Defining the Production Role of Laser Technology in PCB Fabrication into the Millennium

By

Larry W. Burgess
LaserVia™ Drilling Centers, L.L.C.
Wilsonville, Oregon, USA

Fabrizio Pauri
Pluritec Italia S.p.A.
Burolo d'Ivrea, Italy

ABSTRACT
Laser technology has been around for nearly 30 years, but has only recently found "production" acceptance in the circuit board marketplace as a method for producing blind vias, especially within Surface Mount Pads. Today seven, maybe more, laser systems have been introduced into the circuit board industry. Confusion exists about which system to use and what technologies support which market segments. Each of these systems has clear strengths and weaknesses. This paper will describe the strengths and weaknesses of <u>all</u> the known systems. The authors will profile current use of lasers for drilling blind vias, profile routing, and where the future is believed to be headed.

Key Words: Laser, BGAs, QFPs, Microvia, Via-in-Pad

INTRODUCTION
The most costly process in the fabrication to today's multilayer printed circuit board (PCB) is the process of making z-axis interconnections or vias. This is driven at the fabrication level by two factors, the size of the vias including microvias (≤ 0.150mm diameter) being demanded and the growing number of vias that are on a panel.

> *"Of all the interconnection methodologies, the manner in which holes (or vias) are produced has the most effect on the relationship of the interconnecting structure and how it is produced."* [1]

The following statement from a major electronic equipment manufacturer in the communications field has been quoted from a paper delivered at IPC Expo '98[2]:

> *It has been shown that the size of the via capture pad is the major contributor to board complexity in dense circuit designs. All of the microvia technologies directly address this problem by the use of much smaller capture pads, or by the total elimination of capture pads when the microvias are placed directly in the component solder pads. Vias in solder pads have no effect on solder joint reliability.*
>
> *Extensive work with many board suppliers worldwide has shown that there is no correlation between the method that a supplier uses to form microvias and the price an equipment manufacturer is charged for an HDI board. It seems that, although lasers form vias sequentially while the other methods form them simultaneously, the supposed cost advantage of the mass via methods at higher via densities is offset by process difficulties, lower yields, and other factors. It is also apparent that both laser via and photovia methods are less costly than the multilayer mechanically drilled technology against which they really compete. It may be that the cost of putting in microvias is inconsequential in the pricing of the product.*
>
> *Experience and computer simulations show that the improvement in circuit performance gained from the use of high performance materials in the HDI layer is minimal for many applications. Some structures such as 50 ohm striplines cannot be manufactured with HDI dielectrics given existing design rules. The added thickness of a standard FR-4 laminate is needed. Other nonstandard structures are possible, such as lower impedance lines. which might prove useful. For applications where high performance materials are found to be necessary, the laser method for fabricating vias would have an advantage over photolithography at this time. Most of the materials that would be termed "high performance" are easily ablated with a laser, but they are not photoimageable.*

The next question however is: which laser system to use for the production of microvias?

A new laser system has been designed that will actually produce multiple depth vias with a single pulse.[3] The ability to drill down multiple depths with a single pulse provides a very cost-effective method for producing "stacked vias".

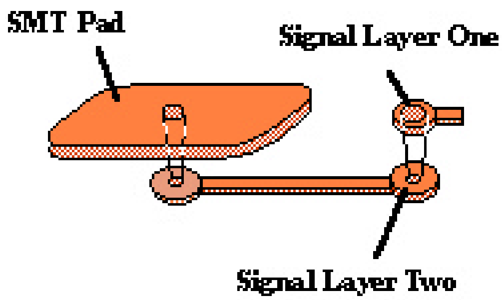


Figure 1. "Via-in-Pad"

SOME BASIC LASER PHYSICS

While many people understand the physics of laser drilling circuit boards many are not aware of the general physics. In laymen's terms, the light generated from a laser is what vaporizes or ablates the material it is focused on.

Vaporization is the action of making a solid material move to its gaseous state. When a laser beam is directed through a specific lens at a material, the energy released by the laser can be sufficient to vaporize that material.

When ablation occurs using a laser beam, the light is absorbed by the substrate material and a reaction occurs that breaks the chemical bonds within the material so that the material can be removed. The most commonly seen ablation in the circuit board industry is when UV light is directed toward a positive reacting photo resist where the chemical bonds within the resists are broken and the resist can be developed away. Eximer lasers are used to ablate organic materials.

The most confusing reality about laser technology is the fact that the denser the material the more energy is needed to vaporize it. Copper is the most dense material followed by the glass in FR4. The organic polymer that is normally Epoxy, is not dense and therefore takes very little energy.

The challenge when using a very high-energy source like a laser to remove different materials is to control the energy so as to not damage the materials that react violently to the high energy. There are several ways to control this energy. First is to use a short wave laser that can pulse at a very high rate. With this technique a very "hot" laser beam (measured in either joules or watts) can be pulsed in rapid fashion to remove most dense materials. The absorption of the beam is also a major consideration that must be noted. It should also be noted that with the use of this high-energy beam, the beam diameter is limited. Otherwise too much energy will be emitted onto the material and create a large managed area. So the beam diameter is limited in size for removing dense materials like copper and FR4. This forces these high-energy lasers to use a technique called trepanning for removal of material in an area greater than the beam diameter. Trepanning is done by moving the beam over the desired area in such a fashion that the energy is spread out.

The high-energy beam lasers that are finding use for removing copper and FR4 are from the Ultraviolet (UV) segment of the light wavelength chart. It might not be clear yet, but the high energy, short wave length that allows these lasers to vaporize dense materials also is the reason why they are quite slow in processing circuit board panels with the ever-increasing microvia demand.

On the other side of the wavelength spectrum are the long wavelength lasers or Infrared (IR) lasers. While these lasers are not able to remove copper with the longer wavelength they emit, they are used in metal cutting where a single material is involved because they are cheaper to operate. These lasers naturally penetrate deeper and therefore are usually not pulsed at the same rate as the UV laser.

The IR lasers are naturally reflected by metals especially copper and therefore can use a larger beam size over a conformal mask and emit enough energy to penetrate deep into the dielectric material.

While the IR lasers are not able to remove copper and are also slow in removing FR4, they need to spend less time over a given organic material than the UV which needs to be pulsed a great number of times. In addition the UV laser has to trepan to remove a typical area of organic material for today's circuit board plating techniques.

With the IR laser beam it is possible when using a proprietary beam delivery system, to pulse the laser beam over a copper etched window (conformal mask) a single time. In fact it has been reported the multiple vias can be effectively single pulsed using an over sized defocused beam.[3]

More specific information on the UV and IR laser technologies will be covered later in this paper.

THE LASER MICROVIA CHALLENGE

All of the areas surrounding the fabrication and manufacturing (assembly) of a Printed Circuit Board must be understood in order to make a qualified and quantified decision about technology advancement. The major and most visible areas include:

- Design
- Fabrication
- Assembly
- Test

Design:

Each of the above listed printed circuit manufacturing categories introduces limitations for processing PCB's. For example, the Design may demand controlled impedance, or high speed signal processing. The introduction of either of these two technical issues now involves component selection, component placement, dielectric material selection, dielectric thickness selection and signal integrity. The result of the introduction of either of these two technical issues at the design level can have a significant effect in the Fabrication, the Assembly and Testing of these circuits.

The signal integrity of a circuit has a major effect on how the layup of the signals layers are placed in relationship to each other and if power and/or ground layers are needed to insure signal integrity. Often when a circuit has been electronically simulated, it can force the circuit designer into a fixed set of rules for the finished Computer Aided Design (CAD). Many times a highly skilled CAD designer will have to introduce "work-arounds" to accommodate the required design features, when the CAD tool is not programmed to automatically follow the designers wishes.

The fiercely competitive CAD world, especially the auto-routers that are used to connect to the "pins" or component interconnections, responds rapidly to eliminate the "work-arounds" used by CAD designers. Today's difficulty with interconnecting staggered vias using an auto-router will surely be accomplished before the year 2000.

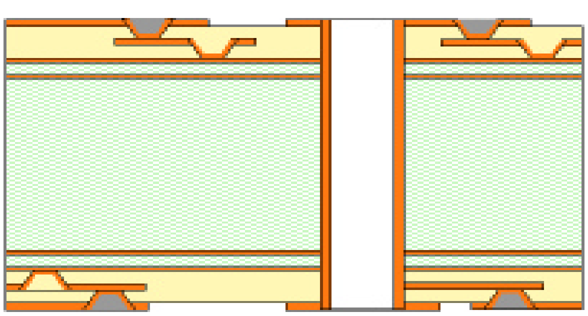


Figure 2. Buildup Technology "Staggered Vias"

Even though a technology issue like the staggered via can be solved, it does not mean it will be the most cost effective method for fabricating the circuit board. In the case of staggered vias versus stacked vias, the staggered vias take several extra process steps and in some cases can double the cost of fabricating the circuit board.

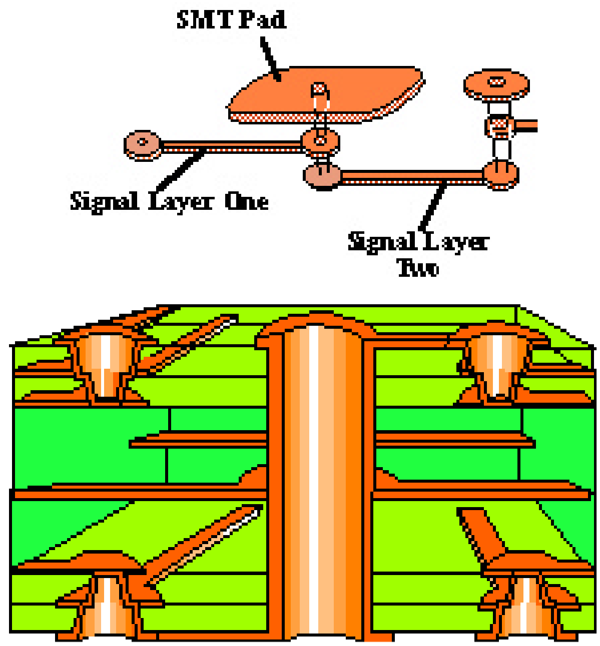


Figure 3. "Stacked Vias"

Fabrication:

Today Z-axis interconnections are finding the most activity, as drilling has become the highest single process step in the fabrication process. The demand for reducing the diameter of the drilled holes, called microvias, along with the ever-increasing number of Z-axis interconnections are the two main driving forces behind the cost increases for drilling.

This demand for microvias has further complicated the increase in z-axis costs. Especially when the focus is on the demand for blind microvias, which are the most effective or cheapest interconnection methodologies from the CAD designer's point of view. Designers use a costing chart to prioritize the various methods for interconnecting circuits. The method of choice or the one that allows the most density is generally the cheapest from the CAD designer's point of view. However, this interconnection choice has not always been the cheapest at the Fabrication stage of building circuit boards. Today it is clear the blind microvia is the Z-axis interconnect method that needs to be fabricated. As the designs move to demand multiple depth interconnections, which can be done by the build up method shown in Figure 2, or the stacked method shown in Figure 3. With the stacked method, the vias can be laser drilled in the same fashion as the mechanical drilling is done, and save the costs of producing a nearly complete second panel, which is demanded of the buildup technologies.

The great effort to increase the output of laser drilling equipment has finally made laser drilling a viable alternative to mechanically drilled blind vias and now can be considered a true production process. This is not the case, however with all laser drilling processes. The key to introducing a true production process happens only when all of the physics are understood and taken into consideration. It is important to match the circuit design with the material and laser process.

It is further important to know what the true average output of the laser system really is and the peak output. This can only be determined when a test circuit is drilled with the various laser systems.

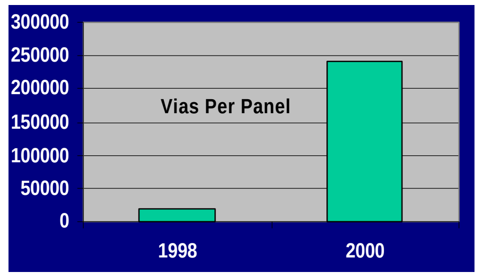
Assembly:
The most significant effect on the assembly is directly related to the selection of components at the design level. However much of the fabrication process can determine how successful the assembly process will be.

The decrease in component Input/Output (I/O) pitch of the distance between pad is on a constant decrease and expected to stay at 0.5mm for a period of time. This fine pitch has a significant effect on the assembly operation and the manufactures of equipment for assembly. With the decrease in component pitch the design and fabrication areas need to find methods to interconnect inside the component footprint and the method of choice is now "via-in-pad" coupled with the requirement for new soldering techniques. Many new techniques are being introduced such as nickel palladium, organic copper coatings and of course gold is finding new interest as a cover for copper oxidation prevention.

Test:
The challenge at the testing level is directed toward methods for interconnecting to microvias. The decrease in feature size of the components and component pads on the outer layers of the circuit boards has complicated the ability to use the standard bed of nails testing. Placing probes on component pads has long been the last choice of testing programs and is extremely more complicated with Via-in Pad and the fine pitch small component pads being introduced.

One solution is to design the circuits using blind microvias to place rows of test pads in strategic areas that can be connected to conventional probes for testing. Another method that is finding acceptance in the printed circuit arena from the integrated circuit world is Boundary Scan Testing.

THE CHALLENGING FUTURE
In 1997 an article projected the increase of interconnections (directly relating to microvias) that were produced on a panel and what is to be expected as we enter the Millennium.[4]



- **1998: 20,000 vias per Panel**
- **2000: 240,000 vias per Panel**

Figure 4. Projected Growth in Vias/Panel

TODAY'S LASER DRILLING OPTIONS
There are several laser systems being used in today's market to drill printed circuit boards, they include:
Ultraviolet Lasers:
- Eximer Laser
- Neodymium-doped, Yttrium-Aluminum-Garnet (Nd:YAG)
- Neodymium-doped, Yttrium-Lithium-Fluorine (Nd:YLF).

Infared Lasers:
- Continuous Wave Carbon Dioxide (CO_2) Laser
- Transverse Excited Atmospheric Carbon Dioxide (TEA CO_2) Laser
- Sealed Radio Frequency Excited Carbon Dioxide (Sealed RF Excited CO_2) Laser

Metal-Chemical Lasers:
- Copper Vapor Laser (CVL)

The two of the three laser categories from the above list of lasers systems that are finding expectance into the Printed Circuit Board Fabrication market are the UV laser and the Infrared laser systems. The Copper Vapor Laser is not at the moment an accepted laser drilling platform. It has a very short pulse and extremely high pulse rate. CVL lasers have also been configured to produce high pulse repetition rate output in the ultra-violet. This is done through frequency doubling and mixing techniques.

Each laser system has strengths and weaknesses and should be studied prior to use and purchase. The Nd:YAG, Nd:YLF, TEA CO_2 and Sealed RF Excited CO_2, are four laser systems finding acceptance into the PCB Industry. We will focus on these two categories which included the four laser systems types that are successfully being introduced into the printed circuit board industry.

<u>UV Lasers</u>:
There are two types of UV lasers being introduced. They are the Neodymium-doped, Yttrium-Aluminum-Garnet (Nd:YAG) and the Neodymium-doped, Yttrium-Lithium-Fluorine (Nd:YLF).

The Nd:YAG with it's frequency shifted state (266 & 355nm) is a continuously pumped, repetitively q-switched laser system and the Nd:YLF is a diode pumped, q-switched laser system. Both metals and organic materials (dielectric materials) are readily absorbed by the frequency of the beam that exits these two UV laser systems. Much effort has been given in an attempt to move the absorption toward the dielectric material away from the metal absorption characteristics, however the UV's still are absorbed by the metals at a higher rate than the organic materials. This serves the UV laser systems well in the removal of copper foils from the surfaces of circuit board panels, but creates very tight process controls for dielectric removal. The typical high energy focused beam with a short wave length from the UV lasers must enter the dielectric window of a conformal mask either after it has been chemically etched or vaporized by the UV laser in a near exact position in order to remove the dielectric material. Furthermore the typical small beam diameter that is delivered needs to trepan the opening in order to remove the dielectric material for today's typical fabrication plating process. This of course adds significant time to the laser processing of large panel areas, resulting is significant high per blind microvia costs.

<u>Infrared Lasers</u>:
There are also two types of Infrared laser systems being introduced that are both Carbon Dioxide. [Reports of another kind of CO_2 laser for drilling circuit boards in Japan have been noted, but little information on this laser in known.]

The CO_2 laser is situated to drill organic polymers with its long wavelength and natural tendency to be reflected off of metal, especially copper.

The two types of CO_2 laser systems are the Sealed RF Excited CO_2 and the TEA CO_2. The other system listed above have found little acceptance into the market primarily due to the fact that they do not effectively drill a broad range of dielectric materials, they are expensive to run, hard to control or they are not situated to drill large panel areas.

"AT THE END OF THE DAY"
While all the information on the laser system can be quite confusing to the non-laser using engineer, at the end of the day, in a production environment, the question is: "How many panels can be produced with each system?" Or when it really comes down to determining the value of a laser system it is how many vias per second and how much do they cost, so that these costs can be passed on to the customer.

To weed through all the capabilities and understand the true outputs of the various laser systems is a difficult task as published outputs are generally not given from an agreed "common ground" specification. Many capabilities are published using peak drilling speeds and do not represent the true output, which should be the average laser drilled via output for a panel. In addition, for measuring true production capabilities, load, alignment and unload should be part of the average laser drilled via output equation. Laser drilled via output is always circuit design dependent, so it is even more important to set a standard for testing the output of laser systems. This issue is not dissimilar from the confusion that has plagued circuit board mechanical drilling room engineers for years.

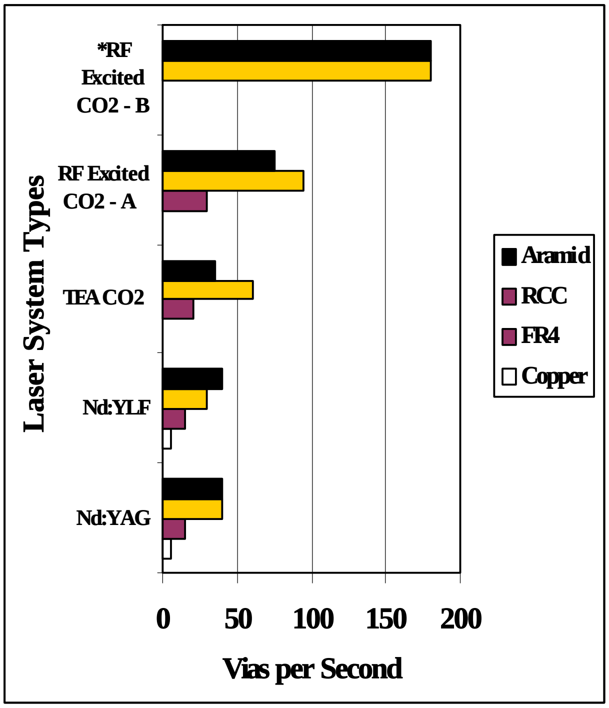
While the laser systems have the advantage of eliminating the per drill bit costs, many do have an operating cost with replacement crystals, recharging gasses and general maintenance costs that are not commonly known.

Since laser drilling technology is still an emerging technology, maintenance costs are not readily available for comparing the laser system. It can be generally stated however that the Sealed RF Excited CO_2 does have a 20,000 working hour guarantee from one vendor[5], which clearly makes it the least expensive to operate of the laser systems known to the authors and described in this paper. While in a production mode the costs of operation are very important, it is the laser drilled via output that should first be studied.

CYCLE TIME- "The real factor"
What should really be studied is the "cycle time" for loading, aligning, laser drilling and unloading a circuit board panel to understand the output from any given laser drilling system.

At the moment, the leading laser technologies are the RF Excited CO_2 using non-woven reinforcement. What can be compared however are the capabilities and general outputs of each system in the following graph:

Blind via diameter: 0.152 mm (0.006")
Aramid: 0.0887 mm (0.0035")
RCC: 0.051 mm (0.002")
FR4: 0.051 mm (0.002")
Copper: 0.018 mm (0.0007")



**This system has a proprietary beam delivery system*

Figure 5. Laser System Capacities**

**Please note: to produce an accurate comparison, a test circuit would have to be processed with each laser technology under similar conditions.

SEQUENTIAL-MASS FORMING PENDULUM

PCB fabricators traditionally have a mass forming approach that comes from their chemistry background, where although processes are a sequence of bathes, each panel is processed in the same time. On the other side, drilling and testing processes are purely sequential, they are in fact a sequence of point to point actions and are considered the real pain in the back by fabricators. Laser drilling equipment manufacturers tried to push their machine as a natural evolution of mechanical drilling (laser as a cutting tool). This brought to what has been defined the 'monkey syndrome', where a mere imitation occurs instead of a real interpretation of the needs. Second generation manufacturers are more sensitive to the real value of the processes. Would any PCB fabricator use a router to remove copper from a surface, as a sequential process? So let's assume that any process that can be kept as mass production is more appreciated by fabricators. Laser blind microvia drilling involves 2 different phases: copper removal and dielectric removal. Early laser manufacturers claimed that their laser could do both the processes, some of them also boosted that they could plate using the laser! What about transmuting copper to gold! A more equilibrated approach should free the laser from this overwhelming responsibility and find where the laser beam is actually needed and fully exploited.

If copper removal could be performed in the traditional 'mass formation' way, this choice should be made in order to relegate the laser to the most critical aspect: dielectric removal. Think now what this could mean: the laser beam can freely fly over the panel, looking for the bare dielectric to remove, without any depth control or trepanning or spiraling. But -a fabricator would say- this means productivity! You said that! The magic word: PRODUCTIVITY.

What is interesting for a real industrial environment is how the process flows, how fast it is, what's the actual throughput.

Mass forming is by far faster and more cost-effective, but requires a strict control over the process. This doesn't frighten fabricators, keeping a process under control is exactly their job: they know how to do it!

CONCLUSION

The microvia processing decision is a difficult one at best. Without considering the other competing microvia technologies, one must really understand which laser technology is right for the current and future emerging microvia market. Clearly the UV laser systems offer the most flexibility with the ability to drill copper, FR4 dielectric materials along with the newer microvia materials like Aramid, unsupported epoxy or polyimide materials and photo-dielectrics. However, the processing speeds (vias/second or panels per hour) are not generally acceptable for production. On the other hand, the CO_2 systems with material processing limitations clearly enjoy production capability today and should continue to gain output capability as new developments are introduced.

The general observation for the laser microvia drilling technology determination choices are:

1. ***"Purchase capital equipment for capability today"***

   or,

2. ***"Purchase for production output tomorrow, in the emerging laser drilling market."***

REFERENCES

[1] Karl Dietz, NEMI Roadmap, 1998

[2] Kevin Arledge and Tom Swirbel, "Microvias in Printed Circuit Design", IPC Expo 98, pp S08-1-1 through S08-1-8

[3] Larry W. Burgess and Paul D. Madden, "Designing and Fabricating Multi-Depth Via-in-Pad PCB's: Production", IPC Expo 98, pp S17-2-1 through S17-2-4.

[4] Terry Costlow, Electronic Engineering Times, September 1997

[5] Synrad Corporation, Mukiteo, WA

BIOGRAPHIES

Larry W. Burgess has over thirty years experience in the interconnect packaging disciplines. He holds a Bachelor's Degree in chemistry and has held Management and Engineering Management positions at fortune 100 electronic companies. He is President and Chief Technical Officer at MicroPak Laboratories, Inc., where he has licensed technology to Sandia National Laboratories. MicroPak has recently formed a joint venture with Pluritec. Currently Mr. Burgess has just opened the first in a series of Laser Drilling Centers in North America to support the upcoming demand for laser drilled blind microvias.

Fabrizio Pauri holds an advanced engineering degree (Laurea in Ingegneria Meccanica) from Politecnico di Milano. Since 1995 he has been employed at Pluritec Italia in the Research and Development Department as the Project Manager of laser microvia drilling machines. Currently he is developing processes and new techniques for laser drilling existing and new circuit board dielectric materials.