Experimental Demonstration of a Simplified SOA Nonlinearity Mitigation scheme

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Abstract: We experimentally demonstrated a digital learned-filter mitigation scheme for semiconductor optical amplifier-induced nonlinear distortion of single-polarisation 32 GBd 16QAM and 64QAM signals in a back-to-back configuration.

1. Introduction

The semiconductor optical amplifier (SOA) is a versatile device, offering benefits for a number of applications. It is suitable for amplification in transmission systems with bandwidths of over 100 nm [1,2], can be monolithically integrated into InP PICs, for example providing amplification within optical transceivers, and has applications in optical switching. Compared to Erbium-doped fibre amplifiers (EDFAs), SOAs can potentially reduce energy consumption and space requirements for optical networks.

However, a drawback of SOAs is their signal-dependent phase and gain response [3], which can cause significant signal distortion. A number of methods have been proposed to mitigate the nonlinear impairments introduced by the SOAs [4–7]. However, many of these require precise knowledge of the device parameters, some of which cannot be easily measured and can vary with temperature and ageing. All of the methods are either (i) based on the computationally complex Runge-Kutta (RK) method or (ii) do not mitigate the nonlinearity and show improvement by dealing with the nonlinearity with sophisticated decision algorithms [8].

In this work, we propose a simplified method in which a finite impulse response (FIR) filter and the Henry factor are estimated using automatic differentiation [9]. The performance of this simple mitigation scheme is compared with that of the approach based on the RK solution of a time-domain model of the SOA. Both techniques are experimentally demonstrated using a single polarization (SP) SOA and a coherent transmission system transmitting 32GBd signals of 16-quadrature amplitude modulation (QAM) and 64-QAM.

2. Semiconductor optical amplifier nonlinearity mitigation

A lossless time-domain model of an SOA is described in [3], expressed as

$$\tau_S \frac{dh(t)}{dt} \approx G_0 - h(t) - \left[e^{h(t)} - 1\right] \frac{|E_{\text{in}}(t)|^2}{P_{\text{sat}}} \tag{1}$$

$$E_{\text{out}}(t) = E_{\text{in}}(t) \exp\left\{ \left(\frac{1 - j\alpha_{\text{H}}}{2} \right) h(t) \right\} \tag{2}$$

with E_{in} and E_{out} being the optical fields at the SOA input and output respectively, τ_S the carrier lifetime, G_0 the unsaturated gain, P_{sat} the saturation power, α_{H} the Henry factor (i.e., linewidth enhancement factor) and $h(t)$ the gain exponent. In this work, we compare two mitigation approaches: firstly, the RK approach, in which the inverse of (1) and (2) are solved using the fourth-order RK method, and, secondly, a digital filter backpropagation approach, in which the gain exponent is approximated with a FIR-filtered version of the instantaneous field power, $|E_{\text{in}}|^2$. In contrast to the method described in [4] which used 10 blocks comprising of an infinite impulse response filter and a phase compensator, our work investigates the use of a single FIR filter and phase compensator, making it easier to implement. The gain exponent is then applied to the signal following Eq. (2), which is then passed to a conventional equaliser.

3. Experimental setup

The experimental setup, shown in Fig. 1, was designed to replicate the use of an SOA booster at the output of each modulator in a dual-polarisation transmitter. The setup consisted of a 100 kHz external cavity laser (ECL) modulated by an IQ modulator driven by a 92 GS/s arbitrary waveform generator (AWG), creating a single polarisation IQ-modulated signal. An EDFA followed by a variable optical attenuator were used to control the power

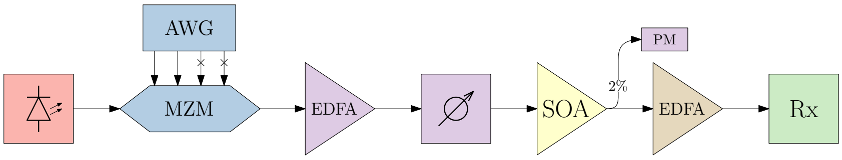

Fig. 1. The experimental setup, in which the power into the SOA can be precisely controlled.

into the discrete semiconductor optical amplifier under test, following which, a 2% power tap was used to measure the power out of the SOA. The SOA current was kept constant at 100 mA, and the input power was varied to investigate the nonlinear distortion. A second EDFA was used to keep the power into the receiver constant. At the receiver side the ECL local oscillator was polarisation aligned with the signal.

In the receiver digital signal processing (DSP), shown in Fig. 2, after analogue-to-digital conversion (ADC), the receiver skew is compensated. From then on, the processing blocks differ between the approaches. For the RK approach, shown in Fig. 2.(a), the first step is to undo the phase and amplitude distortion from the SOA. Using precise knowledge of the device, the differential equation is numerically solved in reverse using the fourth-order Runge-Kutta method, as described in [4]. Following this, the carrier frequency offset (CFO), root raised cosine (RRC) matched filter and adaptive equaliser, followed by carrier phase recovery (CPR) are applied. Finally, the signal-to-noise ratio (SNR) is calculated. The model parameters are perturbed to find precise parameters. As can be seen in Fig. 2.(a), this update loop stretches across multiple DSP blocks, preventing the use of error backpropagation to intelligently update the parameters, in contrast to the case of the simplified method in which the feedback loop is much shorter.

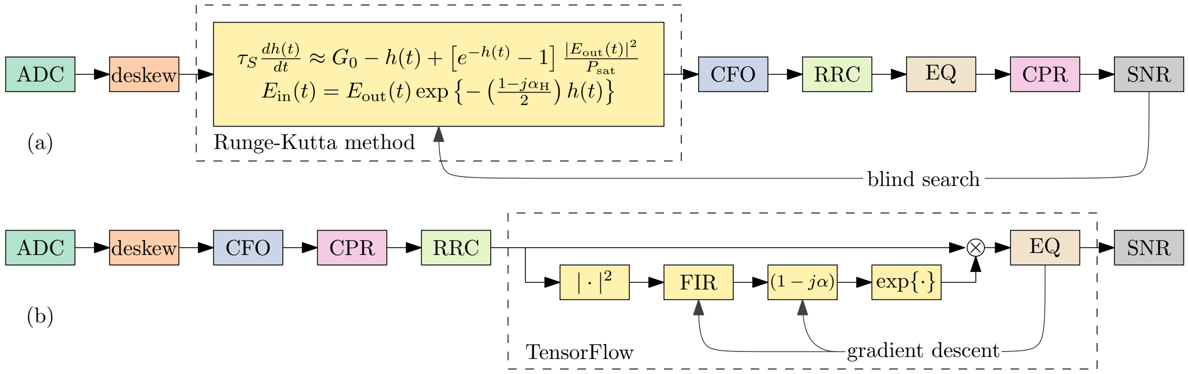

Fig. 2. Receiver DSP block diagrams for (a) the RK-based nonlinearity mitigation approach and (b) the proposed simplified nonlinearity mitigation method.

In the simplified SOA nonlinearity mitigation scheme, as shown in Fig. 2.(b), the CFO is found and corrected, and, with a moving average filter, CPR is performed. After applying the RRC filter, the I and Q components are processed at 2 samples-per-symbol using a learning approach with a simple FIR filter gradient using automatic differentiation, implemented using TensorFlow. The instantaneous power is FIR filtered. A high-order FIR filter was used in our study (255 taps), to enable narrow bandwidths to be achieved. It was initialised with a truncated sinc function (in the time domain) and α_H was initialised at 1. The equaliser following the digital backpropagation stage is a 2×2 by 21 taps filter. The loss is the mean squared error between the sent and received symbols, or the received symbol and the nearest constellation point, for data-aided and decision-directed approaches respectively, where the first can be considered supervised learning, the latter, unsupervised learning. The error is used to simultaneously update the equaliser taps as well as the taps of the model FIR and the estimated Henry factor. The Adam optimiser from TensorFlow was used, in which the learning rate is lowered between epochs. The training was carried out in 16 epochs on the first 98304 symbols of each trace, followed by a single pass on the last 32768 symbols of each trace, with only unsupervised updates being allowed. Updates were performed after each batch of 512 symbols.

4. Results

The SNR was chosen to quantify system performance as it includes both noise and signal distortion and is defined as $\text{SNR} = \frac{\mathbb{E}\left[|X|^2\right]}{\mathbb{E}\left[|Y-X|^2\right]}$, where X and Y are the transmitted and received signals respectively. In Fig. 3, the measured SNR is plotted, without and with nonlinearity mitigation. Both the RK and the simplified approaches achieved performance improvements at SOA output power levels above -6 dBm. It can be seen that the performance of the two techniques was comparable, with the simplified approach performing better in some cases, while for

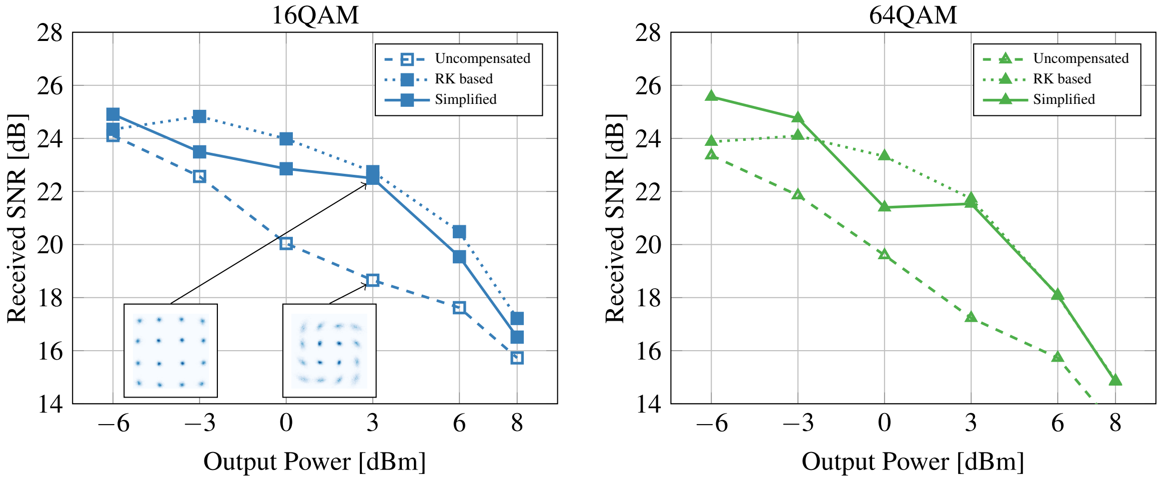

Fig. 3. Results with the RK approach, based on an SOA time-domain model and the machine-learning-assisted digital filter backpropagation approach or 32 GBd 16-QAM, 32 GBd 64-QAM and 64 GBd 64-QAM. The insets show the received constellation after equalisation with and without the simplified nonlinearity mitigation.

other cases the RK approach works better, depending on signal power and format. We speculate the results of the simplified method for 0 dBm to be an anomalous SNR value requiring further investigation. In most cases for 64-QAM, the simplified model performs as well as, or better than, the RK method, due to its ability to accurately learn the device parameters.

With the simplified approach, the time between consecutive updates is within a batch, i.e., 512 samples, in contrast to the RK approach where the parameters were only updated after the whole sequence was decoded. This made finding accurate device parameters for the RK model more difficult, resulting in less accurate parameter estimation.

This study shows promising results and could be extended beyond the single-polarisation and single-channel scenario. The techniques used, estimating the population inversion using the received signal intensity, could potentially be scaled to two polarisations [10] and multiple channels [11]. This would require further investigation.

5. Conclusion

We experimentally investigated nonlinear distortion due to semiconductor optical amplifiers and demonstrated a novel simplified technique for SOA nonlinearity mitigation. The performance of this method was experimentally compared with that of a conventional approach, in which a time-domain model of the SOA is solved using the Runge-Kutta method, and was found to achieve similar performance with a shorter parameter estimation time. Further work is required to show how this method scales for multi-wavelength transmission systems.

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