PhD project for fall 2017
« Numerical modeling of light diffusion in nanostructured optical fibers »

Host laboratories: Inria Sophia Antipolis - Méditerranée, Nachos project-team (principal host) and INΦNI laboratory, Optical fiber team, University Nice Sophia Antipolis.

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Optical fibers are used in many applications such as telecommunications, sensors (stress and/or temperature measurements, gyroscopes, chemical detection, etc.), medical, machinig or marking of materials, etc. The luminescence properties (for lasers, telecommunication repeaters, etc.) are generally obtained by doping with rare rarth (RE) ions. Despite the wide variety of applications, of all the available glasses, only silica glass (SiO2) has found a great commercial interest for optical fibers. All other proposed glasses (fluorides, chalcogenides) impose limits on the cost of manufacture, reliability and operation of the apparatus, even if they provide good luminescence properties to RE. Today, applications require RE-doped materials having "enhanced" intrinsic optical properties, including spectroscopic properties that would not appear in a pure silica glass. For example, increasing the number of accessible wavelengths (e.g. blue emission for underwater LIDAR - Light Detection and Ranging), widening the fluorescence emission band (increasing the data rate), reducing the laser threshold or photo- and radio-blackening, will allow to develop new laser sources of power or new fibers adapted to the difficult and extreme conditions as in the detection and the applications in space or nuclear.

To meet these new demands, one of the main routes of research is based on a glass containing nanoparticles and the control of light scattering processes induced by nano-heterogeneities [1]. For a large number of applications, the light scattering must be minimized and the new luminescence properties are due to the integration of rare earth ions in dielectric nanoparticles (DN) with different composition and local structures than those of the silica-based matrix. Using this approach, the luminescence properties of rare earth ions are adapted by choosing the DN composition. However, there are applications requiring very strong light scattering as in the case of random lasers. Unlike conventional lasers based on an optical cavity closed by mirrors, random lasers do not have mirrors. Light is confined in the amplifier medium by multiple scattering. Such lasers are presumed to have a low laser threshold. The development of this new generation of optical fibers is currently limited by the lack of knowledge related to the manufacturing processes on the one hand and the lack of understanding of the main phenomena underlying the interaction between light and nanoparticles in the optical fibers on the other hand. The present PhD project addresses this second problem.

The Optical fiber team at the INΦNI laboratory has developed an original way of manufacturing these optical fibers, and has invested in the study of the manufacturing process, analysis of the spectroscopic properties of RE ions and of the chemical composition of the DNs. The process used is based on the Modified Chemical Vapor Deposition (MCVD) process and the "dipping" technique which are the most widely used industrial processes for preparing silica-based preforms (glass bars converted into optical fibers by hot drawing). In the adopted approach, the nanoparticles are obtained directly during the manufacturing process by taking advantage of heat treatments. Phase separation mechanisms are triggered by the introduction of alkaline ions such as magnesium. One of the advantages of this way of proceeding is that there is no manipulation (nor the potential risks associated) of DNs by an operator. The Optical fiber team has reported changes in the luminescence properties of RE ions in DN-doped fibers [2]. For example, a widening of the emission band is observed and explained by the presence of the RE ions in the nanoparticles when they have a size > 50 nm. However, the transmission of light in such fibers is very limited. The light scattering approach using the Rayleigh model requires the smallest possible nanoparticles (less than 10 nm). However, it is known that the Rayleigh approach suffers from limitations. For example, it has been observed that by increasing the volume fraction of the nanoparticles, the measured light transmission is superior to that expected with respect to Rayleigh (leading to ultra-transparency) [3]. In addition, the studies are generally concerned with mono-dispersed nanoparticles in size. However, the formation of nanoparticles by phase separation leads to a high polydispersity in size, typically from a few nm to a few hundreds of nm. It is therefore necessary to be able to systematically study the effects of light scattering induced by the presence of nanoparticles in the core of optical fibers. In this problematic, a numerical approach, in addition to the experimental way, can facilitate study. This is a central point of the PhD proejct proposed here.

The numerical simulation of the propagation of light in interaction with matter uses numerical methods for the resolution of Maxwell's equations, possibly coupled with complex laws of the behavior of matter (linear or non-linear media, possibly dispersive). The propagation of light in a nanostructured fiber presents characteristics that are also challenges for numerical modeling: geometrical complexity (the structures involved are rarely of simple form eg rectilinear or planar), the heterogeneity of the propagation media, the variability of scales of space and time (multi-scale character).

Different numerical methods have been developed to solve the Maxwell equations in time or harmonic regime. Among these, methods based on a discontinuous Galerkin formulation have been extensively studied in recent years. By combining the advantages of finite element and finite volume formulations, a discontinuous Galerkin formulation makes it possible to construct an arbitrarily high order resolution method adapted to the discretization of irregular geometries. Thus, discontinuous Galerkin methods have several strengths:

- They are naturally adapted to the discretization of discontinuous functions and to the discretization of heterogeneous propagation media;
- They lend themselves to the use of unstructured meshes (non-orthogonal and non-uniform) for the discretization of complex geometric shapes. Moreover, these meshes may have floating nodes (non-conforming meshes);
- They make it possible to obtain an accuracy of arbitrarily high order;
- They allow non-conformity of the discretization (i.e. of the mesh) and the approximation (i.e. the degree of interpolation can be defined at the level of each element of the mesh). In other words, they provide an ideal framework for the development of self-adaptive resolution strategies;

- Because of their local character, they are perfectly adapted to parallel computing.

Such discontinuous Galerkin methods have been extensively studied in recent years in the Nachos project-team at Inria for the numerical simulation of phenomena of electromagnetic wave propagation in the radiofrequency/microwave spectrum, aiming at applications in electromagnetic compatibility, electrical vulnerability and bioelectromagnetism [4]-[5]-[7]-[8]-[9]. More recently, the team started to study such methods for the numerical modeling of nanoscale light/matter interactions (i.e. nanophotonics) in the temporal domain [6].

The general aim of this PhD project is the study of the phenomena of light scattering induced by nano-heterogeneities in optical fibers, and more particularly of the influence of the degree of heterogeneity. Since the experimental measure allows only partial information on these phenomena to be accessed, the use of modeling and numerical simulation is necessary to characterize in more detail the propagation of an electromagnetic wave in a nanostructured optical fiber core, the ultimate aim being to obtain quantitative information making it possible to adapt the manufacturing procedure of this type of optical fiber in order to optimize their efficiency in transmission of information. This thesis project will therefore include a main focus on the theory and numerical simulation of the phenomena of light/matter interaction in a nanostructured fiber core. More precisely, it will be necessary to develop a new numerical methodology to account for the light scattering effects induced by the presence of nanoparticles in the core of optical fibers by considering two nano-heterogeneity regimes:

Firstly, moderately heterogeneous fibers will be considered and an existing numerica methodology of the discontinuous Galerkin type will be adapted and exploited to study the light scattering losses associated with different characterization parameters (e.g. polydispersity in size). In particular, the relevance (and hence the applicability limits) of this methodological approach will be evaluated according to the degree of heterogeneity.

In a second step, we will study more precisely the case of very heterogeneous fibers with in focus the random fibers. It will be a question here of studying the conditions leading to the amplification of the signal, again as a function of characterization parameters. To model and simulate with precision and efficiency this type of configuration, we will try to develop a new variant of the methodology considered for the case of moderately heterogeneous fibers, in order to take into account the multiscale character pronounced due to the heterogeneity. This methodology will then be exploited to study such questions as the influence of the volume fraction of the nanoparticles and the polydispersity in size on the optical losses. Parametric studies will be carried out requiring the realization of numerical simulations involving a variety of geometric configurations of fibers. For this purpose, a tool for the automatic generation of geometrical configurations will be developed, which will allow us to explore intervals of values of the volume fraction of the nanoparticles on the one hand and the diameter of the nanoparticles (polydispersity in size) on the other hand.

In addition, comparisons will be made with measurements, for the purpose of validating numerical approaches on the one hand, and to qualify proposals for adapting the fiber manufacturing process on the other hand. This experimental component will rely on the ability to prepare optical fiber samples as developed at INΦNI laboratory but also on a collaboration with the ICGM (Charles Gerhardt Institute of Montpellier) for the production of silica-based solid samples containing Nanoparticles of controlled sizes and volume fractions. The production of such samples is already under way in the framework of another project financed by the ANR. Such monoliths will then be inserted into glass tubes and then drawn into optical fiber. These samples will study the diffusion of light by monodisperse nanoparticles with or without optical guidance. The size polydispersity studies will cover fibers prepared by the method developed at INΦNI laboratory or from monoliths prepared specifically.

Finally, the thesis will also include a software development component which will see the implementation of the new methodological contributions resulting from the work carried out in this thesis in the DIOGENeS[1] software suite, whose development started in December 2015 at Inria Sophia Antipolis-Méditerranée. This software suite is dedicated to the numerical modeling of problems of nanostructured wave/matter interaction. It integrates different variants of the family of discontinuous Galerkin methods previously discussed, resulting from research carried out in the Nachos project team. Ultimately, this software suite is intended to be exploited, developed in collaboration with researchers physicists and engineers.

Preferred academic background: Master in applied mathematics or scientific computing.

Procedure: applicants should contact Stéphane Lanteri, Stephane.Lanteri@inria.fr, and submit a CV, covering letter and the names of two academic referees.

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