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Theoretical analysis and fabrication of tapered fiber

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ABSTRACT

Adiabaticity criteria and optimal shapes for tapered fiber are theoretically analyzed. In the analysis, it is discovered that a narrower taper waist can be achieved by using a small hot-zone length or increases the elongation distance. The tapered fiber fabrication based on flame brushing technique is then demonstrated using a homemade fiber tapering rig. The heat source comes from an oxy-butane torch with a flame width of 1 mm. Two stepper motors are incorporated in the rig to control the movement of the torch and translation stage. A biconical tapered fiber with a waist diameter as small as 400 nm can be achieved with the rig. To achieve low loss tapered fibers, the shape of the taper should be fabricated according to adiabaticity criteria, whereby the longer transition length is desirable. Tapered fibers with linear and decaying-exponential profiles have been successfully fabricated.

1. Introduction

Tapered fibers have recently attracted considerable interest as promising building blocks for a wide variety of photonic applications [1,2]. For instance, Tian et al. [3] reported a fast, highly sensitive and low-cost tapered optical fiber biosensor that enables the label-free detection of biomolecules. This is owing to their unique optical guidance properties that include a relatively low loss, strong evanescent fields, tight optical confinement, and controllable waveguide dispersion. They possess large refractive index contrast which is able to provide tight field confinement that makes tapered fibers particularly suitable for nonlinear optical applications [4]. Tapered fibers also offer an advantage of the ease of integration with conventional single mode fiber (SMF) as well as the access to the evanescent field provided by tapering since the light is guided by the boundary between the taper and the external environment. The external environment may be chosen to determine the number of modes supported by the waist, the bend tolerance and may provide a means of tuning through index of refraction or absorption control [5].

To produce high quality tapered fiber based devices, the tapered fibers used should have the following properties: high adiabaticity, uniform microfiber diameter, low surface roughness, and suitable microfiber diameter with large evanescent field. The tapered fiber diameter has a direct influence in the evanescent field and coupling coefficient of the tapered fiber coupling region in most devices. Basically, tapered fibers with thinner diameter have stronger evanescent field and thus yield higher coupling coefficient between two or more microfibers when they are put in a close contact with each other. Therefore, most tapered fiber based devices are assembled from tapered fibers with small diameter within 0.8–3 μm [6]. Besides, thin tapered fiber can be easily bent or coiled into smaller bending radius and thus smaller tapered fiber device can be produced. However, the difficulty in handling these tapered fibers increases with smaller diameter as thinner tapered fibers are very fragile and lossy.

Tapered fiber fabrications have been demonstrated by using a wide range of techniques: laser ablation [7], electron beam lithography [8], bottom-up methods such as vapor–liquid–solid techniques [9], and top–down techniques such as fiber pulling [10] or direct draw from bulk materials [11]. Among those methods, the flame heating technique has proven to be one of the most versatile, which can fabricate tapered fiber with good physical properties [12]. In this paper, tapered fiber fabrication is demonstrated using an automated fiber tapering rig based on flame brushing technique. The fabrication rig employs an oxy-butane torch, microcontroller and stepper motors. With the improved system, the problems of high insertion loss due to non-uniformity of tapered fiber can be reduced dramatically. Additionally, the system may realize fabrication of tapered fiber with waist diameter less than 1 μm or possibly in nano-range diameter. Adiabaticity criteria and optimal shapes for tapered fiber are also theoretically analyzed.

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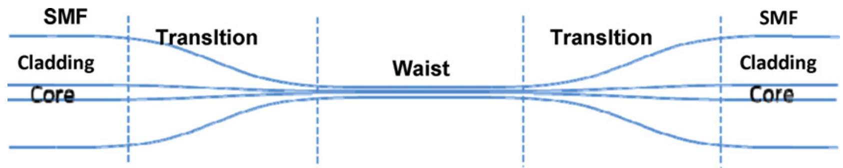

Fig. 1. Typical diameter profile of a tapered fiber.

2. Theoretical analysis of the tapered fiber

Tapered fiber is fabricated by stretching a heated conventional SMF to form a structure of reducing core diameter. As shown in Fig. 1, the smallest diameter part of the tapered fiber is called waist. Between the uniform un-stretched SMF and waist are the transition regions whose diameters of the cladding and core are decreasing from rated size of SMF down to the order micrometer or even nanometer. As the wave propagating through the transition regions, the field distribution varies with the change of core and cladding diameters along the way. Depend on the rate of diameter change, the energy transfer from the fundamental mode to a closest few higher order modes varies, which determines to the loss of the propagating wave power. The accumulation of this energy transfer along the tapered fiber may result to a substantial loss of throughput. This excessive loss can be minimized if the shape of the fabricated tapered fiber satisfies the adiabaticity criteria everywhere along the tapered fiber [13].

Fig. 2 gives an illustration of a tapered fiber with decreasing radius. z denotes the position along the tapered fiber. Theoretically, an adiabatic tapered fiber is based on the condition that the beat length between fundamental mode LP_{01} and second local mode is smaller than the local taper length-scale z_t.

$$z_b < z_t \tag{1}$$

Refer to illustration in Fig. 2, z_t is given by

$$z_t = \frac{\rho}{tan\Omega} \tag{2}$$

where $\rho = \rho(z)$ is the local core radius and $\Omega = \Omega(z)$ is the local taper angle. The beat length between two modes is expressed as

$$z_b = \frac{2\pi}{\beta_1 - \beta_2} \tag{3}$$

where $\beta_1 = \beta_1(r)$ and $\beta_2 = \beta_2(r)$ are the propagation constants of fundamental mode and second local mode respectively. From the above equations, Inequality of the tapered fiber can be derived to

$$\left|\frac{d\rho}{dz}\right| = \tan\Omega < \frac{\rho(\beta_1 - \beta_2)}{2\pi} \tag{4}$$

where $d\rho/dz$ is the rate of change of local core radius and its magnitude is equivalent to $\tan\Omega$. For the convenience of usage and analysis, the inequality of (4) can also be rewritten as a function of local cladding radius $r = r(z)$ as;

$$\left|\frac{dr}{dz}\right| < \frac{r(\beta_1 - \beta_2)}{2\pi} \tag{5}$$

Based on this condition, adiabatic tapered fiber can be acquired by tapering a fiber at a smaller reduction rate in diameter but this will result to a longer transition length. Considering practical limitations in the fabrication of fiber couplers or microfiber based devices, long tapered fiber may aggravate the difficulty in fabrication. For the purpose of miniaturization, short tapered fiber is preferable. To achieve balance between taper length and diameter reduction rate, a factor f is introduced to the Inequality function of (5) and yields

$$\frac{dr}{dz} < \frac{fr(\beta_1 - \beta_2)}{2\pi} \tag{6}$$

where the value of f can be chosen between 0 and 1. Optimal profile is achieved when $f = 1$. Practically, tapered fiber with negligibly loss can be achieved with $f = 0.5$ but the transition length of the tapered fiber is twice longer than that of the optimal tapered fiber.

When a glass element is heated, there is a small increment in the volume under the effect of thermal expansion. However, the change in volume is negligibly small not to mention that the volume expansion wears off very quickly once the heat is dissipated from the mass. It is reasonable to assume that the total volume of the heated fiber is conserved throughout the entire tapering process. Based on this explanation, when a heated glass fiber is stretched, the waist diameter of the fiber is reduced. The calculation of varying waist diameter and length of extension can be made based on the idea of 'conservation of volume' [13]. Birks and Li [13] have presented simple mathematical equations to describe the relationship between shapes of tapered fiber, elongation distance and hot-zone length. Any specific shape of tapered fiber can be controlled by manipulating these parameters in the tapering process. Fig. 3 provides schematic illustrations of heated fiber with reducing waist

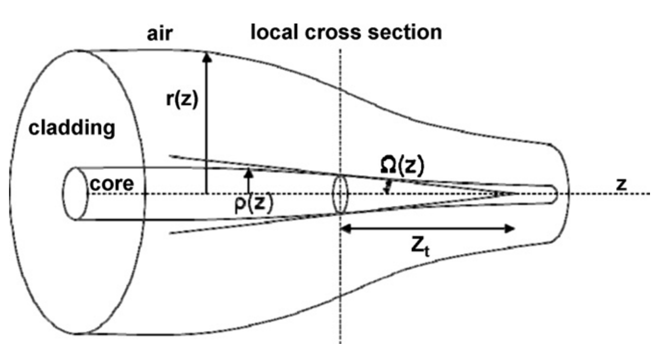

Fig. 2. Illustration of the taper transition.

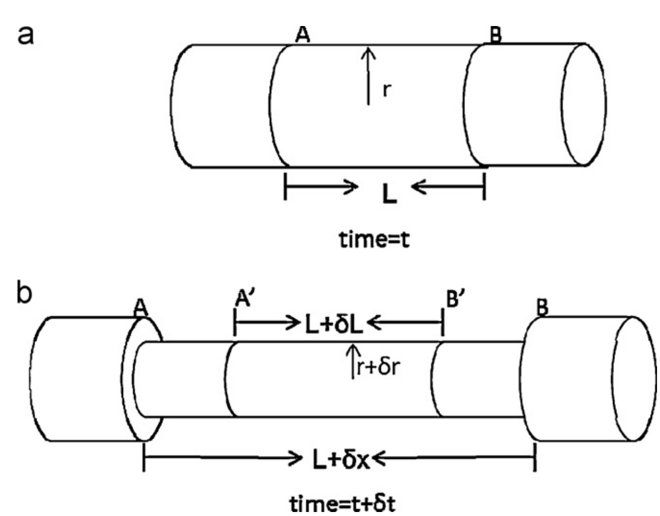

Fig. 3. The cylinder illustrates an SMF (a) before heating (b) a short while after heating, where the diameter of the SMF has been reduced when it is stretched.