Optics Communications 282 (2009) 4119–4123

Contents lists available at ScienceDirect

Optics Communications

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

Photoetching of spherical microlenses on glasses using a femtosecond laser

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ARTICLE INFO

Article history:
Received 28 April 2009
Received in revised form 8 July 2009
Accepted 8 July 2009

PACS:
42.62.−b
42.79.Bh
81.05.K

Keywords:
Microlenses
Femtosecond laser pulses
Laser direct writing
Glasses

ABSTRACT

We fabricated spherical microlenses on optical glasses by femtosecond laser direct writing (FLDW) in ambient air. To achieve good appearances of the microlenses, a meridian-arcs scanning method was used after a selective multilayer removal process with spiral scanning paths. A positive spherical microlens with diameter of 48 μm and height of 13.2 μm was fabricated on the surface of the glass substrate. The optical performances of the microlens were also tested. Compared to the conventional laser direct writing (LDW) technique, this work could provide an effective method for precise shape-controlled fabrication of three-dimensional (3D) microstructures with curved surfaces on difficult-to-cut materials for practical applications.

1. Introduction

Microlenses and microlens arrays are extensively used in a wide range of applications, such as collimation of lasers, optical computing and photonic imaging [1–3]. Present techniques for the fabrication of microlenses, which mainly include photo-resist reflow technique [4], moving pattern lithography technique [5], gray-tone photolithography technique [6], are difficult to meet the demands of high precision and simple process. In the past decades, a significant amount of works has been carried on laser direct writing (LDW) techniques. For example, a F_2 laser was adopted to ablate and form microlenses on the end faces of hard-clad silica fibers by a rotational scanning technique. However, a mismatch of the fiber rotation axis resulted in some surface irregularities of the fabricated microlenses and the laser-ejected melt could be observed due to the thermal effects [7]. Moreover, contour scanning techniques were introduced to fabricate spherical microlenses on optical polymers using an ArF laser [8]. Guo et al. reported the fabrication of microlenses with arbitrary shape by femtosecond laser two-photo photopolymerization (TPP) technique [9]. However, these techniques can only be used for the processing of photopolymers. It still remains difficulties for precise fabrication of high-aspect-ratio microstructures, in particular with curved surfaces, on glasses which combine chemical inertness with better mechanical, thermal and optical properties than photopolymers.

Femtosecond laser ablation process provides an effective method for the fabrication of three-dimensional (3D) microstructures on a series of difficult-to-cut materials, such as glasses [10], metals [11], and ceramics [12]. The micro-regions of these materials, when irradiated by focused femtosecond laser pulses with the energies higher than material ablation thresholds, would be etched out and 3D microstructures could be fabricated in this top-down processing way. Over the past decades, femtosecond laser-assisted wet etching technique was widely applied in micromachining of 3D structures [13,14]. In recent years, a multi-step processing method, which combines procedures of femtosecond laser direct writing, thermal treatment, chemical wet etching and postannealing, was employed to fabricate 3D optical components, such as micro-mirrors [15], microlenses [16] and an integration of micro-mirrors and microlenses [17]. This technique is suitable for fabrication of complex 3D structures embedded in photosensitive glasses. Here we use a femtosecond laser dry etching technique based on LDW for precise fabrication of spherical microstructures. The technique could be used for precise processing of a wide range of materials. It is essential to optimize the ablation parameters to accurately control the removal volume of materials by each pulse. Furthermore, the obstruction of debris and residual thermal effects should also be avoided in order to obtain smooth surfaces.

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0030-4018/$ - see front matter
doi:10.1016/j.optcom.2009.07.017

In this paper, we present a precise micromachining process that is based on femtosecond laser ablation for the fabrication of 3D microstructures with curved surface, which has great potential applications in Micro Electromechanical System (MEMS), micro optics devices, and medical micro devices, etc. As an example, positive spherical microlenses were fabricated on the surface of glasses in ambient air. In the processing procedures, we at first employed a selective multilayer removal process with spiral scanning paths to get a tough spherical cap structure, and subsequently utilized a meridian-arcs smooth process to achieve a good appearance of the microlens. The experimental results indicate that the thermoelastic shock wave plays an important role during the process of femtosecond laser ablation of glasses in ambient air when pulse energies are well above the ablation thresholds. The dependence of processing quality on ablation parameters was also discussed.

2. Fabrication process

For the experiments, the sample was a 15×15 mm^2 K9 optical glass substrate with the thickness of 3 mm. The laser source was a Ti: sapphire oscillator–amplifier system (FEMTOPOWER Compact Pro, FEMTOLASERS), which delivered 800 nm, 30 fs Gaussian laser pulses at a repetition rate of 1 kHz. A 50× microscope objective (Olympus, NA = 0.5) focused the laser beam onto the sample surface. The incident pulse energy could be continuously varied by a variable attenuator and a mechanical shutter was employed to control the transit of laser beam. The sample was fixed onto a computer-controlled three-axis stage (M-505.2DG, Physik Instrumente), following a preprogrammed pattern. The machining process was monitored by a CCD camera.

In the initiation of the processing procedures, the microlens was fabricated by a selective multilayer removal process. As depicted in Fig. 1a, a sequential accumulation of annular-shape regions was removed layer-by-layer in a top-down method. For each layer, the sample was continuously translated in a spiral pattern and the laser pulses removed the materials of the annular-shape region by such spiral scanning path with a constant tangent velocity. In this experiment, the interval of the spiral, λ, was set to 1 μm, which is smaller than the diameter of the focal spot. The outer radius, Φ_o, of the annular-shape regions is represented by $\Phi_o = R + \lambda$, where R is the designed radius of the microlens, and was fixed to 25 μm in the experiment. The inner radiuses Φ_i of each layer can be determined by:

$$\Phi_1 = \left[R^2 - (R - l_1)^2\right]^{\frac{1}{2}}$$

$$\Phi_i = \left[R^2 - \left(R - \sum_{j=1}^{i-1} l_j\right)^2\right]^{\frac{1}{2}} \quad (i \geqslant 2)$$

Here, i is the layer ordinal and l_j is the thickness or step size of the layer j in vertical directions. After the removal process was finished in one layer, the sample was returned to the starting point and then stepped towards the objective for the distance l_j, followed by the removal process of the next layer. Other parameters of the microlenses are: R = 24 μm, l_j = 2.5 μm and the height of the spherical cap H = 15 μm.

The multilayer process has been widely used for the micromachining of 3D microstructures by the TPP technique [9,18]. The precision of the fabricated 3D microstructures are sensitive to layer thickness. A smaller layer thickness is essential for a better appearance, but necessitates a large number of processing layers and longer processing time. Moreover, it is not suitable to obtain curved surfaces with good appearance only by means of multilayer removal process. Therefore, after the multilayer removal process, air flow was used to clean the debris deposited on the spherical cap and subsequently, a special smooth process was provided to minimize the processing layers and improve processing quality, as shown in Fig. 1b. The focal point scanned the surface along a meridian-arc path of the spherical cap fabricated by the multilayer process. Subsequently, the sample rotated clockwise by the center axis of the spherical cap for 1° and then the focal point scanned along another meridian arc path. This process repeated until the surface of the spherical cap was totally scanned by femtosecond laser pulses. In our experiments, the smooth process was totally consisted of 360 meridian-arcs, which guaranteed the intervals between adjacent arcs smaller than ablation width. After photoetched, the sample was immersed and treated in ultrasonic bath for 5 min both in water and acetone in order to clean the residual ejections of material off the curve surface.

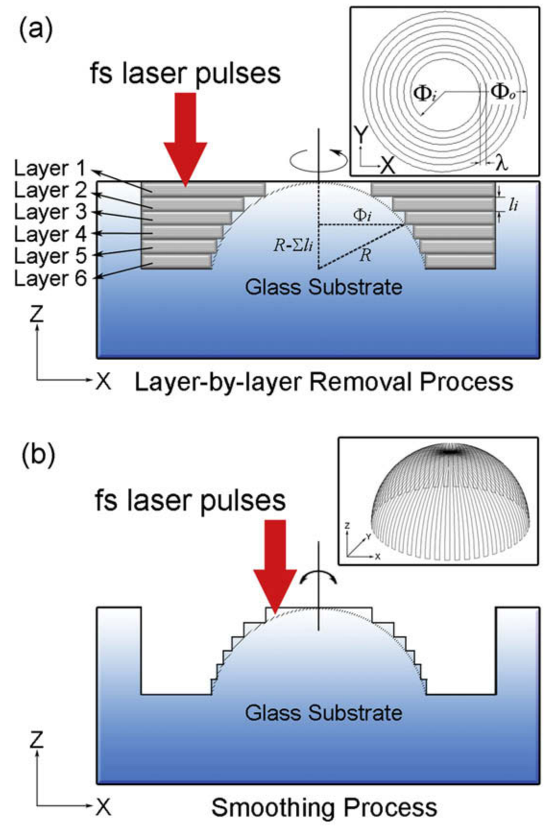

Fig. 1. Schematic of the fabrication procedures of spherical microlens: (a) the layer-by-layer removal process. Shadow regions show the regions would be removed by the laser pulses. Materials were eliminated from Layer 1 to Layer 6 by spiral scanning path. (b) The smooth process by a meridian-arcs scanning path.

3. Results and discussion

3.1. Optimization of parameters

In the past, micromachining of materials was carried out in different processing environments. The most common one was water-assisted process [19,20]. It is believed that the presence of water enhances the machining quality by removing the ablation debris and cooling the material efficiently. Unfortunately, for the precise microfabrication, bubbles generated by vaporization and ionization of water should be minimized to avoid disturbances. Therefore, the pulse energy was limited close to the threshold fluence of the optical breakdown and processing velocity was also relatively low, which would reduce the processing efficiency. Moreover, processing of some hard-to-cut materials with high