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Dedicated to Professor Jan Dorosz
on the occasion of his 65th birthday

Novel constructions of optical fibers doped with rare – earth ions

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Abstract. In the paper the research on rare-earth doped and co-doped optical fibre conducted in the Laboratory of Optical Fiber Technology at the Bialystok University of Technology is presented. Novel active fibre constructions like multicore, helical-core and side detecting ribbon/core optical fibers were developed with a targeted focus into application. First construction i.e. multicore RE doped optical fibers enable supermode generation due to phase - locking of laser radiation achieved in a consequence of exchanging radiation between the cores during the laser action. In the paper a far – field pattern of 19 – core optical fiber-doped with Yb^{3+} ions, registered in the MOFPA system, showed centrally located peak of relatively high radiation intensity together with smaller side-lobes. Another new construction presented here is helical-core optical fibers with the helix pitch from several mm and the off-set ranging from 10 μm to 200 μm. The properties of helical-core optical fiber co-doped with Nd^{3+}/Yb^{3+} were also discussed. In the field of sensor applications novel construction of a side-detecting luminescent optical fiber for an UV sensor application has been presented. The developed optical fiber with an active core/ribbon, made of phosphate glass doped with 0.5 mol% Tb^{3+} ions, was used as a UV sensing element.

Key words: optical fibers, Rare earth ions, multicore optical fiber, helical core, upconversion, neodymium, ytterbium.

1. Introduction

Development of rare – earth doped optical fibers and laser diode pumping techniques enabled to produce high-power fiber lasers, telecommunication amplifiers and amplified spontaneous emission (ASE) sources with a very good quality of the radiation beam [1–5]. In particular the modified chemical vapour deposition (MCVD) method has played an essential role in high quality double clad silica optical fibers [6, 7]. However, despite the high technological level of active fibers made of MCVD, there exist some limitations of silica glass as a laser medium itself. In particular, high strength of Si-O-Si bonds limits maximum concentration of rare earth ions in silica glass (e.g. 1500 ppm Er^{3+}). It results from RE clusters formation, which leads to interionic interactions [6]. Another essential aspect consisted in an increase of non-radiative decays probability, which is a consequence of high phonon energy of silica (1100 cm^{-1}). Taking above into account numerous works have been done in order to develop a novel glass host for active optical fibres [8–11]. It has been shown that the choice of the glassy matrix for production of the active fiber has a crucial impact on its spectroscopic properties. For example aluminosilicate optical fibers working on the spectral range of 1 μm were presented [2, 3] and the main advantage of the proposed host was the lower RE clustering effect, which in consequence allowed to obtain a luminescence emission gain over a shorter length of a fiber [4]. Double-clad multicore optical fibers, which have been introduced in recent years, offer new possibilities in the field of short-length fiber lasers design [12–16]. In this construction, the amount of doped rare - earth element ions is higher than in typical single core fibers, which is proportional to the number of cores. Moreover, multiple cores in fiber cladding reduce the length of the fiber which is necessary to absorb the pumping radiation [17–19]. The second way to enhance the emission of an active optical fiber could be active optical fibers with the helical eccentrically located active core. The proposed construction enables to obtain a high absorption coefficient of the pumping radiation and a larger diameter of the core realised due to a helical core which also fulfils the role of a mode selector [20–22]. Development in optical sensing, biological analysis, biomedical diagnostics and RGB displays towards the construction of a new radiation sources operating in the visible spectrum. It should be characterized by: high selectivity, good beam quality of high-power density fiber toward directs optical fibers doped with rare-earth ions sources of radiation. Visible light sources, either in the form of laser or broadband source, relies on IR to VIS upconversion mechanism [18, 19]. The Yb^{3+}/RE systems are especially interesting because they can be pumped directly by a commercial laser diode (976 nm) [23–26]. Specific spectroscopic properties of glasses doped with lanthanides enable to construct new sensors based on measurement of radiation. Fiber-optic sensors have many advantages over conventional optical sensors [27, 28]. The former are small in size, light, electrically safe and resistant to electromagnetic interference. Moreover, it offers the possibility of distributed measurements along the whole sensor length [29, 30].

The paper presents investigation on technology of special optical fibers doped and co-doped with rare-earth ions which are conducted in the Laboratory of Optical Fiber Technology in the Bialystok University of Technology. The following new constructions of multicomponent active optical fibers are presented: multicore, helical core, upconversion emission and side – detecting whose parameters enable to its application for constructing broadband sources of optical radiation and compact UV sensors.

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2. Multicore optical fibers

Double-clad multicore optical fibers offer new possibilities in constructing of high-power short-length fiber lasers [31–35]. The main advantage is higher concentration of embedded rare earth ions than in typical single-core fibers which is proportional to the number of cores. As a result of placing multiple cores in fiber internal cladding makes it possible to reduce the length of the fiber which is necessary to absorb the pumping radiation [34]. A new approach concerns the development of optical fibers lasers with low divergence of a beam. If the condition of coherent radiation generated in individual cores is fulfilled, then in the far - field diffraction pattern a centrally located peak of high intensity and low divergence (i.e. supermode) would be obtained, along with symmetrically placed side-lobes of significantly lower intensity [35]. Furthermore, angular divergence of the central peak decreases proportionally to the number of emitters (i.e. elements of the matrix) generating mutually coherent radiation (with the ratio $N^{0,5}$, where N is the number of emitters). Eventually, the width of a laser beam profile in a phase-locked multicore fiber is several times smaller than usual, which is impossible to achieve in a standard single-core active fiber. Multicore fibers whose cores are placed in a common cladding make it possible to achieve higher power output in comparison to common double-clad fibers, but at the same time they keep good quality of laser beam. Designing of a multicore optic fiber should enable phase-locking of the radiation generated in each of the cores in the fiber working as a fiber laser. In the project [36] aluminosilicate multicore optical fibers doped with Nd^{3+} and Yb^{3+} with phase-locking phenomenon were developed. Elaborated optical fibers were fabricated using the modified rod-in-tube method. The proposed optical fibers constructions facilitate phase-locking of the radiation from particular cores operating in a fiber laser system. The model of phase-locking of the radiation generated in particular cores is based on exchanging a part of mode as a result of coupling between the cores [35]. During each passage of the photon flux through a resonator an exchange of some part of the generated radiation takes place between adjacent cores. In consequence, the phase difference of the radiation generated in the cores is smaller after each passage. Radiation from cores is coupled with the radiation from the adjacent cores. Single-mode cores are placed in a common cladding. The analyzed optical fibers have the following parameters: diameter of the cores $2r = 10\ \mu$m, normalized frequency $V = 1.9 - 2.4$, distance between the cores $d = 18 - 25\ \mu$m. The spatial distribution of the emitted laser radiation for each core is described by a Gaussian function.

$$E_m(x, y, z = 0) = A_m \exp\left[\frac{r^2}{w_0^2} + i\varphi_m\right], \tag{1}$$

A_m – max. amplitude of field m-th core, $r^2 = (x - mx_d)^2 + (y - ny_d)^2$ – cores coordinates w_0^2 – mode field radius, φ_m – phase of radiation generated in m-th core.

A complete description of the laser beam generated from the n-th core in plane z is expressed by the following equation:

$$E_n(x, y, z) = \frac{w_0}{w(z)} \exp\left(-\frac{((x - x_n)^2 + (y - y_n)^2)}{w^2(z)}\right) x$$
$$\exp\left(-i\left\{k\left[\frac{((x - x_n)^2 + (y - y_n)^2)}{2R(z)} + z\right] - \Psi + \Psi_{n0}\right\}\right), \tag{2}$$

where

$$k = \frac{2\pi}{\lambda}, \qquad Z_0 = \frac{\pi w_0^2}{\lambda},$$
$$w(z) = w_0\sqrt{1 + (z/z_0)^2}, \qquad R(z) = Z_0\left(\frac{z}{Z_0} + \frac{Z_0}{z}\right),$$
$$\Psi = \arctan(z/z_0).$$

The diffraction pattern in the Fraunhofer diffraction region has been calculated according to the formula:

$$U(x, y, z_d) = \frac{e^{(-ikz_d)}}{i\lambda z_d}$$
$$\cdot \iint U(x_1, y_1, z_1) e^{\frac{-ik}{2z_d}[(x - x_d)^2 + (y - y_d)^2]} dx_1 dy_1, \tag{3}$$

where $k = \dfrac{2\pi}{\lambda}$, x_1, y_1 – coordinates of cores, z_d – observation distance.

The far-field intensity pattern is proportional to the square of the field amplitude averaged in time $|U(x, y, z)|^2$. In order to calculate the far-field pattern a method based of the two – dimensional FFT transform based on the Cooley-Tukey algorithm has been used.

$$F(p, q) = \sum_{m=0}^{M}\sum_{n=0}^{N} f(m, n) e^{-j\left(\frac{2\pi}{M}\right)pm} e^{-j\left(\frac{2\pi}{N}\right)pn}, \tag{4}$$
$$p = 0, 1, \ldots, M - 1, \qquad q = 0, 1, \ldots, N - 1.$$

The steps required to compute the Fourier transform are: discretize the near field, compute the DFT using FFT algorithm, and relate the integer parameters back to spatial coordinates. Figure 1 shows results of the near and far-field simulation, assuming that radiation phases generated in particular cores are equal. The central peak intensity is much higher than in case of emitters working independently. It should be also noted that the laser spot diameter in phase – locked multicore fiber lasers is inversely proportional to the number of cores. The highest quality factor of the laser beam is obtained when the value of normalized frequency is low and the distance between the cores is small. Then the intensity of the central peak is high and the amount of energy contained in the side lobes is low.

In order to realize supermode generation, as far as geometric and material parameters of a double-clad multicore active optical fibers have to be concerned. Figure 2 shows the cross-section of the face of the produced optical fibers. High numerical aperture (0.58) of the inner cladding facilitates effective pumping.

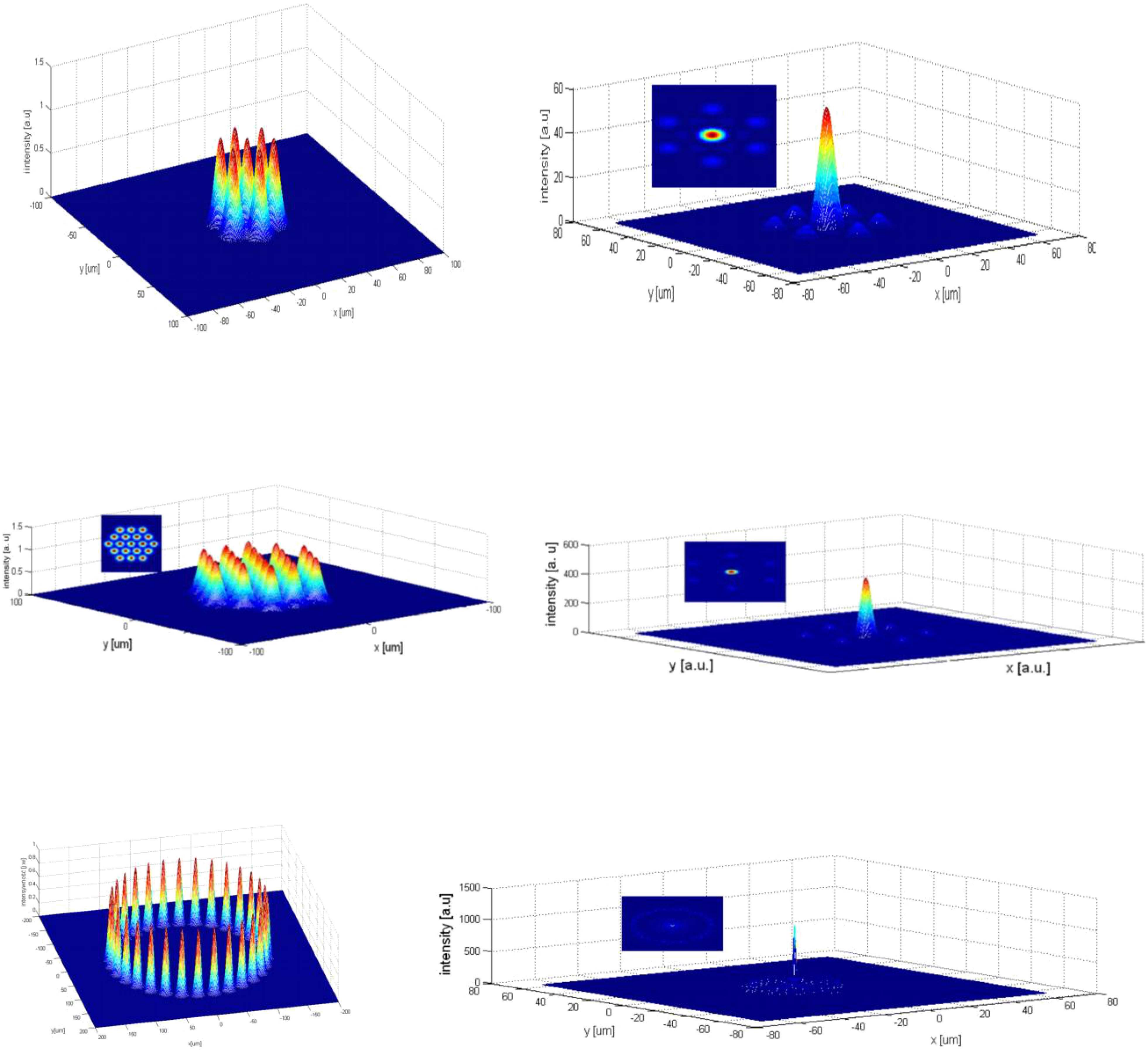

Fig. 1. Near – field (left) and far – field (right) patterns of multicore phase – locked optical fibers, $V = 2.4$, $d = 25$ μm (distance between cores)

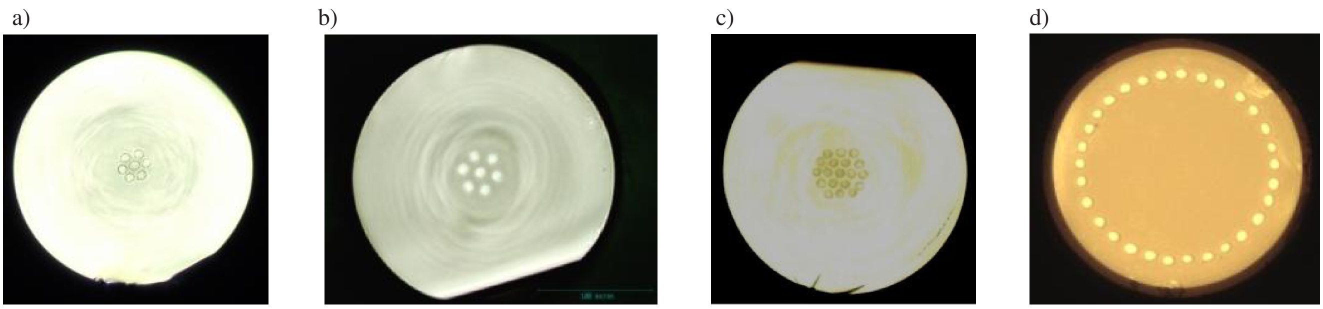

Fig. 2. Cross-section of the fabricated double-clad 7-core doped with Yb^{3+} (a), 7-core doped with Nd^{3+} (b), 19-core doped with Yb^{3+} (c), 30-core doped with Nd^{3+} (d) optical fibers

The manufactured optical fibers are characterized by strong luminescence as a result of pumping with a semiconductor laser diode (Yb^{3+}: $\lambda = 980$ nm). Luminescence bands at 1020 nm (Yb^{3+}:$^2F_{5/2} \rightarrow {}^2F_{7/2}$) and 890, 1060 and 1330 nm (Nd^{3+}:$^4F_{3/2} \rightarrow {}^4I_{9/2}$, $^4I_{11/2}$, $^4I_{13/2}$) were obtained (Fig. 3).

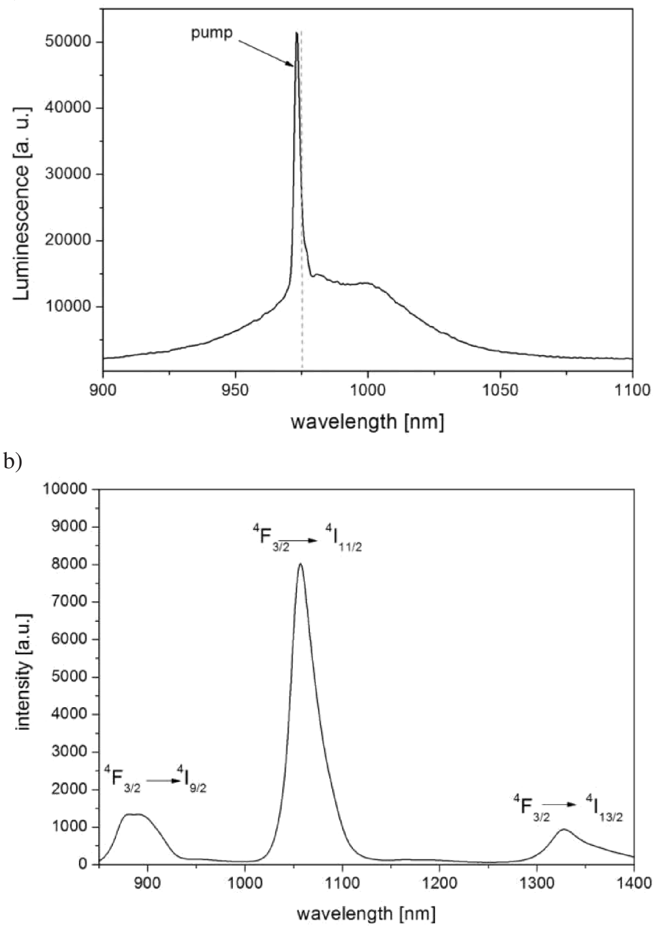

Fig. 3. Luminescence spectra of: 19-core optical fiber doped with Yb^{3+} (a), 7-core optical fiber doped with Nd^{3+} (b)

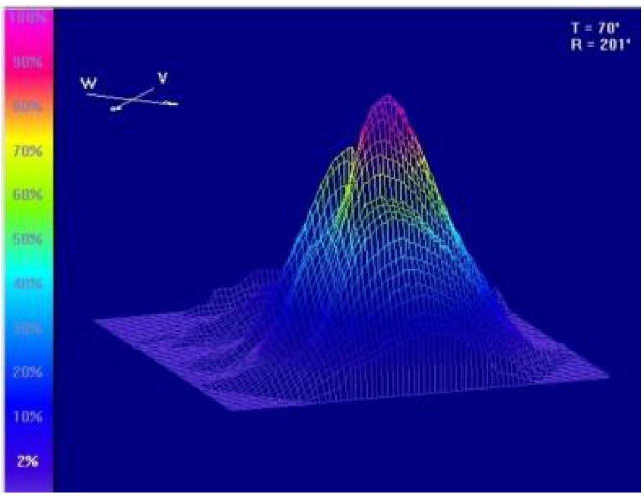

Fig. 4. Far – field pattern registered in 19-core Yb^{3+} – doped fiber

The experimental setup for measurement of the far – field of active multicore fiber consists of: NUFERN LMA 20/400 Yb^{3+} seed laser, 2 pump modules ($P_{\max} = 30$ W), side coupler, laser beam analyzer. The seed laser was pumped using a 980 nm laser diode. The fabricated 19-core optical fiber doped with Yb^{3+} was coupled by manufactured by authors side coupler and pumped by AlGaAs laser diode ($\lambda = 980$ nm). The far – field diffraction field pattern of fabricated multicore fiber was measured by laser beam analyzer (Newport KEP-3-IR3).

The experimentally registered far-field pattern of the fabricated 19-core optical fiber doped with Yb^{3+} consists of a central peak with high intensity and side lobes (Fig. 4), which confirms of phase – locking in the fabricated multicore optical fiber.

3. Helical core optical fiber

Helical core optical fiber co-doped with Nd^{3+}/Yb^{3+} is another construction discussed in the paper [37]. A specific feature of that fiber relays on the possibility to obtain a high absorption coefficient of the pumping radiation and a larger volume of the core with a helical shaped core works as a mode selector. In case of the active helical-core optical fiber construction, apart from issues connected with a synthesis of glasses and seeking new methods of its formation, geometric parameters of the core are also important – eccentricity, pitch of the helix and diameter of the coil are critical parameters [38, 39]. Preparation of such a fiber requires both optimisation of optical parameters of the core and the cladding, and also geometry of the helix. The method of drawing should allow for circumvolution of the formed optical fiber perpendicularly to the direction of its drawing (z-axis). The methods of drawing known so far do not fulfil these requirements. In order to achieve that rotating of preform or set of crucibles during the technological process were used. Radiation losses in the helical-core optical fiber result mainly from two mechanisms. They include microbend losses and losses caused by the field interference between subsequent coils of the helix. The relations describing losses of the energy impulse (modes) in the helical-core fiber are generalised results for a circularly bent optical fiber. Propagation losses of the helical core depend strongly on the pitch length and the coil radius, the impulse length and the state of polarization [39]. Figure 5 and 6 present the results of calculations for single mode operation in helical core optical fiber with parameters shown in Table 1. The construction and conditions of forming the helical-core optical fiber enabled to obtain the helix pitch from several mm and the off-set ranging from 10 μm to 200 μm. By the rotation of preform a series of optical fibers with a different pitch of the core helix was produced (Table 1). Different values of the helix pitch were obtained through the change of the rotational speed of the perform. Producing optical fibers of such a type requires selecting the appropriate temperature of the drawing process (rotational speed), which allows to obtain the demanded helix pitch.

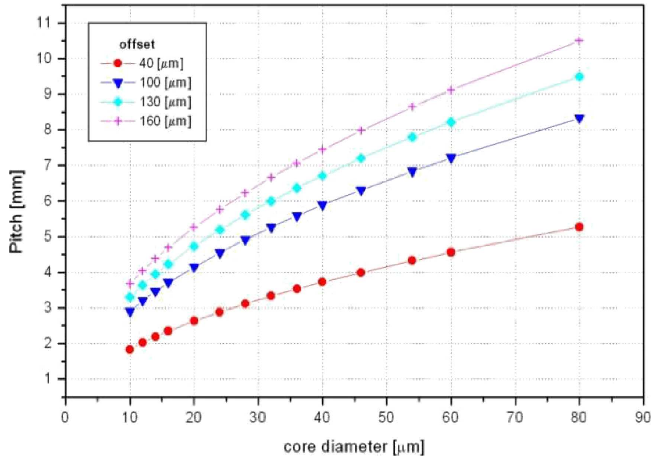

Fig. 5. Helix pitch vs. core diameter for different offset of the core, NA = 0.12

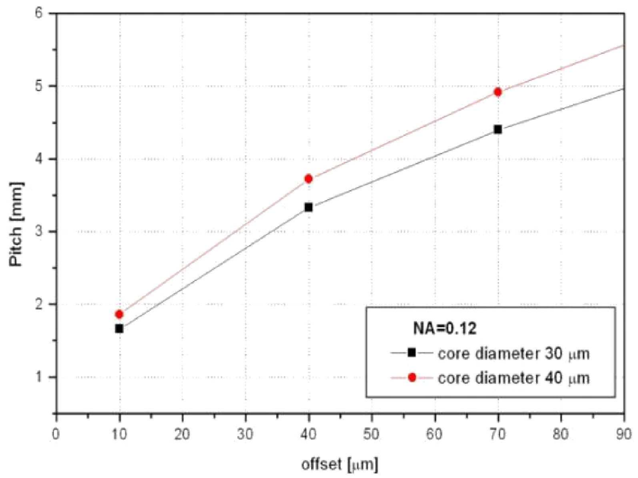

Fig. 6. Helix pitch vs. core offset for core diameter 30 μm and 40 μm, NA = 0.12

Figure 7 (inset) shows a cross section of oxyfluoride, silicate helical-core optical fiber with the NA = 0.127, core diameter (40 μm), core offset (130 μm), helix pitch: 12.5 mm. Luminescence spectra (Fig. 7) of the optical fiber doped with $0.15Nd^{3+}$:$0.75Yb^{3+}$ (mol%) show strong emission band at 1.06 μm $^4F_{3/2} \rightarrow {}^4I_{11/2}$ (Nd^{3+}) and other bands at: 0.9 μm $^4F_{3/2} \rightarrow {}^4I_{9/2}$ (Nd^{3+}), 1 μm $^2F_{5/2} \rightarrow {}^2F_{7/2}$ (Yb^{3+}) and 1.34 μm $^4F_{3/2} \rightarrow {}^4I_{15/2}$ (Nd^{3+}).

Table 1
Parameters of manufactured helical core optical fiber

Parameter	Value
Core diameter	40 μm
Optical fiber diameter	400 μm
Numerical aperture *NA*	0.127
Helix pitch *P*	12.5 mm
Core offset r_o	130 μm

It should be noted that the observed broadband emission was obtained as an effect of the energy transfer ($Nd^{3+} \rightarrow Yb^{3+}$) in the manufactured helical core optical fiber. The percentage efficiency of energy transfer calculated according to the Dextera-Forster model for the core glass co-doped with $0.15Nd^{3+}$: $0.75\%Yb^{3+}$ is 60%.

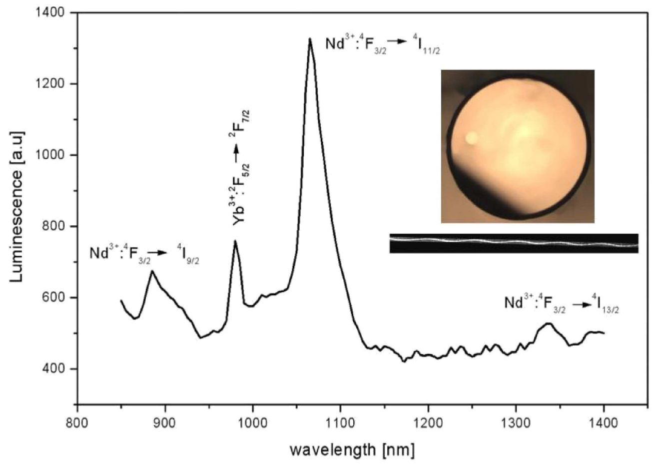

Fig. 7. Cross section of double clad, helical-core (inset) and luminescence spectra of fabricated optical fiber co-doped with $0.15Nd^{3+}$:$0.75Yb^{3+}$ ions

4. Upconversion emission in tellurite optical fiber co-doped with Yb^{3+}/Ho^{3+}

Visible emission in optical fiber co-doped with lanthanides was realised via upconversion energy transfer process achieved in tellurite, germanate based glassy matrix [40]. Luminescence in the elaborated glasses and optical fibers were obtained as a result of infrared frequency upconversion to the visible range [41–43]. The efficiency of the upconversion process strongly depends on the type of the used matrix, and in particular on the energy of phonon vibrations [44, 45]. The lower of the maximum lattice vibrations frequency $h\omega_{\max}$ leads to the higher probability of energy conversion. The most popular silica glass is a well-known high phonon- and high band gap-energy glass. The silica fibers are characterized by low losses at VIS spectra region. However, relatively short lifetime of excited levels related to upconversion emission, and high probability of multiphonon processes disqualify them as a candidate for the upconversion optical fibers. Among the materials with low phonon energy are fluoride and HMO (Heavy Metal Oxide) glasses, whose phonon vibrations are in the range 300–600 cm^{-1}. Unfortunately, low mechanical and thermal resistance make it difficult to use these kinds of glasses in optical fibers manufacturing. The problem can be overcome by using tellurite glasses having relatively low phonon energy (750 cm^{-1}), and exhibiting higher thermal stability [46–48]. The tellurite optical fiber was manufactured using a modified double - crucible technique. Figure 8 presents a cross-section of the fabricated tellurite optical fiber co-doped with 0.5%mol Yb_2O_3/ 0.1%mol Ho_2O_3.

Luminescence bands at the wavelengths of 545 nm and 658 nm ($^5S_2(^5F_4) \rightarrow {}^5I_8, {}^5F_5 \rightarrow {}^5I_8$), were obtained as a result of the upconversion energy transfer between Yb^{3+} and Ho^{3+} ions. However, the shape of the upconversion emission spectra of the optical fiber is significantly different from the typical luminescence spectra of the tellurite glass. The amplified spontaneous emission bands resulting from the optical transition in the energy structure of holmium was observed. The intensity of the emission band at 545 nm ($^5S_2(^5F_4) \rightarrow {}^5I_8$) of the fabricated optical fiber is several times smaller than the intensity of the emission band 657 nm ($^5F_5 \rightarrow {}^5I_8$). In addition, the peak emission corresponding to the transition $^5F_5 \rightarrow {}^5I_8$ is shifted by 3 nm towards longer wavelengths. This phenomenon is related to reabsorption of the emitted ASE signal. Interesting from the viewpoint of analysis of the conversion processes of the tellurite optical fiber is appearance of emission band at 507 nm. Changing the geometry of interaction of the optical pump radiation with the active core of the produced tellurite optical fiber leads to population of higher Stark levels $^5S_2$ ($^5F_4$) and subsequent emission at 507 nm.

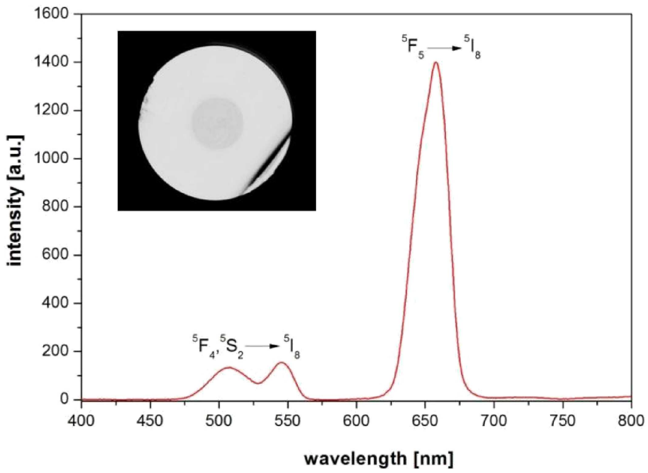

Fig. 8. Cross-section and luminescence spectra of the fabricated tellurite optical fiber co-doped with 0.5%mol Yb_2O_3/ 0.1%mol Ho_2O_3. Dimensions 60/200 μm, NA = 0.56

5. UV side-detecting optical fiber doped with Tb^{3+}

The construction of the fabricated optical fiber is based on the designed sensing fiber with an active core/ribbon located on the side of the fiber [49]. A modified structure of the side-emitting fiber allows coupling of optical signal from the core/ribbon to the undoped cladding area of the optical fiber. The cladding area was made of glass with a higher refractive index, hence the signal of luminescence is transmitted from the core/ribbon to the undoped clad and propagates inside due to total inner reflection. The fiber diameter is 350 μm and the radius of the active, semi-circular core/ribbon, which is located in the fiber side surface, is 50 μm. In addition, the absorption edge of fabricated phosphate glass at 200 nm enables to efficient absorption of UV radiation by the Tb^{3+} ions.

Figure 9 shows the photograph of the fabricated fiber and the luminescence spectrum obtained as an effect of UV excitation.

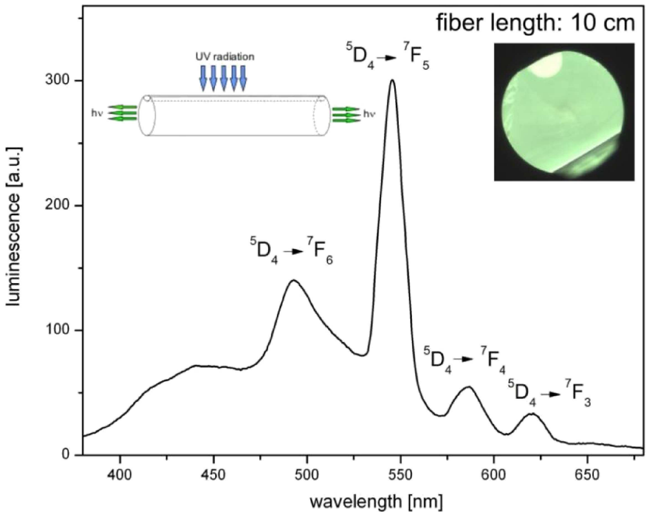

Fig. 9. The emission spectrum of phosphate side-detecting optical fiber doped with 0.5 mol%Tb_2O_3 and in inset cross-section of fabricated fiber and scheme of measurement setup

As a result of the absorption of UV radiation from the side surface of the optical fiber it was possible to measure the luminescence of Tb^{3+} ions at the end of the fiber (the scheme inside the set of Fig. 9). The asymmetry of fabricated fiber geometry enables effective UV absorption in a half-space. The maximum intensity of green emission was measured in the opposite position of the active core/ribbon and the output window of the deuterium lamp. The luminescence signal was collected at the end of the optical fiber.

6. Conclusions

The paper presents investigation on technology of optical fibers doped and co-doped with rare-earth ions, which are conducted in the Laboratory of Optical Fiber Technology at the Bialystok University of Technology. The constructions of multicore, helical core, upconversion and side-detecting active optical fibers were developed within the framework of completed projects [36, 40]. New multicore optical fibers doped with neodymium and ytterbium are characterized by luminescence at 1 μm. Moreover, it was proposed the achievement of supermode generation can be obtained by exchanging radiation between the cores during the development of the laser action. The phase – locking phenomenon of 19-core optical fiber doped with Yb^{3+} ions was confirmed by measurement of far-field pattern which consists of a central peak with high intensity and side lobes. In the fabricated optical fiber with helical core made of oxide-fluoride silicate glass co-doped with Nd^{3+}/Yb^{3+} ions luminescence of the manufactured optical fiber differs from the emission spectra of as meted active glass used for a core. It could be possibly caused by high losses of a spontaneous emission because of a helically shaped core. However, broadband emission of the fabricated fiber in the range of 1 μm enables to use elaborated optical fibers for construction of compact amplified spontaneous emission sources of radiation. Upconversion emission in optical fibers was achieved in a low phonon tellurite glass matrix. The optical fiber co-doped with Yb^{3+}/Ho^{3+} was manufactured using a modified for this purpose double – crucible technique. Luminescence bands at 545 nm and 658 nm ($^5S_2(^5F_4) \rightarrow {}^5I_8, {}^5F_5 \rightarrow {}^5I_8$) obtained as a result of the upconversion energy transfer between Yb^{3+} and Ho^{3+} ions were measured. Observed differences between luminescence spectra of bulk glass and optical fiber are related to reabsorption of the emitted ASE signal. Moreover, changing the geometry of interaction of the optical pump radiation with the active core of the produced tellurite optical fiber leads to population of higher Stark levels $^5S_2(^5F_4)$ and subsequent emission at 507 nm. Conducted analysis of upconversion amplified spontaneous emission (UASE) allows to optimize the emission properties of the manufactured tellurite optical fiber co-doped with 0.5 mol% Yb_2O_3/0.1 mol% Ho_2O_3 and indicates its numerous application in photonics. In the first time a new sensing optical fiber construction with the core/ribbon doped with Tb^{3+} was presented. The selection of phosphate glass enabled the shift of the absorption edge to the UV-C range. Strong absorption band at the wavelength of 248 nm (Tb^{3+}) enables detection of UV radiation. A strong emission band in the characteristic green colour emission resulted from the $^5D_4 \rightarrow {}^7F_5$ transition of terbium ions was achieved in fabricated glass excited by UV radiation. Luminescence measurement of the fabricated optical fiber confirms its ability to selective detection of the radiation in the UV range and can be used in the construction of luminescence UV sensors.

To summarize, the presented research on technology and designing of optical fibers co-doped with RE ions open possibility to construct compact VIS-NIR ASE optical fiber sources as well as UV radiation sensors.

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