A fiber-compatible spectrally encoded imaging system using a 45° tilted fiber grating

Guoqing Wang[a], Chao Wang*[a], Zhijun Yan[b], Lin Zhang[b]
[a]School of Engineering and Digital Arts, University of Kent, Canterbury, United Kingdom CT2 7NT; [b]Aston Institute of Photonic Technologies, Aston University, Birmingham, United Kingdom B4 7ET

ABSTRACT

We propose and demonstrate, for the first time to our best knowledge, the use of a 45° tilted fiber grating (TFG) as an in-fiber lateral diffraction element in an efficient and fiber-compatible spectrally encoded imaging (SEI) system. Under proper polarization control, the TFG has significantly enhanced diffraction efficiency (93.5%) due to strong tilted reflection. Our conceptually new fiber-topics-based design eliminates the need for bulky and lossy free-space diffraction gratings, significantly reduces the volume and cost of the imaging system, improves energy efficiency, and increases system stability. As a proof-of-principle experiment, we use the proposed system to perform an one dimensional (1D) line scan imaging of a customer-designed three-slot sample and the results show that the constructed image matches well with the actual sample. The angular dispersion of the 45° TFG is measured to be 0.054°/nm and the lateral resolution of the SEI system is measured to be 28 μm in our experiment.

Keywords: Diffraction gratings, image detection systems, tilted fiber Bragg gratings, angular dispersion

1. INTRODUCTION

As a new type of imaging technology, spectrally encoded imaging (SEI) maps transverse spatial coordinates of the object into wavelength of the illuminating light [1]. This technology is based on unique one-to-one mapping between space and optical wavelength that is achieved by using optical diffraction devices, such as a diffraction grating for one dimensional imaging [2] and the joint use of a virtually imaged phased array (VIPA) and a diffraction grating for two dimensional (2D) imaging [3]. One feature of SEI technique is the large number of resolvable points thanks to the broad spectral bandwidth of the light source and high angular dispersion of the diffraction element. SEI imaging technique has been successfully used in endoscopy [1]. Recently, ultrafast implementation of SEI using time-stretch dispersive Fourier transform (DFT) has been reported and found wide application in ultrafast microscope [3], laser scanner [4] and flowing particle screening [5]. Ultrafast SEI technique has shown great potential in real-time high-throughput imaging and highly sensitive measurements [6].

Diffraction gratings, as the key component in SEI-based imaging systems, enable the one-to-one space-to-wavelength mapping and offer high angular dispersion due to its high groove density. However, free-space diffraction gratings suffer from bulky configuration, high cost, complicated alignment, high coupling loss with fiber-optic components, and more importantly, low energy efficiency due to the inherent strong zero-order reflection. This problem becomes more severe if multiple gratings are used or the diffraction grating also collects light for imaging [3-6]. To miniaturize the SEI system is a true challenge because the bulky and costly diffraction devices are always required. These difficulties prevent SEI's wide use in practical imaging applications where low-cost, energy efficient and compact imaging devices are desired.

In this work, we propose and experimentally demonstrate a highly efficient, fiber-compatible SEI system using a 45° tilted fiber grating (TFG). The 45° TFG presented as a highly efficient, compact, and in-fiber lateral diffractive element in the SEI system, replaces the bulky and highly lossy free-space diffraction gratings in conventional SEI systems [3-6], improves the diffraction efficiency and reduces the volume of the SEI systems. We confirmed our proposal by a proof-of-concept experiment and the results show that the TFG has a high diffraction efficiency of 93.5% within a 40nm spectral band. In addition, the TFG-based diffraction scheme is particularly attractive to ultrafast real-time DFT-SEI systems, as the TFG is inherently compatible with optical fibers that provide chromatic dispersion, hence greatly

*C.Wang@kent.ac.uk; phone 44 1227 827621

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reducing diffraction loss and coupling loss between free-space and fiber optics. Therefore the TFG enables energy-efficient and miniaturized SEI systems for practical imaging applications.

2. ANALYSIS OF 45° TFG

2.1 Structure and characteristic of TFG

The concept of TFG was first proposed by Meltz et al. in 1990 [7], and its mode matching mechanism was described by Erdogan and Sipe [8]. Like normal fiber Bragg gratings, TFGs have periodical refractive index variation in axial direction, but its boundary surface of the varied index is tilted with respect to the fiber axis instead of perpendicular to it, which endows it with unique optical properties compared to normal fiber Bragg gratings (FBGs) and long period fiber gratings (LPFGs). In small angle (<10°) TFGs, the propagated light in the fiber core region can be coupled into both co-propagating core mode and counter-propagating cladding modes in specific wavelengths, resulting in multiple resonances at the transmission spectrum. Due to this feature, tilted fiber Bragg gratings can be used as gain flattened erbium fiber amplifiers [9], add-drop filters [10, 11], modal power distribution measurers [12] and refractometers [13, 14].

In a large angle (for example, 45°) TFG (as shown in Figure 1), the situation will be changed greatly. Both types of mode couplings are not supported, and lateral diffraction of light from fiber core region into open space is resulted due to the largely tilted grating structure. The lateral diffraction angle is strongly wavelength dependent to satisfy broadband phase matching condition, which makes the TFG a perfect candidate for a compact, in-fiber diffractive element. Another interesting feature of large angle TFGs is that it shows high sensitivity to the polarization state of the incident light. This unique feature allows us to develop it as a highly efficient diffractive optical fiber element by properly controlling the polarization of the incident light for a wide range of attractive applications. For example, they can serve as in-fiber polarimeters [15, 16], twist sensors [17], polarization-dependent loss equalizers [18], in-fiber polarizers [19, 20], and have been successfully applied as an in-fiber diffractive device in a miniature optical spectrum analyser [21] and low-cost optical coherence tomography [22]. Here we propose and demonstrate, for the first time to our best knowledge, the use of a 45° TFG in a new spectrally encoded imaging system featuring compactness, high energy efficiency and good system stability.

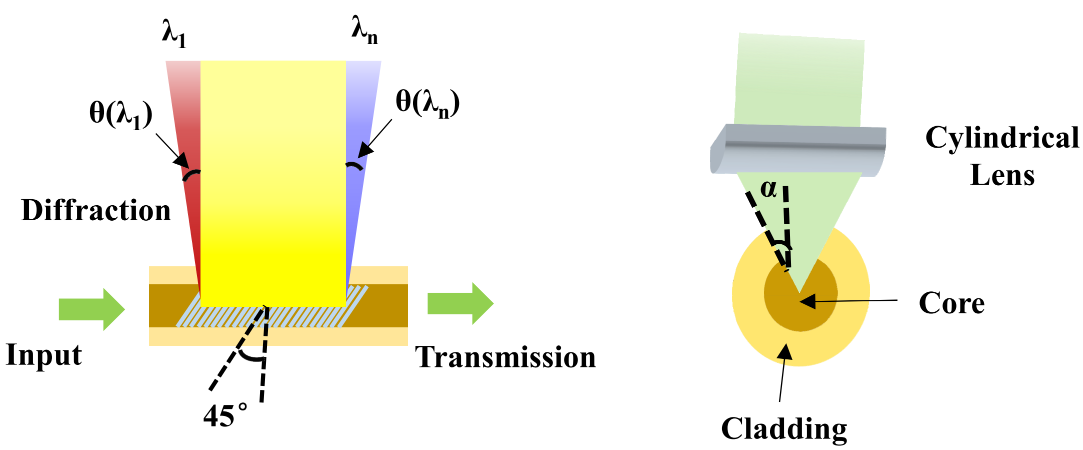

Figure 1. Structure of a 45° TFG. Broadband incident light is diffracted from fiber core into free space with wavelength-dependent diffraction angle.

2.2 Angular dispersion of a 45° TFG

The structure of a 45° TFG is illustrated in Figure 1. Broadband lateral diffraction is formed when the incident light is propagating through the TFG due to the largely tilted reflection. As lateral diffraction angle is strongly wavelength dependent in order to meet broadband phase matching condition, the light with different wavelengths will be diffracted at different angles. This makes a 45° TFG a perfect in-fiber diffraction device.

For a given optical wavelength, the maximum angular dispersion of a TFG could be obtained at a tilt angle of 45° [21]. The angular dispersion of a 45° TFG in its first order diffraction is formulated as [22]

$$D = \frac{d\theta(\lambda)}{d\lambda} = \frac{1}{\Lambda} \tag{1}$$

where λ is the wavelength of incident light, θ is the angle of lateral diffraction, and Λ is the period of the TFG, which is 748 nm for our designed TFG. The TFG used in our proposed SEI system has a tilt angle of 45°, which ensures the maximum angular dispersion. In addition, the nominal direction of diffraction is perpendicular to the fiber axis, which makes it much easier for design and alignment of associated imaging optics in real practice.

To fabricate a 45° TFG as an efficient in-fiber diffractive device, the standard scanning phase mask technique using continuous-wave UV-light at 244 nm [23] was implemented to write it directly into a standard telecom single-mode fiber (SMF-28). In comparison with normal FBGs, the phase mask was rotated by 33.3° to achieve the required 45° slanted grating fringes. The length of the fabricated 45° TFG is 24 mm, ensuring that a high efficiency of diffraction is achieved [19].

The performance of the fabricated 45° TFG is evaluated regarding the specification requirements for SEI. Figure 2 shows the measured relation between the diffraction angle and the illuminating wavelength (red dotted line) within a 40 nm spectral band (1530 – 1570 nm). A linear fitting (blue line) is also plotted in Fig. 2, which confirms that the diffraction angle and the illuminating wavelength has very good linear relation, with a correlation coefficient of 0.9994. The angular dispersion of the 45° TFG is thus estimated to be 0.054°/nm from the measured results, and the theoretically calculated angular dispersion value is 0.073°/nm according to Eq. (1), and the discrepancy is mainly due to the non-ideal tilt angle of the fabricated TFG.

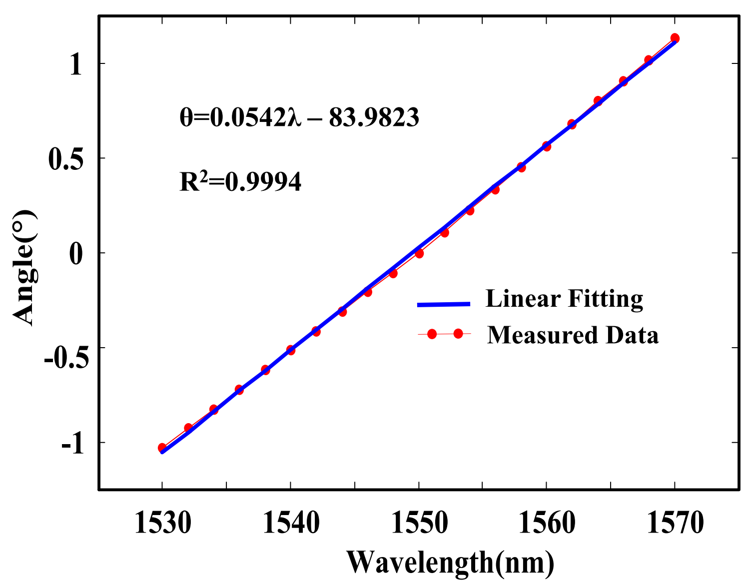

Figure 2. Measured diffraction angler as a function of illuminating wavelength for the fabricated 45° TFG (red-dotted line). Linear fitting result is also shown (blue line) to estimate the angular dispersion.

2.3 Diffraction efficiency of the 45° TFG

To measure the diffraction efficiency of the fabricated 45° TFG, an experiment is performed and the result is illustrated in Figure 3. As there is no Bragg reflection nor coupling to cladding modes in the 45° TFG, when the incident light propagates through the TFG, a portion of it is diffracted into open space while the remaining part keeps propagating in the fiber core. Therefore, diffraction efficiency of the TFG can be estimated by the ratio between the diffracted optical power and the sum of diffracted and propagated power.

As the 45° TFG has a strong sensitivity to the polarization state of the incident light, the power of lateral diffraction from the 45° TFG is largely dependent on the polarization state of the incident light with respect to the tilted grating structures [19]. Measured maximum diffraction efficiency at a properly controlled polarization state of incident light is shown in Figure 3. The average diffraction efficiency of the TFG is as high as 93.5% across the broad wavelength range from 1530 to 1560 nm, which is much higher compared to normal free-space diffraction gratings (up to 75%). This verifies the utility of the 45° TFG as a highly efficient in-fiber diffractive element.

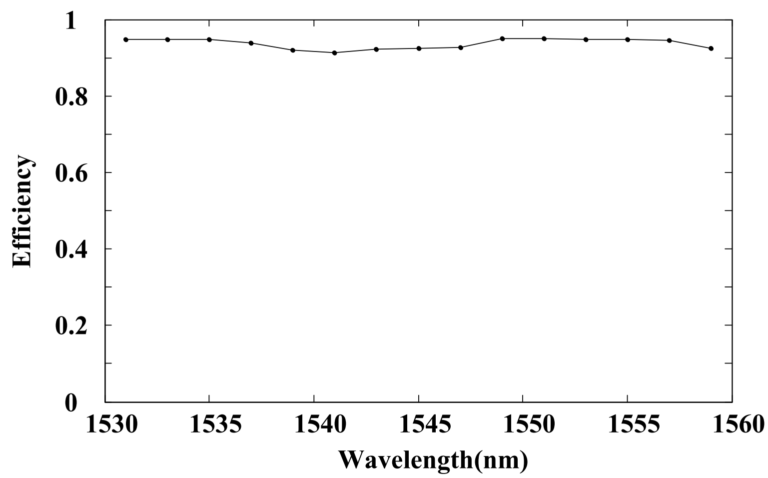

Figure 3. Measured maximum lateral diffraction efficiency of the TFG at a properly controlled polarization state.

The diffraction efficiency of a 45° TFG is also dependent on the length of the TFG [19]. The longer the TFG is, the higher the efficiency is, and vice versa. However, there is an exponential decay in propagation direction for the emitted intensity profile. Noting that the beam size of the diffracted light is determined by the active length of the TFG, which should be carefully selected to ensure good diffraction efficiency, and at the same time to avoid strong decay in the emitted intensity profile along the axial direction.

3. SYSTEM DESIGN AND EXPERIMENT

3.1 System design

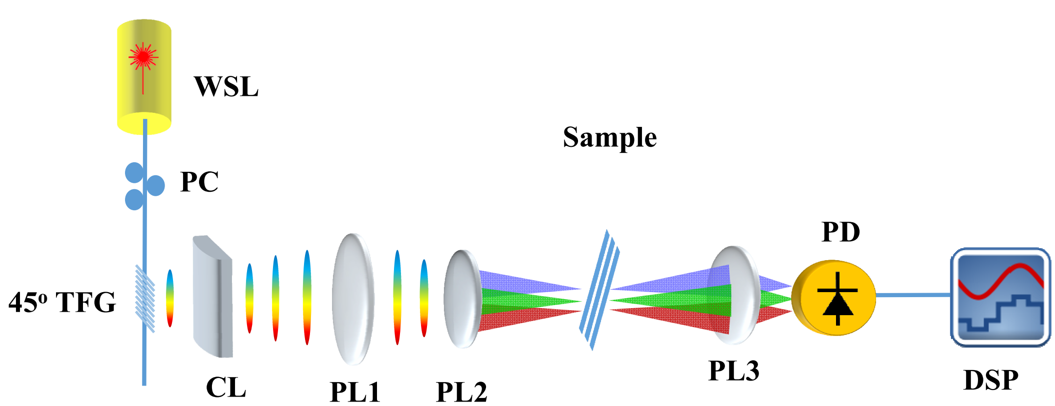

Figure 4. Schematic diagram of the SEI system based on a 45° TFG. WSL: wavelength swept laser, PC: polarization controller, TFG: tilted fiber grating, CL: cylindrical lens, PL: plano-convex lens, PD: photo-detector, DSP: digital signal processing.

The schematic diagram of the highly efficient SEI system based on a 45° TFG is shown in Figure 4. To provide broadband illuminating incident light, a wavelength swept laser (Agilent 8168E) was employed. Here a CCD camera or sophisticated optical spectrum analyser is not required for spectrum measurement, which can be done using a single-pixel photo-detector in a fast manner due to the use of a tunable laser rather than a broadband light source. Light from the laser was launched into the fiber containing the 45° TFG, where light was diffracted into open space from fiber core through one side of the 45° TFG. A polarization controller (PC) was employed in the system to maximize the overall diffraction efficiency as the lateral diffraction of light is strongly polarization-dependent. The use of 45° TFG as an in-fiber diffractive element can significantly reduce the volume of the imaging system, the optical insertion loss and the complexity of the system as well as increase the efficiency and stability of the SEI system.

To obtain vertical beam collimation, a cylindrical lens with a focal length of 20 mm was placed after the 45° TFG. The beam-width of the diffracted light is determined by the length of the 45° TFG. The diffracted light beams with different wavelengths are largely overlapped in space. Therefore, a lens set, consisting of two plano-convex lenses with focal lengths of 250 mm and 200 mm, respectively, separated by 190 mm, is required to focus different colours of light into separate spatial coordinates on the object plane to achieve the unique space-to-wavelength mapping. The lens set is placed 60mm after cylindrical lens. A custom-designed three-slot sample with a size of 2.0 mm by 2.0 mm is used as the test target and placed in the object plane. Our designed SEI system is operating in a transmission mode. After the light propagates through the target, the image was encoded onto the spectrum of the illuminating light thanks to the space-to-wavelength mapping. The spectrally encoded light is focused by another plano-convex lens and detected by a single pixel photo-detector (PD). The SEI image was reconstructed in the digital domain by decoding the spectrally encoded information. Compared to conventional SEI systems that operate in reflection mode where the diffraction gratings also collect the reflected light for imaging [3-6], our proposed SEI system in transmission mode has the advantages of zero reflection disturbance and low reception loss.

3.2 Experiment

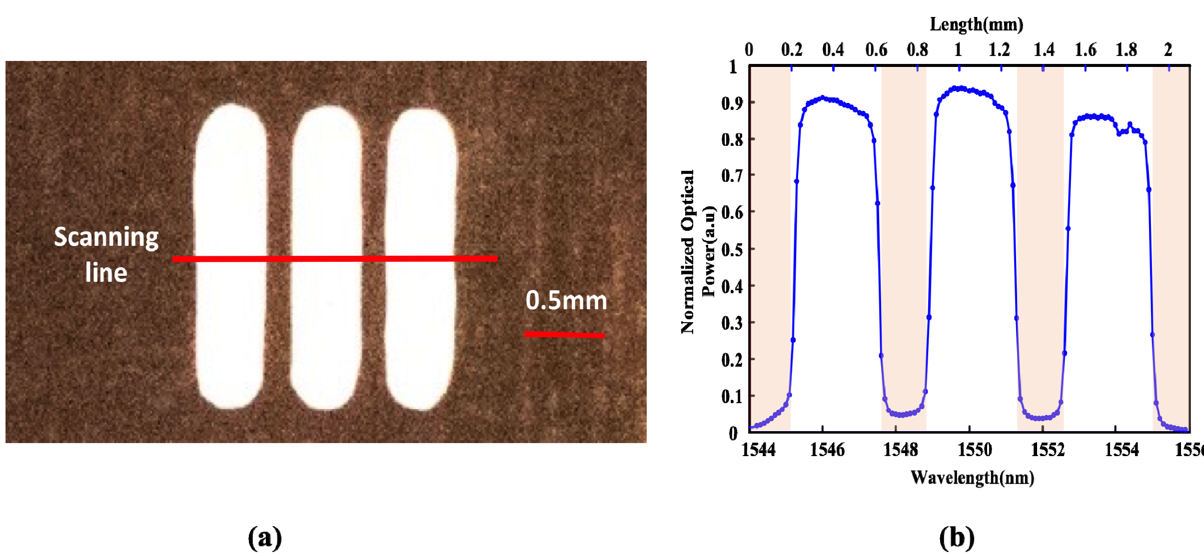

Figure 5. Imaging results using the TFG-based SEI system. (a) CCD image of the three-slot sample; (b) 1D line scan image of the sample captured by the SEI system. The lateral resolution is estimated to be 28 μm based on the point spread function of a sharp edge in the target.

We performed spectrally encoded imaging of the three-slot sample to verify our proposed 45° TFG-based SEI system. A CCD image of the custom-designed test target is shown in Figure 5(a). The transparent slots were surrounded by an opaque substrate. Brown shadow areas represent the opaque parts. Each slot has a width of 0.4 mm and is 0.2 mm apart from the adjacent slots. As a proof-of-concept demonstration, one dimensional (1D) line scan imaging was carried out by rapidly sweeping the laser wavelength. The step of wavelength scanning is 0.1 nm and the scanning range is 12 nm from

1544 to 1556 nm. The reconstructed 1D image of the three-slot sample is shown in Figure 5(b). The three-slot pattern is also shown in the Figure as a background. It clearly verifies that the reconstructed image matches well with the actual sample.

Lateral resolution of the 45° TFG-based SEI imaging can be estimated by measuring the point spread function (PSF) of a sharp slot edge in the target. In our proof-of-concept experiment, lateral resolution of the SEI system is estimated to be 28 μm. This lateral resolution can be easily improved by using a high-quality objective lens with shorter focal length and larger numerical aperture. Note that while only 1D line scan imaging is demonstrated in this work, 2D imaging can be achieved by either using a galvanometer minor to provide the other scanning axis or moving the sample in the vertical direction.

4. CONCLUSION

In summary, we proposed and experimentally demonstrated a new highly efficient, fiber-compatible, and cost-effective spectrally encoded imaging system based on a 45° TFG. As an in-fiber diffraction element, the 45° TFG replaces the bulky and lossy free-space diffraction gratings in conventional SEI systems. A 24-mm long 45° TFG was fabricated with its angular dispersion measured to be 0.054°/nm within a wide spectral range of 40nm (from 1530 to 1570 nm) and lateral diffraction efficiency measured to be as high as 93.5%. As a proof-of-concept demonstration, 1D line scan imaging of a custom-designed three-slot target was performed using the 45° TFG-based SEI system. The spatial resolution is measured to be 28 μm, which could be further improved by using an objective lens with shorter focal length and larger numerical aperture. Our design significantly reduces the volume, complexity and optical insertion loss and improves the efficiency and stability of the conventional SEI systems. The developed technique holds great promise in various applications where portable and low-cost SEI imaging systems are needed. In addition, as the 45° TFG-based diffraction element is inherently compatible with optical fibers that provide chromatic dispersion, it is particular attractive in ultrafast real-time SEI system based on dispersion-induced time-stretch dispersive Fourier transform, which will significantly increase the temporal resolution for ultrafast and high-throughput measurements.

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