SHORT TERM SCIENTIFIC MISSION (STSM) – SCIENTIFIC REPORT

The STSM applicant submits this report for approval to the STSM coordinator

Action number: 41055

STSM title: Modeling nonlinear beam propagation in the cross-section of photonic crystal fibers for grating inscription applications

STSM start and end date: 21/05/2018 to 08/06/2018
Grantee name: HOVIK BAGHDASARYAN

PURPOSE OF THE STSM/

(max.500 words)

Photonics crystal fibers (PCFs) occupy a specific niche in the fiber laser domain [1-3]. They already managed to enter that market owing to their unprecedented properties. Success stories include large mode area (LMA) PCFs for high power laser applications and double-clad PCFs allowing for efficient pumping. PCFs nevertheless remain very challenging waveguides when attempting to photo-inscribe gratings in their core region. Fiber Bragg gratings (FBGs) often serve as cavity mirrors in fiber-based laser systems [4,5] and their fabrication in structured fibers is far from being trivial due to the presence of air holes in the cladding region. The air holes tend to scatter, reflect and refract the grating inscription beam on its way to the core region and thus impede efficient grating growth. Moreover, as the active region of those PCFs is often not photosensitive to UV light, alternative grating writing methods should be used, such as inscription with high intensity femtosecond pulse lasers operating in the infrared range (about 800 nm). In this case a highly non-linear multi-photon absorption process is responsible for the required index change, which seriously complicates the picture when considering grating fabrication in PCFs.

Research into the issues of femtosecond pulse-based grating inscription in PCFs has been conducted for almost a decade. One particular research track deals with modelling the propagation of the writing beam from the outside of the fiber to the PCF core region, with of the aim to understand the interaction processes and to suggest workable solutions enabling efficient grating growth [6,7]. The majority, if not all, of those efforts took into account only the linear interactions mechanisms by solving Maxwell's equations without taking into account the non-linear susceptibilities terms of material. The objective of this short term scientific mission (STSM) was therefore to establish a methodology for modelling non-linear beam propagation in the PCF cross-section in view of grating inscription.

References 1:

1. A.M.R. Pinto and M. Lopez-Amo, All-fiber lasers through photonic crystal fibers (Review article), *Nanophotonics*; 2(5-6), pp. 355–368, (2013).
2. L. Michaille et.al., Multicore Photonic Crystal Fiber Lasers for High Power/Energy Applications, *IEEE J. S.*

T.Q.El., **15**, No. 2, pp. 328-336, (2009).
3. J. C. Knight, Photonic crystal fibers and fiber lasers (Invited), *J. Opt. Soc. Am. B,* **24**, No. 8, pp.1661-1668, (2007).
4. O. Xu et. al.: Proposal and analysis of two-cavity Fabry–Perot structures based on fiber Bragg gratings, *J. Opt. Soc. Am. A* , **26**, No. 3, pp. 639 – 649, (2009).
5. X. Zhu et. al., 976 nm single-frequency distributed Bragg reflector fiber laser, *Opt. Lett.,* **37**, No. 20, pp. 4167-4169, (2012).
6. T. Baghdasaryan et.al., Numerical modeling of femtosecond laser inscribed IR gratings in photonic crystal fibers, *Optics Express*, **23**, No. 2, pp. 709-723, (2015).
7. F. Berghmans et.al., Challenges in the fabrication of fibre Bragg gratings in silica and polymer microstructured optical fibres, *Laser Photonics Rev*., pp. 1–25, (2013).

DESCRIPTION OF WORK CARRIED OUT DURING THE STSMS

(max.500 words)

To achieve the goal of STSM, the Fiber Optics Communication (FOC) laboratory from Armenia and Brussels Photonics (B-PHOT) joined forces to apply a Finite Difference Time Domain (FDTD) method in order to solve the complex 2D or even 3D multi-boundary electromagnetic problem. B-PHOT has extensive experience in using FDTD simulations in view of grating inscription using the commercially available software FDTD Solutions from Lumerical inc. However, they have never implemented simulations that take into account the non-linear nature of interaction. A literature review revealed that the multiphoton absorption and impact (avalanche) ionization processes in dielectrics can be treated separately which is a reasonable assumption provided the laser pulses are sufficiently short, say of the order of tens of picoseconds, or shorter [1,2]. Based on this hypothesis we derived the mathematical expressions describing a five-photon absorption process for the incident femtosecond pulses at the wavelength of 800 nm, with the non-linear coefficients obtained from the literature [3], such that the expressions can be solved with an FDTD approach. The FDTD Solutions software allows introducing custom non-linear models using the so-called ‘Flexible material plugin framework’. During the STSM we obtained an accurate formulation and a discretization scheme for the non-linear polarization terms of for pure silica at the wavelength of interest. The implementation of the non-linear model in FDTD Solutions using the C++ programming language is now being continued. The experience of the FOC laboratory allowed introducing a dedicated numerical method for solving the non-linear electromagnetic interaction problems without approximations. The approach, known as the method of single expression (MSE), has proven powerful for solving wavelength scale boundary problems as it does not require any application of the superposition principle and owing to the use of a backward propagation approach [4-6]. By using the MSE it has been calculated plane wave interaction with the slab of dielectric where non-linear (intensity dependent) absorption is analysed. In the further stages of the collaboration comparison of the results and validation of the FDTD Solutions plugin is planned.

References 2:

1. E. Arola, Theoretical Studies on Multiphoton Absorption of Ultrashort Laser Pulses in Sapphire, *IEEE J. Q. E.*, **50**, No. 8, pp. 709-720, (2014).
2. B. Rethfeld, Unified Model for the Free-Electron Avalanche in Laser-Irradiated Dielectrics, *Phys.Rev.Lett*., **92**, No.18, pp. 187401-1--187401-4, (2004).
3. V. V. Temnov et al., Multiphoton Ionization in Dielectrics: Comparison of Circular and Linear Polarization, *Phys.Rev.Lett*, **97,** pp. 237403-1-- 237403-4, (2006).
4. H.V.Baghdasaryan, “Method of backward calculation”, in the book: “Photonic Devices for Telecommunications: how to model and measure”/ Editor **G.Guekos**, Springer, pp.56-65 (1999).
5. H.V. Baghdasaryan, T.M. Knyazyan, “Problem of Plane EM Wave Self-action in Multilayer Structure: an Exact Solution”, *O.&Q.El.*, **31**, No.9/10, pp.1059-1072 (1999).
6. H.V. Baghdasaryan et.al., Metal-dielectric Multilayer Structure Supporting Surface Plasmons: electromagnetic modelling by the Method of Single Expression” *O.&Q.El.*, **47**, No.1, pp. 3-15 (2015).

COST
EUROPEAN COOPERATION
IN SCIENCE & TECHNOLOGY

DESCRIPTION OF THE MAIN RESULTS OBTAINED

(max. 500 words)

We derived the relevant mathematical expressions describing five-photon absorption process at the wavelength of 800 nm as a basis for the theoretical analysis of non-linear interactions of strong femto-second laser pulse with SiO_2. We have also started the implementation of plasma generation and the plasma absorption model in the FDTD Solutions environment using C++.

The expressions and the discretization of the non-linear polarization of pure silica will allow modelling non-linear propagation of a high intensity grating writing beam in a photonic crystal fiber cross-section. As these expressions require a specific form for implementation in FDTD Solutions, contacts with Lumerical Inc. have been taken and discussions are in progress.

By using the MSE, we have calculated the effect of a linearly polarised plane wave incident on a dielectric slab including non-linear (intensity dependent) absorption. We implemented this by considering that the electromagnetic wave amplitude is decreasing along the propagation towards the output interface of the slab. We showed that the multi-photon absorption will take place mainly at the illuminated interface of layer, what can bring to ionization process on the interface at the further increase of incident wave' intensity.

FUTURE COLLABORATIONS (if applicable)

(max.500 words)

We successfully initiated non-linear modelling of grating inscription in photonic crystal fiber and we managed to establish and test the strategy for implementing the non-linear model in FDTD Solutions. Further collaboration is required to achieve the ultimate goal, which is a full model and analysis of non-linear high intensity femtosecond pulse propagation through a photonic crystal structure. The realisations and joint efforts conducted during this STSM allow progressing the work based on frequent web-based meetings. Given the novelty and the interest in this research, not only from the point of view of the applications but also from that of basic radiation-matter interactions and science, we are convinced that 2 journal publications and conference publication will be achieved, with a first publication which is already in preparation.