All–Optical Diffractive Deep Neural Networks Enabled by Liquid Crystal

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ABSTRACT

In this paper, we introduce a novel approach utilizing a 5–layer all–optical D^{2}NN constructed with photo–induced liquid crystal alignment technology to create LC–based tunable phase retarders, experimentally achieving a classification accuracy of 89% with 500 random hand-written digits from the test MNIST dataset.

1 Introduction

Optical Neural Networks represent a novel approach to artificial neural networks by utilizing light for extensive computations rather than traditional electronic signals. This method offers distinct advantages, including large bandwidth, high interconnectivity, and the ability to process information in parallel. Notably, the Diffractive Deep Neural Network (D^{2}NN) architecture is capable of learning to execute various functions through passive diffractive layers trained via deep learning. The results of these computations are manifested in real-time during wave propagation at the speed of light, eliminating additional energy consumption. This innovation opens up diverse applications, such as image classification, logical operations, and medical diagnosis. Additionally, the inherent holographic properties of light enable further enhancement of parallel processing by multiplexing parameters like phase, amplitude, polarization, orbital angular momentum, and wavelength[1].

In this paper, we introduce a novel approach utilizing a 5–layer all–optical D^{2}NN constructed with photo–induced liquid crystal alignment technology to create LC–based tunable phase retarders.

2 Experiment

According to Huygens–Fresnel principle, each point on a given layer acts as a secondary source of a wave, the amplitude and phase are determined by the product of the input wave and the complex–valued transmission coefficient at that point[2]. Therefore, in the D^{2}NN architecture, each optical unit on the diffractive layers performs as an artificial neuron which manipulates the wavefront of propagated light to further connect to other neurons on following layer, as shown in Fig. 1.

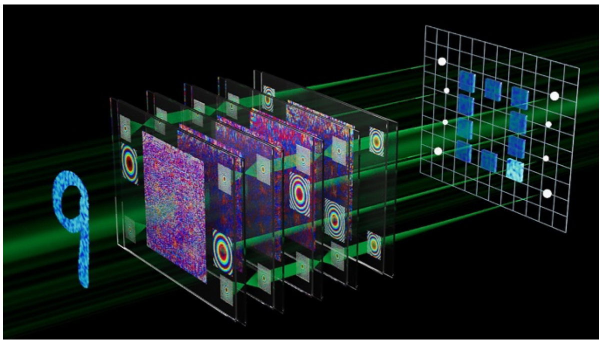


Fig. 1 All–Optical Diffractive Deep Neural Networks Enabled by Liquid Crystal[3]

The connectivity between layers is an important factor that directly affects the diffraction of optical neurons. Therefore, the first impact of a fully connected network requires that the diffraction angle of all neurons to be large enough to cover all the neurons on the next layer. In this case, the diffraction layer number, the distance between each layer, the neuron size and number, and the detection area size are the discussed as key factors affecting the classification accuracy of the network[4]. By fixing size of 5 μm, a total number of 1000 × 1000 artificial optical neurons on each layer, and layers distance of 5 cm, all–optical D^{2}NN is trained with 55,000 images (5000 validation images) from the MNIST training dataset and tested using 10,000 from the test dataset, achieving the highest classification accuracy of 97.7% via the simulation.

The D^{2}NN architecture leverages microscale multi–domain LC retarders as optical neurons to manipulate the geometric phase of incident light. We systematically simulate pixel–level displacements to enhance alignment tolerance during experiments, achieving robust resilience against misalignment interference with a 2–pixel tolerance in the x and y directions.

The photo–induced LC alignment technology is employed to create LC–based tunable phase retarders, serving as the diffractive layers in the D^{2}NN. Unlike the conventional rubbed polyimide alignment layer, the photo–sensitive sulfonic azo–dye SD1 (DIC, Japan) can be aligned in–plane by exposure to polarized blue or ultraviolet light. This alignment layer then influences the neighboring LC molecules through intermolecular forces. When irradiated by light with a spatial distribution of polarization azimuths, the easy axis of SD1 reorients perpendicular to the polarization azimuth, aligning the LC molecules in the same direction as the incident light, further introducing a geometric phase retardation.

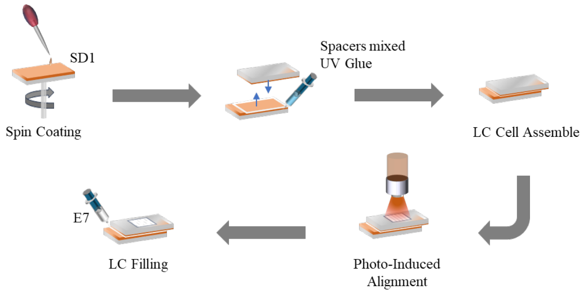


Fig. 2 Fabrication process for tunable photo-induced liquid crystal retarders[3]

The LC retarders for D^{2}NN are fabricated following the LC device manufacturing standard as shown in Fig. 2. Initially, a clean Indium Tin Oxide glass substrate is spin–coated with 0.5% SD1 at 3000 rpm for 30 seconds, followed by baking on a hot plate at 100 ℃ for 10 minutes to remove the N, N–Dimethylformamide solvent completely. Subsequently, 2 μm spacers mixed with UV glue are dispensed along the substrate's edge, which is then assembled face to face with another SD1 substrate. The UV glue is cured using a 365 nm UV LED, creating walls and maintaining the LC cell gap. The assembled LC cell undergoes irradiation by a DMD–based pattern alignment exposure system. By rotating the polarizer in front of the LC cell, patterns at different polarization azimuths are sequentially imprinted onto the LC cell, establishing the LC device with the desired azimuthal angles distribution. LC E7 (n_o= 1.498294, n_e= 1.698424 from HCCH, China) is filled into the LC cell on a hot plate at 80 ℃. As the temperature decreases, the LC molecules align according to the SD1 micro–pattern, acting as tunable diffraction phase retarders for the D^{2}NN.

The corresponding fabricated LC retarders are fabricated with artificial neuron size of 5 μm in 1000 × 1000 arrays, resulting in a modulation area size of 5 mm × 5 mm for each diffractive layer.

3 Results

To experimentally validate our precisely aligned 5–layer D^{2}NN, we project 500 hand–written digits (50 per digit) from the MNIST test dataset using DMD, as presented in Figure 5(a), with the computing output captured by a CCD. The intensity profile at the output layer is depicted in Figure 5(b), with green dash squares representing the trained detector regions for the displayed digit nearby. For instance, as shown in Fig. 3, when inputting the digit "0" through the network, the CCD records the highest intensity distribution in region "0" compared to other regions, aligning with the simulated classification result.

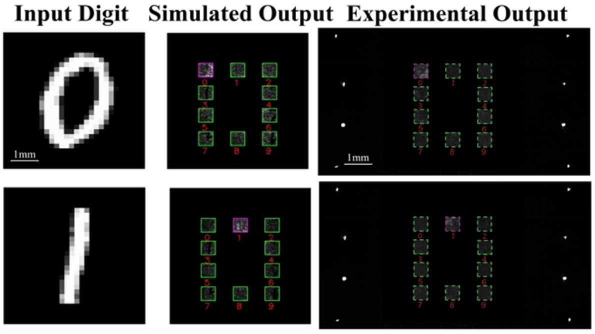
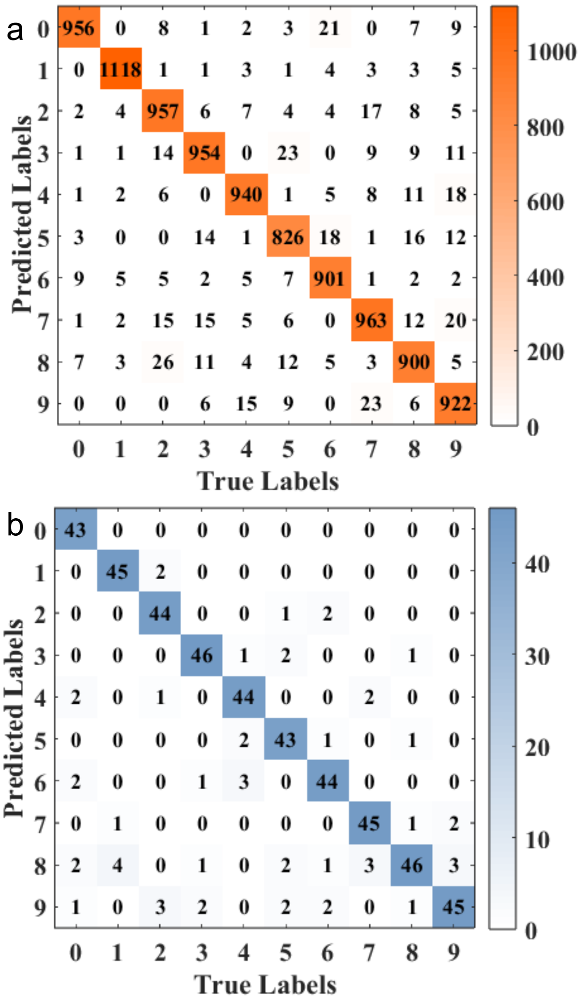


Fig. 3 Simulated and experimental output results of hand-written digits "0" and "1"



a

	0	1	2	3	4	5	6	7	8	9
0	956	0	8	1	2	3	21	0	7	9
1	0	1118	1	1	3	1	4	3	3	5
2	2	4	957	6	7	4	4	17	8	5
3	1	1	14	954	0	23	0	9	9	11
4	1	2	6	0	940	1	5	8	11	18
5	3	0	0	14	1	826	18	1	16	12
6	9	5	5	2	5	7	901	1	2	2
7	1	2	15	15	5	6	0	963	12	20
8	7	3	26	11	4	12	5	3	900	5
9	0	0	0	6	15	9	0	23	6	922

b

	0	1	2	3	4	5	6	7	8	9
0	43	0	0	0	0	0	0	0	0	0
1	0	45	2	0	0	0	0	0	0	0
2	0	0	44	0	0	1	2	0	0	0
3	0	0	0	46	1	2	0	0	1	0
4	2	0	1	0	44	0	0	2	0	0
5	0	0	0	0	2	43	1	0	1	0
6	2	0	0	1	3	0	44	0	0	0
7	0	1	0	0	0	0	0	45	1	2
8	2	4	0	1	0	2	1	3	46	3
9	1	0	3	2	0	2	2	0	1	45

Fig. 4 Confusion matrices of (a) simulation results and (b) experimental results

The confusion matrices in Fig. 4(a) and (b) display the classification accuracies of the network as 94.37% for the simulated results and 89% for the experimental results. Despite our efforts to align all 5 layers meticulously, the small pixel sizes of 5 μm on each layer pose a challenge, requiring a 2–pixel displacement tolerance of 10 μm, which can be operationally challenging and prone to disturbances.

4 Conclusions

In conclusion, this paper details the implementation and experimental validation of a 5–layer all–optical Diffractive Deep Neural Network (D^2NN) utilizing photo–induced liquid crystal alignment technology to create LC–based tunable phase retarders. Further optimization of more precise alignment methods is currently underway to demonstrate the practical feasibility of the LC–based all–optical D^2NN in real–world applications.

References

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