Experimental Demonstration of Probe-Signal-Integrated Remote Doppler Metrology Using Structured Light Fields Guided Through 40-km Seven-Core Fiber

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Abstract *We firstly demonstrate the probe-signal-integrated remote rotational Doppler metrology through 40-km seven-core fiber. The rotation speed of the rotating object can be measured accurately by the structured light fields at a long distance.*

Introduction

In recent years, the rotational Doppler effect has been widely applied in the field of measuring rotational motion. Doppler velocimetry is generated for detecting the motion of surfaces [1], and fluids [2]. Typically, a superimposed vortex beam is used in experiments to illuminate the rotating object [3, 4]. The Doppler shift detected from the scattered light is linearly related to the angular velocity.

Lavery et al. observed the single-valued Doppler shift within an OAM-carrying white light backscattered from a rotating object, which demonstrates the rotational Doppler effect is achromatic [5]. Recently, A. Anderson et al. proposed an experiment with incoherent light measuring a rotational motion [6]. The Doppler frequency shift could be observed from a petal intensity pattern. It demonstrates that the fields of petal intensity patterns have an OAM correlation, which provides a simpler option for the measurement method. However, most of the experimental measurements use SLM or projection devices, which are not compact for transmission over long distances.

In this paper, we use a 40-km seven-core fiber to create the petal intensity pattern with rotation symmetry. The return signal received by the center core of the fiber carries the Doppler frequency shift. In addition, by lighting up the differently distributed outer cores within the fiber, we achieve the measurement using different structured light fields. Thus, this method achieves a probe-signal-integrated remote Doppler metrology with structured optical fields at a distance of 40 km.

Concept and principle

Fig. 1 shows the proposed seven-core fiber rotational Doppler metrology. The fiber fan-in/fan-out (FIFO) module is designed to select which core would be lit up or not. The six outer cores are chosen to output the light and illuminate the particle. And the center core is used to collect reflected light from a rotational particle. The return signal light is again transmitted via optical fiber to the FIFO module and output from the detection port. On the one

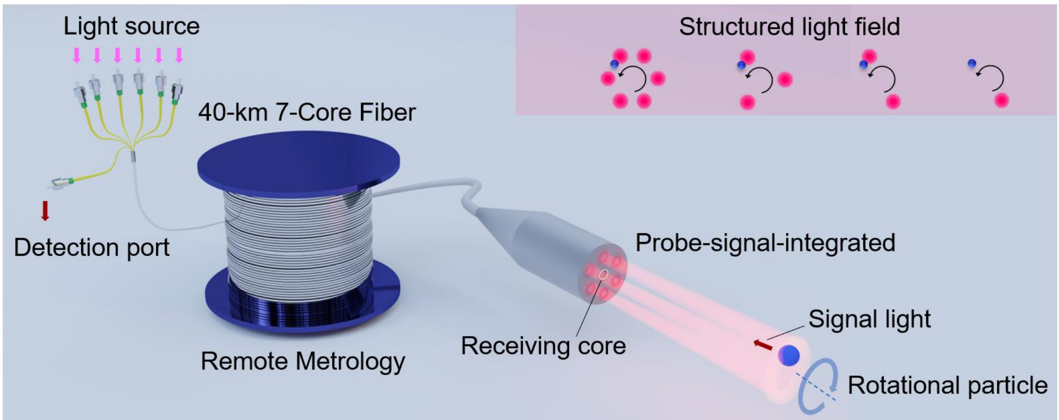

Fig. 1: The concept of the remote rotational Doppler metrology through a 40km seven-core fiber.

hand, all six outer cores are lit up to generate a lobed intensity pattern of six petals. It has a correlation with the rotational Doppler effect raised by the superposed OAM beams of ± 3 order. For the rotational Doppler effect excited between a $\pm\ell$ petal beam and a rotating object at an angular velocity of Ω, the frequency shift $\Delta f = 2\ell\Omega$ could be observed from the return signal in the center core. Hence, the angular velocity can be calculated by the Fourier analysis. On the other hand, only three or two cores with circular symmetry distribution are chosen instead of lighting up all the outer cores. Even if only one core is lit, the probe light would still periodically illuminate the rotational particle and then reflect signal light. The structured light fields modulate the intensity signal in the time domain. This modulation corresponds to a certain periodicity in the results, so that a single value is generated in the frequency domain related to the rotation speed and the pattern of the light field. Therefore, this probe-signal-integrated rotational Doppler velocimetry could measure the angular velocity by generating different scalar light fields through a 40-km seven-core fiber.

Experimental setup

Fig. 2(a) illustrates the experimental setup of a seven-core fiber Doppler measurement system. The 1550nm laser output is divided into six ports connected to six outer cores, respectively. Each input power is controlled at approximately 11 mW. Fig. 2(b) shows the experimental seven-core fiber. After 40 km of fiber length transmission, the output light is collimated by the objective lens (UPLFLN 20$\times$/0.50) to illuminate the DMD (Texas Instruments DLP7001, 1024 × 768 micromirror array). As Fig. 2(c) shows, the center core is selected as the detection core to collect the light reflected by the DMD surface. Fig. 2(d) shows the measured intensity profile of the illumination beam when all six outer cores are lit up. The rotational motion of the particle is simulated by the DMD. The signal light turns back through the fiber and the output of the center core is connected to the PD (Amplified Detector PDA50B2) for data collection. An oscilloscope is used to observe signals and perform Fourier analysis. Therefore, the peak frequency linearly related to the particle's rotational speed can be observed in the Fourier spectrum. Hence, the angular velocity of the particle can be calculated. In experiments, the rotational motion in one cycle is divided into 200 patterns to be loaded onto the DMD, under high-speed switching to simulate the rotating particles. One of the patterns loaded on the DMD is shown in Fig. 2(e). The DMD patterns are switched in the forward or backward sequence to simulate different orientations of rotational motion.

Results and discussions

First, all six outer cores are lit up, and the rotational speed is measured by the seven-core fiber rotational Doppler measurement system. The typical results are shown in Fig. 3. The time domain intensity signals at the rotational speed of 20 and 40 revolutions per second (rps) are shown in Fig. 3(a) and (c), respectively. In Fig. 3(b) and (d), two Fourier spectra show that the peak frequencies are 120 and 240 Hz at the corresponding speed, respectively. The frequencies are six times the magnitude of rotational speed, which fit with the theoretical values. By setting the time for each pattern to be shown on the DMD, the speeds of particle rotation are 10, 16.67, 20, 25, 33.33, 40, 50, 66.67, 83.33, and 100 rps, respectively. As shown in Fig. 3(e), the peak frequency is proportional to the angular velocity.

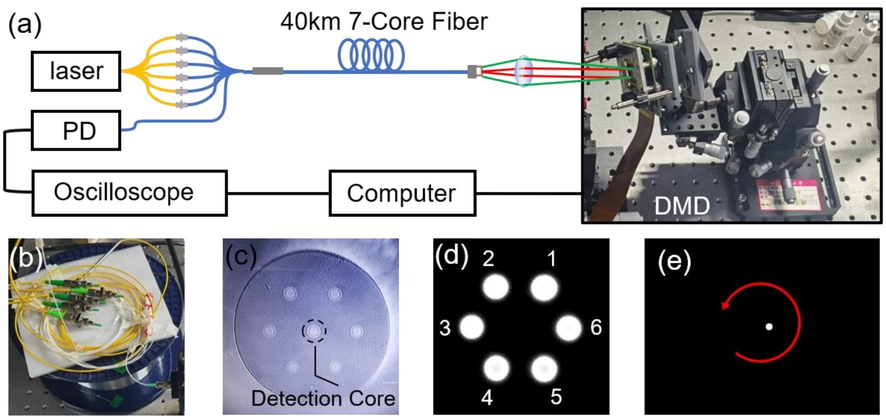

Fig. 2: (a) Experimental setup of seven-core fiber Doppler measurement system. PD: photo diode. DMD: digital micromirror devices. (b) The experimental seven-core fiber. (c) Cross-section of the 7-core fiber. (d) The measured intensity profiles when all the outer cores 1~6 are lit up. (e) The pattern loaded onto the DMD.

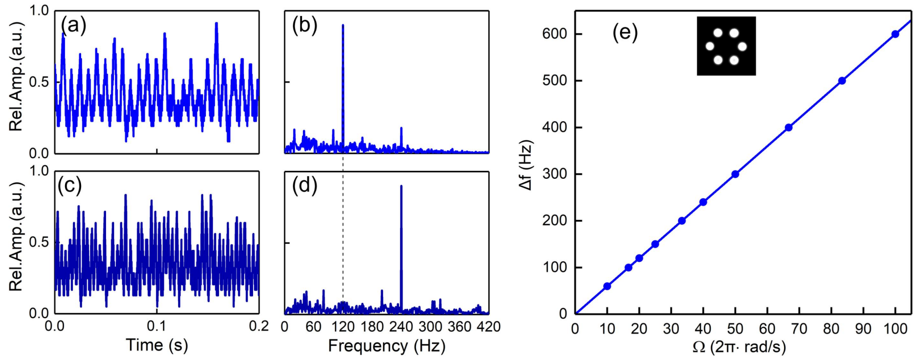

Fig. 3: The performance of seven-core fiber Doppler velocimetry for rotational speed measurement. The typical results of (a), (b) the time domain intensity signals, and (c), (d) the Fourier spectra of detected signals under the angular velocity of 20 and 40 revolutions per second (rps), respectively. (e) The measured frequencies with a linear relation of different rotational speeds.

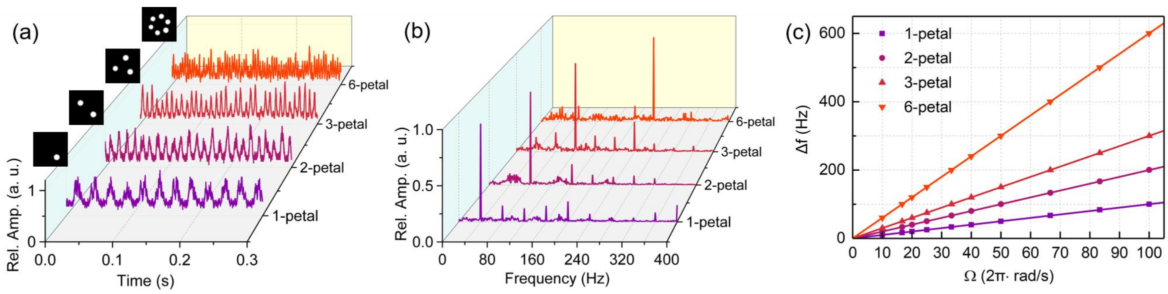

Fig. 4: The results for different structured light fields. (a) The time domain intensity signals, and (b) the Fourier spectra of detected signals under the angular velocity of 40 revolutions per second (rps) for intensity fields of 1, 2, 3, 6 petals, respectively. (c) The measured frequencies for different light fields and rotational speeds.

Next, different structured light fields are generated by lighting up several outer cores instead of all six. The rotational particle at angular velocity Ω is simulated by DMD. In Fig. 4 four different colors indicate four intensity fields. The results shown in Fig. 4(a) are the time domain spectrum at a rotational speed of 40 rps. The four left insets in Fig. 4(a) are measured intensity profiles of 1, 2, 3, and 6 petals, respectively. The modulated time domain intensity signals are in the form of trigonometric functions with different periodicity in four light fields. And Fig. 4(b) shows the results in the Fourier spectrum for four illuminating patterns. There are four frequency peaks at 40, 80, 120, and 240 Hz corresponding to the four light fields. All the variable speed measurement results are shown in Fig. 4(c). All four curves show a linear correlation between frequency and velocity. The slope of the curve is related to the light field pattern. These measured results are in good agreement with theoretical expectations.

Conclusion

In summary, we have demonstrated the rotational Doppler velocimetry by using a 40-km seven-core fiber to generate different light fields, which could measure the angular velocity. With only one fiber used in it to probe and collect signals, the system configuration is compact. Our results show that seven-core fiber rotational Doppler velocimetry can achieve long-range detection and effectively reduce costs.

Acknowledgements

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