

Ultrafast UV Laser Trimming Process Characteristics Analysis for Flexible Display Panels

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Abstract

This study investigates the laser trimming characteristics of ultraviolet (UV) and deep UV pulse lasers for processing multilayer display panels. The influence of pulse laser parameters, including pulse duration and wavelength, on trimming quality and thermal effects was analyzed by measuring cutting profiles and ablation efficiency. Experimental results reveal that trimming quality and efficiency in multilayer display panels are significantly affected by laser parameters. In particular, the interfaces between layers are highly influenced by differences in optical properties, optical field distribution and thermal characteristics, with layer-specific optical absorbance playing a critical role in adhesion quality. These findings highlight the importance of optimizing laser parameters to enhance ablation quality in multilayer structures. This study provides insights into the mechanisms of multilayer laser trimming, offering guidance for determining optimal conditions for advanced display panel micromachining and improving the quality of laser trimming for cutting-edge technologies.

Author Keywords

Flexible display; OLED; Laser trimming; Display panel trimming; Ablation; Ultra-fast pulse laser; Deep UV;

1. Introduction

The demand for producing sub-micrometer features with high speed and low cost is critical in the manufacturing of advanced devices, such as flexible display panels and semiconductors. However, conventional machining methods are often inadequate due to the intricate geometries, unusual dimensions, and complex material properties of these devices. The emergence of advanced engineering materials has further highlighted the limitations of traditional machining techniques. Among modern methods, laser trimming has become one of the most widely used machining technologies for display shape processing. This technique offers several advantages, including high production speed, flexibility, non-contact processing, and the elimination of the need for specific fixtures [1, 2]. Despite its versatility, the quality of laser trimming is highly sensitive to process parameters, such as laser power and scan velocity, which significantly influence the precision and overall outcome of the process [3-5].

The most common approach to laser-based micromachining is high-power laser trimming, which focuses intense thermal energy onto a specific area of the material, melting and removing it with the aid of a covering gas. However, this method can result in undesirable thermal effects, including the formation of a heat-affected zone (HAZ), which can compromise the surrounding material and reduce overall processing quality [6, 7].

Furthermore, in multilayer structures, the high temperatures generated by a tightly focused laser beam can severely impact the adhesion characteristics at the polymer interfaces within the laser-

affected area. To overcome these challenges, ultrafast pulsed lasers, such as UV pulse lasers, have emerged as an effective solution. By employing short pulse durations, these lasers enable direct sublimation of materials into the gas phase, minimizing thermal diffusion into the bulk material. Unlike conventional thermal processes, laser ablation trimming is predominantly influenced by the optical properties of the materials, enabling precise material removal with minimal thermal penetration depth [8-10]. UV laser ablation is particularly advantageous for processing polymers and display panels, owing to its high absorption efficiency and ability to achieve precise material removal. Despite the progress in UV pulse laser applications, a comprehensive study addressing the unique characteristics of flexible display panel trimming using short-pulsed UV lasers has not yet been explored. Particularly for multi layered flexible display panels, each layer exhibits distinct optical and thermal characteristics. When laser pulses interact with such structures, these differences significantly affect the optical field distribution and thermal behavior within and across the layers, ultimately influencing the quality of the trimming process.

In this study, we aim to address these challenges through a systematic investigation. Specifically, the research focuses on the following objectives: (1) Analysis of thermal effects in multilayer flexible display panels during laser trimming. (2) Evaluation of laser pulse duration and peak pulse power dependencies in trimming. (3) Investigation of deep UV laser applications for flexible display panel processing. By examining the interaction mechanisms of UV pulse lasers, this research seeks to establish optimal trimming conditions and advance flexible display manufacturing technologies.

2. METHODS AND MATERIALS

(a) Numerical calculation

To elucidate field distribution in a polymer layer, numerical calculation was performed using the FDTD method. This method has previously been used to successfully explain near-field optical characteristics [11]. The FDTD simulation method adopts a focused Gaussian beam incident wave.

(b) Optical Set-up

The optical setup illustrated in Fig. 1 employs a UV and deep UV pulse laser ($\lambda = 355, 266$ nm, Coherent, PA USA) as the light source. The laser beam reflects on mirrors 1-4 and then traverses a quarter wave plate that is used for adjusting the circular polarization. Then, the beam enters an X-Y scanning galvanometer (AGV-14HPO, Aerotech, PA USA) with flat field f-theta lens to produce a nearly perfect focusing system. The processing specimen was mounted on a precision 2-axis (x, y) motion control system (PRO280LM, Aerotech), allowing accurate positioning of the specimen surface in the laser's focus.

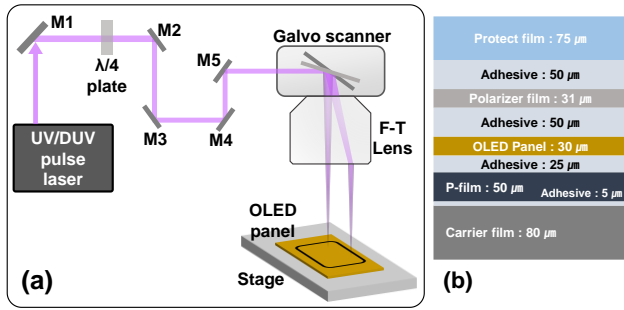


Figure 1. (a) Illustration of the optical set-up used for laser trimming. M: Mirror, SHG: Second harmonic generator, THG: Third harmonic generator, G-X, Y: Galvanometer X and Y, QWP: Quarter wave plate. (b) Schematic of multi-layer display panel specimens.

3. Result

(a) Evaluating thermal effect in laser trimming

To confirm the laser trimming characteristics and quality under different laser parameters, a series of laser trimming experiments were conducted. While keeping the laser power constant, we varied the laser frequency, which in turn affected both the pulse peak power and the overlap rate. Specifically, the laser power and scan speed were held constant, while the laser pulse frequency was adjusted to different values: 100, 40, and 1000 kHz. Although the total energy delivered to the display panels remained consistent across all conditions, changes in the laser fluence and overlap rate were observed, as described in Equation (1).

$$\text{Fluence}(\text{J}/\text{cm}^2) = \frac{\text{Laser power (W)}}{\text{Frequency (Hz)} \cdot \text{Laser spot area (cm}^2\text{)}} \quad (1)$$

The laser beam size was measured using a beam profiler, resulting in a beam diameter of 32 μm . The fluence values for each frequency condition are 6.21, 1.55, 0.62 J/cm^2 .

To study the effect of laser fluence on processing, we fixed the laser power and speed at 5 W and 300 mm/s, respectively. Additionally, different frequency divider values were applied to each frequency condition to ensure that the pulse-to-pulse distance remained fixed at 100 μm .

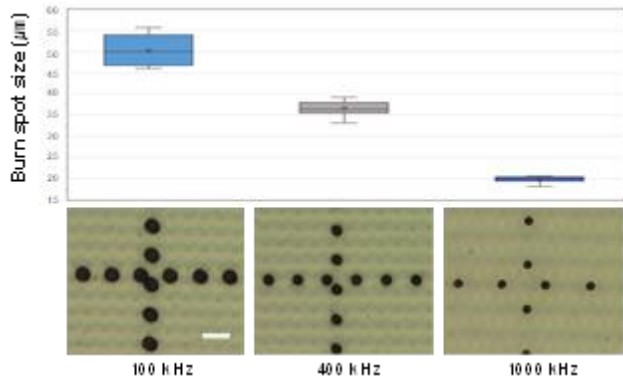


Figure 2. Laser burn spots for different frequencies: 100, 400 and 1000 kHz (Scale bar = 100 μm). The laser burn spot size was measured 53.1, 37.8 and 20.1 μm respective conditions.

The laser burn spot size was measured, and images were captured for each condition, using the same laser power and scan speed but varying frequency. The resulting burn spot images are shown in Fig. 2. These experimental results demonstrate how varying the laser frequency affects the fluence, overlap rate, and ultimately, the processing characteristics of the display panels. Further

analysis of these results will help in optimizing laser parameters for improved processing quality.

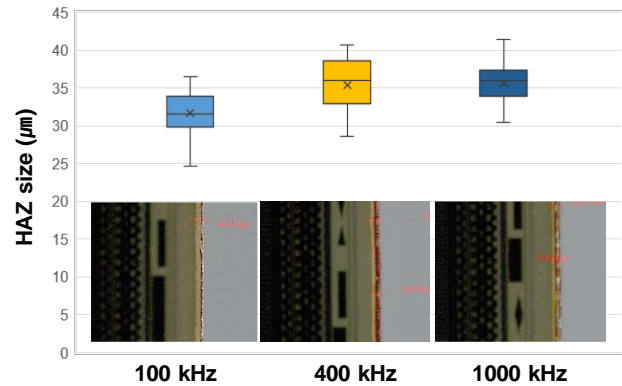


Figure 3. Measured HAZ Values at Fixed Laser Power and Scan Speed with Varying Frequencies.

Flexible OLED panels were trimmed, and the heat-affected zone (HAZ) was measured, as shown in Fig. 3. The laser power and scan speed were kept constant while varying the frequency to 100, 400, and 1000 kHz. The HAZ values measured were 31.6 μm , 35.4 μm , and 35.6 μm , respectively. These results indicate that higher frequencies slightly increase the HAZ value, but the difference is only 12.6%. This suggests that under consistent energy conditions, the HAZ outputs are nearly identical.

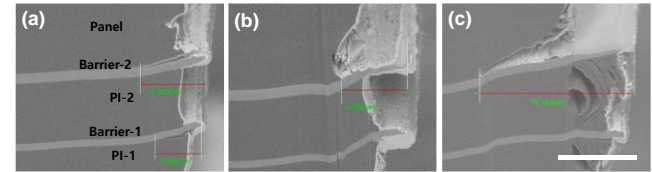


Figure 4. FIB Images Post Laser Trimming at Varying Frequencies. Laser Frequency: (A) 100 kHz, (B) 400 kHz, and (C) 1000 kHz. Scale bar = 5 μm .

The FIB results reveal a significant impact of frequency on trimming profile quality, as detailed in Figure 4. At high frequencies (1000 kHz), noticeable damage to the panel area occurs compared to lower frequency cases. Specifically, detachment of the polyimide (PI) layer from the display panel is more pronounced at 1000 kHz (10.16 μm), while detachment at 100 kHz and 400 kHz conditions measures 4.25 μm and 4.336 μm , respectively. This detachment could serve as a precursor to display panel damage from external impacts, emphasizing the need for optimized laser frequency to mitigate such risks.

The frequency dependence of trimming quality is primarily influenced by thermal effects, as thermal conditions significantly impact the adhesiveness of the various display panel layers. The temperature and heat generated during the laser process can be calculated equation 2, with the results shown in Fig. 5.

$$\sum_{N=1}^{N_p} \Delta T(t, N) = \frac{Q}{r \cdot c_p \cdot \sqrt{(4 \cdot p \cdot k)^3}} \sum_{N=1}^{N_p} \frac{\left[\frac{t - N-1}{f_L} \right]}{\left(\frac{t - N-1}{f_L} \right)^3} e^{-\frac{1 \cdot r^2}{t \cdot 4 \cdot k}} \quad (2)$$

Q = Pulse energy (J), p = density, c_p = thermal capacity, λ_{th} = thermal conductivity of adhesive, t = time (second), r = distance (m), f_L = laser frequency, $N = N_{th}$ laser pulse, $[x]$ = step function.

From the calculation results, it is evident that even under the same laser energy conditions, higher frequencies result in additional heat due to heat accumulation. For instance, at 1000 kHz, the laser

frequency condition generates approximately 40% higher temperatures compared to the 100 kHz condition. This thermal disparity on the display panel causes adhesion transitions at the interface of the adhesive layers. These transitions were experimentally analyzed, confirming the relationship between laser frequency, thermal effects, and trimming quality.

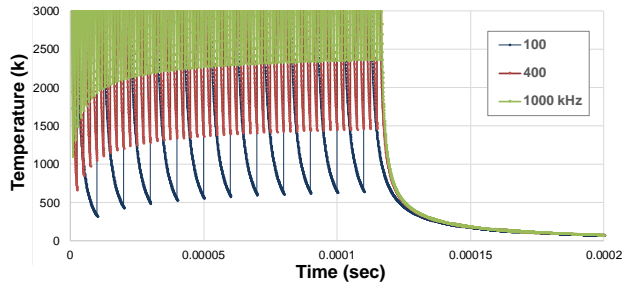


Figure 5. Temperature trend calculation graph of the PET layer when vary the laser frequency to 100, 400 and 1000 kHz under the same conditions of laser processing power and scan speed.

(b) Laser trimming analysis with laser pulse duration

Typically, the ablation efficiency of a pulse laser is proportional to its peak power. Therefore, a shorter pulse duration can increase the ablation efficiency while reducing the thermal effects on the material. To experimentally investigate the impact of pulse duration on the quality and efficiency of laser processing in display panel trimming, we compared two laser systems: one with an 8 pico second (ps) pulse duration and the other with an 850 femto second (fs) pulse duration. Both systems were operated under identical conditions of laser power and scan speed. After processing, the trimming profile was analyzed across the various layers of the display panel. The results showed that for polymer layers such as PET and adhesive, which have low melting points, higher frequency and ps laser conditions led to relatively improved trimming performance due to the higher heat generation. In contrast, for the display panel layers made of PI, which has a higher melting point and greater heat capacity, the opposite trend was observed.

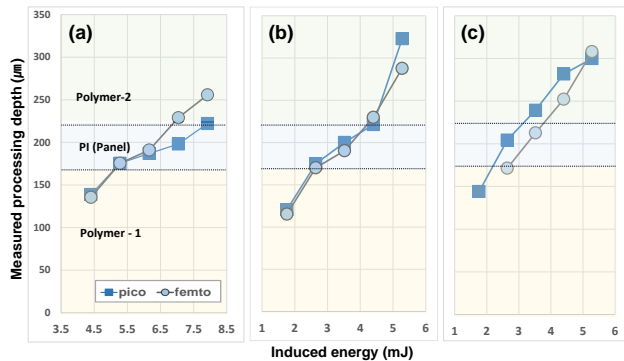


Figure 6. Analysis of processing depth based on induced optical energy for different laser frequencies (a) 100 (b) 400 and (c) 1000 kHz with fixed laser power, scan speed and laser spot diameter.

To completely cut the panel under conditions of a total energy of 0.44 mJ per laser pass and a frequency of 100 kHz. The ps laser required a total energy of 3.08 mJ. In contrast, the fs laser achieved complete trimming with only 2.2 mJ. A similar trend was observed under the 400 kHz condition, where increased overlap rates and additional heat generation (due to lower pulse peak power) were evident. For complete panel trimming at 400 kHz: The ps laser required 2.2 mJ however fs laser required only

1.76 mJ. At a frequency of 1000 kHz, where the pulse peak power is lower and the overlap rate is significantly higher, it was observed that the ps laser achieved complete panel trimming with a total energy of just 0.88 mJ and the fs laser required 1.32 mJ for the same result. These results suggest that at 1000 kHz, the trimming process is primarily governed by thermal effects rather than ablation, as the increased overlap rate results in significant heat generation. This shift from ablation-driven to thermally-driven processing underscores the importance of optimizing laser parameters to balance processing efficiency with the potential for thermal damage to the panel structure. These 100, 400 kHz results highlight the improved processing efficiency of the fs laser, attributed to its higher ablation efficiency. The ability to achieve trimming with reduced energy demonstrates decreased total energy input and thermal effects, leading to improved processing quality and reduced damage to the panel.

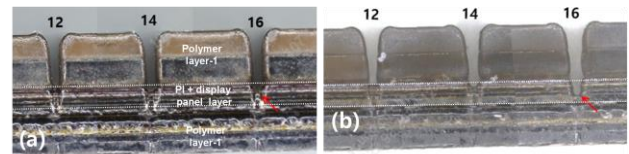


Figure 8. With a laser frequency 100 kHz and fixed laser power, scan speed. The laser energy per scan is 0.44 mJ. The cross-sectional images of the panel trimming after varying the number of scans is shown for (a) ps (b) fs lasers. Scale bar = 100 μm .

To further analyze the machinability of the panel, we magnified the cross-sectional images of the regions marked with red arrows in Fig. 6(a, b) and presented them in Fig. 7 for a detailed comparison of laser performance. The analysis revealed that for PI layers, which have a higher melting point compared to polymer layers, the processing efficiency decreased when exposed to higher optical energy. However, when a fs laser was applied, the processing depth and efficiency increased under the same number of scans. These findings suggest that for polymer layers with relatively low melting points, the use of a fs laser, which offers higher ablation efficiency, can significantly enhance processing performance. This highlights the importance of selecting appropriate laser pulse durations tailored to the material properties for optimal laser processing efficiency in display panel applications.

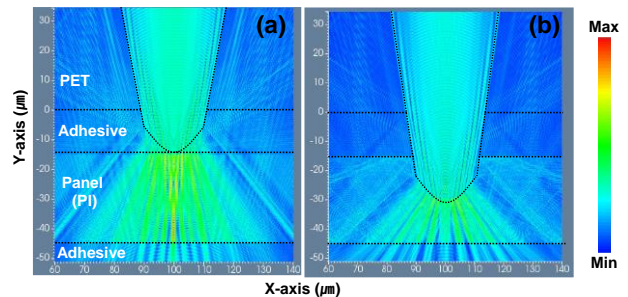


Figure 8. Field distribution calculation results when laser pulse induced display panel layers, (a) after completing the processing of the upper polymer, showing the field at the topmost part of the panel. (b) Field simulation results when the laser is applied to a partially processed panel.

Moreover, as shown in Fig. 8, field simulation results indicate that repeated processing in partially laser induced areas can localize the field within the panel region. This localization phenomenon causes physical and thermal damage to the panel, especially in repeated trimming scenarios. Especially, localized field near

panel area can transferred to thermal and relatively high thermal capacitance characteristics of PI layer can increase temperature of this area. This heat can make display panel layer weaker, therefore after laser trimming when inject outer shock like panel drop, panel take damage easily.

(c) Deep UV Laser Trimming Analysis

Additionally, the processing performance of a deep UV laser, which exhibits a high absorption rate in polymer and PI-based materials, was compared to that of UV ps and fs lasers under identical conditions. As shown in Fig. 8, the deep UV laser demonstrated relatively higher processing efficiency. Under the same energy input, the deep UV laser achieved greater processing depths compared to the UV ps and fs lasers. Moreover, the processing stagnation observed in the panel regions using the ps laser was not evident with the deep UV laser. This suggests that even at relatively lower peak pulse power, the deep UV laser exhibits improved ablation efficiency.

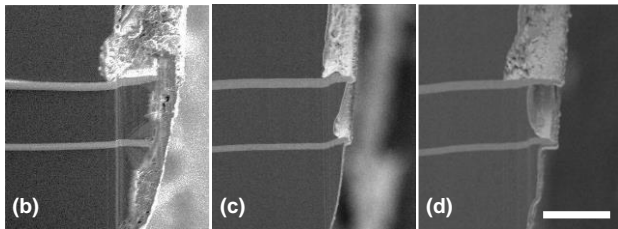
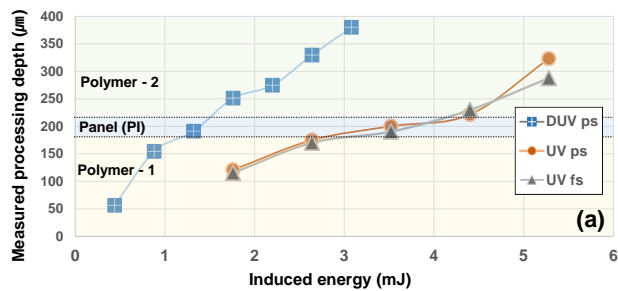


Figure 9. (a) Laser processing depth graph as a function of induced laser energy for each laser type and FIB cross sectional image of the display panel trimmed with a (b) deep UV ps (c) UV ps (d) UV fs laser. Scale bar = 5 μm .

While the FIB images of trimmed display panel cross-sections revealed minimal differences in the final processed surfaces across the laser types, the use of a deep UV wavelength characterized by its high absorption rate significantly enhances processing performance. This improvement allows for complete display panel trimming with lower thermal effects and reduced energy input. These advantages are expected to contribute to enhanced panel strength and quality after laser trimming.

4. Conclusion and Discussion

In summary, we have theoretically and experimentally obtained characteristics of multilayer display panel processing. The reflective index significantly affected the processing efficiency and characteristics. Also, the experimental result shows optical and thermal properties of each layer and spatial structure significantly affected the processing efficiency and characteristics. Therefore, by using different processing conditions from the single layer, we can significantly enhance the quality of multilayer trimming.

We believe the results of this study can be helpful for the

determination of process conditions according to the precision machining area such as display panel laser trimming and development of laser cut process technology.

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