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Computer-free computational imaging: optical computing for seeing through random media

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Abstract

Diffraction Deep Neural Network enables computer-free, all-optical “computational imaging” for seeing through unknown random diffusers at the speed of light.

*Computational imaging*¹ is an emerging field that seeks to push the fundamental limits in imaging systems by synergistically integrating optics and computation. In recent years, significant advances have been made by leveraging deep learning in computational imaging². By combining novel deep neural network (DNN) architectures and domain knowledge in optical physics, the performance limits in various systems are continuously being re-defined, including spatial resolution^{3,4}, depth-of-field⁵, space-bandwidth product⁶, imaging speed^{6,7}, sensitivity to low-photon count⁸, and resilience to random scattering^{9,10}. Of particular interest by Luo et al.¹¹ is the ability to overcome random scattering by a DNN.

A notable advance demonstrated in this work is how the DNN is being designed and implemented to enable “computer-free” computational imaging. The majority of the deep learning-based techniques rely on a modern computer (or a computer cluster) to perform both training and deploying the DNNs. As such, the “cost” associated with the deployment (e.g., power consumption, data bandwidth, size, and weight) is fundamentally limited by the computing hardware requirement (e.g., GPUs). In the past few years, *optical computing* solutions, in particular *optical* neural networks (ONNs), emerge as a promising alternative to enable highly efficient “computing” at the speed of light

using only optical and photonic components¹². While optical computing and ONNs have been extensively studied about 30 years ago¹³, including impressive demonstrations, such as face recognition¹⁴, recent advances in photonic devices and the emergence of extremely large DNNs have re-fueled the research interest in ONNs¹². Such novel optical computing devices promise to significantly reduce the power, bandwidth, size, and weight and enable “edge computing” directly on systems, such as surveillance cameras and autonomous vision systems.

In this work, the diffractive deep neural network (D²NN) pioneered by the Ozcan group¹⁵ is implemented for performing a challenging task for imaging through random diffusers. The D²NN is physically constructed by a series of transmissive diffractive surfaces (Fig. 1), in which the “neurons” are embodied by the phase profiles of the “pixels” on the diffractive surfaces and the interconnections are described by the physics of optical diffraction. The D²NN is first trained to perform the task of optically reconstructing images of arbitrary objects that are covered by an unknown, random phase diffuser. The result of the training stage consists of a set of phase profiles that are subsequently fabricated to construct the ONN. A remarkable result demonstrated by the authors is that

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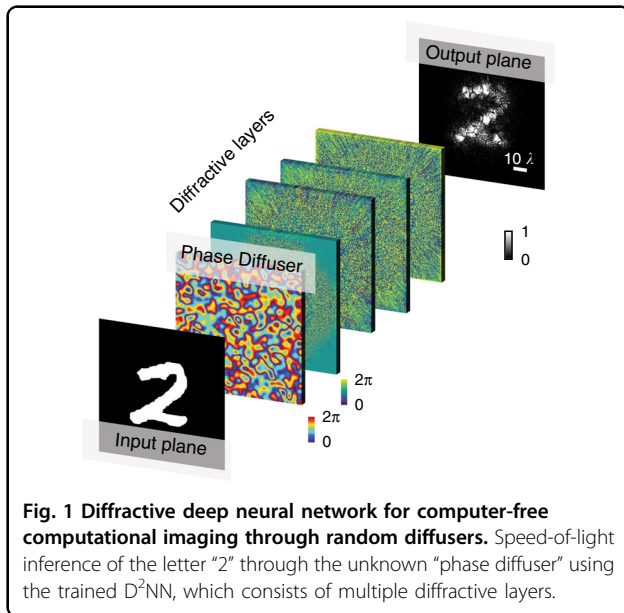
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the trained D²NN can all-optically reconstruct the unknown objects through an unknown, new diffuser (that has never been used during training). As such, it implies that this ONN architecture has sufficient generalization power, similar to its digital counterpart¹⁰, to be robust to random unknown scattering changes. This makes a major advancement in optical computing towards many applications that require robustness

against degraded visions, such as astronomical imaging, surveillance, and autonomous driving.

Published online: 14 February 2022

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