Precision Engineering 38 (2014) 183–189

Contents lists available at ScienceDirect

Precision Engineering

journal homepage: www.elsevier.com/locate/precision

Lensed plastic optical fiber employing hyperbolic end filled with high-index resin using electrostatic force

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ARTICLE INFO

Article history:
Received 6 October 2010
Received in revised form 4 September 2013
Accepted 12 September 2013
Available online 18 September 2013

Keywords:
Electrostatic force
Lensed plastic optical fiber
Aspherical microlens

ABSTRACT

The step-index (SI) and graded-index (GI) plastic optical fibers (POFs) are strong candidates for short-distance transmission, fiber-to-the-home (FTTH) networks, automobile applications and interchip interconnections. The GI POFs which has been proven to reach distances as long as 1 km at 1.25 Gb/s has a relatively low NA. Therefore, the efficient coupling of GI POFs to the light source has become critical to the power budget in the system. Forming a lens-like structure directly on the fiber end is preferred for simplicity of fabrication and packaging, such as polishing and fusion, combing different fibers with the cascaded fiber method and hydroflouride (HF) chemical etching. These approaches are well established, but applicable only to glass. This work proposes a novel structure of a lensed plastic optical fiber (LPOF). The fabrication of the LPOF is demonstrated and the coupling efficiency exceeds 72%.

1. Introduction

Plastic optical fibers (POFs) of the step-index (SI) and graded-index (GI) types are strong candidates for short-distance transmission, fiber-to-the-home (FTTH) networks, automobile applications [1] and interchip interconnections [2]. The primary advantage of POFs over glass optical fibers (GOFs) is that they can be manufactured with larger cores, because of the differences between their elastic properties. Larger cores allow for much simpler and less expensive coupling between transmitters and fibers than is possible with GOFs. In spite of progress in this area, few analyses or experiments have been performed to elucidate the optical coupling configurations of POFs [3,4]. One of the reasons for this lack of analyses or experiments is that the high numerical aperture (NA) of SI POFs, 0.5, is well known. The wide acceptance angle of the SI POFs, associated with the high NA, provides a high coupling efficiency when POFs are connected to a light source such as a light emitting diode (LED) or a laser diode (LD). However, the GI POFs, such as the commercially available Lucina fiber, a trademark of Asahi Glass Company, Ltd., which has been proven to reach distances as long as 1 km at 1.25 Gb/s (GI POFs), has a relatively low NA (0.18). In the implementation of the GI POFs for a high-speed short-range communication network, the low NA will increase the complexity of packaging at a low acceptance angle of the light source. Therefore, the efficient coupling of GI POFs to the light source has become critical to the power budget in the system. Efficient coupling for a POFs system normally involves either a separate lens or the direct formation of the lens at the end of the fiber [4]. Forming a lens-like structure directly on the fiber end is preferred for simplicity of fabrication and packaging. The approaches for generating a lensed end in a GOF, such as polishing and fusion [5,6], combine different fibers with the cascaded fiber method [7,8] and hydroflouride (HF) chemical etching [9]. These approaches are well established, but applicable only to glass. The melting point of POFs is about 100 °C and they are unsuited to fusion; polishing is an expensive process to reduce the package cost of POFs, and the etching procedure still poses the problem of the control of the curvature of the microlens on the fiber end.

This work proposes a novel structure of a lensed plastic optical fiber (LPOF). A UV-curable adhesive is dropped on the cleaved plastic optical fiber to form a hemispherical fiber end. An electrostatic force is then applied to shape the polymer liquid from a hemisphere into a hyperboloid or near-cone shape. This novel manipulation can be utilized not only to control the surface of the micro lens, but also to fabricate an aspherical lens after UV curing of the photosensitive polymer. The advantages of this design are that can (1) it supports large-scale production, (2) the hyperboloid shape of the fiber end can reduce the spherical aberration and increases the coupling efficiency between the LD and the fiber. The measured method of coupling efficiency was quoted form [11].

The rest of this paper is organized as follows. Section 2 presents the principle based on which a light source is focused into the POF, and describes the determination of the structural parameters of the proposed lensed fiber. Section 3 then presents the experimental setup and shows experimental results. Section 4 provides a brief discussion and summary.

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http://dx.doi.org/10.1016/j.precisioneng.2013.09.003

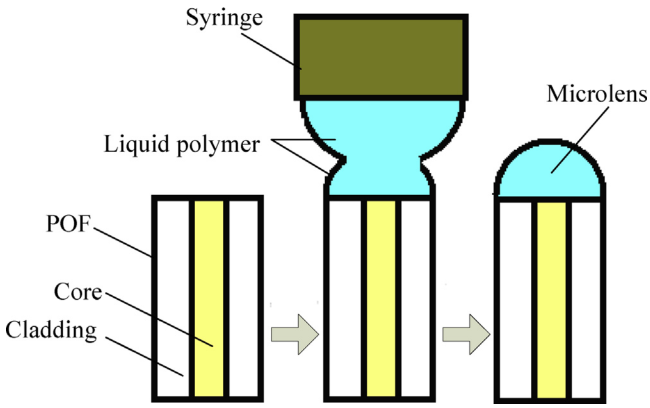

Fig. 1. The process of dropping UV-curable liquid on the fiber end.

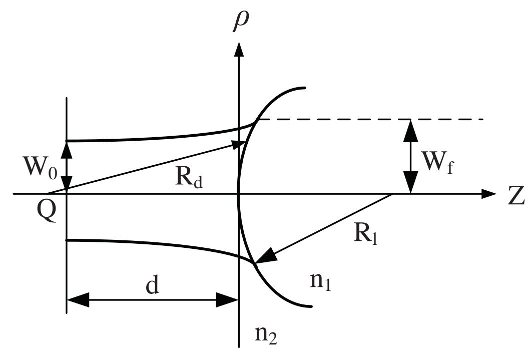

Fig. 3. Idealization of laser to fiber coupling.

2. Design and analysis

2.1. Analysis of volume of microlens

Fig. 1 schematically depicts the dropping of UV-curable liquid on the end of the fiber. The UV-curable liquid is dropped on the cleaved end of POF using a precise syringe. The droplet adopts a spherical shape to minimize the surface energy associated with the surface tension. The radius of curvature R_c of the lens and the volume V of the deposited liquid polymer can be calculated from the height and radius of the lens; these equations can be written as (1) and (2) based on [1].

$$R_c = \frac{1}{2h}(h^2 + r_f^2) \tag{1}$$

$$h = \alpha - \frac{r_f^2}{\alpha}, \quad \alpha = \left(\frac{3V + \sqrt{\pi^2 r_f^6 + 9V^2}}{\pi} \right)^{1/3} \tag{2}$$

Here, h is the height of the lens and r_f is the radius of POF, 250 μm. Notably, V (volume) is determined by the surface tension coefficient of the liquid polymer and the initial liquid volume from the syringe. The surface tension coefficient can be controlled by the temperature or the viscosity of the liquid polymer. A UV-curable liquid polymer with constant viscosities is synthesized to reduce the variable. As a result, the volume of the lens V is only a function of the volume of the liquid from the syringe. Four samples with different liquid volumes from the syringe were prepared and the radii of the curvature of the lenses were measured; Fig. 2 summarizes the results. As expected in Eqs. (1) and (2), a larger V results in a smaller radius of curvature. The variation of the radius becomes more sensitive to a change of V (Fig. 3).

2.2. Design of surface of lens

In the design of a perfect lens, mode matching theory is considered first, based on [2], these equations can be shown as (3)–(11).

The laser ray is approximated as a Gaussian beam, the beam waist is indicated as Eq. (3); the curvature of the Gaussian beam is given by Eq. (4), and the angle of divergence is given by Eq. (5). The phase error was reduced according to Eq. (5). According to Eq. (3), the efficiency, neglecting aberrations and reflections, is maximized by choosing the separation $z = d$ so that $w = w_f$, which is the core radius of the POF, 62.5 μm. If, for instance, the divergence is 25° and w_0 is taken as 0.58 μm and n_1 is 1.5 for a polymer material, then $d \sim 135$ μm from Eq. (3) and R_d equals 135 μm from Eq. (4). As a result, the curvature of the lens R_l is calculated using Eq. (6) as 67.5 μm;

$$w^2(z) = w_0^2 \left[1 + \left\{ \frac{\lambda z}{\pi w_0^2} \right\}^2 \right] \tag{3}$$

$$R(z) = z \left[1 + \left\{ \frac{\pi w_0^2}{\lambda z} \right\}^2 \right] \tag{4}$$

$$\theta = \tan^{-1} \left[\frac{\lambda}{\pi w_0} \right] \tag{5}$$

$$\frac{1}{R_d} = \left[\frac{n_1 - n_2}{n_2} \right] \frac{1}{R_1} \tag{6}$$

This analysis suggests that hemispherical microlenses, regardless of their fabrication technique, are not ideally suited to collecting all of the radiation that emanates from a laser source. Therefore, the model microlens for just this purpose is derived here. A surface that refracts planar waves of constant phase to a single point is sought. When light rays are focused into a single point through this surface, the wave front becomes spherical and has the same phase. However, in lens of spherical surface, the lengths of the optical paths that pass through different parts of the lens are not all equal. As a result, the phase differences among the focused light rays induce spherical aberration, meaning that the light rays cannot be focused onto a single point and produce large light spot, as shown in Fig. 4. Hence, an aspherical surface is required to

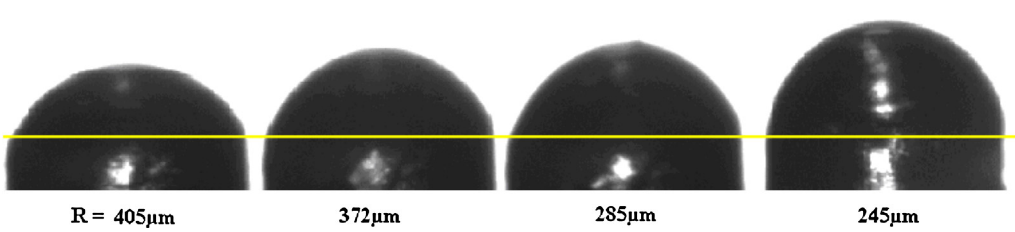

Fig. 2. Microphotographs of fabricated lens-tips with various radii of curvature.