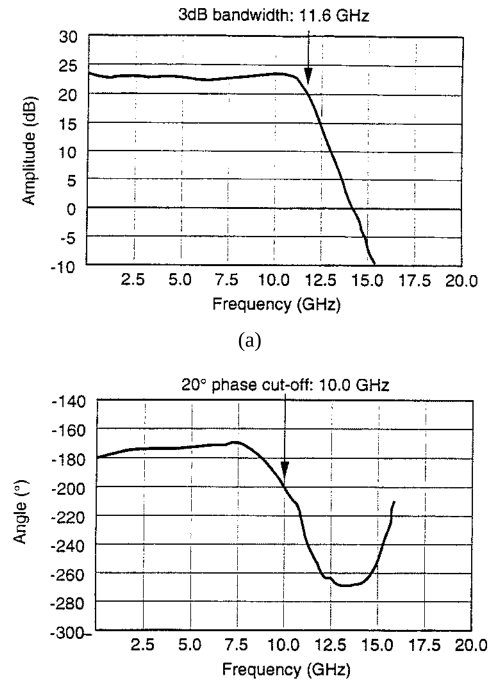

Fig. 3. Measured frequency response of the 10 Gb/s receiver. (a) Amplitude response. (b) Phase response.

variances of the noise sources are given by (modified from [5]):

$$N_{\rm shot}({\rm mark}) = 4eI_s(1-c_{\rm isi}^{+})B_e \tag{1}$$

$$N_{\rm shot}({\rm space}) = 4eI_s(c_{\rm isi}^{-})B_e \tag{2}$$

$$N_{\rm shot}({\rm ASE}) = 2eI_{\rm sp}B_e \tag{3}$$

$$N_{\rm sp\text{-}sp} = I_{\rm sp}^2\frac{B_e(2B_0-B_e)}{2B_0^2} \tag{4}$$

$$N_{\rm s\text{-}sp}({\rm mark}) = 4I_sI_{\rm sp}(1-c_{\rm isi}^{+})\frac{B_e}{B_0} \tag{5}$$

$$N_{\rm s\text{-}sp}({\rm space}) = 4I_{\rm sp}I_sc_{\rm isi}^{-}\frac{B_e}{B_0} \tag{6}$$

where B_e is the 3 dB-bandwidth of the receiver. The thermal noise variance $N_{\rm rec}$ of the receiver was calculated from the measured input noise current spectral density of the receiver using:

$$N_{\rm rec} = \int_0^{+\infty}\frac{d\langle i^2\rangle}{df}H^2(f)\,df. \tag{7}$$

The standard deviations for marks and spaces are given by (8), found at the bottom of the page.

By assuming Gaussian noise distributions, we determined the following analytical expression for the BER:

$$\text{BER} = \frac{1}{4}\text{erfc}\left[\sqrt{2}\left(\frac{(1-c_{\rm isi}^{+}-\tau)I_s}{\sigma_1}\right)\right] + \frac{1}{4}\text{erfc}\left[\sqrt{2}\left(\frac{(\tau-c_{\rm isiI_s}^{-}}{\sigma_0}\right)\right] \tag{9}$$

$$\sigma_{1,0} = \sqrt{N_{\rm shot}(\text{mark, space}) + N_{\rm shot}({\rm ASE}) + N_{\rm rec} + N_{\rm sp\text{-}sp} + N_{\rm s\text{-}sp}(\text{mark, space})} \tag{8}$$

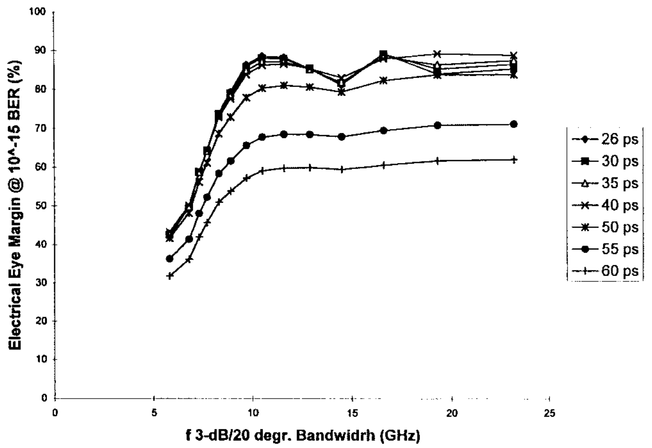

Fig. 4. Calculated electrical eye margin as a function of receiver bandwidth for the back-to-back configuration.

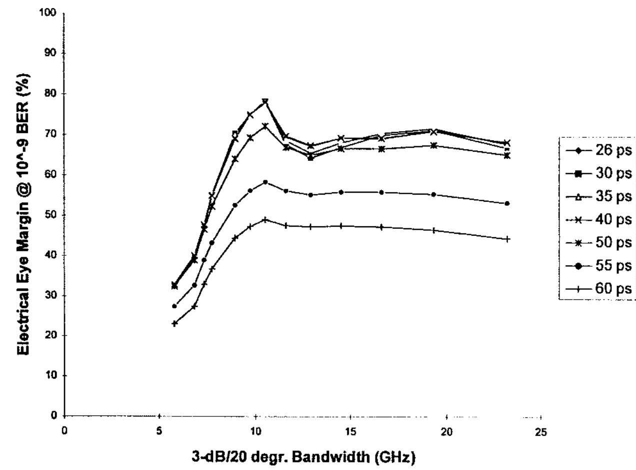

Fig. 5. Calculated electrical eye margin as a function of receiver bandwidth for the 120-km transmission configuration.

where τ is the decision threshold level setting relative to the rail-to-rail voltage of the decision circuit. From this expression the minimum achievable BER of the transmission system or the system electrical eye margin (the range of the decision level voltage where BER $< 10^{-9}$ relative to the rail-to-rail voltage of the decision circuit) can be calculated.

III. Results

Fig. 4 shows the calculated electrical eye margin at a BER of 10^{-9} as a function of the receiver bandwidth. The widest electrical eye margin of 89% is achieved when the 3-dB amplitude bandwidth is approximately 10 GHz for a rise/fall time of 26 ps. The figure shows that the electrical eye margin is improved dramatically with 27% from 59% to 86% by decreasing the 10%–90% rise/fall time from 60 to 40 ps. Speeding up the rise/fall time to values faster than 40 ps does not lead to significant additional improvement of the electrical eye margin. It is worthwhile to note that the optimum receiver bandwidth is at baudrate (10 GHz) which is in conflict with acdpeted practice that suggests approximately 0.6× baudrate (6 GHz). The reason for this discrpancy is that we considered an optically amplified system where the optical power level at the receiver input is well above the receiver sensitivity. Therefore, the impact of thermal noise is negligible and the system is dominated by ISI which can be reduced by increasing the receiver bandwidth.

Fig. 5 shows the calculated electrical eye margin margin at a BER of 10^{-9} after 120-km transmission as a function of the receiver bandwidth. The maximum achievable electrical eye margin is 78% for a 3-dB bandwidth of 10 GHz and a rise/fall time of 26 ps. Thus, the optimum receiver bandwidth remains at 10 GHz. Note that (as in the back-to-back configuration) the electrical eye margin is increased substantially by reducing the rise/fall time from 60 ps to approximately 40 ps. Further increase of the transmitter speed does not lead to additional improvement of the electrical eye margin. The significant reduction in optical SNR from 47 dB to 33 dB due to the ASE noise from the used fiber amplifiers and the spectral broadening of the optical signal due to SPM in the transmission fiber do not reduce the optimum receiver bandwidth. Apparently, a reduction of the receiver bandwidth in order to reduce the noise power will only increase the ISI and will lead to a system performance degradation instead of improvement.

IV. Conclusion

We investigated the effect of the transmitter speed and receiver bandwidth on the electrical eye margin performance of a 10-Gb/s NRZ optical fiber transmission system. Results show: 1) near optimum system performance is achieved when the 10–90% rise/fall-time of the NRZ data signal at the transmitter is 40 ps, only marginal improvement is obtained using faster speeds, 2) the widest system margin is achieved when the 3-dB amplitude bandwidth of the receiver is at 10 GHz (i.e., the baudrate) for both the back-to-back and the 120-km transmission system configuration. The result that the optimum receiver bandwidth is at the baudrate (10 GHz) is in conflict with accepted practice which suggests approximately 0.6× baudrate (6 GHz). The reason for this discrepancy is that we considered an optically amplified NRZ transmission system where the optical power level at the receiver input is well above the receiver sinsitivity. Therefore, the impact of thermal noise is negligible and the system is dominated by ISI which can be reduced by increasing the receiver bandwidth.

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References

[1] D. Marcuse, *Theory of Dielectric Optical Waveguides*. San Diego, CA: Academic, 1991.
[2] R. J. Nuyts and Y. K. Park, "Dispersion equalization of a 10 Gb/s standard fiber transmission system using dispersion compensating fibers," *J. Lightwave Technol.*, submitted for publication.
[3] B. W. Hakki, private communication.
[4] C. D. Chen, J.-M. P. Delavaux, B. W. Hakki, O. Mizuhara, T. V. Nguyen, R. J. Nuyts, K. Ogawa, Y. K. Park, C. S. Skolnick, R. E. Tench, J. Thomas, L. D. Tzeng, and P. D. Yeates, "A field demonstration of 10 Gb/s–360 km transmission through embedded standard (non-DSF) fiber cables," *Electron. Lett.*, vol. 30, no. 14, pp. 1159–1160, 1994.
[5] J. A. Nagel, S. M. Bahsoun, D. A. Fishman, D. R. Zimmerman, J. J. Thomas, and J. F. Gallagher, "Optical amplifier system design and field trial," in *Proc. OAA'92,* Santa Fe, NM, 1992.