POLITECNICO DI TORINO
Repository ISTITUZIONALE

Investigation on digital twin model of 3x3 Mach-Zehnder Interferometer mesh

*Original*
Investigation on digital twin model of 3x3 Mach-Zehnder Interferometer mesh / Ma, T., Marchisio, A., Da Ros, F., Curri, V., Bardella, P., Carena, A.. - (2025). (International Conference on Numerical Simulation of Optoelectronic Devices (NUSOD) ód (Pol) September 14–18, 2025) [10.1109/NUSOD64393.2025.11199402].

*Availability:*
This version is available at: 11583/3002154 since: 2025-07-28T09:09:52Z

*Publisher:*
IEEE

*Published*
DOI:10.1109/NUSOD64393.2025.11199402

*Terms of use:*

This article is made available under terms and conditions as specified in the corresponding bibliographic description in the repository

*Publisher copyright*
IEEE postprint/Author's Accepted Manuscript

©2025 IEEE. Personal use of this material is permitted. Permission from IEEE must be obtained for all other uses, in any current or future media, including reprinting/republishing this material for advertising or promotional purposes, creating new collecting works, for resale or lists, or reuse of any copyrighted component of this work in other works.

(Article begins on next page)

19 November 2026

# Investigation on digital twin model of 3x3 Mach-Zehnder Interferometer mesh


Teng Ma
*Politecnico di Torino*
Torino, Italy
teng.ma@polito.it

Andrea Marchisio
*Politecnico di Torino*
Torino, Italy
andrea_marchisio@polito.it

Francesco Da Ros
*Technical University of Denmark*
Lyngby, Denmark
fdro@dtu.dk

Vittorio Curri
*Politecnico di Torino*
Torino, Italy
vittorio.curri@polito.it

Paolo Bardella
*Politecnico di Torino*
Torino, Italy
paolo.bardella@polito.it

Andrea Carena
*Politecnico di Torino*
Torino, Italy
andrea.carena@polito.it



***Abstract*—A physics-based digital twin model of a 3-by-3 Mach-Zehnder Interferometer (MZI) mesh is established by interpolating the experimental data with an accurate mathematical representation, then utilized to investigate the wideband capabilities of the device to implement programmable logic functions. Most of the evaluated functions perform correctly over a broad wavelength range (1524 nm – 1568 nm) under the voltage configuration determined at 1550 nm. The findings showcase the potential of digital twin model in Photonic Integrated Circuit (PIC) design, allowing novel designs in photonic computing and telecommunication applications.**



***Index Terms*—Digital twin model, Mach-Zehnder Interferometers, Wideband capability.**


## I. Introduction

The digital twin, a concept first adopted in the aerospace industry, was defined as "an integrated multiphysics, multiscale, probabilistic simulation of an as-built vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its corresponding flying twin" [1]. Due to its capability to characterize and model electronic devices accurately and efficiently, the digital twin exhibits favorable prospects in the semiconductor industry [2].

Photonic Integrated Circuits (PICs) are an emerging technology that focuses on detection, generation, transmission, and manipulation of photons [3], commercially applied in several fields such as optic communication, biomedicine, and photonic computing, exploiting the physics of structures such as Mach-Zehnder Interferometer (MZI). The digital twin model introduced in [4] is adopted in this work to verify the capability of a thermally tuned 3-by-3 MZI mesh [5] to implement user-defined logic functions over a wide wavelength range. The results show that the fitted model can successfully perform wideband logic operations, implying promising potential for digital twin modeling of PIC.

## II. Digital Twin Model

The reference device (Fig. 1) is a 3-by-3 MZI mesh realized on a Silicon-on-Insulator (SOI) platform, part of a C-band optical switch developed by the Technical University of Denmark (DTU) [6], where the input signals are linearly summed

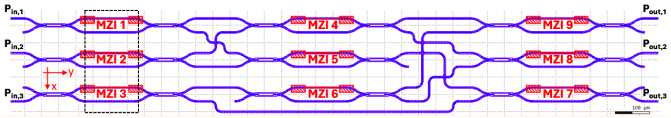



Fig. 1. Mask of the reference device. The Ti heaters are shown in red, the waveguides in blue. The black rectangle defines the area for thermal analysis.

at the three output ports by thermal tuning of the MZIs. The single MZI comprises two 2-by-2 Multi-Mode Interferometers (MMIs) and ∼267 µm long bent waveguides, while thermal tuning is regulated by a Thermo-Optic Phase Shifter (TOPS). A transmission matrix-based model is developed to accurately describe the single component [4]:

$$\overline{T}_{\mathrm{MMI}_p} = \begin{bmatrix} \alpha_{\mathrm{MM}_p}\sqrt{\gamma_1} & j\alpha_{\mathrm{MMI}_p}\sqrt{1-\gamma_2} \\ j\alpha_{\mathrm{MMI}_p}\sqrt{1-\gamma_1} & \alpha_{\mathrm{MMI}_p}\sqrt{\gamma_2} \end{bmatrix} \tag{1}$$

$$\overline{T}_{\mathrm{p}} = \begin{bmatrix} e^{-\alpha_{\mathrm{p}}L}e^{j(\kappa n_{\mathrm{eff},1}(T)L+\delta\varphi)} & 0 \\ 0 & e^{-\alpha_{\mathrm{p}}L}e^{j(\kappa n_{\mathrm{eff},2}(T)L-\delta\varphi)} \end{bmatrix} \tag{2}$$

where $\alpha_{\mathrm{MMI}_p}$, $p = \{\mathrm{in}, \mathrm{out}\}$ are the insertion losses for input and output MMIs, $\gamma_j$ are the corresponding splitting ratios, $\alpha_{\mathrm{p}}$ are the propagation losses through the waveguide, $L$ is the length of the MZI arms, $\kappa = \frac{2\pi}{\lambda}$ is the wavenumber at operating wavelength $\lambda$. The $\delta\varphi$ terms represent phase correction that can be adjusted with the optimization routine (e.g. particle swarm optimization (PSO) [7]) to fit experimental data. The two quantities $n_{\mathrm{eff},1}(T)$ and $n_{\mathrm{eff},2}(T)$ are the effective refractive indices of the MZI's waveguides. The Ti heater undergoes Ohmic heating when an external voltage is applied, resulting in modified optical properties of the waveguides. The dependency of $n_{\mathrm{eff}}$ on the temperature is expressed as a first-order Taylor expansion:

$$n_{\mathrm{eff}}(T(V)) = n_{\mathrm{eff}}(T_0) + \left.\frac{\mathrm{d}n_{\mathrm{eff}}}{\mathrm{d}T}\right|_{T_0} (T(V) - T_0) \tag{3}$$

Thermal crosstalk can significantly affect the device behavior: in the area shown in the black rectangle in Fig. 1, the temperature variation caused by a single heater can perturb the temperature (and the corresponding effective index) of all the vertically stacked ($x$ direction) waveguides. We assume, at

the same time, that this coupling effect is negligible in the $y$ direction. The temperature distribution in the $x$ direction can be established by summing the independent contributions from the three heaters, solving the 1D heat equation for each source individually, under the ideal adiabatic boundary conditions. The obtained results have been validated using a complete 3D thermal simulation, performed in COMSOL Multiphysics, of the heaters - waveguides system. Fig. 2 shows the spatial distribution of temperature variation when different voltages are applied to 3 heaters, indicating that the approximated 1D method accurately mimics COMSOL thermal simulations. From this example, it is immediately evident that thermal cross-talk affects the device, and is non-negligible not only between neighboring MZIs, but also between the two arms of the same MZI. The adopted numerical approach is convenient for its computational efficiency. Using the temperature variations estimated with this method, we can compute $n_{\text{eff}}(T(V))$ in each waveguide, which can then be used in (2). The total transmission matrix can be then obtained by cascading the three constitutive elements of the MZI, which can be used to compute the output field at the two output ports of the MZI:

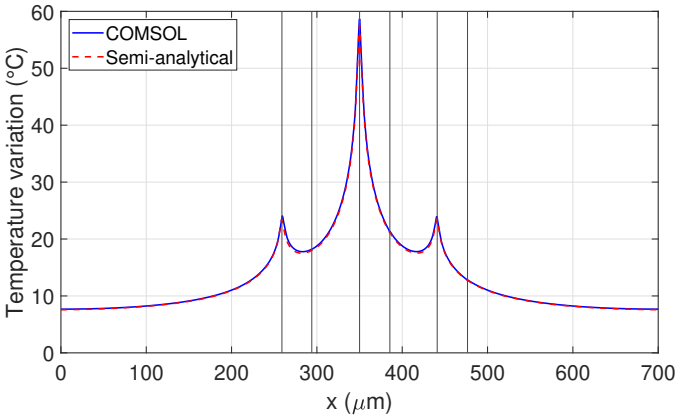



Fig. 2. Example of spatial distribution of temperature variation for $V_{\text{in},1} = 1V$, $V_{\text{in},2} = 2V$, and $V_{\text{in},3} = 1V$ applied simultaneously to the three heaters, simulated in COMSOL Multiphysics (solid blue line) and restored using numerical method (dashed red line).

$$\overline{T} = \overline{T}_{\text{MMI}_{\text{out}}} \overline{T}_{\text{p}} \overline{T}_{\text{MMI}_{\text{in}}} \tag{4}$$

We fine-tuned the parameter $\delta\varphi$ in Eq. (2) by adopting the PSO algorithm, to precisely fit the experimental measurements executed to assess the behavior of the real device. The method successfully accounts for possible manufacturing imperfections, effectively implementing a well-established digital twin model of the reference device.

## III. Evaluation of Wideband Programmability

The digital twin model was deployed in an initial assessment of the capabilities of the mesh as a programmable logic device [4]. A data set with 6 million entries was created with randomized values of the nine MZIs driving voltages, considering the $2^3 = 8$ possible permutations of the signals at the three input ports, assumed as Boolean signals with values 1 or 0. From the statistical analysis of the power levels at the three output ports, we estimated three thresholds to convert the output levels into digital states. After this preliminary investigation, we then used the PSO method to find the best control voltages to implement a set of logic functions at the three output ports (such as AND of the three inputs at output port 1, XOR at output port 2, and OR at output port 3). We numerically verified that the device can be used to implement a vast number of logical functions, from the simplest ones (NAND, NOR) to more complex ones (such as 2's complements of the 3 bit binary number at the input); it is also possible to obtain the AND or the OR of the optical signals at port 1 and port 2, depending on the value of the signal at port 3, thus implementing an optically-programmable gate. Although the first analysis was performed at 1550 nm, the device is subsequently simulated over a wider wavelength interval ranging from 1524 nm to 1568 nm. This operation required a proper evaluation, based on FDTD simulations performed in Synopsys RSoft™ of the dispersion of the effective index and the coupling coefficients. The digital twin exhibits the wideband programmability expected from the reference device, being able to consistently implement a plethora of programmable logic functions on the entire C-band, proving the potential of the model to explore the properties of PICs.

## IV. Conclusions and Outlook

We developed a digital twin model of a 3x3 MZI mesh by calibrating the model parameters to fit the experimental data, thus describing crucial effects such as thermal crosstalk and tolerances in the production process. Applying the combination of driving voltages determined by the model at 1550 nm, we estimate the capability of the reference device to perform multiple programmable logic functions on the entire C-band.

## References


[1] E. Glaessgen and D. Stargel, *The Digital Twin Paradigm for Future NASA and U.S. Air Force Vehicles*, p. 7. 2012.

[2] S. Behrendt, T. Altenmüller, M. C. May, A. Kuhnle, and G. Lanza, "Real-to-sim: automatic simulation model generation for a digital twin in semiconductor manufacturing," *Journal of Intelligent Manufacturing*, 2025.

[3] L. Coldren, S. Corzine, and M. Mashanovitch, *Diode Lasers and Photonic Integrated Circuits*. Wiley Series in Microwave and Optical Engineering, Wiley, 2012.

[4] A. Marchisio, L. Tunesi, E. Ghillino, V. Curri, A. Carena, and P. Bardella, "Comprehensive thermal crosstalk model of meshed MZI topologies for neuromorphic computing," in *AI and Optical Data Sciences VI*, vol. 13375, p. 133750F, SPIE, 2025.

[5] A. Marchisio, A. Cem, Y. Ding, V. Curri, A. Carena, F. Da Ros, and P. Bardella, "Optimization of 3x3 neuromorphic photonic network for programmable Boolean operations," in *SPIE Photonic West: Physics and Simulation of Optoelectronic Devices XXXII*, vol. 12880, pp. 191104–8, 2024.

[6] Y. Ding, V. Kamchevska, K. Dalgaard, F. Ye, R. Asif, S. Gross, M. J. Withford, M. Galili, T. Morioka, and L. K. Oxenløwe, "Reconfigurable SDM switching using novel silicon photonic integrated circuit," *Scientific Reports*, vol. 6, no. 1, p. 39058, 2016.

[7] A. Marchisio, E. Ghillino, V. Curri, A. Carena, and P. Bardella, "Particle swarm optimization-assisted approach for the extraction of VCSEL model parameters," *Opt. Lett.*, vol. 49, pp. 125–128, 1 2024.