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Paper:

Diamond Machining of Holograms Using Fine Rectangular Shaped Cutting Tools

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Diamond machining is a flexible process ensuring an excellent workpiece precision. In combination with fast tool servos, which dynamically modulate the depth of cut, diffractive microstructures and holograms can be machined. The complexity and functionality of the structure depends on the flexibility of the machining process. Novel diamond tool geometries with fine rectangular shaped cutting edges and a width below 20 μm extend the machinable structure geometries. This paper presents fundamental cutting experiments using these novel tools with widths of the cutting edge of 10 μm and 20 μm to machine diffractive microstructures with a rectangular shaped profile. Particularly, the influence of the feed on the uniformity of the structure width and on burr formation on the structure edges is investigated. Using these tools together with fast tool servo assisted diamond turning holograms for multiple wavelengths can be machined, forming different intensity patterns in dependence of the wavelength.

Keywords: diamond turning, microstructure, hologram, diamond tools

1. Introduction

For realizing compact and highly functional optical systems, surfaces with complex microstructures are essential. Applications for such diffractive optics range from classical spectroscopic gratings, intra-ocular lenses, security features on banknotes to high-performance optical instruments [1]. The achievable complexity of these structures depends on the available degrees of freedom of the manufacturing process.

Many diffractive microstructures consist of a periodic structure with at least one constant structure characteristic, e.g. structure angle or structure height, and are continuous in one direction. Common manufacturing processes for these structures are lithography, laser machining or diamond cutting [2]. For more complex structures with multiple height levels, only few manufacturing processes provide the necessary machining flexibility, accuracy and economic efficiency.

Diamond machining offers this flexibility and obtains an excellent precision for a variety of structure geometries [3–5]. Typical diamond machined structures, which are mainly continuous in the direction of feed, are blazed gratings [6] and Fresnel lenses [7, 8] with structure sizes ranging from a few hundred nanometers to several micrometers of the groove depth. They can be machined using milling, turning or grooving processes for continuous structures [9] and also for interrupted structures consisting of several segments, e.g. to machine multi focus Fresnel lenses [10].

The structure complexity can be increased by adding an additional in-process tool movement. One possibility is to twist the tool during a grooving process for fabricating blazed gratings. With the twist axis perpendicular to the workpiece surface, this allows for an adjustment of the groove width [11]. Another approach is to change the depth of cut by using a dynamic axis to actuate the cutting tool. This can be achieved with the linear axes of the machine tool (slow slide servo) or with an additional actuator (fast tool servo). Both techniques enable the machining of freeform and structured surfaces [12, 13]. Also, multileveled diffractive optics can be generated, e.g. by combining a linear broaching process with a slow slide servo [14] or by applying a fast tool servo assisted diamond turning process [15].

The method used in the paper is based on a nano Fast Tool Servo (nFTS) as proposed by [16], which modulates the depth of cut in the nanometer range at frequencies of 5 kHz, for machining of diamond turned holograms (DTH).

Previous investigations in this field have focused on machining of DTH using a blazed geometry of the basic diffractive structure. Blaze gratings are typically optimized for one particular blaze angle and a certain wavelength [17]. This, however, limits the functionality of the surface structure to only modulating the phase of the incident light and not of the phase gradient. Therefore, the DTH can so far only be used with monochromatic light of high coherence.

As a new approach to overcome these limitations, an in-process adjustment of the structure angle can enable a combination of the properties of diffractive and freeform optics. With this novel type of hybrid optics, beam shaping of partially coherent radiation can be realized. Such structures could be applied as optical security features to verify the authenticity of a product, for instance by scanning the feature with a smart phone.

To implement a variation of the structure angle, not only an additional rotation of the tool is required, but also a specific type of diamond tools has to be applied. This paper presents fundamental cutting experiments using the novel diamond tools with widths of the cutting edges $< 20\ \mu$m, to establish the basic machining process required for further developments. Furthermore, holograms are machined applying the tools together with the nFTS assisted turning process. With this combination holograms for multiple wavelengths can be machined using only one structured surface to shape two different wavelengths into individual intensity distributions.

2. Machining Process

2.1. Machining Principle

The basic process to machine a DTH is a face turning process, executed on an ultra-precision machine tool. Depending on the process kinematics, especially on the feed and the shape of the diamond tool, a defined structure geometry is cut into the surface. Using fine rectangular shaped diamond tools, the cross section of the resulting structure exhibits a rectangular profile. This fundamental structure will be superimposed with an overlaying pattern consisting of two characteristic features (cf. **Fig. 1**).

The first feature is a modification of the local height level. By adjusting the depth of cut with the nFTS individual segments are generated in cutting direction, each having a defined height. Prior to machining, an optical design is carried out calculating the height of the segments by applying specifically developed algorithms [18]. The nFTS movement is triggered by the encoder signal of the main spindle, which allows for a precise positioning of the segments. There are however, certain limitations of the structure accuracy. The steepness of the transitions between two segments is influenced by the tool clearance angle, which measures $\alpha = 20°$ in order to retain a sufficient stability of the cutting edge but also to enable machining of relatively steep edges when the depth of cut is increased. The second feature is a modification of the structure angle. To change the structure angle the tool mounted on the B-axis will be rotated by the angle β. For this purpose the center of the cutting edge has to match the center of rotation, requiring a precise adjustment of the tool.

2.2. Machining Requirements

The implementation of this machining process, with the aim to achieve the full complexity of the structure, requires several development steps:

i) nFTS with sufficient positioning accuracy,
ii) basic machinability of rectangular structure,
iii) tool adjustment on center of rotation of B-axis,

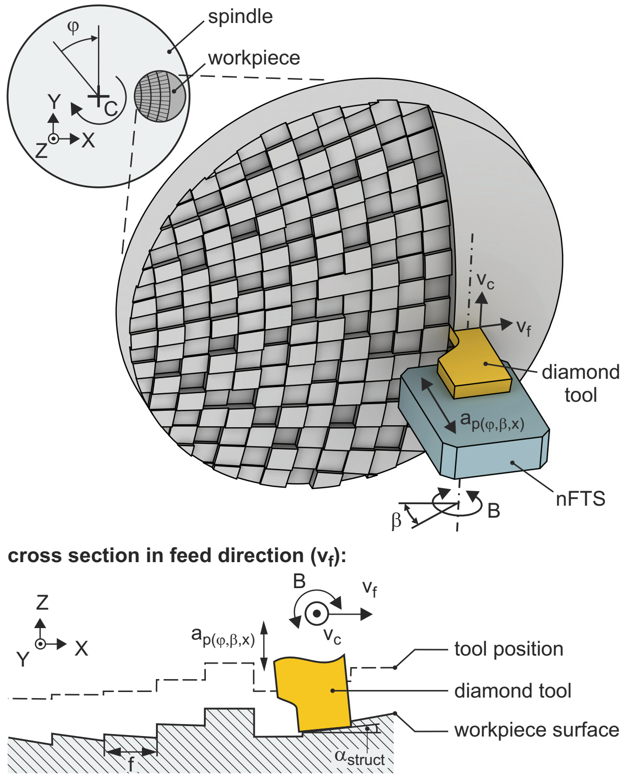

Fig. 1. Process principle for diamond machining of holograms with varying structure angle.

iv) in-process tool rotation to adjust structure angle.

The assessment of the positioning accuracy (i) was verified by optical measurements and by machining and evaluation of reference structures. The main results are summarized in section 3. An investigation of the basic machinability (ii) is presented in this paper in section 4, whereas the tool adjustment on the B-axis (iii) and the adjustment of the structure angle (iv) will be subject of future research.

In regard to the basic machinability, it is the objective to apply the rectangular shaped diamond tools to machine a structure with a rectangular profile, as depicted in **Fig. 2(a)**. It is essential, that the grooves and protrusions of the structure exhibit an equal width without burr at the edges and a surface finish of optical quality (i.e. Sa ≤ 10 nm).

The groove width w_g will always be the same as the diamond tool width w_t, regardless of the feed. However, the protrusion width w_p and burr formation will significantly depend on the feed. In case of a larger feed ($f > w_t$) the protrusion width will increase and the formation of burr on the vertical edges is more likely. Using a smaller feed ($f < w_t$) will lead to a smaller protrusion width, since to grooves and protrusion slightly overlap and more material will be removed from the vertical flanks of the protrusions (cf. **Fig. 2(c)**).

All deviations of the ideal structure ($w_g = w_p$) as well as burr on the edges will decrease the optical efficiency of the DTH. Therefore, an equal width of protrusions and grooves is intended, but formation of burr has to be

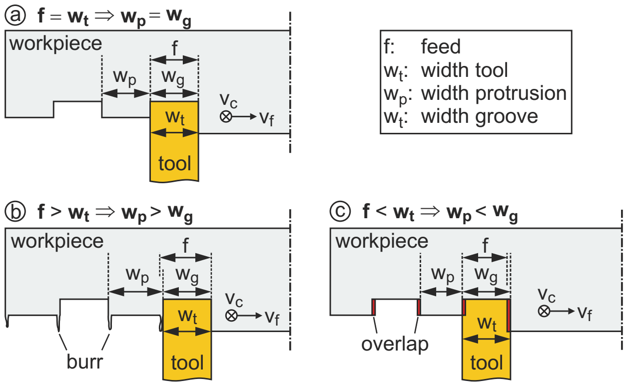

Fig. 2. Influence of feed f and tool width w_t on structure generation.

avoided at the same time. To accurately adapt the feed, the tool width has to be determined in advance and suitable machining parameters have to be identified.

3. Assessment of Nano Fast Tool Servo

The machining of DTH requires a high positioning accuracy of the piezo-driven nFTS. Due to the negligibly hysteresis of the piezo ceramic an open-loop control can be used. To control the nFTS the correlation of stroke and applied control voltage has to be known. In a first step, the displacement depending on the control voltage (-5 to 5 V) was measured optically by a laser interferometer. The maximum stroke at a control voltage of 5 V measures 1059 μm and a maximum deviation of the nominal stroke of 1.8 nm was determined within five measurements.

Since the actuator is not equipped with any further guidances, the cutting forces will directly act on the piezo ceramic. Therefore, the positioning accuracy has also to be verified while the load of the cutting process applies. This was examined by machining reference structures in nickel silver with alternating height levels from 0 to 1000 nm and a stepwise increase of the depth of cut by 100 nm, as depicted in **Fig. 3**.

The resulting structure was measured by white light interferometry and a circular profile was analyzed. The height values were determined by calculating an average of each segment. Compared to the measured deviation, the evaluation of the machined structures leads to higher deviations of the nominal stroke, as shown in **Fig. 4**. Within three experiments, an average deviation of 2.6 nm was determined, with a maximum of 6.8 nm. This results in a slightly lower positioning accuracy compared to the sole measurement, due to the cutting forces. However, the overall accuracy is still sufficient to operate the system open loop.

4. Diamond Turning Experiments

4.1. Process Preparations

The basic machinability and applicability of fine rectangular shaped diamond tools is assessed in diamond

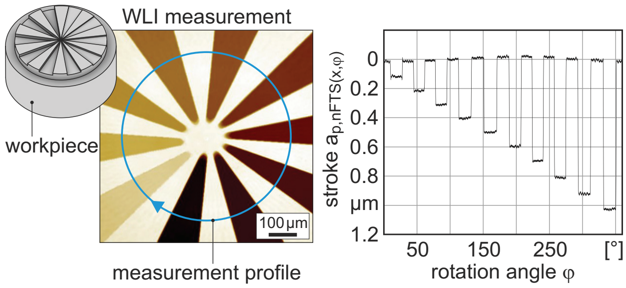

Fig. 3. Evaluation of positioning accuracy by machining of reference structures.

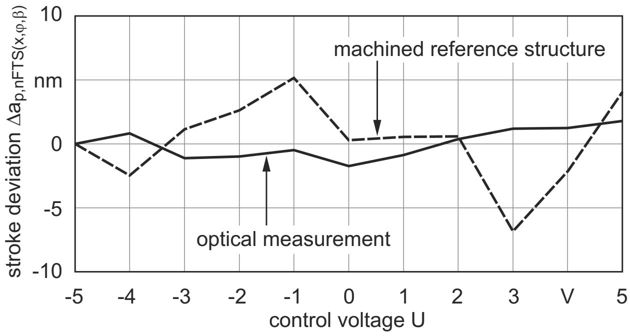

Fig. 4. Deviation of nominal stroke assessed by optical measurement and by evaluation of machined structures.

turning experiments. To machine the rectangular shaped microstructure, the depth of cut $a_p = 1$ μm alternates by 200 nm, which is adjusted by the nFTS after every workpiece revolution. The cutting zone is lubricated by an oil spray mist, which also supports the removal of chips.

Since the structure geometry mainly depends on the tool geometry and the corresponding feed, the tool width w_t has to be determined prior to machining in order to adapt the feed. For this purpose every diamond tool is examined with a microscope at 1000× magnification. The two tools used in this study had nominal widths of $w_t = 20$ μm and 10 μm. However, due to manufacturing tolerances deviations of the nominal width occur resulting in a tool width of $w_t = 21.74$ μm and 12.04 μm, respectively (cf. **Fig. 5**). Owing to the optical measurement principle of the microscope, the measurement results deviate by up to 0.3 μm. Based on these measurements, different feeds were defined according to **Table 1**. For both tools feeds slightly larger and smaller than the tool width, as well as approximately equal to the tool width were used.

As workpiece material for this preliminary machinability study pure aluminium (Al $>$ 99.7%) with an ultra-fine grained crystalline structure was used. The average grain size measures approximately 400 nm [19]. This material features homogenous material properties, which result in a uniform material removal and an equally distributed load applied on the fragile tool tip. Investigations on diamond turning of this aluminium yielded an excellent surface finish of Ra $<$ 4 nm, which qualifies it for machining of optical surfaces [20].

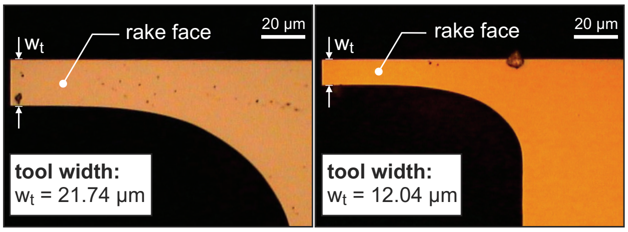

Fig. 5. Measurement of tool width w_t with light microscope (magnification 1000×).

Table 1. Feed variations corresponding to tool width w_t.

Tool width w_t (μm)	feed f (μ m)		
	$f > w_t$	$f \approx w_t$	$f < w_t$
21.74	24	22	20
12.04	13	12	11

4.2. Influence of Feed on Structure Accuracy

The machined structures were analyzed by a confocal microscope to determine the structure accuracy, i.e. the surface roughness, burr formation on the structure edges and the widths of grooves and protrusions. For every set of parameters three experiments were conducted and for each sample four defined positions on the edge and center of the workpiece were measured. A selection of representative measurement results are shown in **Figs. 6** and **7**. For each feed a top view of the surface is given, and additionally the corresponding profile.

The structure machined with the larger tool (w_t = 21.74 μm) and a feed of $f = 24$ μm exhibits a continuous burr along all structure edges. The amount of burr was reduced significantly by applying the feed of $f = 22$ μm. However, even though the feed approximately equals the tool width w_t burr is frequently observed with widths of several hundred nanometers up to 1 μm. Moreover, even very thin burrs remain attached to the structure edges and are not removed by the cutting operation.

Only by applying the lowest feed of $f = 20$ μm, which leads to a small overlap of grooves and protrusions, no burr is formed on the structure edges.

Regardless of the feed, all structures show an artefact on the surfaces, which is caused by a damage of the cutting edge. Furthermore, the surfaces of the grooves and protrusions appear slightly tilted, due to a minor misalignment of the diamond tool. The tilt measures 0.2°.

The structures machined with the second tool (w_t = 12.04 μm) show similar results. Also, for the largest feed of $f = 13$ μm a continuous burr without any interruptions is formed along all edges. With a feed of $f = 12$ μm, the surface exhibits a homogenous profile and burr is only observed occasionally. The lowest feed of $f = 11$ μm results in a homogenous structure without burrs, since grooves and protrusions slightly overlap. Due to a minor misalignment of the diamond tool, the surfaces appear slightly tilted. Also, the corners of the grooves exhibit a blunt profile, which might be caused by tool wear.

Since a uniform structure width was intended, the widths of grooves and protrusions were assessed depend-

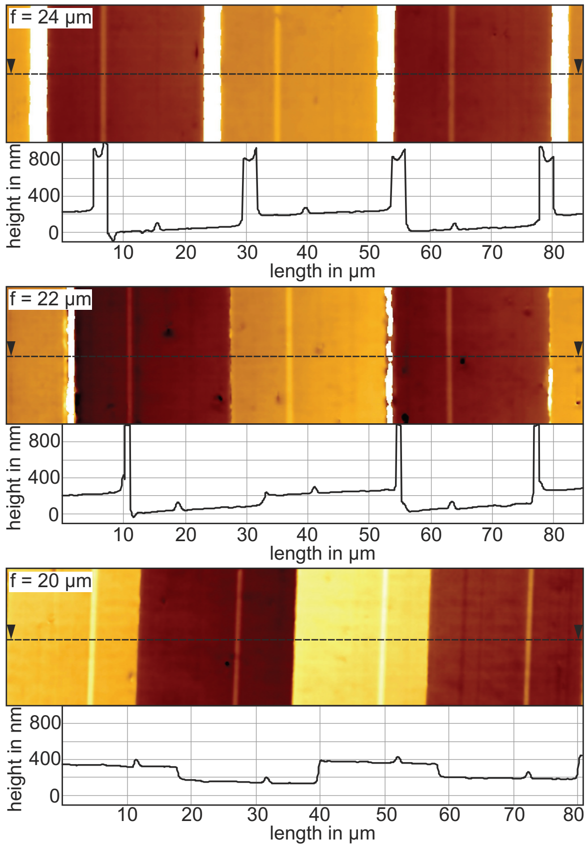

Fig. 6. Surface structure machined with tool width 21.74 μm depending on the feed f.

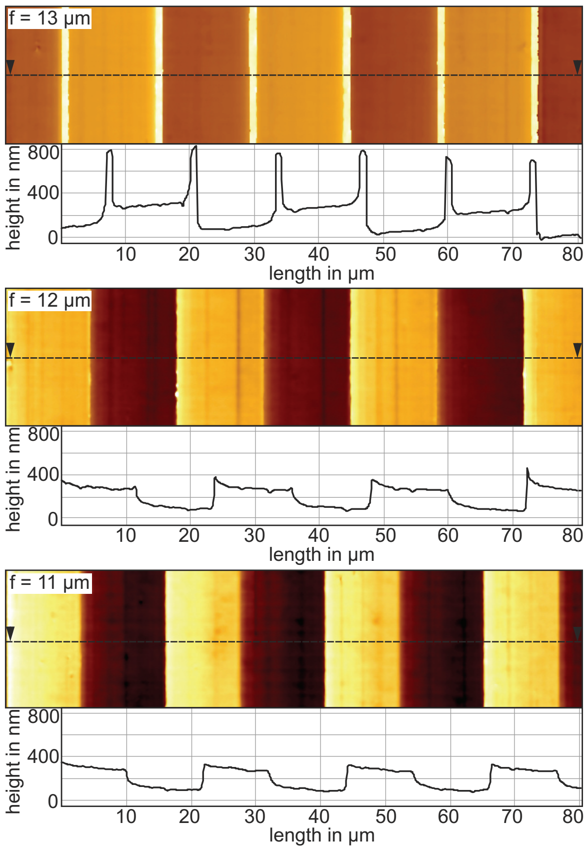

Fig. 7. Surface structure machined with tool width 12.04 μm depending on the feed f.

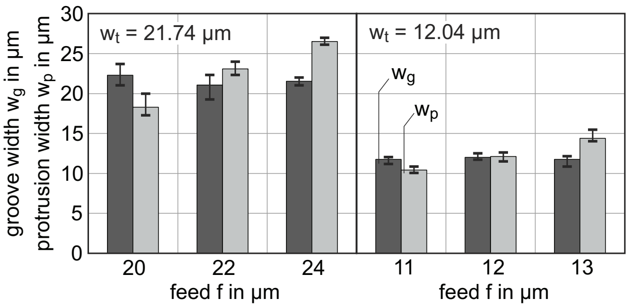

Fig. 8. Comparison of groove width w_g and protrusion width w_p depending on the feed f.

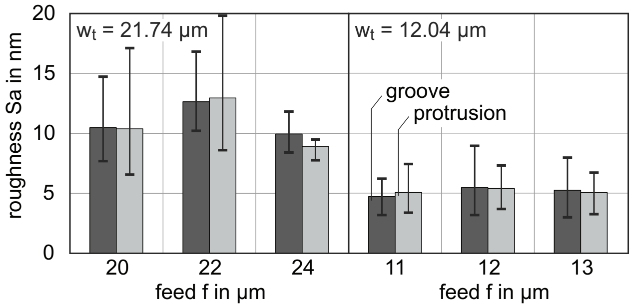

Fig. 9. Surface roughness Sa measured on the grooves and protrusions.

ing on the feed (cf. **Fig. 8**). The most distinct differences are observed when the feed is greater or smaller than the tool width. The best results in terms of a consistent structure width were achieved for $f = 12$ μm. This should also be the case for $f = 22$ μm, nevertheless, the differences between w_g and w_p, which should be approximately equal, add up to about 2 μm in average. These deviations are influenced by the remaining burrs, which lead to an inaccurate assessment of the width. The formation of burr for this feed, on the other hand, is most likely caused due to an inaccurate measurement of the tool width.

In conclusion, to machine structures with equal width of grooves and protrusions and without burr, two aspects have to be considered: the first is a precise measurement of the tool width and the second is the applied feed. In order to avoid burrs at the edges, the feed should be set slightly smaller than the tool width. An overlap of approximately 300 nm should be applied, which was the average deviation when determining the tool width by optical microscopy.

4.3. Surface Roughness

Besides structure accuracy, the surface roughness on grooves and protrusions is also important for the optical functionality. The measurement results for the surface roughness Sa are summarized in **Fig. 9**. The lowest roughness values were achieved with the smaller tool width ($w_t = 12.04$ μm) and the average roughness measures approximately Sa = 5 nm (error bars indicate maximum and minimum values). For the larger tool width significantly higher roughness values between 10 and 12 nm were measured. This is presumably caused by the larger measurement area, which may include more surface defects. For the samples evaluated here, the roughness is mainly increased by the surface artefact caused by the damaged cutting edge. Nevertheless, with an intact cutting edge an average surface roughness well below Sa = 10 nm can be reached, satisfying the requirements for an optical surface finish.

5. Machining of Diamond Turned Holograms

Finally, to verify the applicability of fine rectangular diamond tools a DTH was machined and tested in an optical setup. As workpiece material nickel silver was applied, which has a high reflectivity in the visible spectrum. The workpiece containing the structured surface has a diameter of 20 mm. Using a tool width of $w_t = 20$ μm and 2000 structure elements per revolution, up to 1,000,000 segments are machined in total.

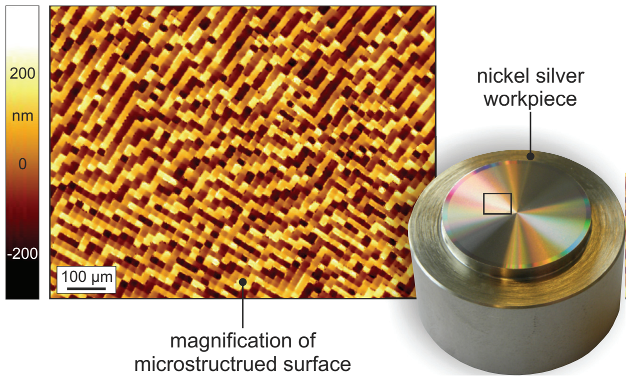

Fig. 10. Microstructured surface of a diamond turned hologram.

The resulting microstructured surface, as shown in **Fig. 10**, represents a relief hologram, which is capable of modulating the phase of coherent radiation incident to the surface.

In previous research, a blazed geometry was used as basic structure. Since blaze gratings are typically optimized for a certain wavelength, it was only possible to fabricate DTH for one specific wavelength. With the rectangular structure profile generated with the novel diamond tools this limitation can be overcome. In addition to the changed tool geometry the stroke of the nFTS of 1 μm allows for structuring over a larger vertical range to enable shaping of multiple wavelengths, and thus, machining of multi-colored holograms.

To verify the functionality of the DTH the structured surface was illuminated with two wavelengths $\lambda_1 =$ 633 nm and $\lambda_2 = 532$ nm and the intensity distribution of the reflected and shaped beams was measured in the propagation plane by a CCD (charge coupled device) camera. Depending on the wavelength different intensity patterns are formed (cf. **Fig. 11**). Both patterns were reconstructed in good quality without crosstalk between each other.

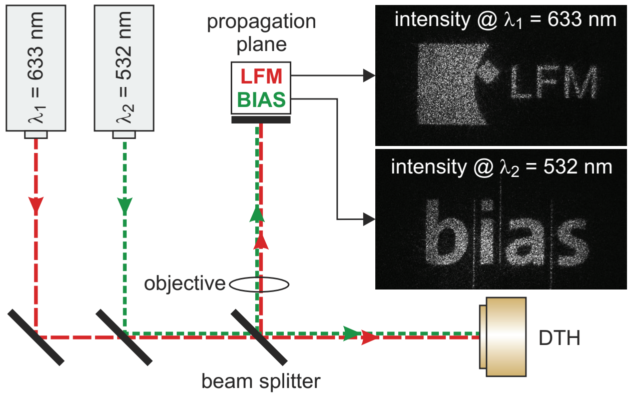

Fig. 11. Multi-colored hologram showing different intensity distributions depending on the wavelength.

6. Summary and Conclusions

The machining of complex microstructures requires flexible manufacturing processes. Fast tool servo assisted diamond turning is a suitable technology to generate diffractive microstructures with complex optical functionalities, such as holograms. Novel diamond tool geometries with fine rectangular shaped cutting edges and a width below 20 μm further extend the machinable structure geometries.

This paper presents fundamental cutting experiments using the novel tools with widths of the cutting edge of 10 μm and 20 μm to machine diffractive microstructures with a rectangular shaped profile. The tool widths w_t of both applied tools were measured with a light microscope and widths of $w_t = 21.74$ μm and 12.04 μm were determined. Based on these measurements different feeds were selected ($f > w_t$, $f \approx w_t$, $f < w_t$) and applied in diamond turning experiments. The resulting microstructures with rectangular profiles (cf. **Fig. 2(a)**) were analyzed in regard to the resulting width of grooves w_g and protrusions w_p, as well as the formation of burr in dependence of the feed. To generate structures with $w_g = w_p$ the feed has to be equal to the tool width. However, to entirely avoid the formation of burr on the edges a minimal overlap of adjacent structures (approx. 300 nm) is necessary. A crucial requirement to achieve good machining results is a precise measurement of the tool width. In terms of surface roughness an optical surface finish in the order of Sa = 5 nm can be realized.

Applying the tools together with a nano Fast Tool Servo allows for machining of diamond turned holograms, which are capable of shaping laser beams with different wavelengths into individual intensity patters using only one structured surface.

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