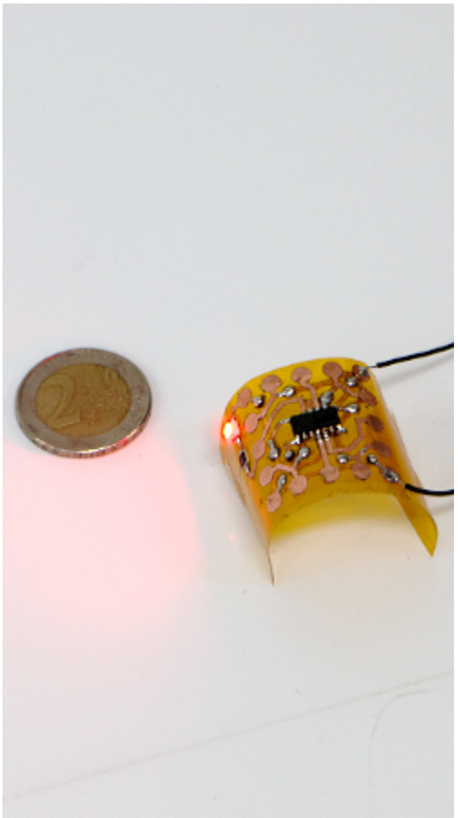

Figure 1: A flexible PCB, consisting of a micro-controller and LED, fabricated using the presented technique

DIY Fabrication of High Performance Multi-Layered Flexible PCBs

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ABSTRACT

We present a novel DIY fabrication workflow for prototyping highly flexible circuit boards using a laser cutter. As our circuits consist of Kapton and copper, they are highly conductive and thus support high-frequency signals, such as I2C. Key to our approach is a laser machine that supports both a CO2 laser as well as a fiber laser to precisely process respectively Kapton and copper. We also show how the laser cutter can cure soldering paste to realize VIAs (Vertical Interconnect Access) and solder components. In contrast, previous approaches for prototyping flexible PCBs through laser cutting only considered CO2 lasers which can not process metals. Therefore these approaches mainly used ink-based conductors that have a significantly higher electrical resistance than copper.

KEYWORDS

Fabrication, Flexible PCBs, DIY

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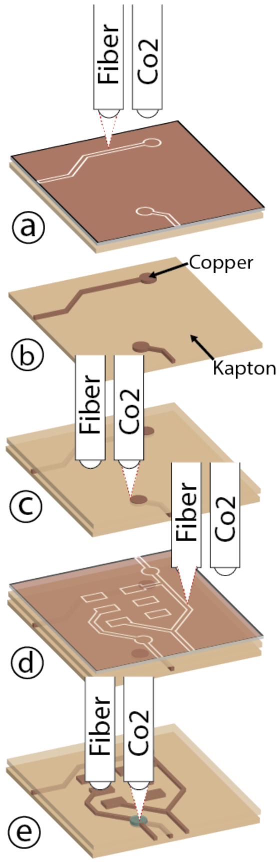

Figure 2: (a) Cutting copper traces first circuit layer, (b) removing excess copper (c) cutting VIAs from second layer of Kapton, (d) cutting circuit traces second circuit layer, (e) curing VIAs

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INTRODUCTION

Recently, there is an increasing interest in making flexible circuit boards using DIY equipment in Makerspaces and Fablabs [7, 10]. These techniques empower interaction designers to make functional prototypes, allow for fast design iterations and encourage experimentation with new interface ideas, such as interactive textiles and skin [2].

Similar to popular prototyping procedures for rigid PCBs, makers experimented with DIY chemical processes, such as etching copper on flexible materials[1] and selective evaporation of copper on flexible materials using stencils[2]. Although these approaches result in highly conductive copper traces, they require advanced knowledge and careful treatment of chemicals. The approach presented by Perumal et al. [1] makes prototyping flexible copper circuits more convenient but requires special layered material, not yet commercially available. Alternatively, vinyl cutters are used to cut circuits directly from copper sheets [3, 8]. These techniques are however limited to single-layered designs and restricted to traces of at least a few millimeters wide [8].

Over the past few years, a significant portion of research in personal fabrication focused on accessible techniques for depositing conductors on flexible substrates, such as silver nanoparticle ink [4] or PEDOT:PSS [11] conductive inks. Alternatively, CO2 laser cutters can cut circuit traces from carbon-filled silicone [10] or plastics coated with conductive ink [3]. Lin et al. [5] demonstrated laser patterning Kapton to introduce graphene with electrical conductivity. These research efforts, however, use carbon or ink-based conductors with a high electrical resistance as metals, such as copper, can not be processed with a CO2 laser cutter.

We present a novel DIY fabrication technique for making flexible PCBs by stacking layers of Kapton and copper tape. Key to our approach is the combination of a CO2 and fiber laser. By using one of the lasers, we can selectively ablate either copper or Kapton and also cure solder paste for making VIAs and for soldering components. As such, our approach offers a convenient approach for prototyping high performance multi-layered flexible circuits within a single machine. Figure 1 shows a two-layered flexible circuit fabricated with our technique.

LASER CUTTING FULLY FUNCTIONAL CIRCUITS

Our approach, shown in Figure 2, builds up a stack of interleaved layers of thin-film Kapton and copper tape which are processed layer per layer by respectively the CO2 laser or the fiber laser of

[1] https://www.kobakant.at/DIY/?p=240

[2] https://www.youtube.com/watch?v=FYgIuc-VqHE

the machine. The Kapton layers serve as carrier (base-layer), insulator (in between copper layers), and protective layer (top-layer), while the copper layers provides the electrical designs. The initial layer of the stack is a layer of Kapton tape to provide an insulated base for the PCB. Next, a layer of copper tape is placed over the Kapton tape (a). The traces of the first layer of the circuit are then laser cut with the fiber laser and the remaining copper is removed using tweezers (b). A new layer of Kapton tape is then placed over the traces. To realize (buried) VIAs between circuit layers, this top layer of Kapton is cut at the location of the VIA using the CO2 laser (c). A new layer of copper tape is placed on the top of the stack and the traces of the next circuit layer are cut with the fiber laser (d). In addition, the VIAs holes are also cut and all remaining copper is removed. The resulting VIAs holes are filled with solder paste and cured by engraving the region with the CO2 laser (e). One could use a similar technique for soldering components to the top circuit layer. This process can be iterated multiple times to create multi-layered flexible PCBs.

Key to our approach is the precise processing of one layer of material without cutting the layers below. While cutting VIAs in Kapton is convenient as CO2 lasers can not cut the copper layer below, fiber lasers can engrave plastics (i.e. Kapton) and therefore require fine-tuning. To precisely target one layer of copper, we calibrate the fiber laser on a sheet of copper tape with Kapton underneath. This calibration process consists of patterning a circle enclosed in a slightly larger square. The first pattern is cut at very low power and the power is incrementally increased until the square can be peeled off while the inner circle remains attached, as demonstrated in Figure 3. This is the final power setting to cut through only a single layer of copper.

Our technique supports buried VIAs to interconnect more than two copper layers at the same time. To reliably interconnect multiple layers, the solder paste requires a sufficient contact area with the copper traces in each layer. Therefore, the cross-section of buried VIAs have the shape of an inverse pyramid-like stacking structure (Figure 4). We require a minimal VIA hole diameter of 1 mm at the bottom and diameter increments of at least 0.5 mm per layer. As buried VIAs interconnect multiple circuit layers, they oftentimes save space in compact circuit designs that would otherwise require separate VIAs to interconnect all individual layers.

PRELIMINARY TECHNICAL EVALUATION

To test the robustness our novel fabrication method, we prototyped a two-layered FPCB consisting of 30 circuit traces, 10 traces of 0.5 mm, 1 mm, and 2 mm. Every circuit trace crossed both layers using a VIA for a total of 60 sub-traces and 30 VIAs. The copper and Kapton used in this sample, have a thickness of respectively 90 and 38 microns. Both have an adhesive back. To test the robustness of the FPCBs, we repeatedly flexed the sample using a robotic arm, as shown in Figure 5. We monitored the conductivity of all traces and VIAs every 500 cycles. Three sub-traces of 0.5mm broke after respectively 2000, 2500, and 3000 cycles. All remaining 57 sub-traces, including the 30 VIAs still worked after 5000

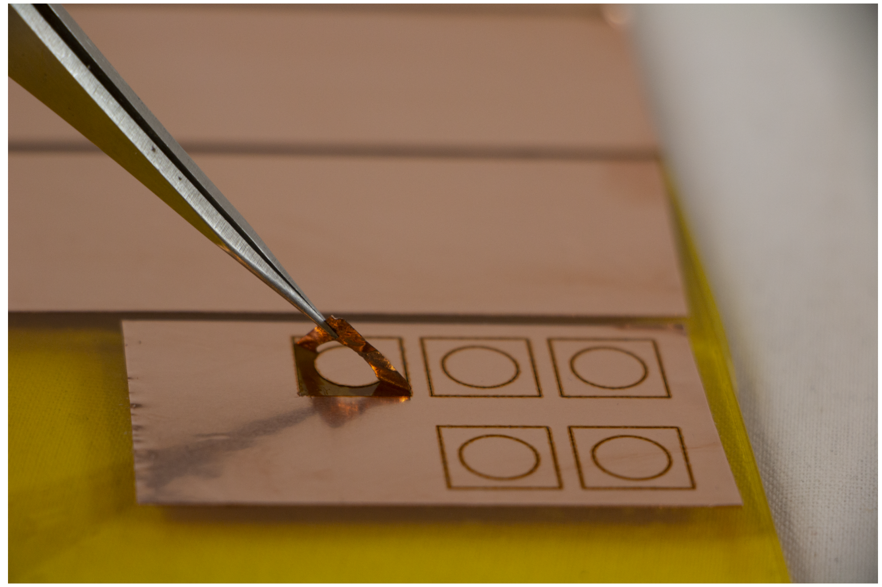

Figure 3: Calibrating the fiber laser to only cut one layer of copper.

cycles. After closer inspection, we noticed cuts in the small copper traces of 0.5mm as a result of material fatigue.

DISCUSSION AND FUTURE WORK

Although the presented technique already offers significantly value for makers to prototype flexible PCBs, this work in progress article has several limitations that offer interesting challenges for future research.

First, our technique requires precise calibration of the height of the fiber laser for every circuit layer (Figure 3). However, this is acceptable as even advanced circuit designs fit on two-layered circuits. However, when three or more circuit layers are needed, the stack of materials is thicker in some circuit regions that use these additional layers. In these situations, the fiber laser's focal point (height of the cutting table) requires precise control per region. More research is required on how to do this efficiently.

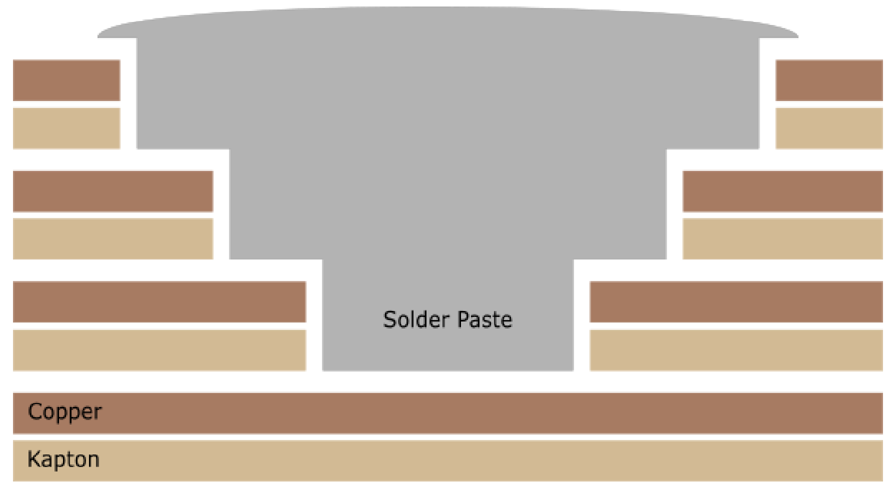

Figure 4: Stacking layers in an inverse pyramid-like structure to create multi-layer VIAs.

Second, for soldering components on the flexible PCB, the CO2 laser is used in engraving mode. In this setting, the laser is defocused, and the heat is distributed over the component footprint region to cure the soldering paste. The power settings for engraving requires precise control to avoid damaging components. Our current calibration process starts by defocusing the laser and burning some marks on a piece of paper by changing the laser height. The correct height is when the burned paper region reaches the same proportion of the component footprint. Then, the laser power is calibrated up the point to melt soldering paste on top of a copper region and proceed to solder the components on the FPCB. Future work requires to define a configuration file for the vast existing components options and avoid doing a manual calibration. Furthermore, this technique is restricted to soldering components that have connectors or leads exposed. In addition, automatic placement of components and solder paste will benefit the workflow by reducing manual work and increasing accuracy.

Third, A black residue appears as a result of laser cutting the adhesive from the Kapton film. This residue interferes when soldering the VIAs since the particles isolate the copper from the soldering paste. To prevent this issue, we calibrated the CO2 laser in the same way as the fiber laser, obtaining fewer residuals as a result. Cleaning the surface with isopropyl alcohol helps to remove the residues, but is a time-consuming and tedious task.

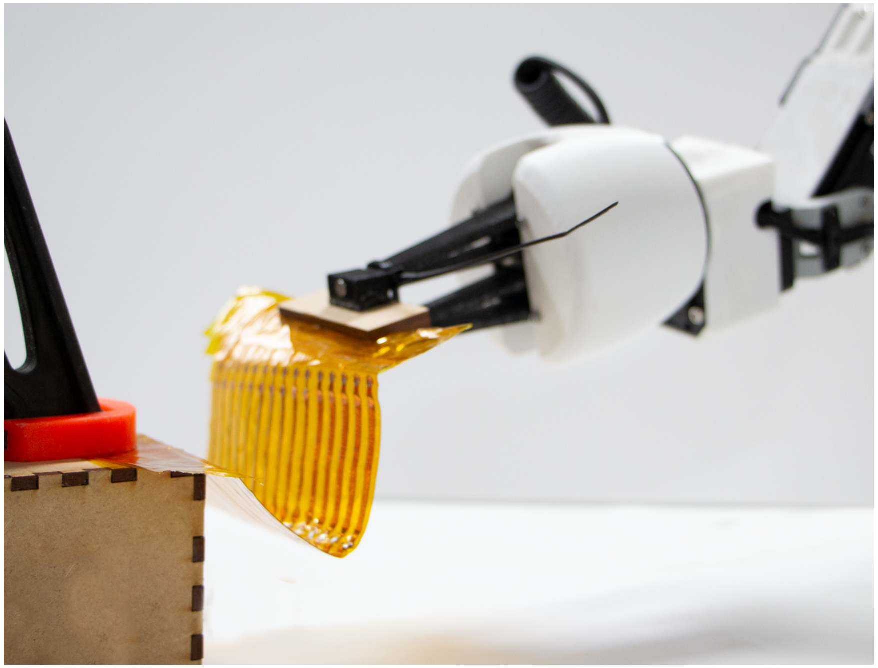

Figure 5: Testing the robustness of the FPCBs by using a robotic arm.

Last, a more deeper analysis of the durability of our flexible PCB is needed. In the future, we plan more extensive studies on the durability and lifetime of our FPCBs in different situations. In addition, we also want to conduct a user study to understand the usability of this fabrication process.

CONCLUSION

This work contributes to a steady stream of research on using laser cutters as all-around fabrication machines [3, 5–7, 9]. While continuing our research efforts in this direction, we believe our work reveals a novel potential of laser machines. This could trigger more research and justify acquiring fiber laser cutters in maker labs.

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