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Understanding the Influence of the Structured Cladding on the Reflectivity of Femtosecond Laser Written Gratings in Photonic Crystal Fibers

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ABSTRACT

Fiber Bragg gratings have been essential elements in fiber optical communication for more than two decades. Although writing gratings using different inscription methods in step-index fibers has become a standard procedure, femtosecond laser based fabrication of such gratings in specialty fibers such as photonic crystal fibers (PCFs) has proven not to be straightforward. This is due to the presence of air holes in the cladding region, which impede sufficient amounts of optical energy to reach the core region. An important consequence of the presence of air holes in the cladding, which is sometimes disregarded, is the non-uniform distribution of the laser intensity in the core region, which results in an equally non-uniform refractive index change in the PCF core cross-section. To study this issue we have built a dedicated model based on coupled mode theory that allows estimating the reflectivity of the grating by modeling the intensity distribution in the PCF core region and the resulting non-linear refractive index change using empirical data. We clearly see that the limited overlap of the fiber mode with the index change reduces the reflectivity of the grating, and that the extent of this effect depends on the angular orientation of the PCF with respect to the direction of the inscription beam and on the laser beam focusing optics.

Keywords: fiber Bragg grating, photonic crystal fiber, numerical modeling, femtosecond laser.

1. INTRODUCTION

Photonic crystal fibers (PCFs) can be fabricated with a cladding region that is formed by a periodic lattice of air holes that run all along the fiber length [1]. The design freedom of the air holed cladding allows achieving unique optical functionalities and optimizing such fibers for different applications. Example of such applications include optical communications [2], optical sensing [3], non-linear optics [4] and fiber lasers [5]. For many of these one targets to enhance the properties of PCFs by means of fiber Bragg gratings (FBGs) and hence many publications have already reported on the inscription of FBGs in PCFs [6]. A major problem encountered when fabricating a FBG in the core region of a PCF stems from the presence of air holes in the cladding region. These usually impede effective delivery of the transversely incident inscription beam to the core region [7-10]. This issue is exacerbated when trying to fabricate FBGs by means of femtosecond laser pulse based inscription methods [13-14]. With such methods grating formation is the result of multi-photon absorption processes that create the required index changes [15]. For these absorption processes to take place and hence for achieving effective grating growth, very high laser intensity levels are required in the fiber core region.

Literature commonly reports on three phenomena observed when writing FBGs in PCFs that result from the presence of air holes in the cladding [6]. First, the air hole lattice has a detrimental influence on the amount of optical energy reaching the core region, which results in a weaker grating growth or even in no grating growth at all [6,11-14]. Second, grating growth is sensitive to the angular orientation of the cladding relative to the direction of the writing beam which means orientation of the PCF often should be controlled during FBG inscription to guarantee optimal grating growth if any [6,11,14]. Third, the multiple interactions of the inscription light with the holey cladding structure leads to a significant non-uniformity of the optical intensity distribution across the core region of the PCF [12].

In this paper we focus on this third issue applied to femtosecond pulse IR laser inscription. We show how the non-uniform cross-sectional distribution of the optical intensity in the core region leads to non-uniform induced index changes. The limited overlap of the guided mode with this non-uniform index change leads to a low reflectivity of the grating, even if the peak index change is high.

Our manuscript is structured as follows. In Section 2 we discuss the femtosecond grating inscription conditions and the PCF under study. Section 3 deals with the modeling of the cross-sectional intensity distribution in the PCF core region, with the theoretical model that relates intensity to refractive index modification and with the resulting induced refractive index distribution. We elaborate on the influence of the non-uniform index distribution on the reflectivity of the grating in Section 4. In Section 5 we suggest a possible solution to homogenize the induced index distribution over the PCF core region and we conclude in Section 6.

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2. IR FEMTOSECOND GRATING INSCRIPTION CONDITIONS AND PCF UNDER STUDY

We consider interferometric grating inscription with a 800 nm wavelength. Femtosecond grating inscription using a phase mask technique in standard and photonic crystal fibers has already been demonstrated with a Ti:Sapphire laser operating at this wavelength [11-12]. For the sake of simplicity we start from pure two beam interference as illustrated in Fig. 1a. We take the grating inscription parameters of the setup reported by C. Smelser, *et al.* [17] in order to mimic a realistic configuration. As we have described in details in [16], it is important to consider the actual wave vector component propagating in the fiber cross-section when simulating the optical intensity reaching the core in such a configuration. For the setup used here, we should use a wavelength of 826 nm.

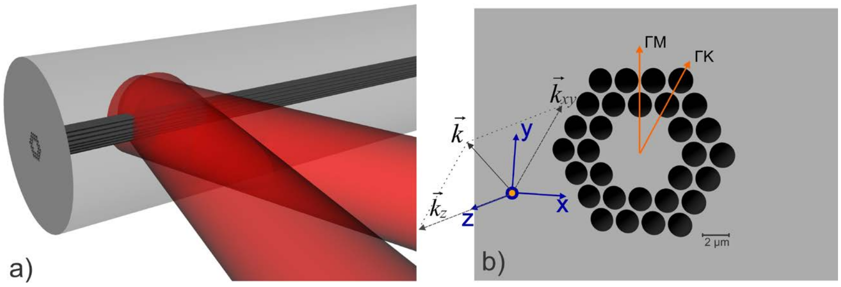

Figure 1. Illustration of a) two interfering beams that transversely propagate to the PCF core region and b) cross section of the considered PCF.

The PCF microstructure that we work with is illustrated in Fig. 1b and consists of a hexagonal lattice with 2 rings of air holes, with an air hole pitch of 2 µm, and air hole diameter of 1.8 µm. The core region diameter is around 5 µm. We designed this structure to minimally impede delivering light to the core region. Our simulations show that the average amount of the optical energy reaching the core region is almost the same as if no air holes were present in the cladding region. However, the cladding causes a significant redistribution of the intensity in the core region, which also results in a highly non-uniform cross-sectional index change, as discussed in the following section.

3. Refractive index modification in the PCF core region and implications of the intensity redistribution

Figure 2a shows the transverse intensity distribution in the PCF core region as modeled with Lumerical FDTD Solutions software [18]. This distribution has been obtained with the illumination illustrated in Fig. 1 and including transverse scanning of the inscribing laser beam. This is often practiced to increase the overlap of the index change region with the fundamental mode. A more detailed description of our modeling approach can be found in [16]. We used a peak intensity of the incident Gaussian beam $I = 3\times10^{13}$ W/cm^2.

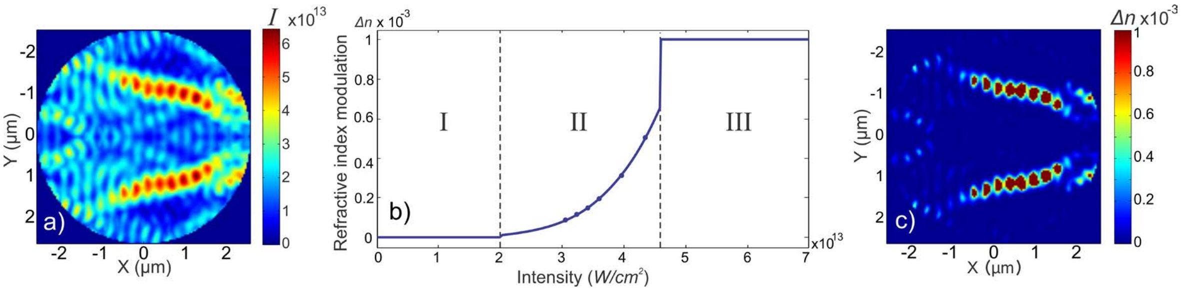

Figure 2: a) Intensity distribution in the PCF core region; b) Model for relating intensity to refractive index change; c) Calculated refractive index distribution in the PCF core region.

Index changes in pure silica created by femtosecond pulse IR laser sources result from a multi-photon absorption mechanism. For the 800 nm wavelength considered here, five photon absorption leads to grating growth. Using empirical data from literature [17], we propose a simplified model that relates the intensity in a certain point of the core region with the refractive index modification. This model is illustrated in Fig. 2b. We distinguish between three intensity regions. The first corresponds to intensities below the threshold value of $I = 2\times10^{13}$ W/cm^2, below which no index change takes place. For intensities exceeding this threshold, but smaller than $I = 4.6\times10^{13}$ W/cm^2, a reversible so called Type I refractive index change is induced. In this range the induced index change is proportional to the fifth power of intensity: $\Delta n = C \cdot I^5$, where C is a constant that depends on the illumination conditions and on the inscription setup. For intensities above $I = 4.6\times10^{13}$ W/cm^2, saturation of the index change is achieved and taken as $\Delta n = 10^{-3}$.

The resulting induced refractive index modification corresponding to the intensity distribution of Fig. 2a is shown in Fig. 2c. The refractive index values are strongly varying across the PCF core region. Irreversible Type II refractive index change regions can be observed in the core, although the peak intensity of the laser pulse was well below the Type II threshold. This points to the possibility of writing high temperature stable Type II gratings in PCFs with laser beam intensities that are lower than those required for writing such gratings in conventional step-index fiber.

We have also calculated the average of the induced index change over the PCF core cross-section. If no air holes are present in the cladding and for an incident intensity $I = 3\times10^{13}$ W/cm^2, the average induced index change is 0.74×10^{-4}. For our PCF, this value becomes 0.78×10^{-4}. Although the difference is small, this indicates another interesting implication of the intensity redistribution in the core region and the non-linear nature of the index change.

4. PCF REFLECTIVITY DEPENDENCE ON THE PCF ORIENTATION

Using coupled mode theory we can model the reflectivity of the grating while taking into account the non-uniform distribution of the index change. To do that we accurately calculate the coupling coefficient by considering the exact overlap of the fundamental propagating in the PCF with the induced index change distribution. A more detailed explanation of this approach can be found in [12]. This can be done as a function of the angular orientation of the PCF with respect to the direction of the writing beam.

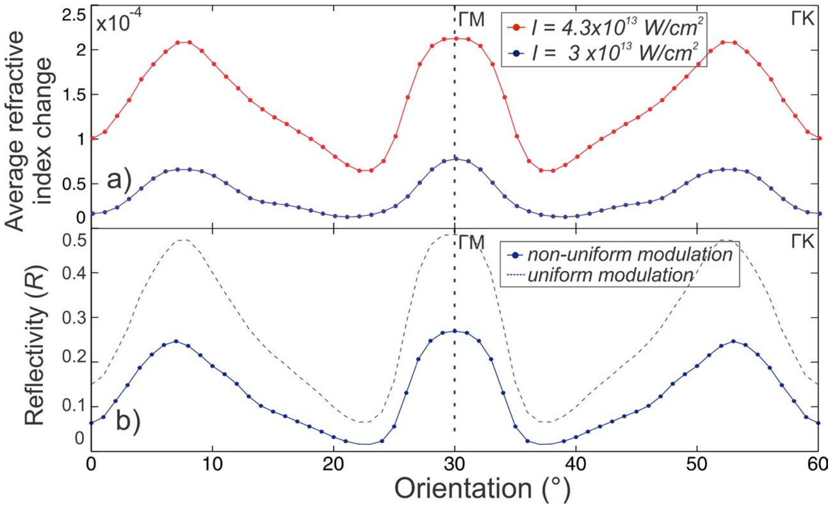

Figure 3. Modeled a) average of the induced index change in the PCF for two intensity levels and b) reflectivity of the FBG for a beam intensity of $I=4.3\times10^{13}$ W/cm^2 as a function of the angular orientation of the PCF.

Figures 3a and 3b show the influence of the PCF orientation on the average index change and on the reflectivity of the grating, respectively. ΓM and ΓK directions of the hexagonal lattice are indicated in Fig. 1b. There is a significant angular dependence, yet grating growth appears possible for all orientations. The optimal orientation for grating writing for this PCF is along the ΓM direction of the hexagonal lattice. From Fig. 3a we conclude that increasing the peak intensity of the pulse by less than 50% leads to a more than doubled average index change. This is again a consequence of the highly non-linear nature of index change. Figure 3b also includes the reflectivity calculated by using the average induced index change instead of the non-uniform index distribution. For a grating length of 2 mm and for inscription along the ΓM direction, the reflectivity reaches 25% when considering the non-uniformity of the index distribution, whilst a reflectivity of 50% would be achieved when considering a uniform index change with the same average value. We conclude that when one neglects the non-uniform distribution, the reflectivity is overestimated with a factor of almost two.

5. PCF ROTATION DURING GRATING INSCRIPTION

A possible solution to the problem of the non-uniform induced index distribution and the resulting decreased reflectivity could be to rotate the fiber continuously around its axis during grating inscription. The high intensity regions would then move to other parts of the PCF core along the rotation, which would eventually homogenize the induced refractive index change. To understand what can be expected from such a procedure, we simulated the intensity distribution in the core region for all orientations.

The results for an incident intensity $I = 3\times10^{13}$ W/cm^2 are shown in Fig. 4. We calculated the maximal intensity at every point of the core region for the same illumination conditions as before. We observe intensities above Type II thresholds all across the core region. If we apply our model for the refractive index modulation, which assumes saturation of the induced index change, then we obtain a more or less homogeneous refractive index modulation with an amplitude around $\Delta n = 10^{-3}$ that is characteristic for Type II gratings. The reflectivity from such a grating calculated with coupled mode theory would be almost 99%.

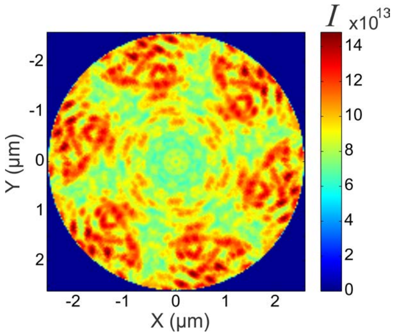

Figure 4. Maximum intensity distribution in core region following continuous rotation of the PCF around its axis.

Rotating the PCF during grating writing would be very difficult to carry out in practice and would result in a much increased inscription time. It is obvious that before considering doing so the pros need to be weighed against the cons and the potential achievement of the required reflection levels should be confirmed experimentally before drawing further conclusions.

6. CONCLUSIONS

We have presented our modeling approach for studying IR femtosecond grating inscription in photonic crystal fibers with interferometric methods. Throughout the paper we have worked with a PCF with two rings of air holes in a hexagonal lattice. We suggested a simplified model for the non-linear refractive index modification in the core region taking place as a result of five photon absorption processes. With the given model parameters, we have found that the intensity redistribution in the core region due to the interaction with the PCF air holes can result in an increase of the average induced refractive index modulation. We have also shown that although the peak intensity of the grating writing beam is below the Type II threshold, Type II high temperature stable grating could possibly be inscribed in a PCF owing to the intensity redistribution in the PCF core region.

Finally we studied the influence of the non-uniform cross-sectional distribution of the refractive index on the resulting spectral properties of the grating. Our approach based on the coupled mode theory revealed that by neglecting the non-uniform nature of the index change one can considerably overestimate the reflectivity of the grating.

In order to achieve a more uniform refractive index modulation in the PCF core we suggested experimenting with continuous fiber rotation during grating inscription. We have calculated the maximum intensity values occurring in the core region during that process and we showed that even if the interference intensity has values below the required intensity to obtain a Type II grating, the field redistribution combined with continuous rotation could result in Type II grating formation in the entire cross-section of the PCF under study.

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