In-Fibre Polarizer for Mid-Infrared Fibre Lasers Based on 45° Tilted Fluoride Fibre Bragg Grating

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Abstract: We report the femtosecond laser inscription of a 45° tilted fibre Bragg grating (TFBG) into ZBLAN fibre. Integrating this TFBG into a mid-IR fibre laser cavity resulted in 20.5 dB output polarization extinction ratio. © 2018 The Author(s)
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1. Introduction

Mid-infrared (mid-IR) fibre lasers developed using rare-earth doped fibres offer significant potential for establishing high brightness diffraction-limited mid-IR sources. However, the output of all-fibre mid-IR lasers to date is often unpolarized due to the lack of polarization selective components in the cavity. Linearly polarized mid-IR fibre lasers with emission wavelengths in the 2-3 μm range are useful light sources in numerous applications such as supercontinuum generation and sensing. In order to achieve linearly polarized operation, in-fibre polarizers are preferred over bulk optic polarizers due to their fully fibre integrated nature that offers alignment-free mid-IR laser systems with no free-space sections.

Recently, Zhou *et al.* fabricated a 45° TFBG in silica fibre with strong polarization extinction ratio (PER), which was shown to be an ideal polarizer to achieve linearly polarized near-IR laser operation [1]. However, this concept needs to be extended to soft glasses to implement in-fibre polarizers for mid-IR lasers. Unlike conventional fibre Bragg gratings (FBGs), in TFBGs the planes of modified refractive indices are tilted with respect to the fibre axis. In this paper, we demonstrate TFBG fabrication using the femtosecond (fs) laser direct-write technique [2]. This process involves a nonlinearly induced refractive index modification which is typically in the order of 10^{-4} [3]. Hence, the tangent of the Brewster angle for a periodic grating pattern with different refractive indices, is the ratio of two refractive indices, which is approximately equal to 1, corresponding to an angle of 45°. Therefore, when the periodic grating structures are oriented at 45°, the forward propagating *p*-polarized light will propagate through the TFBG with minimum loss, whereas the tilted structures reflect the *s*-polarized light as radiation modes [1, 4]. To demonstrate the applications of our fs-laser inscribed polarizer, we integrate the TFBG into an all-fibre Ho^{3+}:Pr^{3+} co-doped ZBLAN fibre laser cavity, producing a linearly polarized output at 2843 nm.

2. Tilted Fibre-Bragg Grating Fabrication

The inscription of the TFBG was achieved using a Ti:Sapphire femtosecond laser (800 nm, 1 kHz repetition rate, 115 fs pulse duration). The 147 nJ laser pulses were focused into the core of an active double-clad ZBLAN fluoride fibre, with a core diameter of 13 μm and a numerical aperture (NA) of 0.13 using a 20x oil-immersion microscope objective. The fibre was mounted onto a programmable air-bearing translation stage to move the fibre in a 45° tilted rectangular pattern transversely through the focus of the laser beam and the separation between two parallel planes was, Λ= 1.97 μm [5]. Fig. 1 shows a schematic representation of the inscription process and a differential interference contrast (DIC) microscopic image of the TFBG within the core of the fibre. The physical length of the inscribed TFBG was 16 mm.

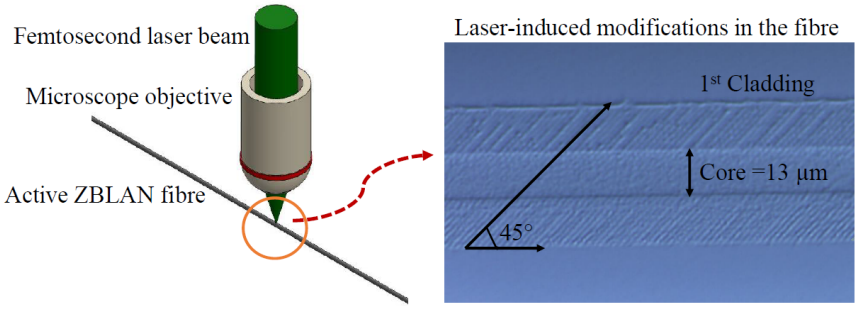

Figure 1. Schematic of the femtosecond laser direct-write process and microscopic image of the TFBG (top-view).

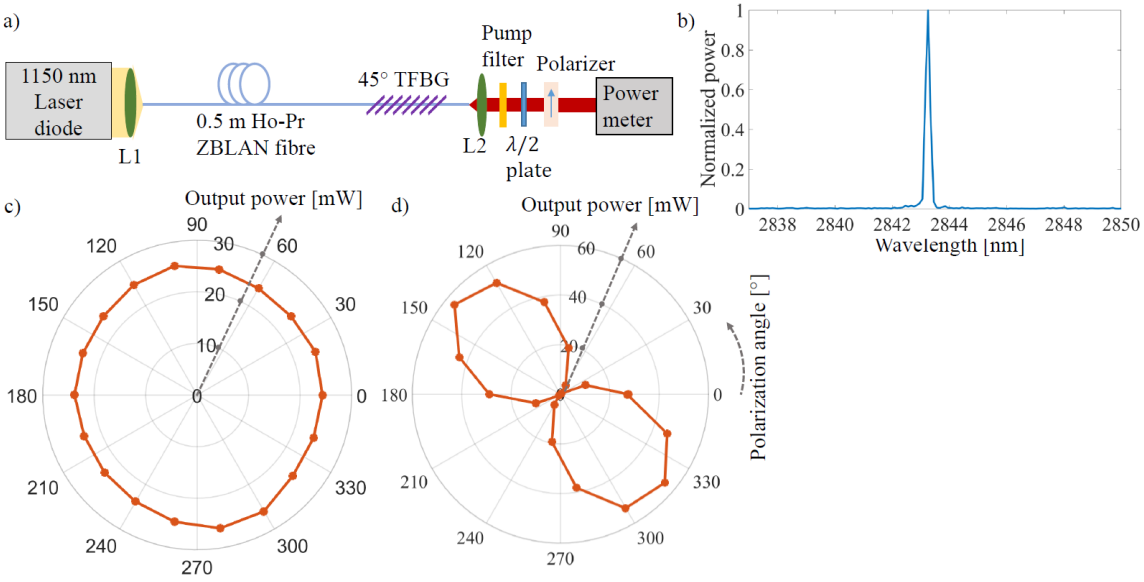

Figure 2. (a) Experimental setup (b) Free-running spectrum of the mid-IR Fabry-Perot laser system (c) PER response of the laser without 45° TFBG and (d) PER response of the laser with 45° TFBG.

3. Polarization Measurements of a Mid-IR Laser with Intracavity TFBG

A Fabry-Perot laser cavity was realized using a 0.5 m long section of double-clad Ho^{3+}:Pr^{3+} co-doped ZBLAN fibre (molar concentration of 35000 : 2500 ppm). The cavity was formed by perpendicularly cleaving the input and output ends of the fibre, and the 4% Fresnel reflection from both the ends acted as low reflectivity broadband mirrors. A high-power multi-mode 1150 nm laser diode was used to pump the active fibre. A free-running lasing peak was observed at 2843 nm from the diode pumped Fabry-Perot laser cavity as shown in Fig. 2(b).

PER is a fundamental parameter to quantify the output polarization state of the mid-IR laser with a 45° TFBG. Quantitatively, the PER is the ratio of maximum and minimum power transmission with respect to all polarization states [1, 4]. Two different laser configurations were analyzed in terms of their PER. The first setup employed a Fabry-Perot mid-IR laser cavity without a TFBG and the latter incorporated a TFBG as a polarization dependent element. In both the cases, the experiment setup consisted of the continuous wave (CW) mid-IR laser cavity followed by a collimating lens, a filter to remove any residual pump light, a half-wave plate, a bulk polarizer and a power meter as depicted in Fig. 2(a). The half-wave plate was used to rotate the polarization from the laser cavity which in combination with the free-space polarizer enabled measurement of the polarization characteristics of the fibre laser. Figs. 2(c) and 2(d) show the PER response of the CW laser with and without the 45° TFBG. Fig. 2(c) indicates that the CW laser output from the Fabry-Perot laser cavity is nearly unpolarized without the 45° TFBG. From Fig. 2(d), we can observe that the maximum transmission is reached at angles around 140° and 320°, while it becomes almost zero at the orthogonal positions 50° and 230°. The laser output with the TFBG shows a maximum PER of 20.5 dB.

In conclusion, we have experimentally demonstrated the polarizing behaviour of a femtosecond laser inscribed 45° TFBG in fluoride fibre. To the best of our knowledge, this is the first demonstration of a linearly polarized all-fibre CW laser system using an in-fibre polarizer in the mid-IR region. Efforts are underway to optimize the femtosecond laser inscription process and to increase the grating length further to obtain an even higher PER.

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