Chapter

Manufacturing Methods Based on Planar Circuits

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Abstract

Manufacture of hybrid 3D-planar circuits, especially those incorporating empty waveguides on substrates, can benefit from most standardized planar fabrication processes, although they are not exactly the same. For this reason, planar circuit manufacturing methods must be adapted to the requirements of these new circuits. Through numerous fabrications and successful designs, several enhancing strategies have been established to improve all the manufacturing phases to achieve better results. They all have been proved in the following substrate-integrated technologies for the manufacturing of microwave devices: ESIW, ESICL, continuous profile, and microstrip. Thanks to these improvements, good-quality prototypes such as transitions, filters, circulators, couplers, antennas, among others, have been fabricated. Throughout the next chapter, these strategies applied along the manufacturing process will be explained: from the first manufacturing phase to the final welding of the whole circuit and taking into account external elements such as wires that may be present in these structures. For this purpose, some devices that have been published will be used as examples.

Keywords: ESIW, ESICL, waveguide, microstrip, planar, 3D, manufacturing, fabrication, substrate integrated circuits, coaxial

1. Introduction

Planar circuit manufacturing processes have a long-term way. Many of the fabrication techniques of planar circuits can be applied to build 3D structures (substrate-integrated waveguides—SIW [1], empty substrate-integrated waveguides—ESIW [2], ridge empty substrate-integrated waveguides—RESIW [3], double-ridge empty substrate-integrated waveguides—DRESIW [4], substrate-integrated coaxial line—SICL [5] and empty substrate-integrated coaxial line—ESICL [6] or a combination with others as a continuous profile [7]) piling up layers of planar substrates.

In this chapter, some strategies and techniques adapted from planar to planar-3D structures will be explained with examples of manufactured prototypes, this philosophy being ideal for microwave prototypes (300 MHz–300 GHz), because the sizes of cavities are small enough to build heaping up with few small height substrates, of no more than 1.5 mm.

The prototypes can be fed with planar circuits such as coplanar or microstrip lines; because of this, at some point the feeding planar line needs to be connected with the inner waveguide or the connector through transitions, which needs to be also taken into account. One of the most typical transitions to do this are tapers, that is, transitions with a progressive geometrical variation of the guide which replicates the 3D launchers but planarly [8, 9]. Another way to do this is through wires [10].

2. Machines

The whole manufacturing procedure needs machines to fabricate each layer and measuring systems to check each manufacturing step.

2.1 Manufacturing machines

To manufacture the different layers, some machines must be used. A few possible ones are explained in the following paragraphs.

2.1.1 Plotter/cutter laser

This kind of machines use lasers to mill, cut, and drill substrates. Lasers are usually conical, so that the incidence angle is not 90°, but slightly lower, being necessary to minimize this effect as it will be explained in section 4.3. Laser machines are slower than mechanical milling machines, but they have a higher precision. In **Figure 1**, an example of these machines can be seen.

2.1.2 Milling machine

These machines use different mechanical drilling tools to mill, cut, and drill. The main downsides are the precision in comparison with laser ones and corner inner cuts, which are rounded because of the cylindrical shape of this tools. Although milling machines are very useful, they have some limitations: First, milling drills sizes vary from 0.2 mm to 3 mm, and their intermediates' values depend on the commercial drilling tools. In **Figure 2**, an example of these machines can be seen.

Both laser and milling machines can work independently or combined, given that mechanical machines are much faster than laser ones, especially in the drilling processes; being good enough for those kind of prototypes or parts in which drilling accuracy is not crucial. The combination of both machines decreases hugely the total production time without decreasing the accuracy, and it is highly recommended for prototypes with rigorous requirements. Resolutions of high-performance machines shift from 0.1 μm to 2 μm, and their repeatability oscillates from $\pm$ 0.1 μm to $\pm$ 2 μm; it depends on the machine. Theoretically, both machines can reach similar resolutions; however, drilling tools tend to be slightly bigger/smaller reducing resolution till 100 $\pm$ μm.

2.1.3 Multipress

These machines press the layers of prototypes and heat them up to high temperatures, melting the soldering paste to weld the prototype. Temperature, pressure, and

Figure 1.
Plotter/cutter laser machine.

time can be configured among a wide spectrum of values. In **Figure 3**, an example of these machines can be seen.

2.1.4 Reflow oven

Reflow ovens heat the prototype up to high temperatures to melt the welding paste and solder the prototype. The pressure must be applied with auxiliar elements such as

Figure 2.
Multipress machine.

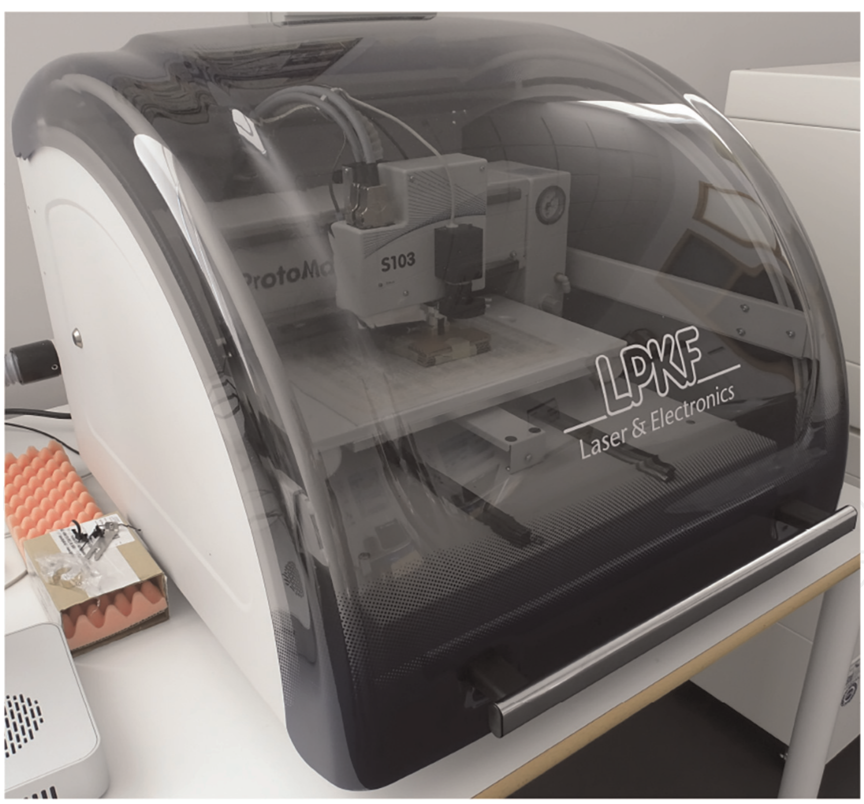

Figure 3.
Milling machine.

screws and nuts. Temperature can be selected to fit the recommended values and times for each soldering paste, this oven reaches around 270 °C (it can be higher depending on the specific model) with 1°C resolution steps. In **Figure 4**, an example of these machines can be seen.

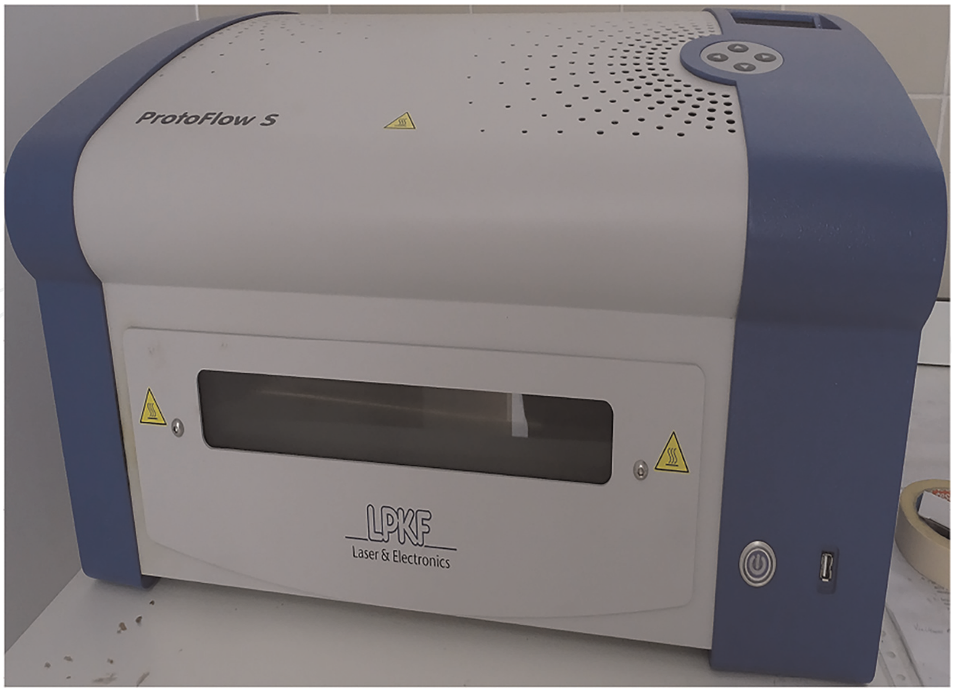

Figure 4.
Reflow oven.

2.1.5 Soldering plate

These hot plate systems have a flat area to heat prototypes and allow manipulation at the same time. They are very useful combined with welders to manually solder specific parts of the structure. In **Figure 5**, an example of these machines can be seen.

2.1.6 Welder

These tools heat up fastly small areas by contacting with the welding head, allowing soldering paste and welding wires to melt. In **Figure 6**, an example of these machines can be seen.

2.1.7 Galvanic metallizer for PCBs

This machine adds a layer of copper to the PCB, being necessary to metallize holes and cuts in the prototype. The layer of metal can be estimated mathematically depending on temperature, time, and current, or it could be measured if necessary. Maximum dimensions for substrates are around 200 × 290 mm/230 mm × 330 mm for the typical models. In **Figure 7**, an example of these machines can be seen.

2.1.8 Through plating hole

Although it is not a machine but a process, this technique is included in this section to exemplify this manufacturing process, which consists of a set of chemicals that can metallize holes without any machine but a vacuum bed and a reflow oven. There are

Figure 5.
Soldering plate.

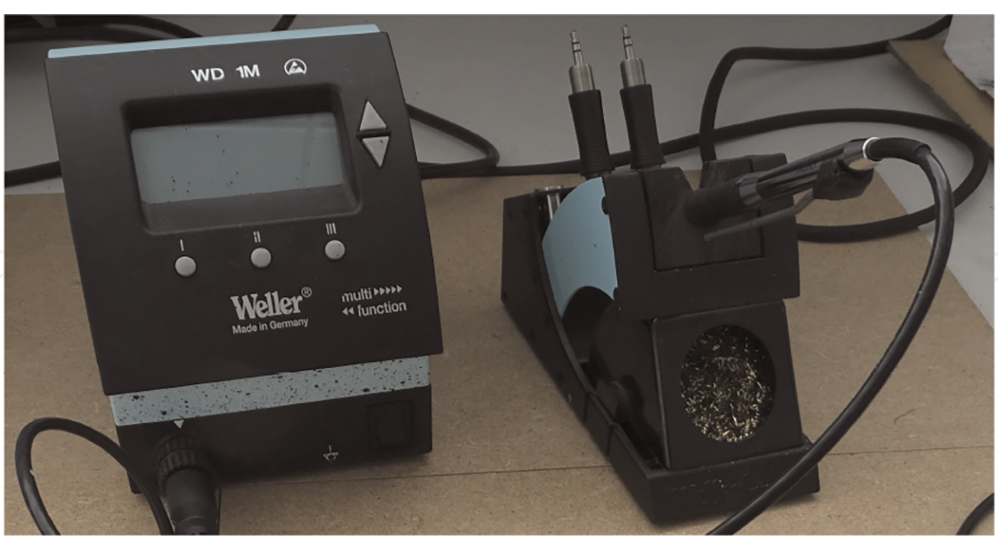

Figure 6.
Welder.

many commercial solutions in the market, and the results are good enough. The vacuum bed makes this dense liquid metal to cross along the wholes, and then, it must be treated with the reflow oven. Laser and milling machines usually include this vacuum bed in their systems. **Figure 8** shows an example of through plated holes.

Figure 7.
Galvanic metallizer.

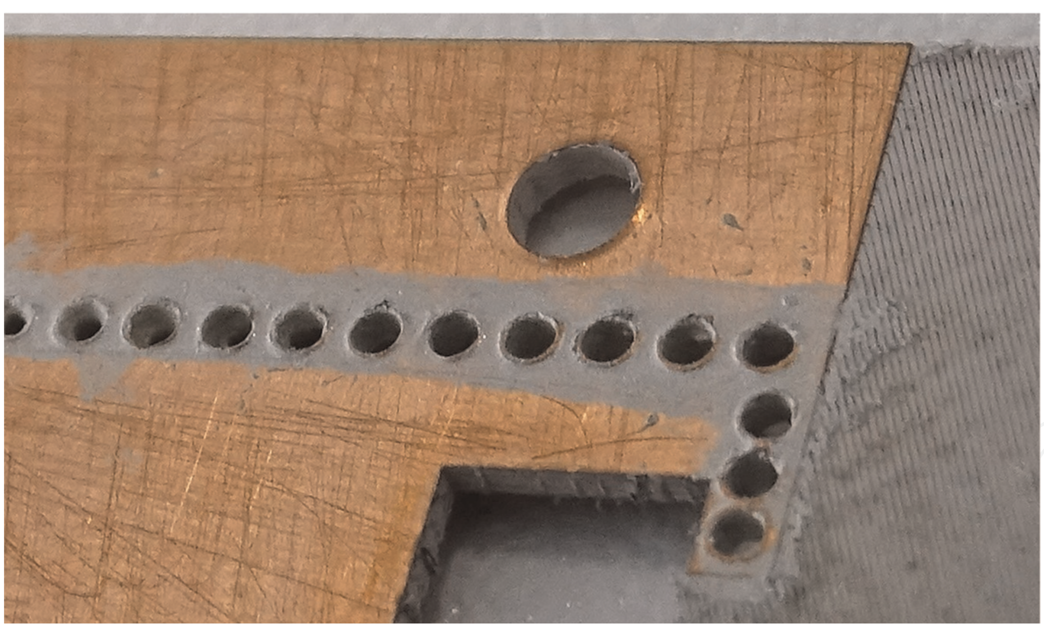

Figure 8.
Through plated holes.

2.2 Measure machines

In addition, high-performance manufacturing machines are needed; so essential are also the measuring machines to improve the results. When the design frequency is increased, the dimensions of the prototype are reduced and manufacturing tolerances become more important, being necessary to characterize and avoid them as much as possible. To do that, some of the measuring machines explained next could be used.

2.2.1 Microscope

It is very important to check the correct metallization of holes and walls, the correct milling of the prototype to avoid shortcuts, etc. To do that, a microscope can be used to check if there are manufacturing errors such as parts of copper that have not been properly removed or vias that are not properly metallized. Once identified, some of these errors can be handly solved to assure the correct behavior of the prototype.

2.2.2 Vision measurement system

This kind of machines are high-efficient systems that allow very high accurate measurements. These machines measure not only distances, but also geometrical 2D shapes, such as holes or lines and their deviations in shape and size from the initial requirements, allowing to compensate systematic errors during the manufacturing process.

2.2.3 Profilometer/surface roughness measuring systems

These instruments measure the rugosity of the layers of the prototypes. They are very useful in order to estimate the effect of metallization.

2.2.4 Vector network analyzer

These N-port devices are capable of measuring S-parameters, magnitude, phase, and time-domain analysis of prototypes. Combined with an anechoic chamber, it can measure antennas and radiation of prototypes.

3. Layer manufacture

As it was explained formerly, to create a 3D structure, an undetermined number of layers have to be piled up. These layers can have different heights and can be manufactured using the same or different substrates, with a careful alignment of them being necessary. **Figure 9** shows an exploded schematic view of a prototype. It shows different layers with different geometries and different heights making up the whole 3D structure.

Figure 10 shows a full assembled prototype besides a euro coin to compare sizes, where it is possible to observe how different layers with different heights (among 0.5 mm and 0.8 mm) are assembled.

These layers are manufactured using standard PCB processes such as cutting, drilling, milling, and plating. Once the layers are manufactured in the PCB, they are carefully extracted to be piled up. **Figure 11** shows the prototype layers before being extracted from the PCB. These PCBs are slabs that can be none, single, or twice metallized. Metallized substrates present a thin metal layer in one or both faces, usually copper. Later on, these PCBs can be additionally metallized such as the slab at the right in **Figure 11** using the process explained in section 2.1.7.

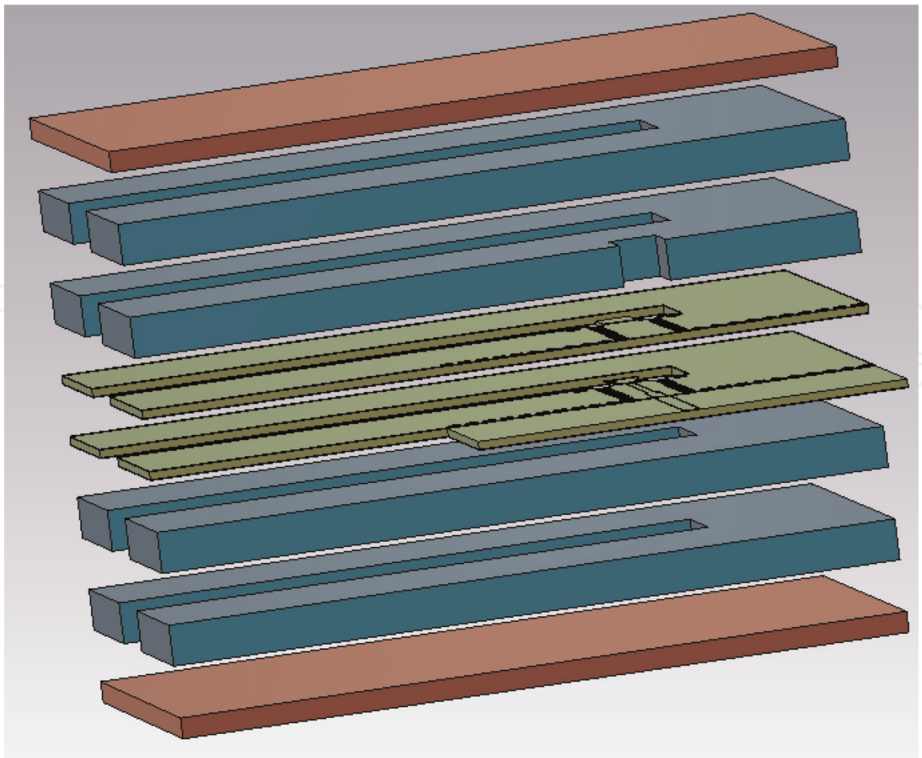

Figure 9.
Exploded view of the layers of a prototype.

Figure 10.
Assembled prototype.

4. Set-up issues for measurement

In this section, some example of feeding lines to feed the prototypes and connect them to a vector network analyzer are shown. Furthermore, a detailed explanation of each one of the issues that can appear during the manufacturing process is expound and analyzed.

4.1 Feeding lines

3D structures based on planar layers must include planar feeding lines such as microstrip lines or coplanar-grounded waveguides to feed the prototypes and connect them to a vector network analyzer. Moreover, prototypes fed with these lines can be accurately calibrated with TLR (Through-Reflect-Line) calibration kits. That allows to move the reference plane to the beginning of the waveguide and removes the losses and effects of the feeding line and connectors. It is recommended to design the prototypes with the same length as the calibration kits, so the same kit can be used to measure multiple prototypes. For different frequency bands, feeding lines with different lengths and widths must be used, and obviously, different calibration kits will be required.

Figure 11.
Layers in PCB.

Depending on the connectors used to measure, the design of the feeding line changes slightly. Usually, these connectors are either typical removable coaxial RF connectors or soldered ones. In **Figure 12**, some calibration kits can be seen with different connectors.

4.2 External metallization

The main raw material for building 3D structures piling up layers is PCBs; there are lots of commercial choices with different characteristics and heights depending on the working frequency and requirements of the prototype. These substrates are made of different components and have none, one (top or bottom), or two (top and bottom) thin layers of copper or other metals. The main idea is to stack different layers of different heights extracted from these substrates to create a whole 3D structure.

With the aim of building a metallic external wall, some layers must be externally metallized, and this can be done with a die cut system similar to the example shown in **Figure 13**. As it can be seen, the layer is almost fully metallized externally except for the small tabs located in the corners, which are needed to hold the structure to the PCB. The substrate around the external metallization of the prototype can be removed by simple exterior cuts shortened enough to hold the structure. The result is a completely metallized edge of these layers, but for the small corners as it was noted before.

4.3 Machine corrections

To reduce errors during the manufacturing process, machinery side effects must be identified and characterized. In case of using a multipurpose UV Laser System such as a cutter/plotter laser, these lasers are slightly tilted [11]. So that substrates will be

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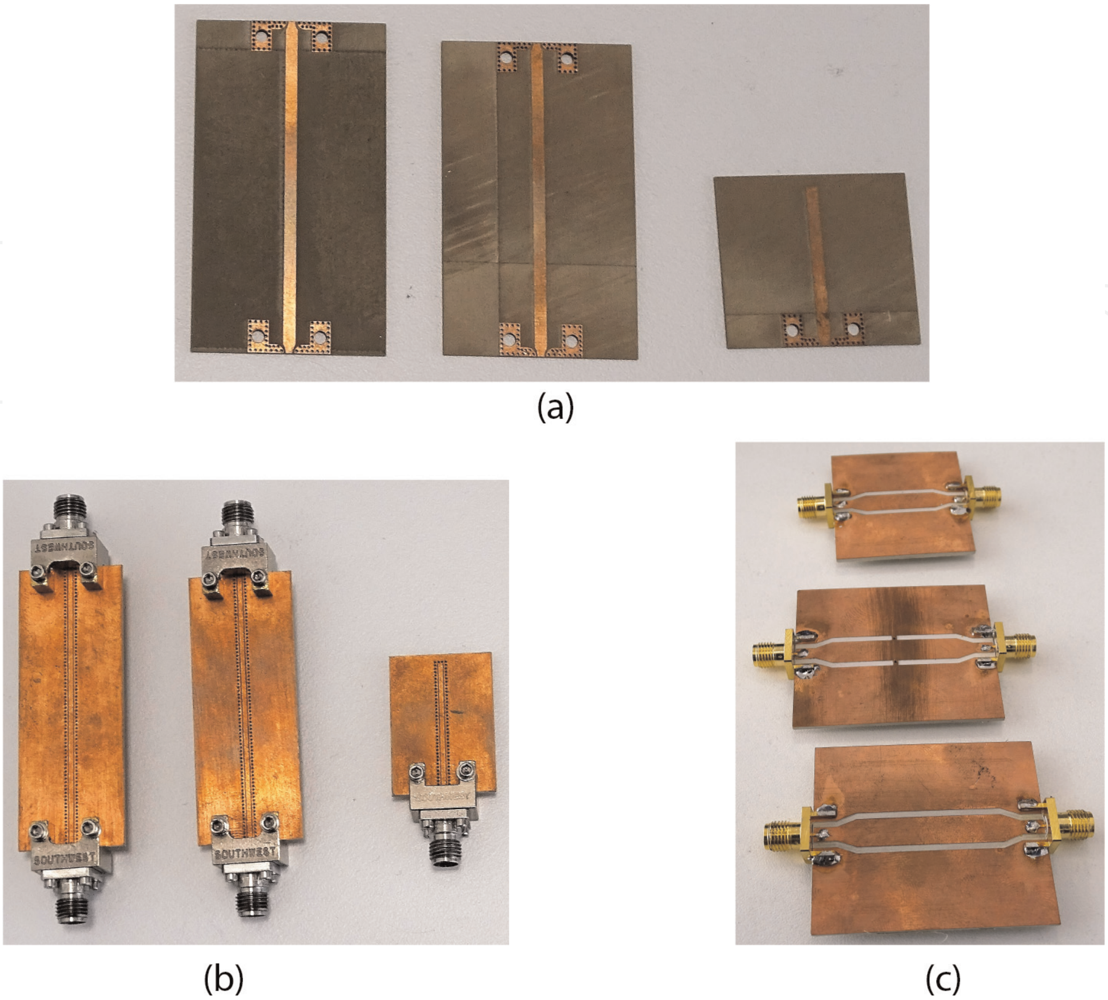

Figure 12.
Calibration kits. a) Microstrip calibration kit without removable connectors, (b) coplanar calibration kit with removable connectors, (c) coplanar calibration kit with soldered connectors.

cut with certain angle, producing a small ramp instead of a 90° cut (see **Figure 14**), which can be measured with a microscope or a vision system to incorporate the proper correction during the design phase of the prototype. Thus, an over-cut equal to the measured deviation compensates the effect of non-perpendicular laser cutting.

As it is shown in **Figure 15**, this ramp can be divided in three points: 1 (upper point of the ramp), 2 (lower point of the ramp), and 3 (middle point or average point of the ramp). Without correction or overcut, points 2 and 3 are lightly smaller than they should be. Over-cutting enlarges this cut adding this laser error and moving the desired size to point 3, the middle point, instead of point 1. This shifting produces point 1 to be a bit larger and point 2 to be a bit smaller; however, on average this cut is just as it should be. By doing this, the frequency shift presented by selective devices, such as filters, is drastically reduced, with the measured parameters of the prototype being more similar to the simulated ones.

Some cuts have complex geometries or are very tiny. These machines may have problems doing them correctly, because of that, additional cutting phases with simple shapes in certain areas are interesting to solve these issues. The same can happen for difficult milling areas and the solution is similar; additional milling layers should be defined, but it must be done carefully to avoid substrate from burning or getting damaged.

Figure 13.
Die cut example.

Although these machines work similar along the time, tools may need to be adjusted manually to seek for optimal performance every few months. This can be done easily using scraps of previous substrates.

If the prototype has holes used to pass through a wire or alignment pins, the overcut must be double to assure enough clearance in the whole hole to pass the wire or pin properly. In case there is a metallization, holes and cuts are reduced due to the presence of the additional metal and need to be taken into account to define the needed overcutting. Metallization can be either measured or calculated depending on the process, with the measured value being preferable when possible.

In case of using a mechanical cutter such as a drilling machine, the drill is really close to a perfect perpendicular cut. However, drilling tools are usually bigger or smaller to the theoretical size, due to fabrication tolerances. To avoid this, the size can be easily measured by doing a small cut in the substrate that we are using and measuring it, applying the proper correction in case it was needed.

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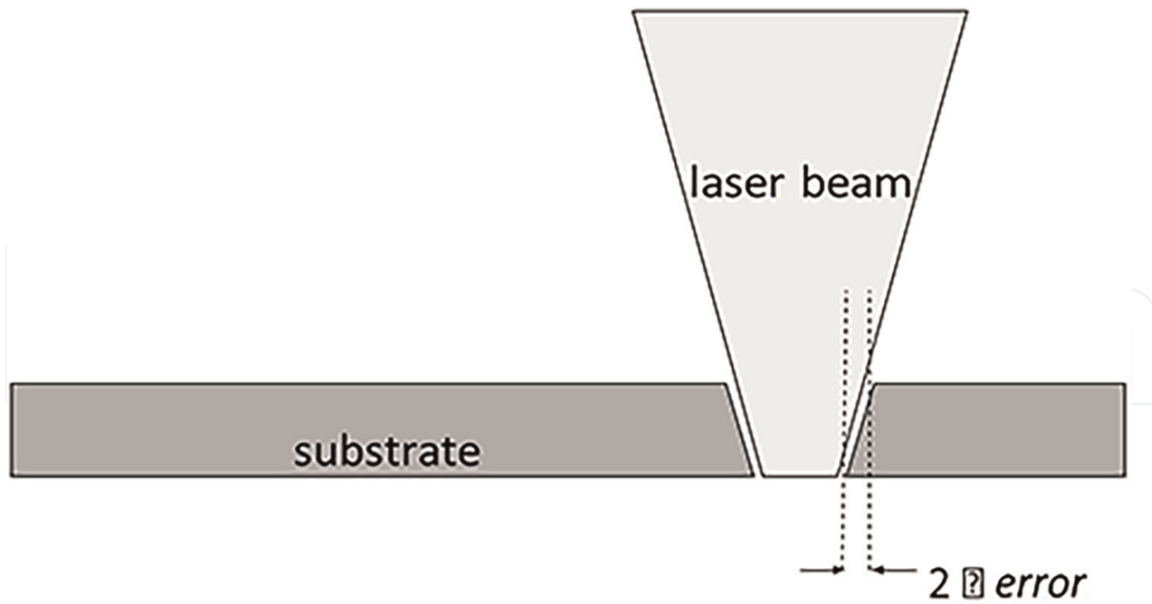

Figure 14.
Laser cut error. Lasers are slightly tilted, and this produces a small ramp instead of a 90° cut with some negative impact.

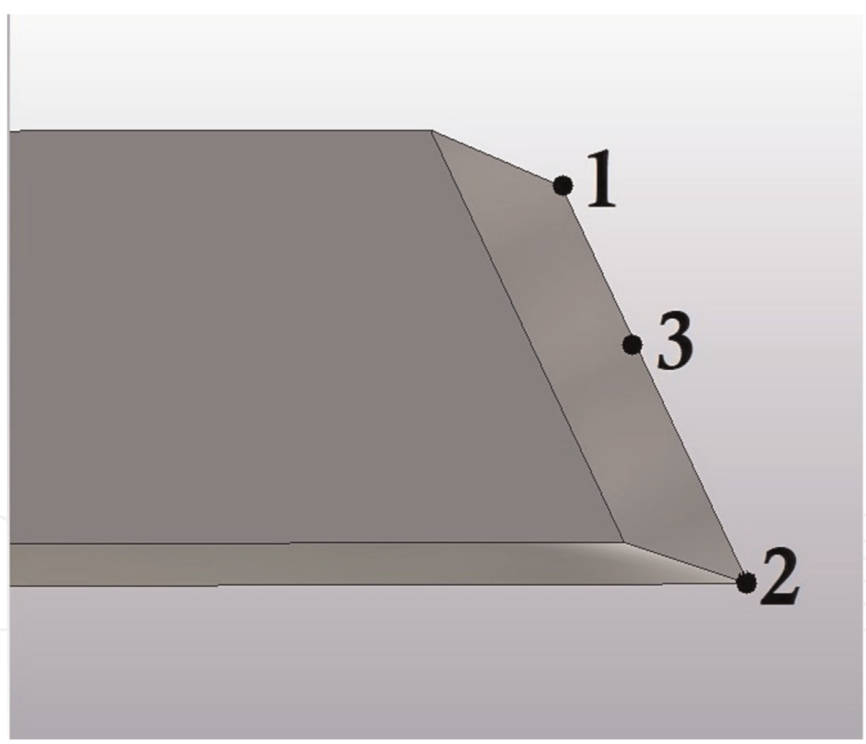

Figure 15.
Laser cut error, Figure extracted from [12].

The absence of these corrections can produce frequency shiftings and misfunctions in the performance of the prototypes, among other effects.

4.4 Assembling and weldering

One of the easiest and better ways to ensemble properly the layers of the prototype is by using alignment rivets, screws, or dowel pins. The position of the alignment holes to pass the pins through is arbitrary as long as they are outside the sensible areas of the circuit, but need to be the same in all the circuit layers [13].

Taking the former into account, the process consists of stacking all the circuit layers and roll out soldering paste between layers. Once all the layers have been stacked, a heating process must be done to melt the paste and weld the different layers of the prototype.

The soldering paste can be rolled out manually, but an automatic dispenser will provide more repeatable results. The soldering paste must be set by small dots and evenly separated among them. If there is too much paste, it will overflow inside the cavity, increasing the losses of the prototype, and producing missmatches and undesired frequency shifts. On the other hand, if there is not enough soldering paste, this will produce a poorly welded device with a highly degraded performance. After having manufactured several prototypes, the technician will have the experience to know almost the exact amount of paste to be used for each kind of circuit.

The first option to align the layers could be to use alignment screws with nuts properly tightened to make the needed pressure all around the prototype and to weld the soldering paste in a reflow oven. However, pressure could be not evenly distributed on the welding area, as it depends on the number and distribution of the screws. Moreover, the pressure done by the screws directly over the prototype layer can externally damage the structure. To prevent this, press covers can be used.

Press covers consist of some additional non-metallized and non-adherent layers that are located above the top cover and below the bottom one to make a more uniform pressure along the prototype. If covers were metallized or adherented, they could be welded to the prototype due to an eventual overflow of soldering paste. Once the prototype has been properly soldered, press covers should be removed, as well as screws and dowel pins.

When the welding among layers is not good enough, the discontinuities between successive layers can result in small cavities. This effect, for structures such as ESIW, will cause the magnetic currents to modify their path by coinciding these cavities with their direction due to the TEM mode (Transverse Electro-Magnetic), degrading the response of the device and causing anomalies. In ESICL lines, however, the magnetic currents do not coincide with the possible discontinuities (cavities) produced; for this reason, welding is not necessary in these prototypes, and screws and nuts can assure a proper performance of the device, this assembling process being quicker due to the lack of welding process.

Rivets work similar to screws for alignment, being the pressure along the prototype uneven and not as tight as screws.

Dowel pins combined with a multipress usually produce better results as pressing machines press evenly the circuit. For this process, press covers (additional layers similar to those described to be used with screws) must be used to protect the circuit. If pressing machines do too much pressure on the circuit, this can lead to a bending of the covers deforming the inner cavities. To prevent this, different press covers adapted to the geometry of the welded area must be designed [14]. The same idea improves the results using screws and a reflow oven; however, whenever possible, press machines and dowel pins give much better results than screws and reflow oven.

Another thing to be taken into account is that the presence of soldering paste produces a little layer of a few microns that can enlarge/enheight the waveguide, with enough pressure while the paste melts this layer being reduced, and this effect can be negligible.

4.4.1 Manufacturing process of vias

Although soldering and fencing vias have different purposes, from the manufacturing point of view, both are metallized holes along the surface layers.

Soldering vias: Soldering vias are metallized holes used to fill in with soldering paste instead of spreading along the layers or to be used as a leak for excessive soldering paste.

Fencing vias: To assure a good isolation of the prototype, sometimes it is necessary to use fencing vias that work as a perfect electromagnetic wall [15], and whose diameter changes with the frequency at which the prototype is designed and the technology used. Fencing vias must be metallized; otherwise, the prototype will have big losses due to the resonant effect of these holes.

These metallized elements can work as resonators if the wavelength of the prototype is similar to the size of these vias, the same happens with the separation between them. The vias must follow these rules and use the formulas for SIWs design [15]:

- They must be equally separated in each row.
- They must be equally separated from the edges of the prototype.
- They must be small enough compared with the wavelength of the prototype.
- They must be separated enough compared with the wavelength of the prototype.

Figures 16 and **17** show an schematic view of fencing vias located around cavities. The layer in **Figure 16** has holes for alignment purposes (blue), vias (purple), and the inner cavity (yellow) named as *long*. In the example of **Figure 17** a separation of 0.1 mm toward the cavity was chosen to fulfill the requirement explained above.

4.5 Procedures requiring more than one soldering phase

Some prototypes, for example, RESIW or DRESIW devices [16], may need to be welded in two or more phases. To make possible a welding process divided into two or more phases, the methods described previously can be combined together. The only requirement for multiple soldering phases is to use different solder pastes with different melting temperatures, so that the following phases will not de-solder the already soldered layers in previous ones. For that, the soldering paste with the highest melting temperature will be used for the initial phase, and soldering pastes with lower melting temperatures will be used afterward when these phases contain the already welded parts of the circuit. This procedure is very useful for ridge prototypes; ridge prototypes may need different pressing covers with different geometries of each one of the pressing phases. **Figure 18** shows these press covers.

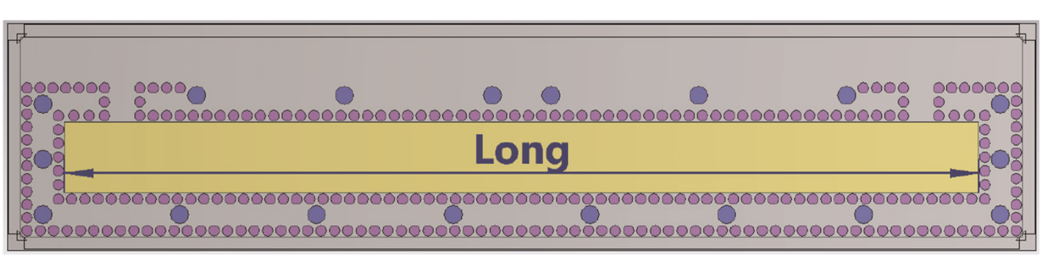

Figure 16.
Vias position.

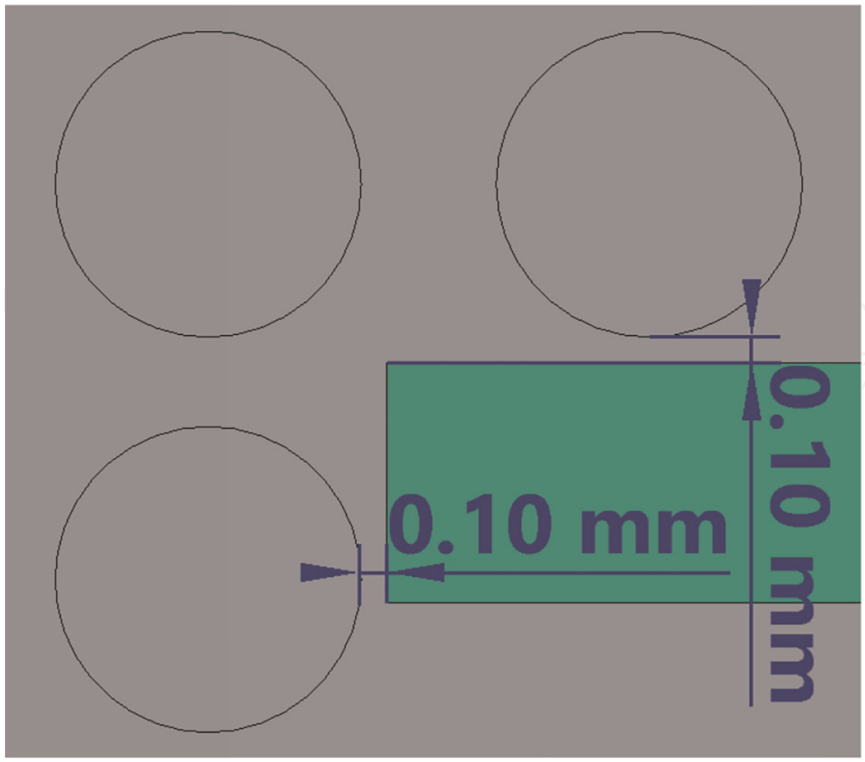

Figure 17.
Vias position toward edge example.

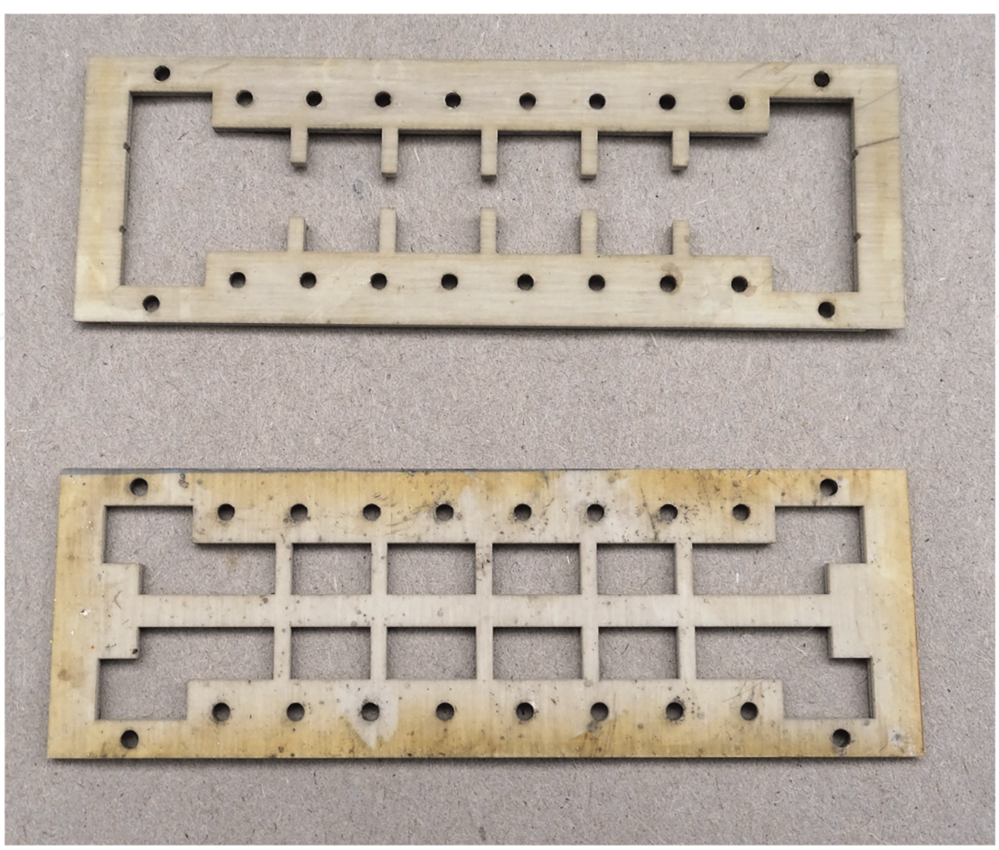

Figure 18.
Press covers of an RESIW filter [14].

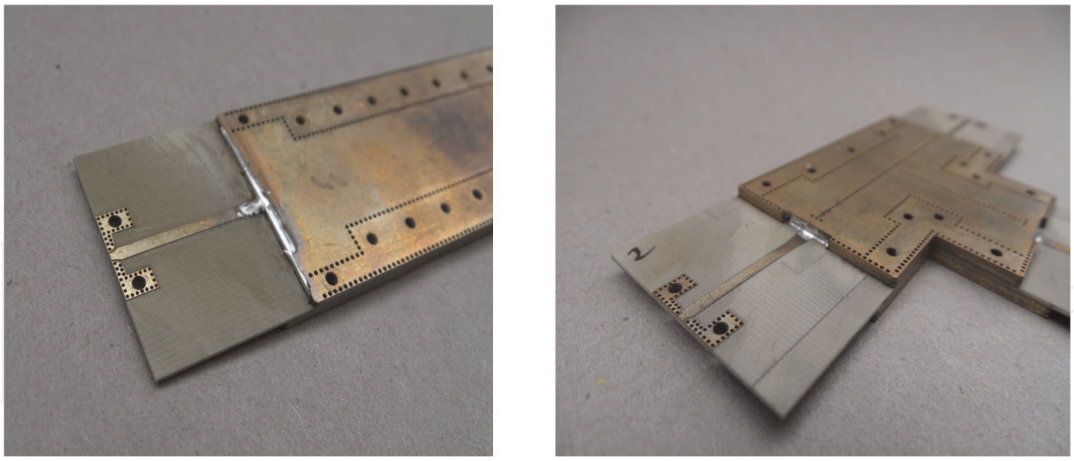

Figure 19.
Handly backing weld prototype examples.

This technique is also quite useful when prototype junctions are not good enough and need to be fixed manually with soldering paste and a welder. Moreover, if there was an overflow of solder paste, it can be removed with a de-soldering iron or roll out manually with a welder. These press covers are different to apply differently pressure in each soldering phase [14].

4.6 Handly backing weld

Some prototypes have sensible areas that need to be welded once the whole circuit has been ensemble. The idea is to roll out some solder paste in this places and melt it with a welder to ensure a good welding. In **Figure 19**, examples of this can be seen.

4.7 External elements

External elements, such as wires and rods, are very useful in order to design transitions [10, 17] or filters [18]. In the case of transitions, wires are used to connect the layers of the prototype (rods can also be used if they are small enough). On the other hand, rods are used as filter resonators.

Two factors are essential when wires and rods are used in the prototypes: their position and shape. Wires must be stretched as much as possible in order to reduce deformations and foldings of itself. On the other hand, the easiest way to ensure the position is through a hole. To assure a good electrical contact in the weldering, the hole must be fully metallized, a galvanic or a through-hole plating metallization is recommended for that. The metallization must be taking into account, as the hole will narrow some microns. If a laser cutting machine is used, the diameter of this hole must be found out by testing different diameters in order to take into account the laser error due to the non-perpendicular hole and the reduction of the hole due to the metallization process, as it was explained in Section 4.3. **Figure 20** shows an example of this testing; in each column each hole is increased by a few microns regarding the previous one.

After the wire is crossed through the hole, it has to be welded to the hole with soldering paste. It must be done trying to minimize the residues of this paste. Once

Figure 20.
Swept hole diameter.

this wire is welded, the spare wire must be removed by cutting it. Then, depending on the structure of the prototype, the other end of the wire can be welded to its own hole. While crossing the wire through the whole, if the hole is very tight, metallization can be detached as the wire pushes it away. Therefore, electrical contact would be spoiled, so that it must be done carefully. If metallization is taken away, performance of the prototype will degrade.

There are other considerations to take into account. If there are more welding phases after weldering the wire, a soldering paste with higher melting point must be used to weld the wire to avoid de-soldering in the following processes which will have lower melting points.

The higher the conductivity of the wire is, the better the results will be. However, due to the small size of these elements in microwave devices, conductors such as brass or tinned copper are enough to achieve good results.

When possible, wires should be replaced by rods. In case wires were used, they must be stretched in order to reduce foldings and deformations.

5. Conclusions

3D prototypes can be done with planar procedures piling up different layers to build three-dimensional structures. The techniques used for manufacturing planar circuits can be adapted to build these prototypes, which can be combined with external elements such as wires or rods.

Different modifications have been shown to improve results in each manufacturing phase; errors and specific features of each machine must be taking into account to reduce its impact in the manufactured layers. Over-cut, under-cut, measurement and estimations are some of the techniques used to reduce these effects.

Regarding the assembling techniques with screws or dowel pins, the issues due to pressure, excess/lack of soldering paste, etc., should be considered. Finally, the use of press covers is also recommended in soldering phases, taking into account that technologies such as RESIW or DRESIW have some variations.

All the information collected in this chapter has been extracted from empirical evidence and real circuits that have been manufactured.

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