# Design and Implementation of Few-Mode Fiber Mode Decomposition and Beam Quality Measurement System Based on Deep Learning

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**Abstract.** This paper presents the design and implementation of a deep learning technology-based characterization and analysis system for the output beam of a few-mode fiber, which is used for real-time monitoring of spot-related parameters in laser application systems. Based on an improved Convolutional Neural Network (CNN) model, a simple and user-friendly system is developed using Python language and Django framework, which realizes the functions of high-speed and automated acquisition of light spot images, real-time mode decomposition of few-mode fibers, real-time measurement of beam quality, and storage of historical analysis data. It supports rapid and automated analysis of few-mode fibers, enabling users to effortlessly perform modal decomposition and real-time measurement of the $M^2$ factor. Through experimental tests, we have verified the effectiveness and accuracy of the system in dealing with few-mode fibers containing three intrinsic modes, which provides an important application value in the field of optics.

**Keywords:** Few-mode fiber; mode decomposition; beam quality measurement; deep learning.

## 1. Introduction

With the advantages of high efficiency, energy saving and flexible regulation, lasers are widely used in many fields, such as industrial production, scientific research, optical communication and military.[1] Few-mode fibers can achieve higher transmission rate and longer transmission distance, and have better optical performance and transmission characteristics, with a very broad application prospect.[2] The mode and beam quality of laser are the core parameters of laser, which describe the transverse energy distribution as well as the longitudinal transmission characteristics of the beam. Accurate and fast characterization of mode components and beam quality is very important in laser applications. Mode decomposition is widely used in laser beam control, laser weapons and other fields. Beam quality measurements are widely used in laser evaluation[3], optical system optimization and other fields. Traditional laser mode decomposition and beam quality measurement require a lot of time and effort, rely on high equipment costs, and have relatively low accuracy due to high operational difficulty.[4] Therefore, it is of great significance to design and develop a mode decomposition and beam quality measurement system for few-mode fibers, which is more professional and targeted for the laser field, to promote the research and application of lasers.

In 2019, Yi An[5] was the first to introduce deep learning algorithms to the study of optical characterization properties of few-mode optical fibers. In 2021, the University of Adelaide[6] Training an improved VGG-16 network to perform complete mode decomposition using individual images of complex light fields captured by phase cameras. In 2022, the National University of Defense Technology[7] first proposed the unsupervised deep learning method based on VGG to be applied to mode decomposition. In 2024, Changsha University of Science and Technology[8] proposed MobileNetV3-Light model that can be deployed in portable devices such as cell phones to deal with mode decomposition of few-mode optical fibers. Since 2019, deep learning has achieved a large number of research results in the field of fiber laser. However, upon closer analysis, it becomes apparent that most of these studies are primarily focused on model research.[9] The application system of deep learning models combined with human-computer interaction has not been fully explored and reported. This indicates that more research work is needed to realize the effective integration of deep learning technology and human-computer interaction system before practical application.

In this study, a deep learning-based few-mode fiber laser spot analysis system is designed and implemented based on Convolutional Neural Networks (CNN) to extend existing research. The deep learning technique is effectively applied to the human-computer interaction of the fiber laser system, which improves the intelligence and practicality of the system, providing users with professional and user-friendly services for the mode decomposition and beam quality measurement of few-mode fibers.

## 2. The Related Works And System Overview

### 2.1 System Analysis

The system needs to be applicable to the development of the laser field and the needs of the relevant users. On the basis of providing basic laser parameters, mode decomposition, and beam quality measurement, it mainly meets the following two demands:

(1) Accurate Mode Decomposition and Beam Quality Measurement: Mode decomposition is the process of accurately extracting individual beam modes from a complex optical system. Conventional methods may be affected by noise, non-ideal conditions, or complex system structures, and thus the use of deep learning-based methods can handle these challenges more effectively. With deep learning models, especially CNN models, the pattern features in the spot image can be learned, so that the presence of individual patterns and their properties can be accurately analyzed and identified. Accurate beam quality measurement requires reliable beam quality measurement metrics, and the beam quality factor $M^2$ chosen in this paper is the most important and common metric for assessing the quality of a laser beam, which is defined as the ratio of the product of the beam waist radius and divergence angle of an actual beam to the product of the beam waist radius and divergence angle of an ideal Gaussian beam.

Good user experience: The system should provide users with a simple and friendly user interface, and also needs to provide users with high-accuracy mode decomposition results and beam quality measurement results. The well-trained CNN model is integrated into the system, and a simple and friendly user interface is designed, allowing users to easily input the spot image data of the few-mode fiber and view the mode decomposition and beam quality measurement results. The result display interface should be clear and able to visualize the results of mode decomposition and the evaluation indexes of beam quality.

### 2.2 System Design

The deep learning-based mode decomposition and beam quality measurement system for few-mode fibers consists of four core functional modules, including the system detection and parameter setting module, the image acquisition and display module, the data processing and analysis module, and the file management module. The overall structural design of the system is shown in Fig. 1.

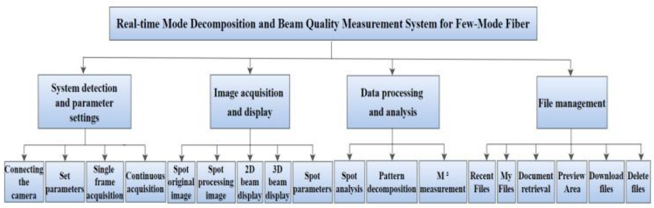


Figure. 1 System functional module diagram

 

Based on the overall structural design diagram shown in Figure 1, the basic execution flow of the system is as follows:

System detection and parameter setting: By building an optical imaging system laser beam introduced into the experimental system and imaging. CCD cameras are used to capture the image data of the laser beam. Finally, the computer is connected through a USB interface, and the camera -matching driver is installed to call the SDK function to connect the camera, set the parameters, real-time capture of the image data, and the camera parameter information and the image data captured. The camera parameter information and captured image data are transmitted to the computer system.

(2) Image acquisition and display: The system automatically controls the CCD camera to transmit the spot image acquired by the optical system to the system according to the set camera acquisition mode and relevant parameters, and performs the pre-processing such as spot detection, cropping, denoising, image enhancement, etc., on the captured image in order to improve the accuracy and stability of the subsequent analysis, and the system needs to display the captured original spot image, spot processing image and the relevant parameters of the spot.

(3) Data processing and analysis: Mode decomposition and $M^2$ factor calculation and analysis are carried out respectively on the measured spot of the measured few-mode fiber. According to the measured spot and the actual construction of the laser experimental system to get the laser source working wavelength, core radius, numerical aperture, normalized frequency V value and other parameters, the system processing analysis can be supported by the eigenmodes, and then use the improved CNN model prediction to get the relevant mode coefficients, that is, CNN prediction of the mode ratio and mode phase information. With the obtained mode coefficients, the beam quality factor $M^2$ of the few-mode fiber can be further calculated.

(4) File management: Manage the laser spot acquisition and analysis data saved into the system by users, supporting functions such as searching, checking, downloading and deleting. After completing the camera connection, system monitoring and parameter setting, image acquisition and analysis, and data processing and analysis modules, users can choose to save the acquired images, mode decomposition and $M^2$ factor measurement results and other related data to the system file management module, which is convenient for subsequent review and analysis.

### 2.2.1 Mode decomposition and beam quality measurement

The fiber studied in this paper is a step-refractive index few-mode fiber, whose refractive index difference between core and cladding is relatively small, which meets the weak-conductance approximation conditions, and thus the line-polarized modes are used in this paper as the object of study. The modes of an optical fiber refer to the eigen-solutions of the field distribution equation of the fiber and the corresponding eigen-values, and the number of eigen-modes that can be supported in an optical fiber depends on a number of parameters, such as the core diameter, numerical aperture, and operating wavelength of the fiber, and is generally characterized by the normalized frequency V, which is defined in Eq. (1). $a$ is the core radius, λ is the wavelength, NA is the numerical aperture of the optical fiber, and nco is the refractive index of the core, and ncl is the refractive index of the cladding.

$$V = \frac{2\pi a}{\lambda}\mathrm{NA} = \frac{2\pi a}{\lambda}\sqrt{{n_{co}}^2 - {n_{cl}}^2} \tag{1}$$

The process of mode decomposition is the process of determining the mode ratios of eigenmodes of different orders and their relative phases with respect to the fundamental mode, and the actual mode decomposition study is often carried out by using the light spot representing the light intensity distribution, which can be captured by experimental devices such as CCD cameras. The beam quality factor $M^2$ can be calculated by inference from the results of mode decomposition.

2.2.2 Network model design

e mainly conduct related work based on improving the existing mature CNN model VGG-16, and the design of the improved model is referred to Yi An[5] related research presented in 2019. Since the laser spot is a single-channel grayscale image, the number of input image channels of the first convolutional layer needs to be modified from 3 to 1, and the size of the convolutional kernel needs to be modified to 3*3*1. The three-layer full connection of the model is modified to two layers, and the image classification function is modified to a Sigmoid function. The modified CNN model contains 13 convolutional layers, 5 pooling layers, 2 fully connected layers, and the pooling method is maximum pooling. A schematic diagram of its structure is shown in Fig. 2.

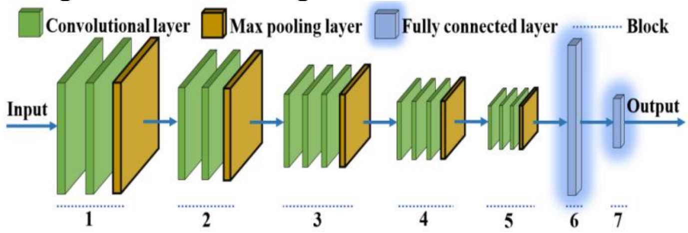


Figure. 2 Schematic diagram of the improved VGG-16 model structure[5]

## 3. System Implementation

### 3.1 Prepare the Dataset

The near-field spot images of the few-mode fiber are generated by the eigenmode superposition given the mode ratios of the eigenmodes of different orders and their relative phases with respect to the fundamental mode. The mode decomposition labels are obtained by processing the given correlation information, and the beam quality factor labels can also be introduced from the correlation information. After the data collection is completed, the spot image data need to be preprocessed with cropping, size normalization, and image denoising in order to meet the requirements of the model inputs and to improve the accuracy of the convolutional neural network for pattern decomposition and beam quality measurement. After the preprocessing, the image data were labeled using a Python scripting tool to indicate the corresponding pattern label and quality label of each image to facilitate the subsequent validation and training of the relevant models. A total of 100,000 data sets were constructed in this study, and the data sets were randomized and divided into training, validation, and test sets proportionally, where the training set accounted for 80%, and the validation and test sets accounted for 10% of the total dataset, respectively.

### 3.2 Model Establishment and Training Tuning

The study combines the deep learning framework PyTorch and the dataset generated from the pre-simulation for customizing the VGG-16 model, and completes the construction of the whole model according to the improved design of the model in the previous section 2.2.2. The mean square error loss function was chosen based on the regression characteristics of the task, and the Adam optimizer was used to help accelerate the completion of the model training process, allow the parameters to adapt to the learning rate and adjust the model parameters. After completing the model construction, the training set is used to train the model, the validation set is used to adjust the hyper-parameters such as the learning rate, and the test set is used to evaluate the performance of the trained model. Finally, the trained model is deployed to a real application for performing real-time few-mode fiber mode decomposition and beam quality measurements.

### 3.3 Model Deployment and System Integration

After completing the training of machine learning models in the cloud environment, the trained models are exported and integrated into the Python application. The back-end part of the application is constructed using the Django framework, and front-end technologies such as HTML5 and JavaScript are used to integrate with the Django back-end, realizing an easy-to-operate and user-friendly interface and interactive experience. In the home page, we provide an intuitive operation flow and clear navigation, which makes it easy for users to browse the execution flow of the whole system. After the user clicks the "Click to connect the camera" button, the program automatically jumps to the system detection and parameter setting module, realizing the connection between the optical imaging experiment system and the software system.

The home page of the system is shown in Fig. 3, the pages for mode decomposition and beam quality measurement based on the deep learning model are shown in Fig. 4 and Fig. 5. The wavelength of the laser source used in the experiment is 1073 nm, the core radius of the few-mode fiber is 4.1 μm, the numerical aperture NA is 0.14, and the value of its normalized frequency V is 3.36 as calculated by Eq. (1), which can support the three eigenmodes of LP01, LP11e , and LP11o .

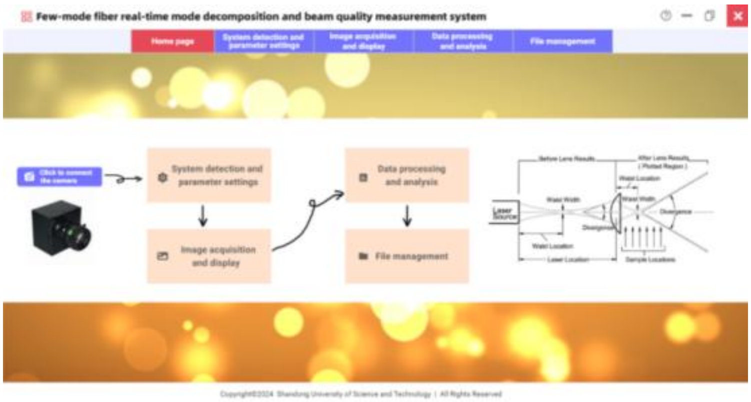

Figure. 3 System home page screenshot

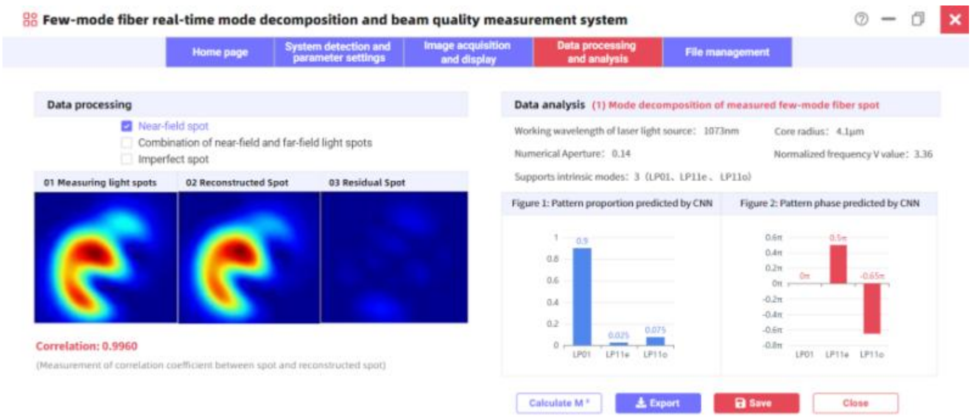

Figure. 4 Screenshot of pattern decomposition page

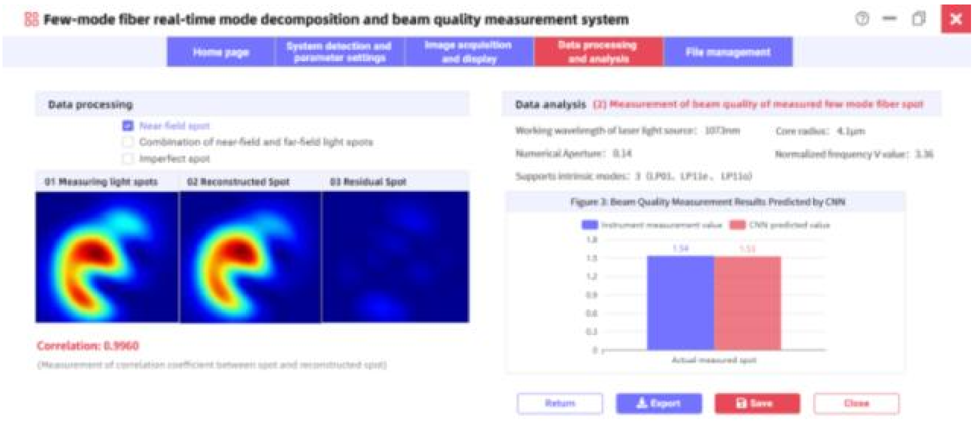


Figure. 5 Screenshot of beam quality measurement page

## 4. Conclusion And Prospect

This study is dedicated to the design and implementation of a deep learning-based real-time mode decomposition and beam quality measurement system for few-mode fibers. We adopted the improved VGG-16 model for training, and designed an easy-to-operate and user-friendly interactive interface, which enables users to easily perform mode decomposition and real-time measurement of $M^2$ factor for few-mode fibers. Through experimental tests, we verified the effectiveness and accuracy of the system in dealing with few-mode fibers containing three eigenmodes. In our future work, we will further optimize and improve the functions and performance of the system by evaluating the performance of the model based on the feedback of the training and validation results, to provide more accurate mode decomposition and beam quality measurements, and to comprehensively enhance the practicality of the system. This will involve adjustments to data preprocessing steps, increasing the diversity of the dataset, improving the annotation quality, and optimizing the adopted CNN model. Different model structures (e.g., ResNet, DenseNet, etc., or custom CNN architectures), hyperparameter settings, and optimizer options can also be tried out during training and validation to obtain the best performance.

## 5. Acknowledgements

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