EPC European PCB Convention 1998
Wiesbaden, Germany, Sept. 29 – Oct.1, 1998

Fundamentals of laser drilling

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I would like to give you an overview for a practical use and a better understanding of the mechanism and interaction of laser beams with material especially relating to the processes of laser drilling.
Initially, I will present you a general and useful classification of laser applications used in PCB manufacturing.

1. Typical applications of laser technology in the manufacturing of PCB's

It is useful to distinguish between the following four groups with some examples:

- Material Removal with
  - Drilling — through and blind holes
  - Cutting — SMD-stencils, ceramic MCM's
  - Grooving — writing, isolation canals between Cu-tracks
- Trimming — resistor trimming
- Surface Treatment — drying of resists and different pastes
- Material Deposition — electroless plating

The material groups with typical examples are:

- Metals (copper, stainless steel)
- Polymere (polyimid, epoxy, teflon, LCP)
- Ceramic (alumina, green ceramic)
- Composite (FR4/5, CEM3, epoxy/aramid)

In the following, we consider the laser drilling process in more detail and one can use these explanations for other laser applications too.

2. Laser beam characteristics

It is advantageous to describe the laser beam relating to its beam shape and pulse characteristic.
The first important parameter is the wavelength of the laserradiation λ (193nm to 10,6µm). We will see later which lasers are typical for laser drilling.

Space distribution

The most important radial distribution of the beam intensity ***I(r)*** will be described by the Gaussian-Curve, also called TEM_{00}-mode, Fig1.

$$I(r) = I_0 \cdot exp\left\{\frac{-2r^2}{w^2}\right\} \qquad (1)$$

Note that by $r=w$ the intensity has decreased to $I_0 e^{-2} \approx 13{,}5\%$ of the maximal intensity I_0. In many practical cases one can approximate the Gaussian distribution by a tophat profile having the same power contended.

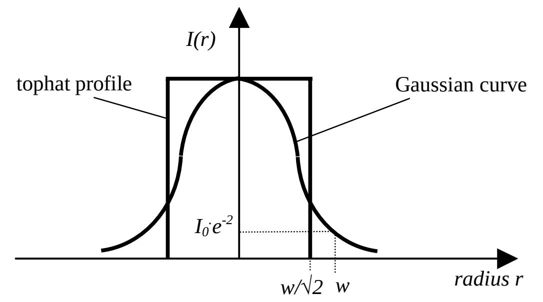

Fig. 1 Intensity distribution *I(r)* of laser beams

The beam radius *w(z)* is given by, Fig.2

$$w(z) = w_0\sqrt{1+\left(\frac{z}{z_r}\right)^2} \qquad (2)$$

w_0 is the beam waist (smallest beam radius) and $\boldsymbol{z_r}$ is a characteristic parameter of the beam propagation called the Rayleigh range where the beam radius has increased to $w_0\sqrt{2}$ by half of the beam intensity and is given by

$$z_r = \frac{\pi \cdot w_0^2}{\lambda \cdot M^2} \qquad (3)$$

The divergence θ (sometimes one can find the full angle 2θ) can be calculated for the far field ($z>z_R$) by

$$\theta \cdot w_0 = \frac{\lambda}{\pi} \cdot M^2 \qquad (4)$$

where $\theta \cdot w_0$ is called the beam parameter product which is constant in every case.

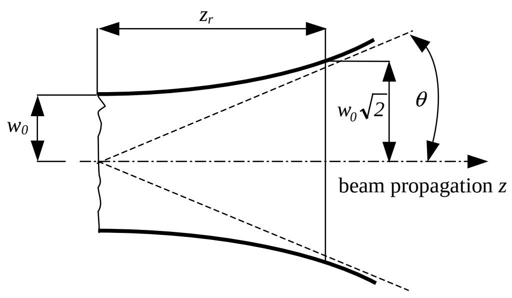

Fig.2 Laser beam radius and divergence

M^2 describes the beam quality and is called the **beam propagation factor** with an ideal theoretical value of $M^2=1$ (TEM_{00}-mode). In practical cases M^2 lies between *1.2* and *15*. Typical values of $2\cdot\theta$ are in the range of $1.1 \cdots 2.5 mrad$ ($\approx 0.06 \cdots 0.14°$).

For practical application, a good quality hole is defined by a high aspect ratio given by the depth of the hole over the diameter. This can be achieved only by a low beam parameter product (M^2 close to one) or, in other words, by a large Rayleigh range by a given spot size.

Temporal distribution

From the pulse diagramm can be derived the following time dependent parameters of the laser beam, Fig. 3.

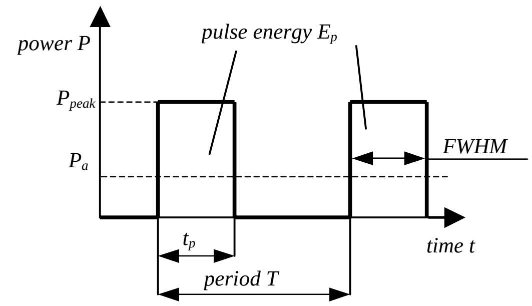

Fig.3 Pulse characteristic of the beam

P_a is the average power of the laser and t_p the pulse duration, which is practically defined by the *FWHM* (full width at half-maximum)

- Repetitionrate $\qquad f_p = \dfrac{1}{T} \qquad (5)$
- Pulse energy $\qquad E_p = \int_{t_p} P\,dt = P_{peak} \cdot t_p \qquad (6)$

  (rectangular pulse)
- Peakpower $\qquad P_{peak} = \dfrac{P_a}{t_p \cdot f_p} \qquad (7)$
- Intensity $\qquad I = \dfrac{P_{peak}}{A} = \dfrac{E_p}{A \cdot t_p} \qquad (8)$
- Fluence $\qquad W = \dfrac{E_p}{A} = \dfrac{P_{peak} \cdot t_p}{A} \qquad (9)$

To remove material during drilling processes the intensity and the fluence respectively have to exceed the typical material threshold. In this way the peak power and not the average power is important.

3. Beam transformation with lenses

For the manufacturing of exact laser holes, it is important to know the location and the size of the Gaussian beam transformed by lenses. We have to distingish between the two cases: focus mode and imaging.

Focus mode

Fig.4 shows the focussing of a Gaussian beam by a lens (system).

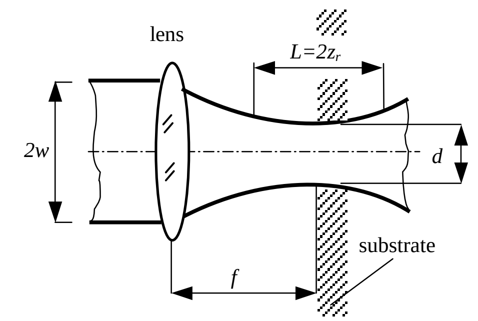

Fig.4 Focus mode

On condition that the divergence θ of the input beam is small the diameter d within the focal plane of the lens can be approximately calculated by

$$d = \frac{4 \cdot f \cdot \lambda}{\pi \cdot (2 \cdot w)} \cdot M^2 \qquad (10)$$

where $2w$ is the diameter of the input beam direct at the lens and f the focal length. Note that both diameters are defined by the e^{-2}-level. The second important parameter is the focus depth L which is given by

$$L = 2 \cdot z_r = \frac{8 \cdot \lambda \cdot f^2}{\pi \cdot (2 \cdot w)^2} \cdot M^2 \qquad (11)$$

To reduce the spot size d by a given λ one can decrease the focal length f or increase the input diameter $2w$ using a beam expander, Fig.5, or both. But, note that a smaller f will reduce the focus depth L. In the practical design this leads to a larger diameter sensitivity of the drilled hole and can decrease the influence of the pure gas to protect the lens.

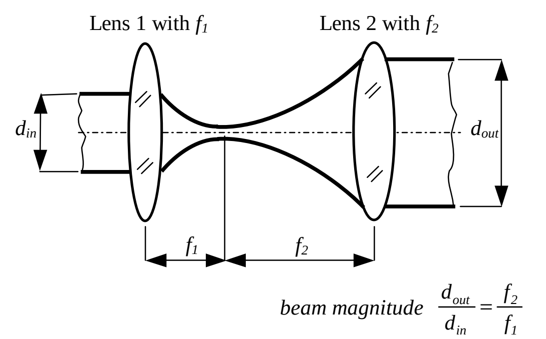

Fig.5 Beam expander

Example:
For a given CO_2-laser drilling system with a modified DIAMOND 64-laser (Coherent) where $\lambda=9{,}4\mu m$, $f=100mm$, $2w=14mm$ (i.e. expanded row laser beam by a factor 2) and $M^2=1.2$ one gets an optical spot diameter of $d=103\mu m$ and a Rayleigh range $z_r=733\mu m$.
If the machine tolerance between the focus lens and the board is equal this Rayleigh range z_r then the optical spot diameter will be realized in the range of 103 ··· 146µm.
The true hole diameter is larger by the factor 1.2···2, dependent on the drilled material.

Imaging

A mask (here a aperture) localized in the laser beam will be depicted by a lens from the object plane to the image plane, Fig.6.

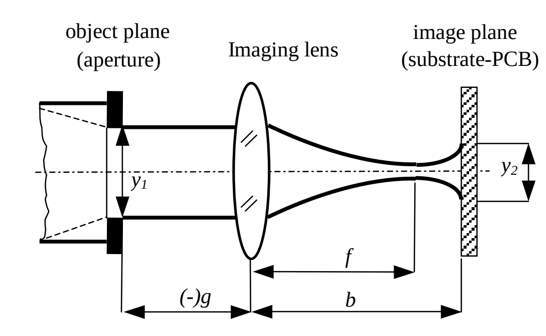

Fig.6 Imaging

The size of magnitude is given by

$$\beta = \frac{y_1}{y_2} = \frac{f-g}{f} \quad \text{with} \quad g = \frac{b \cdot f}{b+f} \qquad (12)$$

Here we neglect the part of diffraction. To realize a small picture y_2 which correlates with a small hole one needs a small aperture y_1 and a large object distance b.
This means for practical application that one can easily vary the hole diameter by changing the aperture.
In practical design, the transmission T of the laser radiation is limited by the aperture and can be calculated by

$$T = 1 - exp\left(\frac{-2r_0^2}{w_0^2}\right) \qquad (13)$$

where r_0 is the radius of the aperture. For example, with $r_0=w_0$ and $r_0=0{,}5w_0$, the transmission T is 87% and 40%, respectively. This can lead to a different optical design, Fig.6 dashed line, where the laser beam is focused onto the aperture to increase the proportion r_0/w_0.

4. Applied lasers for drilling

The lasers currently used in PCB drilling processes may be grouped into the following types, mainly distingished between the active medium and the wavelength λ:

C0₂-laser
λ=10,6µm (IR), more used are the modified lasers with λ=9,3 and 9,4µm (better absorptivity of the material) where most of the pcb materials are able to be drilled with different qualities, except copper.

$C0_2$-TEA-laser
special design of the CO_2's, but with essentially shorter pulses (range of 100ns); drilling of copper is possible (due to high intensity, the absorptivity A 1).

Nd: YAG/YLG -Laser
λ=1,064/1,047µm (IR), this is called the first harmonic wave, but currently and in the future, the frequency multiplied lasers are and will be used.

- λ=355/350nm (UV) frequency tripled corresponds to 3th harmonic
- λ=266nm (UV) frequency quadrupled corresponds to 4th harmonic

In several new developments of laser drilling machines one will find **copper vapor and copper bromid laser** with λ=511 and λ=578nm and **frequency doubled Nd: YAG/YLG-lase**r with λ=532/523nm (green light) also called Second Harmonic Generation-SHG.
The average power is rapidly decreasing with the frequency multiplied lasers which is one of the largest problems for the drilling of hole diameters > 50μm in punching mode.
Trepanning is possible but slow.
The **Excimer-lasers** have several wavelengths due to different gas fillings of the lasers. Typical are λ=193nm (ArF), λ=248nm (KrF), λ=308nm (XeCl), but they are not usually in the PCB-manufacturing.
In the future, the **Ti: Sapphir-laser** may be very useful because they possess ultra short pulses (about 100fs) which will be lead to smallest material damage and the highest hole quality.

5. Interaction between laser beam and material

Laser drilling is a process of material removal by short laser pulses of high intensity which is often called „pulsed laser ablation" and can be classified into thermal, photochemical and photophysical ablation. By thermal ablation, the temperature rise can result in material vaporisation and explosive material blast off. The photochemical (non-thermal) ablation is characterized by direct bond breaking and results in atoms, molecules and fragments of the radiated material. These two types confine the overall ablation process and if both occur simultaneously then it is called photophysical ablation.

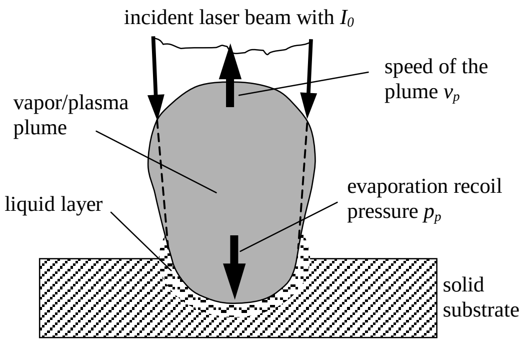

Fig.7 Schematic of laser ablation

It is not possible to find one model only to describe the interaction between laser and material because there are too many different phenomena such as melting, vaporization, plasma formation and its direct interaction with the laser radiation and changing of material properties etc.. Fig.7 represents a schematic of laser ablation.

Temperature distribution

One of the fundamentals of laser processing is the knowledge about the temperature distribution (at least the maximum temperature) by the absorbed laser radiation within the material. This temperature distribution can be estimated by solving the heat-flow equation. A simpified one-dimensional form is given by

$$\rho \cdot c_p \cdot \frac{\partial T}{\partial t} - \kappa \cdot \frac{\partial^2 T}{\partial z^2} = A \cdot I(r) \cdot \alpha \cdot e^{-\alpha \cdot z} \cdot q(t) \qquad (14)$$

where ρ is the mass density, c_p the specific heat, κ the thermal conductivity and it is assumed that all parameters are temperature independent. The relationship between these parameters is given by the thermal diffusivity $D = \kappa/\rho c_p$
Furthermore, the following condition must be satisfied

$$l_T = 2\sqrt{D \cdot t_p} < 2 \cdot r \qquad (15)$$

where l_T is the heat diffusion length and $2r$ the beam diameter. This means that the coupled laser can be considered as a surface energy source. t_p is the dwell time of the laser.
The right side of Eq.14 can be described as the amount of laser energy absorbed per unit volume in a unit time (in J/cm^3). *I(r)* represents the radial distribution of the laser beam according to Eq.1, and Fig.1 and *q(t)* describes the time dependence where in most cases a rectangular pulse can be assumed, Fig.3. The term $\alpha e^{-\alpha z}$ is the attenuation of the beam in z-direction and α is called the optical absorption coefficient. The absorptivity *A* defined between *0* and *1* describes the part of the laser intensity that will not be reflected from the surface.
Important solutions of this heat-flow equation are given for the tophat profile and the Gaussian distribution of the laser intensity by varying the α. As an example, the following

equation shows the solution for a tophat profile with $I(r)=I_0=const.$ and large α (practical > 10^4 cm^{-1}).

$$T(t,z)=\frac{I_0 \cdot A \cdot 2\sqrt{D \cdot t}}{\kappa} \cdot ierfc\left(\frac{z}{2\sqrt{D \cdot t}}\right) \quad (16)$$

Fig.8 and 9 represent the equation graphically for copper drilling with a green laser ($\lambda=523nm$) by using the following parameter: $E=2mJ$, $t_p=35ns$, $d_{spot}=50\mu m$, $A=0.5$, $\kappa=380W/mK$, $D=110 \cdot 10^{-6} m^2/s$.

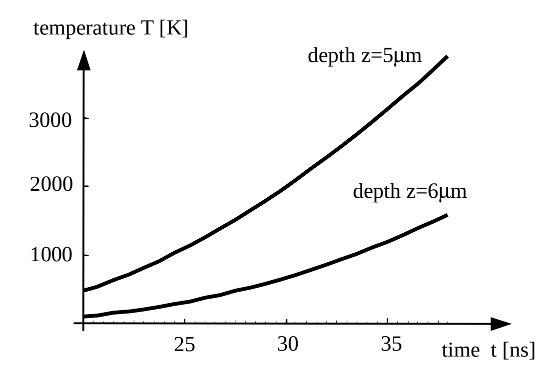

Fig.8 Temperature vs. time by copper

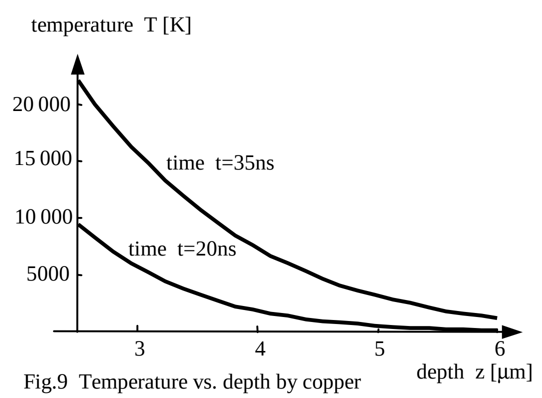

Fig.9 Temperature vs. depth by copper

Estimation of material removal

A rough estimation of the drilling depth Δz can be gotten from the energy balance by ignoring any temerature gradients in the heated volume.

$$\Delta z = \frac{(I - I_{shield}) \cdot A - I_{loss}}{\rho \cdot [c_p (T_{vap} - T_0) + H_{melt} + H_{vap}]} \cdot t_p \quad (17)$$

I is the intensity of the beam, I_s corrects this due to the shielding of the plasma plume, and I_{loss} includes all other energy losses (radiation, conduction, etc.). H_{melt} and H_{vap} is the heat of melting and heat of vaporization, respectively. T_0 is the environment temperature (typ. 20°C) and in case of vaporization T_{vap} represents the vaporization temperature. If we have melting only, then $H_{vap}=0$ and T_{vap} T_{melt} (for example by welding).

Example:

For drilling copper by using the same green laser above–mentioned and the simplification of Eq.17 with $I_{shield}=I_0=0$ and $t_p=350ns$ (pulse width $35ns$ and 10 *pulses*), we get $\Delta z=98\mu m$. The measurement delivers a depth $\Delta z=16\mu m$ and one can see a difference factor of about 5.

Influence of the plasma plume

With the increasing of the laser intensity, vapor will be created and become more and more ionized to transfer in a plasma. This leads to nonlinear effects in the coupling between laser beam and material. The plasma formation begins by exceeding the intensity of vaporization I_{vap} and the created plasma plume absorbs the incident laser radiation partially or complete. With the further increasing of the intensity, this plasma plume expands away from the dense surface towards the incident laser beam, but is confined by the laser beam itself. This propagated plasma plume is called Laser-Supported Absorption Wave (LSAW). Typically, one can roughly distingish between the Laser-Supported Combustion Wave (LSCW) which expands with subsonic velocity and the Laser-Supported Detonation Wave (LSDW) by still higher laser intensities with supersonic propagation velocity.

Two phenomena of the LSCW we have to consider:

In the case of **plasma coupling**, Fig.10, the plasma plume is represented as a disk with thickness d and is strongly coupled to the substrate.First the dense substrate will absorb the fraction AI_1 of the incident laser beam I_0. Additionally, a transfer of the radiation flux $\beta(I_0-AI_1)$ from the heated plasma to the substrate is taking place via heat conduction, radiation and condensed vapor.

It is evident that one needs a large β for a good thermal coupling. Otherwise, the expanding plasma plume increases the temperature distribution on the substrate surface and therefore the effective hole diameter.

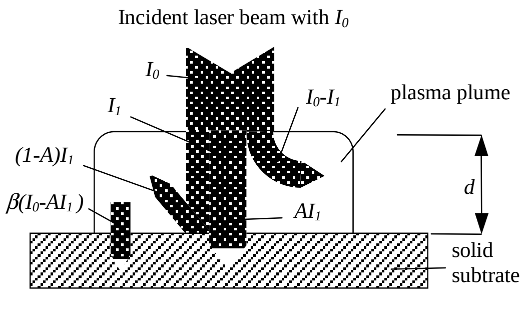

Fig.10 Schematic of plasma coupling

Due to increased intensity ($10^7 \cdots 10^{10}$W/cm^2, depends on λ) the plasma plume absorbs all laser radiation. The radiation flux from the plasma to the substrate will be decreased and the decoupling of the plasma occurs. This is the range of **plasma shielding**, Fig.11.
Because of the explosive propagation of the LSDW a shock wave is created towards and behind the plasma plume. As a result of this, a pressure p_p onto the substrate occurs and can be on the order of thousands of atmospheres. Due to the high velocity of the wave, this pressure decreases very fast.

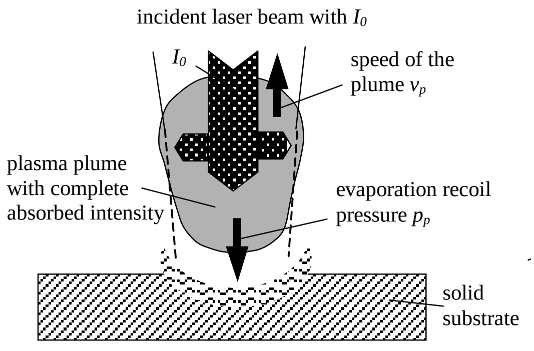

Fig.11 Schematic of plasma shielding

To reduce the influence of the LSDW one needs to dissipate the wave as fast as possible. One possibility in the practical design is the use of a focus lens with a short focus length (but z_r decreases too, see Eq.11).
It is possible, that in one laser pulse multiple cycles of plasma coupling and plasma shielding occur.
Between these cases one needs to find out the optimal laser parameters for every material.

6. References

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