# Femtosecond laser direct inscription of plane-by-plane tilted fiber Bragg gratings

**Andreas Ioannou[1, 2], Antreas Theodosiou[2], Christophe Caucheteur[1], Kyriacos Kalli[2]**
*[1] Electromagnetism and Telecommunication Department, Faculté Polytechnique de Mons, Boulevard Dolez 31, 7000 Mons, Belgium*
*[2] Nanophotonics Research Laboratory, Cyprus University of Technology, 31 Archbishop Kyprianos Street, 3036 Limassol, Cyprus*
**Corresponding author: andrg.ion@gmail.com*

**Abstract:** We report a flexible, plane-by-plane direct write inscription method for the development of tailored, tilted fiber Bragg gratings (TFBGs) using a femtosecond laser; The grating planes are controlled to minimize birefringence, with precise control over the wavelength location and strength of cladding modes

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## 1. Introduction

Tilted fiber Bragg Grating (TFBG) technology has seen a huge rise in interest during the last decade, mostly due to its lab-around-fiber sensing capabilities. In common with uniform FBGs, TFBGs are created when a photo-inscription process takes place along the propagation axis of the optical fiber core, thereby inducing a permanent and periodic modulation of its refractive index. In addition to the core mode coupling at the Bragg wavelength, controlled tilting of the refractive index modulation with respect to the optical fiber axis promotes light coupling from the core to numerous tens (not to say hundreds depending on the tilt angle value [1]) of backward-propagating narrowband cladding modes, typically viewed in transmission. According to the grating's phase matching conditions, each cladding mode has its own effective refractive index and will be sensitive to SRI changes in a narrow range around that particular value. . With the inherent birefringence resulting from the tilted grating planes, which break the cylindrical symmetry of the fiber, TFBGs have been used in numerous applications, including in-fiber polarizers, bend and twist sensors, to name just a few examples. More specifically, for tilt angle values above 20°, excitation of cladding modes in the range 1340-1440 nm. These modes are characterized by an effective refractive index value close to 1. Hence, as already reported in [2], this yields the opportunity to use such highly tilted gratings for refractometry in gaseous media.

## 2. Experiments and results

The TFBGs were inscribed in FiberCore photosensitive single-mode optical fiber using the direct write plane-by-plane femtosecond laser inscription method [3]; a flexible inscription approach offering control of the grating period, and the length, width and depth of the grating planes. Fibre samples were mounted on highly accurate air-bearing translation stages (Aerotech) allowing for controlled movement during the inscription procedure. The femtosecond laser system (HighQ laser femtoREGEN) operated at 517 nm generating pulses of 220 fs duration, and guided through a long working distance objective x50 (Mitutoyo) from above and focused inside the fiber using a third translation stage. The laser inscribed planes had a width of ~800 nm; whereas the other dimensions were controlled by suitable translation stage motion, resulting in a 3-dimensional refractive index change with controlled plane length, depth and grating-plane angle. The energy of pulses at the exit of the laser was measured as 100 nJ per pulse, and with a repetition rate of 50 kHz. Selectively modified structures were inscribed directly into the fibers in a repeatable manner. The jacket of the fiber was not removed, thus retaining the fiber's integrity throughout the initial laser processing [4]. This is especially interesting when such devices are used for applications in telecommunications or mechanical sensing.

The transmission spectrum of a 10-mm, 7° TFBG is shown in Fig. 1. We have also studied the effect of the tilt angle on the grating spectrum. Figure 3 shows the spectra obtained for a tilt angle of 0, 7, 14 and 21°, respectively. As observed for conventional TFBGs [1, 4], the depth of the Bragg and cladding mode resonances decreases as the tilt angle value increases. This technique highlights an important difference compared to the classical inscription methods: as we rely on a direct writing process, the Bragg wavelength does not shift with the tilt angle value, allowing for precise control in its positioning.

The role of laser-induced birefringence has been considered for grating planes corresponding to the fiber core diameter, which offers the strongest cladding mode resonances. Here a polarization controller was placed in the measurement set-up between the optical source and the grating. For all the tested TFBGs, the birefringence is manifested by a maximum shift of the Bragg wavelength of only 8 pm, which is more than an order a magnitude improvement over other femtosecond laser FBG inscription and may be further reduced by controlling the laser inscription fluence. Another interesting feature of the direct write method is the ability to produce high order gratings operating at ~1550 nm, allowing for the study of the behavior of higher order cladding modes located at lower wavelengths. Figure 2 depicts the transmitted amplitude spectra of a 4th and 10th order grating at 1580 nm and 1550 nm, respectively. We observe that the wavelength range over which the cladding mode resonances of a particular grating order extend decreases with the grating order. This arises because the wavelength spacing between neighboring cladding mode resonances decreases, as shown in the insets of Fig. 2.

Finally, a 10th order TFBG was immersed in a salted water mixture whose refractive index was slightly modified by adding small quantities of water. The refractive index of solution was measured with a handheld Abbe refractometer accurate to $10^{-4}$ RIU. The applied demodulation technique was based on the computation of the wavelength shift of the most sensitive cladding mode resonance in the grating spectrum. Figure 4 depicts the obtained results for the 10th, 11th and 12th grating orders, respectively. A linear regression of the raw data yields a refractometric sensitivity of ~28 nm/RIU for the cladding mode resonance at 1506 nm in the 10th order grating. This sensitivity decreases to ~13 nm/RIU at 1257 nm for the 12th order grating. This differential refractometric sensitivity between grating orders can be beneficial in the process of ultrafine refractometry, as reported in [6]. Moreover, from the obtained data, it is expected that the sensitivity can increase at longer wavelengths (9th order grating at ~1720 nm for instance) provided that adequate source and optical spectrum analyzer are used to record them.

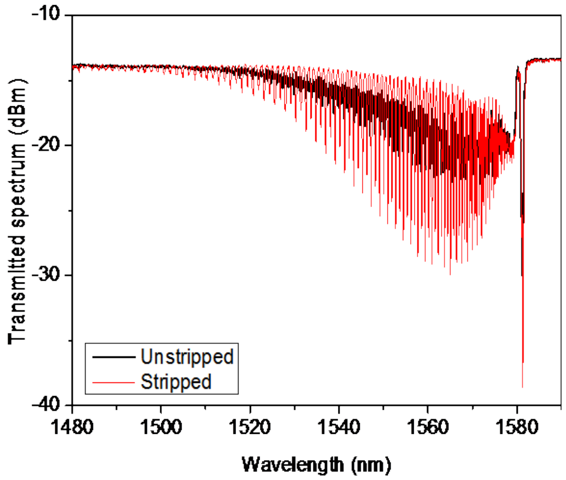

Fig. 1 Transmitted power spectrum of a 7° TFBG with a Bragg peak of ~25dB and a maximum cladding mode intensity of ~15dBm.

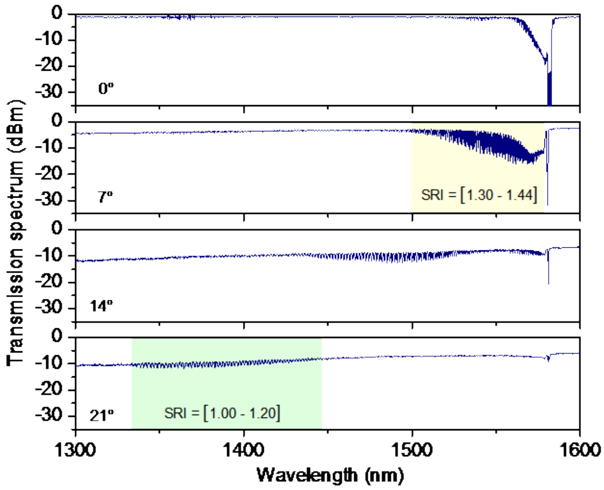

Fig. 2 Transmitted power spectra of 0, 7, 14 and 21° TFBGs.

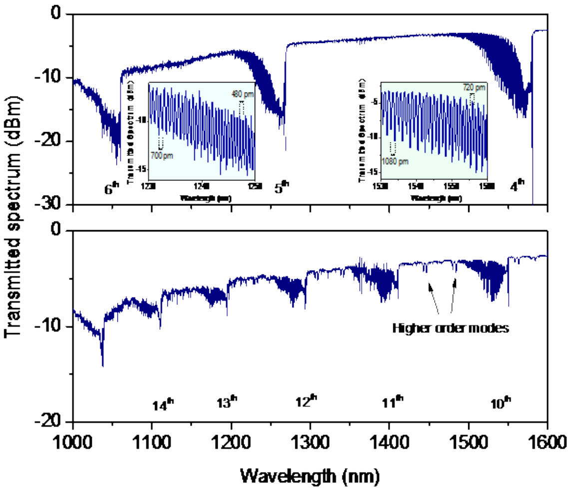

Fig. 3 The 4th and the 10th order gratings at 1580 nm and 1550 nm, respectively, displaying higher order modes at shorter wavelengths. Inset: zoom on the 4th and 5th orders to see the evolution of the wavelength spacing between neighboring cladding modes.

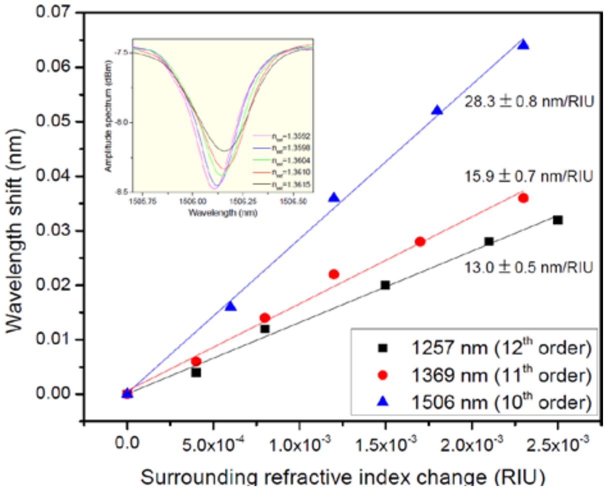

Fig. 4 Refractometric sensitivity as a function of the grating order. Inset: wavelength shift of the most sensitive cladding mode resonance for the 10th order grating.

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