Kent Academic Repository

Wang, Guoqing and Wang, Chao (2016) *Diffraction Limited Optical Time-Stretch Microscopy Using an In-Fibre Diffraction Grating.* In: Frontiers in Optics 2016. . Optical Society of America ISBN 978-1-943580-19-4.

Downloaded from

https://kar.kent.ac.uk/57908/ The University of Kent's Academic Repository KAR

The version of record is available from

https://doi.org/10.1364/FIO.2016.FF2A.5

This document version

Author's Accepted Manuscript

DOI for this version

Licence for this version

UNSPECIFIED

Additional information

Versions of research works

Versions of Record

If this version is the version of record, it is the same as the published version available on the publisher's web site. Cite as the published version.

Author Accepted Manuscripts

If this document is identified as the Author Accepted Manuscript it is the version after peer review but before type setting, copy editing or publisher branding. Cite as Surname, Initial. (Year) 'Title of article'. To be published in *Title of Journal* , Volume and issue numbers [peer-reviewed accepted version]. Available at: DOI or URL (Accessed: date).

Enquiries

If you have questions about this document contact ResearchSupport@kent.ac.uk. Please include the URL of the record in KAR. If you believe that your, or a third party's rights have been compromised through this document please see our Take Down policy (available from https://www.kent.ac.uk/guides/kar-the-kent-academic-repository#policies).

Diffraction Limited Optical Time-Stretch Microscopy Using an In-Fibre Diffraction Grating

Guoqing Wang and Chao Wang
School of Engineering and Digital Arts, University of Kent, Canterbury, United Kingdom CT2 7NT
Author e-mail address: C.Wang@kent.ac.uk

Abstract: Ultrafast optical time-stretch imaging using a 45° tilted fiber grating (TFG) as an in-fibre diffraction device is proposed and experimentally demonstrated for the first time featuring high efficiency, complete fiber-compatibility and diffraction-limited lateral resolution.

OCIS codes: (050.1950) Diffraction gratings; (110.22970) Image detection systems; (060.3735) Fiber Bragg gratings.

1. Introduction

Ultrafast imaging technology is of paramount importance in studying dynamic phenomena, and capturing important rare events in high-throughput screening. Serial time-encoded amplified microscopy (STEAM), which adopts the unique mapping from the spatial information (image) to a serial time-domain data stream using chromatic and spatial dispersion with high-speed single-pixel detection, has enabled ultrafast unprecedented imaging speed of tens of millions frames per second [1]. STEAM technology has been successfully applied in ultrafast laser scanning [2] and flowing particle screening [3], showing great potential in real-time high-throughput and highly sensitive measurements [4].

In STEAM imaging systems, diffractive gratings are essential to encode the spatial information (image) into the optical spectrum of dispersed pulses. However, it is a real challenge to miniaturize the STEAM system as the free-space diffraction gratings are usually bulky and costly. Besides, because of inherent strong zeroth-order reflection, diffraction gratings have limited diffraction efficiency (up to 75%). Another challenge of STEAM systems is significant coupling loss between free-space gratings which offer spatial dispersion for space-wavelength mapping, and optical fibres which produce chromatic dispersion for wavelength-time mapping. More importantly, as the illumination light in STEAM is a time-encoded rainbow beam, the instantaneous illumination light has a smaller beam size than the aperture of imaging optics, making its lateral resolution poorer than the diffraction limit.

In this work, we propose and demonstrate a novel highly efficient, and fiber-compatible optical time-stretch imaging system using a 45° tilted fiber grating (TFG) as in-fibre diffraction grating. Imaging of fast moving objects with a line speed of 46m/s is demonstrated and diffraction-limited lateral resolution is achieved.

2. Experiment and results

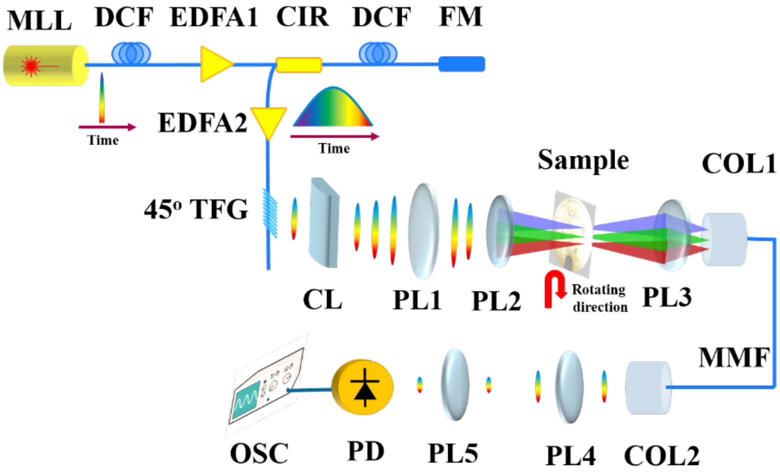

Fig. 1. Schematic diagram of ultrafast time-stretch imaging system. MLL: mode-locked laser; DCF: dispersive compensating fiber; EDFA: Erbium Doped Fiber Amplifier; CIR: circulator; FM: faraday mirror; 45° TFG: 45° tilted fiber grating; CL: cylindrical lens; PL: plano-convex lens; COL: collimator; MMF: multimode fiber; PD: photo-detector; OSC: oscilloscope.

In our set up, the 45° TFG is presented as a highly efficient (diffraction efficiency of 93.5% [5]), compact in-fiber lateral diffractive element. The schematic diagram of ultrafast time-stretch spectrally encoded imaging system is shown in Fig. 1. A mode-locked laser (MLL) with the repetition rate of 50MHz is employed to provide the broadband laser pulse train. The pulse train propagates through the dispersive compensating fiber (DCF) to achieve one-to-one time-to-wavelength mapping, followed by amplification in an Erbium Doped Fiber Amplifier (EDFA). The amplified pulse is launched into the 45° TFG, where light is diffracted into open space. A cylindrical lens with a focal length of 20mm is placed after 45° TFG to obtain vertical collimated beam. A lens set contains two plano-convex lens, with focal lengths of 250mm and 200mm, separated by 130mm is used to focus different wavelength of light into separate spatial coordinates on the object plane to achieve one-to-one wavelength-to-space mapping.

A custom-designed sample, as shown in Fig. 2(a), is placed in the object plane, with a spinning speed of 40,000 rpm, which creates fast moving object at a line speed of 46m/s on the field-of-view range. Transmitted light is detected by a high-speed photo-detector with a bandwidth of 15 GHz. The captured pulse train is shown in Fig. 2(b). A burst of pulses in red frame represent the highlighted features on the sample. Fig. 2(c) shows the reconstructed image of fast spinning sample, clearly showing the holes and short slots.

Conventional STEAM systems suffer from limited lateral resolution poorer than the diffraction limit due to the fact the instantaneous monochromatic illumination light has a beam size much smaller than the aperture size of imaging optics, as illustrated in Fig. 3(a). The presented system overcomes this limitation by largely overlapping the instantaneous illumination beams and easily enlarging beam size due to the use of long TFG, as shown in Fig. 3(b). Diffraction-limited lateral resolution of 27 μm has been achieved. With the same imaging optics, conventional STEAM setup provides a poorer resolution of 45 μm.

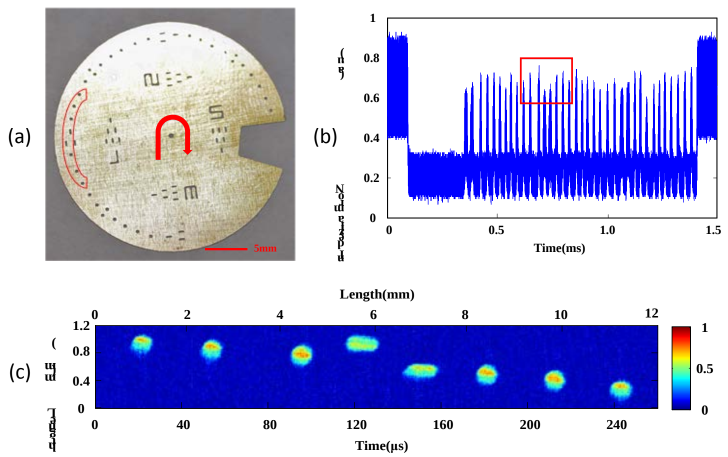

Fig. 2. (a) CCD image of the one-inch sample; (b) Captured temporal waveforms representing the features in the sample; (c) Reconstructed image of the fast spinning object at line speed of 46 m/s.

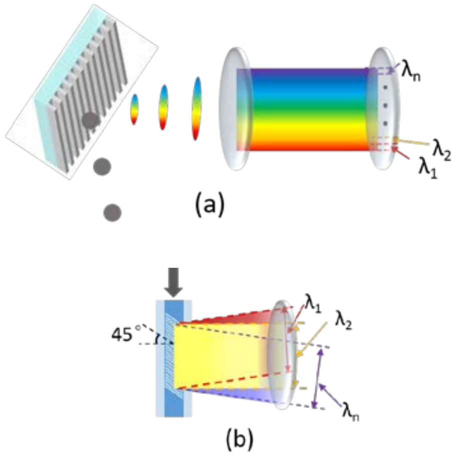

Fig. 3. (a) CCD image of the one-inch sample; (b) Captured temporal waveforms representing the features in the sample.

3. Summary

Our proposed novel highly efficient, fiber-compatible ultrafast time-stretch spectrally encoded imaging system using 45° TFG achieved a line speed of 46m/s. The 45° TFG inherently compatible with optical fibers that provide chromatic dispersion, also there's no coupling loss between free-space and fiber optics. Therefore our proposal enables compact and more energy-efficient ultrafast imaging systems.

4. References

[1] K. Goda, K. K. Tsia, and B. Jalal, "Serial Time-Encoded Amplified Imaging for Real-Time Observation of Fast Dynamic Phenomena," Nature, **458**, 1145-1149 (2009).

[2] K. Goda, A. Mahjoubfar, C. Wang, A. Fard, J. Adam, D. R. Gossett, A. Ayazi, E. Sollier, O. Malik, E. Chen, Y. Liu, R. Brown, N. Sarkhosh, D. Di Carlo, and B. Jalali, "Hybrid Dispersion Laser Scanner," Sci. Rep., **2**, (2012).

[3] K. Goda, A. Ayazi, D. R. Gossett, J. Sadasivam, C. K. Lonappan, E. Sollier, A. M. Fard, S. C. Hur, J. Adam, C. Murray, C. Wang, N. Brackbill, D. Di Carlo, and B. Jalali, "High-throughput single-microparticle imaging flow analyzer," PNAS, **109**, 11630-11635 (2012).

[4] B. Jalali, D. R. Solli, K. Goda, K. Tsia, and C. Ropers, "Real-time measurements, rare events and photon economics," Eur Phys J-Spec Top., **185**, 145-157 (2010).

[5] G. Wang, C. Wang, Z. Yan, L. Zhang, " Highly efficient spectrally encoded imaging using a 45° tilted fiber grating," Opt. Lett. **41**, 2398-2401 (2016).