Thulium-doped fibre laser with FBG inscribed by plane-by-plane, direct-write, femtosecond laser methods

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# Introduction

Fibre lasers are increasingly attractive coherent light sources for many applications given their high efficiency, excellent output beam quality, compact structure, low maintenance requirements and spectral versatility. The inscription of fibre Bragg gratings (FBGs) resonator mirrors directly into the active fibre would improve the laser compactness, and offer further flexibility in design, as the laser resonator is fully integrated into a monolithic structure. In addition, it potentially improves the durability of the fibre laser as there are no splices to the FBGs, which could result in failure under high optical pump and/or laser signal power.

FBGs were inscribed in active fibres mainly using femtosecond lasers either using the phase mask or the Point-by-Point inscription methods; however, both methods have disadvantages. The former method gives little control of the grating’s special extent, and writing in the fibre cladding is unavoidable increasing loss. The latter method demands near-perfect alignment to the fibre’s longitudinal axis if gratings are to be reproduced. However, in practice limited controllability of the inscription parameters usually produces a significant and unpredictable polarization dependent loss and wavelength shift that directly influence the performance of the fibre laser cavity, particularly if the fibre is multi-mode.

On the other hand, the new, direct-write, plane-by-plane (*Pl-by-Pl*) inscription method is an attractive way to tailor FBGs in active fibres for fibre lasers. The core is modified with uniform refractive index planes/sheets perpendicular to the fibre axis, with controlled grating period and spatial extent (width, depth and length) in the core so that lasing is controlled even if the fibre is not single-mode at the wavelength of operation. In this way inscription can be limited precisely to the core without perturbation of the cladding, in contrast to phase mask inscription, and this helps control interaction with cladding modes. As with other methods of femtosecond laser inscription there is no need to strip the polymer coating for FBG inscription. There is excellent control of polarization dependent loss and minimal polarization induced wavelength shifts (a few pm) even for strong, high reflectivity gratings. This is an important advantage of the *Pl-by-Pl* method. Finally, one may readily create tilted gratings with an exact reflection angle, unlike the aforementioned methods.

We have used Thulium doped fibre fabricated by the Institute of Photonics and Electronics in the Czech Academy of Science and have developed different laser (Fabry-Perot) cavities using FBG pairs inscribed directly in to the fibre using the *Pl-by-Pl* inscription method in such a way as to minimize the inscription losses, whereas samples of 45o TFBGs for PDL characterization and future work on mode locking applications have also been produced.

# State of the art

FBG inscription directly into non-photosensitive, rare-earth-doped fibres has relied on material modifications using femtosecond lasers. This is because femtosecond laser pulses induce refractive index modifications through multi-photon absorption, if the fibre is transparent at the wavelength of laser operation and the pulse duration is on a femtosecond time scale. Under these conditions the focussed laser pulse produces index changes without the need to pre-process a material and there are essentially no limitations on which materials may be laser modified. The most common used femtosecond laser inscription methods for fibre lasers are the phase mask inscription method and the point-by-point, a brief schematic diagram of both inscription methods shown in Fig. 1 (a) and (b), respectively. However, both inscription methods have advantages and disadvantages. Some of the advantages of the phase mask method are the short inscription time, high repeatability and the alignment effort. However, each phase mask is limited to a single Bragg wavelength inscription. On the other hand, the point-by-point method offers high flexibility with regard to the grating period but requires significant alignment effort, producing high grating loss whilst also being limited by repeatability issues. Table 1 summarises some characteristics of the two inscription methods.

**Table 1:** Summarise characteristics of the phase mask and point-by-point femtosecond laser inscription methods.

|  |  |  |
| --- | --- | --- |
|  | Phase Mask | Point-by-Point |
| Inscription time | Few seconds | Few seconds |
| Loss | - | High |
| Period of the gratings | Constant | Flexible |
| Repeatability | High | Low |
| Chirping | Yes (extra optics required) | Yes |
| Alignment effort | Medium | High |

a) b)

**Fig. 1:** Schematic diagram of common femtosecond laser inscription methods a) Phase mask b) Point-by-Point.

# Novelty of your work

Academics from the Photonics and Optical Sensors Research Laboratory, Cyprus University of Technology invented and recently patented (currently licenced by Lumoscribe LTD) a new femtosecond laser inscription method for fibre grating inscription; the direct-write, plane-by-plane inscription method. This offers excellent controllability and flexibility of the grating inscription parameters, such as reflectivity, loss, period, chirp, length of the FBG, whilst is also relaxing the alignment effort compared to the point-by-point method. The particular inscription method looks very promising for the development of monolithic fibre lasers structures and fibre laser inscription in active rare-earth doped fibres.

# Future perspectives in the field

The future perspectives of both organisations, Cyprus University of Technology and Institute of Photonics and Electronics in the Czech Academy of Science, are the development of more advanced monolithic structures operating over extended wavelength ranges, including the mid-IR, realising high-power and mode-locked fibre lasers operating in this range.

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