Development of alternative fiber optic Raman probes based on optical fibers with written precision micro-structure defects

A V Bourdine\textsuperscript{1}, D N Artemyev\textsuperscript{2}, I A Bratchenko\textsuperscript{2}, A S Evtushenko\textsuperscript{1}, V S Kazakov\textsuperscript{1}, I A Karptsov\textsuperscript{1}, M Yu Kartashov\textsuperscript{1}, J E Litvinova\textsuperscript{2} and V P Zakharov\textsuperscript{2}

\textsuperscript{1}Povolzhskiy State University of Telecommunications and Informatics, Lev Tolstoy str. 23, Samara, Russia, 443010
\textsuperscript{2}Samara National Research University, Moskovskoe Shosse 34, Samara, Russia, 443086

e-mail: bourdine@yandex.ru

Abstract. This work is devoted to development of alternative fiber optic Raman probes; it consists of silica optical fibers with integrated Bragg gratings and formed precision micro-lens at the core end. We present a method for forming micro-lens by commercial field fusion splicer with its modified software. We demonstrated some results of its experimental approbation. We carried out experimental researches of software settings influence: fusion time and fusion current on micro-lens radius.

1. Introduction
Nowadays medical diagnostics based on optical methods and Raman spectroscopy commands great attention due to its ability for non-invasive analysis of living organisms \cite{1-5}. Application of fiber optic probes provides advantages for both patient and medical staff because it does not require tissue resection, therefore Raman spectroscopy is widely used in various applications for cancer diagnostics \cite{5}. In comparison with free space optical emission propagation, utilization of optical fibers in Raman probes provides improvement of both positioning and light-gathering abilities. Here delivery channel should contain narrow band-pass filter to subtract Raman background in exciting optical fiber. Second filter is required to suppress Rayleigh scattering laser emission, i.e. for Rayleigh scattering filtration in collection fibers, because elastically scattered light of exciting laser is more intensive in several orders in comparison with non-elastically scattered signals of Raman scattering. The most known solutions are based on thin film filters or holographic filters, which require precision positioning and corresponding fixation that involves expensive high quality micromechanical elements. Another one problem of described filters utilization in probes is probe outer diameter, while for various medical applications (for example colonoscopy or cardiovascular endoscopy) access to tissue is limited by anatomy. Here Raman probe outer diameter should be less 2 mm to be used in conventional cardiovascular catheters or endoscope working channels.
Earlier on we proposed alternative solution for described filtration problem based on cascade of fiber Bragg gratings written over Raman probe optical fiber [5]. In the most cases they are conventional silica optical fibers. Here small core diameter leads to problems of Raman scattering collection, while it may be improved by forming special precision micro-lenses with desired configuration. This work is concerned with development of simple method for micro-lensed optical fiber making by commercially available field fusion splicer Ericsson FSU-975 [6] and its modified software settings. We present methods for writing hemispherical lens and balls as well as tapered cones, results of their experimental approbation and results of following carried out experimental research of fusion splicer software settings impact on micro-lensed optical fiber geometry parameters – radius and length (distorted by fusion optical fiber length from its end differing from cladding diameter).

2. Forming of micro-lensed optical fibers with required geometry

We formed micro-lensed optical fibers by commercially available field fusion splicer Ericsson FSU-975 kit. At the first stage the program #9 was used, that provides process of simultaneous pulling and heating of fused optical fiber into an hour glass shape that eventually divides at the tip. Following additional arc smoothes fiber end and makes semi-spherical form transforming it into hemispherical lens, while repeated forced fusion of prepared fibers with “narrowed” ends forms balls corresponding to spherical or ball lens. Samples of prepared hemispherical and ball lenses been made at the end of commercially available multimode optical fiber ISO/IEC Cat. OM2+/OM3 are represented on Fig. 1 (a)... (d).

![Figure 1. Samples of micro-lensed multimode optical fiber ISO/IEC Cat. OM2+/OM3: (a) and (b) hemispherical lenses; (c) and (d) ball (spherical) lenses.](image)

Fabricating of tapered cone requires performing of additional steps. Here during the first stage an up-taper is preliminary prepared by earlier on developed method for writing precision micro-structured defects described in published works [7, 8] (Fig. 2(a)). Up-taper is formed by splicing of two optical fibers under following manually fiber precise movement during fusion process by standard program
“MM-MM”. Then by analogously to hemispherical lens the program #9 is started. As a result center zone of up-taper is heated and pulled with dividing optical fiber to the two desired tapered cones. Additional repeated fusion may be performed when needed to smooth tapered cone end and form hemispherical lens with extremely low radius (Fig. 2 (b)...(d)).

Presented methods and fabricated samples of micro-lensed optical fibers demonstrate potentiality for fabricating fiber optic hemispherical lenses, ball lenses and tapered cones on telecommunication silica optical fiber end by commercially available field fusion splicer kit unlike known solutions based on using of specialized lab equipment [9-11]. However further application in Raman spectroscopy measurement schemes requires manufacturing of described micro-lensed fibers with desired configuration, precision geometry and high repeatability of their parameters.

Therefore additional experimental investigations are required to research fusion splicer modified software settings impact on micro-lensed fiber geometry. Here another problem arises, which is concerned with correct estimation of fiber optic micro-lens key parameters – radius and length. The obvious solution of described problem is visual evaluation of micro-lens geometry by analysis of images of splice burning zone snapshots performed during the fusion process and downloaded to PC via fusion splicer video output. Here a passage from relative parameters normalized on optical fiber cladding diameter to real value is required: it is known [12, 13], that telecommunication silica optical fiber cladding diameter deviation from nominal 125 \( \mu m \) value may amount up to 2 \( \mu m \) and even more. As a result, at first an additional development of method for macro-structure defect geometrical parameters estimation based on analysis of fusion splicer display screen shots was performed.

3. Method for estimation geometrical parameters of optical fiber based on analysis of fusion splicer display snapshot

At first we have selected and prepares 28 samples of 0.5 m commercially available both singlemode optical fibers ITU-T Rec. G.652, G.655, G.657 and multimode optical fiber Cat. OM2+/OM3 and OM2. Then by using EXFO NR-9200HR Optical Fiber Analyzer each sample refractive index profile was measured. Here measured data contains arrays of radial coordinate and refractive index distribution over conditional cross-sections “X-“ and “Y”-view. Therefore tested optical fiber cladding diameter was evaluated according to localized radial coordinates of boundaries cladding / immersion gel on left and right sides over “X”- or “Y”-view and considered as true real value (Fig. 3).

![Figure 3. Example of refractive index profile measurement data: optical fiber sample NA04-02, “X”-view, cladding diameter 123.44 \( \mu m \).](image)

![Figure 4. Visual estimation of fiber geometrical parameters by analysis of fiber end snapshot displayed by fusion splicer and extracted to PC by video output: “X”-view, 81 pixels.](image)

We have marked each fiber sample end to identify it after installation to EXFO analyzer cell. Then these marked ends were set to Ericsson FSU-975 fusion splicer, and digital photos were shot and download to PC via display video output. After necessary image processing (color and contrast correction) performed by conventional graphic editor, fiber cladding diameter estimation in pixels was
produced (Fig. 4). This operation was repeated and performed for each of described 28 optical fiber samples. Statistics of core diameter value distribution in µm and pixels is shown on Fig. 5(a) and (b).

Figure 5. Statistics of core diameter value distribution: (a) µm; (b) pixels.

Therefore by comparing the number of pixels in optical fiber end photo image and real measured fiber cladding diameter after statistical analysis we have got an empirical correction factor 1.5296±0.0174 µm per pixel, that allow to perform direct researches of fusion splicer program settings impact on formed micro-lensed optical fiber geometrical parameters. For example radius of hemispherical lens presented on Fig. 1(a) is 27.45 µm, while ball lens on Fig. 1(d) radius is 96.07 µm and radius of tapered cone pictured on Fig. 2(c) is 9.92 µm.

4. Experimental researches of hemispherical and ball lenses geometrical parameters dependence on fusion splicer software settings

According to proposed method we utilize Ericsson FSU-975 program #9 to fabricate both hemispherical and ball lenses. Here during 2nd stage of fusion optical fiber is simultaneously heated and pulled over burning zone [6]. Therefore we suppose that particular program #9 parameters “Fusion Time 2” and “Fusion Current 2” define micro-lensed fiber geometry, while their preset values are 7 s and 12 mA.

At the first stage we researched “Fusion Current 2” I2 setting impact on radius and length of fiber optic hemispherical lens under fixed “Fusion Time 2” with mentioned above preset value t2 = 7 s. Here I2 was varied from 12 up to 19 mA and lens was formed on the end of silica standard singlemode optical fiber ITU-T Rec. G.652. If I2 was set more 19 mA the lens was break down due to strong burning. After the end of fusion a snapshot of burning zone was download to PC via splicer video output, then hemispherical lens radius R and length L was estimated according to described in section 3 method by taking into account empirical correction factor. Results of described experimental research are presented on Fig. 6 (a), (b).

Then “Fusion Current 2” was fixed to value I2=13 mA, while “Fusion Time 2” was varied over range t2 = 6…13 s. Here lens also destroyed due to long burning under more long fusion time t2>13 s. Diagrams of fiber optic hemispherical lens radius and length dependence on “Fusion Time 2” under fixed “Fusion Current 2” are shown on Fig. 7(a), (b).

Analysis of performed experimental research results demonstrates general trend of fiber optic hemispherical lens both radius and length enlargement under “Fusion Current 2” parameter increasing, while comparison between diagrams of dependences R(I2)/L(I2) and R(t2)/L(t2) allows supposition, that the main impact on lens geometrical parameters is effected by “Fusion Current 2” settings.

During the next step of tests we repeated 3 cycles of forming 3 group of 11 hemispherical and ball lens samples under the constant “Fusion Time 2” fixed on t2=7 s and the same values of “Fusion Current 2” varied over I2=14...19 mA range. Results of lens radius dependence as well as lens length (e.g. length of transition zone) on “Fusion Current 2” parameter are shown on Fig.8. Here a good
repeatability of samples should noticed with also general trend of lens both radius (from 55 µm up to 105 µm) and length (from 140 µm up to 290 µm) enlargement under “Fusion Current 2” increasing.

![Graphs showing the impact of Fusion Current 2 on radius and length of hemispherical micro-lens geometrical parameters.](image)

**Figure 6.** Results of experimental research of “Fusion Current 2” settings impact on fiber optic hemispherical micro-lens geometrical parameters: (a) radius; (b) length.

![Graphs showing the impact of Fusion Time 2 on radius and length of hemispherical micro-lens geometrical parameters.](image)

**Figure 7.** Results of experimental research of “Fusion Time 2” settings impact on fiber optic hemispherical micro-lens geometrical parameters: (a) radius; (b) length.

![Graphs showing the impact of Fusion Current 2 under fixed Fusion Time 2 on radius and length of hemispherical micro-lens geometrical parameters.](image)

**Figure 8.** Results of experimental research of “Fusion Current 2” settings under fixed “Fusion Time 2” $t_2=7$ s impact on fiber optic micro-lens geometrical parameters: (a) radius; (b) length.

5. Experimental researches of tapered cone geometrical parameters dependence on fusion splicer software settings

The same experimental researches were performed for tapered cones. Here after preliminary up-taper forming and a passage to program #9 “Fusion Current 2” was varied over range $I_2 = 9...13.5$ mA while “Fusion Time 2” was fixed at the value $t_2 = 12$ s. Diagrams of tapered cone radius and length...
dependence on “Fusion Current 2” are shown on Fig. 9(a), (b). Then “Fusion Current 2” was fixed at value $I_2 = 11$ mA, while “Fusion Time 2” was varied over range $t_2 = 8…12.5$ s. Here results also in the form of diagrams are represented on Fig. 10(a), (b).

Figure 9. Results of experimental research of “Fusion Current 2” settings impact on fiber optic tapered cone geometrical parameters: (a) radius; (b) length.

Comparison between diagrams of results of performed test series shows general trend of tapered cone radius enlargement with its length reducing under “Fusion Time 2” extension, while “Fusion Current 2” increasing also reduces tapered cone length. Therefore during the next stage of tests we have repeat also 3 cycles of forming 3 group of 10 tapered cones samples but under the constant “Fusion Current 2” fixed on $I_2 = 11$ mA and the same values of “Fusion Time 2” varied over $t_2 = 8.7…14.0$ s range. Results of lens radius dependence as well as lens length (e.g. length of transition zone) on “Fusion Time 2” parameter are shown on Fig. 11. Here also general trend of lens radius enlargement (from 10 µm up to 35 µm) under “Fusion Time 2” can be noticed increasing, while tapered cone length reduces (from 550 µm down to 350 µm) under the same “Fusion Time 2” researched range. Weak instability of manufactured tapered cone samples geometry are explained by some randomizations occurring during the up-taper implementation.

Figure 10. Results of experimental research of “Fusion Time 2” settings impact on fiber optic tapered cone geometrical parameters: (a) radius; (b) length.

6. Comparison between micro-lensed optical fiber type and radius impact on focus distance
During the next test series we have prepared 9...10 samples of each type micro-lensed optical fibers differing by radius. The simplest experimental setup was used for the micro-lens focus distance measurement. It is shown on Fig. 12, based on conventional optical bench and contains 635-nm laser source and photo receiver connected to power meter. Therefore focus distance was localized during
the maximal value of photodiode current detection. Polygon of measured focus distance value distribution between type and radius of micro-lensed optical fiber is presented on Fig. 13.

![Graphs showing focus distance distribution](image)

**Figure 11.** Results of experimental research of “Fusion Time 2” settings impact on fiber optic tapered cone geometrical parameters: (a) radius; (b) length.

![Experimental setup](image)

**Figure 12.** Experimental setup for the micro-lens focus distance evaluation.

![Polygon of measured focus distance value distribution](image)

**Figure 13.** Polygon of measured focus distance value distribution between type and radius of micro-lensed optical fiber.

7. Conclusion
We presented simple method for making micro-lensed optical fibers with required configuration (hemispherical lens, ball lens, tapered cones) and geometrical parameters by commercially available field fusion splicer Ericsson FSU-975 kit and its modified software settings. Method for estimation of optical fiber geometry parameters by analysis of burning zone snapshots performed after completion of fusion was described. Experimental test series were performed concerned with research of software program #9 settings “Fusion Current 2” and “Fusion Time 2” impact on micro-lensed optical fiber key geometrical parameters – radius and length. These provides to select particular combination of
mentioned settings to form at the end of silica optical fiber precision hemispherical micro-lens with desired radius and length from range $R=40\ldots100$ µm and $L=150\ldots300$ µm or tapered cone with required radius $R=4\ldots45$ µm and length $L=100\ldots500$ µm respectively with focus distance varied from 1 up to 8 mm depending on type and radius of micro-lens.

8. References
[1] Utzinger U and Richards-Kortum R R 2003 Fiber optic probes for biomedical optical spectroscopy Journal of Biomedical Optics 8(1) 121-147
[2] Matousek P and Stone N 2012 Recent advances in the development of Raman spectroscopy for deep non-invasive medical diagnosis Journal of Biophotonics 6(1) 7-19
[3] Kong K and Kendall C 2015 Raman spectroscopy for medical diagnostics – From in-vitro biofluid assays to in-vivo cancer detection Advanced Drug Delivery Reviews 89 121-134
[4] Bratchenko I A and Alonova M V 2016 Hyperspectral visualization of skin pathologies in visible region Computer Optics 40(2) 240-248 DOI: 10.18287/2412-6179-2016-40-2-240-248
[5] Bratchenko I A and Artemyev D N 2017 Combined Raman and autofluorescence ex vivo diagnostics of skin cancer in near-infrared and visible regions Journal of Biomedical Optics 22(2) 027005-1-027005-10
[6] Ericsson FSU-975 User Guide 2001 (Ericsson)
[7] Andreev V A and Bourdine A V 2017 Method for precision macro-defect forming in silica optical fiber structure Infokommunikacionnye Tekhnologii 1 18-29
[8] Evtushenko A S and Faskhutdinov L M 2017 Technique for writing of fiber Bragg gratings over or near preliminary formed macro-structure defects in silica optical fibers Proc. of SPIE 10342 103420X-1-103420X-11
[9] Petrov A A and Veiko V P 2005 Application of fiber optic micro-lenses for optical interconnection efficiency improvement Scientific and Technical Journal of Information Technologies, Mechanics and Optics 5/4(20) 68-72
[10] Veiko V P and Zyong V Z 2005 Experimental setup with feedback for nano-probe laser tapering Scientific and Technical Journal of Information Technologies 5/4(20) 73-77
[11] Veiko V P and Novikov B Yu 2008 Optical properties of micro-lenses fabricated by glass-ceramics laser-induced amorphisation method Scientific and Technical Journal of Information Technologies, Mechanics and Optics 8/3(48) 68-72
[12] Listvin A V and Listvin V N 2003 Optical fibers for telecommunication links (Moscow: LESARArt)
[13] Semenov A B 2007 Fiber optics subsystems for modern SCS (Moscow: Akademiya IT – DMK press)