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Optimizing Light Guide Plate (LGP) Micro-Grooves and Micro-Dots Pattern using CO_2 Laser Structuring: Influence of Laser Parameters and Pattern Arrangements on Optical Performances

Raja Murfiqah Raja Mohamad Fouzy[1], Norfazilasari Yasman[1], Mohd Zairulnizam Mohd Zawawi[1,*]

[1] Faculty of Manufacturing and Mechatronics Engineering Technology, Universiti Malaysia Pahang Al-Sultan Abdullah, 26600 Pekan, Pahang, Malaysia

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ABSTRACT

This study investigates the effects of various direct CO_2 laser structuring parameters on the formation of straight parallel micro-grooves on PMMA (Polymethyl methacrylate) substrates for light guide plate (LGP) application. Key parameters examined include laser power, laser scanning speed, and number of lasers passes. Then, based on our previous work, a comparative analysis on the effect of parallel micro-grooves and micro-dots pattern of different pitch on the luminance was evaluated. Then, the study further explored the influence of different micro-dots pattern arrangements and pitch, namely Micro-dots Type I (regular grid) and Micro-dots Type II (staggered hexagonal) on the optical luminance of the LGP. The former results shows that straight parallel micro-grooves exhibit higher luminance compared to micro-dots, based on observation of the physical brightness and luminance reading. The latter revealed that that smaller micro-dots pitch sizes and staggered hexagonal arrangements enhance luminance. This study provides a useful insight in understanding the relationship of laser parameters for the formation of micro-pattern and influences of pattern arrangements in the optimization of light distribution in PMMA LGP for applications such as displays and lighting systems.

1. Introduction

A light guide plate (LGP) is a key element in many optical devices, responsible for directing and diffusing light from a source, such as LEDs, across its surface [1]. The LGP works by internally reflecting light and evenly distributing it through various microstructures etched or printed on its surface. These microstructures manipulate light paths to achieve uniform brightness across the display or device, enhancing visual performance and energy efficiency [2]. Existing methods for creating microstructures on LGP include photolithography [3-5], injection molding [6-9], screen printing [10,11], and embossing [12-15]. Each method has its benefits and drawbacks in terms of precision, cost, and scalability [16-18]. Recent advancements have highlighted the potential of laser-based

* *Corresponding author.*
E-mail address: zairulnizam@umpsa.edu.my

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techniques, particularly ultra-fast lasers and CO_2 lasers. While ultra-fast lasers offer high precision and minimal thermal effects, they are often expensive and complex to operate [19-21]. In contrast, CO_2 lasers provide a balance of cost-effectiveness, precision, and operational simplicity, making them a practical choice for fabricating microstructures on LGP [22].

On the other hands, modern diode lasers can achieve power levels of 30 W and repetition rates of up to 20 Hz, as well as simpler and more cost-effective optical setup due to the absence of mirrors and external beam alignment components. However, the superior marking performance of CO_2 lasers on our target materials justified the use of the CO_2 laser in this study. CO_2 lasers operate at a wavelength of 10.6 µm, which is highly absorbed by a wide range of polymers, enabling efficient energy transfer and superior marking quality. In contrast, diode lasers typically operate at shorter wavelengths (e.g., 450 nm to 980 nm), which are less absorbed by many polymers, resulting in lower marking contrast and effectiveness. Therefore, to achieve the desired micropattern accuracy and optical performance of our light guide plate, CO_2 laser was found to be match well with our current application and purposes.

LGP are typically made from materials such as PMMA (Polymethyl methacrylate) [23,24], polycarbonate [6,25], and glass [2,26]. Each material has unique properties that affect the performance of the LGP. PMMA is often chosen for its high optical clarity, excellent light transmittance, and ease of processing. Compared to polycarbonate, which is more impact-resistant but less transparent, and glass, which offers superior hardness but is brittle and heavy, PMMA provides an optimal balance for applications requiring lightweight, durable, and highly transparent components. Common patterns of a LGP include micro-dots [27,28], pyramid [29] and straight parallel lines [30,31]. Straight parallel lines are particularly effective in achieving uniform light distribution with high efficiency. This pattern simplifies the manufacturing process and enhances the LGP's ability to direct light uniformly across the surface, making it an ideal choice for applications that demand consistent brightness and energy efficiency.

Previous research has extensively explored the effects of CO_2 laser treatment on polymers. For instance, studies have investigated multi-pass CO_2 laser processing on PMMA and proposed CO_2 based techniques for creating microgrooves in PMMA [32-34]. These investigations examined how varying CO_2 laser parameters such laser power, laser scanning speed, and multiple lasers passes influence microgrooves dimensions such as depth and width. However, the type of micropattern on an LGP significantly influences its performance. Different type of pattern affects the way light is diffused and guided through the plate. Therefore, an understanding of microstructure shape, pitch and their arrangement is important to obtain the most optimized design of LGP microstructure.

In this study, the effects of various direct CO_2 laser structuring parameters on the formation of straight parallel on PMMA were investigated. Key parameters examined include laser power, laser scanning speed, and number of laser passes. Then, based on our previous work on fabrication of LGP with micro-dots pattern, a comparative analysis on the effect of parallel micro-grooves and micro-dots pattern pitch on luminance was evaluated. The study then further explored the influence of different micro-dots pattern arrangements and pitch, namely Micro-dots Type I (regular grid) and Micro-dots Type II (staggered hexagonal) on the optical luminance of the LGP.

2. Methodology

A commercial Davi D30 RF CO_2 laser system (Beijing Dawei Laser Technology Co., Ltd.) with a frequency range from 1 kHz to 20 kHz, maximum power of 30 W and 10.6 µm operating wavelength was used in the experiment. Figure 1 shows the schematic diagram of the direct CO_2 laser structuring experimental setup for fabrication of straight parallel micro-grooves on the PMMA substrate. The material used in the experiments was 2 mm thick PMMA substrates with dimensions of 50 mm x 40 mm, a transformation point (T_g) of 115 °C, a transmittance of 92 % and a refractive index of 1.49. Mechanical stylus surface profiler (KLA-Tencor D-100) was used to measure the depth and width of these micro-pattern cross sections. Optical luminance of the fabricated LGP with micro-pattern was measured using a luminance meter, SM208.

To determine the influence of laser power on the width and depth of microgrooves, laser powers ranging from 2 W to 10 W at 2 W intervals were used, while keeping the laser scanning speed constant at 50 mm/sec with a maximum frequency of 20 kHz. To explore the relationship between laser scanning speed and the dimensions of microgrooves, laser scanning speeds from 10 mm/sec to 120 mm/sec, with 10 mm/sec intervals, were applied while maintaining a constant laser power of 2 W. The impact of multiple laser passes on the depth and width of the microgrooves was analyzed by varying the laser passes from one to ten pass while keeping the laser power at 2 W and scanning speed at 50 mm/sec constant.

Finally, the comparative analysis on the effect of pattern type (straight parallel microgrooves and micro-dots pattern) of different pitch (pitches ranged from 0.5 mm to 2.0 mm at 0.5 mm intervals) to the optical luminance was conducted. The detail investigation on the fabrication of LGP with micro-dots pattern can be found in our previous work [28]. For this optical evaluation, the chosen parallel microgrooves were fabricated using a laser power of 2 W and a scanning speed of 50 mm/sec, while the micro-dots were formed using a laser power of 2 W and a scanning speed of 1000 mm/sec. The study then further explored the influence of different micro-dots pattern arrangements and pitch, namely Micro-dots Type I (regular grid) and Micro-dots Type II (staggered hexagonal) on the optical luminance of the LGP.

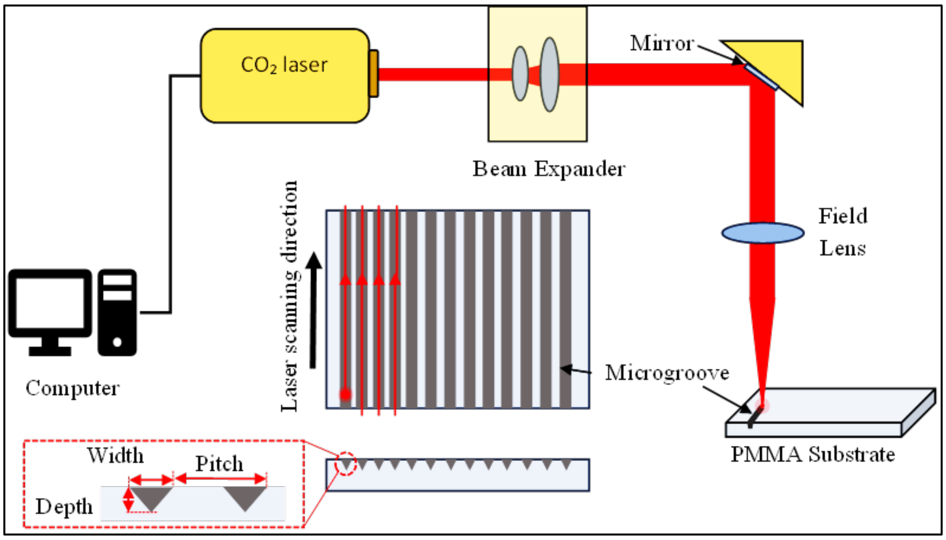


Fig. 1. Schematic diagram of the direct CO_2 laser structuring experimental setup for fabrication of straight parallel micro-grooves and micro-dots pattern on PMMA substrate

3. Results

3.1 Effect of Laser Power to the Formation of Straight Parallel Microgroove Width and Depth on PMMA Substrate

Figure 2 shows the 2-D cross-sections of the microgrooves observed using a surface profiler. Analysis of the cross-sections reveals a proportional relationship between laser power to the width and depth of the straight parallel microgroove. For instance, at a laser power of 2 W, the microgroove exhibited width of 300 µm and depth of 60.345 µm. In contrast, at a higher laser power of 10 W, the width increased by approximately 108 µm, reaching 408 µm and the depth increased by about 102.327 µm, reaching 162.672 µm. The increase in microgroove width and depth can be attributed to the higher laser energy intensity and density striking the surface of the substrate [35,36]. At laser power of 4 W and 6 W, an interesting observation was made, in which the width of both microgrooves remained almost unchanged at approximately 306 µm. This can be attributed to an excessive amount swelling on the top surface, induced by the formation of a softened zone, often referred to as HAZ around the microgroove. This softened material undergoes swelling or expansion, affecting the overall dimensions of the microgroove. This swelling at the surface of the substrate contributes to the unexpected reduction in width [37]. Note that the cross-sectional shape of the parallel microgrooves was also influenced by the TEM_{00} mode RF-pumped CO_2 laser used in the study which produces a Gaussian beam profile. The laser energy density gradually decreasing from the centre of the beam spot to both ends. However, the shape of the microgrooves was consistent, and we did not observe significant distortions or irregularities in the microstructure due to the transverse mode.

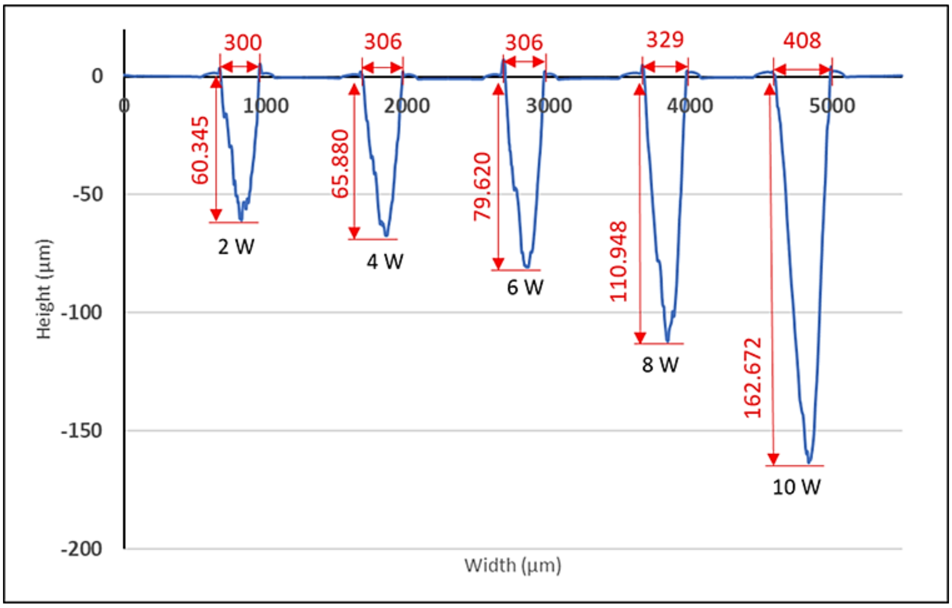


Fig. 2. 2-D cross-section view of straight parallel microgrooves obtained under a constant laser scanning speed of 50 mm/sec. These microgrooves were fabricated with various laser powers, ranging from 2 W (left) to 10 W (right) with interval of 2 W

3.2 Effect of Laser Scanning Speed to the Formation of Straight Parallel Microgroove Width and Depth on PMMA Substrate

Figure 3 shows the 2-D cross section of the straight parallel microgroove observed using surface profiler. From the cross-section, the formation of bulge was noticed at lower scanning speeds, approximately between 10 mm/sec to 40 mm/sec as well as at higher laser scanning speeds, ranging from 90 mm/sec to 120 mm/sec. At higher laser scanning speeds, such as 120 mm/sec, the increased speed may lead to insufficient energy deposition and reduced material melting causing irregularities in the microgroove profile. On the other hand, at low scanning speeds, around 10 mm/sec, prolonged exposure to the laser may result in excessive energy absorption and material accumulation, leading to observed bulge. Interestingly, the bulges are absent at the optimal laser scanning speed, which falls within the range of 60 mm/sec to 80 mm/sec. The absence of bulge is attributed to the optimal laser scanning speed facilitating high spot overlapping and providing better control material removal without causing bulging effect [38].

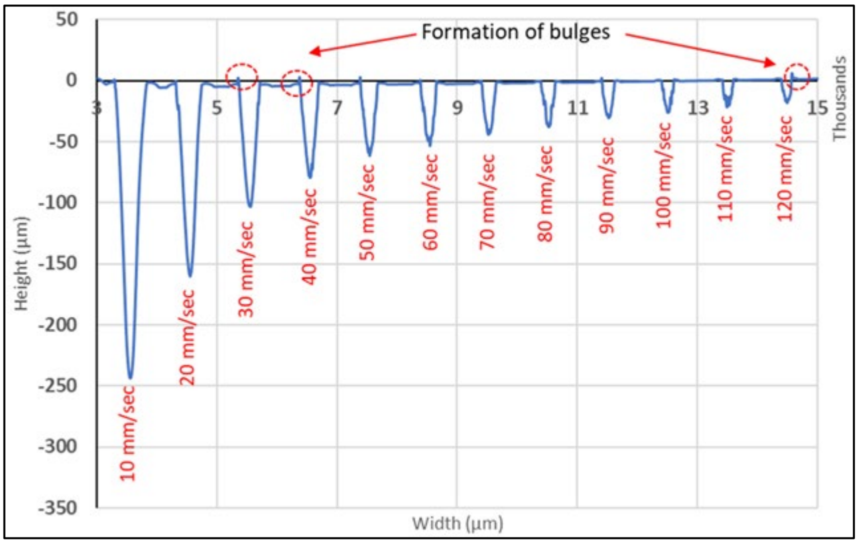
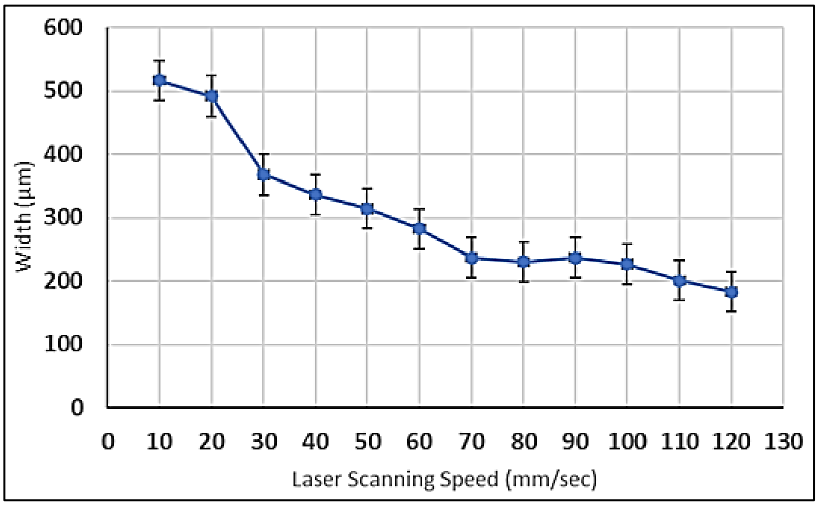
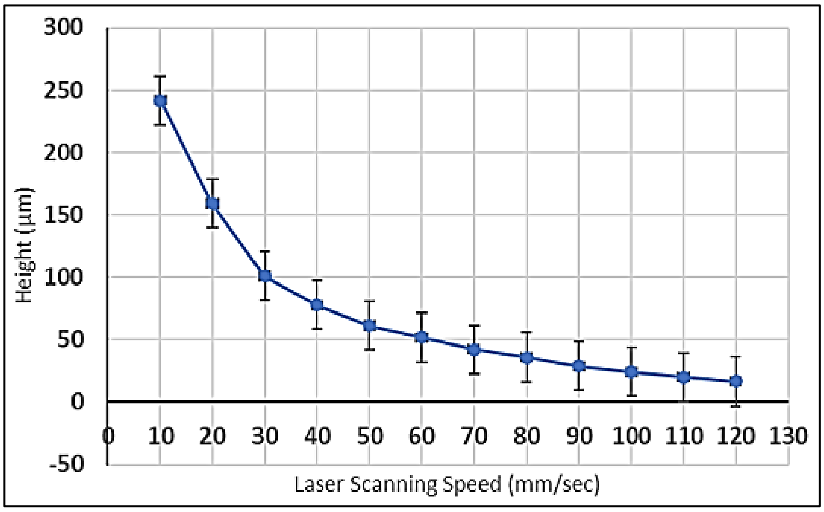


Fig. 3. 2-D cross-sections of straight parallel microgrooves fabricated with a constant laser power of 2W. Various laser scanning speeds were applied, ranging from 10 mm/sec (left) to 120 mm/sec (right) with intervals of 10 mm/sec

Figure 4 shows the effect of laser scanning speed on both width and depth of straight parallel microgrooves. From the graph, it can be concluded that the laser scanning speed is inversely proportional to the width and depth of the microgrooves. As the laser scanning speed increases, the width and depth of the microgroove decreases. For instance, at a slower laser scanning speed of 10 mm/sec, the width and depth of the microgroove were measured at 516.463 µm and 241.836 µm, respectively. Conversely, at a higher laser scanning speed of 70 mm/sec, the width and depth of the microgroove decreased to 321.958 µm and 59.224 µm, respectively. This observation is aligned with the result from previous studies [39,40].



(a)



(b)

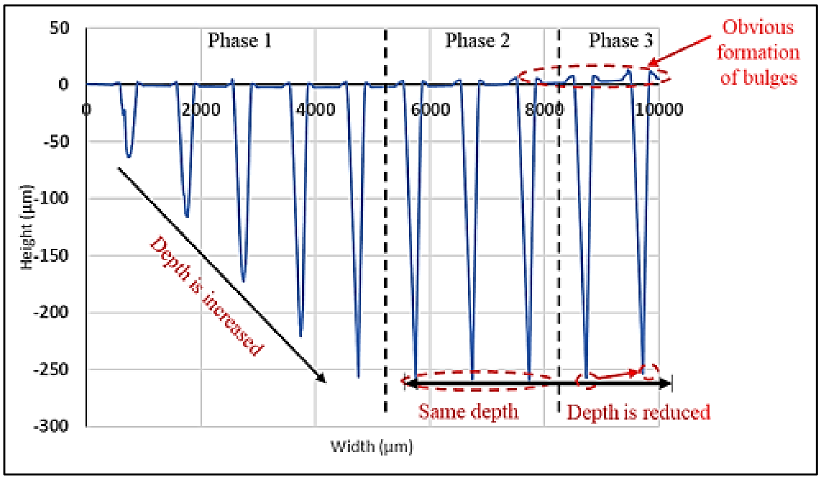
Fig. 4. The effect of laser scanning speed to the formation of the straight parallel microgroove as measured by surface profiler (a) Width (b) Depth

The observed reduction in microgroove dimensions at higher laser scanning speed can be attributed to the limited exposure time of the substrate surface to the laser beam. When the laser scanning speed is increased, the laser beam spends less time interacting with the substrate, leading to a shorter duration energy deposition. This shortened interaction time affects the material removal process, resulting in shallower and narrower microgroove [41]. The minimum width and depth achieved during the experiment were measured at 183.07 µm and 16.564 µm, respectively.

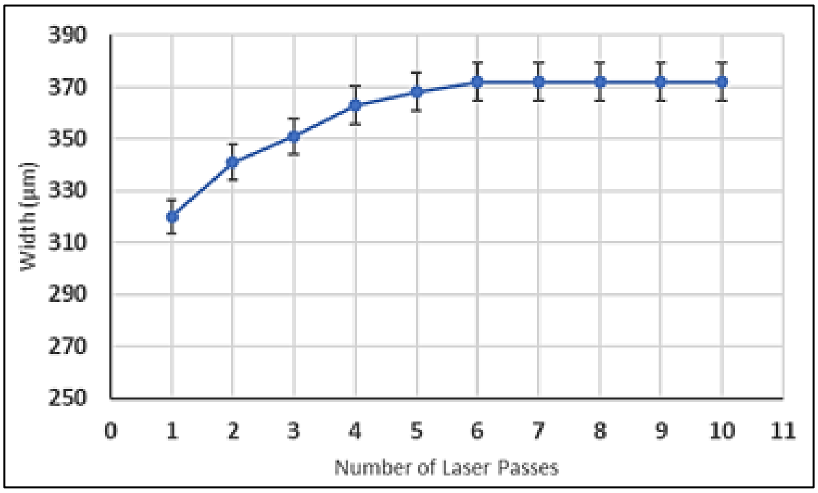
3.3 Effect of Multiple Laser Passes to the Formation of Straight Parallel Microgroove Width and Depth on PMMA Substrate

Figure 5(a) shows the 2-D cross-section profiles of the straight parallel microgrooves observed through a surface profiler. From the observation, each microgrooves exhibit different levels of depth, and they can be categories into three phases: phase 1, phase 2 and phase 3. In phase 1, the figure shows an increasing multiple laser passes that are proportional to the depth of the microgrooves. As more laser passes are applied, the depth of the microgrooves become deeper. This trend could be observed from a single laser pass to the fifth laser pass.

The observed phenomenon of the increasing microgrooves depth with the increasing multiple laser passes can be attributed to the cumulative material removal. In phase 1, the initial laser pass initiates the modification process, causing a slight depth increase. For instance, Figure 5(c) shows the depth of the single pass was increased from a minimum depth of 62.615 µm to a maximum depth of 254.052 µm of fifth laser passes. The increasing of the depth of the microgrooves is due to laser energy density absorbed during each pass contributes to localized heating, leading to further material ablation and has potential to re-crystallization or restructuring of the microgroove walls. This will lead to a consistently deepening of the microgrooves. A similar trend is observed in the width of the microgrooves, as depicted in Figure 5(b), showing an increase in width from a minimum of 320 µm in a single pass to a maximum width of 372 µm after the sixth laser pass.



(a)



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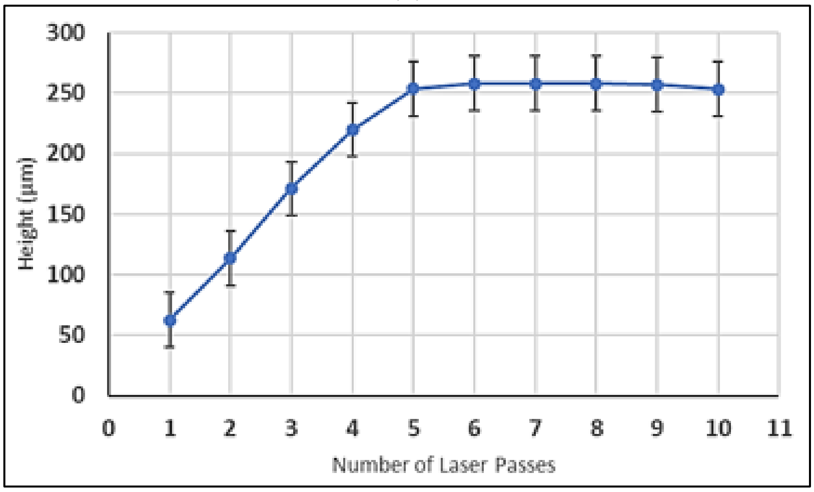


(c)

Fig. 5. The image displays (a) 2-D cross-section profiles of straight parallel microgrooves under a constant laser power of 2 W and laser scanning speed of 50 mm/sec. The number laser passes were varied from a single pass (left) to ten laser passes (right), respectively. The effect of the multiple laser passes on both the (b) width and (c) depth of the microgrooves was observed using a surface profiler, respectively

In the second phase, the microgrooves exhibit a consistent depth from the sixth to the eighth laser passes. For instance, Figure 5(c) shows that the depth of the microgroove during the sixth to eighth laser passes remained constant at 258.095 µm. Notably, starting from the second laser pass onward, the laser beam was no longer hits the focal point. This occurs because it moves onto an ablated surface, leading to defocusing of the incident laser beam on the subsequent surface to be ablated. Consequently, there is an increase in depth as shown in the first laser pass to the fifth laser passes. However, at certain point, the microgroove depth stabilizes, as the laser beam cannot reach the ablated surface anymore. This limitation arises from the fixed focal length of the laser beam employed in this experiment [32,36]. To achieve a deeper microgroove depth, it is suggested to decrease the focal length, ensuring that the laser beam remains focused and can reach the bottom surface of the ablated microgroove.

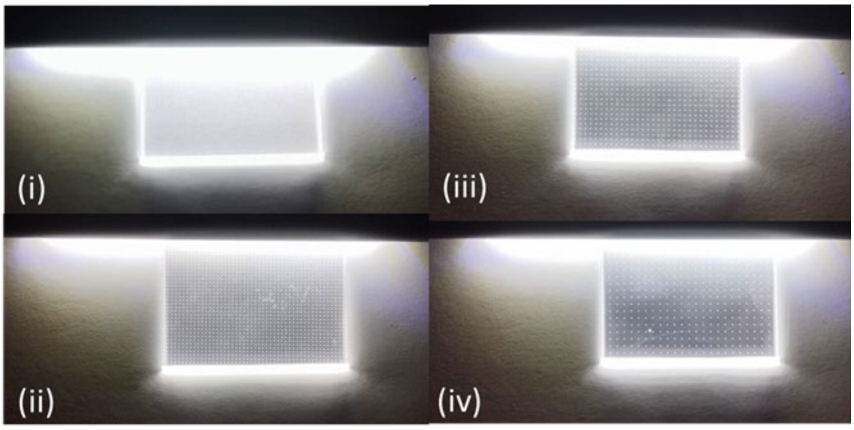
In the third phase, a reduction in depth was observed from the ninth to the tenth laser passes was observed. This intriguing phenomenon is to a result of the formation of a small amount of swelling on the top of the substrate surface. The swelling is attributed to the HAZ, which forms due to the low-energy region of the laser spot. The substantial presence of HAZ also contributes to the formation of a bulge around the microgrooves, as observed by the surface profiler. The bulge formation leads to a reduction in depth. Notably, a similar phenomenon has been reported in a previous study [37].

From the observation, the higher multiple laser passes also resulted in an increase of the formation of bulges. The formation of bulges could be attributed to the reduction in polymer density during the laser ablation process. This reduction in density, especially with increasing multiple laser passes, can result in uneven heating or removal of the material, causing certain areas to become less dense. Consequently, bulges may form on the surface of the substrate [42].

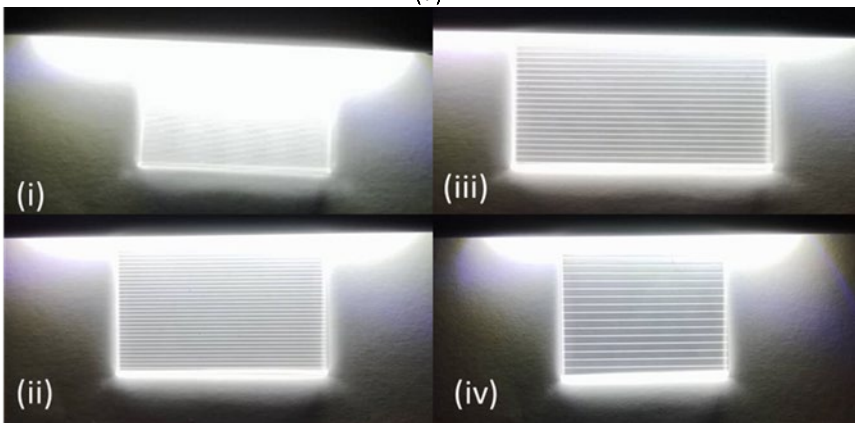
3.4 Effect on Different Pitch of Micro-Dots and Straight Parallel Microgroove on Luminance: A Comparative Analysis

In this experiment, two types of micropatterns were employed, featuring the micro-dots and straight parallel microgroove were employed. The micro-dots pattern was fabricated using a laser power of 2 W and a laser scanning speed of 1000 mm/sec, while the straight parallel microgrooves were fabricated using 2 W and 50 mm/sec. The dimensions of the micro-dots were 228.072 µm in diameter and 33.557 µm in width and 61.224 µm in depth. The average luminance (cd/m^2) of the micropatterns was measured across different pitches, ranging from 0.5 mm to 2.0 mm at interval of 0.5 mm. A single LED light source was strategically positioned at the edge of the LGP, and the average luminance readings were measured using a luminance meter, SM208. This experimental design aimed to explore how variations in pitch size could impact the propagation of light and enhance the overall luminance of the LGP.

Figure 6 shows the results of observation of the physical brightness of micro-dots and straight parallel microgroove LGP with varying pitches: 0.5 mm, 1.0 mm, 1.5 mm and 2.0 mm. The observation reveals that the LGP with a pitch of 0.5 mm exhibits the highest brightness, followed by 1.0 mm, 1.5 mm and 2.0 mm pitches. Although the LGP being constructed from transparent PMMA, certain areas exhibit dark regions, particularly noticeable in micro-dots LGP with pitches of 1.5 mm and 2.0 mm and straight parallel microgroove LGP with pitch 2.0 mm. This phenomenon may be attributed to specific regions within the LGP that do not effectively propagate the light source [43]. Possible factors contributing to these dark regions include variations in micropatterns uniformity, light scattering or internal reflections.



(a)



(b)

Fig. 6. Observation of the physical brightness of microgroove LGP with different pitches of (i) 0.5 mm, (ii) 1.0 mm, (iii) 1.5 mm and (iv) 2.0 mm (a) Micro-dots (b) Straight parallel

Figure 7 shows the comparison of luminance readings between two different types of micropatterns (micro-dots and straight parallel microgrooves) across different pitch sizes, ranging from 0.5 mm to 2.0 mm. From graph, it was observed that straight parallel microgrooves exhibit higher luminance compared to micro-dots. For instance, at a small pitch of 0.5 mm, the average luminance reading for straight parallel microgroove is slightly higher at 1757.67 cd/m^2, while micro-dots show an average luminance of 1730.26 cd/m^2.

In a related study, V-microgroove micropattern was preferred due to its simplicity and ease of design, making them more straightforward to fabricate. These micropatterns also demonstrated high brightness near the side where the light enters the LGP, creating a concentrated and bright region [44]. However, it is important to note that despite the high luminance readings, this design has a drawback, which the light distribution becomes weaker as it moves across the LGP surface away from the entrance side. This is because of the total internal reflection (TIR) effects. The luminance reading of the micro-dots was lower than straight parallel microgroove due to the micro-dots having a smaller surface area compared to straight parallel microgrooves. This could result in less total light emission, leading to a lower luminance reading.

Additionally, the shape and arrangement of micro-dots may lead to more light scattering compared to the more directional path of straight parallel microgrooves. Increased light scattering can result in a diffused distribution, potentially reduced luminance. The influence of pitch sizes on average luminance was also observed. For instance, at a small pitch size of 0.5 mm, both micro-dots and straight parallel microgrooves exhibited high luminance readings, which is 1757.67 cd/m^2 and

1730.26 cd/m^2, respectively. In contrast, at a larger pitch size of 2.0 mm, the luminance readings for both micro-dots and straight parallel microgrooves decreased by approximately ± 800 cd/m^2 and ± 1000 cd/m^2, which the value is 939.81 cd/m^2 and 628.58 cd/m^2.

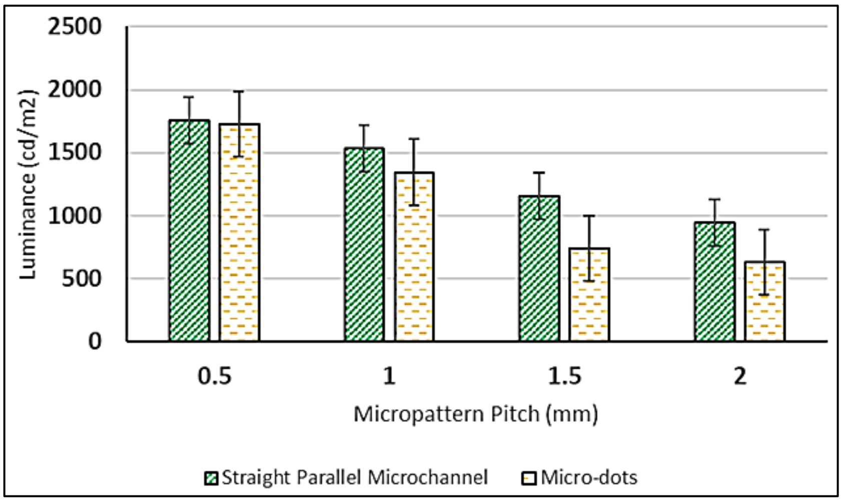


Fig. 7. Effect of different micropatterns, namely micro-dotsand straight parallel microgrooves, with varying pitches of 0.5 mm, 1.0 mm, 1.5 mm and 2 mm on luminance

The reduction in luminance with larger pitch sizes can be attributed to the fact that the micropatterns cover more surface area of the LGP at a smaller pitch size compared to a larger pitch size. This increased coverage at smaller pitches contributes to a more efficient utilization of light. Conversely, larger pitch sizes result a greater surface area of the LGP being covered by fewer patterns, potentially leading to a slowdown in the growth of light utilization [29]. Additionally, the larger surface coverage at smaller pitch sizes may also result in higher material loss within the LGP. This was related to degradation of the mechanical strength of the LGP. Moreover, higher pitch sizes may impact the total reflectance of the LGP, potentially affecting the overall illuminating brightness [45]. In conclusion, it is essential to consider the pitch size factor to fabricate LGP.

3.5 Effect of Different Pitch of Different Micro-Dots Arrangement on Optical Luminance

This section investigates the luminance effects of two different types of micro-dots arrangements, labelled as Type I and Type II (as shown as Figure 8), with varying pitches to understand their optical impact. Micro-dots Type I are arranged in a regular grid pattern (Figure 8: left), while Micro-dots Type II are staggered in a hexagonal or brick pattern (Figure 8: right). Figure 8 presents a top-view image of the micro-dots pattern with a pitch of 0.5 mm obtained from a 3-D LSCM. The figure highlights that the x-axis and y-axis pitches must be similar, even for the hexagonal pattern. The pitches of these micro-dot's arrangements range from 0.5 mm to 2.0 mm in 0.5 mm increments. Both micro-dots patterns were fabricated using a laser power of 2 W and a laser scanning speed of 1000 mm/sec. Each micro-dots have dimensions of 228.072 µm in diameter and 33.557 µm in depth. A single LED light source was strategically positioned at the edge of the LGP, and the average luminance readings were measured using a luminance meter, model SM208. This experimental design aims to explore how variations in pitch size and micro-dots arrangements affect light propagation and potentially enhance the overall luminance of LGP.

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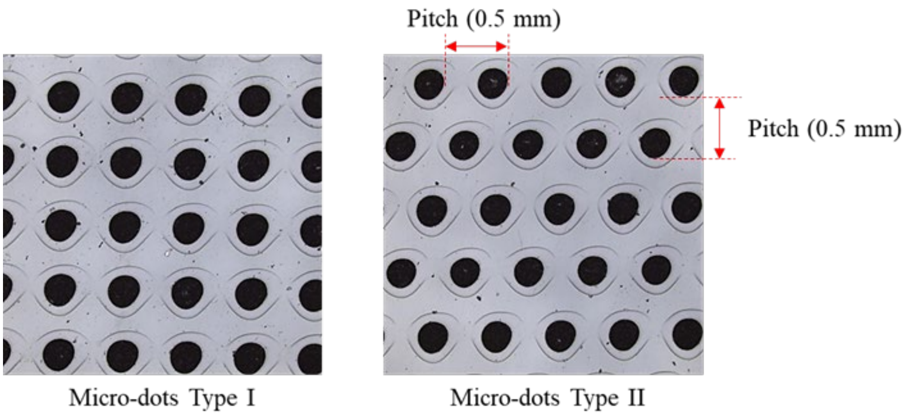

Fig. 8. Top-view image of micro-dots arrangements using 3-D LSCM with a pitch of 0.5 mm

Figure 9 shows the result observation of the physical brightness of both type of arrangements with different pitches. The observation reveals that LGP with a smaller pitch of 0.5 mm exhibits the highest optical luminance for both patterns, followed by 1.0 mm, 1.5 mm and 2.0 mm. The reduction in luminance with larger pitch sizes can be attributed to the fact that the micropatterns cover more surface area of the LGP at a smaller pitch size compared to a larger pitch size. This increased coverage at smaller pitches contributes to a more efficient utilization of light. Conversely, larger pitch sizes result a greater surface area of the LGP being covered by fewer patterns, potentially leading to a slowdown in the growth of light utilization [29]. Additionally, the larger surface coverage at smaller pitch sizes may also result in higher material loss within the LGP. This was related to degradation of the mechanical strength of the LGP [44]. Moreover, higher pitch sizes may impact the total reflectance of the LGP, potentially affecting the overall illuminating brightness [45]. In conclusion, it is essential to consider the pitch size factor to fabricate LGP. It was found that Micro-dots Type II arrangements generally provide better optical performance compared to Micro-dots Type I. This is due to its ability to scatter light more uniformly and reduce localized light intensity peaks. This uniform scattering is achieved because the staggered hexagonal pattern of Micro-dots Type II allows light to be distributed more evenly across the LGP.

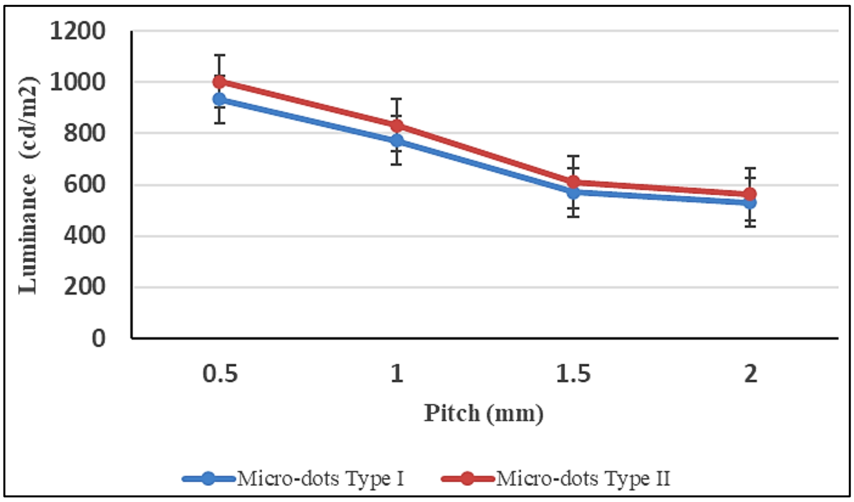

Fig. 9. Effect of different arrangement of micropatterns, namely Micro-dots Type I and Micro-dots Type II, with varying pitches of 0.5 mm, 1.0 mm, 1.5 mm and 2 mm on optical luminance

In contrast, the regular grid pattern of Micro-dots Type I can create areas where light intensity is higher, leading to non-uniform luminance. The staggered arrangement in Type II minimizes the overlap of light rays, ensuring that light is not concentrated in specific regions. This reduction in localized intensity peaks prevents the formation of bright spots, resulting in a smoother and more consistent luminance across the LGP surface. Additionally, the staggered arrangement allows for better diffusion of light, enhancing the overall optical efficiency of the LGP. Moreover, the increased optical performance of Micro-dots Type II can be attributed to the higher surface coverage achieved with this pattern. The hexagonal configuration ensures that the light interacts with a greater number of micro-dots, leading to more effective light extraction and distribution. This pattern also maximizes the use of light emitted from the LED source, improving the luminance efficiency of the LGP.

Furthermore, the enhanced scattering effect of Micro-dots Type II can reduce the loss of light due to internal reflections. By minimizing these losses, the staggered pattern helps maintain higher luminance levels even at larger pitches. This characteristic is particularly beneficial for applications where consistent and high-quality lighting is crucial.

4. Conclusions

This study has demonstrated the significant influences of CO_2 laser parameters on the formation of microgrooves in PMMA substrates. The investigation revealed that both laser power and scanning speed play crucial roles in determining the dimensions of the microgrooves. The use of higher laser power, combined with lower scanning speed allowed for more laser energy density and prolonged interaction between the laser beam and the material, resulting in deeper and wider grooves. Multiple lasers pass further enhanced microgroove dimensions, with the greatest increases occurring up to five passes; additional passes beyond this point showed diminishing returns due to factors such as heat-affected zone expansion and material swelling. Straight parallel micro-grooves were found to exhibit higher luminance compared to micro-dots, based on observation of the physical brightness and luminance reading.

Finally, it was observed that smaller micro-dots pitch sizes and staggered hexagonal arrangements enhance luminance. Overall, this study provides a useful insight in understanding the relationship of laser parameters for the formation of micro-pattern and influences of pattern type and arrangements in the optimization of light distribution in PMMA LGP for applications such as displays and lighting systems.

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