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High precision laser direct microstructuring system based on bursts of picosecond pulses

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Abstract

We have developed an efficient, high precision system for direct laser microstructuring using fiber laser generated bursts of picosecond pulses. An advanced opto-mechanical system for beam deflection and sample movement, precise pulse energy control, and a custom built fiber laser with the pulse duration of 65 ps have been combined in a compact setup. The setup allows structuring of single-micrometer sized objects with a nanometer resolution of the laser beam positioning due to a combination of acousto-optical laser beam deflection and tight focusing. The precise synchronization of the fiber laser with the pulse burst repetition frequency of up to 100 kHz allowed a wide range of working parameters, including a tuneable number of pulses in each burst with the intra-burst repetition frequency of 40 MHz and delivering exactly one burst of pulses to every chosen position. We have demonstrated that tightly focused bursts of pulses significantly increase the ablation efficiency during the microstructuring of a copper layer and shorten the typical processing time compared to the single pulse per spot regime. We have used a simple short-pulse ablation model to describe our single pulse ablation data and developed an upgrade to the model to describe the ablation with bursts. Bursts of pulses also contribute to a high quality definition of structure edges and sides. The increased ablation efficiency at lower pulse energies compared to the single pulse per spot regime opens a window to utilize compact fiber lasers designed to operate at lower pulse energies, reducing the overall system complexity and size.

Introduction

The ongoing trends of miniaturization and short research cycles are pushing the need for direct laser microstructuring, enabling fast turn-over times and design flexibility. A fiber laser source gives an additional design space for tuning the device to the needs of a specific application and contributes to the compactness of the whole design.

Short pulsed lasers are used in a wide range of applications, including efficient material processing in scientific [1] and industrial environments [2,3]. Pulse durations used range from tens of nanoseconds [4] down to a few femtoseconds [5,6]. Fiber laser systems are capable of delivering short pulses at high repetition rates and high powers [1,7], but laser design gets less compact [8] as pulses get shorter down to few ps or less, as a chirped pulse amplification (CPA) approach is required. We have used our custom designed picosecond fiber laser based on a gain switched laser diode [9], which is capable of burst-mode operation while maintaining a compact CPA-free all-fiber design.

Theoretical approaches to laser-matter interaction have shown that bursts of pulses increase the laser ablation efficiency [10], for example through a two-temperature model [11]. Recent developments of very high repetition rate experimental setups have proven the theoretical predictions [12] while using a typical laser beam diameter of above 20 µm. The combination of heat transfer, heat accumulation during laser processing, and pulse duration effects leads to an increased efficiency of material removal with bursts of laser pulses compared to a single pulse.

Pulse duration changes the light-matter interaction significantly. Nanosecond or longer pulses lead to a process of thermal ablation [13], while pulses shorter than a single picosecond keep most of the surrounding material intact, resulting in a non-thermal ablation [14]. We have used the pulse duration of 65 ps that falls in between the typical time scales and the results of laser structuring cannot be simply predicted. The 65 ps pulse duration was chosen as a compromise between achieving the shortest laser pulse duration and having an ability to use a compact all-fiber CPA-free amplifier system.

Previous research by other groups [12,15,16] has shown an increase of ablation efficiency during the laser material processing with bursts compared to processing with single pulses, using laser spots larger than 10 µm. Primary effect is due to the local heating from former pulses in a burst [17], increasing the efficiency for the later pulses. The pronounced effect of the local heating happens when the thermal relaxation time τ_t is comparable to the intra-burst delay between pulses τ_i. The thermal relaxation time can be defined as $\tau_t = \delta^2/\alpha$, where δ is a typical dimension, i.e. spot size on the material or heat conduction depth, and α is the thermal diffusivity of the material [12].

Using a laser beam focused to spots larger than 10 µm gives a favourable comparison of $\tau_t \geq \tau_i$ even at moderate intra-burst repetition rates on both metals and non-metallic materials. The typical heat affected zone growth rate on metals is below 2.5 µm/50 ns (calculation from [18]) due to the three-dimensional heat conduction. The repetition rates above tens of MHz grant that most of the residual heat remains in the interaction volume of the next pulse in a burst at this laser beam spot size. At the same time those laser beam diameters are in line with current industry leading devices used for material processing [19]. Our research has focused on pushing the achievable feature sizes an order of magnitude smaller while preserving short processing times of larger surface areas. Other groups have shown microstructuring with tightly focused laser pulses without beam steering [20], which limits the use of such approaches. We have utilized a 1 µm wide laser spot and nanometer laser beam positioning accuracy, pushing the

limits of precise microstructuring for scientific uses, such as shaping of functional materials, micro-heaters, conductive traces, and microfluidic channels.
Using a tightly focused laser beam for structuring of a copper layer with a high thermal diffusivity constant puts structuring with bursts at an unfavourable predisposition with $\tau_i \approx 20\tau_t$. In this manuscript we demonstrate that bursts of laser pulses improve the ablation efficiency even on the single micron scale with the right choice of parameters but may also lower the efficiency when using too low pulse energies. The transition between the two regimes implies that the two competing effects of shielding and local heat accumulation are taking place. Plasma, vapour plumes, and molten material remains start to leave the target material immediately after the laser pulse absorption [21]. Copper plasma plumes can reach more than 100 µm away from the crater in the longitudinal dimension in the typical time scale of the intra-burst repetition rate [22]. In the same time molten ablation products do not move more than 10 - 20 µm away from the surface and are ejected at an angle, causing little obstruction for the next pulse in a burst [23]. We demonstrate that the ablation efficiency gets larger with increasing pulse energy over a wide parameter window. This finding is in line with the shielding effect reducing efficiency both directly and indirectly.
Microstructuring with bursts of pulses offered two independent improvements over the single pulse ablation, either up to 40 times faster microstructuring times using a comparable pulse energy or a comparable processing time but with an up to 8 times lower pulse energy. The latter effect is useful for the fiber laser design as the pulse energy presents a design limitation [24]. The highest quality of structures created in the copper layer was also achieved by ablation with bursts of multiple pulses.

Methods

The optical design was centred on two key devices: acousto-optic deflectors (AODs) and a picosecond all-fiber laser. Both devices were specially designed for direct microstructuring with nm resolution of the laser beam positioning. Special driver electronics, software, and optics were used with AODs (DTSXY400, AA Opto-Electronic) as the positioning system with the maximal repositioning frequency of 100 kHz. The combination of laser beam steering and sample movement resulted in a system operating at a high repositioning frequency while maintaining nanometer precision, single-micrometer size of the focused laser beam spot, micrometer feature size, and an ability to process larger sample areas with an automatic stitching of fields. Our own picosecond fiber-amplifier based pulsed laser source was used [9], externally frequency doubled to a 532 nm wavelength. A gain-switched laser diode was used as a seed, producing 65 ps pulses at a 40 MHz repetition rate which were further amplified in a four-stage fiber-amplifier. Bursts of pulses were shaped from the pulse train by an acousto-optic modulator.
Relay lenses were used to guide the laser beam pivoting point from the AODs to the back aperture of the working objective. We used a 20x magnification microscope objective with a numerical aperture of 0.5 (Nikon Plan Fluor 20x/0.5) to focus the laser beam on the copper surface (Fig. 1b). The calculated laser beam focus diameter was just below 1 µm and its Rayleigh length around 2 µm. The combination of optics and electronics allowed for the minimal structure size of approximately 1 µm and nm resolution of the laser beam positioning. Nanometer resolution is a consequence of the acousto-optic system, utilizing a direct digital synthesis of a high frequency sound wave. The laser beam deflection happens at angles close to the Bragg condition, which in term gives the deflection angle θ depending on the frequency of sound F:

$$\Theta(F) = \arcsin\left(\frac{\lambda F}{2c_s}\right)$$

where c_s in the speed of sound in the AOD crystal (around 650 m/s) and λ is the wavelength of light (532 nm). The sound wave frequency was set between 56 MHz and 108 MHz with the possibility of being changed in steps of $\Delta F/F<10^{-9}$. Differentiating of the equation above gives the angular step size ΔΘ of approximately

$$\Delta\Theta \sim \frac{\lambda}{2c_s}\Delta F$$

which corresponds to a step size smaller than 1 nm within our optical system. The combination of the laser beam pointing stability, the burst-to-burst energy stability, and the material surface roughness results in the final structure edge roughness. The typical straight structure in a thick copper layer has the edge roughness below 500 nm, measured as the peak-to-peak deviation from a straight line (shown in Fig. 2c, highlighted by the light brown rectangle). The beam pointing stability of the laser source itself causes deviations of the intended focused laser spot position smaller than 20 nm. Experiments were performed with the repositioning time set to 12 µs corresponding to the repositioning frequency of approximately 83.3 kHz. The laser had a precisely synchronised burst emission timing with the timing of the beam repositioning, thus operating at the same 83.3 kHz repetition rate. With a combination of a fast acousto-optic burst modulation, bursts of 1, 5, 10, or 20 pulses with equal energies were delivered at each 12 µs time period (marked τ_R on Fig. 1a). Due to the synchronization each point on the material received a single burst of 65 ps pulses, separated by 25 ns delays (marked τ_i on Fig. 1a, defined by the seed diode frequency).

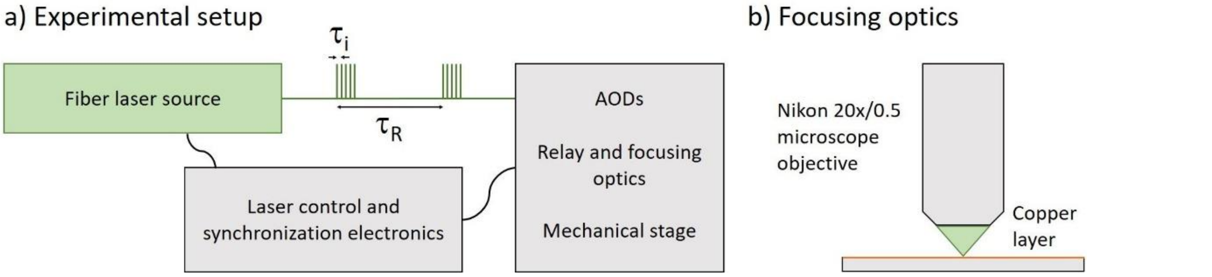

Fig. 1. a) Schematic drawing of the experimental setup. The laser source was coupled into an integrated opto-mechanical system, resulting in a compact device. The two time scales of burst operation are shown to stress the difference between the burst repetition period τ_R and pulse repetition period τ_i. b) Close-up of the laser-focusing microscope objective.

A 5 µm thick copper layer deposited on a typical rigid-flex substrate for printed circuit boards was used for the experiments. The material was chosen for its good heat conduction properties, standard availability, and thickness comparable to the laser beam Rayleigh length.

Structure design was rasterized to points on a square grid and the order of points was mixed randomly prior to material processing. Random pulse positioning order has proven to be efficient [25] and it isolates the effect of the number of laser pulses within one burst from the effects of previous bursts as the average time between assigning the laser pulse to two neighbouring locations is four to six orders of magnitude larger than τ_R.

Results

Microstructuring experiments were carried out using a single design approximately 250x250 µm^2 in size (Fig. 2) with a variable density of laser spots. The design was rasterized on a square grid with a chosen distance between two neighbouring spot positions (typically 100 nm to 1 μm) to assign the laser pulses during the manufacturing process of each separate microstructure. Randomly choosing subsequent pulse locations gave enough time to make the residual heat from previous bursts negligible.

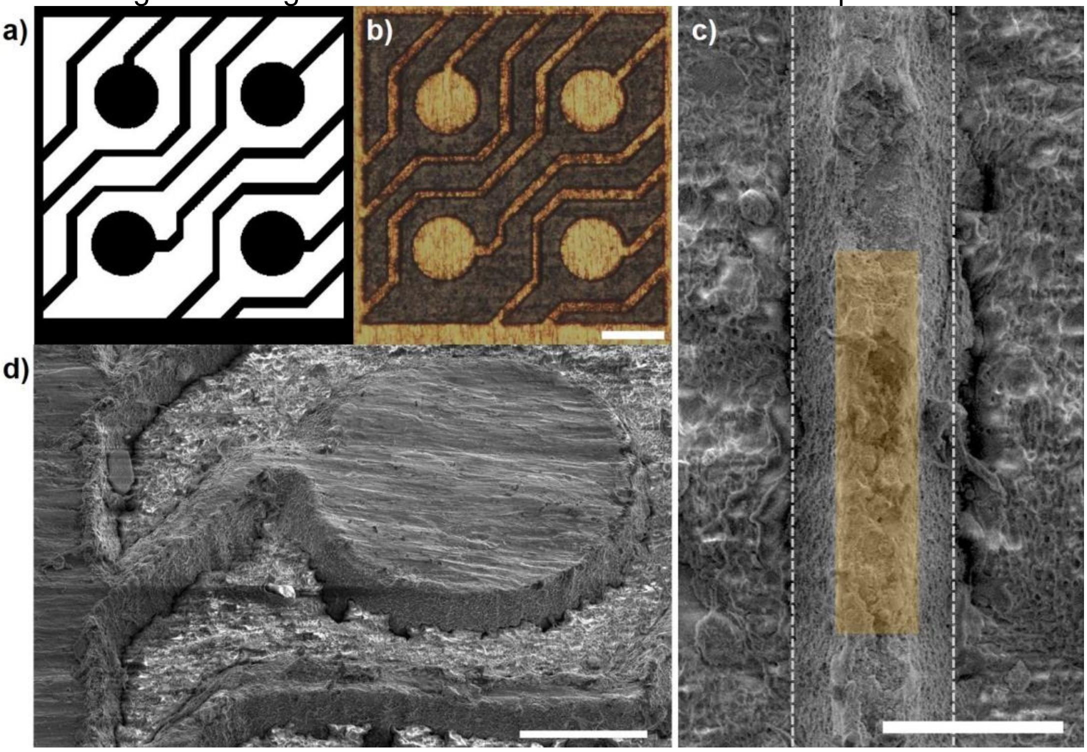

Fig. 2. a) The microstructure design, white areas were to be removed and black areas left untouched. b) The corresponding result of copper structures on a dielectric substrate, the distance between spots was 200 nm. The scale bar equals to 50 μm. c) SEM image of a copper trace. The top of the structure is highlighted by the brown rectangle, white dashed lines denote the bottom of the structure. The scale bar equals to 10 μm. d) SEM image of a copper pad. The copper layer is precisely removed with nearly no damage to the substrate. The scale bar equals to 20 μm.

Each pulse is absorbed in a given volume of the target material, depending on the optical penetration depth. The total incident energy on the metal surface is partially reflected and in a case of shielding also partially absorbed before entering the material. We have analysed the ablation efficiency, i.e. the volume of ablated material per unit of total incident pulse energy, for bursts of 1, 5, 10, and 20 pulses (or PPB - pulses per burst).

Microstructuring with bursts provided an insight to the mechanism of ablation and material ejection. Regardless of the number of pulses in a burst both the ablation efficiency and the amount of material removed were lower than the corresponding effect of a single pulse below certain critical pulse energies. Above a critical pulse energy the ablation efficiency and the amount of material removed grew up to twofold compared to single pulse structuring with the same pulse energy (Fig. 3a). Two competing effects are in action during microstructuring with bursts, shielding of later pulses in a burst [1] against local heat accumulation from the former pulses in a burst [12].

We have tested a simple short-pulse laser ablation model [16,26] against our data on 1 PPB ablation. The model predicts the ablated volume of material as a function of the pulse energy:

$$V(E_p) = A \ln^2\left(\frac{E_p}{E_{th}}\right),$$

where A is the laser-matter interaction volume, E_p is the pulse energy, and E_{th} the threshold energy for ablation. We have found a good agreement between the model and the experimental data as shown on the graph (Fig. 3a, 1 PPB) using A and E_{th} as free parameters for the fit. The data on ablation with multiple PPB shows a distinctive and systematic deviation from the model. The deviation can be described by the two competing mechanisms of shielding and heat accumulation. We have used two different corrections to the model in form of the lowest possible orders of power law approximations for the effective changes of the pulse energy and the threshold energy. We have used empirically defined corrections that correspond well with our experimental data, namely $E_p \rightarrow \frac{E_p}{1+kE_p}$ due to shielding and $E_{th} \rightarrow \frac{E_{th}'}{1+qE_p^3}$ due to heat accumulation. The value of parameter A obtained in the 1 PPB fit was used for all the fits on multiple PPB data as the interaction volume is expected to remain unchanged at low pulse energies. The free parameters were therefore k, q, and E_{th}', where E_{th}' does not exactly correspond to the threshold energy for ablation anymore due to the added corrections. While the original simple model fits well to our 1 PPB data, the model with corrections due to shielding and heat accumulation fits well on the data of ablation with bursts of multiple pulses (Fig. 3a, 5-20 PPB). The resulting functions are also added to the plot of the ablation efficiency for improved clarity (Fig. 3b).

The total amount of removed material per pulse correspondingly grows with pulse energy (Fig. 3a). The critical pulse energy, where the ablation efficiency of a pulse in burst is equal to the efficiency of a single pulse, gets lower with an increasing number of PPB (Fig. 3b). The critical pulse energy is approximately 0.8 µJ, 0.25 µJ, and 0.18 µJ for the 5, 10, and 20 PPB regimes respectively. Longer bursts of pulses deposit more energy to the unremoved material, causing higher ablation efficiencies for latter pulses in a burst.

Single pulse bursts show an increasing ablation efficiency with the pulse energy up to approximately 0.5 µJ where the efficiency becomes saturated (Fig. 3b). The ablation efficiency, defined as the volume of ablated copper material per unit of energy delivered, reaches up to 1.1 $\mu m^3/\mu J$ for bursts of 10 or 20 pulses. Comparing to the highest reported ablation efficiencies with bursts to date (up to 7.5 $\mu m^3/\mu J$ at a 1.73 GHz repetition rate, 1040 nm wavelength, and 26 µm spot size [12]) our result is a factor of 7 lower, albeit at an 40-times lower repetition frequency, about 500-times smaller laser spot area, and at a different wavelength. On the other hand, comparing to a result obtained at a modest frequency by the same group (up to 0.5 $\mu m^3/\mu J$ at a 27 MHz repetition rate, 1040 nm wavelength, and 26 µm spot size [12]), our results shows the importance of the wavelength choice for the material given. The copper layer has a much higher reflectivity at IR wavelengths compared to the green range and all the results are calculated with the incident energy, not the absorbed energy. A crucial difference has to be noted as our results are calculated from the total ablated volume of the microstructure and compared to results based on the ablated volume of single ablation craters. Our previous research for longer laser pulses has showed that the final effect is lesser than the sum of single pulse effects [25].

From the fiber laser design perspective microstructuring with bursts has an additional advantage as the fiber laser design is limited by the pulse peak power. Higher average powers can be delivered to the material and at the same time a higher ablation efficiency compared to single pulses is achieved. Namely, bursts of 20 pulses displayed a significantly higher efficiency at 0.25 µJ energy per pulse on sample compared to single pulses at any energy. Peak powers in IR at the fibers end reached around 300 kW (corresponds to 20 µJ of pulse energy using a measured conversion of 13.7 kW/µJ), but equally fast processing can be achieved with as low as 30 kW of peak power and operation in bursts. Lower required peak powers in the last laser amplifier stages make for a simpler fiber laser design.

Processing times in our microstructuring system are defined by the number of spots in a given microstructure divided by the operating frequency. Each spot receives exactly one burst of pulses regardless of the number of pulses in the burst. We have tried to shorten the processing time using bursts of pulses and have demonstrated up to 40 times shorter times at equal pulse energies comparing bursts of pulses to single pulses (Fig. 3c), i.e. at 0.27 µJ of pulse energy and 20 PPB. The general trend can be summarized with a statement that increasing the number of PPB decreases the processing time at a given pulse energy. This decrease results as a combined effect of an increased ablation efficiency and an increased average power, where using bursts intrinsically enabled both features. Compared to single pulses, equal processing times using bursts can be achieved with up to 5 times lower pulse energies (Fig. 3c), i.e. in the range of 4-6 seconds long processing time per structure of the given size. At the same time the total energy delivered to a given surface gets higher with increasing number of pulses per burst (Fig. 3d), as the average power increases linearly with the burst energy.

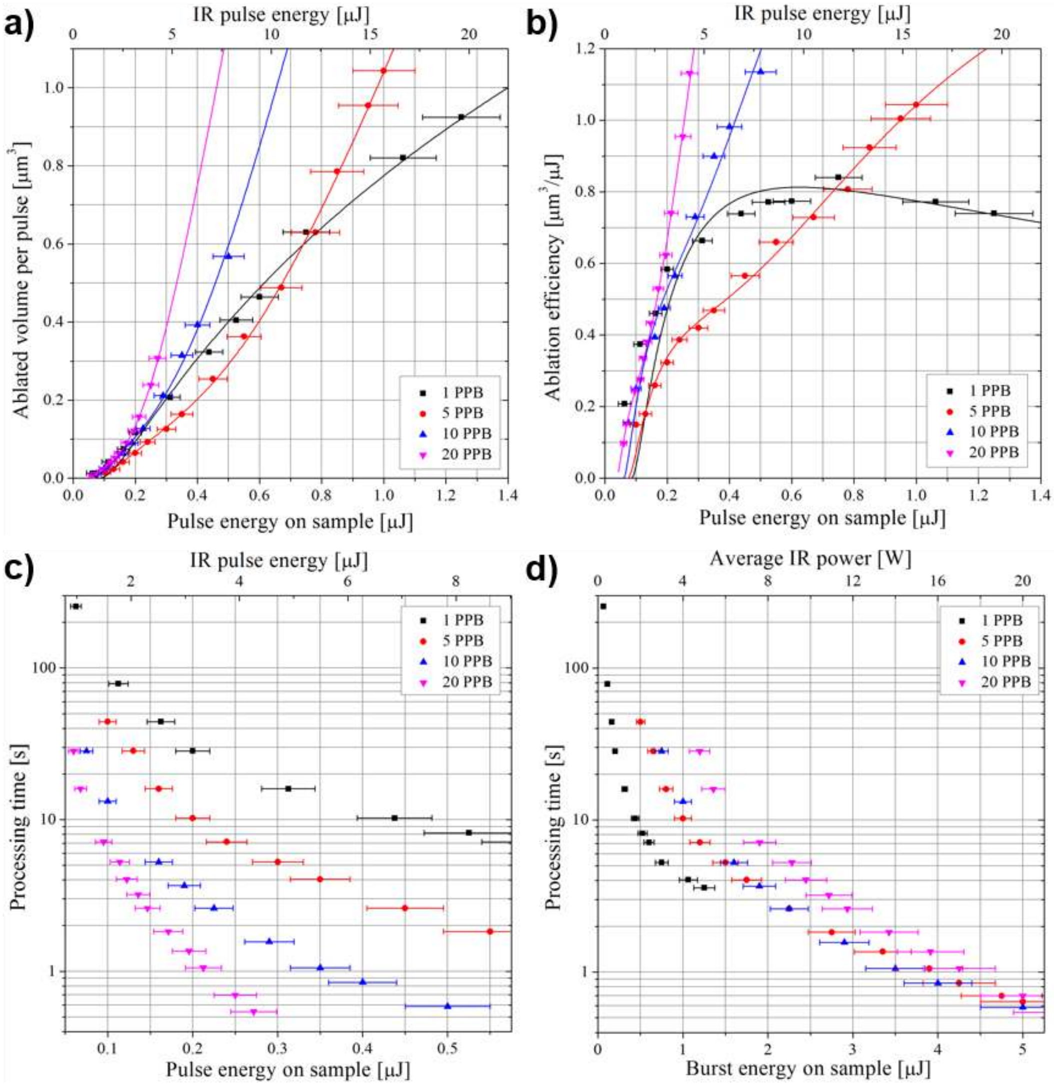

Fig. 3. Measurements of a) the ablated volume per pulse, b) the ablation efficiency, and c) the processing time depending of the pulse energy. The processing time was

also measured depending on the burst energy (d) that is a product of the pulse energy and the number of pulses per burst. The processing time is defined for the structure shown in Fig. 2, which represents a 60% covered 300x300 μm^2 surface of the sample. The IR pulse energy and the average power correspond to laser parameters before frequency doubling. Data sets are labelled with an acronym PPB – pulse(s) per burst. The solid lines in a) and b) are fits of the experimental data to the laser ablation model, described in the text.

Microstructuring with bursts not only proved to be more efficient and faster compared to the single pulse processing, but in general also the achieved structure quality was better. Comparing the amount of molten material on copper parts of structures, the definition of structure edges, and the condition of the substrate the best quality of the copper structures was achieved when processing with 10 pulses per burst, showing well defined edges and the least amount of melting, resulting in an optically clean copper surface. The substrate gets a higher heat accumulation with an increasing number of pulses per burst, showing signs of higher temperatures reached, visible in a form of bubbles. This is in line with the previous findings from graphs in Fig. 3d. Bursts of pulses open a wide parameter window where the structure quality achieved is at least equal to the structure quality achieved by single pulse ablation, but at a lower pulse energy.

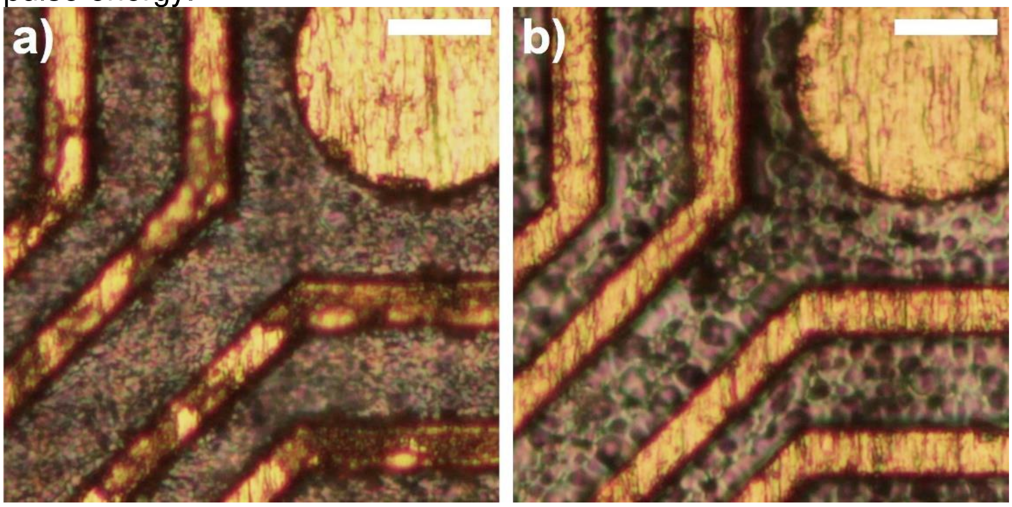

Fig. 4. Structures with a different number of PPB, but with equal processing times (16 seconds). Picture a) shows a structure made with 1 PPB and b) 10 PPB. The structure quality is improved with a greater number of PPB, which can be seen as a cleaner and more uniform copper surface. An increased laser damage to the substrate in form of growing bubbles is visible in b). The scale bar equals to 20 μm.

Conclusion

We have developed an experimental system capable of delivering tightly focused bursts of laser pulses to the chosen points on the material in a chosen sequence. We have demonstrated that bursts of 65 picosecond pulses increase the ablation efficiency during microstructuring up to twofold within the sets of tested parameters and shorten the typical processing time of microstructuring up to 40 times compared to the single pulse per spot regime.

The specific combination of laser parameters, tight focusing, and a highly conductive copper layer material was used to demonstrate a clear advantage of material processing with bursts of pulses. Bursts of pulses are a solution which enables the use of compact fiber lasers, with no losses to the processing speeds and up to 10 times lower peak powers needed compared to the single pulse processing of equal materials.

We have used a simple short-pulse laser ablation model to highlight the difference between single pulse ablation and ablation with bursts of pulses. After validating the model on the 1 PPB ablation data we have developed a correction to the model to account for the opposing effects of shielding and heat accumulation during microstructuring with bursts, achieving a very good match between the model and our data.

Wide parameter space available for a successful creation of microstructures in a copper layer allows to tune the microstructuring process according to the target requirements. The least damage to the substrate is done with low energy pulses in a single pulse regime due to a low total energy input and a wide heat distribution. The fastest structuring was done with bursts of 20 pulses as the product of the burst energy and the ablation efficiency is the highest. The best structure quality was achieved with bursts of 5 or 10 pulses, depending on the processing parameters used, possibly due to the heat distribution effects. Microstructuring with bursts offers good efficiency and an appealing compromise between the structure quality, the structuring speed, and the damage to the substrate. Due to the lower required pulse energies it facilitates the use of fiber lasers for future microstructuring purposes.

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