Fourier-Spectrum-Based Evaluation Method for Optical Fiber Mode Scrambling Performance (Postprint)

Authors: Pang Yuchen, Peng Zifu, Geng Tao, Sun Weimin, Yan Yunxiang

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Abstract

Fiber mode scrambling technology applied to high-resolution spectroscopic observations can effectively improve radial velocity measurement precision, providing a powerful tool for research on frontier scientific issues such as the search for Earth-like planets. Currently, the impact of modal noise generated by fiber transmission on high-resolution spectrometers can no longer be neglected, and how to directly analyze fiber mode scrambling effects through modal speckle patterns of the output light field has emerged as a critical research topic. To address this issue, a Fourier-spectrum-based method for evaluating fiber mode scrambling performance has been developed. Through two-dimensional Fourier spectrum analysis and calculations of image contrast and visibility, comparative analysis was conducted on output speckle patterns from different fibers. Results demonstrate that this method is more universal, unified, and unbiased, providing important methodological support for evaluating the accuracy and effectiveness of fiber mode scrambling effects.

Full Text

Preamble

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A Scrambling Performance Evaluation Method Based on Fourier Spectrum

PANG Yuchen[1],[2],[3], PENG Zifu[1],[2],[3], GENG Tao[1],[2],[4], SUN Weimin[1],[2],[4], YAN Yunxiang[1],[2],[3],[4]

[1]Key Lab of In-fibre Integrated Optics, Ministry of Education, Harbin Engineering University, Harbin 150001, China
[2]Key Laboratory of Photonic Materials and Devices Physics for Oceanic Applications, Ministry of Industry and Information Technology, Harbin Engineering University, Harbin 150001, China
[3]Qingdao Innovation and Development Center of Harbin Engineering University, Qingdao 266000, China
[4]Advanced Photonics Institute, College of Physics and Optoelectronic Engineering, Harbin Engineering University, Harbin 150001, China

Abstract

Fiber scrambling technology for high-resolution spectroscopic observations can effectively improve radial velocity measurement precision, providing a valuable tool for frontier scientific research such as the search for Earth-like planets. Currently, the impact of mode noise generated by fiber transmission on high-resolution spectrometers has become non-negligible, making it an important research question how to directly analyze fiber scrambling performance from output speckle patterns. To address this issue, we have developed a scrambling performance evaluation method based on Fourier spectrum analysis. By applying two-dimensional Fourier spectrum analysis and calculating image contrast and visibility, we conducted comparative analyses of output speckle patterns from different optical fibers. The results confirm that this method is more universal, unified, and non-discriminatory, providing important methodological support for evaluating the accuracy and effectiveness of fiber scrambling.

Keywords: spectrograph; telescope; imaging; radial velocity; image processing

1. Introduction

In modern astronomical detection, searching for Earth-like planets in habitable zones and studying their atmospheric composition to find extraterrestrial life represents a key area of research in astronomy. In recent years, the radial velocity method based on the Doppler shift principle has discovered the second-largest number of exoplanets after the transit method. Current short-term (10^1 min) radial velocity measurement precision has reached the 1 cm/s level [1]. Compared to the approximately 9 cm/s radial velocity signal induced by Earth-like planets in habitable zones around Sun-like stars [2], mode-locked laser astro-comb systems can meet the measurement precision requirements but cannot maintain measurement stability for over a year. Moreover, due to their manufacturing complexity, such high-precision astro-comb systems are currently only commercially available from Menlo Systems in Germany, and the actual measurement precision achieved varies when the comb is used with different spectrometers. Therefore, it is essential to improve spectrometer measurement precision to enhance radial velocity measurement accuracy.

To ensure the accuracy of spectral measurements and radial velocity precision, optical fibers are used in astronomical spectrometers to transmit light collected by telescopes. However, when coherent light is transmitted through multimode fibers, interference between different modes produces bright and dark laser speckle patterns in the near-field output [3, 4]. During our experiments, we also discovered similar speckle-like patterns under incoherent white light illumination [5], which exhibit the same dependence on fiber length. Fiber scrambling technology can effectively suppress the generation of both types of speckle patterns and improve radial velocity measurement precision.

Since the scrambling performance of single circular fibers is limited, Chazelas et al. [6] tested a polygonal-core fiber in 2010. Two years later, Spronck et al. [7] and Feger et al. [8] conducted comparative experiments on the intensity distributions in near-field and far-field for polygonal and circular fibers, demonstrating the superior scrambling characteristics of polygonal fibers.

Generally, fiber scrambling performance is evaluated comprehensively from both near-field and far-field perspectives. Near-field evaluation methods can be broadly categorized into three types. The first is the scrambling gain coefficient (SG), a classical metric for near-field scrambling performance. Initially defined as the ratio of stellar light lateral displacement at the detector input to the displacement of the point spread function (PSF) in the spectrometer [9], SG is expressed as:

$$SG = \frac{d/D}{f/F}$$

where d is the stellar light displacement, D is the fiber diameter, f is the PSF displacement, and F is the full width at half maximum (FWHM) of the PSF. However, since the incident displacement d in actual observations constantly changes, researchers believe that a series of continuous results is more convincing than a single SG value, and thus provide centroid drift maps alongside SG for comprehensive evaluation [6, 10, 11]. The second common method involves plotting intensity distribution curves, which are one-dimensional intensity profiles along single-pixel slices through the image centroid [12, 13]. Scrambling performance is assessed by analyzing the smoothness and fluctuations of these curves. The third and emerging method is image analysis based on Fourier power spectrum, which obtains the power spectral density of near-field speckle patterns through two-dimensional Fourier transformation and analyzes radially averaged power spectra drawn through the image center to evaluate scrambling performance [14, 15].

However, in experiments using these methods to verify the scrambling performance of non-circular fibers, we discovered asymmetries in scrambling gain and centroid shift. Inspired by the third method, this paper proposes a fiber scrambling performance evaluation method based on Fourier spectrum. By performing two-dimensional Fourier transformation on near-field speckle patterns, we obtain normalized spectra through rotational averaging, then analyze and compare spectral curves between different fibers while calculating contrast and visibility after low-pass filtering for quantitative evaluation. Compared with previous methods, our approach offers more unified and comprehensive image processing, effectively avoids randomness, and ensures the accuracy and effectiveness of fiber scrambling performance evaluation.

2. Experiments

Non-circular fiber scrambling methods [16–19] achieve mode redistribution by altering the fiber core shape to disrupt light propagation paths within the core, thereby attaining scrambling effects. To verify the scrambling enhancement of non-circular fibers, we constructed a scrambling test optical system that can both simulate and detect incident spots entering different positions on the fiber end face (simulating telescope system injection offsets) and collect near-field speckle images from the fiber output.

2.1 Tested Fibers

We tested three fiber types with the following parameters:

1. **Circular-core step-index multimode fiber (SI)**: Core diameter 105 µm, cladding diameter 125 µm, numerical aperture (NA) 0.22.

2. **Square-core step-index multimode fiber (SQ)**: Core dimensions 100 µm × 100 µm, cladding dimensions 330 µm × 330 µm, NA 0.22.

3. **Octagonal-core step-index multimode fiber (OCT)**: Core diameter 200 µm, cladding diameter 660 µm, NA 0.22.

2.2 Test Platform

To evaluate the scrambling performance of different fiber types, we designed and built a scrambling test optical system with the optical path shown in [Figure 1: see original paper]. The system can use various laser or LED sources as incident sources to simulate stellar signals. After reflecting off the measurement fiber end face, the incident spot passes through a beam splitter cube into an end-face observation imaging system for real-time monitoring of injection offset conditions. The near-field detection device consists of a variable-magnification telecentric lens and a high-precision camera (4024$×$3036 pixels) to capture near-field speckle images.

2.3 Experimental Results

Using the optical system shown in [Figure 1: see original paper], we obtained speckle patterns with both a 650 nm red laser and an incoherent LED source. [Figure 2: see original paper] shows the output speckle patterns obtained with the 650 nm laser source, while [Figure 3: see original paper] shows patterns obtained with the incoherent LED source. Both figures only display results for center injection. In each figure, the three rows correspond to circular, square, and octagonal fibers from top to bottom, while the four columns represent fiber lengths of 0.5 m, 1 m, 2 m, and 5 m from left to right.

From [Figure 2: see original paper], clear laser speckle mode noise is visible, with speckle size and intensity decreasing as fiber length increases. Polygonal fibers exhibit smaller and weaker speckles. [Figure 3: see original paper] reveals a new phenomenon we discovered under incoherent LED illumination—similar to laser speckle mode noise, which we term “mode patterns” [5]. This phenomenon also shows fiber length dependence. The special patterns observed in the central region of 1 m and 2 m circular fibers in [Figure 3: see original paper] are attributed to the fiber end-face polishing process.

2.4 Analysis Methods

2.4.1 Centroid Shift Analysis To simulate stellar signal offset effects, we used a five-dimensional translation stage at the fiber input to control incident spot displacement in both x and y axes on the fiber end face. The step size was 10% of the fiber diameter, with seven positions (including the origin) measured at each step while collecting near-field speckle images. Due to manual adjustment of the translation stage, small errors occurred with each movement. To reduce random noise, we continuously captured 10 images at each position for averaging, and performed three independent measurements in each direction while keeping the same person in a fixed position to improve result accuracy.

We first processed the experimental near-field speckle images using the most classical analysis method—centroid drift maps and scrambling gain calculations. The results are shown in [Figure 4: see original paper] and [Figure 5: see original paper], respectively. In each figure, the upper three subplots show results from x-axis offsets, while the lower three show y-axis offset results. The horizontal axis represents relative injection offset (ratio of source displacement to test fiber diameter). The vertical axis in [Figure 4: see original paper] shows centroid shift of the near-field output, while [Figure 5: see original paper] shows the scrambling gain coefficient SG. Error bars represent variations among the three repeated measurements.

The line graphs in [Figure 4: see original paper] clearly show that near-field centroid shift is not linearly related to relative injection offset, meaning SG distribution is asymmetric about the origin, as shown in [Figure 5: see original paper]. Avila et al. [20] observed incomplete symmetry in output patterns in 2010, and more explicitly stated in 2022 [21] that SG distribution is asymmetric relative to center injection, with near-field speckle patterns changing differently along injection offset directions and depending on fiber path geometry. Ye et al. [16] also found non-linear relationships between output centroid drift and injection position offset during measurements. Earlier studies [22] attributed this to coma aberration and concluded that injection angle affects results more than offset position. Based on these findings and our experimental results, we confirm that classical evaluation methods using centroid drift maps and SG coefficients produce asymmetric and uncertain measurements.

These results directly affect spectrometers where the fiber near-field is imaged onto spectral lines. In high-resolution spectrometers requiring long-term stability and high radial velocity precision, the fiber' s inherent scrambling characteristics decouple the spectrometer from various changing environmental conditions (such as temperature, pressure, and telescope position) during transmission, while ensuring stable and uniform illumination at the spectrometer input. Fiber-fed spectrometers image the fiber output directly onto the detector, where small changes in fiber output appear as small changes in the image plane, manifesting as spectral line displacement or shape changes. Therefore, when the light source undergoes symmetric offsets of equal distance but opposite direction at the fiber input, the fiber output should theoretically produce similarly symmetric centroid shifts and nearly identical scrambling gain coefficients. However, our validation experiments yielded asymmetric results, causing spectral lines to shift and deform to varying degrees. This complicates spectral calibration by producing different error magnitudes across spectral regions, makes measurement results difficult to reproduce between observations, and increases measurement instability.

Beyond the asymmetry issue, our calculations also revealed that polygonal fibers showed no obvious improvement in scrambling performance compared to circular fibers based on centroid shift alone—a result inconsistent with direct morphological features observed in images. We speculate this may be caused by non-uniformity on fiber surfaces and camera sensitivity variations. Therefore, evaluating fiber scrambling performance and its resulting spectral line shifts and deformations solely through centroid shift and SG is incomplete.

2.4.2 Visibility Analysis To reduce error accumulation from multiple processing steps, we directly analyzed the collected speckle images and proposed another quantitative approach—calculating contrast and visibility. Since our research focuses on large-area mode patterns and to avoid influence from special central patterns caused by the polishing process, we calculated contrast and visibility across subsets of the entire speckle distribution, with the sampling method shown in [Figure 6a: see original paper]. In [Figure 6b: see original paper], C represents contrast and V represents visibility. Contrast is the ratio of standard deviation to mean value of image grayscale data, while visibility is the difference-to-sum ratio of maximum and minimum grayscale values. Both metrics reflect brightness differences in an image; smaller differences indicate lower contrast between bright and dark regions, weaker modal speckles, and better fiber scrambling performance.

[Figure 6b: see original paper] shows calculated contrast and visibility for the three fiber types. Polygonal fibers exhibit lower contrast and visibility than circular fibers, proving they have fewer modal speckles and superior scrambling performance. Both metrics decrease with increasing fiber length, again confirming the length dependence of mode patterns. However, relatively large error bars at some points indicate that this manual random sampling method still contains certain randomness.

3. Fourier Spectrum-Based Speckle Analysis Method

The two evaluation methods used in Chapter 2 both suffer from significant randomness and uncertainty. We sought a more universal processing method focused on modal variation analysis, combining qualitative analysis through two-dimensional image Fourier transform spatial frequency spectra with quantitative calculations of contrast and visibility.

3.1 Fourier Spectrum Analysis

We first normalized the intensity of experimental images to ensure each image had equal energy in the spatial domain, then performed two-dimensional fast Fourier transformation (2D FFT). The resulting two-dimensional spectrum decomposes energy intensity into contributions from different spatial frequencies [23], where bright and dark spots indicate the degree of grayscale difference between a pixel and its neighbors (the magnitude of grayscale gradient), representing spatial frequency magnitude. To clearly display differences between fiber spectra, we rotationally averaged the 2D spatial frequency images to obtain normalized frequencies in one dimension. Using bilinear interpolation, we rotated each spectrum by 1° for 179 rotations (spectrum images are axisymmetric, so 180° covers all spatial frequencies). After superimposing these 180 images, we extracted data from any direction to plot one-dimensional spectra. [Figure 7: see original paper] shows one-dimensional spectra for the three fiber types at four different lengths, with the vertical axis representing normalized frequency and the horizontal axis representing one-dimensional spatial frequency. Since the high-precision camera used for near-field image collection has 1.85 µm pixels, spatial frequency is simply expressed in μm^{-1} and plotted up to the Nyquist frequency (270 μm^{-1}).

In Fourier spectra, high-frequency components characterize regions with sharp grayscale variations, with their intensity representing speckle strength. Low-frequency components correspond to slowly varying grayscale regions; larger proportions indicate fewer mode patterns and better fiber scrambling performance. The intensity proportions at different frequencies for each fiber at four lengths are shown in [Figure 8: see original paper].

For spatial frequencies below 10 μm^{-1}, the curves essentially overlap, indicating stable speckle sizes across fiber types and lengths. Octagonal fibers show significantly larger low-frequency component proportions than the other two fibers, with more power distributed at lower spatial frequencies, demonstrating fewer speckle patterns and superior scrambling performance. The flattening portions at the rear of curves can be considered high-frequency noise; we suspect differences in noise frequency among the three fibers result from minor exposure time variations.

Applying the same image processing to the offset injection experimental images from Section 2.4.1, [Figure 9: see original paper] shows results for 5 m fiber length, with circular (SI), square (SQ), and octagonal (OCT) fibers from top to bottom. The left vertical axis in each plot represents normalized frequency after rotational averaging of 2D Fourier spectra, while the right vertical axis shows intensity proportion at each spatial frequency. The left three plots show results from x-axis offsets, right three from y-axis offsets, with legend percentages representing injection offset distance as a ratio of test fiber diameter.

The offset injection curves do not completely coincide with center injection curves. To accurately compare curve dispersion differences between fibers, we calculated root mean square (RMS) deviations. RMS values between each offset curve and the center curve were computed for each fiber and offset direction in [Figure 9: see original paper], with average RMS values for each offset direction shown in (RMS is dimensionless, like normalized frequency).

The data in clearly show larger differences between curves for circular fibers, indicating injection offset affects circular fiber Fourier spectra more significantly, while polygonal fibers maintain more stable states, again confirming their superior scrambling characteristics.

3.2 Contrast and Visibility

While Fourier spectra provide valuable qualitative analysis of scrambling performance, they are more suitable for fields with numerous speckles and large intensity fluctuations [23]. The mode patterns generated by LED illumination in our experiments are relatively sparse, resulting in small curve differences between the three fiber types. Therefore, we introduce contrast and visibility calculations for quantitative analysis. To address the special central patterns from polishing shown in [Figure 3: see original paper], we needed an image processing method to remove or weaken these patterns, enabling direct calculation across the entire core region without manually extracting subsets, thus avoiding the randomness of three sampling attempts described in Section 2.4.2.

To filter out high-frequency special patterns at fiber centers, we selected a Butterworth low-pass filter [24]—intermediate between the sharply filtering ideal low-pass filter and the smoothly filtering Gaussian low-pass filter. This filter has two adjustable parameters: cutoff frequency D_0 and order n [25]. For 2D images, D_0 is the distance from a frequency domain point to the center, and larger n produces steeper filter shapes with more pronounced ringing effects. We used the frequency at which the intensity proportion difference among the three fiber types is maximized at the same length as the cutoff frequency D_0, then compared our Fourier spectral curves with Butterworth low-pass filter functions of different orders, finding suitable orders of 1–5. We then processed experimental images repeatedly using low-pass filters with orders varying from 1 to

5 in 0.2 increments, ultimately finding that a filter with $n = 2.2$ provided optimal filtering while maintaining image clarity. This Butterworth low-pass filter was then applied to all center-injection experimental images, with calculated contrast and visibility results shown in [Figure 10: see original paper]. Before filtering, we selected a 1000 pixel × 1000 pixel region at the speckle pattern center for calculation, with results shown in [Figure 10a: see original paper]. [Figure 10b: see original paper] shows contrast and visibility after filtering, and [Figure 10c: see original paper] shows the improvement degree from filtering. In the legends, C represents contrast and V represents visibility.

[Figure 10: see original paper] demonstrates that polygonal fibers have lower contrast and visibility than circular fibers, longer fibers have lower values than shorter fibers, and filtering produces the most significant improvement for polygonal fibers. All results confirm that polygonal fibers exhibit significantly superior scrambling performance compared to circular fibers. Applying the same method to the offset injection experimental results from Section 2.4.1, [Figure 11: see original paper] shows contrast statistics and [Figure 12: see original paper] shows visibility statistics, with horizontal axes representing relative injection offset and vertical axes being dimensionless ratios.

Combined results from [Figure 11: see original paper] and [Figure 12: see original paper] show that polygonal fibers have significantly lower overall contrast and visibility values than circular fibers, with smaller variations between different lengths, again confirming better scrambling performance. Furthermore, contrast and visibility exhibit better symmetry than centroid drift ([Figure 4: see original paper]) and scrambling gain ([Figure 5: see original paper]), matching our experimental offset results more closely and providing more convincing evidence.

These experiments demonstrate that both qualitative Fourier spectrum analysis and quantitative contrast and visibility calculations can accurately reflect actual optical field variations and scrambling performance differences, enabling more accurate and reasonable evaluation of scrambling effects and validating the feasibility of our method. Stürmer et al. [10] noted that near-field measurement methods are not directly related to radial velocity errors but only serve for comparing different fibers or scrambling methods—meaning the method can only compare scrambling performance between different fibers or approaches, not directly replace centroid shift and SG calculations or directly improve radial velocity measurement precision. We propose applying this method to assist centroid shift calculations before spectral data processing, screening out images with distorted and offset spectral lines caused by external influences (such as fiber surface uniformity, illumination dependence of optical components, detector sensitivity, etc.), and ultimately selecting images most suitable for spectral analysis and calibration. These selected images should guarantee stable centroid shifts, high scrambling gain coefficients, low contrast and visibility, and good symmetry and uniformity. This pre-processing screening reduces handling of spectrally abnormal images caused by external influences, ensures data quality and result reliability, and effectively improves spectral processing efficiency.

4. Summary

Fiber scrambling is a crucial technical means for improving radial velocity measurement precision. Addressing the asymmetry and uncertainty issues in single-performance-index SG evaluation, this paper proposes a comprehensive fiber scrambling performance evaluation method based on Fourier spectrum analysis combined with contrast and visibility analysis. This method integrates multiple features including fiber near-field centroid shift SG measurement, spectral analysis, near-field symmetry, and uniformity to comprehensively evaluate fiber scrambling performance. It compensates for the insufficient stability of SG measurement as a single performance index, effectively avoids random selection errors in fiber near-field scrambling analysis, reduces interference from external environments on scrambling performance evaluation, and achieves more universal, unified, and non-discriminatory comprehensive scrambling performance evaluation. This enhances the reliability of comparative scrambling performance assessments between different methods and supports the development of high-performance fiber scrambling technologies for high-resolution spectral analysis.

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