

Advanced neural network depicts precise structural colours

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Abstract

A mixture probability sampling network is proposed to address the challenge of non-unique mappings between colour and nanostructures. This network successfully outputs structural colours with almost 100% precision, depicting wide-gamut nano-paintings.

Keywords: Structural colors, Metasurfaces, Neural network

Structural colours, which manipulate light at specific wavelengths through nanostructures, offer a novel strategy to achieve stable, customisable, and ultra-dense colouration¹. The key to producing desirable colour effects lies in the precise control of the various degrees of freedom. Metasurfaces^{2,3} have emerged as a powerful and controllable tool to achieve this goal. Metasurface-based structural colours have been demonstrated using various mechanisms by accurately tailoring the optical response of light, such as plasmonic resonances⁴⁻⁶, Mie resonances⁷⁻⁹, Fabry-Pérot resonances^{10,11}, and bound states in the continuum (BIC)¹². In addition, the ease of fabricating metasurface-based structural colours enables high-density colourful pixels, transforming structural colours from laboratory demonstrations into promising candidates for next-generation microdisplays¹³.

Designing metasurface-based structural colours that can achieve optimal colour effects requires fine-tuning numerous geometric parameters, which is a task where traditional forward design is limited by its time-consuming and computationally intensive nature. In contrast, the rapid

growth of artificial intelligence networks provides unprecedented capabilities to solve complex multidimensional problems efficiently¹⁴⁻¹⁶. However, when designing metasurface-based structural colours, previously developed neural networks face challenges in achieving precise colouration because of the one-to-many relationship between colour and geometry^{17,18}.

In a newly published paper in *Light: Science & Applications*, an international research team from Tongji University and the National University of Singapore developed a novel neural network called the mixture probability sampling network (MPSN) that can effectively overcome these limitations¹⁹. As illustrated in Fig. 1, the MPSN integrates a mixture density network (MDN) with a pre-trained forward network. The MDN generates Gaussian mixture distributions of structural parameters, while the pre-trained network learns the correlation between the optical performance and structure to evaluate the quality of output designs. Further, the system improves the probability of identifying the structural parameters that best match the target colour by sampling the Gaussian mixture distribution multiple times and inputting the results into the pre-trained network.

As a demonstration, the system was tested on a square-ring pillar metasurface. A dataset containing 8,411 samples was constructed using rigorous coupled-wave analysis. The

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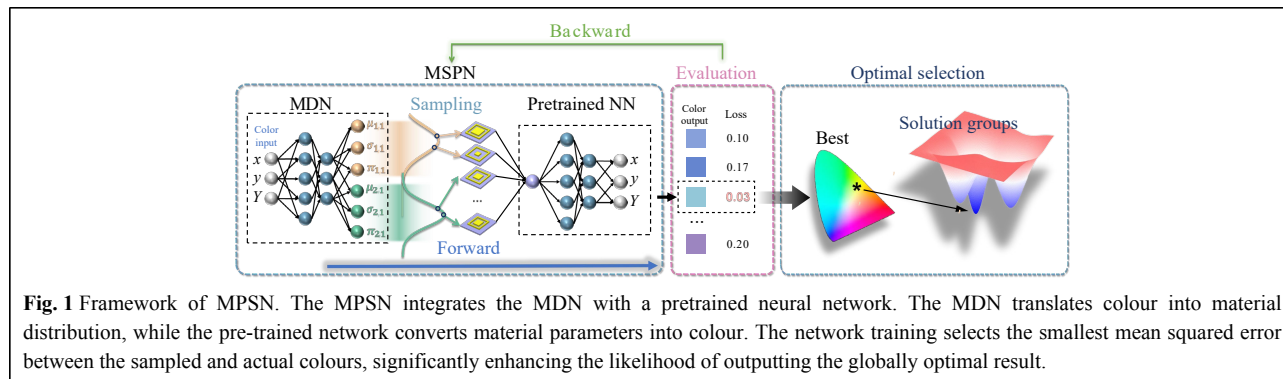
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MPSN achieved a prediction accuracy of 99.9% with a mean absolute error below 0.002. In the CIE 1931 chromaticity diagram, the designed colours exceeded 100% of the sRGB colour gamut, demonstrating exceptional colour reproduction and wide-gamut performance. Experimental validation included the fabrication of a 16-color palette and institutional logos, confirming the high fidelity between design and measurement.

The proposed MPSN framework is not limited to colour engineering; it provides a universal strategy to address the non-uniqueness problem in nanophotonic inverse design using neural networks. For example, high-efficiency topological waveguides can be automatically generated and cascaded^{20,21}; meta-atoms with precise chromatic dispersion crucial for achromatic meta-devices can be easily designed^{22–25}, and meta-units for multidimensional light-field modulation can benefit from this approach^{26,27}. This method, which incorporates frameworks such as physics-informed neural networks, has the potential to reduce data dependency while enhancing physical interpretability and generalisation capability, thereby accelerating the practical application of intelligent photonic design in areas such as virtual reality²⁸, biosensing²⁹, and quantum optics^{30,31}.

Data availability

All data are available from the corresponding authors upon reasonable request.

Conflict of interest

The authors declare no competing interests.

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