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A numerical study on the importance of non-uniform index modification during femtosecond grating inscription in microstructured optical fibers

Tigran Baghdasaryan*, Thomas Geernaert, Hugo Thienpont, Francis Berghmans
Vrije Universiteit Brussel (VUB), Brussels Photonics Team B-PHOT, Pleinlaan 2, B-1050 Brussels, Belgium

ABSTRACT

Fiber Bragg grating (FBG) inscription methods based on femtosecond laser sources are becoming increasingly popular owing to the (usually) non-linear nature of the index modification mechanism and to the resulting advantages. They allow, for example, fabricating fiber gratings that can survive temperatures exceeding 700°C, which can be an asset in the domain of fiber sensing. However applying femtosecond laser based grating fabrication to microstructured optical fibers (MOFs) can be challenging due to the presence of the air holes in the fiber cladding. The microstructured cladding not only impedes light delivery to the core in most cases, but also causes a non-uniform intensity distribution in the MOF core.

To deal with these challenges we present a modeling approach that allows simulating how the reflectivity of the grating and the nature of the index modulation are affected by the inscription conditions. We rely on transverse coupling simulations, empirical data and coupled mode analysis to model the induced index change and the resulting grating reflectivity. For IR femtosecond grating inscription we show that due to the intensity redistribution in the core region, irreversible Type II index changes can be induced in a MOF at laser peak intensities below the Type II threshold for step-index fibers. The resulting non-uniform induced index change has repercussions on the reflection spectrum of the grating as well. Our coupled mode analysis reveals, for example, that although the average index change in the core region can be high, the partial overlap of the core mode with the index change region limits the reflectivity of the grating.

Keywords: photonic crystal fiber, microstructured optical fiber, fiber Bragg grating, femtosecond laser

1. INTRODUCTION

Fiber Bragg gratings (FBGs) are essential elements in optical fiber technologies [1]. They are being used in a wide range of applications, e.g. in optical communications, fiber lasers and fiber based sensing [2]. To induce the refractive index change in the fiber core region that is required to form the grating, traditional methods use the photosensitivity of this doped core region to ultraviolet (UV) light. Hydrogen loading is also practiced often to increase the photosensitivity even further and to allow for highly reflective gratings to be inscribed. To make this index change periodic, near field interference from phase mask or two beam interference from a split laser beam (Talbot interferometer configuration) is often practiced.

New methods for grating writing use high intensity femtosecond pulses to induce the index change in the fiber core [3]. Such methods have several advantages compared with traditional UV writing methods. First, gratings can be inscribed in almost any type of glass and even in polymer without any need for photosensitizing the fiber material. Refractive index change takes place as a result of a highly non-linear multi-photon absorption process [3]. This also means that femtosecond lasers with different wavelengths can be used for that purpose. Femtosecond gratings inscribed with UV [4], visible [5] and near infrared (IR) [6] laser wavelengths were already demonstrated. Second, gratings can be inscribed through the fiber’s polymer coating, which allows preserving the mechanical strength of the fiber [7]. This is usually done with a near infrared wavelength, such as the emission of a Ti:Sapphire laser at 800 nm, where absorption of the polymer coating is low.

Third, gratings withstanding temperatures up to 700°C can be inscribed with femtosecond lasers [8]. This makes such gratings very attractive for industrial sensing applications, where the fiber is exposed to high temperatures.

* tbaghdas@b-phot.org; phone 0032 (0)2 629 3662; fax 0032 (0)2 629 3450; www.b-phot.org
Finally, so-called point-by-point (PbP) inscription can also be carried out with femtosecond lasers [9]. For PbP inscription, high intensity pulses are tightly focused to the fiber core region, with the fiber positioned on a high accuracy translation stage. By moving the fiber along its length and finely adjusting the translation speed taking into account the repetition rate of the laser, it is possible to induce a periodic index modulation in the core. Every single pulse of the laser is creating a single period of the grating period.

Many reports and studies deal with femtosecond laser based fabrication of gratings in conventional step index fibers [3-9]. Today much attention is paid to the use of this technique to form gratings in specialty fiber. One of these specialty fiber classes is referred to as microstructured optical fibers (MOFs) [10]. In such fibers light is confined in the core region owing to the presence of a holey cladding. The core can therefore consist of pure silica. MOFs consisting of doped silica are also used for fiber lasers [11-12]. In spite of this doping the fiber core region is not necessarily photosensitive to UV light. Hence for such MOFs, femtosecond grating writing methods provide a unique means to enhance the functionality of the fiber with grating structures.

However, the application of those methods to MOFs is not always straightforward due to the problems associated with the presence of air holes in the cladding region [13]. On its way to the core, the grating writing beam interacts with the structured cladding, which usually impedes transverse coupling of optical energy to the core region [14]. The presence of air holes in the cladding region also results in a strong transverse coupling dependence on the angular orientation of the fiber relative to the direction of the writing beam, which requires accurate orientation of the fiber with rotation stages to achieve any grating growth or to make it more efficient [14-16]. We have reported on those issues in several publications already we and we have shown both experimentally and numerically that insufficient control over the orientation can lead to absence of femtosecond written grating growth in certain MOFs [17-19]. We have also found optimal designs for the MOF cladding that can support grating writing if accurately fabricated and oriented [20-21].

More recently, we have also reported on another phenomenon that can affect the reflectivity of the grating inscribed with femtosecond writing methods in MOFs [22-23]. Due to the presence of air holes in the cladding, the intensity distribution in the core region is usually non-uniform. Taking into account the non-linear mechanism creating the index change under femtosecond laser illumination, the resulting index change can be even more irregular. The influence of this non-uniformity on the resulting grating reflectivity is the topic of the current report. We have developed a dedicated modeling approach that allows estimating the influence of the holey cladding for different MOF orientations on the resulting grating reflectivity. The manuscript is structured as follows: in the second section we model refractive index modification in the core region based on transverse coupling simulations and empirical data. In Section 3 methodology for calculating reflectivity of the MOF with coupled mode theory is presented and in Section 4 we applied those methods for a specific MOF to study the influence of the MOF orientation during grating inscription. We close our paper and conclude with Section 5.

2. Modeling Refractive Index Change in the MOF Core Region During IR Femtosecond Grating Writing

In our study we consider interferometric grating inscription using 800 nm wavelength femtosecond pulses. For the sake of simplicity we have assumed that the interference pattern results from pure two beam interference as illustrated in Figure 1a. This assumption is valid, for example, in a Talbot interferometer grating writing configuration [4]. For phase mask inscription it has been shown that if the fiber is positioned at a certain distance from the phase mask, a two beam interference pattern can be observed in the core region as well [24]. This results from the walk off effect of the different diffraction orders and from the short temporal length of the pulses (for more details see [24]).

As a reference fiber we have considered a commercially available MOF labeled ESM-12-01 [25]. The cross-section of the MOF is shown in Figure 1b, where GM and GK directions of the hexagonal lattice are indicated. The MOF has 5 rings of air holes, the outer cladding diameter is 125 µm and the core is formed by omitting a single air hole in the center of the hexagonal lattice. The air hole pitch is 8 µm and the air hole diameter is 3.68 µm.

This fiber was used in one of the first demonstrations of IR femtosecond grating inscription with phase mask method in MOFs by Mihailov et al [16] and has also been used in several other studies related to grating writing. For the sake of referencing the results we will use the same illumination conditions as in Mihailov et al [16] and Smelser et al [6]. More specifically, we consider a phase mask with a period of 3.2 µm resulting in a FBG period equal to 1.6 µm (third order grating). It is more important for our simulations that the ±1st diffracted orders from the phase mask are impinging on the fiber under the angle of 14.43°. To model the intensity distribution in the fiber core we consider a 2 dimensional (2D) problem of beam propagation to the core region. As we have already explained in details in [22], the wave vector
component that lies in the cross section of the fiber interacts with the air holes, hence for transverse coupling the simulation wavelength of the impinging beam should be tuned to correspond to that component of the wave vector.

**Figure 1.** a) Illustration of transverse coupling of two beams to the core region and b) cross-section of ESM-12-01 MOF with the indication of hexagonal lattice directions.

Therefore and although the results presented further in the work use 800 nm wavelength femtosecond pulses, the particular inscription conditions require using the following wavelength in the simulations:

\[
\lambda' = \frac{\lambda_0}{\cos(\alpha)} = 826\text{ nm}
\]

where \(\lambda_0 = 800\text{nm}\) is the wavelength of the femtosecond beam and \(\alpha = 14.43\) is the angle between the first order diffracted beam and the normal to the fiber.

Using this information, we modeled the optical intensity distribution in the MOF core region during femtosecond grating inscription using a 2D cross section model of the fiber. A more detailed explanation of the simulation approach can be found in earlier work [26]. We used a finite difference time domain (FDTD) method with commercially available FDTD Solutions software [27]. Note that we also implemented a so-called beam scanning procedure, which is also practiced in actual experiments to increase the overlap of the grating writing beam with the core region [6,16]. The beam waist radius in the focal point modeled here is 2.4 \(\mu\text{m}\) (taken from [6]), and the core radius is around 4 \(\mu\text{m}\). Hence beam scanning from \(+\pm 5 \mu\text{m}\) with a step of 0.5 \(\mu\text{m}\) guarantees full overlap of the beam with the core region. An example of the intensity distribution in the core region calculated with this approach is depicted in Fig. 2a. Here we considered ESM-12-01 MOF with beam incidence along \(\Gamma K\) direction of the hexagonal lattice. Note that it was generated by taking maximal values of the intensities observed in each point of the core region considering all simulations including the beam scanning procedure. The beam is impinging from the left to the right, i.e. along the positive direction of the X axis, while the beam scanning occurs along the Y axis.

**Figure 2.** a) Example of maximal intensity distribution in the MOF core region, b) proposed model for reconstructing the induced index change as a function of the intensity at 800 nm and c) modeled induced index change in the core region corresponding to the intensity distribution of a).

The peak intensity of the Gaussian beam in the focal point modeled here was \(I = 4.3 \times 10^{13} \text{ W/cm}^2\); this is the case when no air holes are present in the cladding region. From literature we conclude that such intensity level usually induces a Type I
reversible index change in conventional step index fibers [6]. However, in Fig. 2a we see various intensity values ranging from almost 0 to \( I = 4 \times 10^{13} \, \text{W/cm}^2 \), which is slightly less than the peak intensity when no air holes were present. Such a non-uniform distribution is caused by the strong interaction of the laser beam with the air-holed cladding of the MOF.

To proceed with our modelling we need to find a method that allows relating each intensity value in a certain point of the core region to an induced refractive index change at that location. To do so we rely on empirical data that can be found in open literature [6]. Fig. 2b graphically represents our model. We can distinguish between three different regions. The first region corresponds to intensity values below \( I = 2 \times 10^{13} \, \text{W/cm}^2 \), which do not induce any index change. Indeed, due to the non-linear nature of this index change, there should be a certain threshold for such a process and this particular intensity value for 800 nm pulses was reported in [6]. The second region correspond to intensities between \( I = 2 \times 10^{13} \, \text{W/cm}^2 \) and \( I = 4.6 \times 10^{13} \, \text{W/cm}^2 \). Note that at 800 nm the refractive index change takes place as a result of an at least 5-photon absorption process, hence the refractive index change should depend on the 5th power of the intensity:

\[
\Delta n = C \cdot I^5
\]  

(2)

where \( C \) is a constant that depends on the illumination conditions and exposure time. In our case we took values reported in [6] for grating growth in standard step index fiber and for similar experimental conditions as we modeled above. 6 points in the region from \( I = 2 \times 10^{13} \, \text{W/cm}^2 \) to \( I = 4.6 \times 10^{13} \, \text{W/cm}^2 \) for refractive index change values indicated in Fig. 2b are taken from [6] and the constant \( C \) is chosen in such a way to fit those point. In the given region the largest modeled induced refractive index change is \( 6 \times 10^{-4} \). It is also important to note that the refractive index changes in this region are Type I and reversible.

Above \( I = 4.6 \times 10^{13} \, \text{W/cm}^2 \), irreversible Type II index changes are induced. We consider these to be constant for all intensities above this value. This assumption simplifies the model and explains the saturation of the index change. We take a refractive index change of \( 1 \times 10^{-3} \) for those intensity values.

Fig. 2c shows the resulting modeled index change in the core region that corresponds to the intensity distribution corresponding to Fig. 2a using the model shown in Fig. 2b. The pattern of the index change is much ‘sharper’ than the intensity distribution pattern, which is a result of the highly non-linear nature of index change. There is considerable area in the core region where no index change took place. As we have shown previously [23] this particular MOF exhibits very poor transverse coupling properties and for optimal orientations less than 40% of the light is reaching the core region. As a consequence index change regions are also very limited throughout the core.

### 3. Modeling reflectivity of the grating with coupled mode theory

Our next target is to model the grating reflectivity based on the refractive index modification pattern obtained with the above mentioned procedure. The process of the reflectivity calculation is schematically illustrated in Fig. 3. We used coupled mode theory to calculate the overlap of the fundamental mode of the MOF with the refractive index pattern generated in the MOF core region by femtosecond pulses. To estimate the grating reflectivity we consider coupling of the forward propagating fundamental mode of the MOF with the same mode propagating in the opposite direction.

![Figure 3. Schematic illustration of the approach that was used to model the reflectivity of the grating in the MOF.](image-url)
We first modeled the fundamental mode of the MOF at 1550 nm using commercially available MODE Solutions software, which is illustrated in the left upper corner in Fig. 2. An important step for estimating the reflectivity of such a grating is the calculation of the coupling coefficient of this mode with the given refractive index modification profile [28]. We used the following formula for that purpose:

\[
\kappa = \frac{\omega}{4} \int \int \Delta \varepsilon(x,y) \vec{E}_r \cdot \vec{E}_r^* \, dx \, dy
\]

where \( \vec{E}_r \) is the normalized intensity distribution of the MOF fundamental mode, \( \Delta \varepsilon \) is the transverse permittivity distribution of the grating in the cross section of the MOF derived from the refractive index distribution using the following assumption:

\[
\Delta \varepsilon \equiv 2n_{core}\Delta n
\]

The integral in Eq. 3 calculates the overlap of the fundamental mode of the MOF with the refractive index modification pattern, which takes into account the non-uniform nature and the distribution of this index change in the core region. Finally, using the coupling coefficient from Eq. 3, we calculated the reflectivity of the grating with the following equation from coupled mode theory:

\[
R = \tanh^2(\kappa L)
\]

where \( L \) is the grating length, which we assumed to be 2 mm for the further calculations.

### 4. INFLUENCE OF THE MOF ORIENTATION ON INDUCED INDEX CHANGE AND REFLECTIVITY OF THE GRATING

In Section 2 and 3 we have introduced our approach for modeling the distribution of the induced refractive index change in the MOF core region and the resulting reflectivity of the FBG inscribed with IR femtosecond pulses, which takes into account the non-linear nature of the index change mechanism. Here we will apply this methodology to study the influence of the angular orientation of the MOF relative to the direction of the writing beam on the average of the induced index change and reflectivity of the FBG.

Here again we considered the ESM-12-01 MOF with cross-section shown in Fig. 1b and we studied MOF orientations within a range of 30° (due to symmetry of the lattice) from the \( \Gamma \) to \( \Gamma M \) directions of the hexagonal lattice. Fig. 4a shows the dependence of the average of the induced index change in the core region on the MOF orientation. Note that...
0° corresponds to the ΓK direction, while 30° corresponds to the ΓM direction. The results are shown for two peak intensity values of the Gaussian beam of $I=3\times10^{13}$ W/cm$^3$ and $I=4.3\times10^{13}$ W/cm$^3$, which are both below the Type II index change level when applied to step index fiber. For this MOF we can hardly find any index changes in the core region for a range of orientations from 15° - 45°. For the other orientations the induced index change also remains quite weak and reaches $0.85\times10^{-5}$ for the higher intensity and optimal orientation along ΓK directions. Remarkably, whilst the peak intensity is increased by less than 50% (red curve in Fig. 4a), the average of the induced change increases by around 8 times. This is a result of the highly non-linear nature of the index change and evidences the high sensitivity of the induced index change to the power and peak intensity of the femtosecond pulses.

The solid line in Fig. 4b shows the dependence of the resulting grating reflectivity on the orientation of the MOF calculated by the approach presented in Section 3 for the laser pulse peak intensity level of $I=4.3\times10^{13}$ W/cm$^3$. The reflectivity curve follows the shape of the index change curve and we find a low peak reflectivity of $0.4\times10^{-3}$ for the ΓK orientation of the fiber. Around the ΓM direction we do not see any reflectivity. The importance of the orientation on grating growth demonstrated here is in good agreement with the results reported in literature [16].

The dotted line in Fig. 4b gives the reflectivity of the FBG if the values of the induced index change from Fig.4a are directly used in the coupled mode theory, without taking into account the non-uniform nature of index change. These yield a threefold larger estimate, which emphasizes the importance of taking into account the non-uniform nature of the index change in MOFs for estimating the reflectivity of the grating. Reports in literature often assume a uniform distribution of the index change over the core when calculating the induced index change value from the measured reflectivity. This method thus estimates the effective index modulation without taking into account the precise distribution throughout the core region, which leads to an underestimation of the peak values of the induced refractive index change and may thus complicate the interpretation of the inscription process

5. CONCLUSIONS

In this report we have presented a methodology for modeling induced index changes in the core region of pure silica MOFs based on transverse coupling simulations and empirical data for IR femtosecond grating inscription by taking into account the highly non-linear nature of the induced index change. We have shown that non-uniform intensity distribution in the MOF core region as a result of the interaction with the structured cladding causes and of the non-linear nature of the index change can result in highly non-uniform index change distribution in the cross section of the MOF core. We have also detailed our approach for estimating the reflectivity of the resulting fiber Bragg grating by taking into account the non-uniform nature of the index change. We have used coupled mode theory for that purpose and we have calculated the coupling coefficient by considering the complete overlap integral of the MOF fundamental mode with the induced non-uniform index distribution. We have applied this methodology to the commercially available ESM-12-01 MOF, and we have studied the influence of the angular orientation of the MOF on the induced index change and resulting reflectivity. We have shown that for a large range of orientations around the ΓM direction of the hexagonal lattice we do not see any index change appearing. The ΓK direction, however, is much better suited for grating inscription, which confirms experimental results from literature.

We have also calculated the reflectivity of the grating using both the average of the index change uniformly distributed over the core region and the exact pattern of the non-uniform index change. By doing so we have demonstrated the importance of taking into account the non-uniform nature of the index distribution. Not doing so leads to considerable differences in calculated reflectivity.

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