Stereolithography with variable resolutions using optical filter with high-contrast gratings

Yuanrui Li  
Ming Hsieh Department of Electrical Engineering, University of Southern California, Los Angeles, California 90089

Huachao Mao  
Daniel J. Epstein Department of Industrial and Systems Engineering, University of Southern California, Los Angeles, California 90089

He Liu, Yuhan Yao, Yifei Wang, and Boxiang Song  
Ming Hsieh Department of Electrical Engineering, University of Southern California, Los Angeles, California 90089

Yong Chen  
Daniel J. Epstein Department of Industrial and Systems Engineering, University of Southern California, Los Angeles, California 90089

Wei Wu  
Ming Hsieh Department of Electrical Engineering, University of Southern California, Los Angeles, California 90089

(Received 9 July 2015; accepted 26 October 2015; published 18 November 2015)

A three-dimensional printing approach based on stereolithography with variable printing resolutions was invented to solve the trade-off between throughput and resolution. In this technology, the variable fabrication resolutions are achieved by switching laser wavelength. The key component to enable this technology is an optical filter based on high-contrast gratings. The optical filter has been designed and numerically studied using the finite-difference time-domain method and was fabricated using nanoimprint lithography. The minimum printing resolution of the accordingly constructed stereolithography apparatus is reduced to 37 μm. Variable pixel sizes from 37 to 417 μm have been demonstrated. Using the designed and fabricated optical filter is a promising method to optimize the manufacturing efficiency of the stereolithography process. © 2015 American Vacuum Society.

[http://dx.doi.org/10.1116/1.4935336]

I. INTRODUCTION

Additive manufacturing (AM), commonly known as three-dimensional (3D) printing, has been a fast developing area for more than three decades. It is a process that uses information from a computer-aided design file to build a 3D physical object. It has significant advantages over traditional manufacturing methods in (1) rapid creation of 3D prototypes, and (2) cost-effective production of patterns and molds with complex surfaces.¹ Many materials have already been used in additive manufacturing such as polymer, metal, and ceramic.² There are several technologies that have been developed for additive manufacturing, including stereolithography, binder printing (3DP), fused deposition modeling, selective laser sintering (SLS), etc.³ Among these technologies, stereolithography⁴ is the first commercially available prototyping machine and one of the most widely used AM processes.¹

The stereolithography process uses photocurable resin, which consists of monomers that can be polymerized into large molecules. In the apparatus (Fig. 1), a laser source creates a laser beam that is deflected by two gyro-mirrors. Next, the laser beam is projected on the surface of the resin in a liquid tank and traces a cross-section of the object that is being printed. A Z stage stays below the liquid resin surface at a depth that is smaller than the light curing depth. After a layer has been cured, the Z stage moves down the distance of the thickness of a layer.

The production efficiency of stereolithography is determined by many factors, such as light spot diameter, scanning speed, hatch space, and curing depth.⁵ Among them, light spot diameter is the most direct way to determine the production efficiency. The diameter of the light spot is determined by the entire optical system and could be difficult to control precisely. Therefore, most stereolithography systems set the spot diameter as a constant.⁶ The specific value is a tradeoff between the size of the part that is being built and the desired resolution, which is typically about 0.1%–0.5% of the overall dimension.¹ For this reason, a variable beam spot that can improve production efficiency while keeping high resolution is a promising direction for stereolithography. With a variable beam spot, a large spot can fill an open area quickly and a small spot can build features that require high resolution. Many studies have been carried out on methods to change spot size.⁵–⁷ Miller et al. developed a SLS workstation that has two laser spot sizes by pulling an aperture into and out of light path.⁶ Sim et al. used lenses with different focal length to produce different laser spot sizes.⁷ Cao et al. reported a
sintering process that uses a dynamic focusing mirror to change spot size. Several specimens demonstrated more than 25% building time saving.5

Most of the studies involved the dynamic motion of optical components such as lens or physical aperture. Hence, cost of the systems would be increased due to the requirement of precise control of the motion during the fabrication process.

In this work, we presented a new method of changing light beam spot size by using two laser wavelengths and a specially designed optical filter based on high-contrast grating structure. For one of the wavelengths, the filter is almost transparent, which gives a larger spot size, while for the other wavelength, the filter works as an aperture and only part of the area is transparent, which gives a much smaller beam spot size. The advantages of this method over the previous approaches are: (1) the filter could significantly reduce the spot size of the laser beam that has been focused by lens; (2) as long as the optical system is well adjusted initially, no precise adjustment is needed during the fabrication process; (3) only an optical switch that can switch between the two wavelengths is needed during the continuous manufacturing process; (4) wavelength switching is faster than other spot size adjustment methods; (5) the shape of beam cross-section can be modified into any geometry in a fashion similar to the shaped-beam electron-beam lithography.8

II. EXPERIMENT

A. Stereolithography setup

Figure 2 shows the stereolithography setup used in this work. A light beam was created by a collimated laser source. Lasers with 405 and 445 nm wavelength were used in the experiment. The beam was then focused by the focusing lens. Next, the beam was deflected by the X mirror and Y mirror to scan on the surface of the target. The target is coated with UV-curable resin.

B. Optical filter design and fabrication

The optical filter in this work is composed of a bottom quartz layer, a TiO2 grating layer, and a top planarization layer. Gratings at center area were etched off to provide an aperture for 405 nm light. The working principle of high-contrast gratings can be described as follows: When light is incident on the gratings, lateral
guided modes are generated, resulting in resonance and reradiation. When the transmitted waves interfere destructively, transmission disappears, and strong reflection occurs.\textsuperscript{19,21,22} In the area where gratings were etched off, there is no high refractive index contrast. Therefore, no strong reflection would occur. As a result, light can get through this area. However, in this area, some quartz gratings might be created during the process of etching off TiO$_2$ gratings. Hence, a planarization layer that has similar refractive index as quartz was applied to eliminate undesired resonance. The reflection spectrum can be tuned by adjusting the geometry of the gratings, including $P$, $L$, and $H$ in Fig. 4. In this work, TiO$_2$ was selected because among all materials with low loss at this wavelength range, TiO$_2$ has the highest refractive index. Since the light sources are polarized, the filter was designed for this specific polarization (TM), and 1D grating design was used.

The fabrication process is summarized in Fig. 5. The gratings were fabricated by using nanoimprint lithography. First, a Si mother mold was fabricated by interference lithography. Then, a glass mold was duplicated from the Si mother mold by transferring pattern to a layer of UV-curable resist on a glass substrate. The filter substrate was prepared by deposition of a 400 nm thick TiO$_2$ thin film using direct current magnetron sputtering on top of a quartz substrate. The grating pattern was transferred from the glass mold to the TiO$_2$ layer via nanoimprint, lift-off, and RIE etching process. In the lift-off process, 10 nm thick chrome mask was made by electron beam deposition and worked as etching mask in the following RIE etching. An RIE etching recipe that was developed by Liu et al.\textsuperscript{20} with a gas combination of SF$_6$, C$_2$F$_8$ and O$_2$ was used. Figure 6 shows a SEM image of finished TiO$_2$ gratings.

After TiO$_2$ gratings were fabricated, an additional step of photolithography and RIE etching was carried out to etch away TiO$_2$ gratings in a circular area with a diameter of 96 $\mu$m. This area can virtually be any shape depending on the requirement of application. Finally, a planarization layer was applied for aforementioned reason. Two-hundred nanometer thick UV curable resist was spin coated and cured to be the planarization layer.

C. Transmission of the filter

Optical transmission of the grating area was measured and compared with simulation in Fig. 7. Numerical simulation was performed via finite-difference time-domain (FDTD) method using Lumerical FDTD solutions software. In the spectrum, the measured center wavelength of reflection matches the simulation result very well at 405 nm. Transmission at 405 nm is 10% while at 445 nm is about 80%, which means 405 nm light will be mostly reflected by the gratings while 445 nm light will pass.

D. Printing demonstration

The design purpose of the filter is to greatly reduce the spot size of 405 nm laser while keeping the spot size of 445 nm laser similar to the unfiltered one. Four groups of lines were printed to verify this effect. The target surface was a quarter of 4-in. Si wafer coated with 0.4 ml liquid photocurable resin. After patterns were printed, the sample was rinsed by isopropanol to remove uncured liquid resin. Finally, linewidths were characterized by an optical microscope. Figure 8 compares the linewidths of lines printed by the unfiltered beam and the filtered beam for both the 405 nm laser and the 445 nm laser. The beam spot size of the 405 nm laser was much more reduced than the 445 nm laser. For example, at laser power of 120 mW, spot size of 405 nm light was reduced from 372 to 50 $\mu$m while spot size of 445 nm light was only reduced from 332 to 258 $\mu$m due to slight reflection and material loss. There is no corresponding data for some power values since the resin cannot be fully cured in such low power. Additionally, the unfiltered beam
of power below 30 mW could not print solid pattern, which confirms that small pattern below 100 μm can only be printed with the filter.

In order to demonstrate changing pixel size by switching wavelength, a test pattern was printed, which is shown in Fig. 9. The optical filter was installed in the stereolithography system during the printing process. The thinner lines (37 μm wide) were first printed by the 405 nm laser. Then, the wavelength of laser was changed to 445 nm to print the thicker lines (272 μm wide).

III. EFFICIENCY TEST BASED ON DIGITAL MODEL

The purpose of having a variable beam spot is to improve the manufacturing efficiency when the object that is to be built has both small features and large features. To demonstrate the improvement, a digital model of a microfluidic device is created as shown in Fig. 10. The device has an overall dimension of 40 mm (length) × 20 mm (width) × 2 mm (height). A channel inside the block has a cross-section of 200 × 200 μm. The beam sizes are taken from the data of 120 mW laser power in Fig. 8. The small spot is 50 μm in diameter from the 405 nm laser, and the large spot is 258 μm in diameter from the 445 nm laser. The distances of travel of the beam spots to build this device are shown in Table 1. The

![Fig. 7](color online) Experimental and simulated transmission spectrum of the TiO2 gratings.

![Fig. 8](color online) Comparison of the linewidths of patterns printed by unfiltered beam and filtered beam: (a) 405 nm laser and (b) 445 nm laser. The beam spot size of the 405 nm laser was much more reduced than that of the 445 nm laser. There is no corresponding data for some power values since the resin cannot be fully cured in such low power.

![Fig. 9](color online) Printed pattern with both big feature (one vertical line, printed by 445 nm laser) and small feature (three horizontal lines, printed by 405 nm laser). Area between the features is the surface of silicon wafer. Microscope was focusing at the top of the features. Black areas are shadows that are on the surface of the wafer and are enlarged due to out of focus. With optical filter installed in the printing system, variable spot size was achieved by only switching wavelength.

![Fig. 10](color online) Digital model of a microfluidic device. The block has a dimension of 40 mm (Length) × 20 mm (Width) × 2 mm (Height). The cross-section of the channel is 200 × 200 μm.
speed of the spots is a constant during real manufacturing process. So, the distance of travel is proportional to manufacturing time. If both of the spots are used, the small spot can build features of the channel, and the large spot can fill other volume in the block. If only one spot can be used, in order to keep the resolution of the channel the same, the small spot will be used to build the whole object. As a result, using the two different beam spots saves 87.6% of manufacturing time, which is a significant improvement.

IV. DISCUSSION

The measured transmission spectrum did not match the simulation result perfectly. Several factors might affect the filter’s performance. First, TiO$_2$ has some surface roughness that can be observed from the SEM image. Also, the sidewall profile was not strictly vertical. Additionally, the deposited TiO$_2$ has larger loss than the ideal value used in the simulation, especially in short wavelength range, which was not included in the simulation model.

A high-contrast grating is chosen in this work for its small thickness compared with a conventional multilayer coated optical filter. Two wavelengths are used in this work for concept demonstration. In future work, the filter can be placed at close proximity of the surface of the resin and multiple layers of high-contrast gratings can be integrated into a single filter which can give more beam shapes for multiple wavelengths. In comparison, the conventional filter, if being used in a similar way, will suffer more reduction of resolution in beam shapes due to diffraction of light that travels through thicker material.

Generally, 405 nm laser is able to cure more resin than 445 nm laser at same power level due to higher photon energy. However, when the filter was being used, the 405 nm laser printed thinner lines than the 445 nm laser, which confirms the effectiveness of the filter.

V. SUMMARY AND CONCLUSIONS

In summary, an optical filter based on high-contrast gratings is designed and fabricated by nanoimprint lithography. The function of cropping 405 nm light beam and transmitting 445 nm light beam is achieved. By using the filter, the minimum printing resolution of the current setup is reduced to 37 $\mu$m. Variable beam spot size is realized by exchanging wavelength. This work shows a promising way to optimize the manufacturing efficiency of the stereolithography process.

ACKNOWLEDGMENTS

The authors would like to thank Max Zhang and Jianhua Yang of Hewlett Packard Labs for their help with TiO$_2$ film deposition. This project is supported in part by Wei Wu’s start-up fund at University of Southern California.

5. Y. Cao, D. Li, and J. Wu, Rapid Prototyping J. 19, 100 (2013).

<table>
<thead>
<tr>
<th>Small beam spot only</th>
<th>Small and large beam spot</th>
<th>$d_{\text{small only}}$ (mm)</th>
<th>$d_{\text{small}}$ (mm)</th>
<th>$d_{\text{large}}$ (mm)</th>
<th>$d_{\text{small}} + d_{\text{large}}$ (mm)</th>
<th>$d_{\text{small only}}$</th>
<th>Time saved (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>473961</td>
<td>12706</td>
<td>45808</td>
<td>58514</td>
<td>8.10</td>
<td>87.6</td>
<td>8.10</td>
<td>87.6</td>
</tr>
</tbody>
</table>