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Abstract. Edge-lit light guide panels (LGPs) with micropatterned surfaces represent a new technology for developing small- and medium-sized illumination sources for application such as automotive, residential lighting, and advertising displays. The shape, density, and spatial distribution of the micro-optical structures (MOSs) imprinted on the transparent LGP must be selected to achieve high brightness and uniform luminance over the active surface. We examine how round-tip cylindrical MOSs fabricated by precision micromilling can be used to create patterned surfaces on low-cost transparent polymethyl-methacrylate substrates for high-intensity illumination applications. The impact of varying the number, pitch, spatial distribution, and depth of the optical microstructures on lighting performance is initially investigated using LightTools™ simulation software. To illustrate the microfabrication process, several $100 \times 100 \times 6\ \mathrm{mm}^3$ LGP prototypes are constructed and tested. The prototypes include an "optimized" array of MOSs that exhibit near-uniform illumination (approximately 89%) across its active light-emitting surface. Although the average illumination was 7.3% less than the value predicted from numerical simulation, it demonstrates how LGPs can be created using micromilling operations. Customized MOS arrays with a bright rectangular pattern near the center of the panel and a sequence of MOSs that illuminate a predefined logo are also presented. [DOI: 10.1117/1.JMM.12.2.023002]

Subject terms: optical light guide panels; edge lighting; micro-optics; micromilling.

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1 Introduction

Edge-lit backlighting has been used extensively in developing a variety of small- and medium-sized liquid crystal displays (LCDs) for computer monitors, flat screen television, cell phones, and digital cameras. The light guides in the backlit modules are designed to frustrate total internal reflection (TIR) and uniformly redistribute the light rays emitted from multiple LEDs across the active surface area with minimal optical losses along the nonactive edges and faces.[1] The shape, density, and spatial distribution pattern of the micro-optical elements imprinted on the surface of the flat light-guide panel (LGP) are often "optimized" to improve the overall brightness and luminance uniformity. Optical simulation tools, such as LightToolsTM and TracePro,™ are often used to determine the distribution of micro-optical elements for the desired brightness and uniformity properties.[2,3]

A similar concept to edge-lit displays can be used to develop illumination sources for automotive applications, interior workspace lighting, residential lighting, and advertising displays. For example, the primary advantage of using plastic light guide technology for automotive applications is that a properly designed edge-lit LGP with multiple light-emitting diodes (LEDs) will deliver higher intensity illumination for less energy than a traditional lamp and reflector. In addition, the edge-lit illuminator will require far less space for actual installation because it can be constructed as thin as the optically transparent substrate and can be curved to fit the geometry of the surrounding vehicle surface. Spatial constraints play an important role in vehicle design for seamlessly integrating lighting in the exterior shell of the vehicle or increasing trunk space by eliminating bulb-based lighting fixtures. Similar spatial and energy constraints exist in work-space lighting applications and advertising displays.

Optimizing the performance of the LGP requires careful design of the shape and spatial distribution of micro-optical elements on the patterned surface. This has been achieved by varying the size of the micro-optical structures (MOSs),[1,4,5] changing the pitch between adjacent MOSs,[6] or simultaneously adjusting both size and pitch. The spatial distribution of the MOSs can also be varied across the LGP surface such that the element density increases with distance from the LED sources.

Manufacturers of edge-lit backlighting technology for LCD displays have also incorporated additional components in their designs that include separate reflectors, diffusers, and microprism sheets to improve the local and global luminance properties. However, these costly diffusive sheeting and brightness-enhancement films are not necessary in this work, because absolute luminance uniformity and the minimization of Moiré fringe effects[7] are not significant design constraints in developing automotive illuminators for convenience, safety lighting, or stylistic interior lighting systems.

The primary objective of the research described in this paper is to examine how round-tip cylindrical optical structures fabricated by high-precision micromilling can be used to directly create high-intensity, uniformly illuminated LGPs

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on optically transparent low-cost plastic substrates. Although the focus is on small, flat polymethyl-methacrylate (PMMA) waveguide sheets, the same design principles can be extended to larger, or even curved, illuminating structures. Unfortunately, currently available optical design software tools do not permit accurate simulations of curved-panel surfaces and, therefore any analysis of nonplanar structures at this time would be largely the result of ad hoc trial and error studies. Furthermore, no separate reflective coatings or microprism optical sheeting is incorporated in the light-emitting panel structures considered in this study. The optical performance of an LGP can be enhanced with opaque reflective coating on the nonactive surfaces, but the additional material layers complicate the analysis and significantly increase the fabrication costs.

High-precision micromilling is the manufacturing process of choice for creating prototypes because it permits near optical quality structures to be fabricated using a ball-end milling tool. The optical performance of the micropatterned LGP can be modified by changing the shape of the individual microelements (disk, hemispherical, pyramidal), adjusting the element depth, or optimizing the density and spatial distribution of the surface elements. However, from a micromilling perspective, complex shapes, such as micropyramids, require extensive intermittent changes to the tooling and elaborate machine coding that greatly increases manufacturing time and costs. As a consequence, each micro-optical element is a round-tipped cylinder with a fixed radius and adjustable depth. This simple, straightforward, top-down manufacturing procedure increases the viability of producing LGP illuminators for a broad spectrum of commercial applications.

The impact of varying the micro-optical element depth and pitch on light uniformity for a particular LGP design will be initially investigated using the commercially available optical simulation software LightTools.™ The design of the MOSs in terms of ball-end cylinder geometry and spatial distribution over the active LGP surface are presented in the following section. The micromilling process used to fabricate the round-tip cylindrical MOSs on the PMMA substrate is summarized in Sec. 3 and results from several experimental studies are provided in Sec. 4. These include LGPs without micropatterned surface, with a uniformed distribution of fixed radius and depth MOSs, "optimized" array with varying depth MOSs, and a customized pattern in the center of the LGP. Finally, concluding remarks and a discussion on future work is provided in Sec. 5.

2 Design of Micro-Optical Structures

The microstructure pattern used to reflect and refract light as it travels through the LGP must transform the point light sources originating from multiple LEDs into a uniformly illuminated region on the emitting surface, with minimal losses along the edges or nonactive regions of the panel. Figure 1(a) illustrates the basic movement of light rays traveling inside an optically transparent LGP with uniform depth micro-optical elements imprinted on one surface. Each ray emitted from the light source travels in a straight line through the homogenous material with a constant refractive index (η) until it hits an artifact (microstructure) in the medium or a waveguide surface (edge, face). By introducing artifacts in the waveguide medium (glass or plastic) it is possible to redirect the rays so that they may exit at predefined regions of the waveguide. The micro element, Fig. 1(b), is a cylinder with a hemispherical end similar to the optical structure created by plunging a nonthrough hole in the substrate with a ball-end mill.[8]

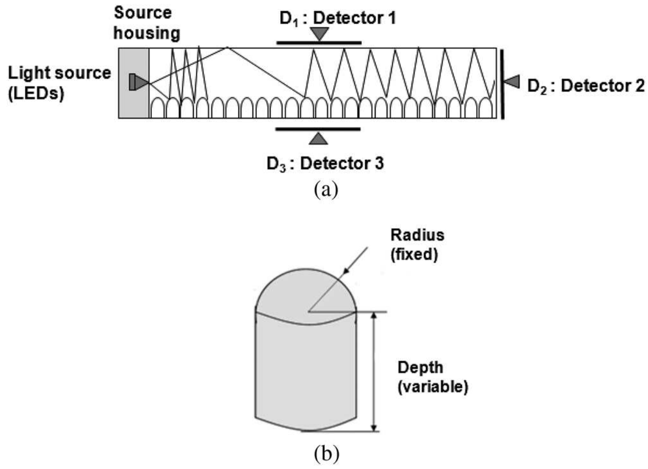


Fig. 1 Transmission of light rays through an optically transparent wave guide. (a) Side view of a LGP with micropatterned surface (lights rays tend to exit from side opposite micropatterns). (b) Geometry of a single round-tip cylindrical micro-optical structure (MOS).

Lightweight plastic PMMA is selected as the substrate material in this research because it has very good optical properties and does not expand significantly in hot work environments.[9] The illumination patterns arising from concave micro-optical elements micromilled on a ($100 \times 100 \times 6$ mm^3) optically transparent plastic substrate was first examined using LightTools™ optical design software. For the simulation studies and later physical experiments, the light source is comprised of nine LEDs placed 12 mm apart along one edge of the PMMA panel. A customized light source housing unit is constructed to minimize light loss at the entrance of the LGP. Significant losses can also occur if the light source radiation pattern does not match the acceptance angle of the LGP. A misalignment between the source housing and LGP can cause light rays to hit the light receiver located just above the active illuminating surface. Finally, if more intense light is required for a particular application then the number of LEDs can be increased.

Several virtual light detectors (D_1, D_2, D_3) (see Fig. 1) are used to measure the illumination patterns formed on the two dominant faces of the edge-lit LGP and the distant edge parallel to the LED housing unit. For the simulation study, a gray-scale contour plot is created by LightTools™ and the corresponding X-X' and Y-Y' cross-sectional profiles. The illumination characteristics are given in terms of lux, which is a measure of illuminance, or luminous emittance, and reflects light intensity over an already defined region.

2.1 *Single Micro-Optical Structure*

The impact of a single round-tip cylindrical MOS on the illumination pattern for the optically transparent PMMA substrate was first examined using the optical design software LightTools.™ The radius and depth of the MOS is 0.5 mm. In Fig. 2(a) the simulation results clearly show

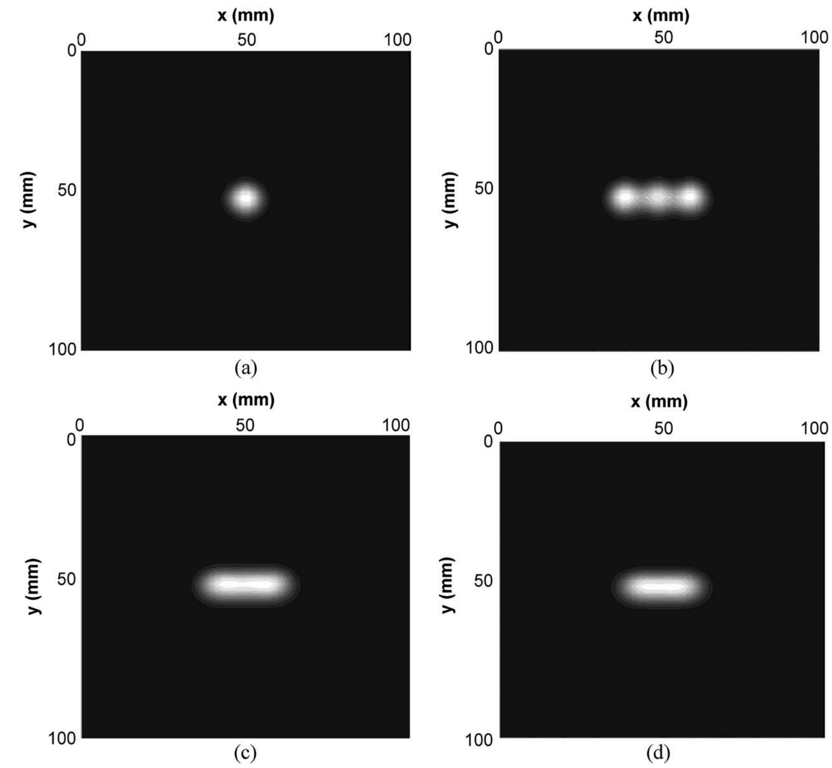


Fig. 2 The illumination patterns for LGPs with round-tip cylindrical MOSs located at the Y-axis mid-point of the wave-guide. Each MOS has a depth of 0.5 mm and the illumination is provided along the top edge (nine LEDs spaced 12 mm apart). (a) Single MOS. (b) Three MOSs. (c) Five MOSs. (d) Nine MOSs.

that a round-tip cylindrical MOS imprinted on the dominant face opposite the active illuminating surface will enhance light-scattering and increase the number of light rays exiting through the active LGP surface.[3] As well, the simulation results indicate that if the light rays do not strike an artifact they shall progress unimpeded to the edge opposite the light source. From the perspective of designing an illumination panel, these unimpeded rays represent light loss and must be minimized for efficiency.

2.2 *Multiple Micro-Optical Structures*

A relatively large uniform illumination pattern will require multiple MOSs to be imprinted on the LGP surface. To investigate the effect of several neighboring elements on the formation of the illumination pattern, simulations were performed using a lateral row (X-direction) of several adjacent elements parallel to the LEDs. Figure 2(b)–2(d) is the illumination patterns for a row of three, five and nine microstructures, respectively. The X-X' and Y-Y' cross-sectional views of the light intensity profiles through the middle row of the LGP for the four cases is given in Fig. 3. The radius and depth for all cylindrical microstructures in this study are fixed at 0.5 mm, with the pitch (or center-to-center distance between microstructures) being 10 mm for the three elements and 2.5 mm for the nine elements. The preliminary results show an 80% increase in the average illumination for the larger number of elements. One additional reason for the observed improvement is the smaller gap (2.5 mm) between microstructures for the row of nine elements.

The impact of increasing the number of MOSs with respect to distance from the light source was explored by creating neighboring columns with multiple identical

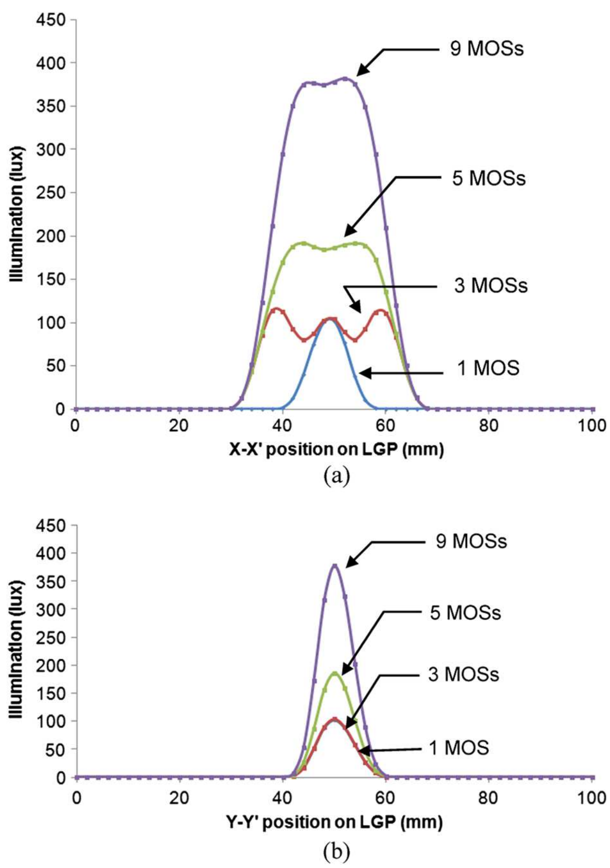


Fig. 3 The cross-sectional views of the light intensity profiles given in Fig. 2. (a) X-X' cross-sections with respect to the MOS distribution. (b) Y-Y' cross-sections with respect to the MOS distribution.

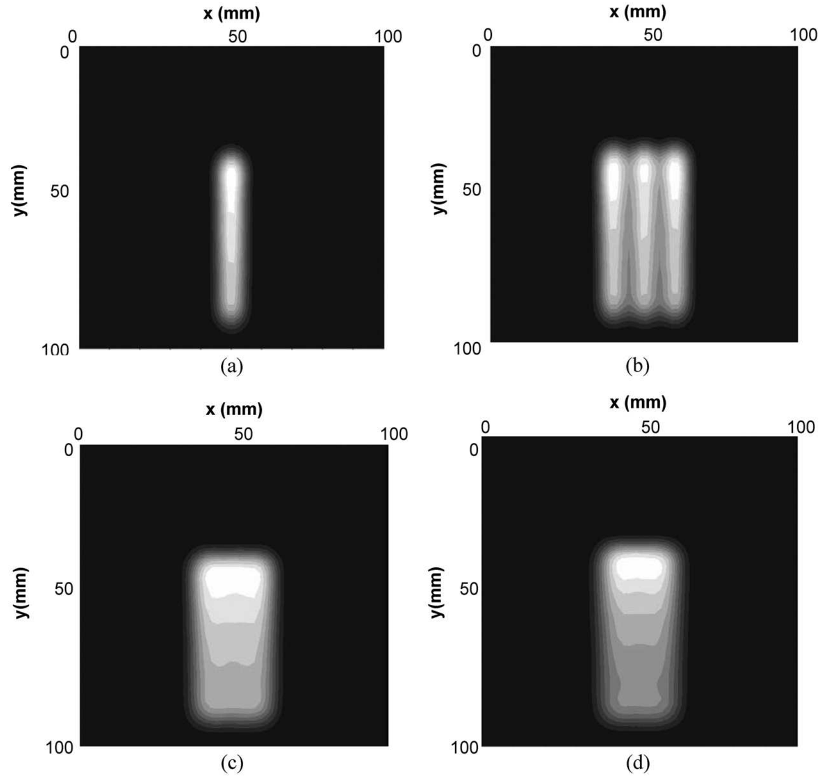


Fig. 4 The illumination patterns for LGPs with one or more rows of 26 identical microstructures starting near the middle of the wave guide. Each microstructure has a depth of 0.5 mm and the illumination is provided along the top edge (nine LEDs spaced 12 mm apart). (a) Single row of MOSs. (b) Three rows of MOSs. (c) Five rows of MOSs. (d) Nine rows of MOSs.

microstructures. Figure 4 shows the illumination patterns for LGPs with one, three, five, and nine rows of 26 identical microstructures starting near the middle of the wave guide. Each microstructure has a depth of 0.5 mm and the illumination is provided by nine LEDs spaced 12 mm apart along the top edge. The X-X' and Y-Y' cross-sectional views of the light intensity profiles are given in Fig. 5. The larger number of neighboring MOSs produces a much brighter and uniform pattern, but there is drop in intensity as the rays propagate from the LED light source towards the distant edge. The regions of the LGP farthest from the source receive less light because the size of the microstructures are too small to impede most of the incident light rays. Therefore, it will be necessary to create a patterned surface with a densely packed arrangement of elements and deeper microstructures.

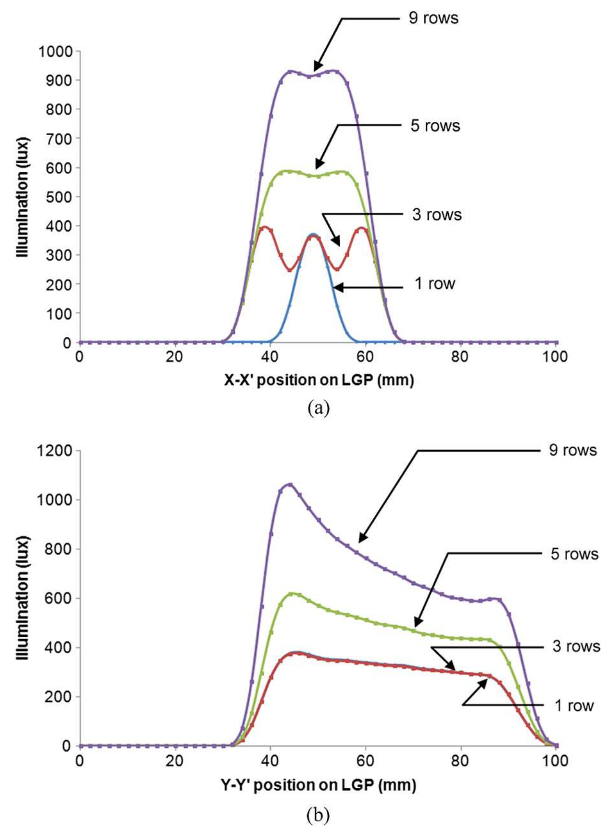


Fig. 5 The cross-sectional views of the light-intensity profiles given in Fig. 4. (a) X-X' cross-sections with respect to the microstructures distribution. (b) Y-Y' cross-sections with respect to the microstructures distribution (light travels from left to right).

2.3 *Two-Dimensional Arrays of Micro-Optical Structures*

Hexagonal element arrays of equal diameter cylindrical microstructures as shown in Fig. 6 are simulated to explore the impact that MOS distrubutions can have on illumination intensity and uniformity. The packing of microelements in a two-dimensional (2-D) array is quantified by the fill factor[10] which is often maximized in a LGP design to capture the maximum amount of light and generate minimum light losses. The fill factor describes the percentage of total area occupied by the microstructures to the total area of the LGP, and is given by

$$\text{fill factor} = \frac{r^2\pi}{\Delta_x \Delta_y}, \tag{1}$$

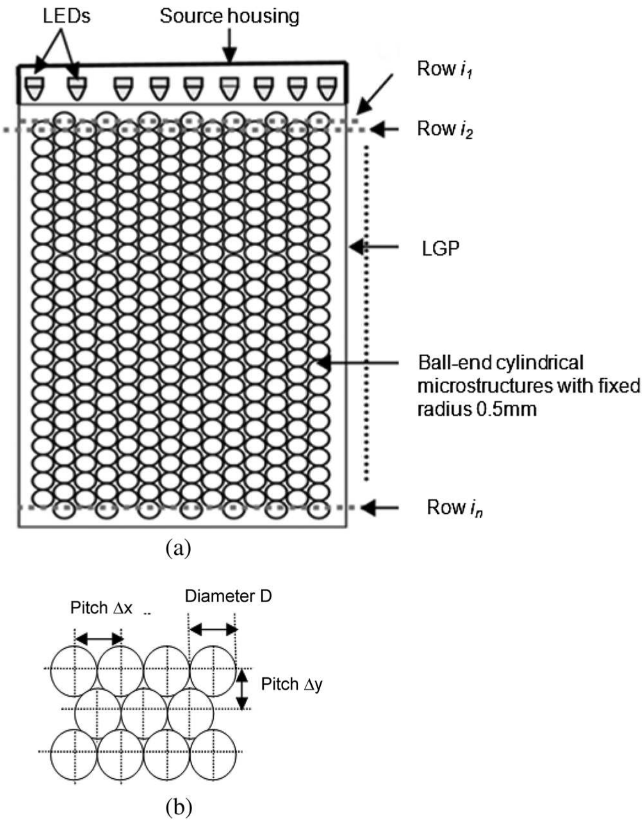


Fig. 6 (a) LGP with a hexagonal array of equal-sized cylindrical microstructures. The patterned array was created using a ball-end micromill with a fixed radius (0.5 mm) and hexagonal arrangement (pitch $\Delta x = 1$ mm, $\Delta y = 1$ mm). (b) Fill factor calculation for hexagonal array arrangement of microstructures (adapted from Ref 10).

where Δ_x and Δ_y are the pitch in X and Y directions, respectively. The radius of the microstructure is r and the pitch between microstructures is $D - \Delta_x$.

If the diameter and pitch of the microelements is 1 mm, then the fill factor for a hexagonal array ($\Delta_y = \frac{1}{2}\sqrt{3}\Delta_x$) is 90.7%. Based on these simple calculations, a hexagonal array of elements has a high fill factor, which means that this type of spatial distribution of elements is capable of emitting more light than the rectangular array. The hexagonal packing of MOSs also suggests that there is no unimpeded "through paths" for the light rays emanating from the source. Therefore, if the depths of the cylindrical microstructures are allowed to vary then it should be possible to guarantee that all light rays will strike an artifact before it reaches the distant edge.

From a design perspective, the goal is to adjust the minimal number of optical system parameters needed to create high intensity, uniform illumination over the desired LGP surface area. Two measures are introduced to examine the impact that parameter changes will have on the LGP performance. The first is a measure of illumination uniformity, U_E, given by the ratio of average illumination (E_{ave}) to the maximum illumination ($E_{\max}$) over the active surface region,

$$U_E = \frac{E_{\mathrm{ave}}}{E_{\max}}. \tag{2}$$

This ratio, U_E, will approach unity for a near-uniform illuminating surface. The second measure is the coefficient of nonuniformity, C_{NU}, which is defined as the difference between the maximum ($E_{\max}$) and minimum ($E_{\min}$) illumination with respect to the average illumination (E_{ave}) in the active area,

$$C_{\mathrm{NU}} = \frac{(E_{\max} - E_{\min})}{E_{\mathrm{ave}}} \times 100. \tag{3}$$

From a practical perspective, this measure provides the designer with insight about the maximum deviation in illumination around the mean or average value.

Figure 7(a) shows the simulation result for a LGP patterned with fixed-sized microstructures (radius and depth of 0.5 mm) organized in a hexagonal arrangement. The pitch of the MOSs in this array is 1 mm. The average illumination over the active surface region was determined to be 44,090 lux with a maximum value of 184,706 lux near the LED source. These results provide a uniformity ratio of $U_E = 0.24$. However, the illumination decreases rapidly from the LED sources and, as a consequence, the majority of light emitted from the LGP occurs over the first 30 mm with the remaining panel area being largely ineffective.

The impact of varying microstructure depth along the length of the optical LGP was then examined. Once more a hexagonal array of MOSs with a pitch of 1 mm and individual radii of 0.5 mm was created. However, the depth of microstructures was varied linearly from the light source to the opposing distant edge. For the arrangement shown in Fig. 7(b), the optical elements in the first row (i_1) near the light source had a depth of 0.1 mm while those at the farthest row (i_n) were 5.5 mm. The maximum depth is constrained by the 6-mm thickness of the LGP substrate. The LightTools™ simulation of the micropatterned LGP showed that a linear incremental change in microstructure depth produced an average (E_{ave}) and maximum ($E_{\max}$) illumination of 44,065 and 148,349 lux, respectively. The ratio of maximum-to-average illumination is $U_E = 0.29$, an improvement compared to the LGP with microstructures of uniform depth and radius. Although the X-X' cross-sectional profile is generally uniform, as shown in Fig. 7(c), the Y-Y' cross-sectional profile exhibits a nonuniform illumination across the entire active surface, Fig. 7(d). A significant amount of light is emitted within the first 30 mm from the light source. From these observations it is clear that the depth of the microstructure needs to be varied in a nonlinear manner in order to achieve a uniform illumination pattern over the entire active region.

2.4 *Sequential Optimization of Microstructure Depth*

Although "optimal performance" can be achieved for each application using a unique combination of the substrate material, microstructure radius and depth, MOS density, and spatial pattern distribution, from a manufacturing perspective it would be far more beneficial to reduce the number of variable parameters to "one." In other words, the ultimate goal of this research was to produce a high-intensity, uniform illumination pattern by varying only one, easily adjusted, MOS design parameter. From the simulation study using the LightTools™ software, it can be concluded that the depth of cylindrical microstructure will

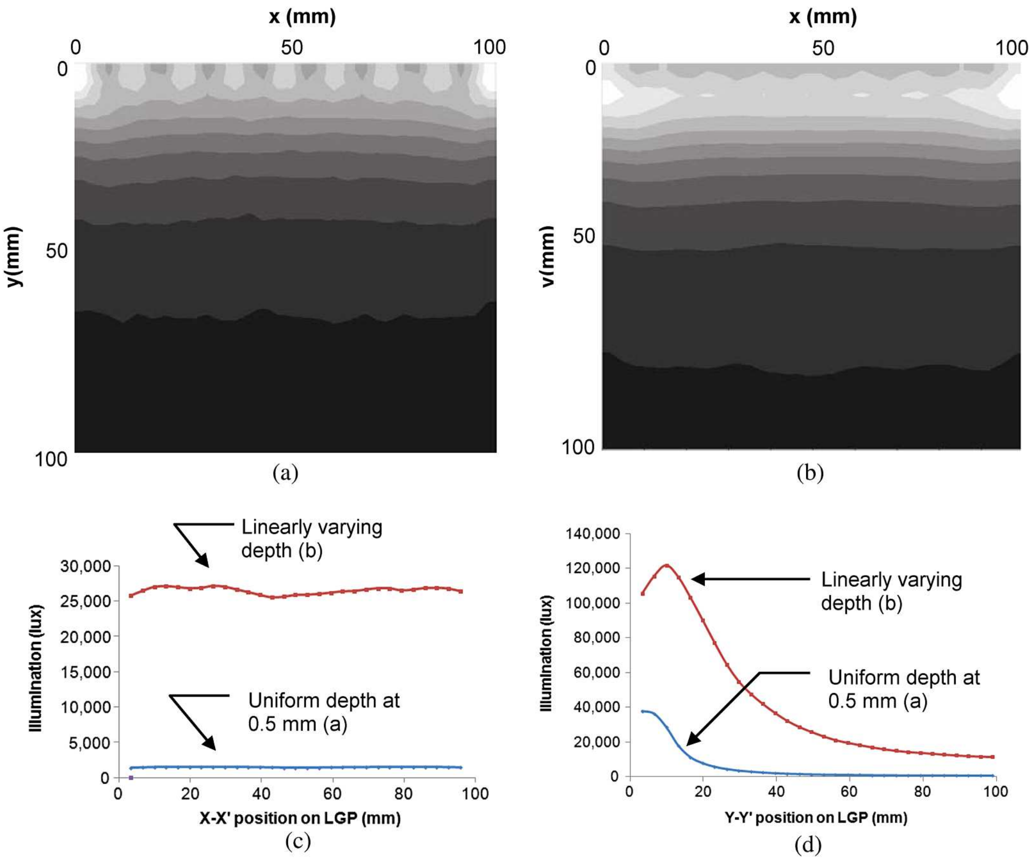


Fig. 7 Illumination pattern and cross-sectional profiles for a hexagonal arrangement of microstructures. Each microstructure has a radius of 0.5 mm and the illumination is provided along the top edge (9 LEDs spaced 12 mm apart). (a) Illumination pattern of the LGP for uniform depth of 0.5 mm. (b) Illumination pattern of the LGP for linearly varying depth from 0.1 mm at the light source to a microstructure depth of 5.5 mm at the distant end. (c) X-X' illumination profiles. (d) Y-Y' illumination profiles (light travels from left to right).

have a significant effect on illumination distribution and it is, therefore, a critical parameter in controlling the LGP performance. It should be possible to achieve "near optimal" performance[8] and to contour the illumination pattern on the active surface of the LGP by altering only the depth of the individual MOSs during the micromilling operation. Precision micromilling will also enable MOSs with near optical quality surfaces to be fabricated directly on the PMMA material.

The optimized depth values of the MOSs across the LGP, for high-intensity uniform illumination, were determined by a sequential optimization method that used the LightTools™ software. In this procedure, the MOS depth was fixed for each row, but allowed to vary between 0 and 5.5 mm for each row from the leading edge near the light source to the distant edge of the LGP. These boundary conditions for MOS depth were selected based on a PMMA sample thickness of 6 mm. Further, the desired target was set to an average luminance of $44,000 \pm 20\%$ lux over the entire 100×100 mm^2 surface. The reference value of the average luminance was selected by taking into consideration the average luminance value obtained from a hexagonal array arrangement with uniform sized MOSs (see Fig. 6).

The sequential optimization procedure began by performing several iterative simulation tests on the first row of MOSs using different depth values. For each selected depth value the average luminance was determined and the depth that provided the target illumination was selected for all MOSs in the corresponding row. The procedure then examined the MOS depths in the next row. In this manner, the MOS depth for the each n'th row was calculated by taking into account an average luminance for the LGP area covered by n-1 rows of MOSs. This sequential process continued until the entire LGP had been covered. During optimization, all other design parameters, such as MOS diameter, number of MOSs in each row, distance between rows, and others factors remained fixed.

Based on the simulation study for the 100×100 mm^2 LGP, the MOS depth in the first row, nearest the light source, was determined to be 0.095 mm. This is not unexpected because the depth of microstructures near the source should be small in order to permit more light rays to travel the full length of the LGP. Following the same procedure, the MOS depth values were observed to increase only slightly with each successive row reaching a depth of 0.25 mm at a distance of 80 mm from the light source, Fig. 8. However, at this distance the MOS depth needed to be increased significantly to 4.5 mm in order to reach the desired average luminance value. The depth of the MOSs would again increase significantly to a depth of 5.5 mm over the final 5 mm of the LGP. The sudden increase in MOS depth is likely caused by insufficient light flux propagation through PMMA material over a fairly long length (over 80 mm) of the LGP. This observation will, however, require additional study and is left for future research.

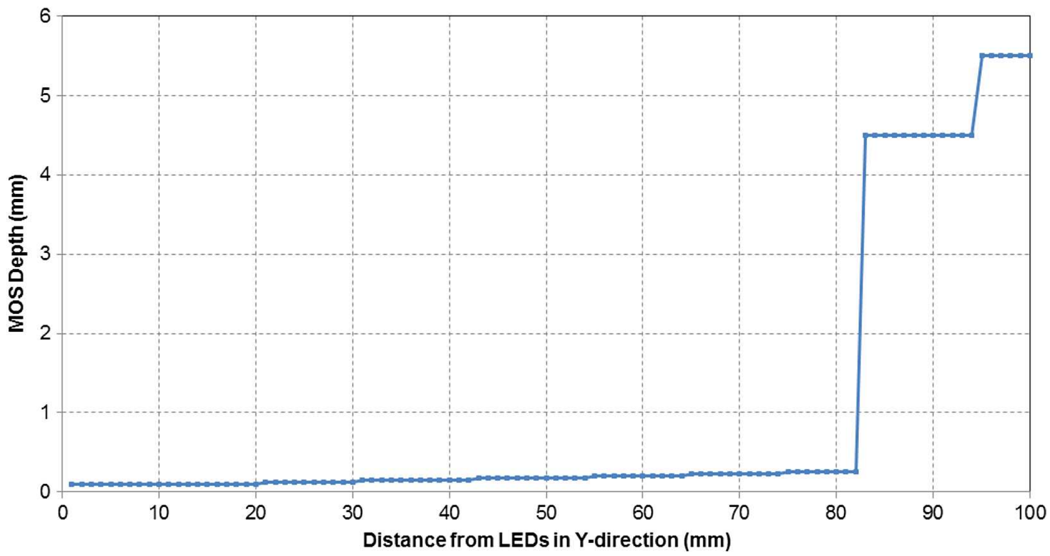


Fig. 8 Change in depth of MOSs over the length of the LGP for the proposed optimization approach.

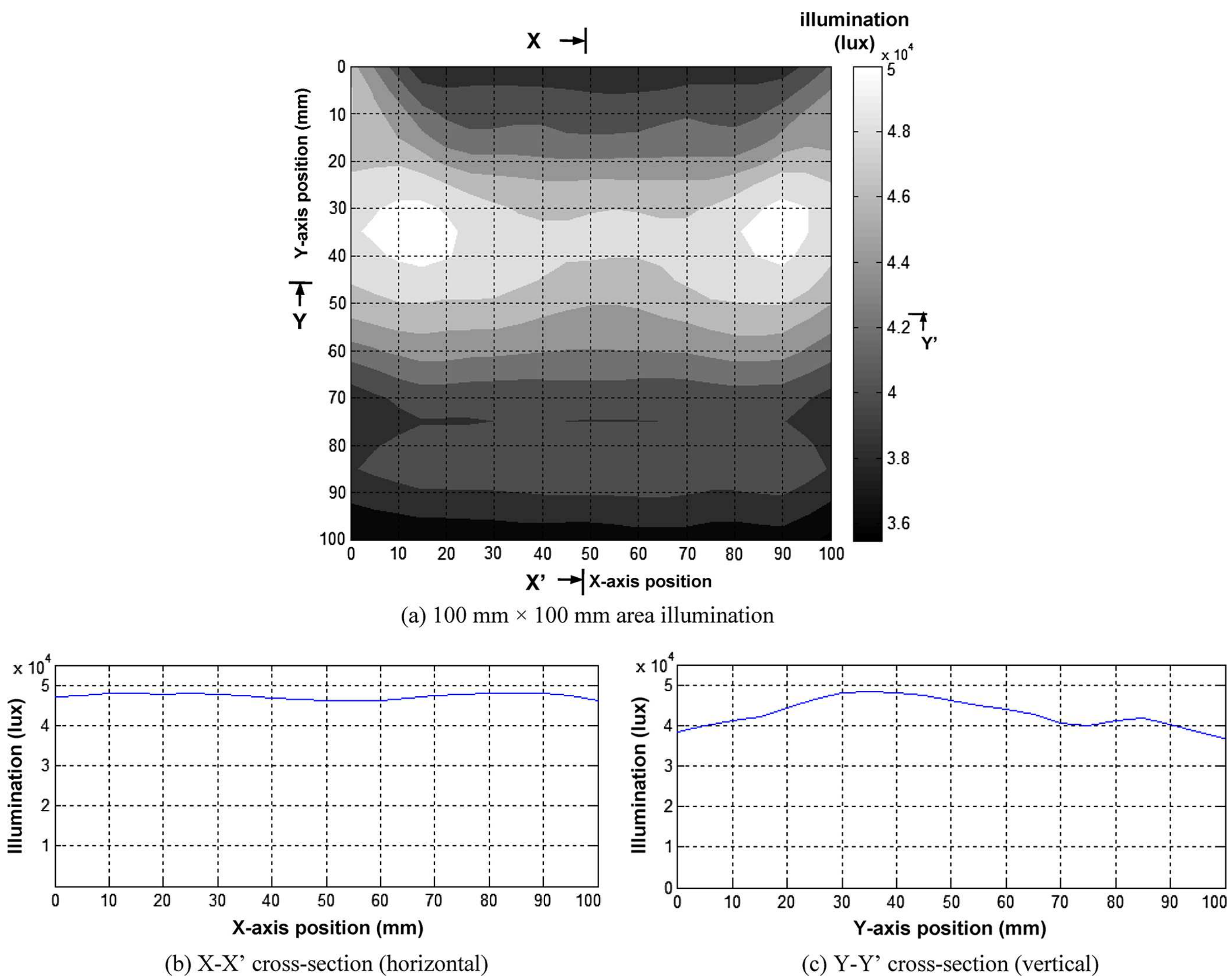
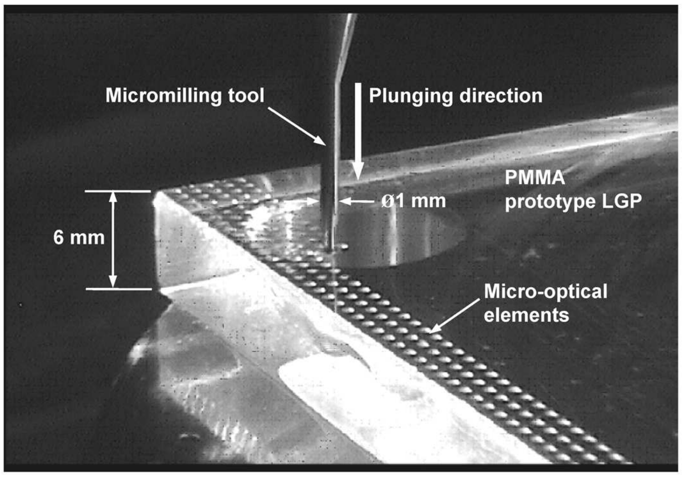


Fig. 9 Near-uniform illumination for an LGP with microstructures distributed "optimally" from light entrance edge to opposite distance edge. (a) Illumination pattern on the active surface for LGP after selecting "optimal" MOS depths. (b) X-X' illumination profile. (c) Y-Y' illumination profile (light travels from left to right).

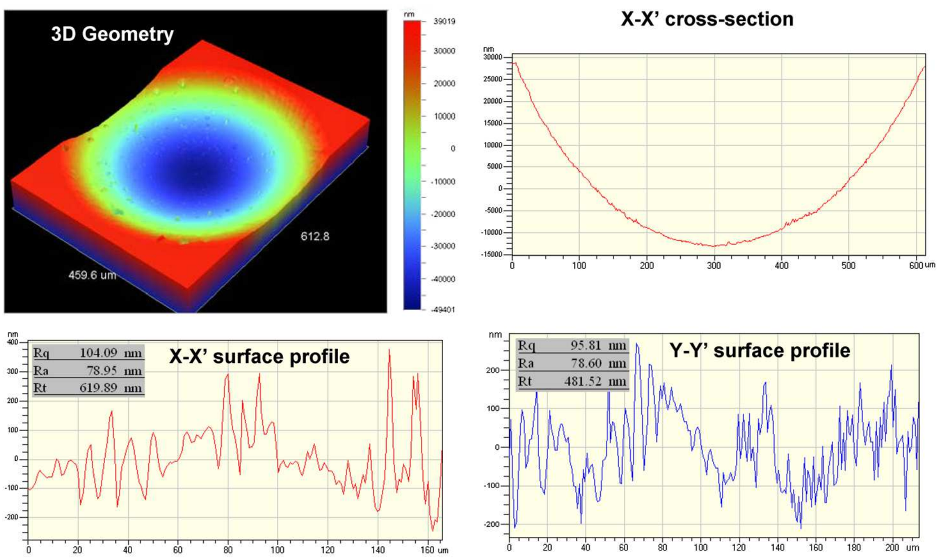
Using this sequential optimization approach to determine the appropriate MOS depths, it was possible to achieve uniform illumination with a mean value near 44,000 lux. Figure 9(a) shows the illumination pattern on the active surface of the simulated LGP after selecting "optimal" MOS depths having a mean value (E_{ave}) of 43,442.6 lux over the entire $100 \times 100\ \mathrm{mm}^2$ area with a maximum illumination ($E_{\max}$) of 50,857.9 lux, and minimum illumination ($E_{\min}$) of 35,470.9 lux. The corresponding coefficient of nonuniformity was 35.4%. Figure 9(b) and 9(c) shows the cross-sectional profiles in the middle of LGP along X and Y axis, respectively. Based on the simulation results, the minimum, average, and maximum illumination were determined to be 37,003, 43,741, and 50,857 lux, respectively. The X-X' illumination profile has a mean value of 47,244.9 lux with a maximum illumination of 48,130.4 lux, minimum illumination of 46,071.3 lux, and standard deviation of 725.1 lux. Therefore, the coefficient of nonuniformity was calculated to be 4.4%. The Y-Y' illumination profile is less uniform with respect to the X-X' illumination profile having a mean value of 42,871.3 lux with a maximum illumination of 48,361.9 lux, minimum illumination of 36,701.1 lux, standard deviation of 3520.6 lux, and a coefficient of nonuniformity of 27.2%.

3 Fabrication of Microstructures in LGP

In this research, micromilling is used to directly create round-tip cylindrical MOSs on the planar optically transparent PMMA substrates, as shown in Fig. 10. The fabrication process involves varying only the depth of the cylindrical microstructures. Several physical prototypes of LGP made from PMMA material with cylindrical microstructures are produced to validate the design and fabrication methodology discussed in Sec. 2. Rotational speed, feed rates, depth per pass, and cooling pressure are typical process parameters in micromilling operations in order to achieve low surface roughness value and high-machining quality.[11]



(a)



(b)

Fig. 10 Micromilling fabrication and verification of microstructure surfaces. (a) Photograph showing the fabrication of the round-tip cylindrical MOSs on the prototype LGP. (b) 3-D geometry, cross-section, and two surface profiles. Average surface roughness was ~78 nm R_a (near optical quality surface finish). Note that the waviness may be the result of deflections in the machine-cutting tool, errors in the tool geometry, and machine vibrations.

In this study, ball end tungsten carbide (WC) cutting tools with a diameter of 1 mm were used for milling microstructures in the optically transparent PMMA LGP substrate. Each machining cycle that produced a micro-optical structure involved plunging the high-speed rotating tool into the LGP surface to a depth of 50 μm, and then lifting the tool above the substrate surface for cleaning and chip evacuation. The process was repeated until the desired depth was reached. The rotational speed of the cutting tool was 30,000 rpm and axial cutting feed rate was 10 mm/min, with the free-run motions associated with approaching and removing the rotating tool from the cutting zone performed at 1200 mm/min. In addition, the machining operation was accompanied by air-oil mist, under a pressure of three bar, providing vibration-free cutting and more effective chip removal.

Since the shape of the final aperture produced by micromilling is defined by the cutting tool geometry, it was necessary to accurately measure the dimensions of the actual tool prior to machining. The tool geometry was measured using a Blum™ laser tool setting sensor with an accuracy of ± 0.5 μm, and the true diameter of the milling tool was found to be 1 mm $\pm$ 1 μm. It was also necessary to examine the positional accuracy of the micromachining system to ensure that the microstructures can be imprinted at precise locations on the LGP surface. Although the positional accuracy was determined to be ± 0.1 μm, the accuracy of microstructure locations on the LGP surface was found to be within ± 2 μm due to the instabilities in the cutting process and cutting tool run-out.

Once fabricated, the LGP prototype samples were tested for surface finish before undergoing illumination measurements. In this research, a WYKO NT1100 optical profiling system from Veeco Instruments Inc., New York, USA, was used to measure the surface quality (e.g., line profiling surface roughness, R_a) and visualize the quality of the three-dimensional (3-D) MOSs created in the PMMA. The average surface roughness of the cylindrical micro-optical structures was measured to be $\sim$78 nm R_a which corresponds to a near optical quality surface finish.

4 Experimental Results and Discussion

4.1 *Performance of Fabricated LGP Prototypes*

The experimental set-up as shown in Fig. 11 was designed to measure the luminance characteristics of the micromilled LGP samples in a darkened room. Nine LEDs were arranged in a linear array and attached to one edge of the vertically standing micromilled PMMA LGP sample. The LED light source provided uniform illumination across the edge-lit face of the LGP. A digital lux meter (DX-200D) with a measuring range up to 200,000 lux was then used to measure a 1×1 cm^2 area on the illuminating LGP surface. Light emitted from this active illuminated area was collected through a light-collection funnel having a conical shape and 1×1 cm^2 square end. The light collection element of the digital lux meter was mounted on a manual XYZ motion platform with a position accuracy of ± 0.5 mm. During the measurement procedure, the light collection element was placed in front of each 1×1 cm^2 subregion of the LGP and the corresponding lux value was recorded.

Figure 12 represents the measured illumination pattern for optimally distributed micro-optical structures (MOSs) on the 10×10 cm^2 LGP prototype. The minimum, average, and maximum illumination values were 38,382, 40,770, and 42,800 lux, respectively. For this case, the illumination uniformity across the LGP was found to be 89.2%. The experimental results are approximately 7.3% less than the average illumination values predicted from the numerical simulations. The difference in the experiment and simulation results can be explained, in part, by the surface irregularities and optical imperfections of fabricated MOSs that modify the light propagation pathways through the LGP.

Figure 13(a) shows the propagation of light through a LGP with no microstructures on the patterned surface. For this test sample, all light rays were transmitted to the edge opposite the entrance by TIR without any significant scattering on the active surface during light propagation. Figure 13(b) shows the illumination performance of the customized array fabricated using the method described in Sec. 2.4. By creating a shallower depth of microstructures near the light source and deeper depths at the farthest end of the LGP, light was guided out the active illuminated surface. The photographs also show evidence of over-saturation effects and increasing amounts of stray light due to the geometrical and optical impurities in the illuminated LGPs.

Figure 14 demonstrates that it is possible to create illuminating shapes at different locations in the LGP for signature

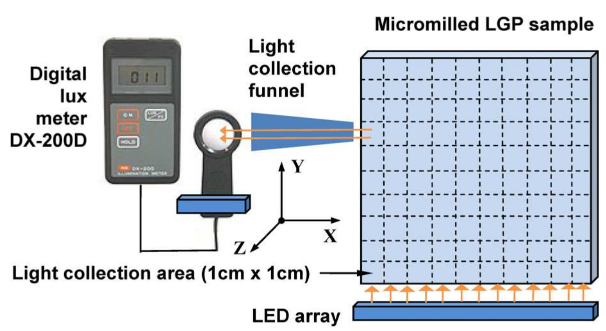


Fig. 11 Experimental set-up used to measure the luminance characteristics of the micromilled LGP samples.

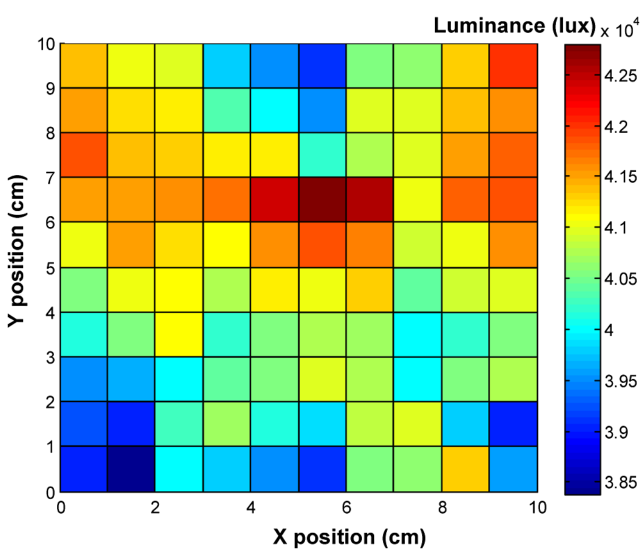


Fig. 12 Measured illumination pattern of the micromilled LGP sample with optimally distributed MOSs.

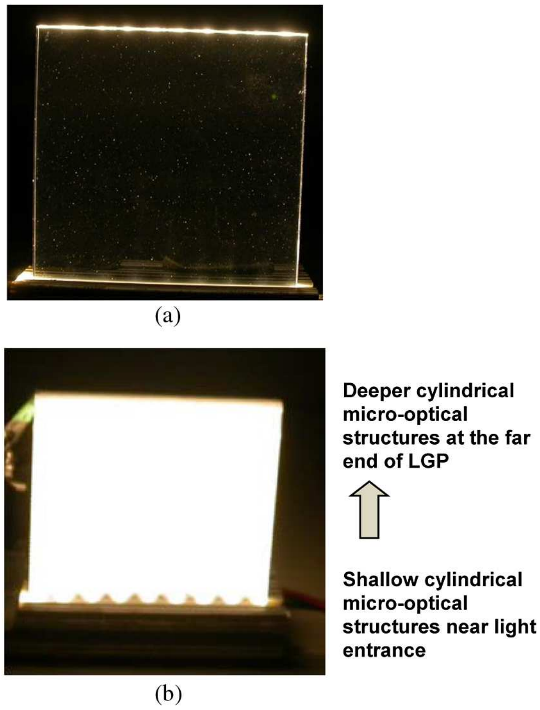


Fig. 13 Illumination of a fabricated LGP with (a) no MOSs on the patterned surface and (b) LGP with optimized array of MOSs (with varying depth of MOS). The illumination pattern for the optimized array is similar to Fig. 9(a).

lighting applications and clearly shows near-uniform lighting across the selected region and very little refractive light at the nonpatterned (i.e., transparent) areas of the LGP. In addition, the photographs show that the boundary of the pattern is easily visible.

5 Discussion

Micromilling customized LGPs is a relatively quick and cost-effective solution to making prototypes for analysis and exploring design improvements. The uniform array of micro-optical structures was fabricated in less than 4 h. However, it took nearly seven hours to fabricate the optimized array of micro-optical structures. The diagonal pattern shown in Fig. 14(a) was made in less than 40 min. The quality of the surface finish for the fabricated part is near optical grade, which is more than adequate for illumination applications. It may be possible to significantly improve the quality of surface finishes through different combinations of micromilling parameters, but this direction requires further investigation and a more in-depth study.

Although this direct method of fabricating micropatterned LGPs may not be suitable for mass production, because it requires several hours to fabricate a functional array of microstructures, the LGP prototype can be coated and used as a tool for low- to medium-sized production runs. The micromilled PMMA sample can be first coated by sputtering or evaporation, and then used as a master (positive) to produce a tool insert (negative) by electroforming. The electroformed tool insert would consist of a thin activation layer and a thicker wear-resistant layer of nickel (or nickel alloys). After electroforming and postproduction machining,[12] the master can be used for part replication through injection molding.

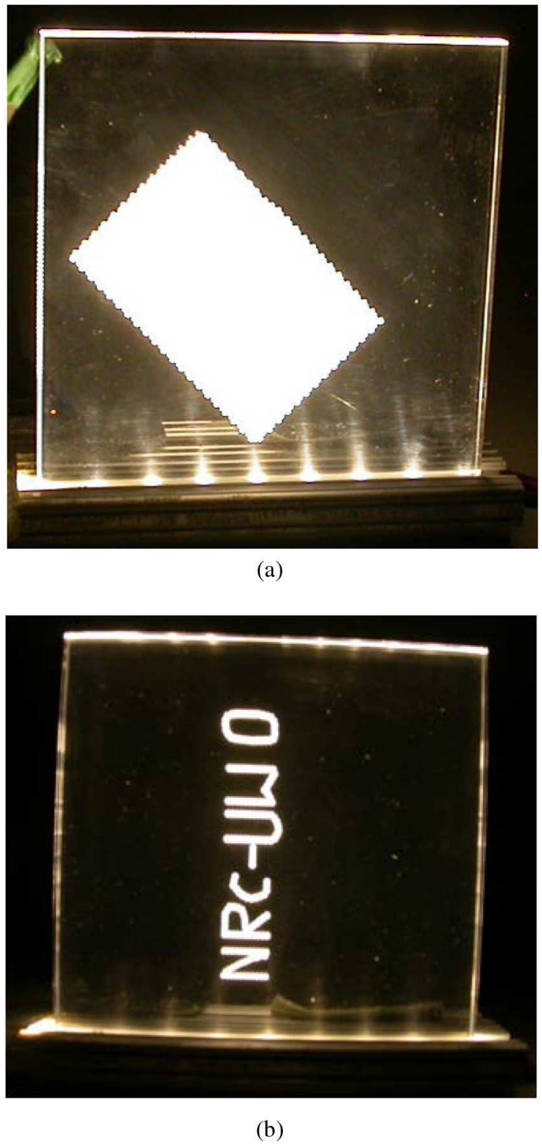


Fig. 14 Illumination results for a ($100 \times 100 \times 6$ mm^3) LGP with predefined MOS patterns. (a) Uniform illumination over selected region near the center of panel. (b) Illumination of the NRC-UWO logo.

6 Conclusions

The design and microfabrication of an edge-lit LGP for illumination applications was described. The basic methodology involved micromilling cylindrical micro-optical structures (MOSs) on an optically transparent plastic substrate. Through numerical simulation it was demonstrated that the depth of the individual MOSs was one of the most critical parameters for controlling the illumination pattern.

Several flat LGPs were fabricated using a micromilling operation. The micro-optical structures with a 0.5-mm radius were distributed in a hexagonal arrangement with a fixed pitch of 1 mm. The only variable was the depth of the individual micro-optical elements that comprise the hexagonal array. The experiments demonstrated that the LGP prototypes performed as predicted through simulation, and that the illumination performance of the LGP could be improved through an optimization design process. By selectively varying the depths of the microstructures in different regions of the panel it was possible to obtain near-uniform illumination across the entire panel surface. Other tests showed that it was possible to illuminate selected regions of the panel for signature lighting applications.

The proposed micromilling fabrication method can be considered a cost-effective approach to rapid prototyping functional plastic light pipes, light tubes, and light curtains with optical and semi-optical surface qualities. Another benefit over other light guide microfabrication techniques is that the 5-axis micromilling approach can produce high quality optical elements on complex 3-D free-form, (i.e., nonplanar) substrates.

Further research is necessary to transform the micromilled LGP into a production tool. As well, additional studies are necessary to explore how contoured or bent LGPs can be micromilled to produce uniform illumination. Finally, it is also necessary to explore whether the customized LGPs satisfy the Society of Automotive Engineers and Economic Commission of Europe standards for automotive lighting. The experimental findings showed that there is a strong correlation between the depth of cylindrical micro-optical structures and illumination pattern.

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