M2 INTERNSHIP MIDTERM REPORT

FABRICATION OF MICROFIBER KNOT AND MICROFIBER TIP

Laboratoire Kastler Brossel, March-May 2015

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Introduction

The Kastler Brossel Laboratory (LKB) is one of the main actors in the field of fundamental physics of quantum systems. Many new themes have appeared recently in this field, such as quantum entanglement or Bose-Einstein Condensation in gases, which leads to a constant renewal of the research carried out in the laboratory. Presently our activities focus on several forms: cold atoms (bosonic and fermionics systems), atom lasers, quantum fluids, atoms in solid helium; quantum optics, Cavity quantum electrodynamics; quantum information and quantum theory of measurement; quantum chaos; and high-precision measurements. These themes lead not only to a better understanding of fundamental phenomena, but also to important applications, such as better more precise atomic clocks, improvement of interferometric gravitational wave detectors and new methods for biomedical imaging [1].

Our group is mainly working on Quantum Optics. The group centers its research area on the quantum properties of light that is produced by various optical systems. It consists of experimental and theoretical studies concerning quantum fluctuations of light, generation of entangled states, interaction between quantum light and matter, nanophotonics, and quantum metrology. One direction of interest is the development of original devices coupling semiconductors nanocrystal to photonics structure as nanofiber or photonic crystal cavities. The group is also working on the general them of multimode quantum optics, where the system under study has many degrees of freedom and thus possibly conveys a huge amount of information. In this particular research direction, optical frequency combs that span over many frequency modes are the multimode resource. The group explores this subject both theoretically and experimentally, from the introduction of new concepts to the improvement of highly sensitive measurement and applications to quantum information processing. Multimode approach of classical and quantum imaging are attracting the group recently as well. Spatial modes of light are information carriers, used either for classical communication within optical fiber or quantum networks. This involves the thorough characterization of multimode fiber along with the derivation of quantum limits in parameter estimation. Another interest of the group is the polariton quantum gas in semiconductor quantum well micro cavities [2].

1 Preliminary

1.1 Microfiber knot

Broad applications have been found from optical resonators in optical processing, sensing, and active devices, where optical resonators have been fabricated in many different forms such as Fabry-Pérot, microsphere, toroid, and recirculating fiber loops [3]. Resonators made from microfibers (optical fibers tapered down to micrometer-scale diameters) have attracted wide interest recently for their potentially high Q factor [4]. Microfibers exhibit extraordinary properties such as a large evanescent field, strong confinement, easy configurability and high robustness [5]. There are three main types of microfiber resonators: the microfiber coil resonator, microfiber loop resonator, and microfiber knot resonator [4]. With interfiber twisted coupling between the microfibers, microfiber knot resonator provides a more rigid knot structure [6], which makes microfiber knot resonator attracts most of our interest among all these microfiber resonators.

1.2 Microfiber tip

We define microfiber tip as a single mode microfiber, which has a taper end with the scale of micrometers in diameter. To migrate solution of nanocrystals onto microfiber, we are now using pipette in our lab, which can hardly fulfill the request to attach a single nanocrystal on the microfiber. Compared with pipette, microfiber tip is much smaller in the size of attachment area between the fiber tip and the solution, which provides possibility to have a single nanocrystal on the microfiber.

1.3 Motivations

1.3.1 Fabrication of Microfiber Knot

Recently, our group get interested in microfiber knot resonator. Fabrication of the microfiber knot is certainly the base of further research.

In case to measure transmission of the microfiber knot resonator, a single mode should go through our single mode fibers. The V number is a parameter, which determines the number of modes of a step-index fiber. It is defined as

$$V = \frac{\pi}{\lambda} dNA = \frac{\pi}{\lambda} d \sqrt{{n_{core}}^2 - {n_{cladding}}^2}$$

where λ is the vacuum wavelength, d is the diameter of the fiber core, and NA is the numerical aperture. For V values below≈ 2.405, a fiber supports only one mode per polarization direction [7]. Therefore, with given values of the single mode fiber (Thorlabs SM600) and wavelengths of HeNe laser and diode laser, we obtain a maximum value of the fiber diameter of the microfiber knot around 400 nm. We are trying to manage a microfiber knot with the fiber diameter of 400 nm.

1.3.2 Fabrication of Microfiber Tip

We desire to fabricate microfiber tips with a small diameter of the taper end and to keep tip as stiff as possible, which can be used in promising fields such as replacing pipette to manipulate micro-amount solutions.

2 Materials and methods

2.1 Materials

To fabricate microfiber knots, we use single mode fiber (Thorlabs SM600), with a 125 μm cladding diameter. We use HeNe laser and diode laser to measure the transmission.

2.2 Methods

To pull a microfiber, we use the flame-brushing method [8], as shown in Fig.1. We heat a small region of microfiber (without cladding) by a flame of 0.42 millimeter-length fed by hydrogen and oxygen (to avoid usual combustion products which could interrupt the process). To obtain tapers with an extremely uniform waist diameter and taper transitions with well-designed length and shape, the flame keeps relatively scanning (the flame is fixed while the two motors move to gain scanning) along the fiber [9]. Any dust or impurity will cause a failure of the pulling process. Thus, the fibers are handled with care in a dust-free environment.

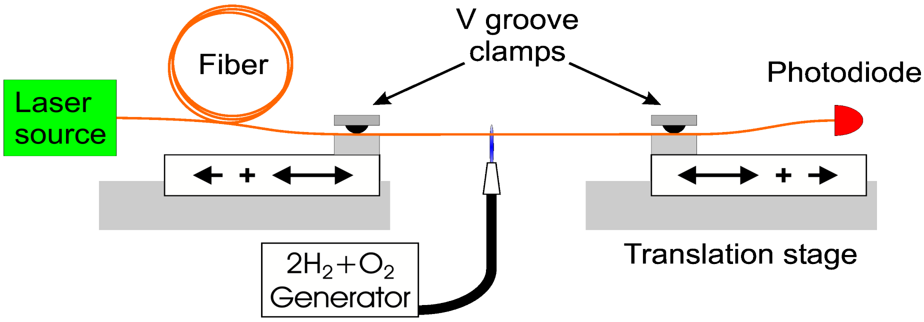

Fig.1 Flame-brushing site. Typical tapering bench as used by the LKB group.

2.2.1 Knot the fiber ends

Once the fiber is stretched with an extremely uniform waist diameter, we turn off the flame, release the two clamps, and lift up the two end of the fiber. After getting the two motors back to their original positions, we manually knot the two ends of the fiber, decrease the size of the knot until it arrives at a proper size (Fig.7), gently put the fiber with a knot in the center back onto the motors, and close the two clamps. Great care has to be taken all over the manipulation process. We can control the motors to continuing stretching the fiber to decrease the size of the microfiber knot.

2.2.2 Stretch the fiber till breaking

In order to have a microfiber tip, we stretch the fiber until it breaks and we will get two pieces of microfiber tips at one time. The main difference between the methods to obtain a knot and a tip is the locus of the motors, which move according to a PVT (position, velocity, and time) file, generated by MATLAB (a piece of code is shown as an example in Annex A).

3 Results and Discussion

3.1 Microfiber Knot

To our knowledge, among all reported microfiber knot resonator, the smallest fiber diameter and resonator diameter are 1 μm and 46 μm, respectively. When we first try making a microfiber knot, we started with 4μm for the fiber diameter of the waist and with a free end on each side, that is, we did not introduce a laser into the fiber. The microfiber has a possibility to break easily in every procedure (see 2.2.1). Even though we succeed to obtain a knot, it is full of dust around the knot at first (Fig.2b). We define waist diameter as the fiber diameter of the knot, waist length as the length of the taper waist, and taper angle as the intermediate taper angle, which is the same as the taper angle near the waist and near the cladding.

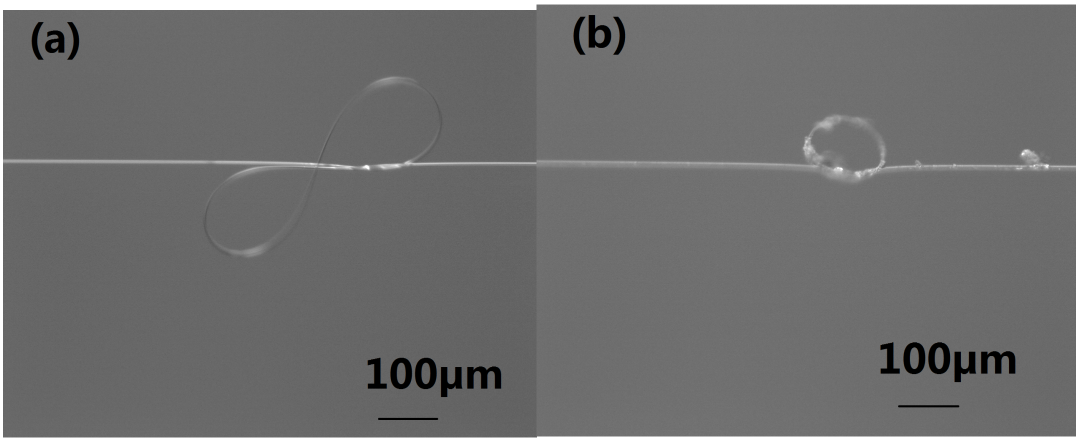

Fig.2 (a) The shape of the number "8" appears each time while pulling the microfiber to have a knot, which will disappear automatically when the diameter of the knot is decreased down to several hundred micrometers; (b) First success of a microfiber knot with dusts around it. Waist diameter: 4 μm, waist length: 1.5 cm, knot diameter: 70 μm-100 μm ellipse, taper angle: 2.5e-3 rad.

With further attempts paying attention to get clean environment around the flame-brushing site, we get to be able to obtain clean knots with the same waist diameter. Carefully following procedures to knot the fiber (see 2.2.1), we are able to manage to make a knot with two free ends (Fig.3a). We move to try with laser on, which makes the manipulation process quite different and more complicated, especially with one end of the fiber fixed on the pulling site to introduce the HeNe laser which is fixed 5 meters away from the flame-brushing site.

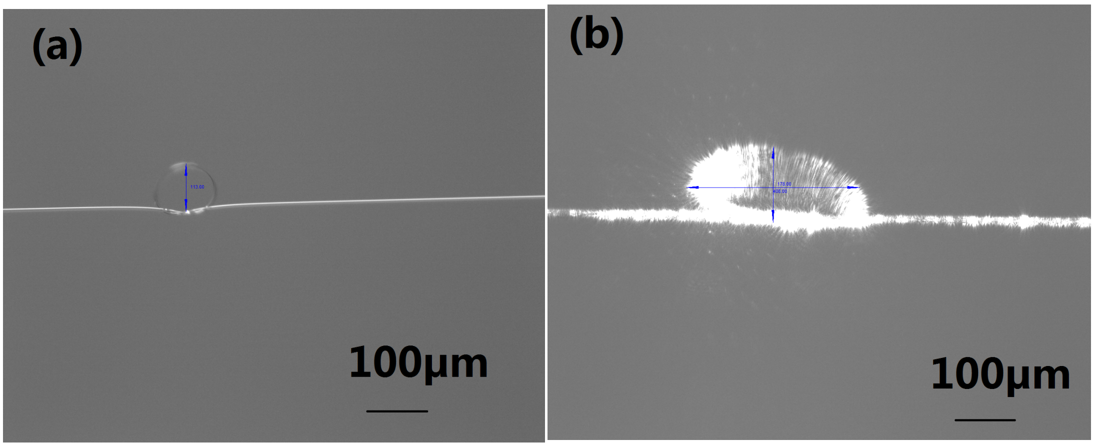

Fig.3 (a) A clean knot. Waist diameter: 4 μm, waist length: 1.5 cm, knot diameter: 80 μm-100 μm ellipse, taper angle: 2.5e-3 rad. For a knot with fiber diameter of 4 μm, we have a successful rate of over 60%, which is increased from less than 10% at first, by avoiding imperfect manipulations, which give chances to easily break the fiber; (b) The microfiber with the knot is shining due to the HeNe laser. We introduce HeNe laser to measure transmission of the microfiber knot. The laser should not make the fiber shine.

Then we start to work with a diode laser that is beside the flame-brushing site, which makes manipulation simpler because two ends of the microfiber can be removable.

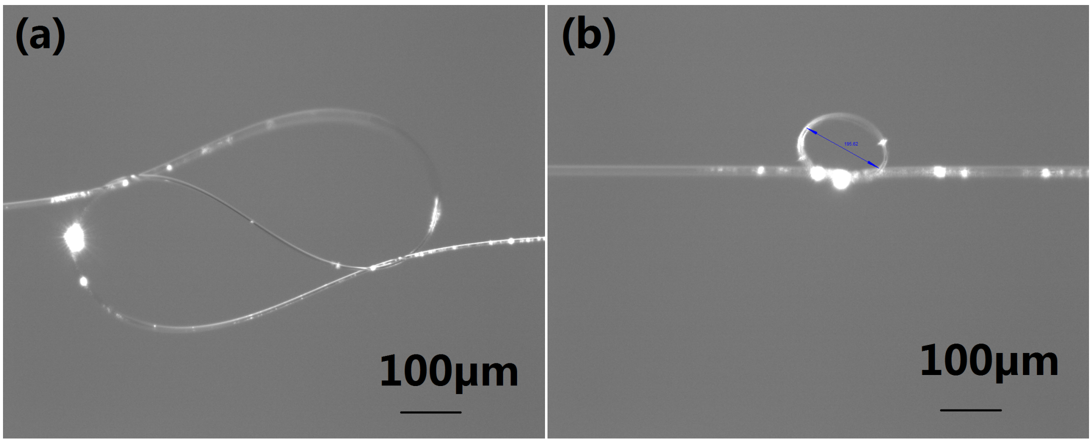

Fig.4 (a) As shown in figure 2, a similar shape of the number "8" appears frequently no matter if the laser is on or not, which will not destroy the knot while pulling later on. (b) A microfiber knot with diode laser going through. Waist diameter: 4 μm, waist length: 1.5 cm, knot diameter: 120 μm-135 μm ellipse, taper angle: 2.5e-3 rad.

Basically, in order to have a single mode in our fiber, 4μm for the fiber diameter of the knot is not small enough. We then move to decrease the diameter of the microfiber waist. We manage a microfiber knot with the waist diameter of 2μm (Fig.5).

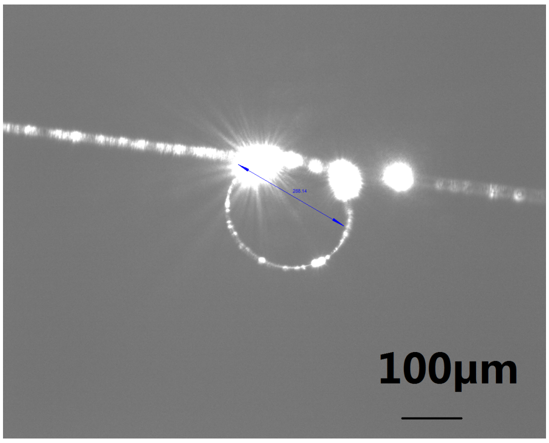

Fig.5 A microfiber knot with diode laser going through. Waist diameter: 2 μm, waist length: 1.5 cm, knot diameter: 120 μm-135 μm ellipse, taper angle: 2.5e-3 rad.

We need to keep the knot onto a metallic stage and then into a box in order to avoid contamination as much as possible. In such a process, the microfiber with a knot may break because of vibration of the air caused by human manipulation, and the attachment of the stage and the microfiber when we use UV glue to glue the fiber onto the stage. Up till now, we can manage to have a knot with the waist diameter of 1.5 μm on the motors, and to keep a knot with the waist diameter of 2 μm onto the metallic stage within the transparent box.

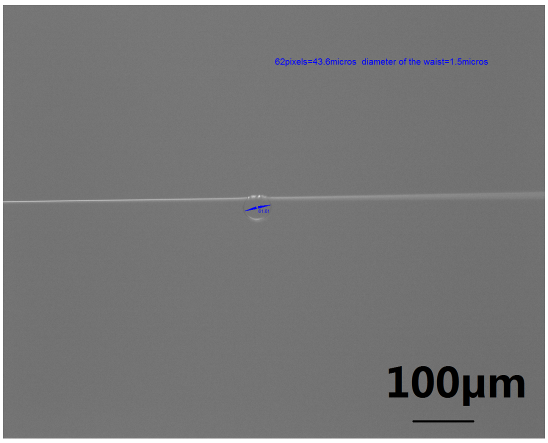

Fig.6 A microfiber knot. Waist diameter: 1.5 μm, waist length: 1.5 cm, knot diameter: 44 μm, taper angle: 2.5e-3 rad.

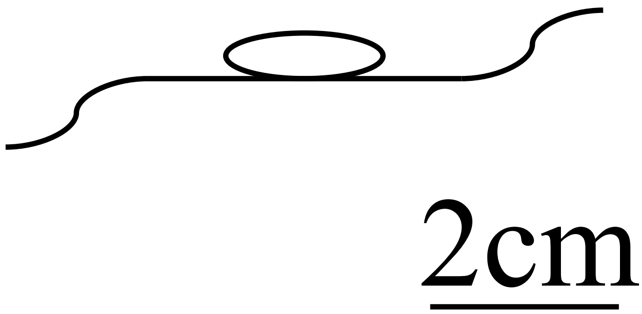

Fig.7 The knot is supposed to be with such a certain shape before being put back onto the clamps.

If the size is smaller than this (Fig.7), it will have much higher possibility to break; if the size is larger than this, the distance between the two clamps will be very large and therefore there will be too much vibration, which makes it more complicated to observe and to characterize the knot, and which makes it easier to break while pulling to decrease the size. The knot should be in the center of the two clamps, in order to reduce the possibility of breaking the microfiber and also to observe the knot easily later on, instead of moving the camera, which will bring dust to the knot and strength the airflow vibrating the microfiber with the knot.

For a microfiber knot with fiber diameter of 1.5 μm, we have a successful rate of one third. To have a single mode transmitting along the fiber, 1.5 μm is still not small enough for the diameter of waist if we use diode laser, which has a wavelength of 780 nm. Attempts with waist diameter of 400 nm are required.

We have tried a number of pulled microfibers to make a knot and we know at which times the microfiber has the largest possibility to break. We can avoid the imperfect manipulations and we will need a list of precautions.

3.2 Microfiber Tip

In order to have a microfiber tip, we need to have a high speed of the motor right before breaking the microfiber. We first think of a parabola formula

$$V(t) = \alpha t^2$$

where $V(t)$ is the same speed of the two motors and α is the parameter we keep changing to get a proper speed. Tips that we get with this formula always have a long tail (strongly bending at the end of the tip) up to 1 mm. We define V_{end} as the speed of the two motors, which stretch the fiber to break.

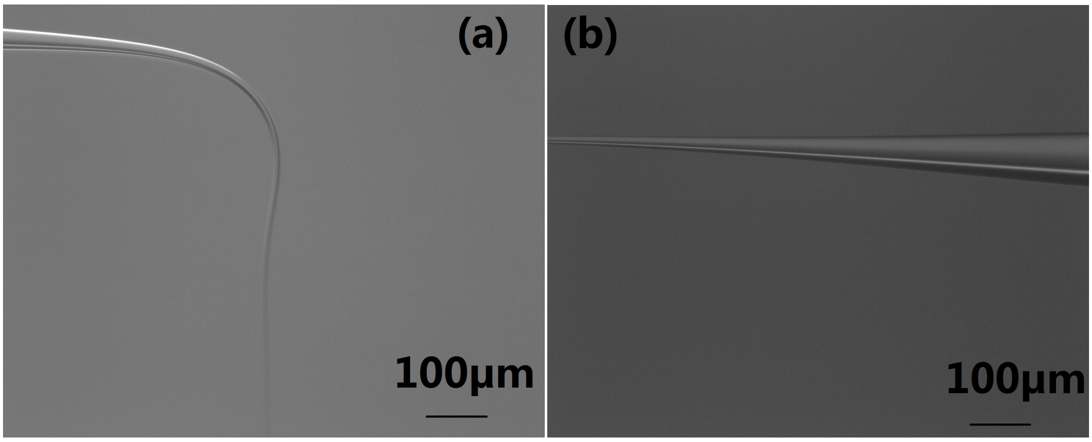

Fig.8 (a) The tip always has long tail in the end, Vend=12.6 mm/s. (b) Profile of the tip right before the long tail.

We reduce the length of the tail and try to cut the end of the tip with a diamond knife.

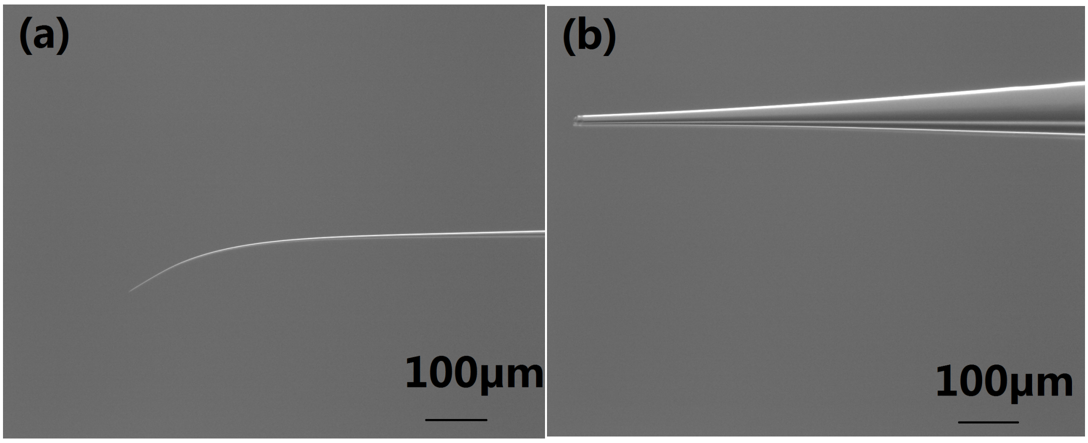

Fig.9 (a) A tip with a shorter tail by increase the final speed of pulling. (b) A tip end without a tail (cut by diamond knife).

We come to know that V_{end}=12.6 mm/s is not high enough to avoid the tail. In order to get a higher final speed, we move to a hyperbola formula

$$V(t) = \frac{\alpha L_0}{r_0 - \alpha t}$$

where L_0 is the flame length and r_0 is the radius of the microfiber. We have much sharper tips with this hyperbola formula.

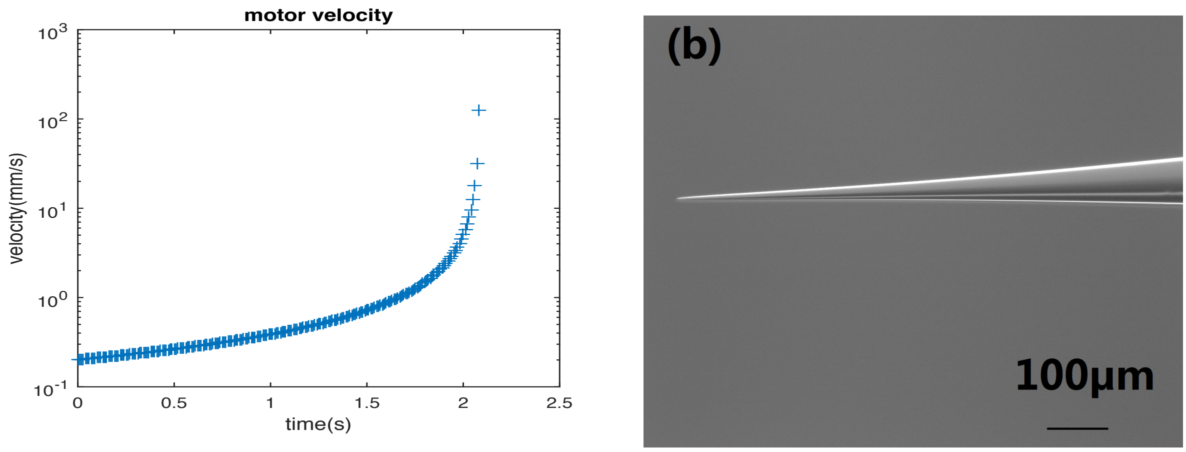

Fig.10 (a) Motor velocity versus pulling time. V_{end}=126 mm/s. (b) A sharp tip without any bending tail.

We keep trying new MATLAB codes to get tips with longer taper (Fig.11b).

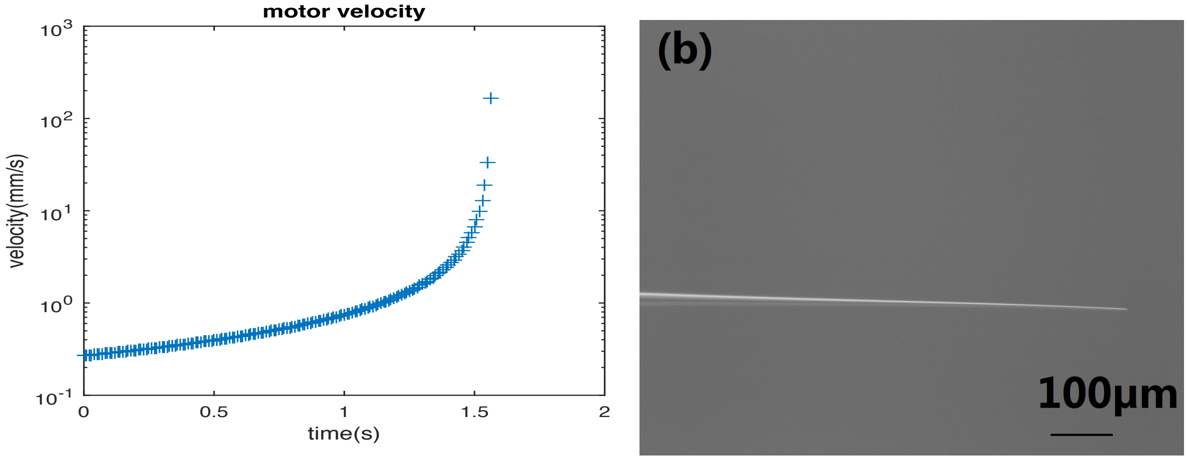

Fig.11 (a) Motor velocity versus pulling time. V_{end}= 168mm/s. (b) A sharp tip, a little bending due to gravity.

From all the tips we obtained, we come to know that the speed of motors, flame height (vertical distance between the flame the fiber) and pulling time can change the linearity of the taper, the length of the taper and the diameter of the tip. Among these parameters, the speed of motors is significantly influenced by the parameters in formula *V(t)*, such as the value of α. Another parameter that makes sense is "deltat", which is defined as the time interval that the motors move apart. The tip shown in Fig.10 is with *α*=0.00004 m/s and *deltat*=0.01 s. These values of α and deltat are precisely influencing the shape of hyperbola curve, that is, the final speed of the motors.

We realize that bending of tips occurs may because the temperature of the broken region in the fiber is too hot, thus we want to try to remove the flame earlier, right before the breaking time [10]. Moreover, with MATLAB we might make change from the formula of *V(t)*, such as adding another parameter beta.

Conclusion

We now manage to make to a microfiber knot with the waist diameter of 1.5 μm, which is supposed to be twice smaller in our case. We need try to obtain knots of this size or at least see how much is the possibility to manage it. Technics needs to be improved and a list of precaution is required.

Experimental variables such as flame height, pulling time and pulling velocity have obvious effect on profiles of the tips we obtain. A further goal is to manage to obtain thinner tips and at the same time it should be as stiff as possible. It will be better if we can conclude a list or a table concerning about the relation between the experimental variables and the profile of the tip.

Annex A

MATLAB code generating a PVT file controlling the motors to stretch the fiber to have a microfiber tip

```
Vin=0; %[mm/s]
alpha=0.00003;
Deltat=0.01; %[s]
L0=0.42;
r0=62.5e-6;

T=2.08;

t=0:Deltat:T;
V=(alpha*L0)./(r0-alpha*t)+Vin;

x=-L0*log(r0-alpha.*t)+L0*log(r0);

Deltax=diff(x);

PVT=[];
PVT(:,1)=ones(length(t)-1,1)*Deltat;
PVT(:,2)=Deltax';
PVT(:,3)=V(2:length(V));
PVT(:,4)=Deltax';
PVT(:,5)=V(2:length(V));

PVT(length(t),:)=[1 5 0 5 0];

figure
```

```
plot(t,V,'+');
figure
plot(t,x,'x','color','r')


%% save to .txt
dlmwrite(['Tip-alpha', num2str(alpha),'.txt'] ,PVT ,'newline','pc');
```

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