Towards Inverse Design of On-Chip Photonic Structures Using Deep Neural Networks

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Quantum computing holds the potential to greatly enhance information processing capabilities, with various implementation strategies currently being explored. One promising route involves leveraging single photons. In order to achieve quantum computing based on single photons, advanced photonic elements are required, such as beam splitters, resonators, couplers, or gratings, ideally integrated in fully on-chip photonic circuits with single-photon sources [1]. In the process of designing such devices, numerical simulations are often a necessary first step, typically done via solving Maxwell's equations by using the Finite-Difference Time-Domain (FDTD) method. This process can be highly time-consuming and computationally-costly, as it usually requires numerous iterations of the simulations with different element geometries and parameters. With the growth of the element complexity or the parameters space, this cost increases, limiting the efficient design.

At the same time deep neural networks (DNNs), one of the approaches of machine learning (ML), have gained substantial attention in recent years, as they are a powerful tool with a wide applicability. They can be employed for predicting physical responses of real physical systems, based on initial data used for training. When trained, DNNs can be used to quickly predict a response (e.g. an optical response) of a new structure, not seen in training. This could revolutionize the capability and efficiency of nanophotonic design. When combined with initial data based on Maxwell's equations solution, there is no need for further iterative, time-consuming electromagnetic simulations. DNNs could be utilized both in forward modeling (predicting transmission spectra from known geometries) or for inverse design (determining structure geometries that yield a desired optical response). This can not only accelerate and improve the design process, but also introduces the potential for discovering novel solutions, unseen in conventional design approaches.

In this work, we use deep learning approach to (a) predict the optical response of photonic elements (1D nanobeam cavities and multimode interferometer beam splitters) and (b) to inversely design the geometry of these elements based on the desired resonant wavelength and transmission ratio. We perform initial FDTD simulations of such devices to train our neural networks, to be able to predict the responses of new devices without the need for further FDTD calculations. We use a combination of convolutional (CNNs) and fully-connected (FC) networks to achieve the best agreement with exact Maxwell's simulations, without the need for a large amount of training data. Importantly, we apply our methods for sources and elements operating at 1.55 μm wavelength (in the third telecommunication window) in a hybrid InP/Si platform. This system has a huge application potential when used with single InAs quantum dots.

References

[1] M. Burakowski, P. Holewa, P. Mrowiński, A. Sakanas, A. Musiał, G. Sęk, K. Yvind, E. Semenova, and M. Syperek, *Optics Express* **32**, 7, 10874 (2024).

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