2023 Conference on Lasers and Electro-Optics Europe & European Quantum Electronics Conference (CLEO/Europe-EQEC) | 979-8-3503-4599-5/23/$31.00 ©2023 IEEE | DOI: 10.1109/CLEO/EUROPE-EQEC57999.2023.10231574

A nonlinear activation function for optical neural networks using a Mach-Zehnder interferometer with a III-V-on-Si amplifier

Yu Zhang[1,2], Hong Deng[1,2], Emadreza Soltanian[1,2], Jing Zhang[1,2], Gunther Roelkens[1,2], Wim Bogaerts[1,2]

1. Photonics Research Group, INTEC-department, Ghent University-IMEC, 9052 Ghent, Belgium

2. Center for Nano- and Biophotonics (NB-Photonics), Ghent University, 9052 Ghent, Belgium

With the benefit of high speed, wide bandwidth, and low latency, optical neural networks (ONN) form a promising neuromorphic computing platform for accelerating artificial intelligence tasks. ONNs contain two kinds of fundamental functional operations: multiply-accumulate (MAC) stages and nonlinear activation function units, as shown in Fig.1(a). In the past years, different optical MAC units have been developed using wavelength-division multiplexing (WDM) schemes [1-2] or coherent multipath interferometers [3]. However, the optical nonlinear activation function units still remain a challenge for the integration of large-scale ONNs. Most nonlinear activation functions are implemented in optical-electrical (OE) conversion schemes [2-3], where processing speed is limited by the latency time of OE conversion. Therefore, an integrated all-optical nonlinear activation function is an attractive solution for optical neuromorphic computing.

In this paper, we propose and experimentally demonstrate an all-optical nonlinear activation function based on a Mach-Zehnder interferometer (MZI) with a semiconductor optical amplifier (SOA) embedded in one arm. We call this circuit, shown in Fig. 1(b), an SOA-MZI. A pre-fabricated C-band InP SOA is heterogeneously integrated into the MZI circuit on IMEC's iSiPP50G platform using micro-transfer printing [4], as shown in Fig.1(c). As the SOA provides both linear and nonlinear gain, as well as optical phase shift under bias current, a nonlinear optical response regime with low activation input optical power and significant optical amplification can be found by selecting a proper operation point of the interferometer. This III-V-on-Si integrated circuit is an enabler for large-scale multi-layered ONNs under both the WDM and coherent MAC schemes. The gain of the SOA varies with optical input power, which can be modeled as $G(P_{in}) = G_0(1+P_{in}/P_{sat})/(1+G_0P_{in}/P_{sat})$, where G_0 is the unsaturated gain, P_{in} is the optical input power, and P_{sat} is the saturation power. At the same time, the phase response of the SOA is also modulated as $\varphi(P_{in}) = \varphi_0 - \alpha\Delta G(P_{in})/2$, where φ_0 is the initial phase with zero optical input power, and α is the linewidth enhancement factor of the SOA. The phase response of the SOA interferes with the reference arm of the SOA-MZI, converting the phase modulation to amplitude modulation, which together with the self-modulated gain results in an optical nonlinear response at low input optical power. The values of G_0, P_{sat}, and φ_0 can be tuned by adjusting the SOA bias current, which gives the reconfigurability of the nonlinear optical activation function. The experimentally measured results of the nonlinear activation function under different bias currents at 1550 nm are shown in Fig.1(d). The optical response resembles the $tanh(x)$ function with a configurable slope and saturation. Under the bias current of 84 mA, the output power saturates at 1.31 mW when the P_{in} >1.28 mW. While under the bias current of 88 mA, a saturated output power of 0.66 mW is realized when the P_{in} >0.64 mW.

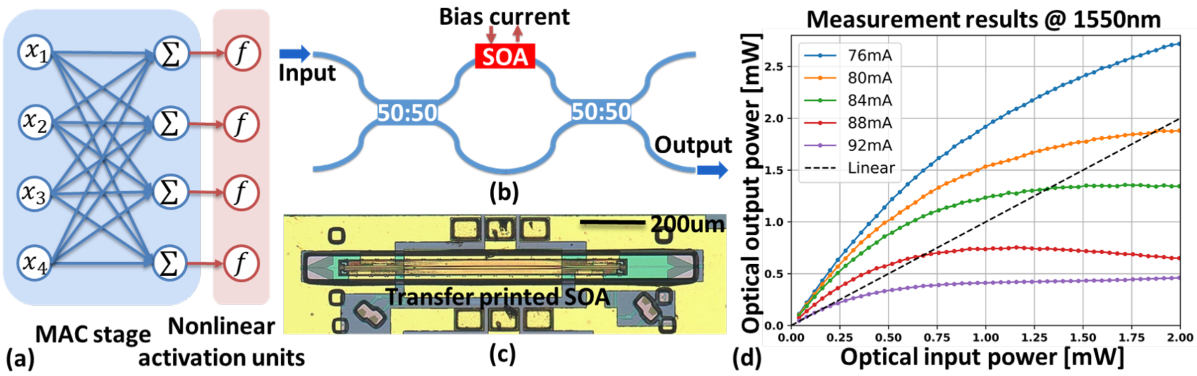

Fig. 1 (a) Structure of a network layer in the deep ONNs. (b) Schematic of the SOA-MZI-based all-optical nonlinear activation function. (c) Microscope image of the heterogeneously integrated SOA-MZI. (d) Measurement results of the nonlinear activation function under different SOA bias currents at 1550 nm.

References

[1] Shi, B., Calabretta, N., Stabile, R. InP photonic integrated multi-layer neural networks: Architecture and performance analysis. APL Photonics, 7(1), 010801 (2022).

[2] Huang, C., Fujisawa, S., de Lima, T.F. et al. A silicon photonic–electronic neural network for fibre nonlinearity compensation. Nat Electron 4, 837–844 (2021).

[3] Shen, Y., Harris, N., Skirlo, S. et al. Deep learning with coherent nanophotonic circuits. Nature Photon 11, 441–446 (2017).

[4] Roelkens, G., Zhang, J., Bogaert, L. et al. Micro-transfer printing for heterogeneous Si photonic integrated circuits. IEEE Journal of Selected Topics in Quantum Electronics, 29(3: Photon. Elec. Co-Inte. and Adv. Trans. Print.): 1-14 (2022).

979-8-3503-4599-5/23/$31.00 ©2023 IEEE