Supplementary Material for

Metasurface-based diffractive optical networks with dual-channel complex amplitude modulation

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Supplementary Note 1: Resource requirements

The training of metasurface-based DON models (DC CA DON and CA Res DON) was performed on a GeForce RTX 4060 Ti. For a 5-layer DC CA DON or CA Res DON model, the training time for each epoch is about 10 minutes. These models can also be trained using only the CPU, although the training will be slower.

Supplementary Note 2: Practical optical systems of DC CA/CA Res DON

Based on our previous work and referring to previous research[s1], we have designed an experimental setup, as shown in the Fig. S1. These experimental devices can be primarily divided into three parts: the input section, the modulation section, and the receiving section. The input section encompasses devices such as laser source, Amplitude Spatial Light Modulator (SLM), and 4f system. Its purpose is to modulate the 45° linearly polarized light that carries grayscale images of MNIST/Fashion MNIST. The role of the Amplitude SLM is to encode the grayscale images into the input light by adjusting the transmittance of each pixel, and the role of polarizer is to generate 45° linearly polarized light. The modulation section is represented by the sample in the Fig. S1, where the DC CA/CA Res DON is placed. Its purpose is to perform DON calculations on the input light and output the predicted results of the network. The receiving section consists of a lens system and a camera. It utilizes the lens system to image the output intensity pattern predicted by the DC CA/CA Res DON onto the CMOS sensor of the camera, allowing the camera to measure the output intensity.

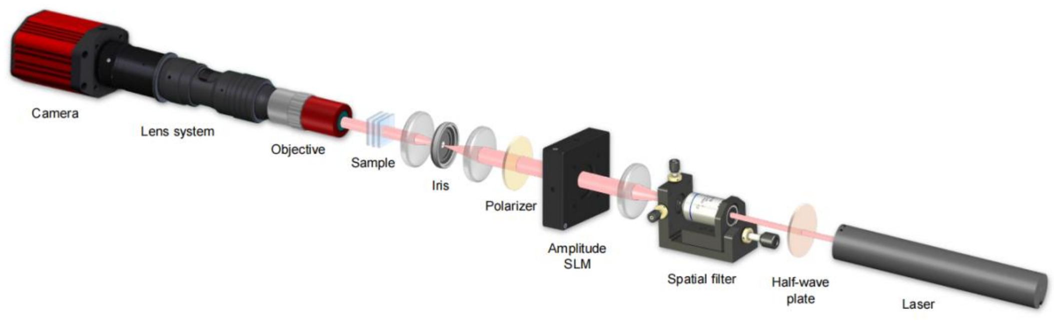

Fig. S1 The experimental setup for DC CA/CA Res DON

Supplementary Note 3: Computing performance of DC CA/CA Res DON

Regarding the computing performance of DC CA DON and CA Res DON, we follow the calculation method described in the Supplementary section of reference[s2]:

(1) **Optical Operations**: The optical operations (OPs) in DC CA DON and CA Res DON consists of four components: wavefront modulation, diffractive weighted connections, linear polarizer channel fusion, and nonlinear activation on the CMOS of camera. In complex operations, we convert them into equivalent real operations, such as representing each complex multiplication as four real multiplications and two real additions, and each complex addition as two real additions.

In order to calculate the total optical operations in DC CA DON and CA Res DON, we set the number of meta-atoms on the metasurface to x and the number of channels to c. For wavefront modulation, each metasurface wavefront modulation on each channel requires x complex multiplications, which is equivalent to $6x$ real operations. Thus, each layer's metasurface wavefront modulation corresponds to $6cx$ real operations. For diffractive weighted connections between adjacent metasurface layers on each channel, it requires x^2 complex multiplications and $x(x\text{-}1)$ complex additions, which is equivalent to $2x(4x\text{-}1)$ real operations. Therefore, the diffractive weighted connections between adjacent metasurface layers correspond to $2cx(4x\text{-}1)$ real operations. For linear polarizer channel fusion, it requires x complex additions, which is equivalent to

$2x$ real operations. Lastly, for the nonlinear activation on the CMOS of camera, it requires cx complex multiplications and x complex additions, which is equivalent to $6cx+2x$ real operations.

In summary, for a DC CA DON with K=2n+1 layers (where n is the number of DC CA units), the total number of optical operations is given by:

$$R = n[6cx(4x-1)+12cx+2x]+4cx(4x-1)+6cx+6cx+2x$$

$$=[(24n+16)cx^2+(6n+8)cx+(2n+2)x] \text{ OPs.}$$

Taking the example of a 5-layer DC CA DON, metasurface size x=100×100, R=12800460000 OPs=12.8 GOPs.

For a CA Res DON with K=2n+1 layers (where n is the number of CA Res units), the total number of optical operations is given by:

$$R = n[6x(4x-1)+12x+2x]+4x(4x-1)+6x+12x+2x$$

$$=[(24n+16)x^2+(8n+16)x] \text{ OPs.}$$

Taking the example of a 5-layer CA Res DON, metasurface size x=100×100, R=6400320000 OPs=6.4 GOPs.

(2) **The computing speed**: Measured in total operations per second (OPs/s) of DC CA/CA Res DON. The computing speed is given by: $v=\frac{R}{\tau}$, where τ represents the system's operational time. In system of DC CA/CA Res DON. When we estimate that the refresh time of the Spatial Light Modulator (SLM) is approximately 2.4 ms, and the refresh time of the camera is approximately 5ms. The operational time can be calculated as τ =5ms.

(3) **Computational Energy efficiency**: Measured the operations per joule (OPs/J) of DC CA/CA Res DON. The computing speed is given by: $\eta=\frac{R}{E}=\frac{R}{P\tau}$, where τ represents the system's operational time, P represents the system's total power. In system of DC CA/CA Res DON. When we estimate that the power of the laser is approximately 10W, the power of the SLM is approximately 18W, and the power of the camera is approximately 20W. The system's total power can be calculated as P=48W.

The computational performance parameters of DC CA/CA Res DON were calculated as shown in the following Table S1.

Table S1 The computational performance of DC CA/CA Res DON

Type	Operations (GOPs)	Computing speed (TOPs/s)	Energy efficiency (GOPs/J)
DC CA DON-3	8.00	1.60	33.33
DC CA DON-5	12.80	2.56	53.34
DC CA DON-7	17.60	3.52	73.34
DC CA DON-9	22.4	4.48	93.34
DC CA DON-11	27.20	5.44	113.3
CA Res DON-3	4.00	0.80	16.67
CA Res DON-5	6.40	1.28	26.67
CA Res DON-7	8.80	1.76	36.67
CA Res DON-9	11.2	2.24	46.67
CA Res DON-11	13.60	2.72	56.67

References

[s1] C. He, D. Zhao, F. Fan, H. Zhou, X. Li, Y. Li, J. Li, F. Dong, Y.-X. Miao, Y. Wang et al., "Pluggable multitask diffractive neural networks based on cascaded metasurfaces," Opto-Electronic Adv., pp. 230 005–1, 2023.

[s2] T. Zhou, X. Lin, J. Wu, Y. Chen, H. Xie, Y. Li, J. Fan, H. Wu, L. Fang, and Q. Dai, "Large-scale neuromorphic optoelectronic computing with a reconfigurable diffractive processing unit," Nat. Photonics, vol. 15, no. 5, pp. 367–373, 2021.