Femtosecond Laser Machining of Flexible Printed Circuit Boards

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Abstract. As the demand grows for high-density electronic components and highly integrated printed circuit boards, femtosecond laser micromachining provides unique opportunities for creating fine conductive tracks and patterns on flexible printed circuit boards (FPCBs) without the use of a mask. Here, the effects of femtosecond laser power and pulse frequency on micromachining depth, surface roughness and copper content of the machined zone were investigated, and optimum laser parameters, i.e., laser power 280 mW and pulse repetition frequency 39.5 kHz, were achieved with the help of a 3D optical profilometer and energy dispersive spectroscopy (EDS). On this basis, a single conductive track with varying widths and two parallel conductive tracks with different widths/spacings were micromachined on FPCBs without noticeable substrate damage. The results indicate that a single conductive line with a feature width as small as 25 µm can be achieved, and two parallel copper tracks can be created with no evidence of the presence of copper residues between the tracks when the pre-defined spacing is no less than 45 µm. In order to achieve high micromachining accuracy, look-up tables that correlate measured widths/spacing of conductive tracks with the pre-defined ones were built. Besides, machining conductive tracks with 135 degree corner is possible and by selecting optimized processing parameters. Finally, a driving circuit for a display panel was micromachined on FPCBs using femtosecond laser, and an average micromachining accuracy of 0.67 µm was achieved. This work will be quite useful for creating high density and precision patterns on FPCBs using femtosecond laser.

1. Introduction
The demand for lightweight and high functionality electronic devices is always a driving force in the development of lighter and compact electronic circuits. Flexible printed circuits (FPC) are flexible circuits with the superior advantages of being flexible, bendable and lightweight, and they are often used across a diverse range of applications, from medical and aerospace to consumer electronics. As the compactness and high-performance of flexible electronic circuits progresses, there is an increasing need for reducing the size and spacing of the conductive tracks.

A flexible printed circuit usually consists of three layers: a metallic layer of traces, e.g., copper, bonded to a dielectric layer substrate, e.g. polyimide (PI), and an intermediate adhesive layer. Currently, the electronics industry mainly uses mask-based photolithography technology for manufacturing FPC boards. The disadvantages of the current technology lie in the complexity of a multiple-step process, including photolithography involving precise mask alignment and wet etching processes with hazardous chemicals; Furthermore, the track width and track spacing using industrial lithography technology is typically not less than 50 µm, which cannot meet the development demand of modern electronic devices.
Various technologies have been utilized to fabricate dense conductive tracks on FPCBs or printed circuit boards (PCBs) among these technologies, pulsed laser ablation offers an excellent solution for precision micromachining of FPCBs and PCBs for small-scale production without the use of a mask. B. Zhang demonstrated that nanosecond pulsed excimer laser structuring of the copper layer on PCBs was implemented to obtain a smaller-sized circuit line/space by conveniently changing the spot size of the laser beam, and the effect of the laser parameters on the laser structuring quality was investigated. A. Alwaidh used a nanosecond UV YAG laser for the micromachining study of FPCBs, and excellent size accuracy for feature sizes less than 50 µm was achieved. In our previous work, a rectangular reservoir on a PCB was created by machining away the copper using femtosecond laser, and no obvious heat-affected zone was observed.

In this paper, the effects of femtosecond laser power and frequency on the micromachining quality of FPCB were investigated by using energy dispersive spectroscopy (EDS) and a 3D optical profilometer (VK-8710, KEYENCE). Laser micromachining processes for a single conductive track and two parallel conductive tracks on FPCBs were studied. The minimum width of a single conductive track and the minimum spacing between two conductive tracks were determined by using scanning electron microscopy (SEM, EVO18, ZEISS), optical profilometer and Ultra-Depth Three-Dimensional Microscope, and look-up tables that correlate measured widths.spacing of conductive tracks with the pre-defined ones were built. On this basis, a display panel circuit was fabricated on FPCB with high accuracy.

2. Experimental

2.1. Materials

FPCs (1 mil PI 1 OZ Cu C/N:18, YONGDESHENG) used in this paper consisted of three layers: a 35.00 µm copper layer, a PI substrate with a nominal thickness of 25.40 µm, and an intermediate adhesive layer with thickness measured to be 15.19 µm using a digital microscope (VHX-7000, KEYENCE).

2.2. Femtosecond Laser Micromachining System

A commercially available 6 W ultraviolet (UV) femtosecond Ti: Sapphire laser (Phoras 15-1000-PP, LIGHT CONVERSION) with a wavelength of 342 nm and pulse width of 330 fs was used in this work. Figure 1 shows the schematic of a gas-assisted femtosecond laser micromachining system. The laser beam is delivered to a galvanometer scanner and then focused with an f-theta lens giving a nominal beam diameter of 20 µm at the focal point. Machining patterns are drawn with built-in tools and filled with cross-hatched lines with a 10 µm pitch, and they are further imported as drawing exchange format file into the control program of the laser micromachining system. Once the program is executed, laser ablation of copper is performed, and the microstructures are achieved by scanning the laser beam across the FPCB surface, which is positioned 0.3 mm below the focal point. The assisted gas is responsible for ejecting the ablated material from the laser-material interaction area.

![Figure 1. Schematic of the femtosecond laser micromachining.](image-url)
3. Results and Discussion

3.1. Optimization of Femtosecond Laser Parameters for Micromaching of FPCB

In order to create conductive trace features with high precision, it is necessary to ensure that the copper layer is completely removed at the ablation zone without noticeable PI substrate damage. Therefore, optimization of laser micromachining parameters is essential to achieve high quality patterns on FPCB.

A series of 3 × 3 mm² squares were micromachined on FPCB with varying laser power and pulse repetition frequency (PRF), while scanning speed of the focused laser beam and number of passes are set as 39 mm/s and 3, respectively. Laser micromachining experiments with varying laser power at constant PRF of 30 kHz were performed, and the copper layer is ablated by evaporation and plasma. Figure 2 shows the effects of average laser power on the ablation depth and surface roughness in the ablation zone, and it is evident that both ablation depth and surface roughness increase with the laser power. When the average laser power is 280 mW, the vaporized depth is approximately equal to the thickness of the copper conductive layer. When the laser power becomes higher than 280 mW, laser ablation of adhesive layer starts and the surface roughness gets worse.

![Figure 2. Influence of laser average power on ablation depth and surface roughness.](image)

Next, the PRF was varied from 20 kHz and 60 kHz while keeping average laser power 280 mW constant in following experiments, and the effect of PRF on ablation depth and surface roughness was investigated. At low PRF, the laser energy density is above the ablation threshold, and the ablation depth increases with the PRF to a maximum at 30 kHz, as shown in figure 3. Moreover, it can be seen that the ablation depth decreases with the further increasing PRF. This is mainly due to the reduced pulse energy at high PRF, which becomes progressively less than the ablation threshold. When the PRF is 39.5 kHz, the ablation depth is equal to the copper thickness. It can also be seen from Fig. 3 that the surface roughness of the ablated zone increases first and then decreases slowly with the increase in PRF. As a result, PRF of 39.5 kHz is used in subsequent experiments, because copper are completely removed and a relative low surface roughness is obtained at this frequency.
Figure 3. Influence of laser frequency on ablation depth and surface roughness.

According to the previous experimental results, 3 × 3 mm² square patterns were micromachined on FPCB with an average laser power of 280 mW and PRF of 39.5 kHz. The EDS analysis were conducted on laser ablation zone of FPCB, with one measurement result shown in figure 4, and the comparison of ingredient content is shown in the table 1, indicating that copper in the ablation zone was almost completely removed, and the content of Cu element decreases, so the proportion in the whole is very small, which can be ignored. It is proved from the microscopic point that the copper on the surface has been completely removed. Depth profile of the micromachined FPCB was measured using a 3D optical profiler. An example of measured depth profile of laser ablated FPCB is shown in figure 5, and it is seen that the depth difference between unablated area of FPCB and ablated area of FPCB is greater than the copper thickness of 35.00 μm. EDS analysis result and depth measurement result together indicate that well-defined copper patterns could be ablated on FPCB with optimized laser parameters.

Figure 4. EDS analysis result of laser ablation zone of FPCB.

Table 1. The comparison of atomic number fraction content before and after processing.

| FPCB                          | Atomic fraction content (%) |
|-------------------------------|-----------------------------|
|                               | C  | O  | Cu |
| The Original copper layer of FPCB | 0.2| 1.1| 98.7 |
| Ingredient content after processing | 74.3| 24.9| 0.2 |
Figure 5. Depth measurement result of laser ablated FPCB.

3.2. Laser Ablation of a Single Conductive Track

Single conductive tracks with pre-defined widths of 15 μm, 25 μm, 35 μm, 45 μm, 55 μm, and 65 μm were micromachined with the above-mentioned optimized laser parameters (average laser power of 280 mW and PRF of 39.5 kHz). The surface morphologies and cross-sectional morphologies of the ablated copper tracks were measured with an optical profilometer and SEM, respectively. Figure 6 shows SEM images of copper tracks with different widths micromachined on FPCB. It can be seen that the cross-section of copper tracks is triangular (figure 6(a)-(b)) or trapezoidal (figure 6(c)-(f)) rather than ideal rectangular, as shown in the right part of each figure. In general, the copper track is well defined, with no evidence of copper in the ablation zones.

Table 2 shows the ablation depths and measured widths of copper tracks with different pre-defined widths. It is seen from the table that the ablation depth ranges from 37.35 μm to 42.52 μm, which is greater than copper thickness while less than the total thickness of the copper layer and adhesive layer, indicating that the copper layer in the ablation zone had been removed without causing damage to PI substrate. Furthermore, the measured widths of the conductive tracks are found to be less than the pre-defined widths of design patterns. To improve the laser micromachining accuracy, a linear interpolation method was used to predict measured track widths corresponding to other unknown pre-defined widths, and a look-up table that correlates measured widths of conductive tracks with pre-defined widths of design patterns was built in advance. For example, when a conductive copper track with a width of 33.44 μm is desired, the pre-defined width is set to 35 μm.

Figure 6. SEM images of copper tracks manufactured on FPCB (d is the pre-defined width of the track).
In addition, it's shown that when the pre-defined width of the designed pattern is 15 μm, the cross-section of the micromachined copper track is triangular instead of trapezoidal or rectangular, as shown in the right side of figure 6 (a). However, this triangular copper track with pointed ends may result in a tip discharge when transmitting high-frequency signals. Therefore, the widths of designed trace patterns should be no less than 25 μm.

Table 2. Average ablation depths and measured widths of copper tracks with different pre-defined widths.

| Number | Pre-defined track width/μm | Measured track width/μm | Ablation depth/μm |
|--------|-----------------------------|-------------------------|-------------------|
| 1      | 15.00                       | 13.18                   | 40.14             |
| 2      | 25.00                       | 21.81                   | 37.35             |
| 3      | 35.00                       | 33.44                   | 41.73             |
| 4      | 45.00                       | 42.19                   | 42.52             |
| 5      | 55.00                       | 51.33                   | 38.97             |
| 6      | 65.00                       | 60.65                   | 40.62             |

3.3. Laser Ablation of Two Parallel Conductive Tracks

In order to find out the spacing limits of laser ablated copper tracks, parallel copper lines with different spacings (widths and spacings are equal) were micromachined on FPCB. SEM images of parallel copper tracks on FPCB with widths/spacings of 35/35 μm, 45/45 μm, 55/55 μm and 65/65 μm are shown in figure 7. It is seen that there are some copper residues in the ablation zone between two 35/35μm copper tracks, as shown in figure 7(a), while 45/45μm, 55/55μm and 65/65μm copper tracks were well defined in figure 7(b), figure 7(c) and figure 7(d), with no evidence of copper residues in between two copper tracks.

Figure 7. SEM images of parallel copper tracks on FPCB (D is the pre-defined spacing of the two tracks).

Table 3 shows the average track spacings and ablation depths measured by the 3D optical profiler. It can be seen the measured copper track spacings are less than the pre-defined ones, and the measured ablation depths range from 35.54 μm to 42.56 μm, indicating that the copper in the laser ablation zone is almost removed. Similarly, a linear interpolation method was used to predict measured track spacings corresponding to other unknown pre-defined ones, a look-up table that correlates measured spacings of two parallel conductive tracks with the pre-defined ones should be built in advance.
Table 3. Average measured track spacing and widths for copper tracks with different pre-defined widths.

| Number | Pre-defined trace spacing/μm | Measured trace spacing/μm | Ablation depth/μm |
|--------|-----------------------------|---------------------------|-------------------|
| 1      | 35                          | 31.55                     | 35.54             |
| 2      | 45                          | 43.16                     | 40.78             |
| 3      | 55                          | 52.36                     | 41.31             |
| 4      | 65                          | 60.44                     | 42.56             |

3.4. Laser Ablation of Two Parallel Conductive Tracks with 135 Degree Corner

In order to ensure that the laser ablation is applied to the actual application, therefore, two parallel conductive tracks with 135 degree corner were micromachined on the FPCB. The line width and line spacing of two parallel conductive tracks were same and pre-defined, widths/spacings of 25/25 μm, 35/35 μm, 45/45 μm are shown in figure 8. The macro morphology was taken by Ultra-Depth Three-Dimensional Microscope, the images were shown in figure 9(a). It can be seen that when the line width and line spacing are 25μm, the line spacing part is not completely removed and over-ablation can be observed. But the track with line width and line spacing of 45μm has been basically formed, and the borders at the corners of the line are clear, without material splashing and over-ablation. Additionally, the corner of conductive tracks 45μm line width and line spacing are measured by Image J measurement software. The result indicated that the angle of the line is 135° in figure 9(b), which is in line with the preset corner angle. The measurement result shows that the line has been accurately formed.

![Figure 8](image-url) Two parallel conductive tracks with 135 degree corner.

![Figure 9](image-url) Forming line with corner (b is the measurement of corner).

3.5. Laser Ablation of Display Panels

A driving circuit of a display panel was micromachined on FPCB using the femtosecond laser. A typical periodic pattern of driving circuit drawn with built-in CAD tool is shown in figure 10(a). According to the single conductive track ablation look-up table, in order to micromachining copper track with width of
30 μm, the pre-defined width of the curve in the pattern is set as 32μm. figure 10(b) shows optical images of micromachined copper track, and no copper residues in the ablation zone can be seen. SEM image of the micromachined copper track is shown in figure 10(c), in which the curved edges features are maintained with high fidelity. The average track width was measured as 29.33 μm, and an average machining accuracy of 0.67 μm was achieved. The result illustrates the success of creating complex micromachined copper patterns on FPCB using femtosecond laser.

![Figure 10](image.png)

**Figure 10.** Images of laser micromachined driving circuit of a display panel: (a) CAD drawing of the driving circuit, (b) optical microscopy image of the micromachined driving circuit and (c) SEM image of the micromachined driving circuit.

4. Conclusions

In this paper, it has been demonstrate that femtosecond laser ablation is a promising solution for high-accuracy laser patterning of FPCB without the use of a mask and any chemicals, and that it can completely remove the copper layer without damaging the substrate. Employing 3D optical profilometer and EDS, the effects of femtosecond laser power and pulse repetition frequency on micromachining depth and surface roughness of the ablated zones were investigated. The results indicate the optimum laser power and pulse repetition frequency for laser micromachining on FPCB were found to be 280 mW and 39.5 kHz. A single conductive track with a feature width of 25 μm was achievable, and two parallel 45/45μm copper lines were micromachined with no evidence of the presence of copper residue between two tracks, besides, machining conductive tracks with 135 degree corner is possible. In the last, a driving circuit for a display panel was micromachined on FPCBs using femtosecond laser, and an average micromachining accuracy of 0.67 μm was achieved. In order to achieve high micromachining accuracy, look-up tables that correlate measured widths-spacing of conductive tracks with the pre-defined ones were built. Last, a driving circuit for a display panel was successfully micromachined on FPCB with femtosecond laser, and an average micromachining accuracy of 0.67μm was achieved. The present study suggests that femtosecond laser is an accurate tool for fabricating fine copper patterns on FPCBs.

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