Coating of optical fiber by thin films for creating sensors based on interaction with cladding modes

L I Yusupova\textsuperscript{1,2} and O V Ivanov\textsuperscript{1,2,3}

\textsuperscript{1}Ulyanovsk State Technical University, 432027, Ulyanovsk, Russia
\textsuperscript{2}Ulyanovsk Branch of Kotel’nikov Institute of Radio Engineering and Electronics of Russian Academy of Sciences, 432011, Ulyanovsk, Russia
\textsuperscript{3}Ulyanovsk State University, 432017, Ulyanovsk, Russia

E-mail: olegivvit@yandex.ru, lesanusupova@gmail.com

Abstract. Transmission spectra of a fiber-optic structure based on a section of SM450 fiber with a small core are investigated when a thin-film coating is deposited to the fiber cladding. A setup for deposition of films on fiber by dip coating process is created. A wavelength shift in the spectra was found in fibers coated by thin polyvinyl alcohol films. The dependence of wavelength shift on drawing speed determining the film thickness is measured.

1. Introduction

Fiber structures with insertions of non-standard fibers, the spectral characteristics of which are determined by interaction and transformation of several fiber mode types, attract considerable interest of researchers due to their simplicity, compactness, and their usability for measuring environmental parameters such as refractive index, chemical composition, humidity, and others [1–4]. Fiber structures with such features find applications as sensors of humidity [5], temperature [6], refractive index of the environment [7, 8], liquid level [9], etc. Sensitivity of the structures that excite cladding modes can be significantly increased by coating the fiber cladding with an overlay having refractive index higher than the cladding refractive index [10].

This paper presents the results of study of a fiber-optic structure with an SM450 fiber insertion having a small core and a thin-film polyvinyl alcohol coating deposited on the cladding. The mode properties and dispersion for pristine fiber and fiber with coating are analyzed. Polyvinyl alcohol films are deposited on optical fiber by the dip coating method. The transmission spectra of the structure are experimentally measured, and the dependence of wavelength shift on fiber thickness determined by the speed of drawing from solution is studied.

2. Thin-core fiber structure with coating and its modes

The fiber structure is formed by a section of thin-core fiber spliced by using a conventional fusion splicer between two standard SMF-28 fibers from Corning. As a section thin-core fiber we used SM450 fiber from Fibercore. The thin-core fiber is cleaved to obtain a section of length 5–20 cm (see figure 1) and spliced between standard fibers. Light from a broadband source is launched into one standard SMF-28 fiber. The other standard fiber is connected to an optical spectrum analyzer. SM450 fiber is designed for single-mode operation at wavelength 450 nm; therefore, this fiber has a small core: \( r_{co} \sim 1.5 \ \mu m \) (NA = 0.12, \( \lambda \) cutoff \( \sim \) 400 nm). The outer cladding has radius \( r_d = 62.5 \ \mu m \). The
polymer jacket of the section of thin-core fiber was removed to allow deposition of film coatings on the cladding surface.

Spectral properties of the structure are primarily determined by properties of the modes of SM450 fiber. SM450 fiber has a small core, so the mode structure of this fiber is significantly different from the mode structure of the standard fiber. In order to calculate cladding modes of SM450 fiber, we used the matrix method, which allowed us to find the modes of multilayer cylindrical optical fibers with an arbitrary number of layers.

The fundamental LP_{01} mode stands out among the other modes and is a core mode up to wavelengths of around 900 nm. Its effective refractive index decreases from the core refractive index and approaches the cladding refractive index with increasing wavelength. After 1200 nm, LP_{01} mode behaves similarly to other cladding modes. Modes LP_{02}-LP_{08} are modes of the outer cladding in the whole investigated wavelength range.

Cladding modes are modes of the entire fiber— their field propagates both through the core and the outer cladding of the fiber. With an increase in the radial mode number, the number of oscillations of amplitude of the field along radius increases; the fraction of the field propagating near the fiber core decreases; and the field amplitude near the outer surface of the cladding increases.

At the junction of the standard fiber and the thin-core fiber, radiation from the core of SMF-28 fiber enters SM450 fiber, and the radiation energy is redistributed between modes of SM450 fiber. Efficiency of energy transfer is determined by matching between mode field profiles of the output and input fibers (overlap integral between the two modes). The core mode profile of SMF-28 fiber has a significantly narrower size at around 1550 nm compared to the modes of SM450 fiber, so there is no transfer of energy to some particular mode, but several modes are excited at the same time.

When a thin-film coating is deposited on cladding of an optical fiber, an additional optical layer is created. This layer changes the propagation constants of cladding modes and, if its refractive index is higher than the cladding index, leads to the appearance of modes of the outer layer. If one needs to increase sensitivity of cladding modes, one way to do this is to cover the fiber with a coating having refractive index higher than that of the cladding.

As the coating thickness increases, the effective refractive indices of cladding modes increase as a result of average increase in the refractive index of the structure. After reaching a thickness of 1 μm, the coating captures the first LP_{01} mode, and the effective refractive index of this mode approaches the refractive index of polyvinyl alcohol. At a thickness of 4 μm, the next LP_{02} mode goes into the coating, while the effective refractive indices of other modes make a jump. A similar jump is repeated approximately every 2.8-μm increase in the film thickness.

3. Deposition of coatings on fiber

Polymeric coatings of polyvinyl alcohol were deposited on optical fibers using dip-coating method, when the fiber is immersed in solution and then drawn out. First, the fiber stripped of polymer coating is immersed in pre-prepared water solution of polyvinyl alcohol. Then the fiber is drawn vertically upward from the solution. The remnants of solution flow down the fiber under the action of surface tension and gravity force. Some part of the solution remains on the fiber in form of a thin liquid film, the thickness of which is determined by the speed of drawing. After that, the film dries and is fixed on the surface of the fiber. The faster the fiber is drawn out of solution, the thicker layer of
material is deposited on the fiber. The film thickness can also be controlled by changing the viscosity (concentration) of the solution. During the drawing process the solution may continue flow down the fiber, which results in smaller film thickness in the upper part of the fiber.

To increase the surface field of fiber modes, the refractive index of the coating must be greater than the refractive index of the fiber cladding. The refractive index of polyvinyl alcohol at a wavelength of about 1500 nm is approximately 1.47 and that of quartz is 1.44, i.e. the required ratio is satisfied. A solution of polyvinyl alcohol was prepared by dissolving powder of polyvinyl alcohol in distilled water on a steam bath during one hour. Concentration of polyvinyl alcohol in the solution can vary from 3.5 to 15% (mass.). In our case, alcohol concentration was 4%. The samples were dried at room temperature for several minutes after deposition of the film. With the parameters of solution and deposition described above, one can obtain films with thickness from hundreds to thousands of nanometers.

To immerse and draw optical fiber out of solution, a setup has been created (figure 2), where the fiber is fixed and can evenly move along the vertical axis. The setup has a stepper motor with a reduction gear mechanism, which rotates a support shaft moving a carriage with speed from 0.1 to 1.7 mm/s. A 20-cm-long section of thin-core fiber is stripped of polymer coating and is fixed with a slight tension between the two clamps on the holder.

![Figure 2. Photographs of the setup (a) and the fiber holder (b).](image)

Thickness of the film deposited by drawing fiber at a speed of 1.632 mm/s was measured using a scanning electron microscope. Images of the fiber obtained with a microscope are shown in figure 3. The measured film thickness is 1.12 microns.

The spectrum of the fiber structure was measured using an optical spectral analyzer 5 minutes after the end of drawing process. After measuring the spectrum, the fiber was washed in water and cleaned with ethyl alcohol. This procedure was repeated several times for different drawing speeds. In this way, the drawing rate was reduced from 0.5 to 1.6 mm/s. The experiment was completed by measuring the transmission spectrum of the uncoated structure.

Figure 4 shows the measured transmission spectra of an uncoated fiber structure (solid curve) and with a polyvinyl film overlay, which was applied by drawing from solution at a speed of 1.51 mm/s (dashed curve). The spectra represent a series of peaks with a distance of order of several tens of nanometers between them. It can be seen that when the film is deposited on the surface of the cladding the entire spectrum shifts to longer wavelengths, while in general its shape remains unchanged. The average wavelength shift of the spectrum is about 10 nm. The reason for the shift of the spectrum is a
change in the refractive index profile of the fiber, which is a result of the fact that the film deposition leads to a displacement of cladding mode profiles and to a change in their propagation constants.

Figure 3. Image of fiber surface with polyvinyl alcohol coating (a) and fiber butt end with a 1.12 µm-thick coating layer obtained by drawing from solution at a speed of 1.632 mm/s (b).

Figure 4. Spectra of an uncoated structure (solid curve) and with a polyvinyl overlay layer, applied by stretching from a solution of velocity 1.51 mm/s (dashed curve).

Figure 5. Dependence of the shift of the wavelength of the transmission spectrum peaks at different speeds of pulling the fiber out of solution 0.59, 0.87, 1.31, and 1.51 mm/s (curves 1–4).
The dependences of the wavelength shift for several peaks in the transmission spectrum obtained at different speeds of fiber drawing from the solution are shown in figure 5. It is seen that, with an increase in the drawing speed, the shift increases from 2 to 10 nm, which is related to corresponding increase in the film thickness. At the same time, there is some increase in the magnitude of the shift for peaks at longer wavelengths.

4. Conclusions
The fiber structures with thin core and overlay film coatings of polyvinyl alcohol can be used in sensor applications as an element sensitive to humidity or chemical composition of the external medium due to sensitivity of refractive index of polyvinyl alcohol to these parameters. The value of the measured parameter can be determined from wavelength shifts of spectral resonances.

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