Fabricating subwavelength fiber tapers using a CO_2 laser

Lei Zhang[a], Lisa Liu[a], Zhiping Cai*[a,b] , Chenchun Ye[b],Guobing Wen[a]
[a]Department of Physics, Xiamen University, Xiamen China 361005;
[b]Department of Electronic Engineering, Xiamen University, Xiamen China 361005

ABSTRACT

A fabricating system of fiber tapers using a CO_2 laser as its heat source has been developed. According to the self-regulating effect of the CO_2 laser in the process of melt-drawn fiber, the relation between the required CO_2 laser power and the moving distance of the motorized stage in the fabrication process of fiber taper is found. The dependence of the required laser power and the moving distance of one motorized stage running is of approximately linear increment, which largely simplifies the computer control.With the relation plus regulating the other parameters, a 1.3 μm diameter fiber taper is fabricated. The tapers fabricated by our system have good shape and size for optical device applications.

Keywords: Subwavelength fiber taper, CO_2 laser, ZnSe lens

1. INTRODUCTION

Fiber tapers are of great interest in several aspects such as elaboration of couplers[1], the Scanning Near-field Optical Microscope (SNOM) probes[2], and fiber microlens[3]. In all applications, controlling the taper shape, especially a tiny diameter of fiber taper, is very important to fabricate an all optical micro-device. Minimizing the radius of fiber taper is also desirable for microphotonic device in optical communication or optical coupling, as well as for subwavelength waveguiding aspects[4]. A taper is made by stretching a heated fiber, which finally forms a structure such as Figure 1. It

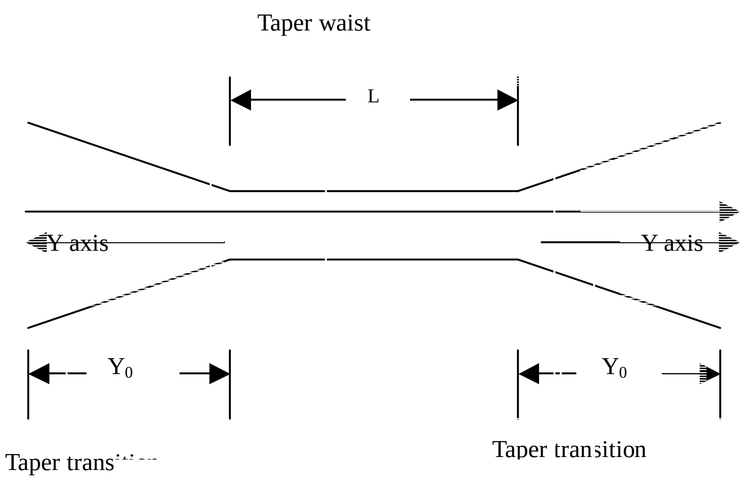

Fig.1 The schematic profile of fiber taper

*zpcai@jingxian.xmu.edu.cn; phone 86 592 2186919; fax 86 592 2186919

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is composed of taper waist and taper transition. The traditional heat source fabricating fiber tapers is the flame. Though it has some advantages such as the high utilizing rate of heat energy and fast heating velocity, the taper shape can't be easily controlled, it is difficult to get a small diameter fiber taper, as the heated fiber is susceptible to the surroundings and the heating area by the flame is large.

To overcome such disadvantages, a CO_2 laser is used to replace the flame as heating source. The CO_2 laser beam is free of contamination, controllable, fast acting, and free of inertia. And it has been used as a heat source to fabricate fiber taper in previous studies[2, 5]. Therefore it can be used as an ideal heating source for controlling the taper shape precisely and fabricating subwavelength fiber tapers. The subwavelength fiber taper also have great use to study the transmission and mode characteristic of light in the subwavelength waveguide.

In this letter we propose a fabricating system of fiber tapers using a CO_2 laser as heating source. And many important parameters which influence the experiment are discussed. Regulating these parameters, we fabricate initially a 1.3 μm diameter fiber taper. And the diameter of taper waist is thinner than the reported 4.6 μm [6].

2. EXPERIMENT

The experiment system of fabricating fiber tapers is shown schematically in Fig.2.

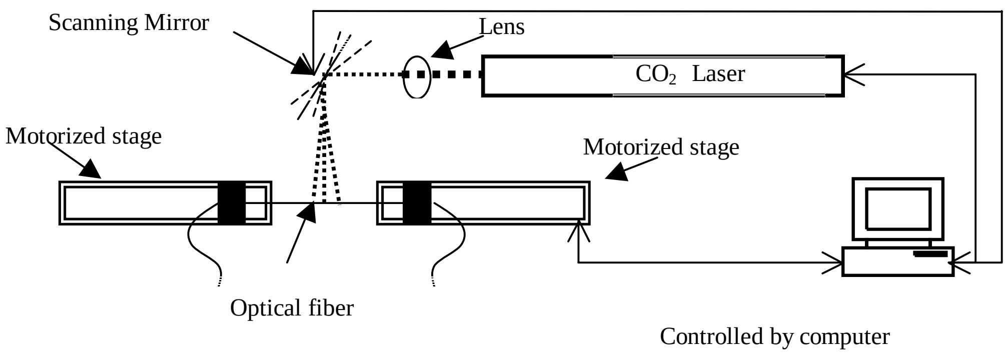

Fig.2 Schematic diagram of the experiment

A 32-W stabilized CO_2 laser is used as the heat source. In the front of the laser a red diode pointer is installed. The red light beam was aligned with the CO_2 laser beam so that the diode beam is used as a guide to direct the CO_2 laser radiation onto the fiber. Following the diode pointer, the laser light is focused by a ZnSe lens. Selecting an appropriate lens is very important in order to make full use of the laser output power. There are two conditions in selecting the lens. Firstly, the focused laser spot size must be a little larger than the diameter of the fiber. Secondly, the absorption of the lens at the wavelength of 10.6 μm must be very low. Therefore a ZnSe lens of 15 cm focal length is chosen in our experiment. The absorption rate of the ZnSe lens at CO_2 laser wavelength is less than 0.25%. The focused laser spot size is approximately equal to 144 μm, which is just a little larger than 125 μm, the diameter of single-mode communication fiber. Therefore the lens meets the experimental need. Finally the light is impinged onto the fiber through a scanning mirror controlled by a computer. The amplitude of scanning mirror controls the hot-zone length, and the frequency controls the optical density of the CO_2 laser light. Two motorized stages controlled by a computer are used to pull the fibers. When the laser is switched on, the fiber is elongated by the two motorized stages. Evidently the entire tapering process proceeds under computer control.

3. EXPERIMENTAL PROCESS

The fabrication process is affected mainly by several physical parameters, such as heating power of CO_2 laser, hot-zone length, the pulling velocity, pulling temperature, etc. In this section, the effects of these parameters on taper size are discussed.

3.1 Heating power of CO_2 laser

The most important parameter in the control of taper size is the optical intensity delivered by the CO_2 laser. According to Grellier's theory[7], the process of heating fiber can be "self-regulating" by using a CO_2 laser to fabricate fiber taper. Based on the effect of heat and constant axial tension, the waist of fiber is elongated so that the diameter of the fiber

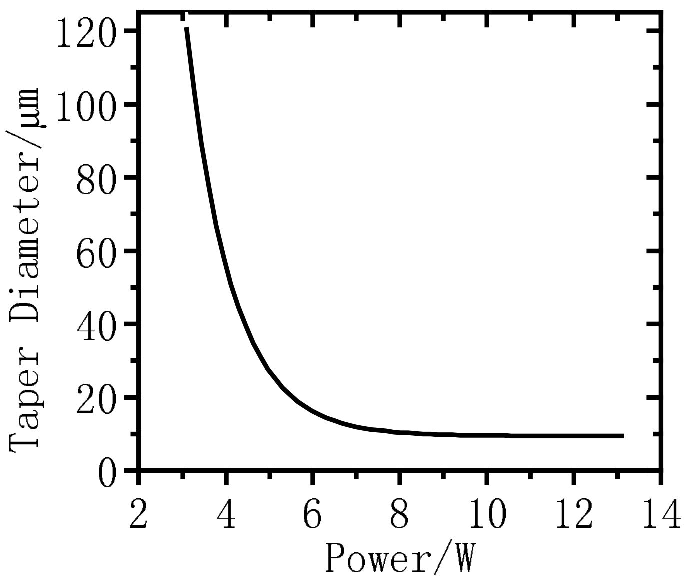

Fig.3 The fiber taper diameter as a function of the laser power

decreases. Eventually the process reaches a point where heat energy is insufficient to soften the optical fiber, which results in stopping of fiber elongation. As a result, the fiber diameter decreases when the heat energy increases. Therefore an appropriate power level must be chosen to get a taper with the desired diameter. In Fig.3 the diameters of fabricated fiber taper are plotted against the laser power.

The fitting expressions is

$$P = a * \exp(-d / b) + c \quad (1)$$

Where P is the optical power absorbed by the fiber, d is the taper diameter. The values of a, b and c are 2238.59,1.03, 9.48, respectively.

As the laser light is focused onto the fiber through the ZnSe lens and scanning mirror, the optical power absorbed by the fiber is less than the output power of the CO_2 laser. Therefore using the expression (1) to fabricate the desired diameter of fiber taper, it is very difficult to control the output power of the CO_2 laser. To overcome the difficulty of laser power control, laser power absorption and thermal transfer in the fiber is further analyzed in the process of the taper fabrication. The result has been published in the 4th International Workshop on Microfactories[8]. According to the result, the relationship between laser power and the moving distance of one linear translation stage can be calculated. The calculated CO_2 laser power is plotted against the moving distance of motorized stage in Fig.4. The data of numerical calculation are shown as dots, and the solid line is the linear fit to the data. The dependence of the required laser power and the moving distance of one motorized stage is of approximately a linear increment. Based on such a linear dependence, it is much easier to control the laser power and the moving distance of one motorized stage. Then we can get many good-qualities fiber taper.

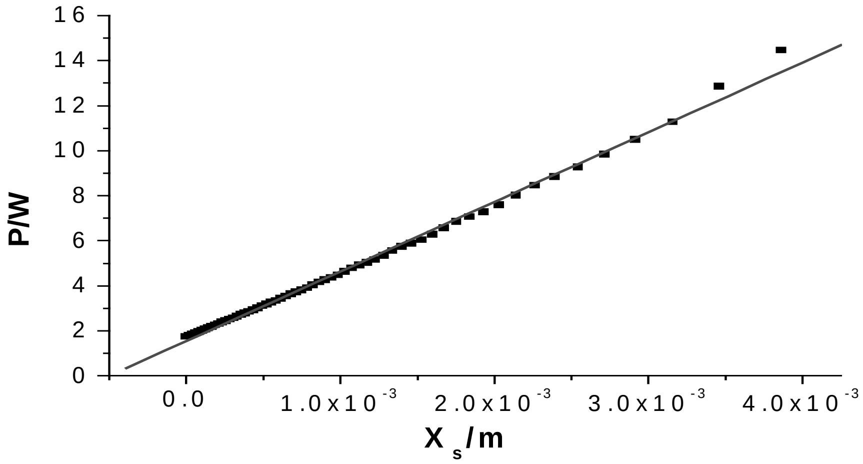

Fig.4 The required CO_2 laser power plotted against the moving distance of the motorized stage. The data of numerical calculation are shown as dots, and the solid line is the linear fit to the data.

3.2 Hot-zone length

Hot-zone length is also very important to the pulling process. The hot-zone length can be changed by changing the amplitude of scanning mirror. Decreasing the hot-zone length will increase the slope of fiber taper and generally shorten the overall taper length. Figure 5 shows the profile of fiber taper. In Fig.5, the diameters of all fiber tapers are equal to 6.4 μm, and their hot-zone lengths are 228 μm, 400 μm, 500 μm, 600 μm, 800 μm, respectively. It shows the basic trend of increasing hot-zone length while holding all parameters fixed, except for laser power.

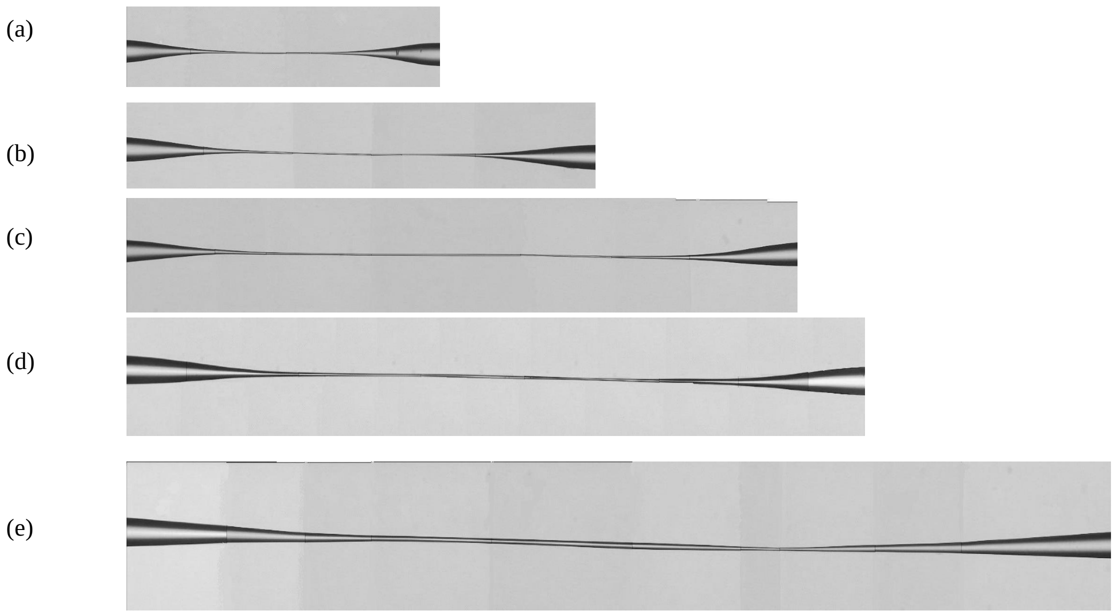

Fig.5 Taper shape as a function of hot-zone length, with all other pulling parameter fixed, except for laser power. The hot-zone length increases from 228, 400, 500, 600 and 800 μm from (a)-(e).

In our experiment, it is found that if the hot-zone length is too long, the energy can't be absorbed sufficiently by the fiber to achieve the melting point of glass fiber. This result in the fiber snapped. If the hot-zone length is too short, the fiber will melt quickly. In order to achieve a thinner fiber taper, the fiber must be pulled with higher velocity, but the process can't be controlled precisely. Therefore to fabricate the subwavelength fiber taper, we must select an appropriate hot-zone length.

3.3 Pulling velocity

The velocity parameter is also a critical factor in the pulling process. The viscosity of the glass in the fiber drops with increasing temperature, and the fiber is stretched by the tension. The heating energy absorbed by the fiber is inversely proportional to the square of fiber taper diameter $2r$. As the diameter of fiber taper becomes thinner, only a little energy is absorbed by the fiber. Therefore in order to make the fiber melt to a thinner diameter, the power of laser must be greatly increased. For example, to soften a 20 μm more than 6 W heating powers is required. From Fig.3, we can see that the power must be exponentially increased in order to meet the demand of power for softening the fiber. According to the Flaming and Brown's study[9], a higher velocity setting means a lower viscosity, but a lower viscosity is easier to get a thinner taper. So we can fabricate thinner taper by setting a higher velocity. But in experiment when the output power of laser is chosen to be 12 W, changing the velocity we found: if the velocity is 0.012mm/s, the fiber taper diameter changes between 5.7 μm and 6.5 μm; but when the velocity is 0.1mm/s, the diameter of taper ranges round about 7 μm. It may be resulted from the following two reasons: firstly, the high velocity will result in the dithering of motorized stages; secondly, the fiber can't absorb enough energy so that the viscosity of the fiber is increased. The two reasons together will bring the result that the fiber can't be pulled thinner.

Except for the above three parameters, other parameters, such as pulling force, heating temperature, also have great effects to the pulling process. But they are decided by the above three parameters in the last analysis, thus we don't discuss them in detail.

4. EXPERIMENTAL RESULT

According to the above analyses, we design an experiment: the output power of laser is increased in term of the expressions (1), and the length of hot zone is chosen as 510 μm, and the pulling velocity is set as 0.23 mm/s. By incessant tries, finally we get a 1.3 μm diameter of fiber taper (see Fig.6); the elongation length of fiber is 1 cm. Fig.6 (a) is the profile of fiber taper, it is magnified by 100 times Motic microscope. The thinner part of fiber taper is shown in Fig.6 (b). From the figure we can see that the fiber taper is very symmetrical in the fiber cross-section, but the thinnest part of fiber is not in the center of the taper, and the length of taper waist is also very long. It may be the

(a)

(b)

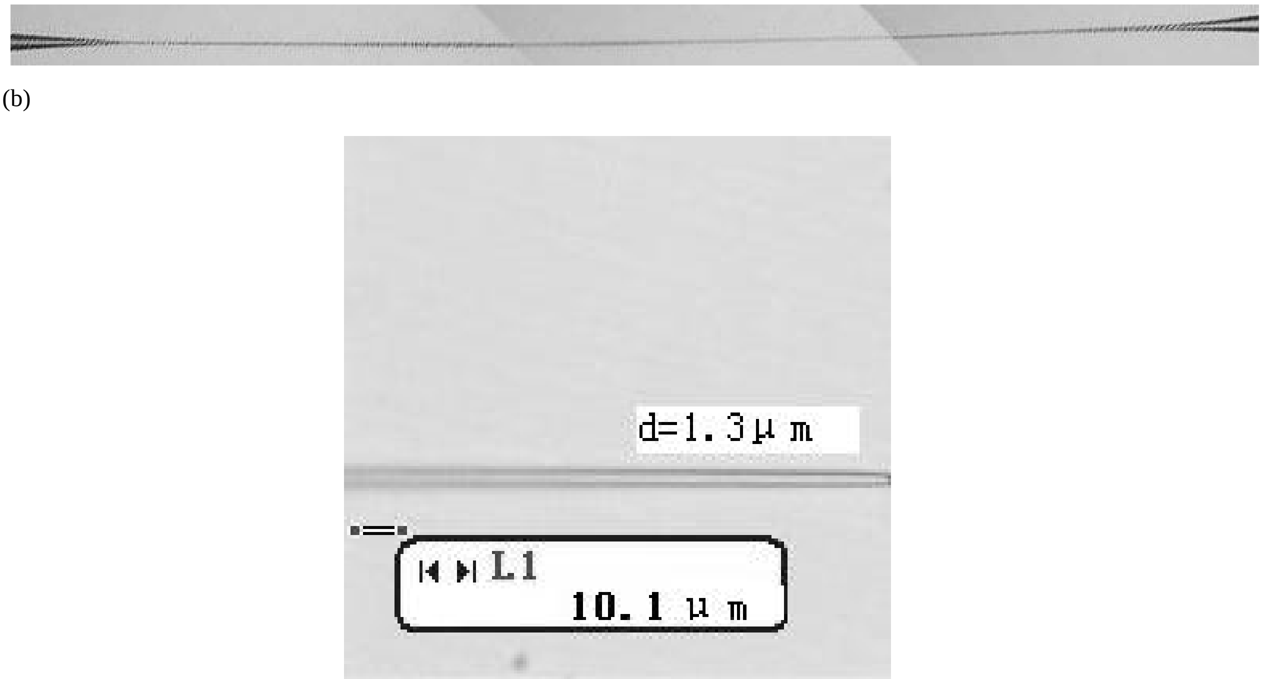

Fig.6 (a) Magnified pictures of a fiber taper, (b) The thinnest part of the taper, and the diameter is 1.3 μm

reason that as the heating power is sufficient to soften the fiber when the diameter becomes small, the fiber can't be further pulled thinner, then the motorized stations have to pull the adjacent fiber, finally results in the over long taper waist.

Meanwhile, from Birks's theory[10] , the radius r_w of the taper waist is predicted to vary with taper extension y as

$$r_w(y) = r_0 \exp[-y/2L_0] \quad (2)$$

where r_0 is the initial fiber diameter and L_0 is the taper waist length. Therefore when the fiber is elongated to 1cm, the theoretical result of taper diameter is less than 0.1 μm by using the expressions (2), but in fact the experimental result is 1.3 μm. It is thought that the theory is based on the condition that all parameters are in ideal state, but in fact with the fiber diameter decreasing, the energy supplied by CO_2 laser is insufficient for softening the fiber, thus the taper diameter we get in experiment is less than the theoritical diameter. From the above discussions, if the relationship between the pulling velocity and the heating power of laser can be well controlled, we believe that the taper of diameter less than 1 μm can be fabricated by our experiment.

5. CONCLUSIONS

We have developed a fabrication system of melt-drawn fiber tapers using a CO_2 laser. With the system a fiber taper of 1.3 μm diameter is fabricated. The tapers have the good shapes and the sizes required for optical devices.We also discuss about some important parameters which influence the taper shape such as the CO_2 laser power, the hot-zone length and pulling velocity, and get a relationship between the required CO_2 laser power and the moving distance of the motorized stage in the fabrication process of fiber taper. All these investigations in the present work have a great help to fabricate submicrometer fiber taper.

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