Meta-optic Accelerators for Image Processing

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Digital neural networks (NNs) and the availability of large training datasets have allowed for rapid progress in the performance of machine-based tasks for a wide range of applications including image analysis, sound recognition, and natural language translation. The enhanced capability has, however, come at a computational cost as increased complexity and accuracy have necessitated the need for ever larger deep neural networks (DNNs). The ever-increasing computational requirements of DNNs have resulted in unsustainable growth in energy consumption and restrictions in real-time decision making when large computational systems are not available. One alternative to DNNs is the use of optical processors that have the advantages of ultra-fast processing times and low energy costs. These systems can be employed as stand-alone processors or as front-end accelerators for digital systems. In either case, optical systems are most impactful when used for the linear matrix-vector multiplications that comprise the convolution operations in DNNs.

Here, we demonstrate the use of meta-optic based optical accelerators that serve as the convolutional front-end for a hybrid image classification system[1]. Spatial multiplexing is achieved by using a multi-channel metalens for image duplication and a metasurface-based convolutional layer, as illustrated in Fig. 1(a), for generating feature maps. Specifically, our meta-optic is designed to generate 9 feature maps, as illustrated in Fig. 1(b). This system has the advantage of being compact while the use of metasurfaces allows for additional information channels in this case, polarization, to be accessed enabling both image and polarization-based classification. The hybrid network utilizes end-to-end design such that the optical components (seen in Fig. 1) and digital components are co-optimized while also incorporating statistical noise resulting in a robust classification network. We experimentally demonstrate the classification of the MNIST handwritten digit dataset with a theoretical accuracy of 94.7% (Fig 1(c)) and experimental accuracy of 93.1% (Fig. 1(d)). We also demonstrate a 93.8% accurate classification of polarized MNIST digits (not shown). This architecture ultimately off-loads over 50% of the computational operations into the optics resulting a significant increase in processing speed, as illustrated in Fig. 1(d). Due to the compact footprint, ease of integration with conventional imaging systems, and ability to access additional information channels, this type of system could find uses in high-dimensional imaging, information security, and machine vision.

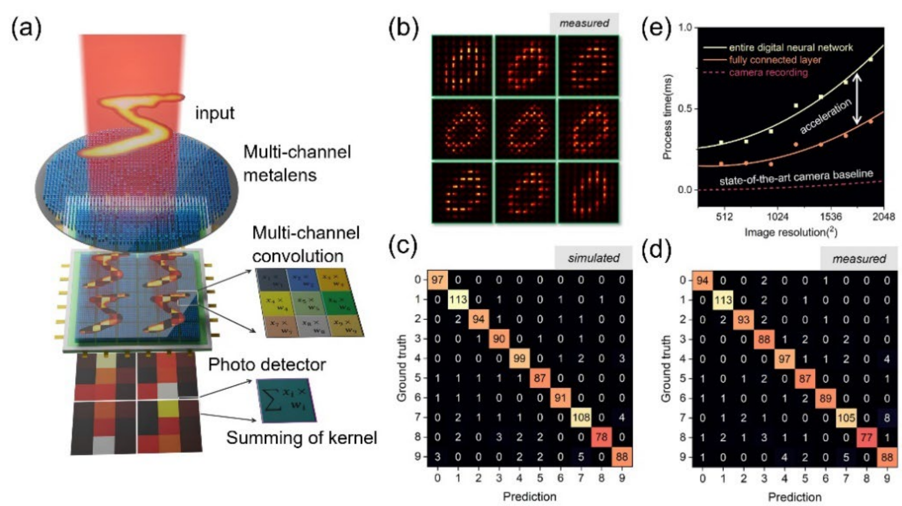

Fig. 1. (a) Schematic of the meta-optic classification system. (b) Convoluted images recorded on camera. These represent feature maps. (c) Simulated and (d) experimental confusion matricies. (e) Computational acceleration associated with the meta-optic.

References

[1] Hanyu Zheng, Quan Liu, You Zhou, Ivan I Kravchenko, Yuankai Huo, Jason Valentine," Meta-optic Accelerators for Object Classifiers", Science Advances 8, eabo6410 (2022).