MultiWave Hybrid Laser Processing of Micrometer Scale Features for Flexible Electronics Applications

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ABSTRACT

MultiWave Hybrid™ laser material processing allows two or more laser wavelengths to be combined into a single beam. This technology has been shown to be advantageous for laser cutting composite and laminate materials, where the individual components have different optical or physical properties. In this work we will explore the application of MultiWave Hybrid technology to the fabrication of flexible electronic circuits. The advantages of using multiple laser wavelengths for manufacturing steps, such as opening vias through a Kapton™ insulator to an underlying copper conductor, will be demonstrated. Several rapid prototyping processes for flexible electronic circuits will be reviewed. These involve selective ablation of conductive materials to pattern an interconnect layer without the need for a costly and time-consuming photolithography process. We will also investigate a process for producing Laser Induced Graphene (LIG) from a commercially-available polymer substrate.

Keywords: Laser processing, materials processing, selective ablation, dual wavelength, graphene, fiber laser, CO_2 laser

1. INTRODUCTION

Laser material processing using a single wavelength beam is well known. Mid-IR lasers are commonly used for cutting and marking plastics and other organic materials because they absorb very strongly in this wavelength regime. Near IR lasers are better-suited to metal processing because most metals absorb near-IR energy but reflect mid-IR energy. When processing a homogeneous material, a single laser wavelength is usually fine. However, many modern materials are engineered composites or laminates, consisting of components with different optical and physical properties. In these cases, the ability to use multiple wavelengths can be very useful.

1.1 MultiWave Hybrid Technology

The laser processing work described below was performed using an XLS10MWH™ from Universal Laser Systems (ULS). The MultiWave Hybrid optics on this laser system combine the beams from up to three different lasers into a single, coaxial beam as shown in Figure 1. Since each laser beam has a different wavelength, the MultiWave Hybrid optics need to manipulate each beam so that when they are combined and passed through a common focusing lens, they will be focused into the same plane. In addition to focusing all three wavelengths into the same plane, the MultiWave Hybrid optics also focus all three wavelengths to a spot size of 25µm. This allows the three wavelengths to work together for processing complex engineered laminates and composites. The three laser beams can also be used independently without the need for adjustments when the wavelength is changed.

The three lasers used in this work are an ytterbium-doped glass fiber laser with a wavelength of 1.062µm, a CO_2 gas laser set up to operate at a wavelength of 10.6µm (primary emission peak), and a second CO_2 laser set up to operate at 9.3µm (secondary emission peak). Each of the lasers has an average power of 50 watts, and the operating parameters of each laser can be controlled independently.

Gas Assist technology is also provided on the laser system. Gas Assist directs a jet of compressed gas along the laser beam axis. The gas can be air, which helps to efficiently remove effluent gasses that are produced by laser processing. This helps to keep the material surface clean and also protects the optics from contamination. The gas can also be an inert gas like nitrogen or argon. Inert gases help to prevent oxidation of the material in the area that is being laser processed. Forming gas can also be used to create a reducing environment. This is often useful for laser surface treatments, where hydrogen terminated bonds are desired.

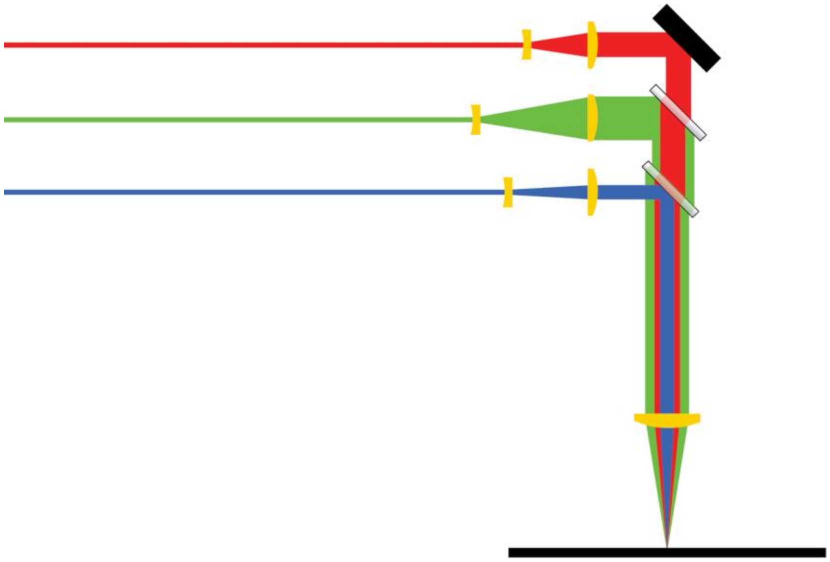

Figure 1. Schematic diagram of MultiWave Hybrid optics showing laser beams with three different wavelengths being individually expanded, and then combined in such a way that they can be focused onto a common plane.

1.2 Laser Cutting Composite and Laminate Materials using Two Laser Wavelengths

Laser processing with a single wavelength is very effective for homogeneous materials, however, composites and laminates are not homogeneous. In fact they are often composed of materials that have very different optical and thermal properties. For example, Carbon Fiber Reinforced Polymer (CFRP) is composed of a carbon fiber fabric encased in a polymer matrix material. The carbon fiber has a dramatically-higher vaporization temperature than the polymer matrix material, and the two materials have very different optical absorption spectra [1]. Both materials absorb well in mid-IR, so a CO_2 laser would be a likely choice for cutting CFRP. However the amount of energy needed to vaporize the carbon fibers is excessive for the polymer, leading to substantial damage near the cut edge. Cutting CFRP with only a near-IR laser can be problematic as well. The carbon fibers absorb this wavelength very well, but the polymer is nearly transparent at this wavelength. As the carbon fibers heat up and vaporize, heat is transferred down the length of the fibers causing the surrounding matrix material to melt. This causes excessive damage near the cut edge.

Klotzbach, et al., proposed addressing this issue by combining a near-IR and a mid-IR laser beam [2]. This allows the near-IR laser beam to vaporize the carbon fiber while the mid-IR laser beam vaporizes the polymer matrix material. They were able to demonstrate that combining the two laser wavelengths improved the cut quality and also increased the cutting speed.

We have verified this proposition by using MultiWave Hybrid technology to laser cut through a sheet of 0.062” (1.6 mm) CFRP. We found that a 50 watt CO_2 laser was able to ablate the polymer matrix material, but did not have sufficient energy to cut through the carbon fabric reinforcing material. The 1.062µm wavelength beam from the Yb-doped fiber laser was able to cut through the carbon fabric, but this wavelength is not absorbed by the polymer matrix. Instead, heat was conducted down the length of the carbon fibers causing the polymer to melt. The best result was obtained with the MultiWave Hybrid process. With this method, the CO_2 laser was able to ablate the polymer, while at the same time the fiber laser cut through the reinforcing fabric. The results are shown in Figure 2. The image on the left shows a cut using only the fiber laser. It shows a relatively large heat-affected zone and many detached carbon fibers. The image at right demonstrates the MultiWave Hybrid process, exhibiting a much smaller heat-affected zone (dark area), and few detached fibers. The MultiWave Hybrid process has the additional advantage of increasing the cutting speed by a factor of two.

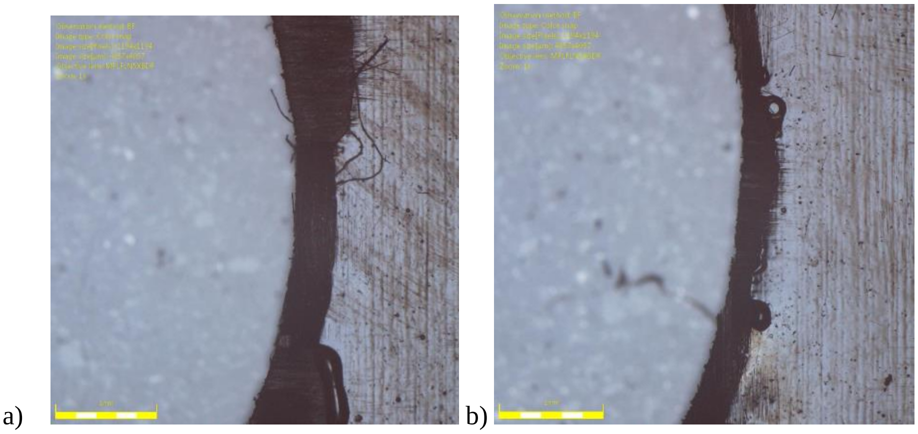

Fig. 2. Scanning electron micrographs of laser cut CFRP using (a) an Yb-doped fiber laser only, and (b) MultiWave Hybrid technology using both an Yb-doped fiber laser and a CO_2 laser.

2. MULTIWAVE HYBRID PROCESSING OF FLEXIBLE ELECTRONIC CIRCUITS

2.1 Selective laser ablation of polyimide to form microscopic vias

Interconnect structures for flexible electronic circuits are commonly constructed using polyimide as the insulating layer and copper foil as the conductor. The copper foil is bonded to the polyimide sheet with an acrylic-based adhesive. The copper is then patterned using a photolithographic process to form the conductor traces. Then another insulating polyimide layer is bonded to the top of the laminated structure to protect the copper. This set of steps can be repeated to form a multi-layer interconnect structure.

Once the interconnect structure is complete, it is necessary to create vias through the insulting layers to make electrical contact with the copper layer. This is done to create conducting paths between copper layers, or to make electrical contact with active devices like logic, display or memory elements. This via formation step can be done using photolithography, however that is an expensive and time-consuming process. It is often more efficient to form the vias by selective laser ablation of the polyimide.

Figure 3 shows the optical absorption spectra of copper and polyimide. The spectra show that the polyimide absorbs strongly at the 10.6μm wavelength of the CO_2 laser, while the copper reflects this wavelength. This process would appear to provide an ideal solution for ablating the polyimide layer without affecting the underlying copper, however, the actual situation is more complex.

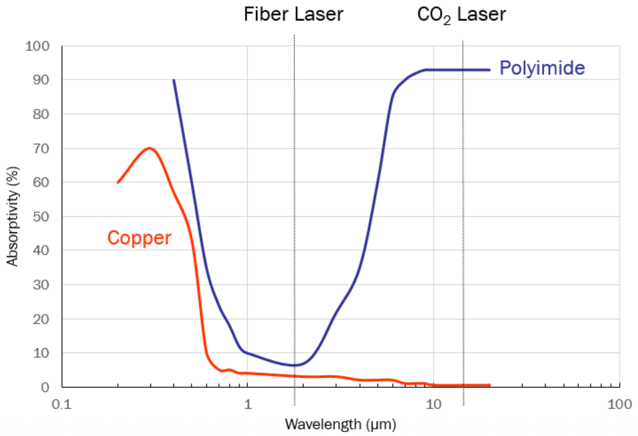

Figure 3. Optical absorption spectra of copper and polyimide [3].

Figure 4a shows that using the CO_2 laser by itself creates a substantial amount of carbonaceous residue. This residue is difficult to remove with the CO_2 laser. Figure 4b shows the result for MultiWave Hybrid processing. In this process, the CO_2 laser ablates the polyimide, and at the same time the fiber laser vaporizes the carbonaceous residue. This leads to a much cleaner via.

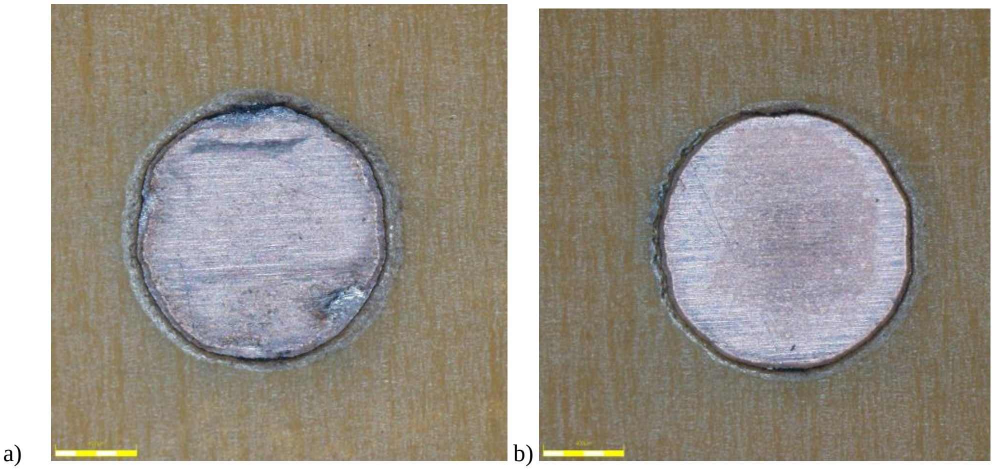

Figure 4. Digital microscope images of two vias thorugh polyimide to copper created by selective laser ablation using (a) a CO_2 laser only, or (b) MultiWave Hybrid technology using both an Yb-doped fiber laser and a CO_2 laser.

While the vias shown in Figure 4 are 1.0 mm in diameter, the selective laser ablation process can be used to create vias as small at 50µm in diameter. Figure 5 shows a digital microscope image of a via created using MultiWave Hybrid technology. The diameter at the bottom of the via measures between 50 and 58µm. Figure 6 shows a 3D rendering of the same via. The rendering shows that the sidewall profile is slightly sloped. This takes up some real estate, but also ensures a void-free via filling processes.

Figure 5. Digital microscope image of a via that was created by selective laser ablation using MultiWave Hybrid technology.

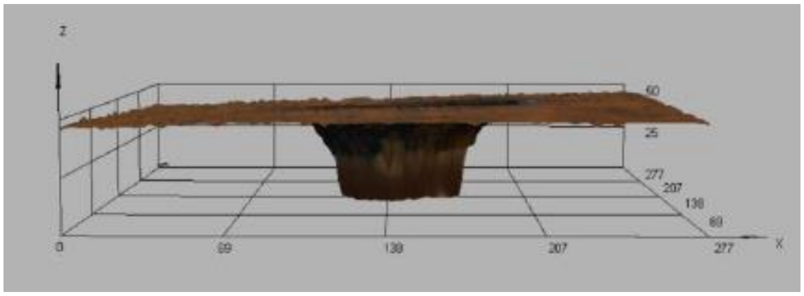

Figure 6. 3D rendering of a via that was created by selective laser ablation using MultiWave Hybrid technology.

2.2 Rapid prototyping of flexible electronic circuits

Laser processing is an excellent method for creating prototype circuits because no masks are required. This allows prototypes to be created and tested in a matter of hours, enabling rapid cycles of learning. One material system that we have investigated for rapid prototyping of flexible electronic circuits is a carbon-based conductive ink that has been silk screened onto a PET substrate. Figure 7 depicts the laser processing steps that are employed in creating a test circuit. Figure 7a shows the blanket carbon ink layer. Figure 7b shows the conductive circuit traces that are created by selectively ablating the carbon ink from the PET substrate. This is done using the 1.062µm fiber laser. This wavelength is absorbed by the carbon, causing it to vaporize. It is transparent to the PET, so the substrate is left intact. Figure 7c shows a serial number that has been marked into the PET substrate using the 9.3µm CO_2 laser. This wavelength is absorbed strongly by the top few microns of the PET, creating a visible mark without affecting the integrity of the substrate. The final step is to cut the circuit to the desired shape. This is done using the 10.6 micron CO_2 laser as shown in Figure 7d.

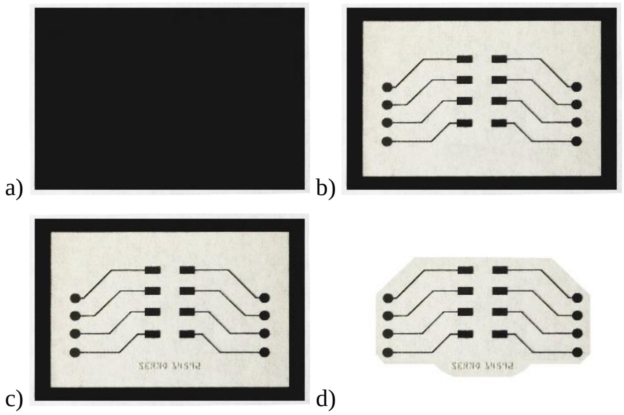

Fig. 7. Sequential process steps for flexible electronic circuit formation: (a) Carbon ink screen printed on PET substrate; (b) Laser ablation of carbon ink using 1.06µm fiber laser to form circuit elements; (c) Serial number marking using 9.3µm CO_2 laser; (d) Circuit cut from the PET web using a 10.6µm CO_2 laser.

Silver ink can also be used for rapid prototyping. However, it does not absorb the 1.062µm laser energy as efficiently as the carbon ink, making selective ablation more difficult. Figure 8 provides a comparison of the conductive line width that can be obtained with three different conductive ink compositions. The top image shows a conductive element created by selective ablation of carbon ink, indicating a minimum line width of 51µm. The center image shows the minimum line width for selective ablation of silver ink as 66µm. The 50:50 mixture of carbon and silver inks in the bottom image has a minimum line width of 56µm.

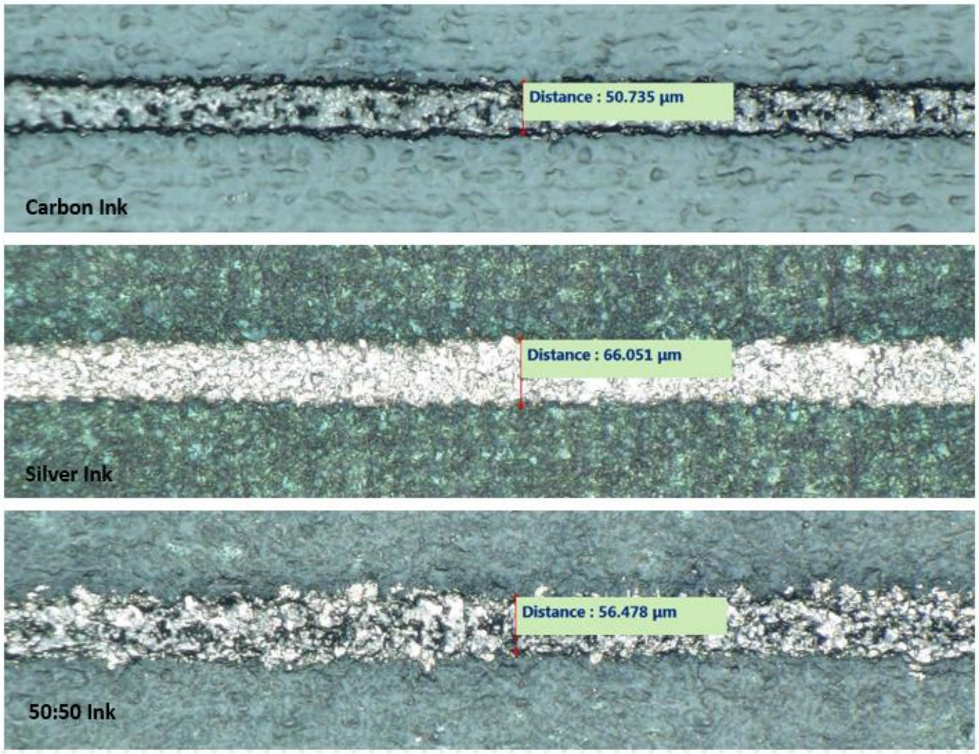

Figure 8. Optical Micrographs showing the minimum line width for selective ablation of three different conductive inks from a PET substrate.

3. LASER INDUCED GRAPHENE

3.1 Laser Induced Graphene

Laser energy can be used to chemically transform the surface of one material to another material. This was demonstrated by Lin et al. [4] when they applied a 10.6µm beam from a CO_2 laser to the surface of a commercially-available Kapton™ (polyimide) film. They found that the pulsed laser irradiation photothermally converted the top 20 to 30µm of the film to a three-dimensional network of graphene layers. These Laser Induced Graphene (LIG) networks are created wherever the laser beam strikes the surface of the Kapton™ film, enabling a direct write process for creating electrically conductive patterns.

In the work described above, the authors used the LIG process to create micro-supercapacitors with specific capacitances greater than 4 mF/cm^2 and power densities of approximately 9 mw/cm^2. In Figure 9, we have re-created the structure of the planar capacitor electrodes using the LIG process on a Universal Laser System XLS10MWH with a 50 watt CO_2 laser. Since LIG is a direct-write process, it lends itself to rapid prototyping, and since the substrate is a readily available polymer film, scaling to high-volume manufacturing is feasible.

Luo et al. [5] have also created a Direct Laser Writing (DLW) process by using an infrared CO_2 laser to irradiate the surface of a polyimide film. They have utilized the DLW process to create flexible strain gauges. They have further optimized the laser pulse duration and the scanning speed to maximize the piezoresistive sensitivity of the DLW-generated sensors.

Both the micro-supercapacitor application and the strain gauge application represent the benefits of laser processing for creating flexible electronic devices. Both processes can be practiced on a small scale using commercially available materials and equipment. They can also be directly scaled to high-volume, roll-to-roll manufacturing techniques.

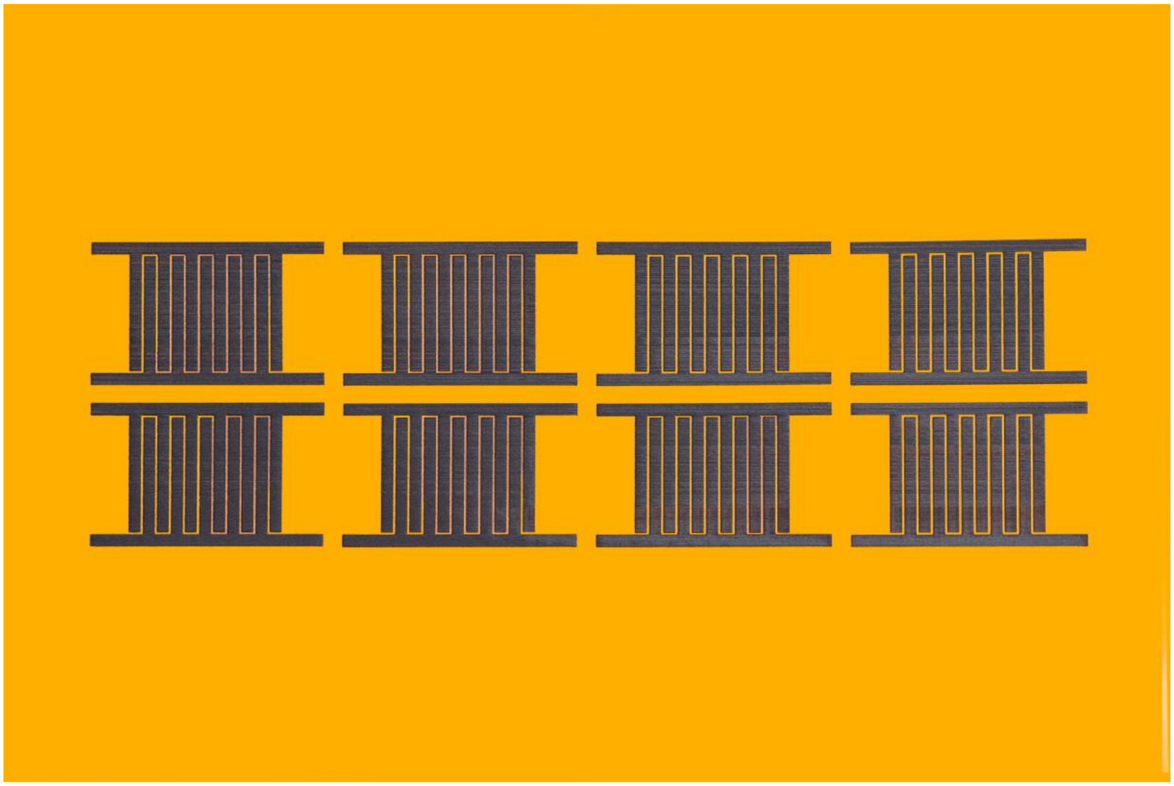

Figure 9. Planar capacitor electrodes created using the LIG process reported by Rice University [4].

4. SUMMARY

MultiWave hybrid technology provides clear advantages when laser cutting in homogeneous materials such as Carbon Fiber Reinforced Polymer (CFRP). We have also demonstrated benefits for rapid prototyping of flexible electronic circuits with minimum feature sizes as small as 50µm. We also demonstrated the production of Laser Induced Graphene (LIG) from a commercial polymer substrate. Together these processes represent the value of MultiWave Hybrid laser processing for both new product development and high volume manufacturing.

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