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Speckle-free laser marking of metals using liquid-crystal-based spatial light modulator

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A liquid-crystal-based spatial light modulator (LC-SLM) is used for laser beam patterning and manipulation in order to produce very small, speckle-free 2D marks on metal surfaces. To avoid speckles within the laser marked area, which is a typical drawback of current SLM-based laser marking processes, an array of “non-interfering” beamlets is produced by the LC-SLM and used for generating micro-patterns. The micro-patterns (e.g. 20×20 pixel datamatrices with overall dimensions of less than 320μm by 320μm) are generated in a series of 16 steps, using a Fresnel zone lens (FZL) which is written into a computer-generated hologram (CGH) that produces an array of beamlets. By shifting off-axis the whole kinoform (FZL+CGH) for each step, the array of beamlets is spatially moved along the imaging plane, producing the required micro-pattern. In comparison to other SLM-based laser marking approaches already reported in the literature, our method not only eliminates (or at least significantly reduces) unwanted speckle interference but also reduces the laser power required for marking.

Keywords: Laser marking, spatial light modulator, picosecond laser, laser material processing, laser ablation

1. Introduction

Liquid-crystal-based spatial light modulators (LC-SLMs) provide the ability to modify both phase and amplitude of linearly polarized light. The high spatial resolution of LC-SLMs (e.g. 1024×768 pixels) coupled with their relatively high optical damage threshold and ease of programming mean that they have started to be used with commercially-available short-pulsed lasers to generate complex beam shapes for effectively parallel processing of various materials [1-6], in contrast to the relatively time-consuming sequential approach of a scanning laser beam. An average laser power handling capability of commercially-available SLMs in the visible and near-infrared spectral range is approximately 2 W/cm^2, but it can be increased to approximately 10 W/cm^2 when a water-cooled heat sink is mounted to the liquid crystal display [4].

An LC-SLM is typically used as a diffractive optical element (DOE) when an appropriate beam pattern needs to be generated with this device. In such a configuration, the LC-SLM unfortunately produces unwanted speckles that affect the quality of the laser marking area. As explained in [6], speckles result from the pixilated (digital) character of the SLM display that introduces discontinuity to the computer-generated hologram (CGH). One of the methods to overcome the speckle problem is to use a series of periodically-shifted CGHs, as reported by Golan and Shoham [7]. Although this approach allows us to reduce the speckles and improve the quality of the laser-making area, as shown by Parry *et al.* [8], it seems to be ineffective when small-scale marks are required, i.e. less than 30×30 μm.

In this paper, we present a SLM-based laser marking method which allows complex 2D micro-patterns, e.g. datamatrices, to be produced without speckles, using relatively low values of the output laser power. In this method, a Fresnel zone lens (FZL) in combination with a computer generated hologram (CGH) is used to repeatedly move an array of diffractive beams (beamlets) across the workpiece surface to sequentially generate the sub-pixel arrays that eventually merge into a designed micro-pattern. Although steering the laser beam with a FZL written onto the SLM display has been already reported by Davis *et al.* [9], this is the first time that this approach has been used with an array of laser spots. The FZL has the important added benefit of defocusing the zero-order beam at the workpiece, thereby preventing its unwanted damage [10].

To demonstrate efficient operation of our approach, we performed an experiment in which a 230 μm square checkerboard pattern was produced by using: (i) the basic approach without speckle reduction, (ii) the speckle reduction technique introduced by Golan and Shoham [7], and (iii) our novel laser marking method. We also demonstrate an alternative approach to our method, in which a series of 16 *different* CGHs sequentially generate the array of diffractive beams at the processing plane. Finally, we demonstrate a possible application of our laser-marking approach for secure data coding of small and valuable metal parts.

2. Experimental setup

Figure 1 shows an optical arrangement of the experimental setup. Here, a linearly polarized laser beam is delivered to the SLM display (Holoeye LC-R 2500) via a half-wave plate and a beam expander. The laser (Trumpf TruMicro 5050 3C) generates 6 ps pulses with a 400 kHz rep-rate, and operates at a 515 nm wavelength. The SLM display has a resolution of 1024 by 768 pixels with a pixel size of 19 µm × 19 µm, and can generate 8-bit holograms with a frame rate of 75 Hz.

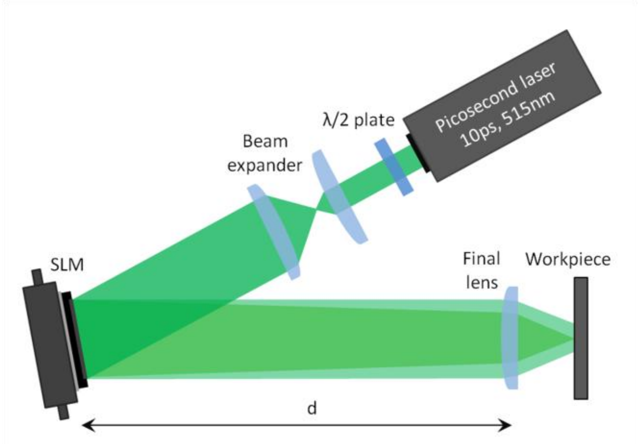

Fig. 1. Schematic diagram of the optical setup used in laser marking experiments.

In all experiments described in this paper, a FZL was added to the CGH using the Holoeye software in order to defocus the zero-order beam at the processing plane, thereby preventing unwanted machining of the workpiece. In this setup, the FZL had a focal length of approximately 1.5 m, whereas the final lens with a 30 mm focal length was placed at a distance (d) of 0.91 m from the SLM display. This two lens focusing system provided a 1.45 mm separation between the zero-order and the diffractive pattern, as calculated using formulae given in [10]. The workpiece was a flat piece of martensitic chromium steel (Chromflex) from Sandvik.

3. Experimental procedure and results

To demonstrate efficient operation of our laser-marking method, we performed an experiment in which a 220 µm×220 µm checkerboard was generated by using four different approaches:

i. Basic approach in which the metal surface was irradiated 16 times using a *fixed* CGH with the software-written FZL. The final CGH represented the Fourier transform of the 8×8 checkerboard, as can be seen in Fig. 2. A single laser irradiation contained a 13.33 ms train of 6 ps laser pulses, corresponding to the duration of a single image frame generated by the SLM.

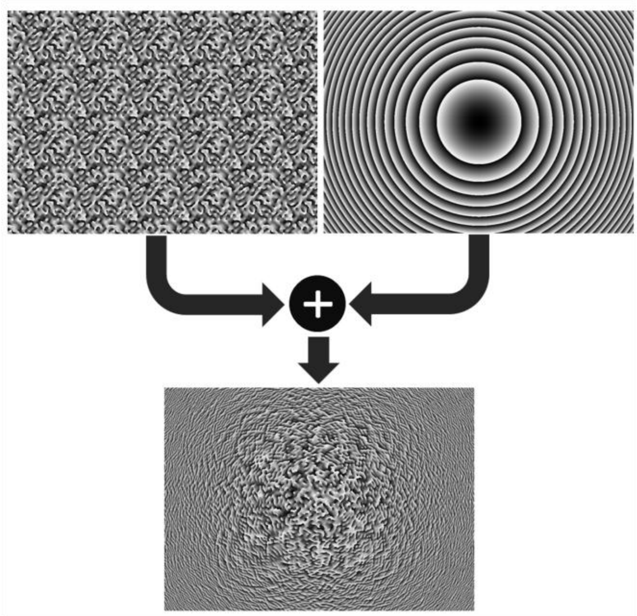

Fig. 2. Generation process of the CGH with the software-written FZL.

ii. A previously reported approach [7, 8] in which the test pattern is produced by 16 trains of laser pulses, but this time the CGH is periodically shifted (vertically and/or horizontally) prior to each laser pulse train. In each shift, the CGH pattern is moved by a given number of pixels, as demonstrated in Fig. 3, and the FZL is subsequently added. Each displaced CGH pattern generates an identical pattern at the workpiece, but with a different speckle field superimposed, effectively reducing speckle by 'time-averaging' over the 16 frames.

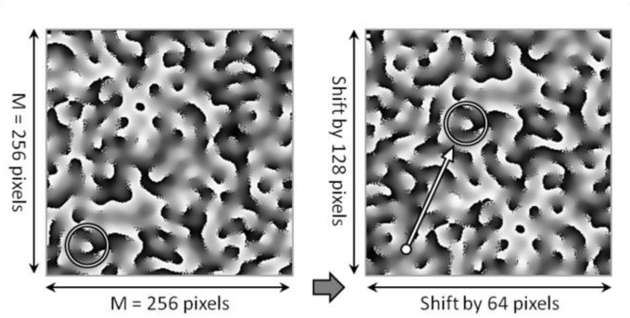

Fig. 3. Demonstration of a periodic kinoform shift for a periodicity c = 4. The CGH is shifted by one period in the horizontal axis and two periods in the vertical axis. The circle tracks a single feature [8].

iii. Our novel laser marking in which a CGH combined with the FZL is used to generate an array of diffractive beams (beamlets), as can be seen in Fig. 4. The beamlets are used to mark in parallel small areas (sub-pixels) of the checkerboard squares. The top left (first) sub-pixels of all squares are illuminated for the first frame of the SLM (13.33 ms). The whole kinoform (CGH+FZL) is then shifted prior to the second frame in order to translate the array of beamlets by one sub-pixel to the right, and afterwards mark the second sub-pixel of each checkerboard square. This process is continued until all 16 sub-pixels have been marked.

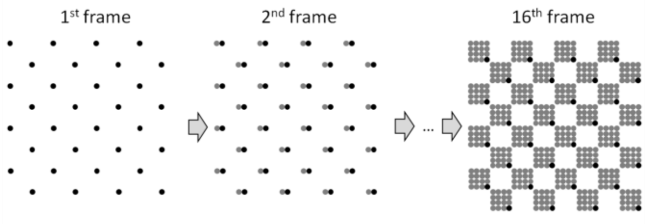

Fig. 4. Concept of the laser marking method described in iii) above. Black and grey dots represent currently and post-marked sub-pixels of the checkerboard, respectively.

iv. An alternative approach to (iii) in which 16 *different* CGHs are used to sequentially mark the checkerboard pattern. Again, the checkerboard squares are marked in parallel, using 16 successive frames – each of which generates an array of sub-pixels. However, rather than moving the whole kinoform (CGH+FZL) between each frame (laser irradiation), a *different* CGH design (together with on-axis FZL) is instead used to generate each of the sub-pixel arrays, as shown in Fig. 5.

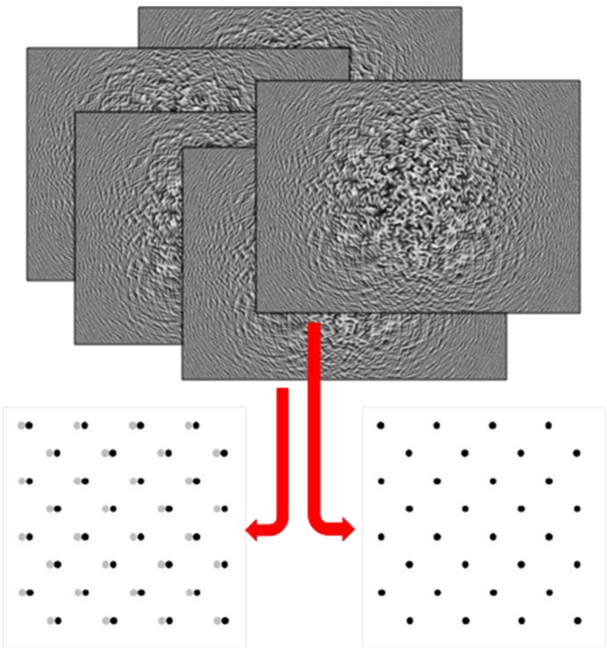

Fig. 5. Concept of the alternative laser marking approach to (iii) above. Black and grey dots represent currently and post-marked sub-pixels of the checkerboard, respectively.

Figure 6 shows the checkerboard patterns which were produced by using one of the four laser-marking approaches described above – in the same order. Patterns presented in Fig. 5 (a) and (b) were generated at an average laser power of P = 7.1 W, using 16×13.33 ms trains of laser pulses. The laser marked areas of Fig. 6 (a) and (b) clearly suffer from speckle interference, even though the pattern in (b) was marked using the time-averaging technique described in (ii) above. Although this technique can efficiently reduce speckles, as reported in [8], in our case the reduction was inefficient because the marked areas were significantly smaller.

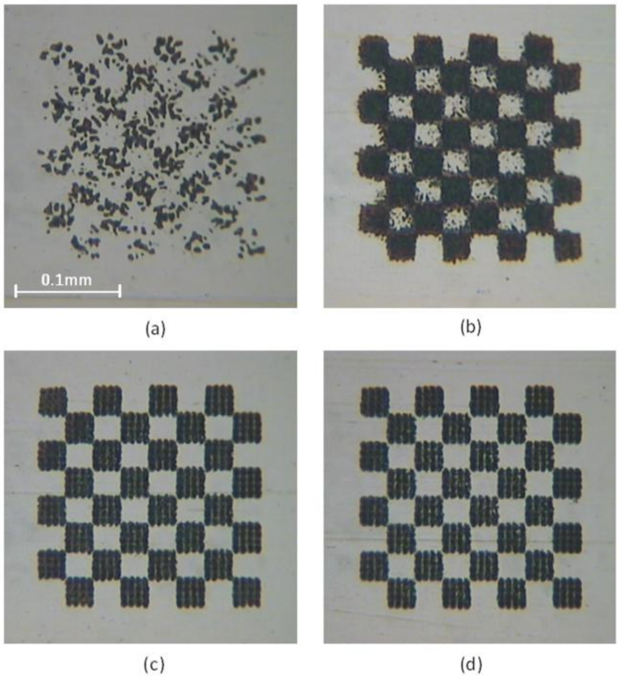

Fig. 6. Checkerboard pattern produced by using four different approaches: (a) basic approach, (b) time-averaging technique, (c) our new laser-marking approach, and (d) an alternative approach to (c). Patterns (a) and (b) were generated at P = 7.1 W, while patterns (c) and (d) were produced at P = 2.25 W.

The checkerboard in Fig. 6 (c), meanwhile, which shows no evidence of speckle, was obtained by using our new approach [i.e. (iii) above]. The average laser power used for marking the pattern was approximately 3 times lower (P = 2.25 W) than for approaches (i) and (ii), whilst the other laser machining parameters were unchanged. To generate the checkerboard, the whole kinoform (CGH+FZL) was repeatedly moved off-axis with a step of 7 pixels (as defined in the Holoeye software) prior to each train of laser pulses.

4. Generation of very small, speckle-free datamatrices

In this section, we present a possible application of our laser-marking approach for secure data coding of small metal parts. Figure 7 shows a 20×20 datamatrix containing coded information of 22 alphanumeric characters.

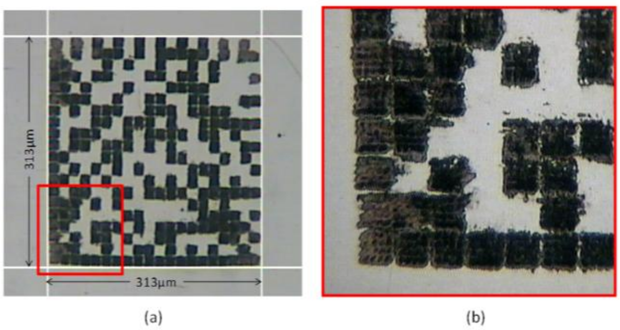

Fig. 7. Datamatrix containing a code with 22 alphanumeric characters. This datamatrix was produced on the surface of Chromflex steel using our invented laser-marking method at P = 10.9 W.

This datamatrix, when is magnified, is readable using e.g. a smartphone with a downloaded datamatrix reader. Since the datamatrix design was larger than the checkerboard pattern shown in Fig. 6, it was necessary to increase the output laser power to 10.9 W in order to achieve decent ablation of the metal. As before, we used 16 laser irradiations (16×13.33 ms trains of laser pulses), but this time the FZL was set up to give an approximately 1 mm separation distance between the zero-order beam and the diffractive pattern. This approach allowed the datamatrix (square) pixels to be reduced in size to only 15.5 μm.

5. Conclusions

We have experimentally demonstrated a simple but novel SLM-based laser marking approach in which an array of beamlets is used for parallel marking the array of sub-pixels to build up arrays of square pixels. This approach allows complex micro-patterns to be produced on the workpiece with excellent surface quality and without visible speckles. This means that such patterns can be easily read with an optical microscope equipped with the datamatrix reader. We believe that this new approach will find application in medicine, industry, and military for secure data coding of small and valuable parts, such as stents, microchips, car/aeroengine components, etc.

The time required for the generation of the datamatrix shown in Fig. 7 has been estimated to be approximately 0.6 s (16×13.33 ms for laser marking and approximately 0.4 s for shifting the whole kinoform between the subsequent laser irradiations). This means that 100 similar micro-patterns can be produced within one minute. Although the processing time seems to be acceptable for mass-marking, we believe that such small datamatrices can be produced with even shorter time if an SLM with higher frame rate were available. Recently, we have found that high quality markings can be generated with only 400 pulses/pixel (compared with the 5333 pulses/frame used here), providing the opportunity to reduce the laser marking time of 20×20 datamatrices to less than 0.42 s.

Finally, although it is possible to generate small micro-patterns by entirely sequential marking using a galvo scanhead with a single focused laser beam, datamatrices with such small scale square pixels would be difficult to achieve with standard galvo scanning systems. Our new SLM-based sequential-parallel approach, meanwhile, provides an efficient, high precision process without the need for moving parts.

Acknowledgments and Appendixes

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