UV Ultrafast Laser Processing using Phase Masks

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Abstract. Based on the combination of short pulse duration with short wavelength, UV ultrafast lasers provide unprecedented material processing quality. A high power UV ultrafast laser system comprises a Ti:sapphire front-end laser whose frequency tripled pulses are amplified in a UV excimer gain module. In this way, subpicosecond pulses are obtained at 248 nm with an average power of up to 10 W. Such pulses are ideally suited for the treatment of solid surfaces with sub-micron precision. A combination of diffractive optical masks with conventional imaging systems allows the generation of complex 2D structures with typical feature sizes of ~ 200 nm on all materials including metals, semiconductors and dielectrics. A new technique for the fabrication of the phase masks or diffractive phase elements used in the experiments is based on excimer laser patterning of dielectric layers. Such phase masks feature a large processed area, high efficiency for VUV to NIR radiation and can be customized e.g. for perfect zero order suppression.

1. Introduction
The unique capabilities of UV femtosecond lasers for the fabrication of submicron features have been demonstrated on a great variety of materials [1-5]. The combination of a short pulse and a short wavelength serves for minimization of the heat affected zone and high optical resolution. Therefore these systems are well suited for the fabrication of submicron patterns on metallic or semiconductor surfaces. In many cases periodic patterns are desired, for example, in optical or tribological applications. To reach a high processing speed, each subsystem has to be optimized. The laser system has to provide high average power [6], and the optical system has to be arranged in a way that enables simultaneously the largely lossless utilization of the provided power and the desired submicron resolution.

Mask projection is a well suited irradiation strategy for simultaneous treatment of extended sample areas. On the other hand, multiple beam interference is very effective in creating a great variety of periodic nanostructures [7-10]. The combination of these two techniques allows the fabrication of well defined, versatile periodic nanostructures over large sample areas [11-13]. Mask techniques applied, for example, in laser hole drilling are known to be rather inefficient. Using amplitude masks, sometimes more than 90% of the laser energy is lost at the mask. To avoid such losses, especially in the case of periodic patterning, phase masks can be used that consist of a structure influencing the phase of the light without exhibiting absorption or reflection. Phase masks are widely used for the fabrication of fiber Bragg gratings. However, these phase masks are mostly used in a contact or proximity mode, which is suitable for a material modification process, but causes problems in an ablation process, because the mask itself obstructs the material removal and can be damaged by ablation produces. Therefore the application of phase masks in a projection arrangement is very
attractive for ablative fabrication of periodic patterns [14]. In this paper we demonstrate the fabrication of highly efficient phase masks and their application as diffractive beam splitters for UV-femtosecond materials processing.

2. Generation of spatially modulated high intensity beams with sub micron patterns
The highest achievable spatial modulation (the smallest period) can be reached by applying short wavelength radiation. The shortest optical wavelength to date at which high power short pulse lasers can be routinely operated is 248 nm. At this wavelength KrF excimer modules provide a very high optical gain for the amplification of frequency converted pulses of Ti:Sapphire laser systems. Following the system architecture depicted in figure 1, subpicosecond pulses of 30 mJ energy can be obtained at a repetition rate of up to 350 Hz resulting in an average power of nearly 10 W [4]. The high available single pulse energy allows the generation of periodic patterns with high peak irradiation over large areas.

![Figure 1](image1.png)

**Figure 1.** UV femtosecond laser system delivering high peak power sub-ps pulses at 248 nm.

The generation of high intensity short pulse laser beams is a key issue in numerous nonlinear light matter interaction studies. Spatial shaping of laser beams, for example, the generation of flat topped, Gaussian, donut-shaped or periodically modulated patterns is a strong requirement for a variety of applications. Specifically, periodic nano-structures are the key features for the creation of specific filters, photonic crystal structures, or for the functionalization of various surfaces. Consequently, there is a great demand to find experimental techniques allowing the generation of such patterns with high power laser beams, thus facilitating a many new applications in science and technology.

Spatial manipulation of high power laser beams is generally a challenging task because the elements creating the desired spatial modulation have to obey stringent design criteria (negligible overall energy loss, avoidance of nonlinear absorption, high quality in terms of phase front aberration).

![Figure 2](image2.png)

**Figure 2.** Principle of multiple beam interference. A diffractive beam splitter generates several partial beams. The mask is imaged on the sample by the lens. The beam selector defines the partial beams that interfere in the image plane.

A straightforward way to generate a periodic spatial modulation is the interferometric combination of two or more coherent laser beams. This technique allows the generating of a great diversity of various periodic patterns by changing the number of interfering beams, their intersecting angles, their polarization, relative intensities or relative phases. In such schemes [7-10], the key component is a special beam splitter for subdividing the input beam in several partial beams (figure 2). This should be a carefully designed diffractive optical element fulfilling the above mentioned conditions. Full phase diffracting elements made of pure fused silica can be ideal tools for this beam splitting task.
3. Preparation of diffractive phase masks
Phase masks operating in transmission consist of an optically transparent substrate, where spatially defined phase variations are either caused by variations of the refractive index, or by a height relief on the surface. For high power applications, especially in the UV, surface relief structures in fused silica are most common. These phase masks are mostly fabricated by a lithographic process including a reactive ion etching step, which makes the large area production rather costly. We suggest here an alternative fabrication process, which is especially suited for binary phase masks for projection applications, where large mask areas with moderate feature sizes are required.

![Fabrication of SiO₂-phase masks by rear side laser ablation of a UV-absorbing SiOₓ-layer with subsequent thermal oxidation to SiO₂](image)

**Figure 3.** Fabrication of SiO₂-phase masks by rear side laser ablation of a UV-absorbing SiOₓ-layer with subsequent thermal oxidation to SiO₂

![Linear and crossed SiO₂-phase grating masks fabricated according the scheme of figure 3](image)

**Figure 4.** Linear and crossed SiO₂-phase grating masks fabricated according the scheme of figure 3

The surface profile of the phase mask is made by laser ablation. As ablation of fused silica is rather difficult, especially if a precisely defined ablation depth is required, the following process is used (figure 3), which is described in detail in [15]:

1. A SiOₓ-coating (x < 2) with a thickness matching to the required phase delay is deposited on a fused silica substrate. SiOₓ (x < 2) exhibits considerable UV-absorption and is thus better accessible to UV-laser ablation compared to UV-transparent SiO₂.
2. This coating is then removed in well-defined areas according to the desired phase pattern using laser ablation. A standard nanosecond excimer laser operating at 193 nm or 248 nm is well suited for this process. A rear side ablation scheme [16] serves for good quality and debris free processing.
3. By a thermal annealing process (heating to about 1200 K) the SiOₓ-coating is then oxidized to UV-transparent SiO₂, resulting in a UV-grade surface relief element. Thickness changes during this oxidation have to be taken into account.

For the application as a diffractive beam splitter for optimized 1st order and suppressed 0th order diffraction, a binary phase grating with a duty cycle of 0.5 (equal width of lines and spaces) and a profile depth of \(d = \lambda / 2(n-1)\) (\(\lambda\) operation wavelength, \(n\) refractive index) is fabricated. For our case (\(\lambda = 248\) nm, \(n \approx 1.5\)) a thickness of \(d \approx 250\) nm is obtained. Such an element is especially advantageous in combination with a Schwarzschild objective, where in a symmetrical configuration the central beam is obstructed and the 0th order cannot be utilized. For the generation of linear and crossed nano patterns, a linear phase grating and a crossed grating (figure 4) were prepared to be used as a diffractive beam splitter.
4. **Sub micron surface patterns on metals and semiconductors**

For the fabrication of periodic nano-structures, laser direct processing with spatially modulated beams offers a great fabrication potential. According to this technique the periodic modulation in the irradiation field converts to a periodic surface relief pattern of the target. The applied short pulse duration (below 1 ps) ensures a high lateral and depth resolution even in the case of metals and semiconductors, since this pulse duration is typically below the electron-phonon relaxation time, and the thermal diffusion length within the pulse duration (<1 ps) is negligible. At the same time the applied UV wavelength (248 nm) provides a lateral resolution well below 0.5 µm. Moreover, no scanning over the sample surface is necessary since the periodic pattern emerges over a large sample area simultaneously due to the applied mask projection technique. Thus highly efficient fabrication of periodic nano-structures on metal and semiconductor surfaces can be accomplished. Figure 5 displays some representative examples of periodic patterns.

![Figure 5. Linear pattern and crossed pattern fabricated using the UV-fs laser system depicted in figure 1 and a Schwarzschild objective for multiple beam interference in the mask image plane](image)

5. **Summary**

UV-femtosecond lasers in combination with diffractive phase masks offer the possibility of efficient large area surface micro- and nanopatterning. Even metals and semiconductor can be structured with unprecedented resolution. SiO$_2$-phase elements used as diffractive beam splitters for these applications can be made by nanosecond excimer laser patterning of SiO$_x$ layers and subsequent oxidation to SiO$_2$.

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