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A through-hole array on optical fibers fabricated by 1-kHz/400-nm femtosecond laser pulses for an in-line/pico-litter spectrometer design

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Abstract

Femtosecond laser machining has successfully been applied to develop a spectroscopic sensing in multi-mode optical fibers by embedding through holes penetrating the fiber core, which could work to be a sample cell for spectroscopic measurements. In this report, the spectroscopic measurement using the pico-litter sample cell will be shown for liquid dye of Rhodamine 6G (R6G). Even with a single cell volume of 20 pL, the absorption spectra are appeared in the visible range centered at a wavelength of 530 nm corresponding to the peak absorption wavelength of R6G solutions.

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1. Introduction

Femtosecond laser machining has been applied for material properties modification for various materials. The applications to micromachining \cite{1,2} have received much attention, particularly because thermal effect can be extremely reduced due to such ultra-short pulses which induce a thermal non-equilibrium condition between electrons and ions. Such non-thermal effects can realize to locate a specific volume modification without thermal damage, functional microstructures therefore can be precisely arranged even in a thin material such as optical fibers. For this reason, optical fiber sensors produced by such machining were previously reported \cite{3-5}. A fiber optic
sensor with a micro hole in single-mode fibers [5] was attempted to measure refractive index (RI) by observing monochromatic light transmitted through the fiber core. The sensor characteristic shows a limited performance in its non-monotonical increase of transmission as a function of RI, depending on the hole diameter to the core diameter.

In this work a fiber optic in-line spectrometer has been developed by femtosecond laser machining on multi-mode optical fibers (MMFs) in order to explore broadband spectroscopy using commercially available optical fibers. The sensor part has a micro through hole with a pico-litter volume, which serves as a sample cells for spectroscopy. The through hole are fabricated and designed to make possible to easy guiding a liquid sample into optical fiber core. A transmitting light through optical fiber could be affected by the liquid properties such as spectral characteristics. With such scheme, efficient spectroscopy would be achieved in a very compact system in which a pico-litter volume of sampling can be made in an in-line optical fiber configuration with removing the complicated, large scale optics of conventional spectroscopic instrument. Spectroscopic measurement is made for Rhodamine 6G (R6G) solutions, in which the broadband spectrum of R6G is successfully observed.

2. Fabrication of through holes to optical fiber

In the experiment, femtosecond pulse trains are irradiated to a commercially-available glass optical fiber (MMF62.5 μm, Miki Inc.) from two directions in order to make a through hole. The core and cladding diameters of the fiber were 62.5 and 125 μm, respectively. The experimental apparatus for fabricating a through hole is shown in Fig. 1. A Ti-Sapphire laser (IFRIT Cyber Laser Inc.) produces 1-mJ pulse energy of 210-fs duration at a wavelength of 800 nm with a 1-kHz repetition rate. The fundamental laser pulses are converted to a second harmonic wave of 240 μJ pulse energy with 350 fs duration at a wavelength of 400 nm after passing through a wavelength converter. The laser beam with a 6-mm diameter is introduced to an objective lens (NA = 0.40) through a train of reflecting mirrors, collimating optics and a dichroic mirror to focus and adjust the beam at a target optical fiber. The objective lens focuses the beam to design spot size of 1.82 μm at the focal point. An optical fiber was mounted on a three-dimensional translation stage equipped with a rotating mechanism to rotate the fiber about its optical axis. The laser focal point was adjusted by moving the stage positions in terms of X, Y, Z and θx.

Irradiation conditions were set to a pulse train of 1 kHz during 1.2 s with a fluence of 6.0 × 10^2 J/cm² will be employed for creating a stable through hole. The second micro hole was fabricated from the opposite side of the first micro hole by rotating the mounted fiber by 180°. Two micro holes hence were mutually connected together in line, which were observed by using an optical microscope with a CMOS digital camera viewing through a dichroic mirror from all directions along the circumference of fiber by rotating the axis.

Fig. 2 (a) and (b) show a schematic drawings viewed from the side and cross section, respectively. Fig. 2 (c) and (d) were obtained in microscopic monitoring from the side and top, respectively, showing that the confronted micro holes are successfully connected together so as to produce a through hole with negligible small cracking around the entrance aperture. The hole sizes are found to be approximately 10 and 18.5 μm in the diameters at the waist and surface aperture, respectively, the volume of which were calculated to approximately 19.8 pL by assuming that the shape of through hole could be approximated to two confronted cones.
Measurement setup consist of a white light source (AQ-4303B, ANDO Co.) and an optical spectrum analyzer (AQ-6315, ANDO Co.) operated by a personal computer. A sensor sample was fixed on a Teflon jig to guide the sensor portion into a liquid. Spectroscopic measurements were performed to investigate the absorption characteristics for liquid dye of R6G (LC5900, Lambda Physik) diluted in ethanol at several concentrations. R6G ethanol solutions were prepared at the concentrations ranging from 0.17 M to 16.5 M (M: mol/L/10⁻³).

3. Measurement results and discussions

Spectroscopic measurements were made on R6G to investigate the absorption spectrum with changing the concentration of R6G. The insertion loss of sensor sample was found to be 0.98 dB. The absorption spectra were shown in Fig. 3, which was obtained as the difference between two spectra with and without R6G in ethanol. The figure shows significant absorption in the visible range centered at a wavelength of 530 nm corresponding to the peak absorption wavelength of R6G solutions [6]. The absorbance becomes larger as the R6G concentration increases, the further details of which are shown in Fig.4 with numerical calculations.

Taking a closer look at the absorbance at 530 nm as plotted in Fig. 4, it is indicated that the absorbance increases logarithmically as R6G concentration increase because the absorption would be limited due to the cross section of through hole corresponds to less than 25 percent of the fiber-core cross section according to microscopic images. The absorbance increases from 0.70 × 10⁻² to 7.5 × 10⁻² by changing the concentration of R6G solutions in a range of 0.17–16.5 M. Absorbance \( A \) is generally indicated in the following Lambert-beer law defined as,

\[
A = -\log_{10} \left( \frac{I}{I_0} \right) = \varepsilon \alpha c L ,
\]

(1)

\[
T = \frac{I}{I_0},
\]

(2)

where \( T \) is the light transmittance, \( \varepsilon \) is the wavelength-dependent molar absorptivity, \( c \) is the concentration of the absorption molecule, \( L \) is the effective path length of the light through the sample, which is indicated as the through hole diameter at the waist. \( I \) and \( I_0 \) are the optical intensities of the incident and transmitted light, respectively. An absorbance should generally increase proportionally to the effective path length according to Lambert law as defined by equation (1). On the other hand, when it is taken account into the effective cross-sectional area and effective optical path length, the absorbance \( A' \) can be indicated in the following formula:

\[
A' = -\log_{10} \left( \frac{I}{I_0} \right) = -\log_{10} \left[ (1 - \alpha) + \alpha 10^{\varepsilon c L} \right],
\]

(3)
where $\alpha$ denote the effective area factor. The formula (3) shows an absorbance in the case of that transmitted light is theoretically divided into two parts of unabsorbent and absorbent area which can be expressed as $(1-\alpha)I_0$ and $\alpha I_0 e^{-\alpha x}$, respectively. The numerical calculations of absorbance were shown in Fig. 4 to compare with experimental results, where absorptivity $\varepsilon_2$ was set to $10.5 \times 10^4$ [6]. It was obtained that the maximum amount of absorbance can be greater, as the factor $\alpha$ becomes greater. Comparing between the numerical calculation and experiment results, when $\alpha$ set to 0.16, the tendency is in agreement with experimental result which shows logarithmical increase. According to Fig. 4, it can be seen that the effective area is smaller than actual one as mentioned before because transmitting light would be scattered by the side surface of through holes to be granulated and cylindrically formed.

4. Conclusions

Using femtosecond laser machining, a fiber optic in-line spectrometer was successfully produced for spectroscopic measurements by embedding a micro through-hole array to multi-mode optical fibers. A femtosecond laser system was configured for fabrication of through holes which can be worked to be a sample cell with a volume of 20 pL.

In the experiment using liquid dye of R6G, absorption spectra were obtained that transmitting light was significantly absorbed at the range centered at a wavelength of 530 nm which corresponds to the peak absorption wavelength of R6G solutions. The absorbance shows no proportional increase to concentration because the effective cross-sectional area could be limited and defined by factor $\alpha$. The numerical model was therefore proposed with consideration of the effective area, which shows agreement with experimental measurement. According to the model and Fig. 4, it can be seen that the effective area is smaller than actual one. With numerical model, it is predicted that the sensor performances can be adjusted by cell arrangement.

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