Development of Miniaturized Fiber-Optic Laser Doppler Velocimetry Sensor for Measurement of Local Blood Velocity

(Fabrication Method for Convex or Concave Lens-Like Fiber Tip and the Characteristics of Sensor Optical System)*

Tsutomu TAJIKAWA**, Mitsuhiko TAKESHIGE***, Wataru ISHIHARA****, Shimpei KOHRI** and Kenkichi OHBA**

**Department of Mechanical Engineering, Kansai University, 3-3-35, Yamate-cho, Suita, Osaka 564-8680, Japan
E-mail: tajikawa@ipcku.kansai-u.ac.jp
***Toyota Boshoku Co., 1-1 Toyoda-cho, Kariya, Aichi, 448-8651, Japan
****Boston Scientific Co., Niiko Bldg. 1-14-11, Nishi-Shinjuku, Shinjuku-ku, Tokyo 160-0023, Japan

Abstract

A new miniaturized fiber-optic laser Doppler velocimetry (LDV) sensor has been developed, which is capable of measuring the local velocity in various semi-opaque and opaque fluid flows, particularly whole blood velocity in vessels. The sensor has a convex lens-like fiber tip as a pickup and an improved optical transmission system with markedly decreased stray light. This paper describes methods for fabricating fiber tips like concave and convex lens and the characteristics of the optical sensor system equipped with the fabricated fiber tip. Conventional fiber-optic LDV sensors developed up to now have not been capable of measuring such opaque fluids because scattered light from scattering particles as erythrocytes has very low intensity, which makes signal-to-noise ratio of Doppler signal received by a sensor pickup significantly decreased. To overcome these problems, convex lens-like fiber tips have been fabricated by chemical etching, in which quartz fibers of multimode graded refractive index have been etched in aqueous solutions of hydrogen fluoride and ammonium fluoride under the appropriately controlled condition of the concentration of the solution, the etching duration time and the etchant temperature to obtain the desired curvature radius of the lens-like surface of the fiber tip. In this fiber-optic sensor, a laser beam emitted from the fiber tip can be focused at any position from about 0.1 to 0.5 mm distant from the fiber tip according to its curvature radius. The convex lens-like etched tip totally reduced the intensity of undesired reflecting light at the fiber end by 1/2 to 1/6 compared with normal cut fiber tip. Consequently, this fiber-optic LDV sensor system is capable of measuring the local flow velocity in semi-opaque and opaque fluids, whose turbidity was about five times higher than by any kinds of previous sensors.

Key words: LDV, Fiber-Optic Sensor, Fiber Tip, Chemical Etching, Blood Velocity
1. Introduction

Numerous studies have investigated about cardiovascular diseases such as arteriosclerosis, aneurysms and so on. It is well known that these problems appear more commonly at bifurcations, curved vessels, tapered vessels, and small vessels where complex blood flow fields occur. It is also known that the flow pattern in such blood vessel having complicated geometry is one of the main pathogenesis of these vascular diseases. Although the knowledge about the detailed velocity fields of local flow through such sites is very important to make clear the pathogenesis of cardiovascular diseases and to detect these diseases early, it is difficult to measure local velocity in whole blood flows accurately and precisely due to the lack of an appropriate measurement method.

In order to measure the local velocity in various semi-opaque and opaque fluid flows, one of the authors developed a laser Doppler velocimeter (LDV) having an optical dual-fiber pickup, which consisted of two optical fibers placed side by side in parallel to separate the transmitting optical component and the receiving component [1]. It was however not capable to measure the local blood velocity using this sensor, because the intensity of the scattered light from the measuring volume was significantly reduced due to the absorption of light by blood. In order to receive the scattered light of high intensity, a fiber-optic LDV probe having a truncated cone-shaped distributed index lens (DIL) of which the diameter was 1 mm was developed. The emitted light from a fiber tip with a DIL was converged at a focal point, where the measuring volume was formed and the scattered light intensity was increased[2-3]. Although this fiber-optic LDV sensor with a DIL could measure the flow velocity in semi-opaque and opaque fluids such suspension of white pigment, it was not able to be used as a sensor for local blood velocity measurement. This is because the insertion of the large sensor head of a DIL inevitably gave rise to a strong flow disturbance, which prevented a precise measurement.

In order to overcome these problems, convex and/or concave lens-like fiber tips were fabricated by a chemical etching technique and then an LDV sensor having a convex lens-like tip was developed. This paper describes both a new method of fabricating a fiber tip as a sensor probe and the characteristics of the sensor optical system with the fabricated fiber tip.

Nomenclature

\[ r \] : Radial position across the fiber \( \mu m \)
\[ r_C \] : Radius of curvature of optical fiber tip \( \mu m \)
\[ d \] : Diameter of etched fiber at its terminus \( \mu m \)
\[ T \] : Etching duration time \( h \)
\[ L \] : Distance from optical fiber tip \( \mu m \)
\[ P \] : Laser power emitted from fiber tip \( \mu W \)
\[ C \] : Concentration of white pigment suspension \( g/l \)
\[ n \] : Reflective index -
\[ f_D \] : Doppler shift frequency \( \text{kHz} \)
\[ \theta \] : Insertion angle of fiber into flow \( \text{deg.} \)

2. Optical Fiber Tip Fabrication by Chemical Etching

2.1 Fabrication procedure and method

Quartz optical fiber consists of core and cladding layers. The core is surrounded by the cladding, and the refractive index of the core is slightly higher than that of the cladding. There are a few kinds of optical fibers e.g. graded index (GI) core multimode fiber, step index (SI) core multimode fiber and step index core single mode (SM) fiber as shown in
Fig. 1. Refractive index distribution of SI and SM fibers is characterized by a uniform
refractive index in the core and sharp decrease of the index at the core-cladding boundary.
On the other hand, the core of GI fiber has a parabolic refractive index distribution which
has the peak at the center.

For realization of the parabolic profile of refractive index in the fiber core, rare-earth
metals like germanium, titanium or phosphorus are doped with gradual density difference in
manufacturing. When a quartz optical fiber end is dipped into a fluorinated acid, silicon
dioxide (SiO₂), which is the main constituent of quartz, dissolves. It is expected that a
distribution of the doping ratio across the fiber core layer affects the etching ratio radially in
a fiber cross-section and so convex and/or concave lens-like fiber tips are formed on the end
surface of the fiber. A buffer solution including hydrogen fluoride (HF) and ammonium
fluoride (NH₄F) was used as an etchant.

In this paper, two multi mode GI fibers 50µm in core diameter and 125µm in cladding
diameter (Fujikura Ltd., GC50/125 and Sumitomo Electric Industries, Ltd., EG-5) and an
SM fiber 6µm in core diameter and 125µm in cladding diameter (Fujikura Ltd., SM6/125)
were etched. The shape of etched fiber tip was observed and measured to investigate the
influences of the volumetric concentration ratio of etchant and etching duration time.

After removing the coated layer such as UV curable acrylic resin, every fiber tip was
normally cut by using fiber cutter (Fujikura Ltd., CT-20). The tip of the prepared fiber was
dipped into the etchant composed of 50wt% aqueous solution (AS) of HF (Daikin Industries
Ltd., HHFSH), AS of NH₄F (Daikin Industries Ltd., HNFSH) and deionized water (H₂O).
The mixture ratio of the buffer solution was defined as the volumetric concentration ratio of
the buffer solutions HF : NH₄F : H₂O = X : Y : Z, and the volumetric concentration ratio of
the etchant was varied as follows:

(i) X was varied from 0.1 to 1.0, when Y = 1.0 and Z = 1.0.
(ii) X was varied from 0.1 to 1.0, when Y = 0 and Z = 1.0.
(iii) Y was varied from 0.1 to 1.0, when X = 1.0 and Z = 1.0.
(iv) Y was varied from 0.2 to 1.4, when Y and Z were maintained at a constant
given value.

GI and SI fibers were dipped into the solutions at 22.5°C. The shapes of the fabricated
fiber tips were observed and recorded at every a half hour by a video microscope
(KEYENCE Co. Ltd., VH-8000 and zoom lens: VH-450).
2.2 Results

Several examples of microscopic images and scanning electron micrographs of the fabricated fiber tips are shown in Fig. 2 and Fig. 3, respectively.

A surface of the paraboloid of revolution such as convex and concave lens-like shapes of various curvature radii was fabricated on the GI type fiber tip and conical convex and concave surfaces were fabricated on the SM type fiber tip, which were controlled by the volumetric concentration ratio of the etchant, the etching duration time and the etchant temperature. In the scanning electron micrographs, the etched fiber tips had smooth surface although dirt and dust adhered to the tip.

<table>
<thead>
<tr>
<th>HF:HF:OH=0.2:0:1.0, SM Fiber</th>
</tr>
</thead>
<tbody>
<tr>
<td>T=1.0h</td>
</tr>
<tr>
<td>50µm</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>HF:NH4F:OH=0.2:0:1.0, GI Fiber (GC50/125)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T=0.5h</td>
</tr>
<tr>
<td>100µm</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>HF:HF:OH=0.3:1.0:1.0, SM Fiber</th>
</tr>
</thead>
<tbody>
<tr>
<td>T=1.5h</td>
</tr>
<tr>
<td>50µm</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>HF:NH4F:OH=0.2:1.0:1.0, GI Fiber (GC50/125)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T=1.0h</td>
</tr>
<tr>
<td>50µm</td>
</tr>
</tbody>
</table>

Fig. 2 Microscopic images of chemically etched fiber tips.

<table>
<thead>
<tr>
<th>GI Fiber (EG-5)</th>
<th>SM Fiber</th>
</tr>
</thead>
<tbody>
<tr>
<td>X:Y:Z = 0.3:0:1.0</td>
<td>X:Y:Z = 0.2:1.4:1.0</td>
</tr>
<tr>
<td>X:Y:Z = 0.3:0:1.0</td>
<td>X:Y:Z = 0.2:1.0:1.0</td>
</tr>
</tbody>
</table>

Fig. 3 SEM images of etched fiber tips.
A dent at the center of the fiber core that was etched for a convex lens-like shape occasionally occurred as shown in Fig. 4. This phenomenon did not necessarily occur in the case of any specific fiber. The dent was considered to be formed by an imperfect parabolic distribution of refractive index which had dipping near the center of the core layer. The dipping was occasionally formed in the process of GI fiber manufacturing by evaporation of germanium (Ge) as the dopant near the fiber center.[4]. As optical fibers with dipped index are not inferior to others in terms of its characteristics of light transmission, such as propagation loss and numerical aperture, those fibers are not discriminated from normal fibers in the commercial market. Therefore, it is indicated that the manufacturing accuracy of an optical fibers affects the results of etching fabrication.

The fiber tip surface etched at the condition of X : Y : Z = 0.8 : 1.0 : 1.0 was kept flat, and finally became a circular cone, as shown in Fig. 5. This result indicated that the etching ratio in the core was equal to that in the cladding, and the fiber tip was etched both from front and side surfaces with same speed and finally it was sharpened.

The relationships among the curvature radius of the etched fiber tip, the fiber tip diameter, and the etching duration time is shown in Fig. 6. Because SM fiber core was very small of 6µm in diameter, it was difficult to obtain a high-resolution image of the fiber tip using an optical microscope. Hence the shape of SM fiber tip surface was not measured.

As the fiber tip surface in the core was etched according to its refractive index distribution, the curvature radius of the etched surface was approximated by the equation:

$$ l = l_0 - \frac{r^2}{2r_c} \tag{1} $$

where $r$ denotes the radial position across the fiber, $l$ is the thickness of lens at $r = r_c$, and $l_0$ is the thickness of lens consisting of a paraboloid of revolution at the fiber axis, $r = 0$. The spatial resolution of the microscopic image was approximately 0.5µm/pixel. Positive and negative radii of curvature represent convex and concave lenses, respectively.

As the concentration ratio of HF increased, the speed of the fiber tip diameter narrowing increased and the radius of curvature of the lens shaped on etched tip became smaller.

When aqueous NH$_4$F was completely removed from the etchant, a concave lens-like tip was shaped on the fiber end as shown in Fig. 6(b). The etching selectivity of SiO$_2$, which
was the major component in quartz fiber, was improved using buffer solutions which consisted of combinations of HF and NH₄F.

By controlling the volumetric concentration ratio of the buffer solution, the convex lens-like tip of the optical fiber was able to be fabricated regardless of differences in optical fiber manufacturers as shown in Fig. 6(a) and (c). When the GI fiber tip was etched to a convex lens-like shape, and the curvature radius at the fiber tip was smaller than 20 µm, the cladding layer was completely removed by chemical etching. Fabrication of small curvature radius of lens-like fiber tip needed increment of HF concentration, which was able to raise the etching selectivity of the cladding layer. After the cladding layer etched out, the side surface of the core layer was directly exposed to the etchant and its cross-sectional area became small, which caused the decrease of the emitting light intensity from the fiber tip.
This result shows that the minimum radius of curvature of a fiber tip is about 17 µm for maintaining a normal function of the optical fiber. In this etching process, NH₄F mainly determined the shape formed on the fiber tip surface of convex or concave as shown in Fig. 6. This result indicates that the dominant factor contributing to the chemical etching of the fiber is hydrogen fluoride as shown in the following equations, and that ammonium fluoride suppresses and controls the effect of hydrogen fluoride in GeO₂ and SiO₂ etching.

\[ XO_2 + 6HF \rightarrow H_2XF_6 + 2H_2O \]  
\[ H_2XF_6 + 2NH_3 \rightarrow (NH_4)_2XF_6 \]

where \( X \) is either Si or Ge.

As a result of simultaneous etching for several optical fibers of the same production lot number, the variation or scattering of the fiber diameter at the final stage of the etching was less than 5%. Furthermore, it was shown from an observation of the outlines of the convex lens-like tips that their radii of curvature were almost same each other under the same etching conditions. So, very precise fabrication of the lens-like tip was attained. This indicates that the etched fiber shape is materially affected by the manufacturing accuracy of the refractive index profile in the fiber core and by the initial shape of the fiber tip whether the flat surface or not, in addition to etchant component and etching duration time, as shown in the case of a fiber with dipped refractive index as in Fig. 4.

3. Evaluation of Optical Characteristics of Etched Optical Fiber

3.1 Focal length of convex lens-like fiber tip

Since measuring the emitted light path from the etched fiber tip was very difficult, it was calculated by the method of ray optics using microscopic images of the fiber tip surface. The assumption was that laser beam of which diameter was the same as the fiber core propagated in the optical fiber and emitted from the end into water of refractive index of 1.33. The outline of the lens-like tip etched by a buffer solution with X : Y : Z = 0.2 : 1.0 : 1.0 was traced and was treated by a polynomial approximation of high degree to calculate the curvature radius of the fiber tip. Figure 7 shows the calculated result of emitting light path from the convex lens-like tip in the case of paraxial rays, which was etched by HF - NH₄F buffer solution during 2 to 4 hours on the tip surface of the multi-mode GI fiber EG-5 manufactured by Sumitomo E.I. Ltd. The focal point of the light
path approached to the fiber tip with increase in the etching duration time. From the results of the previous study [5], it was clarified that the measuring volume must be located within a distance of 300 μm from the tip of the probe because of absorption and multiple scattering by erythrocytes in blood. On the other hand, a too short focal length causes an inaccuracy of measuring velocity due to the effect of the stagnation region of the fiber-optic probe itself. Hence, these results indicated that etching duration time during 3 to 4 hours seems to be most appropriate in blood velocity measurement. The measuring volume, which is formed in water by the convex lens-like tip etched for 3 hours, is estimated under the Gaussian beam assumption [5] by using the focal length obtained from Fig. 7, the wavelength of the light source (He-Ne laser : wavelength $\lambda =$632.8nm and LD : wavelength $\lambda =$830nm), and the beam diameter, assumed the same as the core of the optical fiber as shown in Table 1 and Fig. 8.

$$\text{Spot diameter: } d_s = \frac{4\lambda l_f}{\pi d_l}$$  \hspace{1cm} (4)

$$\text{Confocal length: } l_c = \frac{\pi d_l^2}{2\lambda}$$  \hspace{1cm} (5)

![Fig.8 Schematic diagram of sample volume formed by Gaussian light beam emitted from this fiber-optic sensor having convex lens-like surface](image)

<table>
<thead>
<tr>
<th>Wavelength $\lambda$</th>
<th>Focal length $l_f$ (μm)</th>
<th>Beam waist $d_l$ (μm)</th>
<th>Focal depth $l_c$ (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>632.8nm</td>
<td>220</td>
<td>3.55</td>
<td>31.2</td>
</tr>
<tr>
<td>830nm</td>
<td>220</td>
<td>4.65</td>
<td>40.9</td>
</tr>
</tbody>
</table>

### 3.2 Apparent numerical aperture of optical fiber with concave lens-like tip

As a fiber tip is generally cut in the direction perpendicular to the fiber axis, the numerical aperture of a fiber is determined by its core diameter and the index distribution in the core layer. However, in the case of our fabricated concave lens like fiber tip, the ray emitted from the concave lens like tip would be widened more than in the case using a normal-cut fiber tip. It is expected that the apparent numerical aperture of the etched concave lens like tip is larger than that of the normal-cut fiber tip.

Distribution of the maximum incident angle in the radial direction was calculated by the same method described using ray optics theory under assuming the shape of the fiber tip was a lens consisting of a paraboloid of revolution. The results are shown in Fig. 9.

A range of light incident into the concave lens-like tip was wider than that of the normal-cut fiber. This result suggests that a fiber with a concave lens-like tip contributed to improving the acceptance angle and the efficiency in the junction of a fiber with a fiber or laser diode, and in consequence, to a simplification of the optical devices.

### 3.3 Reflective and receiving characteristics of etched optical fiber at its tip

When a fiber tip was cut normally, as is conventionally done, the previous study [3]
indicated that signal-to-noise ratio as a sensor probe characteristic had become worse due to laser reflection at the optical fiber end. Characteristics of the probe using chemical etched fiber were evaluated by measuring the light intensity of both scattering from test fluid and reflecting at the fiber end.

The outline of the experimental apparatus is shown in Fig. 10. The optical fiber used in this experiment was quartz GI fiber with a multimode coupler (Mitsubishi Gas Chemical Company, Inc., CG5-D2-CP) of 1x2 port configurations. Laser beam from He-Ne laser (He-Ne laser : wavelength $\lambda = 632.8$ nm, power 25 mW) went into the fiber "A", and emitted from the fiber "B" into test fluid of white pigment suspension or distilled water. In emission, part of the laser light was reflected at the boundary between the fiber tip and test fluid. In the case of white pigment suspension emitted light from the fiber "B" was scattered by the scattering particles of titanium dioxide in white pigment, and the scattering light was received by the same fiber. The scattering light and the reflecting light were emitted from the fiber "C". In the distilled water only reflected light was emitted because there is no scattering particle.

The intensities of both the scattered light and the reflected light were obtained by measuring the power of the emitted light from the fiber "C" by a laser power meter, when the concentration of white pigment was systematically increased. An optical fiber a with convex lens-like tip, which was etched by the buffer solution with $X : Y : Z = 0.2 : 1.0 : 1.0$ for 4 hours, and a normal-cut fiber were used.

Figure 11 shows the relationships between received intensities of scattered/reflected light and concentration of white pigment mixture in the test fluid, and "Efficiency" was the ratio of emitted light intensity from the fiber "B" and the light source intensity. This result showed that reflecting light at the fiber tip was decreased as etching duration time became longer i.e. curvature radius on the tip smaller, which meant increase of light efficiency. This is because in the case of normal cut fiber light is reflected according to Fresnel's formula, and in convex lens-like tip light is to Snell's law[6]. But the emitted light efficiency of the smallest curvature radius $r_c = 30 \, \mu m$ decreased significantly because a cladding layer was completely removed and a core layer was etched from side surface. On the other hand, scattering light intensity became larger as curvature radius smaller and concentration of white pigment higher. By use of the optical fiber whose tip has larger curvature and thin cladding layer, higher intensity of light scattering from flow field is expected to be obtained in velocity measurement and signal-to-noise ratio of Doppler signal becomes higher.
Fig. 10  Method to measure scattered and reflected light intensity.

(a) Flat fiber probe.

(b) Etched fiber probe. (X : Y : Z = 0.2 : 1.0 : 1.0)

Fig. 11  Scattered and reflected light intensities from fiber tip.

Fig. 12  Schematic diagram of LDV system.
3.4 Evaluation of performance of LDV sensor probes

By using the optical fiber etched under optimal condition (X : Y : Z = 0.2 : 1.0 : 1.0, T = 3.0 hours), a fiber-optic laser Doppler velocimeter system for the measurement of local blood velocity was set up as shown in Fig. 12. The system works by the mode of a reference beam. A monochromatic light beam from a 25 mW He-Ne laser (wavelength $\lambda = 632.8$ nm), which is perpendicularly polarized (S-polarized light), after passing through a half wave plate, is reflected by a polarized beam splitter (PBS). The reflected beam is focused on the tip of the optical fiber by a lens. The laser beam transmitted in an optical fiber is emitted from a convex lens-like fiber end and is converged at a focal point, at which a measuring volume is formed because light intensity at the focal point is highest among any position in front of the sensor tip. When scattering particles such as erythrocytes pass through the focal point, incident light is scattered by them and its frequency is shifted by the Doppler effect. Back-scattered light is received by the same fiber, and parallel polarized light (P-polarized light) of both the scattered light and partly reflected light at the fiber end, which functions as a local oscillator, pass through the PBS. Superimposition of the scattered light and local oscillator light makes heterodyne interference and the light enters a photomultiplier tube (PMT). A Doppler signal detected by heterodyne interferometry is processed by a commercial spectrum analyzer and recorded by an X-Y recorder.

In this study, the test fluids were opaque and semi-opaque mixtures of a white pigment and physiological saline as a model for blood. Characteristics of the fiber-optic LDV probe were evaluated by investigating the measuring limit of the LDV system when the concentration of the mixture became higher. Experiments were conducted by changing the turbidity of the test fluid flowing in an annular open channel. The turbidity of test fluid was defined as mass concentration "C" of white pigment, and it was changed from 2 g/l to 24 g/l in the experiment. The annular open channel filled with test fluid was put on a disc rotating at a constant speed. The sensor probe was inserted into the fluid, and the angle $\theta$ between the fiber axis and the flow direction was changed from 100 to 140 deg. in 10 deg. increments.

The results are shown in Fig.13. The horizontal axis shows frequency, the vertical axis shows the probability density function (PDF) of the time-averaged Doppler signal. The vertical rigid lines in each graph show the Doppler frequency corresponding to the real velocity which is calculated from the relationships among the tangential velocity of an annular open channel at the fiber tip, its angular velocity, and its turning radius. The peak in each spectrum is the measured Doppler frequency. When a clear peak does not appear in a spectrum and a frequency corresponding to a real velocity is not measured, the turbidity of the test fluid is defined as the measuring limit of turbidity. The measuring limit of turbidity was $C=22$ g/L, for frequency peaks in the spectra disappear under conditions of $\theta=100$ deg. and of $C=24$ g/L. It was made clear from these results that this fiber-optic sensor system with convex lens-like tip was capable of measuring the local velocity in semi-opaque and opaque fluids, in which the mass concentration of the turbid fluid was 5 times higher than the measuring limit of previous fiber-optic LDV sensors [7], and the local velocity was almost the same as the real velocity because the flow disturbance around the probe had little effect on the measurement due to a very thin and small sensor head.

These results indicate that the characteristics of the fiber-optic sensor for measuring the local velocity in semi-opaque and opaque fluids are superior to previous fiber-optic LDV sensors. Therefore, it is suggested that local velocity measurement in whole blood is possible.

4. Conclusions

In order to measure the local velocity in various semi-opaque and opaque fluids such as
whole blood, convex lens-like fiber tip was fabricated by chemical etching with buffer solution of hydrofluoric acid and ammonium fluoride and evaluated its optical characteristics and its performance for LDV. Similar study was made on concave lens-like fiber tip. The followings were made clear by this study.

(1) A surface of the paraboloid of revolution was successfully fabricated on tips of a few kinds of optical fibers of multimode graded refractive index. Its curvature radius was successfully changed as we desire by controlling the volumetric concentration ratio of HF-NH4F buffer solution, the etching duration time and the solution temperature.

(2) This surface on the fiber tip worked very well as a convex micro-lens or a concave micro-lens.

(3) The position and size of the measuring volume formed by the laser beam emitted from the convex lens-like tip were able to be controlled by the curvature radius of the etched surface, by which the optimum tip shape for local velocity measurement in whole blood could be designed.

(4) Apparent numerical aperture of concave lens-like tip was larger than that of the original optical fiber, which means higher optical performance.

(5) A convex lens-like etched tip was able to totally reduce an undesired reflecting light intensity at the fiber end by 1/2 to 1/6 compared with normal cut fiber tip.

(6) Present fiber-optic LDV sensor system with the convex lens-like tip was capable of measuring the local velocity in semi-opaque and opaque fluids, whose turbidity was about five times higher than by any kinds of previous one.

Acknowledgments

This research was partially supported by the MEXT (Ministry of Education, Culture, Sports, Science and Technology) through the "Academic Frontier" Project at Kansai University on “Creation of Realistic Models of Human Tissues/Organs using Nano / Sub-Micro Technology and their Development to Artificial Tissues/Organs”, 2003-2007.

References


Fig. 13 Changes in the PDFs of Doppler signal in TiO$_2$ suspensions of various concentrations.