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Processing of printed circuit boards using a 532 nm green laser

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Abstract

The paper describes a research on assessing the quality of edges resulting from the interaction of laser pulses with a material of rigid and flexible printed circuits. A modern Nd:YVO_4 crystal diode-pumped solid-state laser generating a 532 nm wavelength radiation with a nanosecond pulse time was used for the research. Influence of laser parameters such as beam power and pulse repetition frequency on a heat affected zone and carbonization was investigated. Quality and morphology of laser-cut substrates were analyzed by optical microscopy. High quality laser cutting of printed circuit board substrates was obtained without delamination and surface damage, with a minimal carbonization and heat affected zone. The developed process was implemented on the printed circuit assembly line.

1. Introduction

The use of laser micromachining in the field of electronics is growing dynamically thanks to new innovative production technologies that meet miniaturization and cost reduction. One example is the use of lasers in printed circuit board (PCB) manufacturing processes. For rigid and flex circuits the industry predicts introducing critical dimensions that cannot be achieved at an acceptable cost with the current technology [1]. The industry is constantly looking for innovative laser sources that are compact, lightweight and cost-effective to produce advanced electronics. The main driver behind the use of laser technology is the constant progress in miniaturization - lasers offer a highly accurate, precise and non-contact alternative to conventional machining processes [2,3]. Currently, lasers are used in various PCB production processes, including drilling micro-holes, depaneling, profiling (cutting), exposure processes of anti-soldering masks – laser direct imaging (LDI), repair, trimming, marking, and skiving processes [4].

The choice of the laser type for processing printed circuits depends primarily on properties and thickness of a processed material, pulse duration, wavelength, required power, beam diameter, and process efficiency which will affect the costs of the implemented technology. Apart from the thickness parameter, some materials, due to their structure, are difficult to process for various reasons which certainly include: too low speed of technological process or insufficient cutting quality which affects the possibility of subsequent use of laser processing techniques [5].

Due to the structure of printed circuit board substrates, it is necessary to use a laser that allows for a precise and efficient processing of materials such as: glass mat impregnated with epoxy resin, polyimides or copper foil with a thickness of several to several dozen micrometers [6].

Recently, the most widely used laser in processing printed circuit boards, guaranteeing high precision and quality of the process, was the UV laser with a wavelength of 193 nm to 355 nm [7]. Shorter wavelength radiation, usually accompanied by a narrower pulse width and a low beam quality (M^2), has clearly proven advantages creating a tightly focused spot and minimizing heat affected zone (HAZ) [8]. With the implementation of UV excimer lasers invented in the mid-1970s, and in recent years with the implementation of multiple-frequency semiconductor lasers, new material processing options have emerged. In particular, the ability to remove organic materials, metals and glasses to a given depth with a limited thermal exposure made UV lasers very

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attractive in the electronics industry for general purpose micro-machining and for special needs such as micro-drilling [9]. The basic limitation of modern UV lasers is a small depth of field which affects the processing depth. Due to the efficiency of technological processes, the machining depth usually does not exceed 400–800 µm for typical materials. Achieving greater depths requires re-focusing the beam which significantly reduces the process efficiency. For this reason, UV lasers are usually used to cut flexible circuits made of polyimide, thin FR4 laminates and for drilling micro-holes. High-energy UV laser radiation also places high demands on internal components of the laser and its optics. For this reason, the use of a UV source is not always economically viable for laminates above 800 µm thick as it requires a costly maintenance schedule and a frequent laser source replacement. The average lifetime of such a source is estimated at 10 000 operating hours and the replacement cost typically exceeds 10 000 USD.

Currently on the market there are lasers equipped with pulsed diode-pumped solid-state laser (DPSSL) sources operating in the green range of 532 nm. The new generation of devices is based on the Nd:YVO_4 crystal (neodymium-doped yttrium vandate) with a double second-harmonic generation (SHG) frequency conversion and replaces the common neodymium-doped yttrium-aluminum garnet (Nd:YAG) lasers. One of the most attractive features of the Nd:YVO_4 crystal, compared to Nd:YAG, is the 5 times greater absorption coefficient for a pumping wavelength of 808 nm which is now the standard for high power laser diodes. This enables the miniaturization of Nd:YVO_4 crystals and, thus, the creation of more compact laser systems. For a given, assumed output power, this also means a lower level of pumping energy at which the laser action is induced, thus, extending the lifetime of the laser diode. Also valuable is a wide absorption band of the Nd:YVO_4 crystal which is 2.4 to 6.3 times greater than that of Nd:YAG. In addition to more efficient pumping, the Nd:YVO_4 crystal allows a wider range of diode specifications to choose from [10]. This creates new opportunities for manufacturers of laser systems to choose a diode compatible with the specifications of the target system. Wider pump band also enables the use of diodes with lower tolerances which translates into the cost reduction [11]. Another important feature of Nd:YVO_4 lasers is a constant, strong emission of a single line, and since the crystal is uniaxial, it only produces a polarized beam, thus, avoiding the effect of undesirable birefringence effects on frequency conversion. Although the lifetime of the Nd:YVO_4 crystal is approximately 2.7 times shorter than that of Nd:YAG, due to the higher quantum efficiency of the pump, the slope efficiency of the laser diode can still be kept at a high level [12]. Devices based on the Nd:YVO_4 crystal generate a beam with a wavelength of 532 nm and guarantee the same cut quality as UV sources, with a higher process speed and efficiency.

There are some challenges in the treatment of PCB substrates, including HAZ formation, carbonization, re-deposition of a removed material and contamination. Another difficulty arises from the fact that PCBs reinforced with fibers are heterogeneous because a glass fiber has significantly different thermal-physical properties than resins and epoxy. As a result, different ablation threshold energy densities are obtained for glass fiber and epoxy resin [13].

Subject of the work was the study of various laser parameters influence on the cutting quality in terms of the occurrence of HAZ effects and carbonization of the cut material. The aim of the work was to obtain the highest quality cutting of PCB substrates based on a FR4 laminate and polyimide without delamination and surface damage with the lowest possible carbonization and minimal HAZ effect.

Research to date on the PCB processing using DPSSL 532 nm lasers has only focused on thin flexible printed circuit boards (FPCB), thin (300 µm thick) rigid PCB and thin (100 µm thick) sheet of a copper foil. For the material, a composition copper-polyimide-copper and a flexible cover layer, the purpose was to create a cutting width less than 40 µm in size. The best cutting results in terms of speed maintaining quality, without heating (burning) on the surface, were achieved at 80 W, 25 kHz (100 mm/s), 10 cuts per line and 60 W, 40 kHz (400 mm/s), 10 cuts per line, respectively [2]. In another work the laser was used to demonstrate an efficiency of various PCB manufacturing processes such as via drilling, cutting/profiling and depaneling. Operating the laser at 150 kHz with a 64 µJ energy which corresponds to an average laser power of about 10 W, was turned out be optimal to achieve good quality cuts with the low carbonization and minimal HAZ. Multiple scans were used to increase the cutting process efficiency. An average speed of 50 mm/s was achieved. There is no precise information on the number of scans. Achieved results confirmed that high performance 532 nm wavelength lasers are suitable for processing thin (up to 180 µm) FPCB materials consisting of copper and polyimide, as well as thin (up to 300 µm) rigid PCBs consisting of resin materials [4].

Cutting a 50 µm thick flexible PCB was investigated empirically using a 532 nm laser [14]. Comparison is made between different wavelengths including 532 nm and fundamental 1064 nm laser. The 532 nm laser had the available repetition rate range of 10 ÷ 20 kHz with a pulse duration of 50–70 ns and an average power of >25 W. Cutting speed of >120 mm/s is reported with no evidence of delamination, no measurable recast nor HAZ, and no evidence of dross on either the surface or the base of material.

The works so far have not focused on assessing the usefulness of the investigated lasers in the processing of conventional substrate materials of greater thickness. Our work is focused on the industrial environment where tools should be more flexible, although the process windows should be individually selected and optimized in order to reduce device operating costs. The investigation covers FR4 laminates with a wide range of thickness which, in this case, turned out to be a task no less demanding than development of a technology for cutting thin flexible laminates.

2. Experimental

The Asys DIVISIO 8100 device equipped with the BLIZZ 532-30-V laser system by InnoLas Photonics was used in the study. The system generates an average power of 30 W, with a pulse repetition frequency of 40 kHz, a duration < 20 ns, and a pulse energy of 750 μJ, providing a very high peak power of 37.5 kW for these applications [15]. The laser contains an active Q-switch which enables the accumulation of energy in a non-linear crystal without emitting radiation for most of the pulse repetition period and the stored energy rapid release in the form of very short, highly repeatable pulses. The device allows for a maximum pulse repetition frequency of 400 kHz with an average power of 13.3 W.

The experiment consisted of assessing the impact of laser pulses with a wavelength of 532 nm on the processed material when changing the frequency of pulse repetition frequency (PRF) in the range from 40 kHz to 150 kHz at a diode current of 9 A or 12 A. The measured average power and energy of the pulse decreased with a frequency increase of a PRF pulses repetition (Figs. 1, 2) for the constant value of the diode current.

Duration of the laser beam pulse ranged from 20 to 75 ns depending on the frequency of the laser pulse used (Figs. 1, 2). Shape of the output beam was similar to that of a Gaussian beam. Beam quality factor was $M^2 < 1.4$ for the TEM00 mode. Beam diameter in the focal plane (in the narrowing) was of 30 μm and the divergence angle of the Gaussian beam during propagation was less than 1.6 mrad.

The assessment consisted of observing the shape and form of the resulting trace of the laser beam interaction with the material and identification of such processes as HAZ effect, material carbonization, delamination, loss without melting traces, material spatter. Surface morphology and edge quality of the cut PCBs were analyzed by optical microscopy.

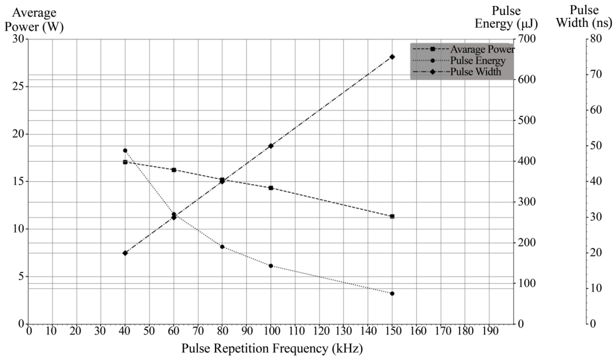

Fig. 1. The change of an average laser power, pulse width and energy as a function of a pulse repetition frequency for a diode current of 9 A.

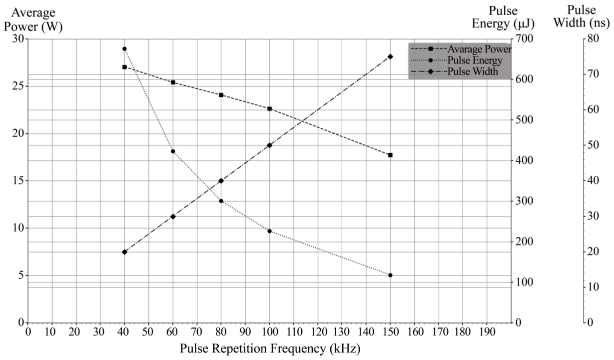

Fig. 2. The change of an average laser power, pulse width and energy as a function of a pulse repetition frequency for a diode current of 12 A.

Two types of PCBs were tested, using in their structure FR4, FR408, 370HR laminates (Fig. 3) and a flexible polyimide AP8525 (Fig. 4) as a base material. The selected materials are commonly used in the production of electronic devices.

Fig. 3. View of the tested PCB made of a FR4 laminate.

Fig. 4. View of the tested PCB made of a polyimide AP8525 laminate.

Various thicknesses of materials were used in the tests, ranging from 0.10 mm to 1.55 mm. In the case of a rigid laminates, the bridges connecting successive PCBs were cut and in the case of a flexible laminate, full cuts were made along the contour of a single PCB.

3. Results and discussion

Scanning speed, number of passes and cooling time between passes for each sample were selected experimentally so that it can be possible to completely cut the laminate. The effective speed was defined as a scan speed divided by the number of passes. Less power, higher pulse repetition frequency and thicker material made the effective cutting speed obviously lower. The highest cutting speeds were achieved for thin FR4 laminates with a thickness of 0.15 mm and the polyimide AP8525 with a thickness of 0.10 mm, achieving a cutting speed of 120 mm/s, and 53.33 mm/s for the frequency of 40 kHz, respectively. For these parameters and for a diode current of 9 A, where the average laser power was of around 17 W, the best cutting results were also achieved, with a minimal HAZ effect and carbonization, the least amount of cavities without any melting marks or material splashes and without delamination (Figs. 5, 6).

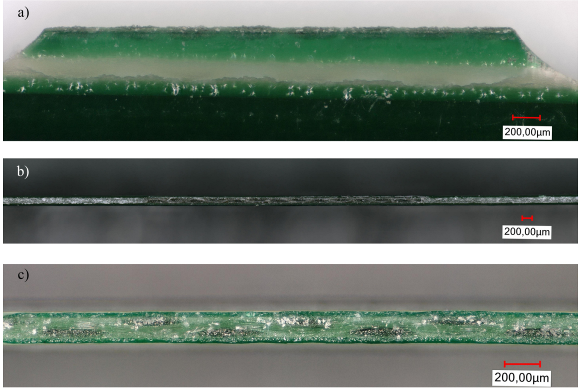

Fig. 5. Cutting effect of an FR4 laminate with a thickness of 0.15 mm at a frequency of 40 kHz and a diode current of 9 A: a) top view, b) cross-section view, c) cross-section view with a magnification of × 500.

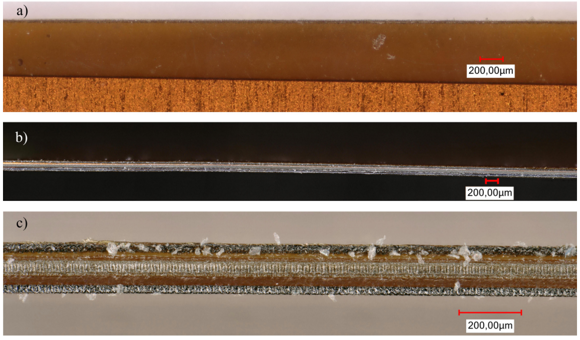

Fig. 6. Cutting effect of a polyimide AP8525 with a thickness of 0.10 mm at a frequency of 40 kHz and a diode current of 9 A: a) top view, b) cross-section view, c) cross-section view with a magnification of × 500.

Slightly worse cutting results were achieved for a 12 A diode current which corresponded to the average laser power of around 27 W. More distinct carbonization of a 0.15 mm FR4 laminate and a slight thermal damage to the AP8525 polyimide of 0.10 mm were noted (Figs. 7, 8). In this case, the cutting speed was of 225 mm/s for a 0.15 mm thick FR4 and of 80 mm/s for a 0.10 mm thick poly-imide, respectively.

It was also noticed that for both diode currents, the edges of both materials are sharp. The results confirm the suitability of a 532 nm laser for a very efficient cutting of a thin FR4 and polyimide substrates.

Satisfactory cutting effects were obtained for FR4 laminates with a thickness of 1.55 mm, but with a much higher carbonization and an effective cutting speed over 30 times lower (Fig. 9).

An effective cutting of PCBs is not possible for the maximum analyzed pulse repetition frequency of 150 kHz and a diode current of 9 A due to the insufficient pulse energy. For a 0.55 mm thick FR408 laminate, a cut quality is comparable to a cut quality of a 1.55 mm thick FR4 laminate at a diode current of 9 A and a pulse repetition frequency of 40 kHz. With the increase of a diode current up to 12 A and a frequency up to 80 kHz, the HAZ effect and edge carbonization significantly increase and cut results become unacceptable from a quality standpoint, especially in very demanding applications. Losses and melting of the material appear without delamination effect.

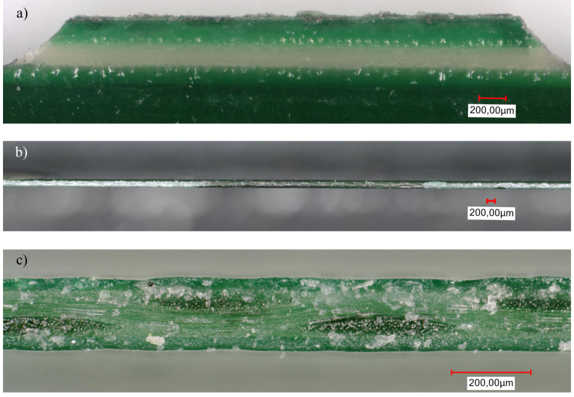

Fig. 7. Cutting effect of an FR4 laminate with a thickness of 0.15 mm at a frequency of 40 kHz and a diode current of 12 A: a) top view, b) cross-section view, c) cross-section view with a magnification of x 500.

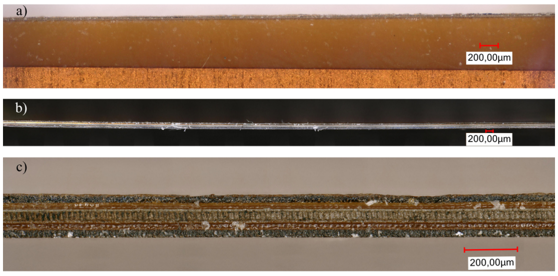

Fig. 8. Cutting effect of a polyimide AP8525 with a thickness of 0.10 mm at a frequency of 40 kHz and a diode current of 12 A: a) top view, b) cross-section view, c) cross-section view with a magnification of x 500.

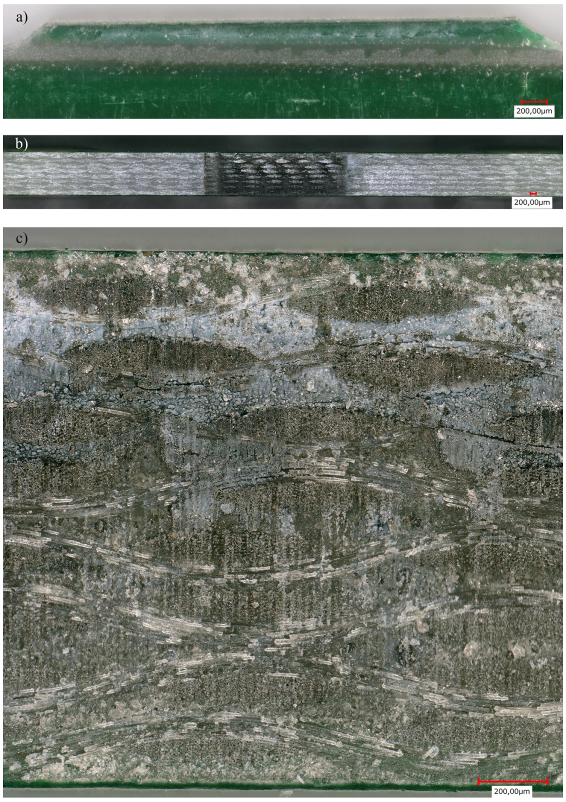

Fig. 9. Cutting effect of an FR4 laminate with a thickness of 1.55 mm at a frequency of 40 kHz and a diode current of 12 A: a) top view, b) cross-section view, c) cross-section view with a magnification of x 500.

In the case of a 0.55 mm thick FR4 and 370HR, the greatest effect of thermal impact on the material, carbonization and numerous traces of melting and losses, especially for a diode current of 9 A, was observed regardless of the PRF (Fig. 10).

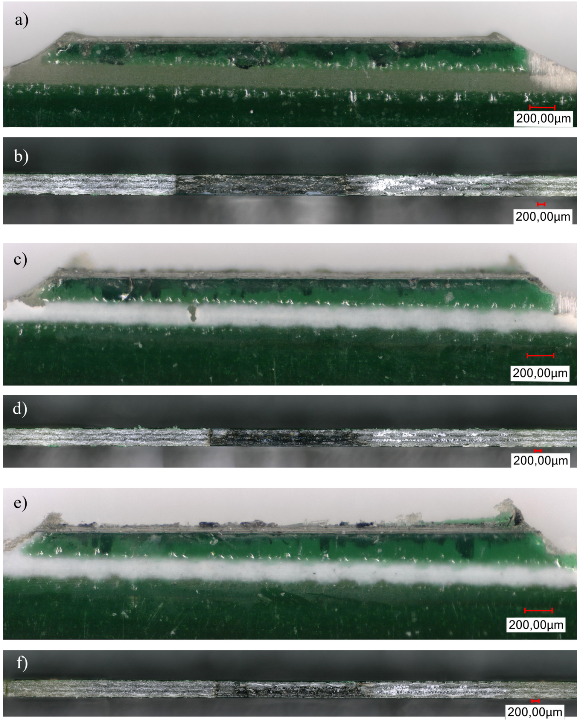

Fig. 10. Cutting effect of an FR4 laminate with a thickness of 0.55 mm for a diode current of 9 A at a pulse repetition frequency: a,b) 40 kHz, c,d) 80 kHz, e,f) 150 kHz (top view and cross-section view).

Too much and too heterogeneous propagation of the HAZ across the nonwoven fabric clearly indicates not optimal cutting parameters. The effect obtained may be influenced by the focus of a laser beam above the material surface which changes a spot diameter and a power density distribution over a larger area of the laminate. The working range – depth of field of monomode lasers with Gaussian beams is a function of wavelength, focal length and spot size mainly. Despite the relatively large field depth: around 1–2 mm, an accurate focal length measurement and a position correction are necessary.

It was also noticed that the greatest HAZ effect occurred at the frequency of 80 kHz and a diode current of 12 A (~24 W) compared to other tested frequencies and a 9 A diode current (~15 W), regardless of the type of material and its thickness.

The occurrence of the HAZ effect is closely related to the glass fibres direction. This is especially evident in the example of a 0.15 mm FR4 PCB where a single woven glass fabric was used. In Fig. 11, the effect of laser pulses on fibres arranged perpendicular to the laser cutting direction is shown. There is a phenomenon of the laser radiation propagation along the glass fibres as in an optical fibre.

Where the HAZ in the form of carbonization is the shallowest and where the carbonization is the most equal, the parameters can be considered close to the optimal ones.

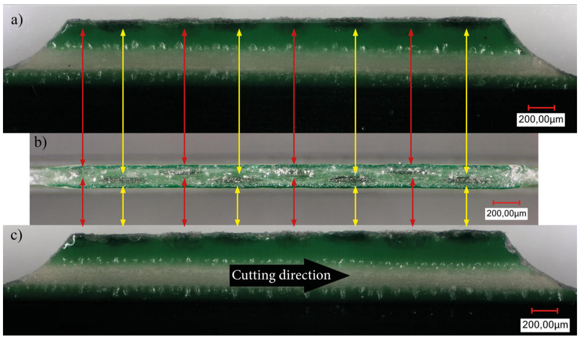

Fig. 11. Impact effect of the laser pulse on the glass fibers of the laminate with a thickness of 0.15 mm for a diode current of 12 A: a) top view, b) cross-section view, c) bottom view.

Table 1 summarizes the results of research and work on a high-quality PCB cutting using a 532 nm laser. It is difficult to find comprehensive research and results in the literature showing the possibilities of using a 532 nm laser in the assembly of electronics. The existing research has been limited to some extent to the case of thin rigid and flexible PCBs.

Table 1
532 nm laser high quality cutting results.

PCB type	**PCB thickness (µm)**	**PRF (kHz)**	**Laser average power (W)**	**Effective cutting speed (mm/s)**
Polyimide AP8525	100	40	17	53.33
FR4	150	40	17	120
FR408	550	40	17	8
FR4	1550	40	27	4.29
Thin Rigid	300	150	~10 (64 µJ)	50
Copper-Polyimide-Copper	NA	25	80	100
Polyimide-Copper-Polyimide	180	20	8 (390 µJ)	11.5
Polyimide-Polyimide	160	20	8 (390 µJ)	11.5
FPCB	< 50	20	11.8 – constant power (< 1 mJ)	120

4. Conclusions

A systematic study of the effect of a pulse repetition frequency on the cutting quality of FR4 and polyimide substrates in terms of the occurrence of HAZ and carbonization effects was carried out. Green laser (532 nm) processing has been shown to provide a good cutting quality on PCB substrates based on FR4 epoxy resin and polyimide. It was also found that the material structure, the average power and the pulse repetition frequency have a significant influence on the cut quality, Optimized laser conditions for cutting PCB substrates based on FR4 and polyimide were identified. An effective and high-quality laser cutting of thin PCB substrates based on FR4 and polyimide has been demonstrated, without delamination, distortion and carbonization at the minimal HAZ effect. A high-quality cut was obtained for the commonly used FR4 laminates with a thickness up to 1.55 mm.

The carried out research focused on high-quality cuts, not process speed. The achieved value of 4 mm/s for a 1.55 mm laminate is much lower compared to traditional chipping methods, e.g., milling which are on average even of 40 mm/s. However, the lack of risk related to damage of the laminate, solder or components and a greater use of the material allow the use of the 532 nm laser, especially in industries going beyond the area of standard applications.

The developed process of cutting PCBs with a 532 nm laser can be widely used and, in terms of cutting quality and efficiency, it can replace successfully the currently used UV lasers in the electronics industry.

Authors' statement

P.C. carried out the literature survey and pool, analyzed the data and wrote the manuscript. M.S. conceived the study and participated in its design and coordination, as well as helped to draft the manuscript. All authors read and approved the final manuscript.

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