Optimal and Low Complexity Control of SOA-Based Optical Switching with Particle Swarm Optimisation

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Abstract

We propose a reliable, low-complexity particle swarm optimisation (PSO) approach to control semiconductor optical amplifier (SOA)-based switches. We experimentally demonstrate less than 610 ps off-on switching (settling) time and less than 2.2% overshoot with 20x lower sampling rate and 8x reduced DAC resolution.©2022 The Author(s)

Introduction

The semiconductor optical amplifier (SOA) has been deemed as a promising candidate to realising high-speed switch demands in an optical circuit switching (OCS) implementation within data centre networks (DCNs)[1],[2]. SOAs make for good space switches due to their wide bandwidth, high optical gain, the high extinction (on/off) ratio and fast sub-nanosecond switching speed[1]. However, SOAs intrinsically suffer from an optical overshoot and oscillatory response to electronic drive currents which directly correspond to its transient response[3],[4] therefore, various techniques and methods have been introduced to optimise the SOA's output[4]–[8]. Among them, particle swarm optimisation (PSO)[4] achieved new state-of-the-art sub-ns switching (settling) times . However, the work used an expensive 12 GSa/s, 8-bit digital to analogue converter (DAC) as part of the control circuit and focused solely on the method as a proof-of-concept without complexity considerations.

As the deployment of SOAs at scale is required within OCS networks, the requirement of FPGAs/RFSoCs or ASICs with embedded DACs which are used to drive SOAs will increase drastically. Reducing the DAC resolution and sampling rate as low as possible allows the utilisation of FPGAs/RFSoCs or ASICs with low cost and low power[9], effectively reducing total cost and power of network. In this work, we propose a new PSO cost function and optimisation window (PISIC-shaped Shell) to reduce the complexity of the drive circuit (DAC sampling rate and resolution) while increasing the optimisation consistency. The new approach results in settling times of less than 610ps and overshoot below 2.2% for

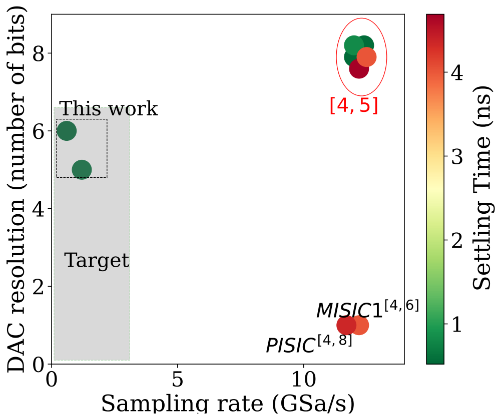

Fig. 1: Control complexity and SOA-based switch settling time of various methods

as low as 0.6 GSa/s (20X lower sampling rates for an SOA with frequency response of 0.6 GHz) and 5-bit (8X lower) DAC resolution than[4], as shown in Fig.1.

Experimental Setup

The experimental setup, as shown in Fig.2, is the same as[4], where an INPhenix-IPSAD1513C-5113 SOA with a 3dB bandwidth of 69 nm, a small signal gain of 20.8 dB, a saturation output power of 10 dBm, a response frequency of 0.6 GHz, and a noise figure of 7.0 dB was used. A 9V SHF 100 BP RF amplifier, enabling a full dynamic range peak-to-peak voltage of 5.5 V was selected. The SOA was driven by an LDX-3200 Series bias cur-

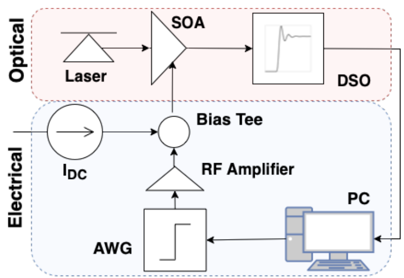

Fig. 2: Experimental Setup

rent source with bias current of 50 mA and a bias tee and modulated by RF driving signals from a Tektronix 7122B Arbitrary Waveform Generator (AWG) providing up to 12 GSa/s sampling frequency. Lower sampling rates were achieved by sample-and-hold, as illustrated in Fig.3(a). A 50 Ω resistor was placed before the SOA, allowing for the maximum allowed dynamic current range of 110 mA to be applied across the SOA. This arrangement allowed us to reverse bias the SOA in its 'off' state and avoid any leakage of optical power in the SOA's off state. The SOA's optical input consists of a Lightwave 7900b lasing system at -2.5 dBm optical power. An Agilent 86100C Digital Sampling Oscilloscope (DSO) sampling at 50 GSa/s with 30 GHz bandwidth with an embedded photodiode was used to display the corresponding SOA outputs of the driving signals and used for optimisation analysis within the PSO.

Particle Swarm Optimisation Design

The PSO algorithm[10], initialised n particles randomly with hyperparameters shown in Tab.1 To guide particles in the optimisation, the PSO search space was also bound by a PISIC-shaped shell[4] illustrated in Fig. 3(a) where particles can only assume values within these limits. Fig. 3(a) further displays the initial step input (red) and PSO-Optimised driving signal (black) with the corresponding SOA outputs in Fig. 3(b) showing the PSO-Optimised output (orange) having effectively settled within the 5% of target set point's (SP) steady state.

PSO optimised the particles according to the minimisation of some cost function. The typical Mean Squared Error (MSE)[4] has the issue that the points of the rising edge and the optical overshoot contribute significantly more to the cost causing the PSO to optimise for solely those regions of the SOA output rather than the entire ON state. Thus, instead of the MSE between the particle solution and the ideal step output target SP in Fig. 3(b), we propose a modified MSE as shown in Eq.(1).

$$Cost = \frac{1}{P_{\text{end}} - P_1} \sum_{i=P_1}^{P_{\text{end}}} X \quad (1)$$

$$X = \begin{cases} [PV(i) - SP(i)]^2 \times 0.75 & \text{for } i < x \\ [PV(i) - SP(i)]^2 & \text{otherwise} \end{cases} \quad (2)$$

The modified MSE between the SOA's corresponding outputs, *PV*, and target *SP* is evaluated within the range where the SOA's output power first reaches the SP's ON state, P_1, and the signal end P_{end}. Although, an allocated number of points x at the beginning of the risen signal were weighted less than the rest of the points, as shown in condition at Eq. (2). Finally, to avoid slow rise time (10:90%) solutions, SOA outputs that reach the SP after a specified threshold were penalised by increasing their evaluated cost by an order of magnitude.

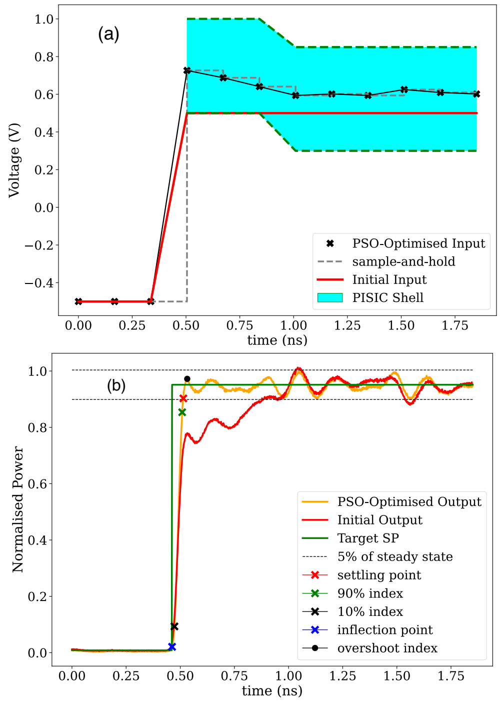

Fig. 3: (a) the optimised SOA optical input and (b) corresponding output at 0.6GSa/s with 6-bit DAC resolution

Complexity Reduction

The complexity of SOA control mainly comes from two parts: sampling rate and DAC resolution. The drive signal sampling rate and resolution was 12 GSa/s and 8-bit whereas the SOA had just a -3 dB frequency response of 0.6 GHz. Therefore, the aim was to explore the minimum possible sampling rate and resolution that does not negatively impact the settling time.

Secondly, the drive signal can be formed by RF coupling the OFF (LOW) signal state and a multi-level ON (HIGH) signal to operate within the PISIC-shaped shell to reduce the dynamic range and resolution of the required DAC. Furthermore, rather than optimising the entire driving signal, as was the case in the previous PSO[4], the PSO was set to optimise the areas determining the rising edge and stability within the ON (HIGH) state of

n	$iterations$	c_1	c_2	ω	$init\ v_f$	$max\ v_f$
320	200	0.2	0.2	0.9	0.05	0.05

Tab. 1: Hyperparameters of PSO

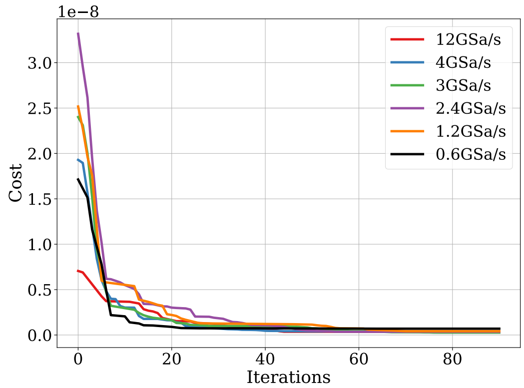

Fig. 4: Learning Curves at different sampling rates

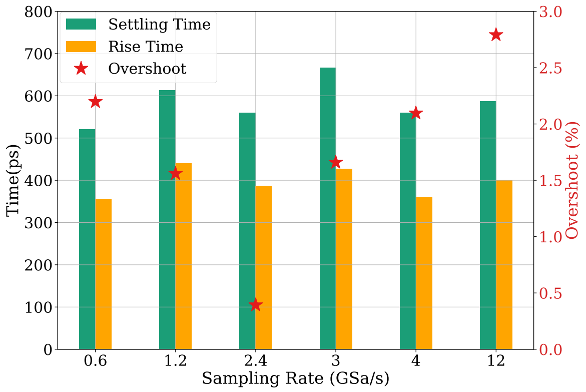

Fig. 5: Rise and Settling times and Overshoot of PSO-Optimised SOA outputs at 6-bit DAC resolution and different sampling rates

the SOA, as this would determine the settling time of the SOA output and by reverse biasing the SOA in its OFF state, optimising the LOW region would be redundant. This allowed for a reduction in PSO complexity, as well as faster convergence to an optimised solution.

Results

The settling time was defined and measured as the time from the SOA output signal's inflection point to the point where the signal settles within the 5% of the defined SP's ON steady state.

Upon reducing the sampling rate from 12 to 0.6 GSa/s (20x reduction) by halving the number of points in the driving signal at each time, and DAC-resolution from 8-bit to 6-bit (4x reduction), the PSO designed drive signals that led to consistently low rise and settling times. Rise time values range between 356-440ps and settling time between 521-667ps, with just 0.39-2.79% overshoot, as shown in Fig.5. The final optimised input and output driving signals are presented in Fig.3. At a further decrease of emulating a 5-bit DAC resolution, the PSO optimised up to 1.2 GSa/s with a rise time, settling time and overshoot of 411ps, 603ps and 1.13% respectively.

The PSO at lower sampling rates maintained a stable behaviour in convergence to an optimal solution, as shown in Fig.4. Thus, the stability of the PSO, hyperparameters and cost function are illustrated as with multiple runs, the PSO converges to solutions with similar costs. This was not observed in the previous[4] implementation of the PSO where multiple runs resulted in significant differences.

Upon running the previous PSO[4] 14 times, the resulting optimal solution would be either invalid (the signal would never settle) or have a very high settling time. Fig.6 displays the distribution of the rise and settling times for all 14 runs as opposed to this PSO and PISIC-shell configuration. The previous implementation led to lower than a 15% success rate in achieving sub-ns settling times whereas this PSO lead to 100% sub-ns settling times. This can be associated to the previously mentioned issue in the objective function where the MSE across the entire signal was taken causing the SOA output's rising edge contribution to the error function overpowering the rest of the signal's contribution by approximately 2 orders of magnitude and hence, the PSO would converge towards any solution with an improvement to solely this region. This can be further observed by the low rise times achieved.

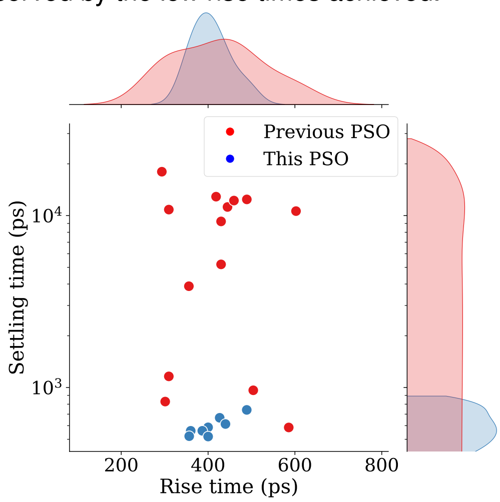

Fig. 6: Distribution of rise times and settling times of multiple runs from previous PSO vs. this PSO implementation.

Conclusion

We proposed and experimentally demonstrated a robust and consistent PSO-based method for SOA driving signal optimisation with significant reductions in complexity. The new approach results in settling times of less than 610ps and overshoot below 2.2% for as low as 0.6 GSa/s (for an SOA with frequency response of 0.6 GHz) and 5-bit DAC resolution. This led to a 20x lower sampling rate and 8x lower DAC resolution while 100% of drive signals led to sub-ns settling times compared to only 15% in previous work.

Acknowledgements

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