In-Fibre Diffraction Grating for Beam Steering Indoor Optical Wireless Communication

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***Abstract*— In-fibre diffraction based on 45˚ tilted fibre grating enables high-efficiency wavelength-controlled laser beam steering for indoor optical wireless communication with unique features of low-loss and seamless integration with existing fibre-to-home networks. In addition, ultrafast user localization (50 million scans per second) based on real-time wavelength monitoring is demonstrated.**

***Keywords*— Beam steering, microwave photonics, optical diffraction, optical wireless communication, tilted fiber gratings, user localization**

I. Introduction

Optical diffraction elements (ODEs) have been widely applied in optical instrumentations. ODEs are also key components for various innovative applications based on optical spectral encoding. Some most recent examples include wavelength-controlled laser beam steering for indoor optical wireless communication [1] and wavelength-to-space mapping for ultrafast laser scanning [2, 3]. Most commonly used ODEs are free-space ruled or holographic diffraction gratings, which however suffer from some inherent drawbacks, such as bulky construction, limited diffraction efficiency (up to 75%) due to the inherent zeroth-order reflection in a non-Littrow configuration, and high coupling loss between free-space diffraction gratings and optical fibres in the systems, where both optical fibres and free-space diffraction gratings are required [1-3]. Therefore, a novel diffraction grating device that is inherently compatible with optical fibres is highly demanded.

A 45˚ tilted fibre grating (TFG) [4] has been proven as a good candidate for in-fibre polarizer [5] since only the p-polarized light can propagate through the 45˚ TFG with extremely low loss. On the other hand, if the incident light is purely s-polarized, all the light will be emitted from the side of fiber into free space due to strong tilted reflection, leading to polarization-dependent highly efficient in-fiber diffraction. This concept has been recently demonstrated in ultrafast high-resolution photonic time stretch imaging [6] and all-fiber laser beam steering based on wavelength tuning for indoor optical wireless transmission [7].

In infrared laser beam steering based indoor optical wireless communication systems [1, 6], mechanical free beam steering is implemented based on the use of diffracting gratings and wavelength tuning. To switch data transmission from one user to another, or to track and follow a moving user, quick and accurate user positioning is always essential to enable mobility in the system. Various user localization approaches have been proposed to locate and track mobile users. However, most of existing those localization systems

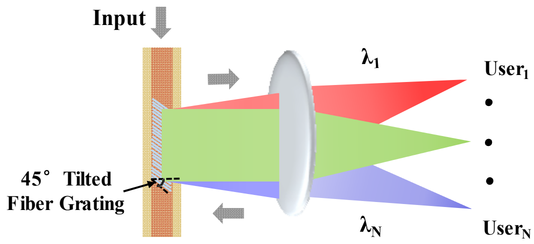

Fig. 1: Schematic showing the principle of using a 45° TFG as in-fibre diffraction grating for wavelength-tunning-based user positioning and laser beam steering.

are separate from the beam steering system making the whole wireless transmission system costly and complicated.

Recently, an endoscope compatible single fibre device that performs simultaneous real-time imaging and laser surgery by merging the high power laser for surgery with a broadband time-stretched pulsed laser source [8] for real-time detecting the image in wavelength domain via wavelength multiplexing has been demonstrated [9]. In this work, we propose and demonstrate a new "two-in-one" design for simultaneous ultrafast user positioning and beam steering using a single 45˚ TFG device. Thanks to one-to-one mapping between spatial coordinates of a remote user and the optical wavelengths, localization is achieved by monitoring the reflected wavelength from a given user, and beam steering and data transmission is then implemented by setting the correct optical carrier wavelength. A proof-of-concept experiment has been carried out to verify the proposed approach. User localization and 2.6 m free-space wireless transmission have been demonstrated with data rate up to 12 Gb/s per beam.

II. Principle

A. 45˚ tilted fibre grating

Unlike normal fiber Bragg gratings (FBGs), where grating structures are perpendicular to the fibre axis, titled fibre Bragg gratings have grating elements with a tilted angle with respect to the fibre axis [4]. A small tilted angle or excessively tilted fibre gratings could couple the transmitted light inside the fiber core into backward or forward propagating cladding modes, resulting in multiple resonances at the transmission spectrum of the core mode signal. This feature makes TFGs an excellent candidate for sensing applications [10, 11].

On the other hand, a 45° TFG enables light coupling from fibre core mode into radiation modes due to its largely

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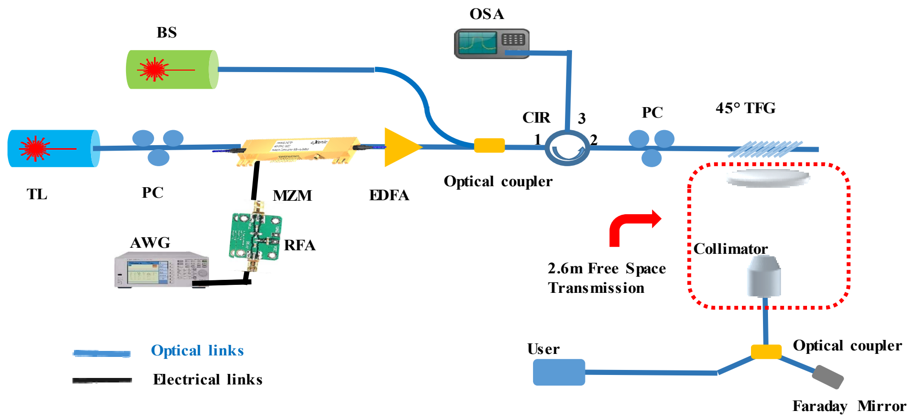

Fig. 2: Schematic of simultaneous user localization and optical beam steering for indoor optical wireless communication using a single 45° TFG device. TL: tunable laser; BS: broadband optical source; AWG: Arbitrary Waveform Generator; RF: Radio Frequency; MZM: Mach-Zehnder Modulator; EDFA: Erbium Doped Fiber Amplifier; 45° TFG: 45° Tilted Fiber Grating; RFA: RF amplifier. CIR: optical circulator.

(yet not excessively) tilted facet angle. Therefore, broadband lateral light diffraction out of fibre core is produced. It is worth noting that the lateral diffraction from the 45° TFG is strongly wavelength-dependent due to the phase matching condition. The angular dispersion of the TFG with a tilted angle of θ is given by [5]

$$D = \frac{d\theta(\lambda)}{d\lambda} = \sin(2\theta)\frac{1}{\lambda} \tag{1}$$

It is evident that the tilt angle of 45° achieves the maximum angular dispersion [12]. A 45° TFG can be used to achieve passive and mechanical free optical beam steering by changing the incident optical wavelength thanks to its extremely wide (more than 100 nm) diffraction window. Thanks to optical path reversibility, the 45° TFG can also work as a good optical receiver for full duplex optical wireless communication [7], as shown in Fig. 1.

B. *User localization based on real-time wavelength interrogation*

To achieve simultaneous user localization, specific optical wavelength that is assigned to that user needs to be identified in real-time manner. This can be implemented by adding another broadband optical source via an optical fibre coupler/combiner in a wavelength multiplexing structure. In the meanwhile, a fibre Faraday mirror is added to each individual user site, which reflects a narrow-band optical signal back to the access point routed by an optical circulator, as shown in Fig. 2. Considering the reception bandwidth of each user is around 50 GHz in existing beam steering system [7], the reflected optical wavelength that determines unique position of the user can be accurately measured using an optical spectrum analyser (OSA) in the access point.

III. Expriments

A 45° TFG was fabricated using the typical UV-light phase mask method. In order to produce the required 45° tilted grating structures, the phase mask is tilted at an angle of 33.7° with respect to the fiber axis. The angular dispersion of the fabricated 45° TFG is estimated to be 0.053°/nm and its diffraction efficiency is as high as 93.5% [7].

To verify the utility of a 45° TFG in simultaneous user positioning and laser beam steering based on wavelength encoding, a proof-of-concept experiment based on the setup shown in Fig. 2 is carried out. A broadband optical source (amplified spontaneous emission from an erbium-doped fibre amplifier) emits broadband light (1530 to 1570 nm) into the 45° TFG. Light is then diffracted into free space forming a spectral shower pointing at various locations. Note that only 1D scanning is demonstrated here. If a particular user is being served, part of the received optical signal will be reflected by the Faraday mirror associated to each individual users. Note that the reflected optical signal has the exactly same wavelength as the optical signal received by the same user. The reflected narrow-band optical signal is captured by the 45° TFG, which can serve as a perfect optical receiver as well as emitter thanks to reversibility of light path. In the experiment, a single-user scenario is studied. The reflected optical wavelength is measured as 1545.2 nm using OSA.

Wireless data transmission serving the located user is then implemented using a continuous wave optical carrier of 1545.2 nm modulated by RF signals with encoded data stream at a Mach Zehnder modulator (MZM).An orthogonal frequency-division multiplexing (OFDM) 16 QAM is first created offline in MATLAB. The complex OFDM symbols created in MATLAB are used to generate a 2.4 GHz bandwidth signal through an arbitrary waveform generator (AWG, Tektronix 7122C) at an intermediate frequency (IF) of 2 GHz. The AWG operates based on 10-bit digital-to-analog conversion (DAC) with a sampling rate of 12 GS/s. Data blocks contains 16-QAM modulated data offers an aggregate data rate of 9.6 Gb/s.

After 2.6 m free-space transmission, which is a typical propagation distance in indoor environment, the received light is detected by a 3 GHz photodetector (PD) at the remote user site. The recovered RF signal is amplified by a second RFA and sampled by a 100 GS/s real-time digital oscilloscope (OSC, Tektronix DPO72304DX). Recorded data is analysed using MATLAB for off-line digital data processing. The constellation of the received 16-QAM OFDM signal for the same user with allocated optical wavelength of 1545.2 nm is shown in Fig. 3. Here the received optical power is -2 dBm. The error vector magnitude (EVM) is estimated as 11.8%.

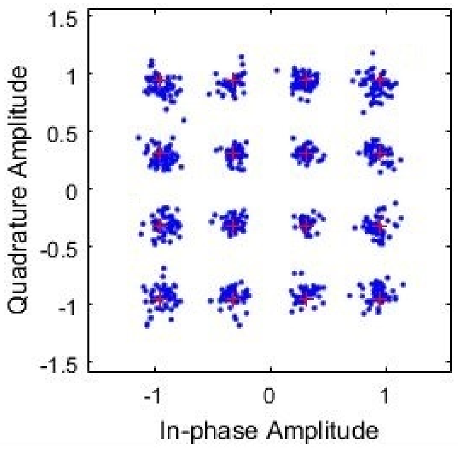

Fig. 3: Constellation of OFDM 16-QAM signal received by the selected user with allocated optical wavelength of 1545.2 nm.

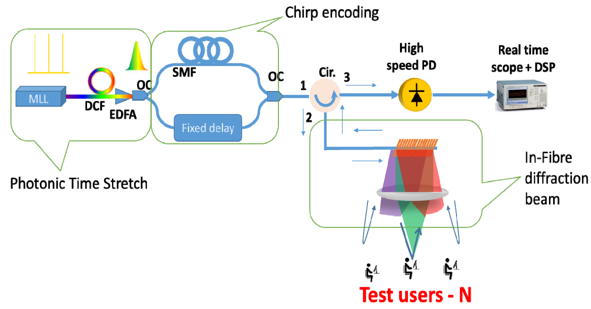

Fig. 4: Schematic of the proposed real-time wavelength interrogation system. MLL: Mode Locked laser, DCF: Dispersion compensating Fibre, EDFA: Optical Amplifier, OC: Optical coupler/combiner, Cir.: Optical Circulator, PD: Photodetector, DSP: Digital signal processing toolbox with storage.

Note that the optical spectrum analyser falls short in fast wavelength measurement due to its mechanical scanning nature. In order to achieve ultrafast wavelength interrogation for real-time user localisation, we have demonstrated that the use of a time stretched broadband pulsed source can serve as a fast wavelength swept source for real-time user scanning [13]. However, the reflected scanning signal from a particular user has a very limited time duration of a few nanoseconds. Determining the instantaneous optical wavelength within such a short period is a true challenge. To address this challenge, we used spectral pre-coding approach where a chirp inducing unbalanced Mach-Zehnder interferometric (MZI) structure, as shown in Fig. 4, with one arm being optical delay line that determines the offset of the chirp while the other arm being a dispersive fibre whose length determines the chirp slope. Instead of directly measuring the instantaneous optical wavelength, instantaneous radio frequency (RF) detection is implemented, which can be converted to optical wavelength values [13].

IV. Conclusions

Unlike normal fibre Bragg gratings, a 45° TFG can serve as a perfect in-fibre diffraction grating device featuring low loss, high diffraction efficiency and inherent fibre compatibility. In this work, we report simultaneous user positioning and laser beam steering in indoor optical wireless communication using the same 45° TFG based on wavelength encoding. Compared to existing user localization solutions, which always use separate components with beam steering, this novel all-fibre two-in-one design simplifies the system and holds great potential in indoor optical wireless transmission with enhanced mobility.

We have also demonstrated a novel approach of ultrafast user localization scheme (up to tens of millions scanning per second) that can be used for optical indoor infrared wireless communication system with photonic time stretch method along with unbalanced MZI to establish wavelength-RF frequency mapping to determine user's spatial location with TFBG system.

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