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Research Article

A Contamination Sensor Based on an Array of Microfibers with Nanoscale-Structured Film

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A contamination sensor based on an array of microfibers with nanoscale-structured film using evanescent field is proposed and demonstrated theoretically and experimentally. When the molecular contaminants deposit on the nanoscale-structured film, the refractive index of the film will change and the additional loss will be produced due to the disturbance of evanescent field. The possibility of the sensor is demonstrated theoretically by using three-dimensional finite-difference time domain (3D-FDTD). The corresponding experiments have also been carried out in order to demonstrate the theoretical results. Microfibers are fabricated by using hydrogen-oxygen flame-heated scanning fiber drawing method and the nanoscale-structured film coated on the surface of microfibers is deposited by using dip coating process. Then an array of microfibers is assembled to demonstrate the feasibility of the device. The experimental results show that contaminants detection with the device can agree well with the results measured by the laser-scattering particle counter, which demonstrates the feasibility of the new type of contaminant sensor. The device can be used to monitor contaminants on-line in the high-power laser system.

1. Introduction

For high-tech industries, such as optical components or semiconductor, not only particle contaminants associated with environment control and cleanroom but also molecular contaminants must be well controlled. In the context of high power lasers for fusion, contaminants have been known to degrade the performance [1–3] which lead to laser-induced damage sometimes, such as the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory. The lasers can create extramely harsh energy, and the fluence levels get closer to the damage threshold of optical components. Furthermore, airborne contaminants on the surface can aggravate this damage. To our knowledge, a few methods of contaminant monitor on-line had been applied successively [4, 5], such as laser-scattering particle counters, microelectromechanical resonators and quartz crystal microbalance. However, they are not applicable any more in the harsh environment because of vacuum condition or strong scattered laser energy.

Comparing with optical fibers used in communication field, micro/nanofibers show interesting properties such as enhanced evanescent fields, tight light confinement, and large waveguide dispersions [6]. Therefore, micro/nanofibers have attracted more and more attention during the last few years. Micro/nanofibers, as one of the most important integrated photonic devices, are used as sensors [7–10], production of stimulated Raman scattering [11], low-threshold supercontinuum generation [12], nanowire lasers [13], low-loss light transmission medium [14], and so on. In 2003, nanofibers with diameter of 50–550 nm had been fabricated with smooth surface and diameter uniformity [15], which provides strong support for practical application of micro/nanofibers as components in future microphotonic devices.

In this paper, a new contaminants sensor based on an array of microfibers with nanoscale-structured film is proposed. When molecular contaminants adhere to nanoscale-structured film, the additional loss will be produced due to refractive index change and the light transmitting through an array of microfibers with nanoscale-structured film will

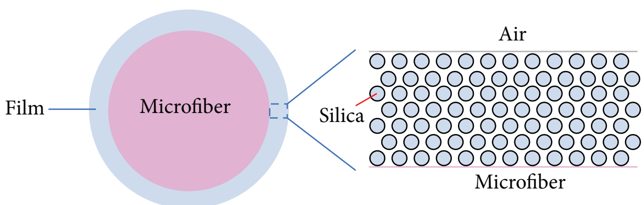


Figure 1: Structure of microfiber with nanoscale-structured film.

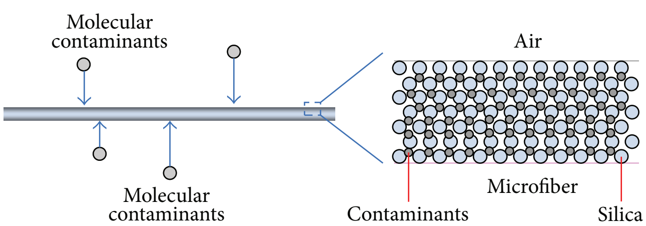


Figure 2: Principle of contaminants adhered to microfiber with nanoscale-structured film.

be disturbed. Compared with other contaminants sensors [16, 17], the new type of sensor is bases on the evanescent field of microfibers surface, so the device is promising for its low cost and easy fabrication. In addition, the device also exhibits significant advantages, such as high sensitivity, compact and simple structure, and immunity to electromagnetic fields.

2. Theoretical Analysis

We assume that the microfibers with nanoscale-structured film have circular cross-section and a step-indices profile. The scheme diagram of the microfibers considered here is illustrated in Figure 1.

The microfiber is assumed to have a circular cross-section with refractive index (RI) of 1.465 and a step-index profile [6]. The film with loose and porous structure is coated on the surface of microfiber. The RI of the film ranges from 1.23 to 1.41. Molecular contaminants are easy to adhere to the surface of the sensing microfibers. The principle is shown in Figure 2.

However, the high-index-contrast microfibers are not common waveguide, where the perturbation theory cannot be applied. Therefore, we have to resort to numerical methods. The additional loss caused by contaminants adhered to film is simulated by means of the three-dimensional finite-difference time-domain (3D-FDTD) method. The computational domain is divided into Yee cells. FDTD method is for solving Maxwell's equations directly at time domain. The electric field (or magnetic field) of each point of space is directly associated with magnetic field of surrounding lattice (or electric field). The length of each wavelength can be divided into 40 cells, and the length of each cell is about 38 nm. The wavelength of the source is assumed to be 1.55 μm, and perfectly matched layers (PML) is used in computational domain. We calculate the additional loss caused by contaminants with respect to refractive index of the film on the surface of microfiber. The results calculated for microfibers with diameters of 1.5, 2.0, and 2.5 μm are

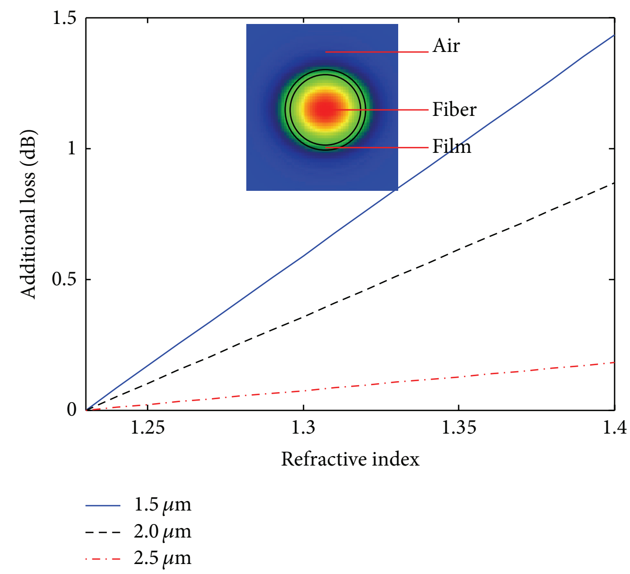


Figure 3: The calculated additional loss caused by contaminants. The inset shows power distribution of a 1.5 μm diameter microfiber with nanoscale-structured film.

shown in Figure 3. As shown in the inset of Figure 3, a 1.5 μm diameter confines the major energy inside the fiber and it leaves an amount of light guided outside as evanescent waves. The additional loss caused by contaminants varies linearly with RI of the film on the surface of microfiber. The sensitivity decreases with the increasing diameter of microfiber. But the change of dynamic range is opposite to the sensitivity. That means suitable sensitivity and dynamic range can be selected by controlling the diameter of the microfiber. If the additional loss caused by contaminants and the material of contaminants are known, the mass of contaminants can be obtained according to Figure 3.

3. Experimental Results

The fabrication of an array of microfibers with nanoscale-strunctured film consists of drawing microfibers, forming nanoscale-structured film using dip coating process and assembling an array of microfibers. The system of fabrication of microfibers is illustrated in Figure 4. We fabricated microfibers with micrometer-order diameter using hydrogen-oxygen flame-heated scanning fiber drawing method [15]. A standard single-mode fiber is placed into the flame. The location of single-mode fiber in the flame can be controlled by using 2D translation systems precisely. Single-mode fiber was fixed on two 3D translation systems controlled by high-precision stepper motor. The entire experimental setup placed in airtight environment was fixed at a heavy platform in order to ensure the stability of the setup. The flame-heated scanning drawing method has certain advantages compared with laser drawing method; both theoretical and experimental results show that the laser power required for drawing microfibers with a uniform diameter is impractically large [18].

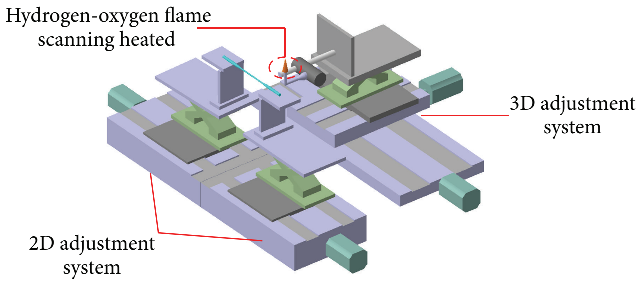


FIGURE 4: The illustration of microfiber drawing method using flame-heated scanning technique. The single-mode optical fiber is placed into the place suitable temperature of hydrogen-oxygen flame using 3D translation systems. Single-mode fiber is drawn down to microfiber based on the flame.

The entire fabrication process of microfibers was controlled by computer program. The temperature in the drawing region and the speed of stepper motors can be adjusted in order to obtain different diameter microfibers with good uniformity of diameter. The uniform and smooth microfibers with diameters ranging from 1.5 to 8 μm are shown in Figures 5(a), 5(b), and 5(c). The higher-magnification scanning electron microscope (SEM) images of the sidewall of 8 μm-diameter, 2.2 μm-diameter, and 1.5 μm-diameter indicate no visible irregularity in the surface of the microfibers.

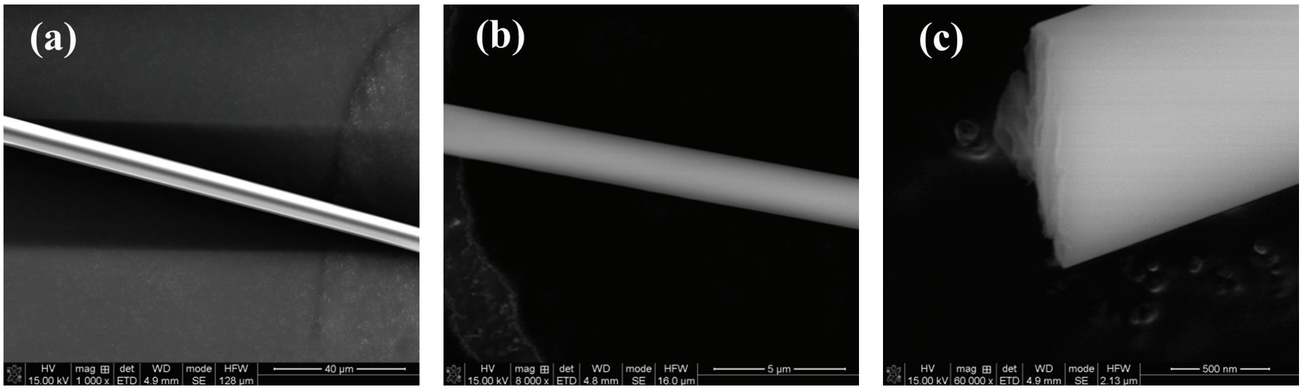
In the experiment, a thin sol-gel film was deposited on the surface of drawn microfibers using dip coating process. The fabricated microfibers were fixed on glass slide. The waist of microfibers cannot be supported by glass slide. The entire system was encapsulated as sensing unit. Sensing unit was washed by alcohol in order to keep the microfibers clean and then a thin sol-gel film was coated by dip coating process. The sol-gel films consist of a layer of porous, near-spherical silica particles, 10 to 40 nm in diameter, and randomly stacked on the substrate surface. Such highly porous films have high specific surface areas and are therefore very susceptible to contamination by vapor adsorption from their environment. Silica films derived by dip coating process with a low refractive index have controlled porosity, which could be adjusted from 65 to 12% continuously. The withdrawal rate was adjusted to give a suitable thickness. In the experiment, the withdraw rate U is 300 mm/min; the liquid concentration η is 1.5%. The atomic force microscope (AFM) images of the surface morphologies of a 1.5 μm-diameter microfiber and the microfiber with nanoscale-structured film are shown in Figure 6. The surface morphologies of microfiber are smooth in Figure 6(a), but Figure 6(b) indicates that nanoscale-structured film is porous, and the roughness of the films is larger than that of microfibers.

Subsequently, a uniform array of 2.2 μm-diameter and 12 mm-length microfibers with nanoscale-structured film was assembled. To demonstrate the feasibility of molecular contaminants with microfibers, the experimental arrangement has been designed and constructed. The assembled array of microfibers with nanoscale-structured has been connected in the system as shown in Figure 7. A laser with 1.55 μm wavelength is used as the source. In order to improve the measurement accuracy, another beam of light is separated from the incident light by optical coupler serves as the reference beam. Due to small surface area of microfiber, an array of microfibers has been adopted to increase the sampling rate to decrease measurement inaccuracy in the experiment. The incident light is split into eight beams which were coupled into an array of microfibers. Light power is transmitted along the microfibers. In the sensing microfibers, the additional loss of transmission light caused by molecular contaminants adhered to film is produced. At last, the light energy is detected with a detector. In order to further improve measurement accuracy of additional loss, lock-in amplify technology is used in experimental setup, and detectors, amplifiers, difference, A/D, and DSP/FPGA phase-locked demodulation are integrated into the application platform. The structure of entire setup is simple and compact. The assembled array of drawn microfibers with nanoscale-structured films is put into the preamplifier SG-III Laser Facility to demonstrate the feasibility of the molecular contaminants sensor.

For the sake of comparison and evaluation, flashlamp "Self-Cleaning" tests of preamplifier SG-III Laser Facility were carried out. Molecular contaminants and particle contaminants were measured by the sensor and laser-scattering particle counters, respectively.

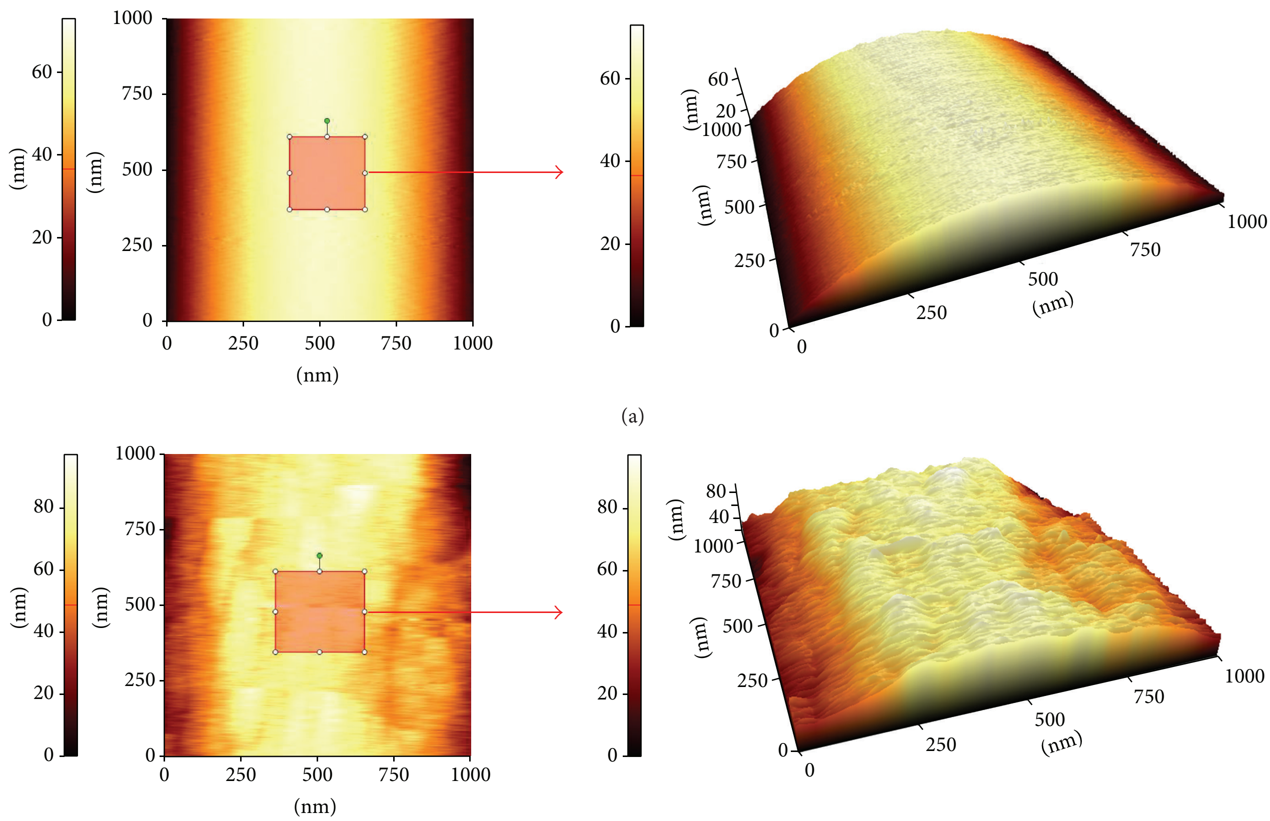
In 10 hours, four flashlamp "Self-Cleaning" tests were carried out. The particle contaminants number and the quantity of molecular contaminants were real-time recorded and shown in Figure 8. Figure 8(a) shows the experimental results of contaminants measured by laser-scattering particle counters from 3.5 h to 5.5 h. The flashlamp energy density was 10 J/cm^2. The number of particle contaminants has experienced two periods, which means two flashlamp "Self-Cleaning" tests from 3.5 h to 5.5 h. Figure 8(a) shows that a period of the variation of contaminants can be divided into four stages: A, B, C, and D. Stage A is flashlamp irradiation. During this stage, contaminants are heated by flashlamp with fluence of 10 J/cm^2. The concentration change of molecular contaminants indicates the significant thermal circulation induced by radiant heating inside the amplifier. Stage B is flashlamp nitrogen purging, which results in the exponential decrease of contaminants concentration after each shot. In stage C, the contaminant concentration slowly increases, indicating the slow removal of contaminants from the walls of the amplifier. Stage D is slab purging, which is similar to Stage B. Slab purging results in the exponential decrease of contaminants after each shot, too.

The additional loss caused by the adherence of contaminants by the new type of sensor was real-time recorded from 0 to 10 h and shown in Figure 8(b). It is clearly shown that the variation of the additional loss has been experienced four periods corresponding to four flashlamp "Self-Cleaning" tests. Compared with Figure 8(a), it is also found that the response of the new type of sensor is fast and accurate. The inset of Figure 8(a) also shows the details of a flashlamp "Self-Cleaning" test. After comparing Figure 8(a) with Figure 8(b) inset, it can be found that the contaminants measured by an array of microfibers with nanoscale-structured film can agree well with the results measured by laser-scattering particle



(a) (b) (c)

Figure 5: SEM images of microfibers: (a) a 8 μm-diameter microfiber; (b) a 2.2 μm-diameter microfiber; (c) a 1.5 μm-diameter microfiber.



(a)

(b)

Figure 6: (a) The AFM images of the surface morphologies of a 1.5 μm-diameter microfiber; (b) the AFM images of the surface morphologies of a 1.5 μm-diameter microfiber with nanoscale-structured film.

counter, which demonstrates the feasibility of the new type of contaminants sensor. And the additional loss is about 0.15 dB; the mass of adherence of molecular contaminants is about 3 pg.

4. Discussion and Conclusion

A new type of contaminants sensor based on an array of microfibers with nanoscale-structured film by evanescent field is presented. The additional loss caused by contaminants adhered to film is simulated by means of 3D-FDTD method. The theoretical results show that the additional loss caused by contaminants varies linearly with RI of the film on the surface of microfiber. For given additional loss, the mass of molecular contaminants can be obtained. The setup has been established to demonstrate the feasibility of the new type of sensor. In the experiment, the sensor was put into the preamplifier SG-III Laser Facility. Contaminants measured

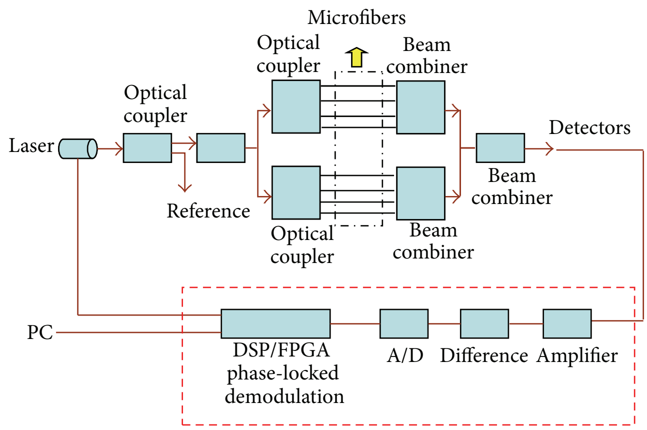


Figure 7: Experimental setup for molecular contaminants sensor based on an array of microfibers with nanoscale-structured film.

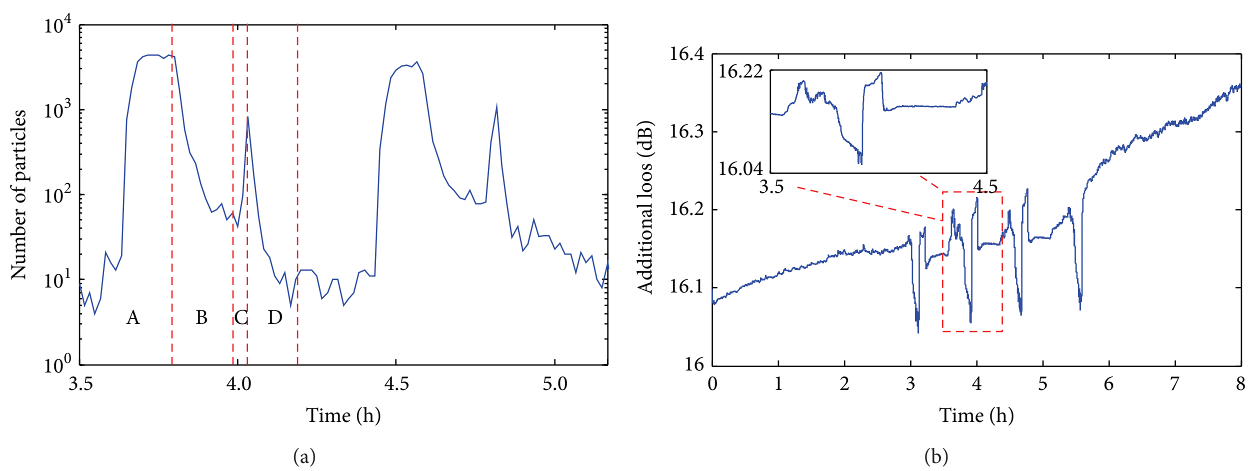


Figure 8: Comparison of experimental results of the sensor and laser-scattering particle counters; (a) the variation of particle numbers measured by laser-scattering particle counters during two periods of flashlamp "Self-Cleaning" test; (b) the additional loss due to the adherence of contaminants dependent on time; the insert shows a period of flashlamp "Self-Cleaning" test.

by the new type of sensor can agree well with the results measured by the laser-scattering particle counter, which demonstrates the feasibility of the new type of contaminants sensor. The experimental results show that the sensor can be used to detect the mass change in the order of pg and to monitor molecular contaminants in high-power laser transmission system. It has advantages such as compact and simple structure and immunity to electromagnetic fields. The contaminants sensor based on an array of microfibers with nanoscale-structured film in this study may provide opportunities for new applications of monitoring vacuum environment.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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