Accelerating Orbital Angular Momentum Complex Spectrum Analysis via Deep Learning

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Abstract: A deep-residual-network-based algorithm is proposed for fast orbital angular momentum complex spectrum analysis with large range and variable intensity. © 2024 The Author(s) conclusions.
OCIS codes: 140.0140 Lasers and laser optics, 050.4865 Optical vortices.

Orbital Angular Momentum (OAM) [1], characterized by helical wavefronts, offers a new degree of freedom for laser beams. This feature suggests that one beam can carry multiple, different OAM modes simultaneously, enabling a broad range of applications ranging from classical to quantum physics [2,3]. Analyzing OAM complex spectrum is essential for designing optical elements, particularly high-dimensional multiplexed modulator, such as the OAM comb [4]. However, common methods, like the Helical Harmonic Expansion (HHE) [5], require time-consuming iterations, constraining the utility in real-time applications. In response, we present a novel scheme that leverages a Deep Residual Network (DRN) to expedite the analysis of OAM complex spectrum [6]. Our method significantly reduces computation time and enables high-precision, real-time analysis across a wide range of OAM modes with varying intensities, phase ratios, and mode intervals. This is achieved without additional modulation, by simply inputting the multiplexed OAM beam's intensity and phase information.

To address the issue of time consumption, we transform the process of iteration into a classification task. This transformation involves mapping the intensity and phase characteristics to different OAM orders within the channel dimension. Consequently, we model the relationship between the features derived from the intensity and phase pattern of the superposed OAM beams and their complex spectrum.

As illustrated in Fig. 1(a), the intensity pattern and phase distribution of the multiplexed OAM beam are processed through the designed DRN to extract feature maps. Multiple rounds of feature extraction yield deep representations. By flattening these representations along the channel dimension, we obtain the confidence vector. This vector demonstrates the probabilities for each individual OAM mode, representing the complex OAM spectrum. As sketched in Fig. 1(b), the proposed DRN consists of four residual blocks [7]. Each of these blocks incorporates a multiple conception structure designed to capture features at different levels. Specifically, the input optical field data is first converted from spatial domain to feature dimensions through a down-sample layer. It then proceeds into the residual block to generate feature map using the designed multiple conception structure. This structure comprises a convolutional layer, a rectified linear unit, and another convolutional layer. To avoid the vanishing of gradients and facilitate training, we have added residual connections before and after the multiple conception structure. As shown in Fig. 1(c), the multiplexed OAM beam, comprising thirteen OAM states with topological charges l = [-99, -82, -65, -48, -31, -14, 3, 20, 37, 54, 71, 88, 105], corresponding intensity ratios [0.066: 0.045: 0.121: 0.088: 0.040: 0.042: 0.079: 0.024: 0.105: 0.070: 0.114: 0.094: 0.106], and relative phases [1.6π, 1.3π, 0.1π, 1.8π, 0.6π, 1.3π, 1.7π, 1.9π, 0.9π, 1.9π, 1.6π, π, 0.9π], is analyzed using the proposed DRN, resulting in an RMSE of 0.002 for intensity spectrum and 0.022 for phase spectrum, with processing times of 0.013 s. Conversely, the HHE results in a higher RMSE of 0.204 and a longer processing time of 14.277 s for the intensity spectrum. As for the phase term, the RMSE is 0.456 and the response time is 16.790 s. A comprehensive evaluation is conducted between HHE and DRN. The results showed that DRN achieved an RMSE of 0.002 for intensity and 0.016 for phase spectrum, with a response time of 0.020 seconds. In comparison, HHE recorded a longer response time of 16.906 seconds for intensity and approximately 350 seconds for phase, with RMSE of 0.006 and 0.225, respectively. In other words, DRN demonstrated a 68.75% improvement in precision for intensity and a 92.89% increase for phase, alongside a 1000-fold and over 10,000-fold acceleration in computation speed, respectively.

Furthermore, we compare the performance between our DRN and HHE across a wide range of multiple OAM modes. Notably, the DRN demonstrates superior accuracy and speed over the HHE in analyzing hybrid OAM modes. Specifically, improvements in Root Mean Square Error (RMSE) for the intensity spectrum are observed at 0.0107, 0.0102, 0.0079, 0.0066, 0.0066, 0.0057, 0.0027 and 0.0022 for the 6, 13, 21, 27, 32, 38, 45, and 50 numbers of hybrid OAM modes, respectively. For the phase term, the enhancements in RMSE are notable at 0.4658, 0.4312, 0.7011, 0.4947, 0.3949, 0.4832, 0.6791 and 0.5963, showcasing the DRN's capability to achieve high precision.

ARTICLE Open Access

Hybrid strategy in compact tailoring of multiple degrees-of-freedom toward high-dimensional photonics

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Abstract

Tailoring multiple degrees-of-freedom (DoFs) to achieve high-dimensional laser field is crucial for advancing optical technologies. While recent advancements have demonstrated the ability to manipulate a limited number of DoFs, most existing methods rely on bulky optical components or intricate systems that employ time-consuming iterative methods and, most critically, the on-demand tailoring of multiple DoFs simultaneously through a compact, single element—remains underexplored. In this study, we propose an intelligent hybrid strategy that enables the simultaneous and customizable manipulation of six DoFs: wave vector, initial phase, spatial mode, amplitude, orbital angular momentum (OAM) and spin angular momentum (SAM). Our approach advances in phase-only property, which facilitates tailoring strategy experimentally demonstrated on a compact metasurface. A fabricated sample is tailored to realize arbitrary manipulation across six DoFs, constructing a 288-dimensional space. Notably, since the OAM eigenstates constitute an infinite dimensional Hilbert space, this proposal can be further extended to even higher dimensions. Proof-of-principle experiments confirm the effectiveness in manipulation capability and dimensionality. We envision that this powerful tailoring ability offers immense potential for multifunctional photonic devices across both classical and quantum scenarios and such compactness extending the dimensional capabilities for integration on-chip requirements.

Introduction

Recent decades have witnessed the rapid development of laser field manipulation, where on-demand tailoring of multiple degrees-of-freedom (DoFs) emerging as a leading area of research[1–7]. The ability to tailor a greater number of DoFs determines the creation of complex optical fields with high dimensionality, which is critical for various applications, including next-generation laser[8], optical tweezers[9], quantum computing[10–13], and holography[14]. Despite that previous techniques have made substantial progress in tailoring limited DoFs, such as polarization[15,16], amplitude[17], and initial phase[18], they still face inherent limitations in dimensionality that hinder the achievement of high-dimensional and multiple DoFs manipulation simultaneously. Orbital angular momentum (OAM), a new DoF, has been considered to enhance tailoring dimensionality due to its unbounded orthogonality[19–22]. However, the phase-only modulation for multiple OAM modes lead to unpredictable overlaps[23], which complicates the integration in single elements and poses challenges to cope with other DoFs. As additional DoFs are introduced, the cost and complexity rapidly grow, leading to higher computational demands and reduced tailoring precision. To overcome these challenges, current schemes for manipulating multiple DoFs often rely on bulky optical components or intricate systems that employ time-consuming iterative methods, sacrificing system simplicity or speed to compensate for

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Hybrid strategy in compact tailoring of multiple degrees-of-freedom toward high-dimensional photonics

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View Web of Science ResearcherID and ORCID (provided by Clarivate)

Source LIGHT-SCIENCE & APPLICATIONS
Volume: 14 Issue: 1
DOI: 10.1038/s41377-025-01857-3

Article Number 167

Published APR 21 2025

Indexed 2025-04-30

Document Type Article

Abstract

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Keywords **Keywords Plus:** ORBITAL ANGULAR-MOMENTUM; ENTANGLEMENT; GENERATION; BEAMS

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Data availability statement The data that support the findings of this study are available within the paper and the supplementary. Additional data related to this paper are available from the corresponding authors upon reasonable request.

Categories/ Classification Research Areas: Optics

Web of Science Categories Optics

Funding

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Funding agency	Grant number	Show All Details
National Natural Science Foundation of China (NSFC)		Show details
National Key Research & Development Program of China		Show details
		Show details
National Natural Science Foundation of China (NSFC)		Show details

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Journal information

LIGHT-SCIENCE & APPLICATIONS

ISSN 2095-5545

eISSN 2047-7538

Current Publisher SPRINGERNATURE, CAMPUS, 4 CRINAN ST, LONDON N1 9XW, ENGLAND

Journal Impact Factor Journal Citation Reports TM

Research Areas Optics

Web of Science Categories Optics

20.6
Journal Impact Factor ™ (2023)

5.22
Journal Citation Indicator ™ (2023)

Letter
Vol. 49, No. 1 / 1 January 2024 / Optics Letters 173
Optics Letters

Deep-learning assisted fast orbital angular momentum complex spectrum analysis

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Received 13 November 2023; revised 30 November 2023; accepted 4 December 2023; posted 5 December 2023; published 22 December 2023

Analyzing the orbital angular momentum (OAM) distribution of a vortex beam is critical for OAM-based applications. Here, we propose a deep residual network (DRN) to model the relationship between characteristics of the multiplexed OAM beam and their complex spectrum. The favorable experimental results show that our proposal can obtain both the intensity and phase terms of multiplexed OAM beams, dubbed complex spectrum, with a wide range of OAM modes, varying in intensity, phase ratio, and mode intervals at high accuracy and real-time speed. Specifically, the root mean square error (RMSE) of intensity and phase spectrum is evaluated as 0.002 and 0.016, respectively, with a response time of only 0.020 s. To the best of our knowledge, this work opens a new sight for fast OAM complex spectrum analysis and paves the way for numerous advanced domains that need real-time OAM complex spectrum diagnostic like ultrahigh-dimensional OAM tailoring.

https://doi.org/10.1364/OL.512147

Orbital angular momentum (OAM) offers a new degree of freedom for laser beams. An OAM carried beam, known as an OAM beam, has received considerable attention in recent years due to its helical wavefront and doughnut shape intensity profile. Previous studies have proved that the complex amplitude of an OAM beam comprises the helical term $\exp(il\varphi)$, with l as the topological charge and φ the azimuthal angle [1,2]. l is the eigenvalue of OAM and also known as the OAM state. Due to the orthogonality of an OAM, different photons from a single beam can carry various distinct OAMs. Such feature suggests that one beam can carry multiple different OAM modes simultaneously, constituting an infinite-dimensional Hilbert space. This introduces an entirely new realm of high-dimensional degrees of freedom for laser beams. The utilization of multiple OAM modes offers numerous applications ranging from classical to quantum physics [3–7].

The OAM complex spectrum characterizes the intensity and phase distribution of various OAM channels in one beam, providing insights into the intensity patterns and wavefront structure of multiplexed OAM beams. The analysis of the OAM complex spectrum is critical for numerical computations, particularly in designing phase-only diffraction optical elements toward high-dimensional multiplexed OAM beams, namely, OAM combs [8]. For example, the self-optimized iterative algorithm [9], and also the pattern search assisted iterative (PSI) algorithm [10], are demonstrated to compute phase-only diffraction grating to generate a multiplexed OAM beam. During the above computing, the OAM spectrum needs to be calculated round after round, since the OAM spectrum disparity between the grating diffraction field and the desired one needs to be continuously evaluated for ongoing adjustments to the grating parameters. The OAM spectrum analysis in the above iteration is usually accomplished through helical harmonic expansion (HHE) [11] where arbitrary beams can be decomposed through helical harmonic as

$$E(r,\varphi,z)=\frac{1}{\sqrt{2\pi}}\sum_{-\infty}^{+\infty}a_l(r,z)\exp(il\varphi), \tag{1}$$

with the complex coefficient $a_l(r,z)$

$$a_l(r,z)=\frac{1}{\sqrt{2\pi}}\int_0^{2\pi}E(r,\varphi,z)\exp(il\varphi)d\varphi. \tag{2}$$

Thus, the computation of both the intensity and the phase of the l-th order helical harmonic, as given in Eq. (2), involves two integrations. First, perform integration over ϕ (azimuthal angle) after multiplying by each conjugate helical phase in the beam. Subsequently, integration is carried out over r (radial distance). Since the values of intensity and phase are independent of the parameter z, the multiple OAM mode complex spectrum can be obtained through hundreds of such iterations. Clearly, as the range of OAM modes increases, the computational time escalates dramatically. Such large computation time brings troubles for high-dimensional multiplexed OAM mode tailoring as mentioned in Refs. [9,10] and finally limits the performances of scenarios which need fast or even real-time high-dimensional OAM tailoring like an OAM encryption [12] and a multi-state OAM shift keying [13].

To overcome the above challenges, in this Letter, we demonstrate a deep-learning assisted approach to accelerate the OAM complex spectrum analysis. The rapid development of computer vision enables the effectiveness of using deep-learning models

0146-9592/24/010173-04 Journal © 2024 Optica Publishing Group

Corrected 23 December 2023

Deep-learning assisted fast orbital angular momentum complex spectrum analysis

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View Web of Science ResearcherID and ORCID (provided by Clarivate)

Source OPTICS LETTERS
Volume: 49 Issue: 1 Page: 173-176
DOI: 10.1364/OL.512147

Published JAN 1 2024

Indexed 2024-03-28

Document Type Article

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Keywords **Keywords Plus:** GENERATION; LIGHT

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Categories/ Classification Research Areas: Optics

Citation Topics: 5 Physics > 5.98 Geometrical Optics > 5.98.523 Orbital Angular Momentum

Web of Science Categories Optics

Funding

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National Natural Science Foundation of China (NSFC)		Show details
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Journal information

OPTICS LETTERS

ISSN	0146-9592
eISSN	1539-4794
Current Publisher	Optica Publishing Group, 2010 MASSACHUSETTS AVE NW, WASHINGTON, DC 20036
Journal Impact Factor	Journal Citation Reports ™
Research Areas	Optics
Web of Science Categories	Optics

3.1
Journal Impact Factor ™ (2023)

1.08
Journal Citation Indicator ™ (2023)

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PHOTONICS Research

Intelligent tailoring of a broadband orbital angular momentum comb towards efficient optical convolution

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Received 27 November 2024; revised 17 January 2025; accepted 10 February 2025; posted 10 February 2025 (Doc. ID 550470); published 15 April 2025

Due to the high-dimensional characteristics of photon orbital angular momentum (OAM), a beam can carry multiple OAMs simultaneously thus forming an OAM comb, which has been proved to show significant potential in both classical and quantum photonics. Tailoring broadband OAM combs on demand in a fast and accurate manner is a crucial basis for their application in advanced scenarios. However, obtaining phase-only gratings for the generation of arbitrary desired OAM combs still poses challenges. In this paper, we propose a multi-scale fusion learning U-shaped neural network that encodes a phase-only hologram for tailoring broadband OAM combs on-demand. Proof-of-principle experiments demonstrate that our scheme achieves fast computational speed, high modulation precision, and high manipulation dimensionality, with a mode range of −75 to +75, an average root mean square error of 0.0037, and a fidelity of 85.01%, all achieved in about 30 ms. Furthermore, we utilize the tailored broadband OAM combs in conducting optical convolution calculation, enabling vector convolution for arbitrary discrete functions, showcasing the extended capability of our proposal. This work opens, to our knowledge, new insight for on-demand tailoring of broadband OAM combs, paving the way for further advancements in high-dimensional OAM-based applications.

https://doi.org/10.1364/PRJ.550470

1. INTRODUCTION

Vortex beams, endowed with orbital angular momentum (OAM), have captivated researchers for several decades. Pioneering work by Allen *et al.* in 1992 demonstrated that these beams [1] are characterized by an azimuthal phase term $\exp(il\varphi)$ with l the topological charge and φ the azimuthal angle, inspiring plenty of applications across diverse domains in both classical and quantum physics [2–8]. Capitalizing on the inherent high-dimensional orthogonality among OAM modes, a beam can carry a series of discrete, selective interval and power weight OAM modes, which are termed as OAM combs [9,10]. Such OAM comb offers significant potential for the transmission of vast amounts of information [11–14] and serves as a flexible key for photonics computing [15–18].

Previous research has introduced various schemes for generating OAM modes, where a single element, such as spiral phase plate or spatial light modulator, typically provides only one OAM mode, limiting scalability [19–21]. As the number of multiplexed OAM modes increases, the cost and complexity will rapidly grow and with the resultant required multiple elements [22–24], it is highly desirable to generate a large number of OAM modes in a simple, scalable, and cost-efficient way, leading to a consensus on the need for a phase-only modulation of OAM combs' on-demand tailoring [11,25,26]. Different from generating single-mode OAM beams directly, creating OAM combs solely through superposing spiral phases is not feasible due to the inevitable mode intensity loss in phase-only modulation [27]. Current schemes, such as mode iteration [27], genetic algorithms [28], pattern-search strategies [29], and adaptive modification [30], have been employed to address this challenge. However, these schemes still face troubles such as initial set dependency, long iteration time, and uncertain convergence.

Inspired by deep neural networks with powerful abilities in extracting high-dimensional features [31–33], there is significant potential to establish an intelligent, data-driven framework for optimizing phase designs [34–36]. In this paper, we propose

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第 44 卷 第 14 期/2024 年 7 月/光学学报 亮点文章·特邀综述

光学学报

光束轨道角动量模态人工智能感知方法研究进展(特邀)

周诗韵[1,2,3],王亦舒[1,2,3],杨觐瑜[1,2,3],高春清[1,2,3],付时尧[1,2,3*]

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摘要 涡旋光束携带的轨道角动量(OAM)作为一种全新的光场调控自由度在超大容量光通信、旋转体探测、高分辨率成像、光信息存储、量子技术等前沿领域展现出巨大的应用潜力。在上述应用中,实现快速、高精度的OAM模态感知十分重要。随着人工智能(AI)在各领域的快速发展,将AI技术作为光束OAM模态感知的新型解决方案引起了国内外学者的广泛关注。本文从AI的应用模型角度出发,对近年来基于AI技术的光束OAM模态感知方法进行了系统性综述,主要包括机器学习、深度学习及混合学习模型下的OAM模式分布探测和多模混合光束谱测量,同时讨论了扰动下基于AI的OAM模态感知方法研究进展。

关键词 轨道角动量;人工智能;模式识别;谱测量

中图分类号 O436 **文献标志码** A **DOI:** 10.3788/AOS231987

1 引 言

1992年,Allen等[1]首次证明了具有螺旋波前exp(i$l\varphi$)的涡旋光束携带有轨道角动量(OAM),其中l为OAM态或拓扑荷数,可为任意整数,φ为角向坐标。以此为节点,OAM作为一种全新的光场调控自由度迅速引起了人们的关注[2]。通过对OAM的调控,可以获得不同阶次的OAM光束,且各阶次间彼此正交,构成一个无穷维度的希尔伯特空间。OAM这一独特属性使得其在超大容量光通信[3-9]、旋转体探测[10-14]、高分辨率成像[15]、光信息存储[16]、量子技术[17-19]等前沿领域展现出巨大的应用潜力。由于OAM的正交性,一束激光中可以同时包含多个不同的OAM成分,不同OAM分布的光束具有不同的强度、相位、偏振分布,适用于不同的应用场景,因此分析和测量光束中的OAM成分及各个OAM模式占比对于其实际应用非常重要。

当前较为成熟的OAM模态感知方法主要是通过干涉[20-21]和衍射[22-28]的相关特性来反推OAM的模式成分和分布。然而,由于光学系统性能和光学器件分辨率等参数的限制,对宽OAM模式范围的多模混合光束的模式识别和OAM谱测量较为困难,且识别速率较低。特别是在非均匀介质或散射介质中传输时,畸变的相位及强度分布会显著降低模式识别的准确率。因此,如何快速、高精度地感知宽OAM模式范围下多模混合光束的OAM模场分布和成分占比,以及在非均匀介质或其他扰动的情况下保证OAM模态感知的准确性,是当前该领域的关键挑战之一。

近年来,人工智能(AI)技术高速发展,以其强大的信息提取和处理能力在各领域引发了新一轮的技术革命。在光学领域中,将光场的响应信息作为输入,使用AI技术辅助处理得到其中的有效特征进而解决相关问题的技术路线取得了一定的成效[29-33],有望突破传统算法带来的限制与瓶颈。当前已有部分国内外科研机构开展了将AI技术引入OAM模态感知的研究工作[34-38]。本文从AI技术的分类及模型角度出发,对近年来基于AI技术的OAM模态感知方法进行了梳理,并进一步对扰动场景下的OAM模态感知研究进行了归纳和总结。

2 基本原理

2.1 基于AI技术的模型分类及原理概述

目前,从应用模型的角度来看,AI技术主要可分为三大类:机器学习模型、深度学习模型和混合学习模型。

收稿日期:2023-12-26;**修回日期**:2024-01-23;**录用日期**:2024-02-27;**网络首发日期**:2024-03-13

基金项目:国家重点研发计划(2022YFB3607700)、国家自然科学基金(62350011,62375014,11834001,61905012)、国防基础科研计划(JCKY2020602C007)、北京市自然科学基金(1232031)

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主分类版本号	2006.01	副分类号	G06V10/82,G06V10/44,G06N3/0464,G06N3/045,G01
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案件状态	等待实审提案	分案提交日	
主分类版本号	2006.01	副分类号	G02B27/00,G02B27/42,G02B27/28
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