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Fabrication of polymer microlenses on single mode optical fibers for light coupling

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ABSTRACT

In this paper, we present a technique for producing fibers optics micro-collimators composed of polydimethylsiloxane PDMS microlenses of different radii of curvature. The waist and working distance values obtained enable the optimization of optical coupling between optical fibers, fibers and optical sources, and fibers and detectors. The principal is based on the injection of polydimethylsiloxane (PDMS) into a conical micro-cavity chemically etched at the end of optical fibers. A spherical microlens is then formed that is self-centered with respect to the axis of the fiber. Typically, an optimal radius of curvature of 10.08 µm is obtained. This optimized micro-collimator is characterized by a working distance of 19.27 µm and a waist equal to 2.28 µm for an SMF 9/125 µm fiber. The simulation and experimental results reveal an optical coupling efficiency that can reach a value of 99.75%.

1. Introduction

In the field of telecommunications, the optical coupling between optical fibers, optical fiber and laser diode, and optical fiber and photodetector is a critical factor. However, it remains difficult to optimize the coupling efficiency because of the residual misalignment of the core of the fibers with regard to the fiber cladding, the difference of the mode field diameter (MFD) of the optical fibers and that of the laser diodes or photodiodes. The problems of centering micro-lenses and the alignment of components significantly reduce coupling.

There are two broad categories of micro-collimators: intrinsic, in which the microlens is an integral part of the fiber, and extrinsic, in which the microlens is a separate component.

Several solutions have been proposed for this in the literature. The techniques primarily used are chemical attack [1], thermal fusion [2,3], polishing [4], photolithography [5,6], micro-molding [7] and gluing spherical or graded index microlenses at the end of fibers [8,9]. Each of these techniques has a residual relative error related to misalignment. In a previous work [10], we used a chemically etched conical micro-cavity (concave cone etched fiber CCEF) at the end of the optical fibers where a spherical microlens is inserted [11]. This technique enabled the reduction of the axial misalignment of the microlenses and thus an increase in the coupling efficiency. Within the scope of the present work, we inject into the micro-cavity a certain quantity of polydimethylsiloxane (PDMS) to form the microlenses. This more compact configuration optimizes the coupling efficiency even more as a result of the possibility of producing a broad range of radii of curvature.

The calculation of the coupling efficiency is achieved from the study of the propagation of the Gaussian beam through the micro-collimator. The optical characteristics, including the width of the waist and the working distance (WD), are determined by means of the well-known ABCD law.

2. Fabrication of the microcollimator

A micro-cavity of known dimensions is first etched into the end of a 9/125 µm single mode fiber by the HF chemical etching process as it is shown in Fig. 1. This fiber is then fixed vertically to an x–y–z micropositioner stage represented in the experimental set-up of Fig. 2. A controlled flow micro-syringe loaded with PDMS is placed end to end, aligned with the fiber. The process of alignment and injection of the polymer into the micro-cavity is monitored and controlled by an acquisition system composed of a horizontal

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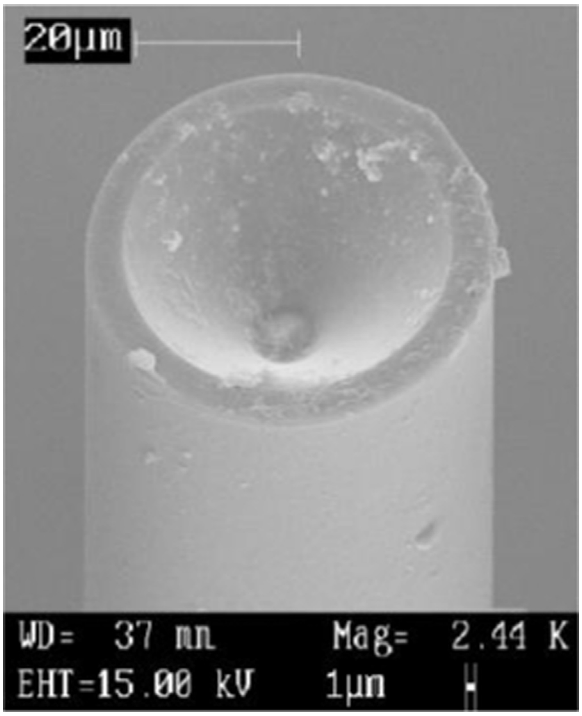

Fig. 1. A SEM magnified view of the micro-cavity.

microscope, a CCD camera and a microcomputer.

The piston of the micro-syringe is actuated by a motorized linear stage until a micro-drop appears at the end of the cannula. The end of the fiber is brought gradually into contact with the PDMS then moved away. As a result, the quantity of polymer received into the micro-cavity forms a microlens because of surface tension effect. The microlens is then polymerized in an oven at a temperature of 100 °C for one hour. Represented in Fig. 3 is the micro-collimator manufacturing process. Shown in (a) is the end of the fiber cleaved straight, which after chemical treatment is transformed into a conical micro-cavity. Illustrated in (c) is the intermediate step of injection of the PDMS, and in (d) the final step relative to the formation of the microlens.

The radius of curvature of the microlenses depends on the width of the microcavities. The dimensions of the microcavities are determined by controlling the time of immersion in the acid medium. Represented in Fig. 4 is a series of micro-collimators of different dimensions. The images (a), (b), (c), (d), (e) and (f) obtained by an optical microscope have enabled the characterization of the micro-cavities by image processing. Consequently, there are micro-cavity widths of 11 μm, 17 μm, 28 μm, 39 μm, 43 μm and 50 μm, respectively. The respective radius of curvature values are 6.12 μm, 10.08 μm, 13.2 μm, 18 μm, 20.3 μm and 30.4 μm.

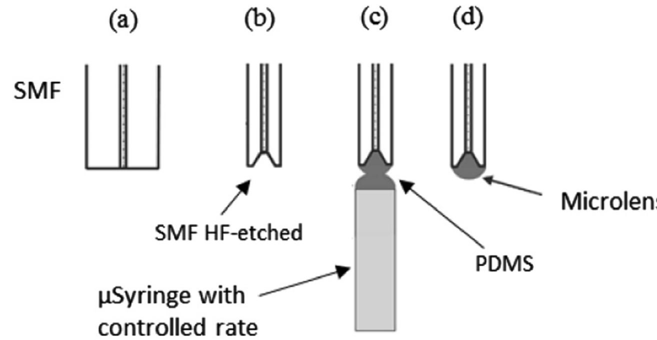

Fig. 3. Micro-collimator manufacturing steps (a) initial fiber, (b) fiber with micro-cavity after acid treatment, (c) contact between the fiber and the micro-drop and (d) formation of a microlens at the end of the fiber.

3. Analysis

The energy distribution of the laser beam in a single mode fiber SMF is assumed to a Gaussian distribution. It is therefore necessary to study the light guidance through the micro-collimator and to determine the most important parameters of the beam, i.e., the width of its waist $2\omega_0'$ and its working distance Z_ω.

We now consider the optical system of Fig. 5, composed of a single mode fiber SMF provided with a conical micro-cavity with width l and height h, as well as a hemispherical microlens with a radius of curvature r and a refractive index n_p affixed to its end. The propagation of the beam through this micro-collimator follows the trajectory illustrated in Fig. 5.

In this figure, $2\omega_0$ is the width of the mode of the fiber, $2\omega_1$ is the width of the mode after travel over a distance d (with $d=h+r$) in the index medium n_p, and R_1 is the radius of curvature. $2\omega_2$ and R_2 are respectively the width of the mode and the radius of curvature of the beam at the output of the micro-collimator, $2\omega_0'$ and $R_0'(=\infty)$) successively designate the new waist and its radius of curvature at the working distance Z_ω.

The mode diameter $2\omega_0$ is calculated by the Marcuse Formula [12] such that:

$$\frac{\omega_0}{a}=0.65+\frac{1.619}{V^{3/2}}+\frac{2.879}{V^6} \tag{1}$$

where a is the radius of the core of the SMF fiber, which is 4.5 μm for a 9/125 μm fiber.

The normalized frequency V is given by

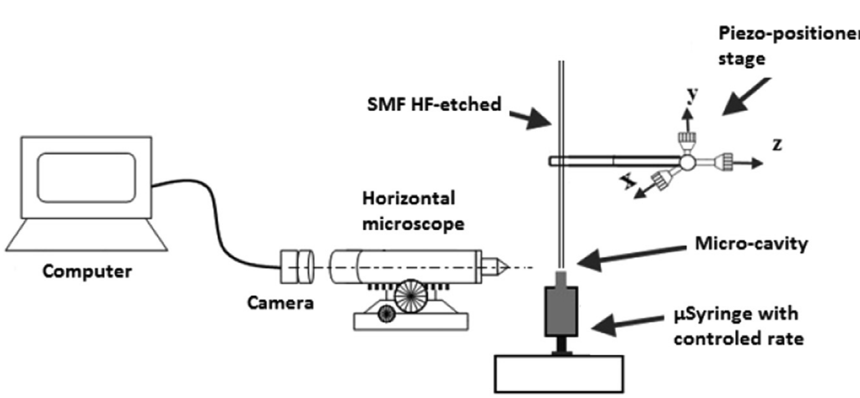

Fig. 2. Micro-collimator manufacturing assembly.