Laser-oriented growth of long polymer tip for scanning optical applications

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Abstract: We report on the laser-oriented growth of a polymer probe with a length of hundreds microns at the end of a single mode fiber. It has a high L/r ratio of 250 and a very low loss of 0.31 dB in optical transmission. It can be applied as an efficient scanning optical source and photo-detector.

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1.INTRODUCTION

Scanning probe technology has been widely used for modern analysis of materials structures in sub-micrometric, nanometric or atomic scale. This technology involves mainly in sensing a variety of weak feedback signals, such as atomic force, electric tunneling current and optical signals. Sensing a nanometric particle via variations of its optical signals by a scanning probe have attracted numerous attentions in the past decade [1-5]. The optical signal obtained by applying a scanning probe optical microscope may be an optical feedback of photoluminescence, scattering, refraction, reflection or transmission [3-6]. The resolution and sensitivity depend normally on probes, including their dimensions, shapes and properties. The most widely applied and commercially available probes are metals or alloys, such as silver, gold, platinum, tungsten and nickel alloy. The advantages of those probes is that their radius can reach the order of ten nanometers, whereas the disadvantage is also obvious that they can only use as a local enhanced optical source in a refraction mode . They can be neither performed in transmission mode nor employed as local detectors of optical signal. In fact, they are not typical SNOM probes. Typical SNOM probes can be divided into two categories, namely aperture optical probes and apertureless optical probes, detailed distinction for their fabrication and function could be found in Ref [7,8]. They are usually involved in the integration of a micro or nano probe on the end of the optical fiber, which may allow them to work as micro or nano lens, optical sources, or detectors. Taking the application as detectors for instances, transmission, Rayleigh scattering, Raman scattering, surface Plasmon resonance, fluorescent signals may be collected directly by these optical probes. They may act as AFM probes as well as optical probes in SNOM. That is to say, they detect and feedback control the distance in a shear force mode and transport or detect simultaneously optical sources or signals. In this ways, both topographies and optical images can be obtained at the same time.

In spite of the promising application of optical probes, manufacturing a micro or nano probe at the very end of fiber is a complex work. During the past decades, numerous efforts have been made to achieve by a variety of research groups. The most available method is so-called mechanical pulling method or melt-stretched etching method [9,10]. The merit of this method is that a small probe radius may be obtained. Its demerit is that its optical transport efficiency is very low. A typical value for the optical transport efficiency in the order of 10-6 has been reported [11]. Low reproducibility and uncontrollability of the probe end shape are other obstacles for its fabrication. Another mostly mentioned method is chemical etching [2,12,13]. Matsumoto et al. [2] have developed a method to fabricate a near field optical fiber probe with nanometric metalized protrusion. A high optical transport efficiency of 5% is reported. Nevertheless, the preparation process is relatively complex and not easy for the manufacture in large scale. In the present work, we will present simple and convenient route for the fabrication of sub-200 nm polymer probes with symmetric end shapes integrated at end of a monomode fiber. Diameters, lengths and end shapes control, first results of optical transport efficiency by the experimental measure and simulation are presented.

2. EXPERIMENTS

A. Photosensitive solution preparation

The basic principle of free-radical photopolymerization method is presented in detail in Ref [14,15].The photosensitive solution consists of three major components: a photosensitive dye of eosin Y, an amine cosynergist MEDA and a multifunctional acrylate monomer PETIA, which is used herein as a solvent. 10% MEDA and 0.5% eosin Y in weight are added into the solvent in succession. The solution is then mixed by a magnetic force agitator for more than 10 hours. It is photosensitive and thermosensitive. Accordingly, it is usually kept at an appropriate temperature (30ºC) for further use of the polymer probe fabrication.

B. Laser-oriented fabrication of polymer probe

This solution is highly sensitive in the spectral region from 450 to 550 nm(the maximum of absorption of eosin Y is centered at 530 nm). Therefore, it will polymerize after being irradiated by an argon-ion laser (514nm or 488nm), a frequency-doubled Nd/YAG laser (532 nm), or a green He-Ne laser (543.5 nm). Particularly, a frequency-doubled Nd/YAG laser is suitable for this system and it is applied in the present work. A modified experimental setup to the free-radical photopolymerization method [16,17] is developed, which is schematically explained in Fig. 1. A drop of photosensitive solution prepared above is deposited on a glass plate. The height of the drop can be adjusted by the amount of the solution and the

contacting angle between the drop and the plate. A well cleaved single mode optical fiber with a core radius of 1.5 μm is approached the surface of the drop slowly, as shown in Fig.1 (a). And the capillarity forces of the small fiber and surface tension of the solution allow them to remain contact even when we raise the fiber until several hundreds microns. The green light coupled from a frequency-doubled Nd/YAG laser into the fiber is guided by the fiber core to its end, where the photosensitive formulation is totally around. Photopolymerization occurs firstly at the root of the fiber when a critical dose of light is integrated into the fiber in the other end. Owing to the Gaussian function formed light dispersion, a tiny polymer lens formed, as shown in Fig.1 (b). This lens will confine the light and permit the oriented polymerization. The polymer acts as a guide and finally forms an self-assembly structured probe. After irradiation, an unpolymerized monomer around the polymer probe make it possible to separate the polymer probe from the solution. By using a solvent of pure ethanol or a mixture of methanol with ethanol, the monomer around the polymer can be washed out [Fig.1 (c)]. The polymer probe fabricated by this method can reach 50~300 μm in length, which is many times longer than that obtained by the free-radical photopolymerization method reported before [18].

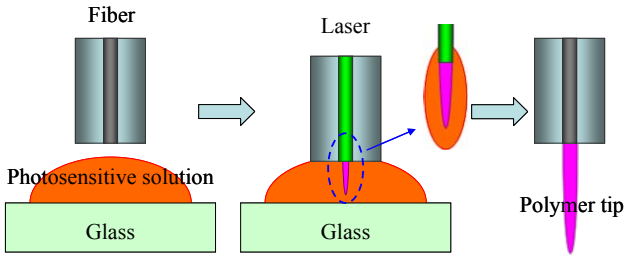

Fig. 1 Experimental setup illustrating polymer tips fabrication

3. RESULTS AND DISCUSSION

A. Controllable fabrication of long polymer probes structure

Fig.2 shows a series of SEM images of polymer probes fabricated at the end of single mode fibers. The cladding diameter and the core radius of those fibers corresponds to 125 μm and 1.5μm, respectively. The exposure time t in this series of experiments is fixed at 2 s. The output light intensity Io measured at the other end of the fiber varies from 250 nw to 1000 nw. With the increase of output intensity Io, the length of the probe increases and the radius of its tip augments. Fig.2 (a)-(c) shows the length changes by using different output intensity, corresponding to 250 nw, 500 nw, and 1000 nw, respectively. By using an intensity of 250 nw, the typical length of the polymer probe can reach 80~100 μm while an exposure time of 2 s is adopted. In the example presented in Fig.2 (a), a length of 94 μm was measured. With the increase of Io, the fabrication process becomes more operable. When the incident intensity is higher than 250 nw (Io >250 nw), the probe fabrication process becomes more easy. With the intensity of 500 nm, the polymer of 123 μm in length was observed (Fig.2 b). When the intensity is up to 1000 nw, the probe length reaches 228 μm, as shown in Fig.2 (c). Moreover, when the intensity is up to 2000 nw, the probe length reaches more than 300 μm. Nevertheless, with increase of its length, the probe tip tends to be easily distorted. A serious distortion is found when we applied an intensity higher than 2000 nw. Taking these two opposite effects into consideration, an output light intensity between 250 nw and 2000 nw is recommended as an suitable value range for the practical fabrication of the polymer fiber by this modified free-radical polymerization method.

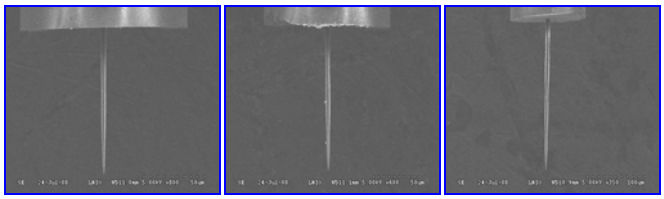

Fig.2 SEM images showing polymer probes by applying intensity of 250nw, 500nw, and 1000nw. Their lengths correspond to 94 μm, 123 μm and 228 μm, respectively. For all cases, the exposure time is kept the same as 2s.

B. Optical characterization of long polymer probes

Microscopy images that were undertaken with and without laser light passing through the optical fiber from the other end was shown in Fig.3 (a) and (c), respectively. The inset of (b) is a magnification showing a long super-straight structure of the polymer probe that fabricated by using 2 s and 500 nw of laser green (λ=532 nm) for its oriented growth. The intensity for the characterization in Fig.3 (b) was 120 nw and the same wavelength of 532 nm. Excepting the extremity of the probe, no apparent loss of light has been observed along the long distance of the polymer, as shown in Fig.3 (c). With the increase of light intensity, a small quantity of light loss has been found. For example, an output intensity of 16.3 μW was measured by using a input intensity of 17.5μw, i.e. a very low loss of 0.31 dB in optical transmission have been detected for this apertureless optical fiber probe.

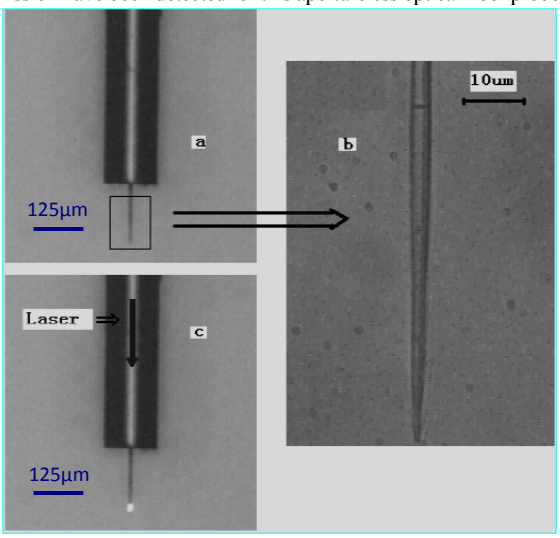

Fig.3 A long polymer probe of 175 μm in length obtained by a free-radical photopolymerization method showing a very low loss in transmission (λ= 532 nm, I0=120 nw).

C. Application as photo-detector

Using a polymer tip with length about 125 μm and tip radius of approximate 500 nm, a sub-micrometric gold particles sample on the glass was observed. The detailed experimental setup has been described in the previous parts. We approached slowly the probe to the surface of the sample from several microns until that they are contacted. Optical images of a gold particle were obtained using a constant working distance mode. Typical images for the distance of 2600 nm and 800 nm are shown in Fig.4 (a) and (b), respectively. With the distance between the probe tip and the particle decreasing, a remarkable increase of resolution has been found. In Fig.4 (a), a FWHM value of 1077 nm was found corresponding to a distance of 2600 nm, while a FWHM value of 653 nm corresponded to a distance of 800 nm. Owning to

effects of Rayleigh scattering, we can not obtain a higher resolution for the far field instance. A scanning near field optical microscope (SNOM) was strongly recommended for higher resolution [4,5,7]. However, we hereby demonstrated experimentally that the long polymer tip is suitable for the application as photo-detector. Particularly, it is a commendable choice for scanning optical microscope via reflecting or reflecting mode that generally needs a small angle of taped structure at its tip end. Presently, our emphasis is paid to demonstrate its possibility for the application as an easy-fabricated optical probe detector. Further attempts for various SNOM applications by using this probe will performed.

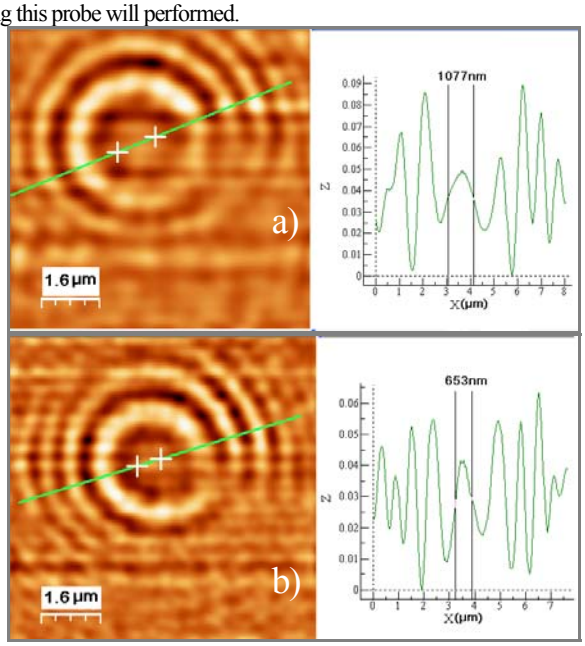

Fig.4 Optical image of a gold particle observed with distance control by an atomic force microscope: a) with a distance of 2600 nm and b) 800 nm, respectively.

4. CONCLUSION

In conclusion, a long polymer probe with sub-micrometric radius has been orientedly grown at the end of a monomode optical fiber. Two parameters of exposure time and intensity for its fabrication have been studied in-depth. The length of the polymer tip is more related to the time and its radius is more sensible with the vary of exposure intensity. However, the increase of the intensity also have an remarkable contribution to a growth in length. With regard to its potential applications, an exposure intensity range from 250 nw to 2000 nw and 1~2 s exposure time is recommended for this fabrication. Compared with the fiber optical probe by mechanical pulling methods, the loss in transmission for this kind of optical probe is extremely low. Using this kind of probe, an application as an optical probe detector has been demonstrated experimentally. Potential applications for the SNOM, in particular for those applications worked in a reflecting mode will be greatly encouraged by this kind of optical fiber probe.

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REFERENCES

1. Y. Inouye, S. Kawata, "Near-field scanning optical microscope with a metallic probe tip," Opt. Lett. **19**, 159-161 (1994).
2. T. Matsumoto, T. Ichimura, T. Yatsui, M. Kourogi, T. Saik, M. Ohtsui, "Fabrication of a near-field optical fiber probe with a nanometric metallized protrusion ", Opt. Rev. **5**, 369-373 (1998).
3. S. Herbert, J. K. Michael, M. J. Thomas, "Microstructured polymer tips for scanning near-field optical microscopy", Ultramicroscopy **71**, 107-110 (1998).
4. K. E. Sang, J. Wonho, A. Yasuhiko, "Near-field optical photoluminescence microscopy of high-density InAs/GaAs single quantum dots ", Appl. Phys. Lett. **80**, 2779-2781 (2002).
5. W. X. Sun, Z. X. Shen, "Near-field scanning Raman microscopy using apertureless probes", J. Raman Spectrosc. **34**, 668-676 (2003).
6. T. Ichimura, N. Hayazawa, M. Hashimoto,Y. Inouye, and S. Kawata, "Tip-enhanced coherent anti-stokes Raman scattering for vibrational nanoimaging," Phys. Rev. Lett. **92**, 220801/1-220801/4 (2004).
7. H. F. Hamann, M. Larbadi, S. Barzen, T. Brown, A. Gallagher, D.J. Nesbitt, " Extinction near-field optical microscopy ", Opt. Commun. **227**, 1-13 (2003).
8. G. A. Valaskovic, M. Holton, G. H. Morrison, "Parameter control, characterization, and optimization in the fabrication of optical fiber near-field probes", Appl. Opt. **34**, 1215-1228 (1995).
9. H. L Ren, C. Jiang, W. S Hua, M. Y. Gao, J. Y. Wang, H. Wang, J. T. He, E. J. Liang, "The preparation of optical fiber nanoprobe and its application in spectral detection", Opt. Laser Technol. 39 1025-1029 (2007)
10. R. C. Dunn, G. R. Holtom, L. Mets, X. S. Xie, "Near-field fluorescence imaging and fluorescence lifetime measurement of light harvesting complexes in intact photosynthetic membranes", J. Phys. Chem. **98,** 3094-3098 (1994).
11. R. Stokle, C. Fokas, V. Deckert, "High-quality near-field optical probes by tube etching", Appl. Phys. Lett. **75**,160-162 (1999).
12. P. Lambelet, A. Sayah, M. Pfeffer, C. Philipona, F. Marquis-Weible, "Chemically etched fiber tips for near-field optical microscopy: a process for smoother tips", Appl. Opt. **37**, 7289-7292 (1998).
13. C. Ecoffet, A. Espanet, D. J. Lougnot, "Photopolymerization by evanescent waves: a new method to obtain nanoparts," Adv. Mater. 10, 411-414 (1998).
14. A. Espanet, C. Ecoffet, D. J. Lougnot, "Photopolymerization by evanescent waves. II: revealing dramatic inhibiting effects of oxygen at the submicrometer scale", J. Polym. Sci. A: Polym. Chem. 3, 2075-2085 (1999).
15. Y. Gilbert, R. Bachelot, A. Vial, G. Lerondel, P. Royer, "Photoresponsive polymers for topographic simulation of the optical near-field of a nanometer sized gold tip in a highly focused laser beam", Opt. express 13, 3619-3624 (2005).
16. M. Hocine, N. Fressengeas, G. Kugel, C. Carré, D. J. Lougnot, R. Bachelot, Pascal Royer, "Modeling the growth of a polymer microtip on an optical fiber end" J. Opt. Soc. Am. B **23**, 611-620 (2006).