Abstract

The dissertation presents research outcomes in the field of fiber optics, concerning an innovative free-form approach based on the nanostructurization method to modify refractive index distribution in optical fibers. Nanostructuring is based on the design of the refractive index distribution in optical fibers and a patented technological procedure for the fabrication of such fibers, in which the effective properties of a material are shaped by at least. Based on the above method, it is possible to fabricate high-quality all-glass optical fibers with designed, specific properties. Nanostructuring is also competitive with other technologies of optical fibers' fabrication due to high flexibility in shaping the distribution of refractive index including breaking the circular symmetry in core and cladding parts. It emerges with additional freedom in shaping the optical properties of the effective material of optical fibers, therefore the method can serve to expand the application potential in e.g. telecommunication, laser, measurement and bio-medical sectors. A comprehensive approach to nanostructured optical fibers is a topic of the project TEAM TECH/2016-1/1 "Nanostructurized microoptical components - towards new functionalities and applications". Presented work results were carried out under the TEAM TECH project.

The main objective of the dissertation is focused on broadening the application potential of free-form refractive index modification in optical fibers based on the nanostructurizaton method, mainly in the telecommunication sector. In the work, was provided an analysis of the advantages and disadvantages of commonly used solutions, including technological limitations, which can be eliminated or improved by using the nanostructuring method. Considering the current research state, and the possibilities of methods used so far, four types of free-form optical fibers were proposed. All structures are composed of pure silica glass elements with appropriate doping levels of germanium dioxide and possibly fluorine. In this way, the refractive index of silica glass can be increased (GeO_2) or decreased (F), making it possible to modify the optical fiber parameters. By using these types of glass, the positive aspects of low attenuation and thermal matching during processing are simultaneously preserved. All the presented fibers have been optimized and numerically tested. Two of the proposed fibers were fabricated by a modifiled stack-and-draw technology and studied experimentally.

The first proposed free-form solution is a hybrid optical fiber. The structure of this optical fiber is based on the use of micro-inclusions of the order of 1 μm in size with a high refractive index, arranged around a core of 2.8-μm in diameter. In this way, the fundamental mode field penetrating the cladding interacts with the placed inclusions modifying the chromatic dispersion. Moreover, it turns out that the distance of inclusions from the core influences individual parts of the spectrum. Thus it is possible to shape the chromatic dispersion profile along with a wide range of wavelengths by forming inclusions rings of different radii. Combining the aforementioned facts and the optimisation process, a flat chromatic dispersion characteristic (-37 ± 2.5 ps/nm/km) in the range of 1.3–2.15 μm was theoretically obtained. The optical fiber was fabricated using less germanium dioxide doping (due to limitations in the availability of highly doped silica rods) than in the optimised design, and the sample was experimentally tested, i.e. geometric and material analysis was performed on a scanning

electron microscope and optical linear properties, including dispersion and effective modal field, were measured.

Another optical fiber presented in the dissertation is a polarization-maintaining optical fiber with an anisotropic core artificially induced by appropriate nanostructurization. It is an optical fiber that, compared to traditionally used birefringent optical fibers, has a layered structure in a form of a circular core. Thus, the birefringence is not induced by stress (as in PANDA or bow-tie type fibers), nor geometrically (as it is the case e.g. in elliptic core fibers), but is achieved by the introduction of an anisotropic material. Moreover, the proposed modification allowed us to obtain a much larger range of single-mode operation, while maintaining compatibility with currently widely used telecommunications optical fibers. The designed structure theoretically achieved a phase birefringence of 1.42×10^{-4} for 15 mol% germanium dioxide doping and similar values of the effective modal field and numerical aperture to the SMF-28 type optical fiber. As before, due to limitations in the availability of doped materials, it was possible to fabricate the optical fiber using a lower germanium dioxide doping than indicated by numerical analysis. The fiber was characterized and experimental results confirmed the ability to maintain polarization in the infrared range and the ease of coupling to telecommunication systems.

An extension of the idea of the previous structure is the polarization-maintaining optical fiber with an artificially anisotropic core, which additionally has a large mode field and belongs to the large mode area types of fibers. The work on this type of fiber was motivated by the increased demand for this type of fiber, to obtain polarized beams at the output of a high-power laser and to minimize adverse nonlinear effects. As part of the work, the numerical optimization of optical fibers with core diameters in the range of 10 - 40 μm based on different GeO_2 and F doping configurations has been verified to propose solutions with phase birefringence above 1×10^{-4}. A significant advantage of the developed optical fibers is the single-mode operation at 1.55 μm, which is not present in commercially available polarization-maintaining optical fibers with such a large core. The proposed structure guarantees full compatibility with the used standards and allows to reduce the thickness of cladding diameter while maintaining a high-quality beam.

The last nanostructured optical fiber presented in the thesis is a few-mode fiber enabling long-distance transmission for spatial-division multiplexing. In this case, the optical fiber optimization was performed using a proprietary script, in which by modifying the number of GeO_2 doped nanorods in the core, the difference between the propagation constants in the first four linearly-polarised modes (denoted: LP_{01}, LP_{11}, LP_{21}, LP_{02}) was maximised. The implemented higher-order mode reduction algorithm made it possible to achieve a minimum value of the difference of effective refractive indices between adjacent modes at the level of 1.9×10^{-3}, which is sufficient in terms of counteracting the intermodal effect along with the optical fiber. The structured design has great application potential for spatial multiplexing, considered the next step for increasing the number of data transmission channels in telecommunications and future quantum networks.