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Sensing capabilities of higher order cladding modes

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ABSTRACT

In this work, 5-mm long TFBGs were inscribed in photosensitive single-mode optical fiber using the direct writing plane-by-plane femtosecond laser inscription method; a flexible inscription approach that enables absolute control of the grating period, length, angle, width and depth of the grating planes. This new fabrication method brings important differences compared to classical inscription methods. Firstly, these gratings exhibit very low photo-induced birefringence (measured ~8pm) and as we rely on a direct writing process, the tilt angle of the inscribed grating does not affect the Bragg wavelength, allowing for precise positioning. In addition, this method enables the high order grating production, allowing a behavioral study of higher order cladding modes located at lower wavelengths in the 1200 – 1600 nm range. 8^{th} order gratings were produced with cladding and Bragg mode resonances in the C+L bands. The temperature and strain sensitivities were measured for both the Bragg and higher order cladding modes, yielding an exceptional performance. The higher order modes exhibit a negative axial strain, up to -1.99nm (more than two times higher than the standard Bragg peaks) and a solid temperature sensitivity of 10.25 pm/°C : At the same time, for the designed order cladding modes (of the 8^{th}) the refractive index sensitivity is measured at 22 nm/RIU.

Keywords: Tilted fiber Bragg gratings, higher order cladding modes, femtosecond, optical fiber sensors

1. INTRODUCTION

Tilted fiber Bragg Grating (TFBG) technology enables lab-around-fiber sensing capabilities, a technology presenting significant benefits and of increasing interest to the wider community. As with uniform FBGs, TFBGs are created when a photo-inscription process takes place along the propagation axis of the optical fiber core, inducing a permanent and periodic refractive index modulation. In addition to the core mode coupling at the Bragg wavelength, coupling from core to cladding modes can be achieved by introducing tilt relative to the index modulation. This tilt induces birefringence and as a consequence breaks the cylindrical symmetry of the optical fiber [1]. According to the grating's phase matching conditions, each cladding mode has its own effective refractive index, sensitive to surrounding refractive index (SRI) changes in a narrow region around that particular index value. We have recently reported that TFBGs made using the Pl-by-Pl technique, offers a great flexibility in the periodicity of the refractive index modulation, and allow the presence of higher order cladding mode resonances. [2]. Excitation of these modes has also been achieved using long period fiber gratings (LPFGs)[3] with a periodicity in the range of 25 μm or

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using eccentric gratings usually made with the PbP technique [4][5]. We focus on even higher order cladding modes, which we will call in the following ultra-high order cladding modes. They can be obtained with a higher-order TFBG (n>5 where n is the grating order) produced in the C+L bands. Their location is at ~500 nm from their corresponding Bragg peak, depending on the designed TFBG order. We study the dependence of these modes on temperature and axial strain changes and show that they are strongly different from those of lower order modes located in the same wavelength range. On top of that, the sensing device can perform refractive index measurements with the designed order cladding modes as well. Figure 1 shows the 8^{th} order TFBG under study.

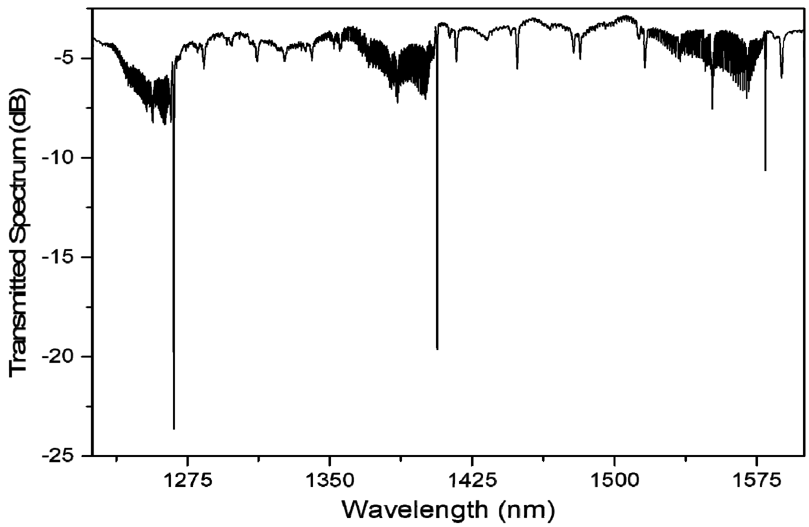

Fig. 1 Transmitted power spectrum of an 8^{th} 7° TFBG with a Bragg peak at 1580nm. Lower order grating orders appears bellow 1500nm. Higher order cladding modes are also present.

2. TFBG FABRICATION

The TFBGs were inscribed at the Cyprus University of Technology, in FiberCore photosensitive single-mode optical fiber using the direct write plane-by-plane femtosecond laser inscription method [6]; 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 fiber jacket was not removed, thus retaining the fiber's integrity throughout the initial laser processing [7]. This is especially interesting when such devices are used for applications in telecommunications or mechanical sensing. Obviously for refractometry applications, the coating is removed. Figure 1 shows the inscription setup.The TFBG transmitted amplitude spectra were recorded using a broadband light source and an optical spectrum analyzer (OSA

Yokogawa AQ6371C, 20 pm resolution). An in-line polarizer was placed in front of the TFBGs for measurement with polarized light.

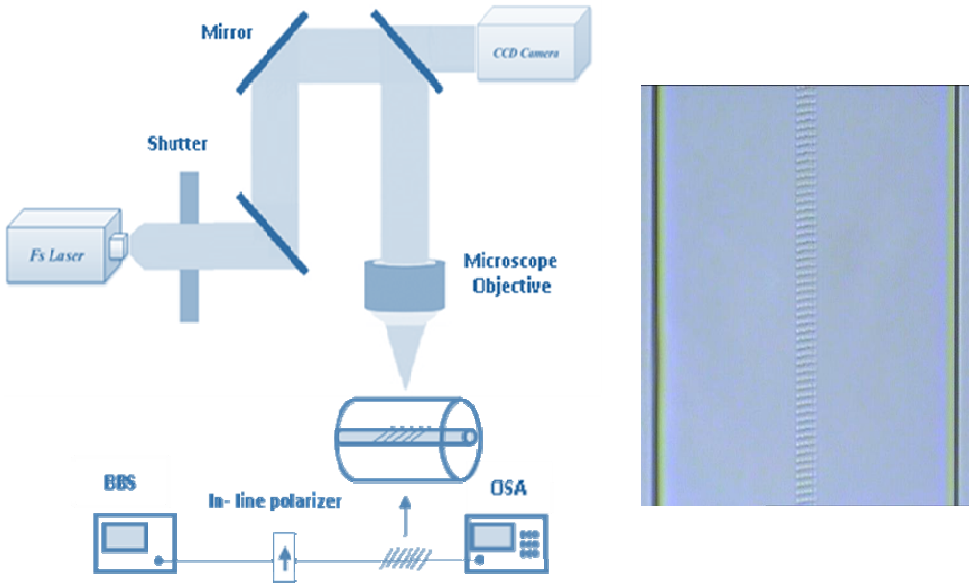

Fig. 2 a) Femtosecond laser inscription set up. Charged couple device (CCD), broadband light source (BBS), optical spectrum analyzer (OSA), b) Microscope image of a 7° TFBGs in fiber with core diameter 8.2 µm.

3. SENSITIVITY MEASUREMENTS

3.1 Temperature sensing

For temperature measurements, the grating was placed in an oven accurate to 0.1 °C. Figure 3 presents the obtained results for the Bragg resonance of the 8th, 9th and 10th grating orders and the closest mode resonances belonging to higher grating orders.

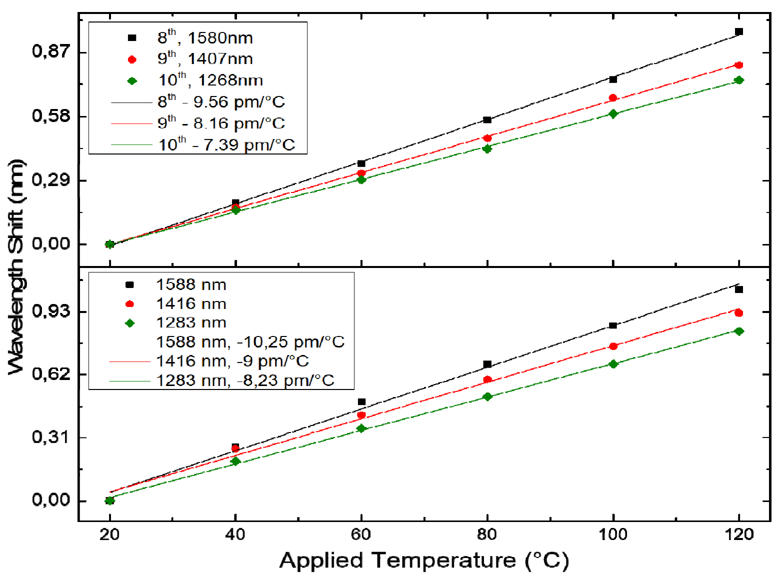

Fig. 3 Temperature sensitivities of the Bragg modes (top) and their corresponding closest higher order modes (down)

Using a linear regression on the measurement data we got sensitivities of 9.56 pm/°C, 8.16 pm/°C and 7.396 pm/°C from the 8th, 9th and 10th Bragg peaks respectively. Similarly from each of their closest mode resonances the sensitivities were 10.25 pm/°C, 9 pm/°C and 8.23 pm/°C.

3.2 Axial strain sensitivity

Figure 4 focuses on the strain results. To obtain them, the fiber containing the TFBG was fixed on a translation stage accurate to 10 μm. Strain was applied from 0-1000με with 100 steps με. Like the temperature sensitivity evaluation the the Bragg resonance of the 8th, 9th and 10th grating orders and the closest mode resonances belonging to higher grating orders was examined.

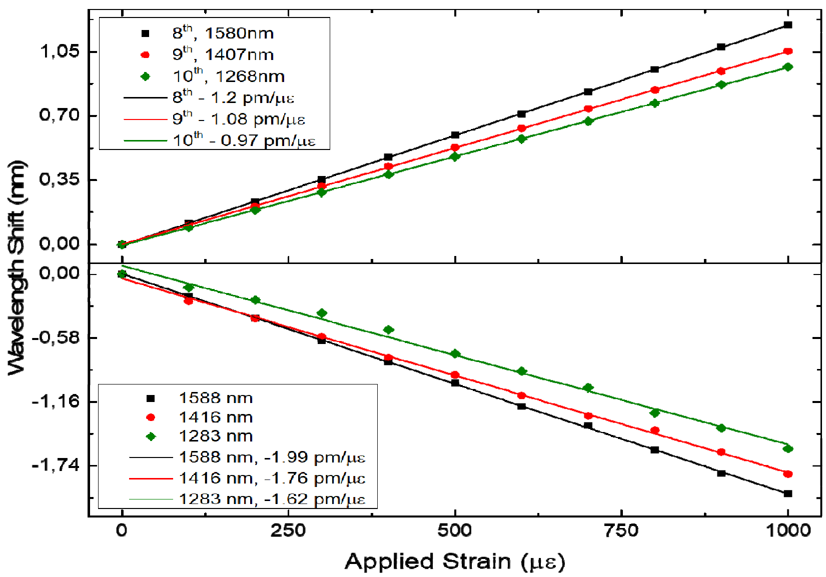

Fig. 4 . Strain sensitivities of the Bragg modes (top) and their corresponding closest higher order modes (down)

While the Bragg peaks exhibit sensitivities of 1.2 pm/ με, 1.08 pm/ με and 0.97 pm/ με respectively, their closest higher order cladding mode resonances show negative sensitivities of -1.99 pm/ με, -1.76 pm/ με and -1.62 pm/ με. The negative sensitivity of those particular modes is only natural since these modes are corresponding to refractive index values bellow the unity.

3.3 Refractive index sensing

The 8^{th} order TFBG was immersed in a salted water mixture whose refractive index was slightly changed by adding small quantities of water. The refractive index of solution was measured with an 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 2 depicts the obtained results for the 8^{th}, 9^{th} and 10^{th} grating orders, respectively. A linear regression of the raw data yields a refractometric sensitivity of ~22 nm/RIU for the cladding mode resonance at 1529 nm in the 8^{th} order grating. This sensitivity decreases to ~16 nm/RIU at 1369 nm for the 9^{th} order grating and furthermore down to 5.31 nm/RIU at 1238 nm for the 10^{th} order.

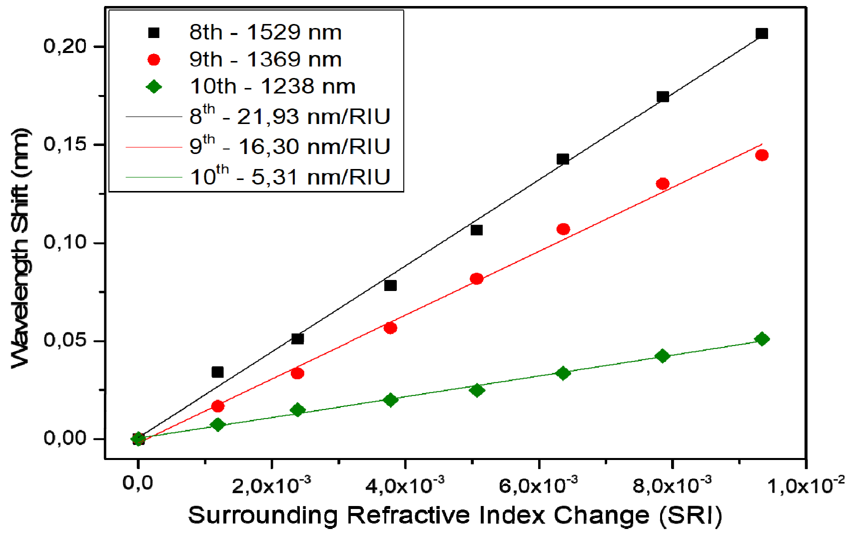

Fig. 5 Refractometric sensitivity as a function of the grating order. Inset: wavelength shift of the most sensitive cladding mode resonance for the 8th order grating.

This differential refractometric sensitivity between grating orders can be beneficial in the process of ultrafine refractometry, as reported in [8]. Moreover, from the obtained data, it is expected that the sensitivity can increase at longer wavelengths (7^{th} order grating at ~1805 nm for instance) provided that adequate source and optical spectrum analyzer are used to record them.

4. CONCLUSIONS

The direct write, plane-by-plane inscription provides immense flexibility and control over the grating parameters; including the spatial extent of the grating, its strength and angle of reflection. The low birefringence and the presence of higher order Bragg modes with their own set of cladding modes and refractive sensitivities renders these TFBGs unique. We have shown that the differential temperature sensitivity is below 1 pm/°C while the differential strain sensitivity is up to 3pm/με; almost three times bigger than the Bragg peak sensitivity [9]. This is maybe one of the best silica fiber cross-sensitivity performances to date.

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REFERENCES

[1] J. Albert, L.-Y. Shao, and C. Caucheteur, "Tilted fiber Bragg grating sensors," *Laser Photon. Rev.*, vol. 7, no. 1, pp. 83–108, 2013.

[2] A. Ioannou, A. Theodosiou, C. Caucheteur, and K. Kalli, "Direct writing of plane-by-plane tilted fiber Bragg gratings using a femtosecond laser," *Opt. Lett.*, vol. 42, no. 24, p. 5198, 2017.

[3] F. Shen, C. Wang, Z. Sun, K. Zhou, L. Zhang, and X. Shu, "Small-period long-period fiber grating with improved refractive index sensitivity and dual-parameter sensing ability," *Opt. Lett.*, vol. 42, no. 2, p. 199, 2017.

[4] K. Chah, D. Kinet, and C. Caucheteur, "Negative axial strain sensitivity in gold-coated eccentric fiber Bragg gratings," *Sci. Rep.*, vol. 6, no. November, p. 38042, 2016.

[5] J. U. Thomas *et al.*, "Cladding mode coupling in highly localized fiber Bragg gratings II: complete vectorial analysis," *Opt. Express*, vol. 20, no. 19, p. 21434, 2012.

[6] A. Theodosiou *et al.*, "Modified fs-Laser Inscribed FBG Array for Rapid Mode Shape Capture of Free-Free Vibrating Beams," *IEEE Photonics Technol. Lett.*, vol. 28, no. 14, pp. 1509–1512, 2016.

[7] A. Theodosiou, A. Lacraz, A. Stassis, C. Koutsides, M. Komodromos, and K. Kalli, "Plane-by-Plane Femtosecond Laser Inscription Method for Single-Peak Bragg Gratings in Multimode CYTOP Polymer Optical Fiber," *J. Light. Technol.*, vol. 35, no. 24, pp. 5404–5410, 2017.

[8] C. Caucheteur, A. Gonzalez-Vila, H. Chikh-Bled, B. Lasri, D. Kinet, and K. Chah, "Temperature influence on the cladding mode distribution in highly localized point-by-point fibre Bragg gratings," 2016, vol. 9916, p. 991629.

[9] G. P. Brady, K. Kalli, D. J. Webb, D. A. Jackson, L. Reekie, and J. L. Archambault, "Simultaneous measurement of strain and temperature using the first- and second-order diffraction wavelengths of Bragg gratings," *Iee Proceedings-Optoelectronics*, vol. 144, no. 3, pp. 156–161, 1997.