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Nonlinear Modeling and Measurement for Tens of Gigahertz Electrical Amplifier in High-baud Multi-level Modulated Coherent Optical System

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Abstract: High baud-rate and high order modulation formats, such as 64-giga-baud 64QAM per wavelength are being popularly researched to enlarge the transmission capacity of coherent optical system. In such multi-level modulations, the influence from electrical amplifier nonlinearity along with strong memory effect from imperfect device design in coherent optical transmitter and receiver becomes more and more significant and needs careful research. In this paper, nonlinear characteristic of a commercially-available electrical amplifier in coherent optical transmitter for tens of gigahertz signal amplification is investigated, measured and modelled by a novel gain-isolated Volterra model. Experiment had verified that the proposed gain-isolated Volterra model can model the impact of electrical amplifier nonlinearity under various gain conditions, and has high accuracy in estimating both distorted waveforms and bit-error-rate penalty in 64QAM coherent optical system.

Keywords: High speed coherent optical communication, Electrical amplifier nonlinearity, Nonlinear modeling with memory effect, Volterra series

1. Introduction

Capacity demand for optical communications in scenarios of inter- and intra- Internet data centers promotes active researches on high baud rate and high order multi-level modulation formats in coherent optical transmissions, such as 64- or 100-giga-baud 64QAM[1,2,3]. In such modulations, the characteristics of individual components in coherent optical transmitter and receiver becomes important[4,5,6]. **Fig. 1** shows the component block diagram of coherent optical transmission system. Data to be sent are modulated on 4 lanes at the transmitter because two orthogonal polarizations and both in-phase and quadrature phase (IQ) tributaries of each polarization of light are modulated to increases the spectrum efficiency. Each lane signal is firstly generated by digital-to-analog converter (DAC) and amplified by electrical amplifier which drives the modulator to emit the modulated light into fiber. At the receiver, full information of optical signal including real and imaginary part on two polarizations are received by dual polarization 90-degree optical hybrid and balanced photodiodes. After analog-to-digital converter (ADC) sampling and receiver digital signal processing, the sent data could be recovered.

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Among these components, electrical amplifier at the transmitter is to amplify the signal to an optimal level to drive the electro-optical modulator, which determines the transmitted signal quality and transmission distance. However, it is well known that the electrical amplifier is always not linear, which generates nonlinear harmonics distortions and causes waveform compression or asymmetries, and then degrades the signal precision and the transmission performance i.e. bit error rate (BER)[5,6,7]. When the transmitted signal bandwidth is tens of gigahertz, the suffered nonlinearity would have strong memory effect, which would significantly raises the difficulty of measuring, characterizing, evaluating and

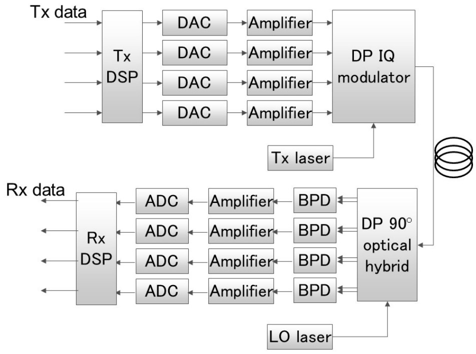

Fig. 1 Component block diagram of coherent optical transmission system. Tx: transmitter; Rx: receiver; DAC: digital-to-analog converter; LO: local oscillator; BPD: balanced photodiode; ADC: analog-to-digital converter

compensating such nonlinear distortions.

In order to understand and combat the electrical amplifier nonlinear characteristics, an accurate nonlinear behavior model is needed. Several works were done in the recent years. Memoryless polynomial model based on measured harmonic distortions of sine wave was used in [7]. Generalized memory polynomial model which was proposed for radio frequency (RF) power amplifier[8] was used in digital pre-distortion to linearize the optical transmitter[9]. Pre-measured look-up table containing the nonlinear input-output relationship was used for nonlinear pre-distortion in [10]. Volterra model is widely used in RF power amplifiers where the amplifier bandwidth is much lower than the carrier frequency[11,12,13].

In this paper, nonlinear characteristic of a commercially-available electrical amplifier with 20 gigahertz (GHz) bandwidth was measured and modelled based on Volterra series. At the beginning, conventional Volterra model was used. However, it was observed to have as large as 1.4 decibel (dB) error in estimating nonlinearity penalty when the input signal was 32-giga-baud NRZ 16QAM modulation. Then, a gain-isolated Volterra model is proposed, which multiplies a correction factor related to signal power onto the nonlinear terms of the Volterra series. Experiment validated that the proposed model has less than 0.5 dB estimation error, even when the electrical amplifier gain changed over the whole operation range (11.6 dB ~ 18.6 dB) and the input signal types cover PAM2/4/8 corresponding to 4/16/64QAM modulation with Nyquist and NRZ pulse shaping. Using the gain-isolated Volterra model, the performance penalty induced by the electrical amplifier nonlinearity was simulated and compared with the modulation nonlinearity of Mach-Zehnder modulator (MZM), which is another important but much simpler nonlinearity source in coherent optical transmitter.

2. Methodology for nonlinearity modelling

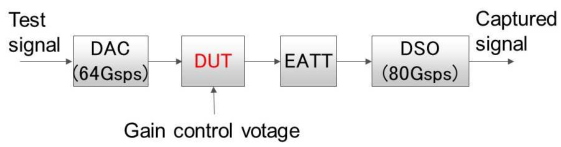

Fig. 2 Experiment setup to measure electrical amplifier nonlinearity. DUT: device under test; EATT: electrical attenuator; DSO: digital storage oscilloscope

2.1 Measurement experiment setup

Experimental setup for measuring and modelling the nonlinearity of electrical amplifier is shown in **Fig. 2**. Noise-like signal with Gaussian distribution is used as the test signal because it covers all the concerned signal levels in time domain and spectrum components in frequency domain, which is believed able to extend the applicable range of the measured nonlinear character and the trained nonlinear model to other input signal types. 64-giga-samples per second (Gsps) sampling rate DAC is used to send the 262144 samples noise-like signal with 32 GHz bandwidth to the typical commercial-available amplifier with 20 GHz bandwidth and adjustable gain from 11.6 dB to 18.6 dB, whose type number is Inphi IN3214SZ. An electrical attenuator (EATT) was used before the Analog-to-Digital Converter (ADC) realized by 80 Gsps digital storage oscilloscope (DSO). The purpose of this is to keep similar ADC input levels under various conditions so that ADC's working status, such as noise floor, were the same.

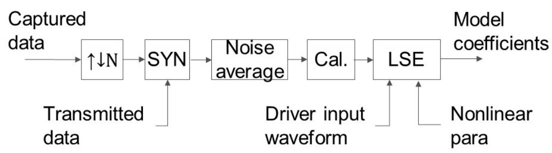

Fig. 3 Receiver signal processing to train nonlinear model. ↑↓N: sampling rate conversion; SYN: synchronization; Cal. : DAC/ADC filter response calibration; LSE: Least-square-estimation

2.2 Model training signal processing

The offline processing of nonlinear model training is shown in **Fig. 3**. The captured data was firstly resampled to 64 Gsps sampling rate based on sinc-pulse interpolated sampling rate conversion, and then synchronized with transmitted data by correlation operation. Because the test signal is sent by DAC in a periodic manner, the captured data could have as long as 150 periods of transmitted length. Thus the noise fluctuations in the received data could be significantly removed by simply 150 times averaging. The filter response of DAC and ADC, which were measured beforehand, could be calibrated by applying transmitted data passing through DAC filter and received data passing through inverse of ADC filter. Then, the input and output waveforms of the amplifier under test were obtained. The final step is to compare the input and output waveforms of amplifier in digital domain and train the nonlinear model coefficients by Least Square Estimation (LSE) method with the specified nonlinear model and parameters. Here the nonlinear model parameters e.g. nonlinear order number and memory length could be determined by measurement, which are discussed in latter section.

2.3 Open set validation

When doing modelling or training process, a notable issue is the over-training problem, which limits the trained model accurate only for the test signal or the training set while significantly inaccurate if the input is changed to the validating set with various types.

To avoid the over-training problem for amplifier nonlinearity modeling, open set validation is used in this paper. Specifically, noise-like signal is selected as the test signal in training stage, while the modulated QAM signals i.e. 4/16/64QAM with NRZ and Nyquist pulse shaping are chosen the input signals to validate the trained nonlinear models.

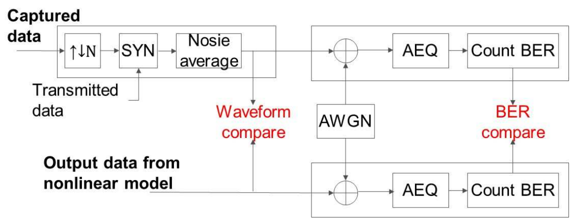

Fig. 4 Receiver signal processing to validate nonlinear model. AWGN: additive white Gaussian noise; AEQ: adaptive equalization; BER: bit error rate

2.4 Model validating processing and indicator

Different from the model training stage, in the model validating stage, the modulated QAM signals of 4/16/64QAM with NRZ and Nyquist pulse shaping were as input signals in the experiment. Experimental setup was exactly same with **Fig. 2**. To validating the accuracy of nonlinear model, waveforms and BERs measured by experiment are taken as the reference. MATLAB-based offline signal processing for the validating are shown in **Fig. 4**. After sampling rate conversion, waveform synchronization and noise removal, amplifier output waveform from measurement could be compared to that from model output. For BER comparison, additional white Gaussian noise was added to both output waveforms and adaptive linear equalization of 31 taps was applied to demodulate and decode the transmission bits and count BER to both model output and measured amplifier output signals.

3. Nonlinearity modelling with Volterra series

3.1 Volterra series

Equation of Volterra series is expressed by

$$
\begin{aligned}
y(n) &= \sum_{k=-(N_1-1)/2}^{(N_1-1)/2} h_k^{(1)} \cdot x(n-k) \\
&+ \sum_{k=-(N_2-1)/2}^{(N_2-1)/2} \sum_{l=-(N_2-1)/2}^{(N_2-1)/2} h_{k,l}^{(2)} \cdot x(n-k)x(n-l) \\
&+ \sum_{k=-(N_3-1)/2}^{(N_3-1)/2} \sum_{l=-(N_3-1)/2}^{(N_3-1)/2} \sum_{m=-(N_3-1)/2}^{(N_3-1)/2} h_{k,l,m}^{(3)} \\
&\cdot x(n-k)x(n-l)x(n-m) \\
&+ \ldots \qquad (1)
\end{aligned}
$$

Here $x(n)$ and $y(n)$ are input and output signals of nonlinear system in the discrete time domain[8]. As can be seen, Volterra series is to model the system transfer function by high order polynomial with full memory terms. N_1 is the linear response length, and N_2, N_3 are the truncated memory length of *2nd*, *3rd* order nonlinear terms separately. Correspondingly, $\{h^{(1)}\}$ are linear response coefficients, and $\{h^{(2)},h^{(3)}\}$ are nonlinear coefficients of each polynomial term which are called Volterra kernels of system and can be trained by Least-Square-Estimation (LSE) method[8]. However, here the amplifier in coherent optical system is to amplify the signal with bandwidth 32 GHz and modeled by small sampling period of 15.625 picosecond (ps), while in previous researches it was to amplify RF signal with much narrower bandwidth e.g. 2-megahertz (MHz) and modeled by large sampling period of 250 nanosecond (ns)[11]. The large signal bandwidth and small sampling period would lead to significant inter-symbol interference and long memory nonlinear effect in our scenario.

Volterra nonlinear model theoretically has high accuracy when nonlinear parameters e.g. order and memory length are properly selected. The capability to dealing with memory effect is rather suitable for the electrical amplifier with large signal bandwidth. Another advantage of Volterra model is that it naturally separates linear term and various orders of nonlinear terms, which can analyze the nonlinearity impact isolated with linear effect, and could be easily applied for nonlinear distortion compensation. What's more, flexible truncation and selection on polynomial terms can efficiently trade off the computational complexity and the model accuracy.

3.2 Experiment results

a) The training stage

Nonlinear parameters of Volterra model including nonlinear order number and memory length, needs determinations before training the coefficients.

To measure the required nonlinear order number, 1 GHz sine wave with peak-to-peak voltage 0.5 volts was sent into amplifier, the output harmonics power were recorded and shown in **Fig. 5**. In the figure, harmonics powers of 2nd, 3rd, 4th, 5th order are normalized by fundamental wave power and shown in unit of dBc. When amplifier gain set 18.6 dB compared to 11.6 dB, 4th and 5th order harmonics are almost unchanged, while 2nd and 3rd order increases >7 dB. From this, the measured nonlinear order number is selected up to 3rd order.

To measure the required memory length of 2nd and 3rd order nonlinearity, test signal of noise-like signal was input to amplifier. Memory length were swept until the model output waveform error stopped decreasing, which was shown in **Fig. 6**. From the result, memory length of 11 samples and 9 samples are selected for the 2nd and 3rd order nonlinearity separately while sampling period is 15.625 ps.

With selected nonlinear parameters, nonlinear coefficients of Volterra model were trained by standard LSE method. There are 66 coefficients for 2nd order nonlinearity and 165 coefficients for 3rd order nonlinearity. Parts of these coefficients are shown in **Fig. 7**. Coefficients at time index 0 represents the contribution from current sample, while those at non-zero time indexes represent the nonlinearity memory effect contributed by neighboring samples. Significant memory effect can be observed from these nonlinear coefficients.

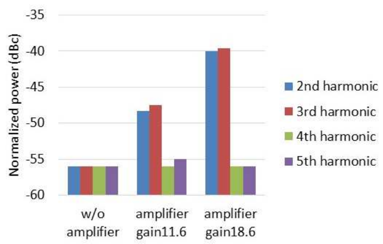

Fig. 5 Nonlinear order number is measured up to the third order by input 1 GHz sine wave

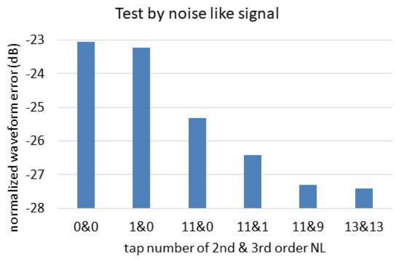

Fig. 6 Memory length of the second and third order nonlinearity are measured by input noise-like signal. Here '11&9' in horizontal axis means that 11 taps assigned for the second order and 9 taps assigned for the third order nonlinearity, and others are similar

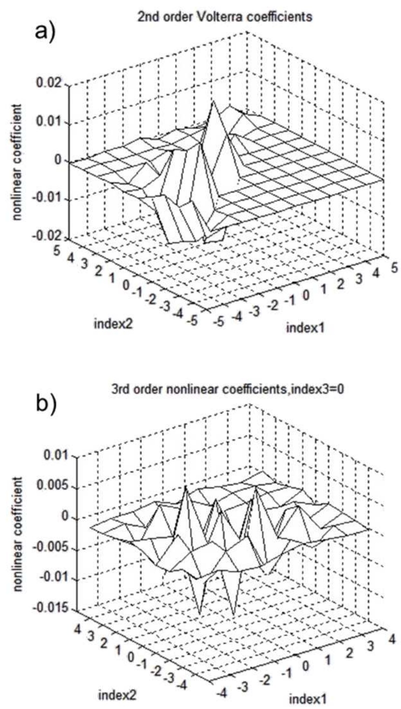

Fig. 7 Nonlinear coefficients of Volterra model of electrical amplifier at gain 18.6 dB. a) The second order nonlinear coefficients; b) The third order nonlinear coefficients

b) The validating stage

With the signal processing as shown in **Fig. 4**, BERs from measured amplifier output and conventional Volterra model output were counted. The added white noise power is fixed to make BER 0.0022 under linear channel. Because adaptive equalizer always equalizes the linear response, the measured BER degradation compared to linear case were considered as nonlinearity penalty, which is expressed by

$$Qpenalty(dB) = Q_{NL}(dB) - Q_L(dB) \tag{2}$$

and

$$Q(dB) = 20\log_{10}(\sqrt{2} \cdot erfcinv(2BER)) \tag{3}$$

Here BER was transferred to Q-factor for comparison because Q-factors relate to SNR in dB unit, and Q-factor penalty was calculated by the Q factor in nonlinear case directly subtracting that in linear case in dB unit. And $erfcinv(\cdot)$ is the inverse of complementary error function. Measured penalty is from amplifier output waveform in experiment, while model estimated penalty is from nonlinear model output waveform.

Results of performance penalty measured by experiment and that estimated by conventional Volterra model are shown in **Fig. 8**. Significant nonlinear penalty are observed in the measured results, which show difference between different input types including 32-giga-baud 2/4/8PAM modulation corresponding to 4/16/64QAM with Nyquist and NRZ pulse shaping. NRZ pulse shows more penalty than Nyquist because it has larger power. PAM8 is more sensitive to nonlinearity than PAM2 because it has more amplitude levels. Taking the measured results as reference, conventional Volterra model exhibits significant estimation error, that is 1.4 dB error for NRZ PAM4 signal and 1.9 dB error for NRZ PAM8 signal. In the following chapter, a novel nonlinear model is proposed to try to solve this.

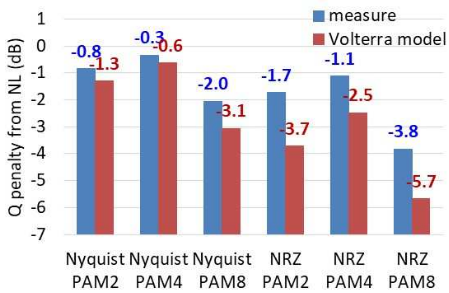

Fig. 8 Q-factor penalty estimation by conventional Volterra model. NL: nonlinearity (amplifier gain 18.6 dB)

4. Proposed nonlinearity modelling method

4.1 Structure and transfer function

Proposed nonlinear model with gain isolation and power correction based on Volterra series is shown in **Fig. 9**. On one hand, the amplifier gain is isolated from the Volterra series, which assumes that nonlinear effect is mainly ascribed to the latter stage after variable gain.

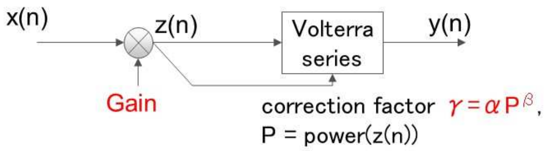

Fig. 9 Proposed nonlinear model with gain isolation and power correction based on Volterra series

This also makes the model available for different gain conditions. On the other hand, an additional nonlinear term correction factor determined by signal power after gain is added to the Volterra series. Then, transfer function of the proposed model can be expressed by

$$z(n) = x(n) \cdot Gain \tag{4}$$

and

$$\begin{aligned} y(n) = &\sum_{k=-(N_1-1)/2}^{(N_1-1)/2} h_k^{(1)} \cdot x(n-k) \\ &+\alpha P^{\beta} \cdot \{ \sum_{k=-(N_2-1)/2}^{(N_2-1)/2} \sum_{l=-(N_2-1)/2}^{(N_2-1)/2} h_{k,l}^{(2)} \\ &\cdot x(n-k)x(n-l) \\ &+ \sum_{k=-(N_3-1)/2}^{(N_3-1)/2} \sum_{l=-(N_3-1)/2}^{(N_3-1)/2} \sum_{m=-(N_3-1)/2}^{(N_3-1)/2} h_{k,l,m}^{(3)} \\ &\cdot x(n-k)x(n-l)x(n-m) \\ &+ \ldots \} \end{aligned} \tag{5}$$

Here $z(n)$ is signal after an ideal gain, $\gamma = \alpha P^{\beta}$ is the nonlinear term correction factor. And P is power of $z(n)$, and α, β are free fitting parameters to be determined. It is assumed that the relationship between signal power P and correction factor γ is a fractional order power function with two parameters α, β, which could extend the model to cover the nonlinear behaviors of higher order polynomial terms and efficiently reduce the estimation error for both distorted waveform and nonlinear power. In the experimental measurement, the correction factor γ could be measured by using the training signal such as noise-like signal under different input powers. The measured results using 8 training signal powers are shown in **Fig. 10**. It is found that higher signal power requires smaller value of correction factor. By applying power function fitting with least squares criterion, parameters α and β were fitted as shown in **Fig. 10** that α equal to 1.16 and β equal to -0.28 and the fitting R-square value is 99%.

4.2 Experiment results

a) Fixed amplifier gain 18.6 dB

Results of performance penalty estimated by proposed gain-isolated Volterra model are shown in **Fig.** 11. As can be seen, penalty estimation error are greatly reduced compared to conventional Volterra model. For all the considered modulation cases, penalty estimation accuracy of gain-isolated Volterra model is seen within 0.3 dB.

Results of waveform estimation of the proposed model is shown in **Fig.** 12. The amplifier output waveform measured by experiment is taken as the reference. Input signal is 32-giga-baud NRZ PAM4 signal. Results show that proposed nonlinear model has higher accuracy than conventional Volterra model in aspect of estimating the nonlinear waveform, which implies that nonlinear compensation scheme based on the proposed nonlinear model would be better than that using conventional Volterra model.

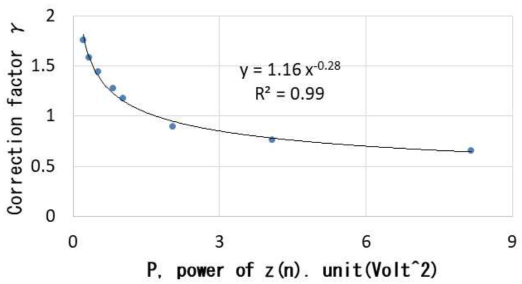

Fig. 10 Correction factor α and β are determined as 1.16 and -0.28 separately by sending noise-like signal with different signal powers

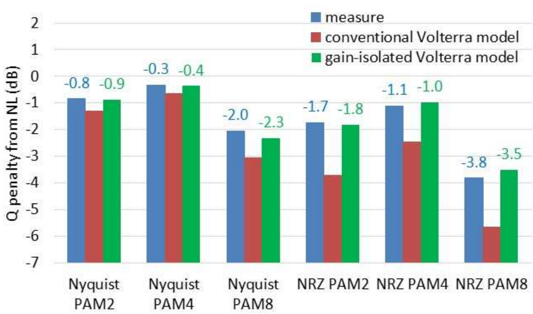

Fig. 11 Q-factor penalty estimation by gain-isolated Volterra model. NL: nonlinearity (amplifier gain 18.6 dB)

b) Various amplifier gain conditions

To evaluate the applicability of the proposed nonlinear model, amplifier gain were set from 11.6 dB to 18.6 dB. Nonlinearity-induced Q-factor penalty estimation errors, defined as the difference of Q-factors by the nonlinear model and by the experiment, are shown in **Fig.** 13. Due to residual nonlinearity impact, the conventional Volterra model has large penalty estimation errors of maximum 2 dB, especially at the large gain region.

However, for all modulated Nyquist/NRZ PAM2/4/8 signals with 8 amplifier gains, gain-isolated Volterra model has always less than 0.5 dB penalty estimation errors, which confirms that the proposed gain-isolated Volterra model has high accuracy under various amplifier gain conditions, and can credibly emulate the impact of amplifier nonlinearity in the experiment.

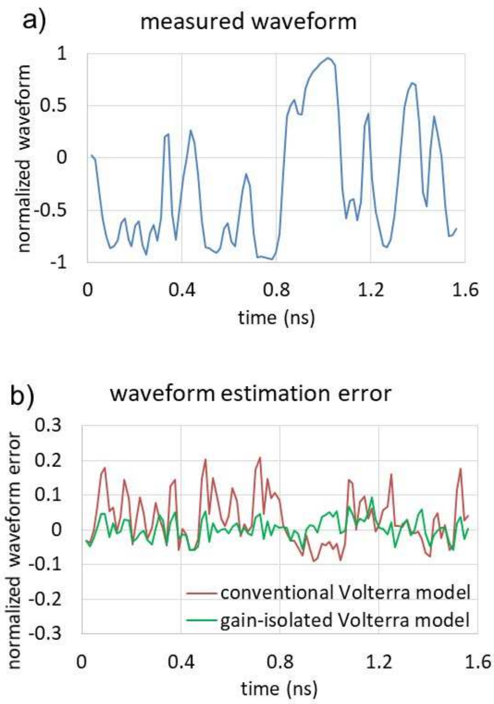

Fig. 12 Waveform estimation when input 32-giga-baud NRZ PAM4 at amplifier gain 18.6 dB. a) measured output waveform as reference; b) waveform error by conventional Volterra model and gain-isolated Volterra

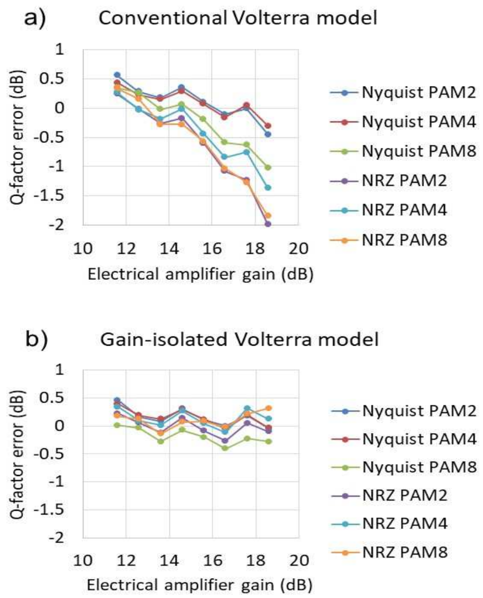

Fig. 13 Q-factor estimation error of gain-isolated Volterra model and conventional Volterra model

5. Nonlinearity penalty comparison of two sources in coherent optical system

Having accurate nonlinear behavior model of the amplifier, performance penalty from electrical amplifier and Mach-Zehnder modulator nonlinearity could be simulated and evaluated entirely. A single wavelength dual polarization (DP) 16QAM/64QAM coherent optical back-to-back transmission system simulation is built as shown in **Fig. 14**. Transmitted signals are DP Nyquist/NRZ 16QAM/64QAM signals of 32-giga-baud. Total transmission bit rate are 256 and 384 giga-bits per second for 16QAM and 64QAM respectively.

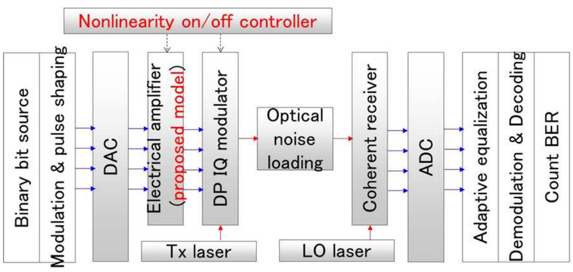

Fig. 14 Dual polarization 16QAM/64QAM coherent system simulation setup with electrical amplifier modeled by proposed gain-isolated Volterra model

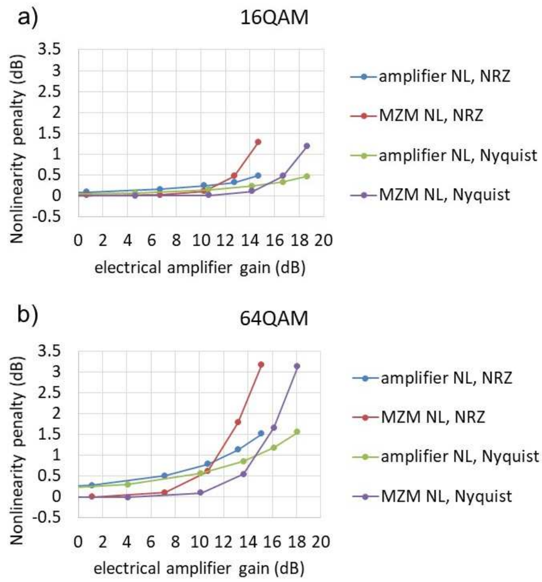

Fig. 15 Simulation results of nonlinearity Q-factor penalty from amplifier and modulator

At the transmitter side, both the amplifier and the modulator induce nonlinear distortions. For the amplifier, the nonlinear characteristics are emulated by the proposed gain-isolated Volterra model measured from experiment. To switch it off, linear response model measured from the same experiment is used. For the modulator, the nonlinear input-output relation is modelled as memoryless sine function, which is the theoretical relation derived from Mach-Zehnder structure. Nonlinearity of the modulator could also be switched off by replacing the Mach-Zehnder modulator by an ideal linear modulator with same modulation efficiency. Modulator pi-phase-shift-voltage uses 3 volts. The DAC output peak-to-peak voltage is always 1 volts and signal peak-to-peak amplitude voltage after amplifier to drive the modulator is changed by amplifier gain from 0 dB to 20 dB.

At the receiver side, 31-taps linear adaptive equalization based on minimum mean square error algorithm is performed to recover the signal. Optical noise power is fixed so that penalty from linear channel is unchanged during investigating nonlinearity penalties. Base BER without nonlinear distortion is set 0.0022. Nonlinearity-induced Q-factor penalty from amplifier and/or modulator were obtained by checking the Q-factor difference between nonlinearity on and off.

Results of nonlinearity penalty from amplifier and modulator in DP Nyquist/NRZ 16QAM/64QAM systems are shown in **Fig. 15**. Modulator nonlinearity was set off when to evaluate pure amplifier nonlinearity impact, and amplifier nonlinearity was set off when to evaluate pure modulator nonlinearity impact. At amplifier gain 18.6 dB, nonlinearity Q-factor penalty from modulator is 3.1 dB while that from amplifier is 1.5 dB for 64QAM case. Q–factor penalties from amplifier and Mach-Zehnder modulator nonlinearity are observed comparably significant. For 64QAM case, when amplifier gain is lower than 15 dB, amplifier nonlinearity is the dominant source of nonlinear distortion; when amplifier gain is higher than 15 dB, modulator nonlinearity becomes the dominant source of nonlinearity. Amplifier nonlinearity penalty is <0.5 dB for 16QAM system which might be ignorable sometimes. However for 64QAM system, amplifier penalty is significantly enlarged to 1.5 dB, which would degrade the transmission performance and need the nonlinear compensation process.

6. Conclusion

Nonlinear characteristic of tens of gigahertz electrical amplifier in coherent optical transmitter is measured and modelled by Volterra models. Novel gain-isolated Volterra model is proposed to increase the accuracy of conventional Volterra model considering both nonlinear distorted waveform estimation and nonlinearity induced BER penalty estimation. The proposed nonlinear model is experimentally validated under various conditions (48 cases in total) including dual polarization Nyquist/NRZ PAM2/4/8 signals corresponding to 4/16/64QAM modulation and 8 different amplifier gain conditions. Results show that estimated nonlinearity penalty errors are less than 0.5 dB in all validation cases. Based on the gain-isolated Volterra model, nonlinearity penalty of amplifier and Mach-Zehnder modulator in coherent optical system are evaluated by simulation.

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