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Note: Fabrication of tapered fibre tip using mechanical polishing method

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Tapered fibre tips fabricated using mechanical polishing method is studied. The fibre tips are formed by sequential polishing flat-ended single mode fibres with decreasing aluminium oxide polishing film grit size. Based on the proposed technique, tapered fibre tips with cone angle ranging from 30° to 130° are fabricated by controlling the polishing angle. Besides the variety of cone angle, considerable smoothness of the fibre tip surface may assist in good metal coating and hence a well-defined aperture can be obtained. In addition, this paper presents a two-step hybrid fabrication method combining the proposed polishing method with chemical etching method to increase the possible fibre tip cone angles achievable by chemical etching method. © *2011 American Institute of Physics*. [doi:10.1063/1.3627374]

Tapered optical fibre tip has been one of the important components in scanning near-field optical microscopy (SNOM),[1,2] forming the optical probe of SNOM. Tapered fibre tips are also suitable for photolithography process in the fabrication of polymeric and silicon optical waveguides where the dimensions of the waveguides are in the range of micrometers to sub-micrometers.[3] Optical near-field is a layer of light produced from a light emitting or irradiated surface. Therefore, the size of optical near-field aperture is not limited by Abbe's diffraction limit[4] but depends on the physical dimension of the aperture itself. Together with metal coating, tapered fibre tips with aperture sizes of several hundred nm in diameter make good candidates for such purposes.[5]

There are two common methods for the fabrication of tapered fibre, namely, heat-and-pull technique[6] and chemical etching using hydrofluoric acid (HF etching).[8–11] The heat-and-pull technique produces fibre tips with small cone angle and smooth surface which enables uniform metal coating. However, this method suffers a setback of low throughput power due to simultaneous reduction of the fibre cladding and core along the tapered region, causing spot size expansion at the fibre tip.[7] On the other hand, chemical etching can be divided into two approaches which are the Turner method[8] and the tube-etching method.[9,10] These methods are commonly used to mass produce fibre tips of large cone angle. Unlike the heat-and-pull technique, the chemically etched fibre tip comprises only the fibre core with reducing diameter towards the tip as the cladding has been totally etched out. Furthermore, short tapered length can be achieved using the chemical etching technique. In this case, the expansion of spot size along the short fibre tip is minimal and higher throughput power can be achieved. The cone angle produced by the chemical etching technique ranges from 8° to 41°.[10] Nevertheless, the Turner method suffers from poor surface roughness and asymmetric tip profile. These problems can be improved by using the tube-etching technique,[9] where the chemical etching process takes place within the polymer coating of the fibre which is not reactive to hydrofluoric acid. In this case, the meniscus height of hydrofluoric acid is always constant throughout the etching process, therefore producing tapered fibre tip with consistent cone angle regardless of the spacing between adjacent fibres. However, control over cone angle of the fibre tip is compromised when using the tube-etching technique. Using different etchant concentration or different fibre types, the cone angles can be varied only in the range from 17° to 36°.[9] Hence, there is a trade-off between the range of achievable cone angles and the symmetry and surface quality of the fibre tip. Pre-treatment before chemical etching and reverse tube-etching technique have been proposed to obtain fibre tips with a wider range of cone angles.[5,11] To improve the throughput power from the tapered fibre tip, formation of evanescent field along the tapered fibre should be minimized using short taper length or larger cone angle.[5] Nevertheless, new approach to achieve large cone angle remains a challenge.

In this paper, we report an alternative method to fabricate tapered fibre tip with controllable cone angle ranging from 30° to 130°. Instead of the heat-and-pull technique and chemical etching, fibre tip can be formed by mechanical polishing of a flat-ended single mode fibre using optical grade polishing films. With the ability of achieving large cone angle, this proposed technique enables fabrication of tapered fibre with higher throughput power.

The polishing technique makes use of the concept of synchronized spinning of the fibre and polishing roller. Figure 1 shows the schematic illustration of the fibre taper fabrication rig. Two dc motors were used to drive the polishing roller and rotate the fibre simultaneously in the polishing process to produce fibre tips with symmetry cone. The speed of the motor can be adjusted by controlling the driving current to the dc motors. In this experiment, the speed of the motor used to rotate the roller is 2π rad s^{-1}, and the fibre is rotated at 0.5π rad s^{-1}. Faster spinning speed may result in shorter process time. Water drop is periodically dripped onto the polishing roller during polishing process for lubrication purposes and to remove debris generated during the polishing process. Aluminium oxide polishing films are rolled and fixed along the surface of the cylindrical roller with a diameter and length of 90 mm and 60 mm, respectively. Two aluminium oxide

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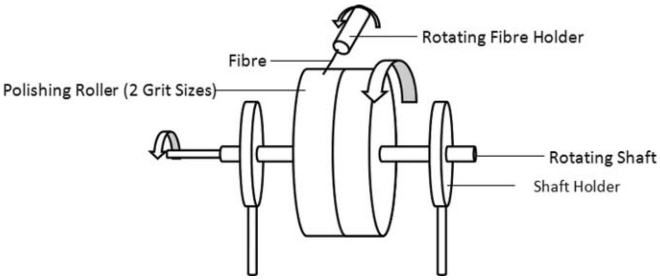

FIG. 1. Schematic illustration of the fabrication rig for fibre tip.

polishing film grit sizes are used in the polishing process, which are 12 μm and 0.3 μm. The smaller grit size indicates slender particle size on the polishing film, thus improving the surface quality of the polished surface. Coarse polishing film was used in the initial stage of polishing to speed up the polishing process, followed by a slender film which was used to achieve smoother surface of the fibre tip. To manufacture a sharp tapered fibre from a flat-ended fibre, the polishing begins with a 12 μm grit size polishing film for 15–20 min, followed by 0.3 μm grit size polishing film for 5–10 min. The change of polishing film grit size from 12 μm to 0.3 μm between subsequent polishing steps is unconventional, but effective in producing a smooth tapered fibre tip.

Cone angle of the tapered fibre tips produced using this method is controlled by adjusting the angle between the fibre and the tangent of the polishing roller, as shown in Fig. 2. The relationship between polishing angle and cone angle of the tapered fibre tip can be written as

$$\alpha = 2\theta, \tag{1}$$

where α is the cone angle of the tapered fibre tip and θ is the polishing angle.

To take advantage of the mass production ability of the chemical etching technique, a two-step fibre tapering technique based on a combination of chemical etching and mechanical polishing is proposed. In this case, a large number of tapered fibres can be batch-produced in a single fabrication process, which usually takes 45 min to complete using 48% concentration of hydrofluoric acid. The ensuing polishing process using 0.3 μm grit size polishing film, which takes ~5–10 min to complete, produces tapered fibre tip with very smooth surface. Regardless of the cone angle produced in the first chemical etching step, the cone angle of the tapered fibre can be controlled by using the desired polishing angle in the second polishing step of the hybrid tapering process.

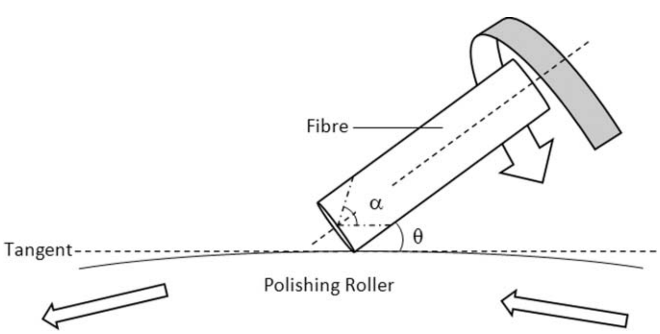

FIG. 2. Geometrical diagram of conical angle formation.

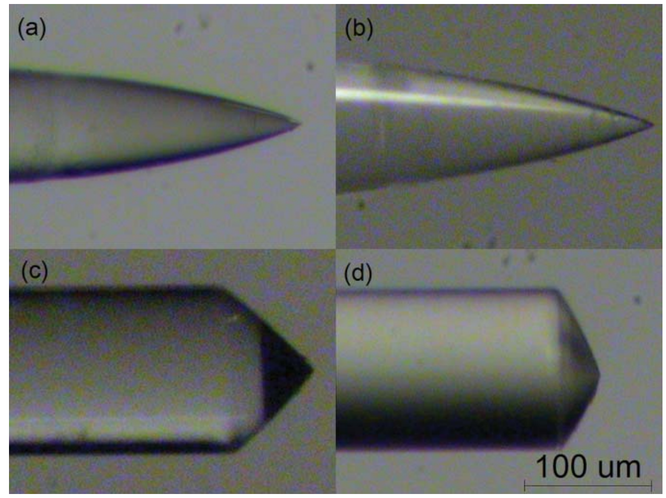

FIG. 3. (Color online) Polishing method (a) Cone angle 30°, (b) cone angle 50°, (c) cone angle 90°, and (d) cone angle 130°.

Fibre tips produced using the polishing method is shown in Fig. 3. Cone angles between 30° and 130° have been fabricated by controlling the polishing angle, θ, exhibiting relatively high flexibility in the selection of cone angle using the proposed method. Fibre tips with larger cone angles require less time to fabricate compared to small cone angle fibre tips. This is due to the smaller contact surface between the fibre end and the polishing roller which translates into small volume of glass to be removed.

Figure 4 shows the fibre tip profiles of different cone angles fabricated using the polishing method. The x-axis denotes the cross sectional position of the fibre tip centred at the fibre longitudinal axis, while the y-axis denotes the axial distance of the fibre. Larger cone angle of the fibre tip corresponds to shorter length of the tapered region of the fibre tip. For fibre tips with large cone angles, the radius of the fibre tip decreases linearly along the axial direction of the fibre, whereas the profiles of fibre tips with small cone angles are

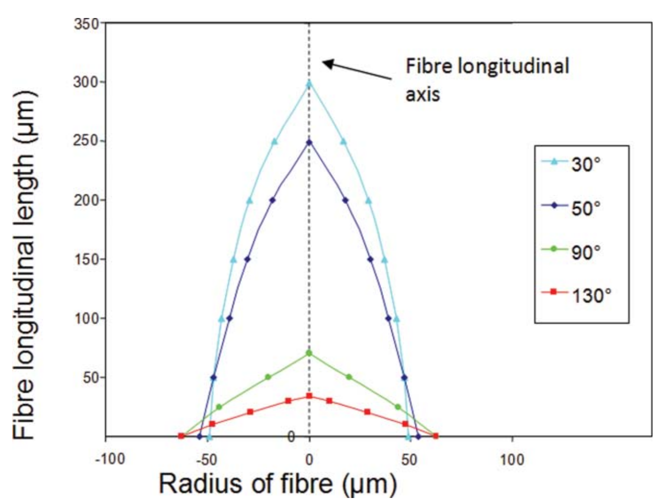

FIG. 4. (Color online) Relation between the horizontal axis and the vertical axis of the cone for each angle.

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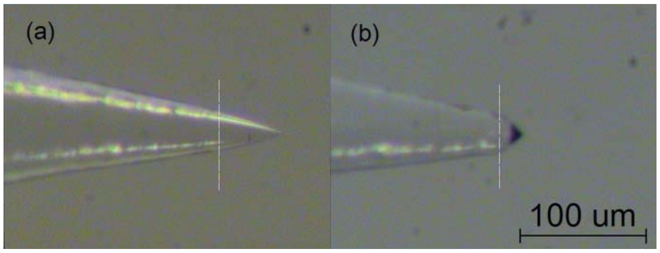

FIG. 5. (Color online) Hybrid method (a) Cone angle 17° (HF etching) followed by 20° (polishing). (b) Cone angle 17° (HF etching) followed by 90° (polishing). Dotted line delineates between chemical etching region and polishing region.

convex in shape and the radius reduction rate increases towards the fibre tip. This is due to minor fluctuation in polishing angle caused by small mechanical vibration between the fibre and the polishing roller during polishing process. The curvature for fibre tip with small cone angle can be alleviated by reducing the polishing speed (rotation of both the polishing drum and fibre), but the slower polishing rate will result in longer fabrication time.

Figure 5 shows optical micrographs of tapered fibre tip fabricated using the hybrid technique. The Tube-etching technique is used to produce tapered fibre tip with a cone angle of 17°. This is followed by mechanical polishing of the tip end to produce cone angle of 20° and 90° as shown in Figs. 5(a) and 5(b), respectively. The dotted lines in the images delineate the boundary between the tapered region with chemical etching only and the tapered region with chemical etching followed by mechanical polishing. Despite the fact that the tube-etching method is an improved method over conventional chemical etching method, surface quality can be appalling. Mechanical polishing can improve the surface quality of the fibre tip. The distinction in surface quality between the chemical etched only surface and the hybrid-treated surface is more obvious in Fig. 5(a), where smoother surface tapered region is achieved with mechanical polishing (fibre tip) compared to tapered region fabricated using chemical etching only. Using Veeco Dektak D150 surface profiler to measure the surface roughness for both etched and polished tapered fibres, the average surface roughness, R_a, of the etched surface ranges from 60–100 nm, whereas the R_a compared to the smoother polished surface with R_a ranges between 20 and 40 nm.

The smoother surface achieved from mechanical polishing will reduce light scattering due to surface roughness and increase the throughput power of the tapered fibre tip substantially. Additionally, the shorter tapered fibre tip resulting from the rapidly reducing radius at the fibre tip will minimize detrimental effect of spot size expansion along the fibre tip.

Metal coating on tapered fibre tip is necessary in the preparation of tapered fibre tip to be used in SNOM and scanning near-field optical lithography (SNOL). Figure 6 shows a tapered fibre tip fabricated using hybrid method after chromium coating using direct current sputtering method. The chromium coating is about 100 nm in thickness. Adhesion of the coating on the fibre is good on both surfaces fabricated with different taper techniques. The smooth surface of the apex is important in metal coating in order to coat a metal layer.

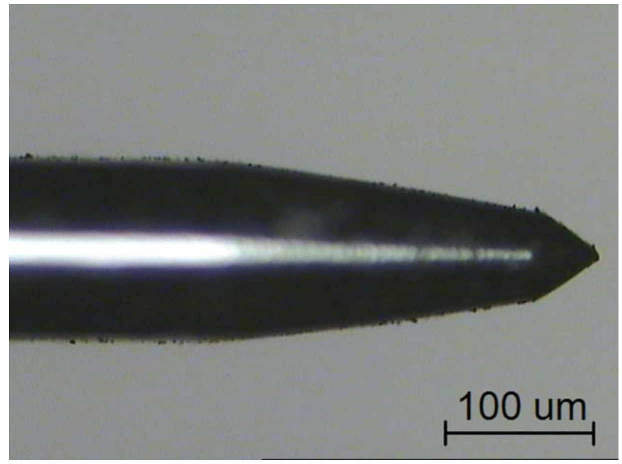

FIG. 6. (Color online) Chromium coated Hybrid tapered fibre.

Fabrication of tapered fibre tips using a mechanical polishing technique as well as a chemical etching-mechanical polishing hybrid technique is demonstrated. Tapered fibre tip using the polishing technique shows very high surface quality as well as a wide range of fibre tip cone angle. Successful metal coating of the tapered fibre tip, a pre-requisite for application as optical probe in SNOM and writing tip in SNOL, is achieved. The method might produce fibre tips with larger cone angle which ensure greater throughput power at the fibre tip with shorter taper length. Furthermore, the simplicity in operation, low cost, and short processing time of the polishing method allows for effective fabrication of high quality tapered fibre tip.

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