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TECHNICAL PAPER

Fabrication of flexible light guide plate using CO_2 laser LIGA-like technology

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Abstract The liquid crystal display (LCD) needs the back light module (BLM) for the light source. The light guide plate (LGP) is the main component of BLM to spread light source to the whole LCD surface and requires for the generation trend of lightweight, easy to carry, and bendable for LCD. In this article, we have demonstrated the fabrication of flexible LGP using CO_2 laser LIGA-like technology which includes the laser ablation of micro-groove polymethylmethacrylate (PMMA) master mold, pouring polydimethylsiloxane (PDMS) to the mold and casting the micro-groove microstructure for flexible LGP application. Different laser powers and micro-groove pitches were used to ablate the PMMA mold with varied groove depths and taper angles. Optical microscope was used to examine the morphology and profile of the final bendable LGP microstructure. Under the varied laser power of 1–12 W, the mean taper angles of PMMA micro-grooves ranged from 28° to 70° and the etching depths were from 44.5 to 281.8 μm. The flexible PDMS LGP had good microstructure duplication after casting. The optical uniformity and luminance of flexible LGP was concerned with structure of micro-grooves and measured using BM9 luminance meter. The maximal light uniformity and average luminance of LGP at some microstructure reaches 75 % and 119 cd/m^2, respectively.

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1 Introduction

The back light module (BLM) is an important component of liquid crystal display (LCD) and includes three primary parts of the optic thin films, the light guide plate (LGP) and the light source (Chien and Chen 2009; Huang et al. 2008). The LGP can redistribute illumination of light source to the front display and the BLM go into the development of lightweight, easy carrying, and bendable panel for future LCD application with the enhanced luminous efficiency and uniformity. It is noted that the microstructure of LGP can affect the luminous efficiency and uniformity of BLM. Varied LGP microstructure are conventionally fabricated by photolithography (Huang et al. 2008; Lee et al. 2008; Chung and Hong 2007), hot-embossing (Park et al. 2007; Chung et al. 2010a) and injection molding (Chiang et al. 2009; Lin et al. 2008) which are involved in the complex steps and long duration. Another knife tool micromachining (Yost et al. 1997; Lee et al. 2004; Xie et al. 2011) is one of common processing for V-groove manufacturing. However, different taper profiles need many types of Diamond head such as sharp, bevel and round angles to accomplish it. Recently, laser machining (Nielsen and Balling 2006; Tan and Venkatakrishnan 2007; Chung and Wu 2007) techniques have been widely applied to microstructure fabrication, which has advantages of direct processing, simple operating and inexpensive equipment. Especially, low-cost CO_2 laser (Chung et al. 2005, 2010b; Nayak et al. 2008) has been used for microstructure machining on polymer and glass materials for microfludic chip application (Klank et al. 2002; Chung and Lin 2011; Hong et al. 2010). But less publication have presented for the application of flexible LGP. In this article, the CO_2 laser LIGA-like technology has been demonstrated for the flexible LGP fabrication. It includes the integration of producing the microstructure of polymethylmethacrylate (PMMA) master mold, casting polydimethylsiloxane (PDMS) on the mold and peeling it to obtain a flexible LGP together with four LED as light source. The taper angles of microstructure affect luminous efficiency and uniformity and can be controlled by varied laser processing parameters. The relationship between microstructure formation and optics property for a flexible LGP application is also discussed.

2 Experimental procedures

The commercial available air-cooled CO_2 laser equipment (VL-200, Universal Laser system Inc., USA) with a maximum laser power of 30 W was used for the fabrication of PMMA mold microstructure. The CO_2 laser has a wavelength of 10.6 μm and a TEM_{00} output of beam with a good quality of M_2 value of 1.4 ± 0.2, which is generated from a sealed-off, RF excited, slab design and a multi-pass, free space resonator. The maximum laser scanning speed was 1,140 mm/s and the largest working area was 409 × 304 mm^2. The focal length of the lens is about 38.1 mm and the smallest beam spot size of the commercial product after standard verification could reach 76 μm which is defined as the diameter at which the intensity drop to $1/e^2$ of their axial values. A constant scanning speed of 114 mm/s was used at varied laser powers from 1 to 12 W to obtain the different depth and taper angle of micro V-grooves onto the PMMA substrate. Figure 1 shows the schematic diagram of the LGP pattern design with different pitches of V-grooves among four regions of the PMMA substrate plate. The region one with the largest pitch is the closest to the LED light sources while the region four far away the light source has the smallest pitch. The common pitch difference between two adjacent regions is 100 μm. Taking the 600 ~ 300 μm LGP pattern for example, the pitches in four regions are 600, 500, 400 and 300 μm, respectively. Three kinds of LGP pattern are designed as 600 ~ 300 μm, 800 ~ 500 μm and 1,000 ~ 700 μm for studying the feature size influence on the LGP optic performance. As the PMMA mold was fabricated, PDMS was poured onto the mold. The PDMS solution and curing agent (Dow Corning Corp., USA) were completely mixed with a weight ratio of 10:1 onto the PMMA model and pumped under vacuum to remove air bubbles within the PDMS solution. The solution was cured at 80 °C for 40 min and then peeled off from the PMMA mold to get the PDMS flexible LGP. The morphology and profile of the laser machined PMMA micro-grooves and the duplicate PDMS microstructure were examined by an optical microscope (OM, OLYMPUS BX51M, Japan). The illumination of flexible LGP in bending shape after LED lighting was examined. The luminance and uniformity of the flat PDMS LGP were measured by BM9 luminance meter. The uniformity (U) of luminance was calculated by 9-point method using equation as $U = L_{min}/L_{max}$, where L_{min} is the minimum luminance and L_{max} is the maximum luminance.

3 Results and discussion

Figure 2a shows the schematic Gaussian distribution of laser power versus position using the low and high laser power irradiation which may affect microstructure profile formation as shown in the optical micrographs of Fig. 2b, c, respectively. The depth of V-groove microstructure increases with the laser power and the profile of the structure is similar to Gaussian-like type. Also, the higher laser power leads to a bigger taper angle and ablation depth. Compared to the conventional cutter fabricated V-groove microstructure in need of a few of varied cutters for the different heights and taper angles, the laser processing only controls the laser power and the scanning speed to fabricate the microstructure of various depth and taper angle. Figure 3 shows the relationship between the laser power and taper angle of PMMA mold at a scanning speed of 114 mm/s and laser powers of 1–12 W and the corresponding cast PDMS microstructure. As mentioned in Fig. 2, the taper angle increases with laser power and nearly reach a maximum angle at high enough laser power due to the penetration effect. Regarding the taper angles of flexible PDMS microstructure after casting, it is close to those of PMMA master mold with little deviation. It indicates that the casting process is feasible for the pattern of rigid PMMA mold transferred to flexible one. In quantitative analysis, the mean taper angle increasing with laser powers as Gaussian function varies from 28° to 70°

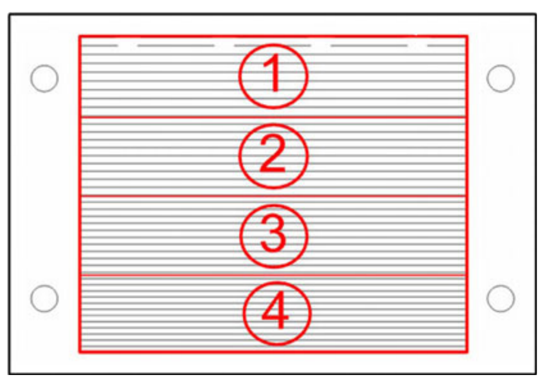

Fig. 1 Schematic diagram of the LGP pattern design with different pitches of V-grooves among *4* regions of the PMMA substrate plate. The region *1* with the largest pitch is the closest to the LED light sources while the region *4* far away the light source has the smallest pitch

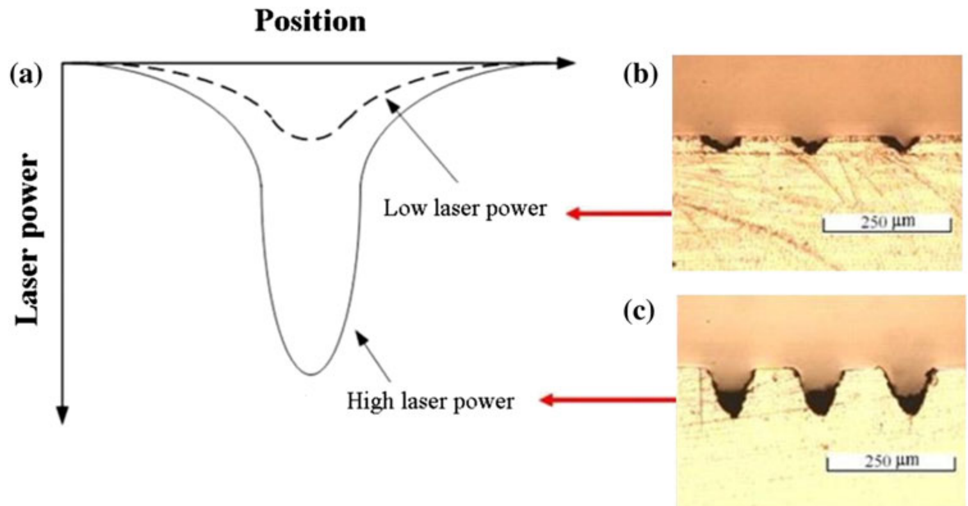

Fig. 2 **a** The schematic Gaussian-like distribution of laser power versus position using the low and high laser power irradiation; optical micrographs of microstructure profile formation at **b** low power and **c** high power of laser irradiation

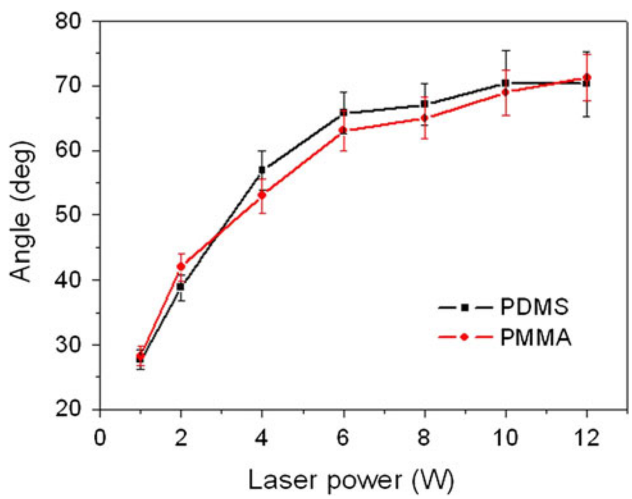

Fig. 3 The relationship between the laser power and taper angle of PMMA mold at a scanning speed of 114 mm/s and laser powers of 1–12 W and the corresponding cast PDMS microstructure

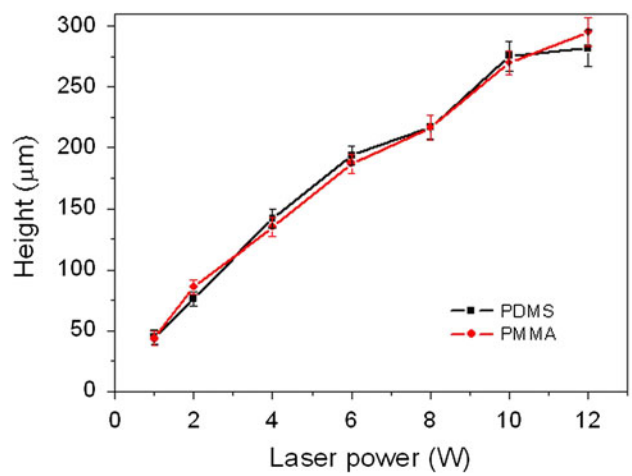

Fig. 4 The height of microgroove of PMMA mold as a function of laser power at a scanning speed of 114 mm/s and laser power of 1–12 W as well as the corresponding cast PDMS microstructure

corresponding to laser power from 1 to 12 W. In details, as the varied laser powers of 1, 2, 4, 6, 8, and 10 W lead to the mean taper angles of the PMMA micro-groove around 28°, 42°, 56°, 64°, 65°, 70° and 70°, respectively. As the laser power is more than 8 W, the angle is about 65° ~ 70° due to the increased depth. Figure 4 shows the microgroove height of PMMA mold as a function of laser power of 1–12 W at a scanning speed of 114 mm/s as well as the corresponding cast PDMS microstructure. It indicates that the depths of both PMMA and PDMS are very close. The mean ablation depth of PMMA mold increases with laser power and varies from 44.5 µm at 1 W to 281.8 µm at 12 W. Although the duplicate PDMS height at 12 W is little lower than that of PMMA at 12 W, it is because the PDMS filling does not reach the bottom of deep groove. However, too high taper angle or depth is not good for the LGP performance.

Figure 5 shows the demonstrated illumination performance of our flexible LGP fabricated by CO_2 laser LIGA-like process: (a) for the test sample packaged with LED light sources before lighting, and (b–d) for the sample after lighting at the varied distortion or bending for proving the feasibility of flexible LGP. Four LED lamps are located at the one side of the LGP and separated equally are used as light source. Each LED lamp is 40 µcd and surface-mount device type. There are no standard for the light source of the flexible LGP so far, therefore we can not compare with other products. However, we can see the illumination of flexible PDMS LGP goes bright lighting in the varied bending shapes. In order to identify the effect of taper angle and pitch size of microstructures on the illumination performance, the average luminance and uniformity of flat PDMS LGP are measured from three kinds of patterns of 600 ~ 300 µm, 800 ~ 500 µm and 1,000 ~ 700 µm as shown in Figs. 6 and 7, respectively. In Fig. 6, the average

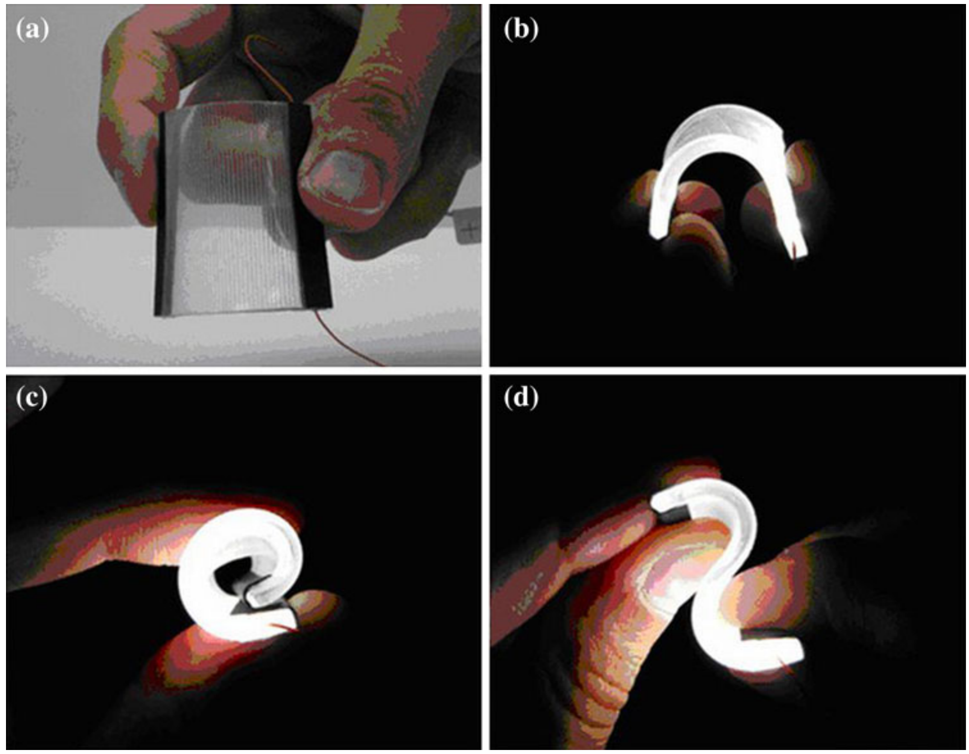

Fig. 5 The illumination demonstration of the flexible LGP fabricated by CO_2 laser LIGA-like process: **a** for the test sample package with LED light sources before lighting, and **b**–**d** for the sample after lighting at the varied distortion or bending

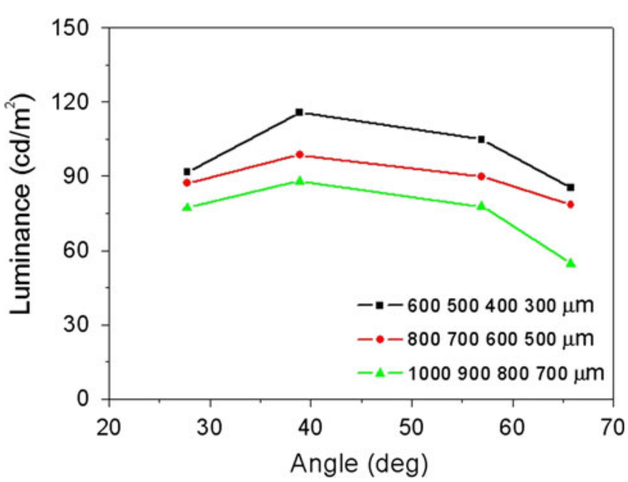

Fig. 6 The relationship between average luminance of the flexible light guide plate and the taper angle at varied pitch dimension

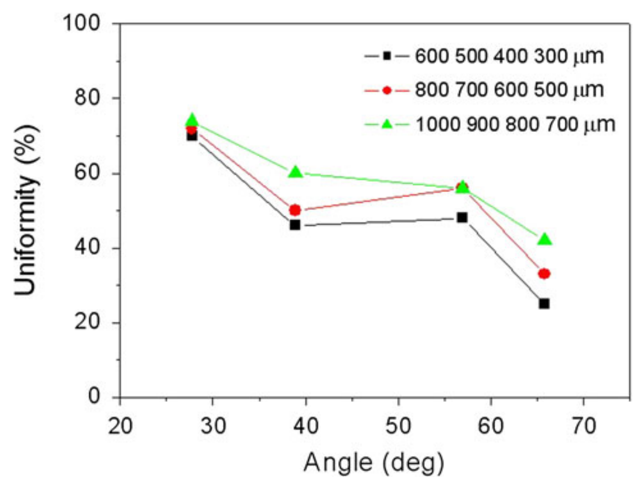

Fig. 7 The relationship between the uniformity of the flexible light guide plate and the taper angle at varied pitch dimension

luminance of the flexible LGP is concerned with the taper angle and pitch dimension. The average luminance increases with decreasing pitch and a maximum luminance occurs at taper angle around 40°. The average luminance of PDMS LGP with the small 600 ~ 300 μm pitches is 119 cd/m^2, which is much higher than the other two patterns of large pitches. It is because the structure destroys the total reflectance of LGP for the enhanced illuminating brightness. In Fig. 7, the uniformity of the flexible LGP is also related to the taper angle and pitch dimension. Roughly, the LGP uniformity decreases with increasing taper angle and with decreasing pitch. The good uniformity among three patterns occurs at taper angle of around 28° and the highest uniformity of 75 % is obtained at the 1,000 ~ 700 μm LGP. Comparing Figs. 6 and 7, an enhanced LGP performance can be optimized the taper angle between 28° ~ 40° and the groove pitch design for good uniformity and high luminance. The CO_2 laser LIGA-like technology is a fast, cheap and efficient method for fabricating the patterned microstructure for the flexible LGP application in future.

4 Conclusions

Fabrication of the flexible LGP has been successfully demonstrated by means of CO_2 laser LIGA-like technology including the laser ablated microstructure of PMMA mold and PDMS casting process. Three kinds of PMMA patterns were fabricated on the pitches of 600 $\sim$ 300 μm, 800 $\sim$ 500 μm and 1,000 $\sim$ 700 μm. Compared to conventional methods of photolithography, knife tool machining, hot-embossing and injection, the CO_2 laser processing and PDMS casting have advantages of fast fabrication, cheap equipment, easy integration and no knife wear and wastage. The mean taper angle and groove depth of PMMA roughly increase with laser power and can be effectively duplicated to PDMS microstructure. The average luminance and uniformity of the flexible PDMS LGP is concerned with the taper angle and pitch dimension. The average luminance increases with decreasing pitch and a maximum luminance of 119 cd/m^2 occurs at taper angle around 40°. The LGP uniformity decreases with increasing taper angle and good uniformity of 75 % occurs at taper angle around 28°. The LGP performance with good uniformity and high luminance can be enhanced by mean of the taper angle between 28 $\sim$ 40° and optimized the groove pitch with the assistance of design software.

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