



# Dielectric Fresnel zone plates on optical fibers for micro-focusing applications

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## ABSTRACT

In this paper, we present a novel fabrication technique for constructing light focusing lenses, dielectric Fresnel zone plates on both flat wafers and tips of plastic optical fibers (POFs). SU-8 zone plate structures are made on glass substrate by photolithography with ink-printed soft mask, and then used as the template for hot embossing on the tip of PMMA POF. Focusing behavior for both 472 and 633 nm laser beams and LEDs in different colors are observed on glass wafers and POF tips, indicating that the proposed dielectric Fresnel zone plates can be built onto both substrate by a direct hot embossing process which may lead to a high volume production at low cost. Light intensity measurement on POFs proves that light focusing is achieved while intensity is maintained. This structure is expected to have broad applications in micro-imaging, micro-focusing as well as point-of-care medical surgeries.

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## 1. Introduction

Micro-imaging and micro-focusing techniques are being widely developed for the applications in bioscience [1], healthcare [1], and daily appliances such as light projectors, LEDs, digital camera CMOS light sensors, anti-counterfeiting tags and solar cell light collectors. One of the key components in the techniques is the micro/nano lens being developed by advanced fabrication techniques such as electron beam lithography [2], X-ray lithography [3], atomic layer deposition [4] and delicate dry etch process. Although great achievements have been made for high quality lenses, the real challenge is how to apply this technique in commercialized manufacture in a fast and cost-effective manner. Furthermore, most lenses of interests are still built on flat wafers with regular shapes made from quartz, silicon and plastics. However, in actual applications, it is frequently required to make lenses on non-standard surfaces.

In this paper, we present a novel fabrication technique for constructing micro-sized light focusing lenses, dielectric Fresnel zone plates (DFZP), on both flat wafers and POF tips. SU-8 zone plate structures are made on glass substrate by photolithography with ink-printed soft mask, and then used as the template for hot embossing on the tip of PMMA plastic POF core. The fabricated zone plate structures on both glass substrate and POF are tested for optical behaviors. Light focusing is successfully achieved by

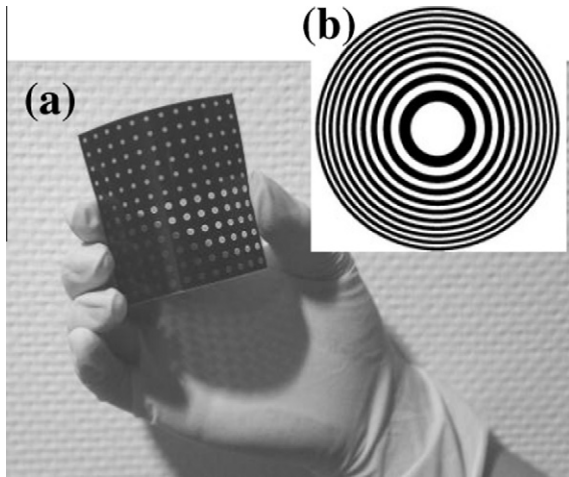
DFZP with very low loss. This device is capable of focusing through a flat structure comparing to normal convex lens while maintaining over 95% light transmission comparing to binary Fresnel zone plate with around 50% transmission. This work has made a promising step towards industrialization of inexpensive zone plates.

## 2. Fabrication details

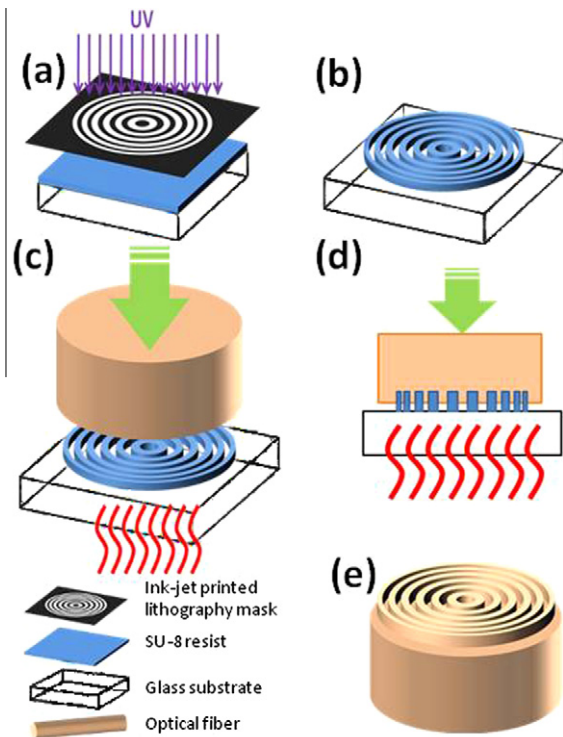
In our work, we employ a simple ink-printing method for the fabrication of the Fresnel zone plate photolithography mask on a plastic sheet as shown in Fig. 1a. The structure of the zone plate is shown in Fig. 1b. The process flow for fabricating DFZP on both substrates is described in Fig. 2. SU-8 negative resist is firstly spin coated at 5 krpm on glass substrate and prebaked on a hotplate at 95 °C for 10 min. Photolithography is carried out followed by development as shown in Fig. 2a and b. The 365 nm UV flux exposure for SU-8 lasts for 10 s, while the development in SU-8 developer lasts for 60 s followed by rinsing in IPA for 30 s. SU-8 resist is very stable after crosslink by UV exposure and unlikely to reflow at temperatures as high as 230 °C. Therefore, the SU-8 DFZP made from photolithography on a glass substrate can be used as the template for hot embossing on the tip of a POF in Fig. 2c. The typical core material for a POF is acrylic material such as PMMA, with a glass transition temperature ( $T_g$ ) no more than 120 °C (depending on the molecular weight of PMMA). Therefore the hot embossing of SU-8 template into a neatly cut PMMA POF cross-section is carried out at temperature of 170 °C, which is well beyond  $T_g$  of PMMA while maintaining the structural integrity of the SU-8 template. In order to preserve the smoothness of PMMA POF core cross section, the POF tip is not in full contact with the SU-8 template and only the SU-8 zone plate structure is imprinted into the PMMA

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**Fig. 1.** (a) Fresnel zone plate photolithography mask made by ink-jet printing method. (b) Structural design for Fresnel zone plate.

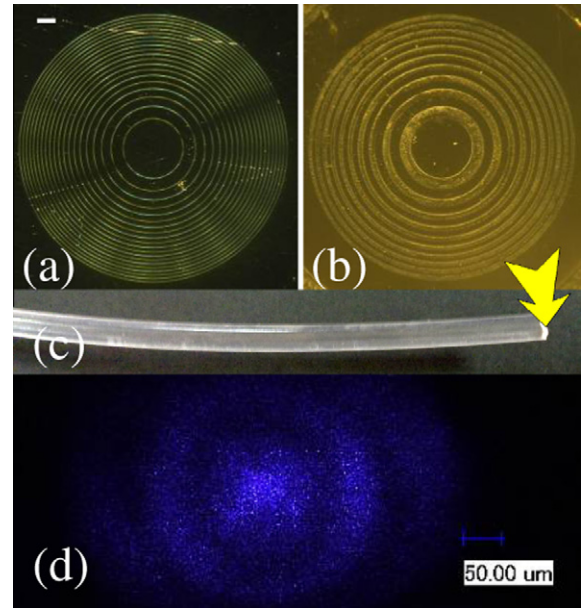


**Fig. 2.** Process flow for dielectric Fresnel zone plate on both flat wafers and optical fibers. Details are described in the article.

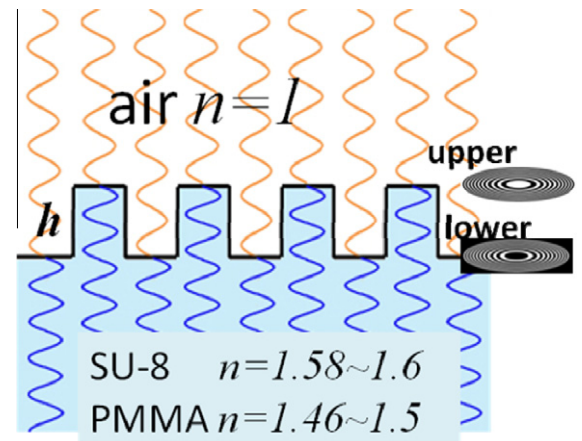
as shown in Fig. 2d. The imprint depth of the zone plate was controlled by imprint parameters such as pressure and temperature, the effect of which on the imprint depth has been carefully investigated (results are not presented in this paper). After the SU-8 template is locally embossed into the POF tip, both parts are cooled down before they are separated in Fig. 2e. In this way dielectric Fresnel zone plate on both flat wafers and POF tips are successfully fabricated as shown in Fig. 3a and b, respectively, in which (b) is the pattern on the tip of the POF shown in Fig. 3c.

### 3. Results and discussion

The structural design is first calculated and focusing behavior is predicted theoretically. The measurement of zone plates on both



**Fig. 3.** Fabricated dielectric Fresnel zone plate of the same size on (a) a flat glass substrate (b) the tip of an optical fiber. The fiber is shown in (c) with the yellow arrow pointing to where (b) is. And (d) a demonstration of the focusing behavior of the fabricated dielectric Fresnel zone plate on the tip of an optical fiber core. The scale bar in the picture (a) is 50  $\mu\text{m}$ . (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)



**Fig. 4.** The output light intensity can be achieved when the phases of the light from upper and lower zone plate are the same. Therefore thickness  $h$  of the structure has to be integer multiple of the wavelength inside the dielectric material.

flat substrate and fiber tip is carried out with 633 nm red laser and 472 nm red laser for focusing and with various LEDs in different colors of white, red, yellow, green, and blue for light intensity comparison between POF with and without DFZP structure on the fiber tip.

#### 3.1. Structural calculation and focusing measurement

For the structural design of the zone plate, the radius of the zone plate is calculated based on the demand of the width of the outmost ring, the focal length and the wavelength of the incident light. The structural calculation for radius and focusing size can be based on normal binary zone plate structural design, respectively, by

$$2\pi r_n^2 = \lambda f \quad (1)$$

**Table 1**

Change of light intensity in the form of voltage from PIN-FET with or without zone plate structure on the tip of optical fiber.

LED	POF without zone plate (mV)	POF with zone plate (mV)	Variation of intensity
White	3.748	3.734	0.4%
Blue	2.602	2.558	1.7%
Red	1.939	1.859	4.1%
Yellow	3.690	3.498	5.2%
Green	3.616	3.474	4.0%

$$\frac{\Delta l}{\Delta r_N} = 1.22 \quad (2)$$

Here  $n$  is an integer,  $r_n$  is the radius for the corresponding ring,  $\lambda$  is the wavelength of the input light,  $f$  is the focal length,  $\Delta l$  is the focus spot size and  $\Delta r_N$  is the distance between two outmost rings.

For a 633 nm red laser beam, the focal length is designed to be around 5 cm for easy measurement. Meanwhile the resolution for ink-printing photolithography mask is 20  $\mu\text{m}$ . Thus the distance between two outmost rings is 20  $\mu\text{m}$  the least. The radius of the zone plate is calculated as 795  $\mu\text{m}$ . Therefore the focal length of the zone plate for 633 nm red laser is around 5 cm, while the minimum focusing size is around 25  $\mu\text{m}$ . In the same manner, with the predetermined structural design, a focal length of 6.6 cm can be obtained by a 472 nm blue laser.

As shown in Fig. 4 a dielectric zone plate can be regarded as two complementary binary zone plates fitted on the top and bottom, which is similar to a phase grating comparing to a binary grating. Therefore the output light will be of the most intensity if it reaches the same phase when it comes out of the top and bottom zone plate. Thus with refractive index  $n$  of PMMA being 1.46–1.5 (depending on the molecular weight) and  $n$  of SU-8 being 1.58–1.6, high intensity can be achieved when the thickness  $h$  of the structure is an integer multiple of light wavelength inside the dielectric material, i.e.,  $\lambda$  divided by  $n$ . So for the 472 nm blue laser, the highest light intensity can be achieved when the thickness of DFZP on fiber tip is around 320 nm or its integer multiple. For the focusing of DFZP on fiber tip, the laser is coupled into the POF at one end and focusing is observed at the other end. Fig. 3d presents the picture of the focusing behavior of the zone plate on the POF tip. The picture is taken under microscope when the focusing spot is about 6.8 cm in distance from the tip and 25–30  $\mu\text{m}$  in size. The spot size in the picture is bigger than the real one because of the light scattering on the background.

### 3.2. Focus calculation and measurement

A PIN-FET light detector is used to compare the output light intensity from the POF with and without zone plate structure on the tip. The PIN-FET has a window with the radius of 2 mm, which can collect light and then convert the light signal into an electrical voltage signal. A digital data collector of model USB-7360B manufactured by ZTIC is employed for the voltage value readout and data analysis on a desktop computer at 1000 Hz for 10 s. Because of the sensitivity limitation of the PIN-FET, the laser light source

early saturates the readout. Therefore LED light source in different colors of white, blue, red, yellow, and green are used for the light intensity comparison.

The light from an LED is coupled into the POF from one end and light intensity is measured on the other end. The results for the comparisons are shown in Table 1, where the light intensities both POFs with and without DFZP remain the same with minor difference within 5%. On the other hand, normal binary zone plate consists of a series of opaque rings, causing an intensity loss up to around 50%. This indicates that the zone plate structure on the fiber tip is capable of light focusing while maintaining the light intensity. Therefore for a normal POF with radius of 2 mm, the output light energy is spread across the whole cross section of the fiber. But when the POF is equipped with the zone plate structure the same amount of light energy is focused within an area of 25–30  $\mu\text{m}$ . Hence the POF is able to pick up much weaker light signal when it is used in micro-imaging applications. Furthermore, for medical micro surgeries with laser and POFs, the process can be more accurate in cell-targeting curing as human cells are normally in the size range of 10–50  $\mu\text{m}$ .

## 4. Conclusion

In conclusion, we have successfully fabricated DFZPs as micro-lenses on both flat wafers and POFs tips. Focusing for both 472 and 633 nm lasers are observed with glass wafers and POF tips, indicating that the proposed dielectric Fresnel zone plates can be built onto both substrate by a direct hot embossing process which may lead to a highly effective fabrication at low cost. Further optical measurements indicate that zone plate on the POF tip is able to achieve light focusing while maintaining high light intensity.

This structure is able to achieve focusing through a flat structure instead of a convex lens. Meanwhile the total transparent material can lower the light loss to the minimum comparing to binary zone plates. It is expected to have broad applications in micro-imaging, micro-focusing as well as point-of-care medical micro surgeries. What's more, this technique makes it possible to make structures on non-conventional substrates such as fiber tips, side or bevel facet and round surface, which opens a new horizon for microfabrication.

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