European Conference on Optical Communication (ECOC) 2022 © Optica Publishing Group 2022

Precise Characterization of Nonlinear Distortion in IM-DD System with Nonnegligible Chromatic Dispersion

Jingnan Li(1), Xiaofei Su(1), Tong Ye(1), Zhenning Tao(1), Hisao Nakashima(2), Takeshi Hoshida(2)

(1) Fujitsu R&D Center, No. 8 Jian Guo Men Wai Ave., Beijing, China, lijingnan@fujitsu.com
(2) Fujitsu Ltd., 1-1 Shin-ogura, Saiwai-Ku, Kawasaki 212-8510, Japan

Abstract *We experimentally verify that the noise-to-power ratio method precisely characterizes nonlinear distortion caused by the interaction among modulation, chromatic dispersion, and detection in the DFB laser-based IM-DD transmission system. The equivalent additive noise model estimates the system performance with the accuracy of 0.5 dB. ©2022 The Author(s)*

Introduction

Nonlinear distortion is the fundamental limitation of optical fiber communication systems. Besides the fiber Kerr nonlinear distortion and transceiver device nonlinear distortion, the chromatic dispersion (CD) also causes nonlinear distortion in the intensity modulation and direct detection (IM-DD) system [1]. In the intensity modulation, the optical power is proportional to the input signal, whereas the optical field is the square root of the input signal. The direct detection is a square operation on the received optical field. If CD is ignorable, the modulation and detection are a pair of inverted nonlinear processes, and the total system is linear. However, the system has a nonlinear-linear-nonlinear structure and the total system is nonlinear if CD cannot be ignored. Although many nonlinear compensations have been proposed [2, 3], the commercialization has many difficulties including the high complexity. Therefore, it is a vital task to characterize nonlinear distortion and estimate nonlinear system performance practically and precisely.

Recently, orthogonal component analysis has been applied to accurately estimate the device nonlinear penalty in optical communication system [4]. However, it needs a precise comparison of the input and output waveforms of the nonlinear system, so the measurement needs very expensive instruments, and the accurate measurement is quite challenging [5].

The noise-to-power ratio (NPR) method [6] is a practical solution, which measures the nonlinear noise by notching some frequency component at the input and analyzing the output spectrum. However, NPR is not a general method. It works correctly only for Gaussian input signal or some special nonlinear system with non-Gaussian input [5]. In some case, the measurement error is as large as 8 dB [7].

In this paper, we investigate the NPR method for the nonlinear distortion in the distributed feedback (DFB) laser-based IM-DD transmission system. The experiment proves that the NPR method works correctly for this specific nonlinear mechanism, and the nonlinear system performance could be accurately estimated within 0.5 dB Q error.

Orthogonal component analysis, NPR, and equivalent additive noise model

The input and output of a nonlinear system are denoted as $x(t)$ and $y(t)$, respectively. The basic idea of orthogonal component analysis is to decompose nonlinear system output $y(t)$ into correlated component $y_c(t)$ and orthogonal component $y_d(t)$. The correlated component $y_c(t) = \sum g_k x(t-k)$ is the best linear approximation of the nonlinear system output [8], where g_k is tap coefficient to minimize the error of $|y(t) - y_c(t)|^2$. Then the orthogonal component is the rest part $y_d(t) = y(t) - y_c(t)$.

The schematic of NPR measurement is shown in Fig. 1(a). Some frequency component is notched at the input spectrum, and the output spectrum is measured. NPR is defined as the power ratio between the regrowth component (yellow part) and the output signal (blue part). The result of this standard NPR measurement is named as $\mathrm{NPR_{Notch}}$. In addition, since the orthogonal component could be considered as the equivalent additive nonlinear noise [4], we define the ratio between the spectrum of orthogonal component (red curve) at notch frequency and the output spectrum as $\mathrm{NPR_{Orth}}$.

The equivalent additive noise model as shown in Fig. 1(b) is established to estimate the system performance. We establish two kinds of models. The first one is the same NPR model. Here, the equivalent linear model has an amplitude-frequency response that is the difference between the input and output spectrums of a nonlinear system. The equivalent additive noise is generated by an additive white Gaussian noise (AWGN) passing through the noise profile filter whose in-band response is obtained by standard NPR measurement and the out-of-band response is the output spectrum directly. The

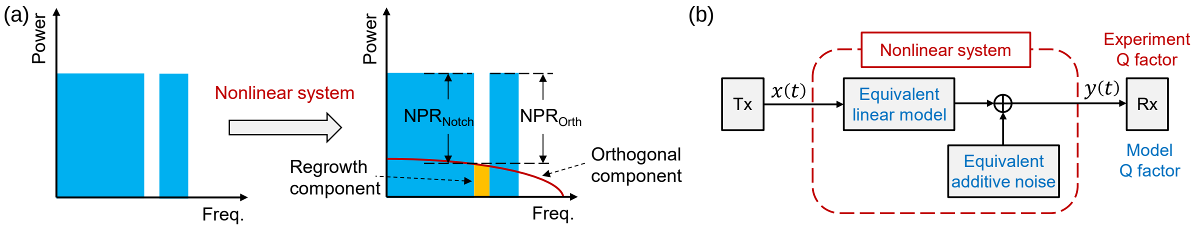

Fig. 1: (a) Schematic of NPR measurement and (b) equivalent additive noise model.

second model is the same orthogonal model, where the tap coefficient g_k describes the equivalent linear model and the orthogonal component with time-cycle-shift of 2000 samples is used as the equivalent additive noise [5]. To focus on the nonlinear effect, we assume there is an ideal linear equalizer in the receiver.

Nonlinearity caused by the interaction among modulation, CD, and detection

At first, we analyze the nonlinear mechanism of the DFB laser-based IM-DD transmission system. The schematic is shown in Fig. 2. According to [9], the optical field of DFB laser is $\sqrt{P(t)}e^{j(2\pi f_0 t+\varphi(t))}$, where t is time, f_0 is center frequency, $P(t)$ is optical power and $\varphi(t)$ is phase modulation. Optical power $P(t) = P_0\big(1 + m \cdot s(t)\big)$, where P_0 is average optical power, m is intensity modulation index and $s(t)$ is modulation signal. Instantaneous frequency $f(t) = f_0 + \Delta f(t) = \alpha/4\pi \cdot [1/P(t) \cdot dP(t)/dt + \kappa P(t)]$, where $\Delta f(t) = 1/2\pi \cdot d\varphi(t)/dt$ is frequency chirp, α is linewidth enhancement factor and κ is adiabatic chirp constant. Although optical power $P(t)$ is linear to modulation signal $s(t)$, the amplitude of the optical field is the square root of optical power, and the frequency chirp causes another nonlinear effect. As a result, the DFB laser has a nonlinear operation between the modulation signal and optical field. Fiber CD is a linear effect in terms of the optical field and described by $exp(-j\beta_2 z\omega^2/2)$, where β_2 is dispersion coefficient, z is transmission distance and ω is angular frequency. Photodetector (PD) has a square-law operation between the optical field and output electrical signal. The DFB laser modulation and PD detection are a pair of inverted nonlinear operations. In the back-to-back (B2B) scenario, the nonlinear operation of modulation and detection are connected directly so that the total response is linear. However, the linearity of the total response is broken when CD

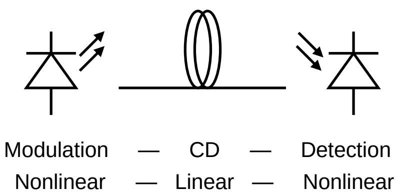

Fig. 2: Schematic of IM-DD transmission system.

is nonnegligible. CD causes inter-symbol-interference (ISI) of the optical field, and this total system has the structure of nonlinear-linear-nonlinear. Such distributed nonlinear structure is widely known as the Hammerstein-Wiener model [10]. In addition, the frequency chirp implies that different pulse amplitude modulation (PAM) levels have different optical frequencies. After transmission with CD, different PAM levels have different delays. As a result, the eye skew, a typical nonlinear effect in the IM-DD transmission system, occurs [11].

Experimental setup, result, and discussion

The experimental setup of the DFB laser-based IM-DD transmission system is shown in Fig. 3. The transmitted digital signal is 4 Sa/sym 25 GBaud PAM8 with 0.15 root raised cosine (RRC) pulse shaping. The notch width is 400 MHz, and the notch frequencies are 1.04, 3.13, 5.21, 7.29, 9.38, and 11.46 GHz. The signal amplitude is adjusted by the root mean square (RMS) value of the digital signal whose full swing is -127~127. The two-tone signal is also used to characterize the nonlinear order. After a digital-to-analog converter (DAC) with 100 GSa/s sampling rate and an electrical driver operating in the linear region, the electrical signal is sent to the DFB module which also operates in the linear region. The laser wavelength is 1545.5 nm. Via 10 km standard single-mode fiber (SSMF) transmission, the received optical power is –6.5 dBm by adjusting the variable optical attenuator (VOA). After PIN trans-impedance amplifier (TIA) receiver and DC block, the spectrum of two-tone signal and waveform of PAM8 with/without notch are captured by electrical spectrum analyzer (ESA) and digital storage oscilloscope (DSO) with 50 GSa/s sampling rate, respectively. We focus on the characterization of nonlinear distortion so that 64-frame averaging is applied to decrease the influence of AWGN in the experimental system. For PAM8 with notch, we calculate NPR$_{Notch}$ in the frequency domain directly. For PAM8 without notch, we calculate NPR$_{Orth}$ after orthogonal component analysis.

We measure nonlinear distortion at different RMS of PAM8 with/without notch. In Fig. 4(a), the black curve shows the spectrum of the orthogonal

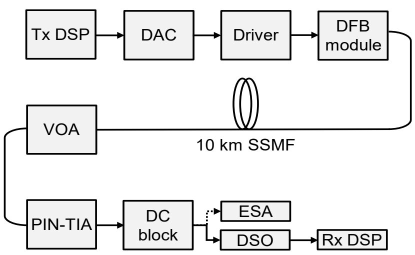

Fig. 3: Schematic of experimental setup.

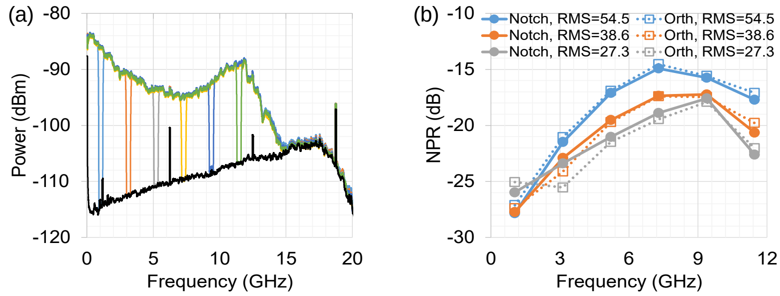

Fig. 4: (a) Measured spectrum and (b) measured NPR.

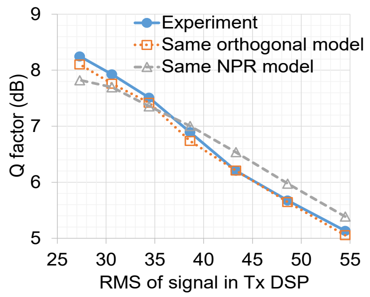

Fig. 5: Q factor of experiment and model.

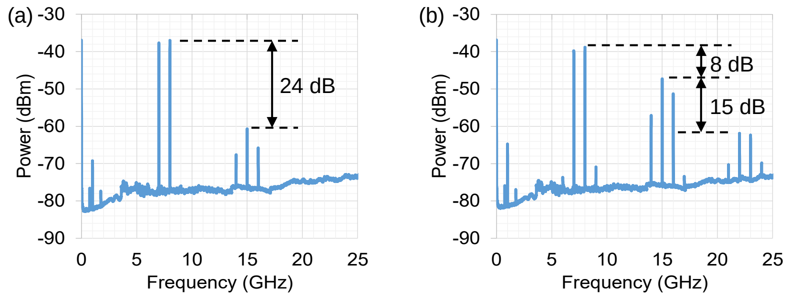

Fig. 6: Spectrum of two-tone measurement. (a) B2B and (b) 10 km.

component when the RMS of PAM8 is 54.5. According to [4], the orthogonal component could be considered as the actual equivalent nonlinear noise. The output spectrums with notch are shown by other colour curves. It is clear that the nonlinear noise measured by notch agrees with the actual nonlinear noise. The spurs in the orthogonal component are caused by DSO imperfection. Fig. 4(b) shows the results of NPR_{Notch} and NPR_{Orth} at different RMS levels. The two curves agree in all the three RMS scenarios, and the average error is 0.75 dB. The notch method can measure correct nonlinear distortion caused by the interaction among modulation, CD, and detection in the IM-DD system. Besides, Fig. 4(b) also shows that the nonlinear distortion is affected by the amplitude of the signal. According to the nonlinear mechanism discussed in the above section, higher modulation signal RMS causes higher frequency chirp and then causes larger eye skew and nonlinear distortion.

Then, we establish the equivalent additive noise model to estimate the nonlinear system performance. In Fig. 5, we obtain the experiment and model Q factors at different signal RMSs. The Q factor of the model agrees with that of the experiment. The maximum Q deviations of the same orthogonal model and same NPR model are less than 0.2 dB and 0.5 dB, respectively. It can be concluded that the same NPR model, as a more practical scheme, has sufficient accuracy to estimate system performance in this specific nonlinear mechanism.

Since the NPR method usually does not correctly measure the nonlinear noise for the PAM system [12], we carry out more experiments to find the reason why the NPR method works here. The results of the two-tone test with 7 GHz and 8 GHz are shown in Fig. 6. In the B2B scenario, the power ratio of the fundamental frequency to nonlinear distortion is 24 dB, whereas such power ratio in the 10 km scenario is only 8 dB. This shows that the dominant nonlinear distortion is caused by the interaction among modulation, CD, and detection. In addition, Fig. 6(b) shows that the 2^{nd}-order nonlinearity is 15 dB higher than 3^{rd}-order nonlinearity, so 2^{nd}-order nonlinearity is dominant.

In [13], we showed that the NPR method works for VCSEL based IM-DD system, where the nonlinear distortion is a lumped 2^{nd}-order distortion caused by VCSEL. Also, in [13], the simulation showed that the NPR method works for the lumped 2^{nd}-order polynomial nonlinear system and does not work for the lumped 3^{rd}-order polynomial nonlinear system. The experiment in this paper shows that the nonlinear order is the key factor, whereas the specific nonlinear mechanism and whether the nonlinear structure is lumped or distributed do not make sense. As long as the nonlinear system is 2^{nd}-order dominant, the NPR method works correctly.

Conclusions

We experimentally verify that the practical NPR scheme accurately characterizes the nonlinear distortion caused by the interaction among modulation, CD, and detection in the DFB laser-based IM-DD transmission system. Nonlinear system performance could be estimated with the accuracy of 0.5 dB based on the nonlinear noise spectrum measured by NPR. We also indicate that the NPR method works correctly as long as the nonlinearity is 2^{nd}-order dominant.

References

[1] W. Yan, B. Liu, L. Li, Z. Tao, T. Takahara, and J. C. Rasmussen, "Nonlinear Distortion and DSP-based Compensation in Metro and Access Networks using Discrete Multi-tone," in *European Conference and Exhibition on Optical Communication*, Amsterdam, 2012, Mo.1.B.2. DOI: 10.1364/ECEOC.2012.Mo.1.B.2

[2] N. Kikuchi, R. Hirai and T. Fukui, "Non-linearity Compensation of High-Speed PAM4 Signals from Directly-Modulated Laser at High Extinction Ratio," in *European Conference on Optical Communication*, Dusseldorf, 2016, M.2.B.4. https://ieeexplore.ieee.org/abstract/document/7767497

[3] N. Stojanovic, F. Karinou, Z. Qiang, and C. Prodaniuc, "Volterra and Wiener Equalizers for Short-Reach 100G PAM-4 Applications," *Journal of Lightwave Technology*, vol. 35, pp. 4583-4594, 2017. DOI: 10.1109/JLT.2017.2752363

[4] X. Su, T. Ye, C. Yang, Z. Tao, H. Nakashima, and T. Hoshida, "Accurate Performance Estimation for Nonlinear System," in *Optoelectronics and Communications Conference*, Hong Kong, 2021, W2A.3. DOI: 10.1364/OECC.2021.W2A.3

[5] Z. Tao, Y. Fan, X. Su, K. Zhang, C. Yang, T. Ye, J. Li, H. Nakashima, and T. Hoshida, "Characterization, Measurement and Specification of Device Imperfections in Optical Coherent Transceivers," *Journal of Lightwave Technology*, 2022. DOI: 10.1109/JLT.2022.3155454

[6] R. W. Koch, "Random Signal Method of Nonlinear Amplitude Distortion Measurement," *IEEE Transactions on Instrumentation and Measurement*, vol. IM-20, no. 2, pp. 95-99, 1971. DOI: 10.1109/TIM.1971.5570700

[7] K. M. Gharaibeh, "On the relationship between the noise-to-power ratio (NPR) and the effective in-band distortion of WCDMA signals," *AEU - International Journal of Electronics and Communications*, vol. 64, pp. 273-279, 2010. DOI: 10.1016/j.aeue.2008.11.015

[8] K. M. Gharaibeh, *Nonlinear distortion in wireless systems: Modeling and simulation with MATLAB*, John Wiley & Sons, Ltd., 2011. DOI: 10.1002/9781119961734

[9] L. Neto, D. Erasme, N. Genay, P. Chanclou, Q. Deniel, F. Traore, T. Anfray, R. Hmadou, and C. Aupetit-Berthelemot, "Simple Estimation of Fiber Dispersion and Laser Chirp Parameters Using the Downhill Simplex Fitting Algorithm," *Journal of Lightwave Technology*, vol. 31, pp. 334-342, 2013. DOI: 10.1109/JLT.2012.2226704

[10] M. Schoukens and K. Tiels, "Identification of block-oriented nonlinear systems starting from linear approximations: A survey," *Automatica*, vol. 85, pp. 272-292, 2017. DOI: 10.1016/j.automatica.2017.06.044

[11] K. Zhang, Q. Zhuge, H. Xin, W. Hu, and D. V. Plant, "Performance comparison of DML, EML and MZM in dispersion-unmanaged short reach transmissions with digital signal processing," *Optics Express*, vol. 26, pp. 34288-34304, 2018. DOI: 10.1364/OE.26.034288

[12] Z. Tao, K. Zhang, X. Su, H. Nakashima, and T. Hoshida, "Nonlinear Noise Measurement for Optical Communication," in *Optoelectronics and Communications Conference*, Hong Kong, 2021, W2A.5. DOI: 10.1364/OECC.2021.W2A.5

[13] C. Yang, T. Ye, K. Zhang, Z. Tao, H. Nakashima, and T. Hoshida, "A Simple and Accurate Method to Estimate the Nonlinear Performance of VCSEL IM-DD System," in *Optical Fiber Communications Conference and Exhibition*, San Diego, 2022, W2A.34. DOI: 10.1364/OFC.2022.W2A.34