Smart spatio-temporal beam shaping with thin-film microoptics

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ABSTRACT

The considerable potential of advanced thin-film microoptics for tailoring light fields of pulsed high-power lasers even at extreme parameters like ultrashort pulse durations, broad spectral bandwidths or vacuum ultraviolet wavelengths is demonstrated. A comprehensive review of the state of the art and the most relevant aspects of this branch of modern optics is given. In particular, applications of structured dielectric, metallic and compound layers and programmable liquid-crystal devices for control and diagnostics of ultrashort pulses in space and time are discussed. Recent theoretical and experimental results of wavefront sensing, pulse diagnostics, multichannel materials processing and information encoding into the phase maps of arrayed pulsed beams of nondiffracting propagation characteristics are presented here.

Keywords: Laser beam shaping, thin-films, microoptics, nondiffracting beams, wavefront sensing, pulse diagnostics

1. INTRODUCTION

Thin-film microoptics (TFMO)[1-6] is a relatively young branch of optics developed by merging different, separately evolved fields of classical optical technologies which mainly comprise (a) design, fabrication and characterization of *thin optical films*[7], and (b) the realm of *miniaturized optics* (microoptics) with feature sizes below the millimeter scale[8-11]. This development was mainly driven by the requirements of new and highly dynamic markets for beam shaping components and systems (e.g. pick-up heads for optical data storage, microlens arrays for digital cameras, collimators for high-power diode lasers) as well as very advanced research applications (e.g. ultra-precise wavefront sensors for starlight analysis in astrophysics).

Recent progress in the field was significantly inspired by tasks like the intra- and extra-cavity spatio-temporal control of intense laser pulses, multichannel laser-material interaction, optical information processing and fundamental quantum mechanical experiments. The application of thin-film microoptical systems promises substantial improvements because of combining all the specific advantages of the particular principles forming their physical and technological basis. Furthermore, if adaptivity is implemented (like, e.g., in electrically addressable liquid crystal layers), more flexible and compact beam shaping systems can be realized as it was already anticipated in the early 1990s[12]. Thickness modulated dielectric multilayer and metal-dielectric composite designs essentially extend the capability of microoptical elements to the control of the spectral phase in space. In general, the field of thin-film microoptics is dynamically developing in the direction of higher precision, enhanced complexity, larger numbers of elements, cost effective mass production and/or smarter functionality.

In this keynote lecture, an overview on the state of the art of tailoring coherent light fields by means of new types of thin-film devices with *spatially variable* or *addressable* parameters will be given. Specific optical properties and degrees of freedom of layer structures and array architectures are pointed out[1]. Relevant issues concerning structural design, fabrication and post processing procedures, component characterization, simulation and the analysis of light propagation and transfer functions are considered. Particular attention will be paid to the manipulation of femtosecond wavepackets in space and time even under extreme conditions with respect to pulse duration and spectral bandwidth[13]. The generation of *pseudo-nondiffrating* Bessel-like beams[14] and needle-shaped beams ("needle beams")[1,15] of large aspect ratios and excellent spectral and temporal transfer functions by means of static as well as programmable layer axicons is demonstrated in detail. Their application to the *multidimensional shaping and diagnostics* of localized waves including

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robust wavefront sensors[16,17], spatially resolved autocorrelators[18-20] or encoding image information in the parameter maps of arrays of few cycle X-pulses ("flying images")[21-23] is shown. Finally, new concepts for next generation microoptical devices and system architectures are presented.

2. TAILORING COMPLEX LIGHT FIELDS WITH THIN-FILM MICROOPTICS

One fascinating aspect of thin-film microoptics arises from the potential to combine spatial features (surface relief) with material properties (types of layers and substrates) and internal structure (number, thickness and composition of layers). The concept of thin-film microoptics enables to realize the first steps toward theoretically proposed highly universal types of beam shapers referred to as *"refractive-diffractive-dispersive structured optical elements"*[24]. The principle of a generalized shaping of amplitude and phase with complex micro- and/or nano-structured thin layers[1] is schematically drawn in Fig. 1.

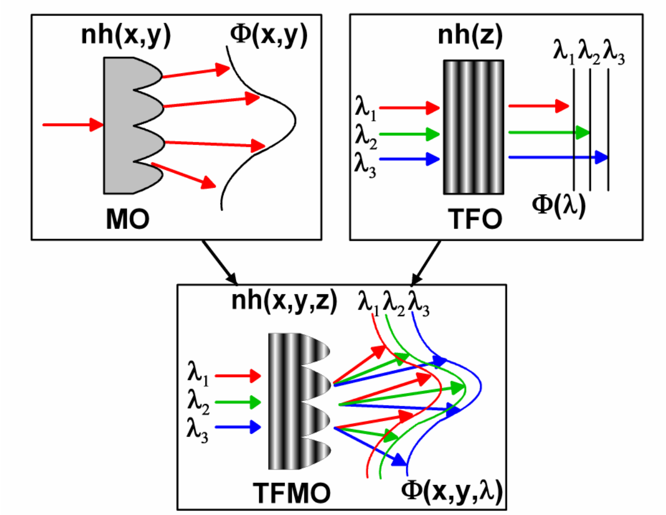

Fig. 1. Tailoring complex light fields with generalized thin-film microoptical beam shapers (TFMO, down below) combining the particular features of microoptics (MO, left above) and thin-film optics (TFMO, right above) (schematically, after[1]). The optical path length *nh* depends on the coordinates in space and can be (as in the case of electrically or optically programmable layers) even time-dependent. For each spectral partition λ_i, an individual wavefront $\Phi(x,y,\lambda_i)$ results from its specific transfer functions.

A part of the basic physical principles of TFMO components is well known from microoptics and thin-film textbooks. Another part, however, requires a better understanding of light propagation in optical layers with minimum transversal or lateral features on nanoscale, vanishing contact angles, stacked arrangement, flexible substrates etc. The art of shaping a light field under extreme conditions with a single and compact TFMO component or system consists in carefully optimizing and balancing the contradictory actions of dispersion, diffraction and refraction and comes out to be particularly challenging for ultrashort, ultrabroadband and ultraintense laser pulses. The situation is complicated by spatial inhomogeneities, space-time coupling phenomena, spectral window functions, nonlinear-optical effects and internal resonance peaks in multilayer structures.

Significant simplifications for ultrashort-pulse applications[25] as well as new functionality with respect to the shaping of pseudo-nondiffracting (localized) waves can be obtained in the special case of very flat and smooth structures. With such *ultraflat structures* of typical structural depths small against their characteristic transversal dimensions (*nanolayer* *microoptics*), a part of the above mentioned problems is tackled and new types of beams are generated which may become of great practical interest. Because of the small angles and the reduced diffraction effects at the edges of flat elements (self-apodization), nondiffracting beams of very extended focal zones ("needle beams") can be physically approximated[1]. Therefore, the generation of beam arrays with reduced cross-talk for multichannel materials processing becomes a relevant option[26,27]. Microaxicons with structure depths of about 30 nm and a transmission down to a wavelength of 120 nm were produced by depositing magnesium fluoride on a substrate of the same material.

Further advantages of ultraflat axicons are the enormous angular tolerance compared to spherical microlenses[16] and the extraordinarily small travel time differences which minimize geometrical dispersion effects thus making the structures attractive for femtosecond laser applications as well[5,13,15].

3. STATIC DIELECTRIC LAYER STRUCTURES

TFMO components can be fabricated by *bottom-up* or *top-down* procedures where either a thin layer or layer system is deposited and subsequently eliminated/modified by an appropriate structuring process, or a direct (point-by-point writing or areal) structured deposition[1]. The most important bottom-up technique is the lithographic sculpturing of thin layers[28,29] which early in the 1970s was used to produce layered waveguides[30,31] and later further developed to obtain high spatial and phase level resolution. Other techniques are related to photolysis induced modifications, ablation or material densification. First trials with bottom-up techniques were undertaken by laser chemical vapor deposition (LCVD) and laser physical vapor deposition (LPVD). An alternative technique which can be more precisely steered is the space-variant vacuum deposition through well-designed *shadow masks*[1]. The know-how of high-precision optics to ensure for depositing very uniform layers is here used for the inverse task, i.e. to generate microstructures by generating defined nonuniformities. The idea of rotating slit masks was known from photographic techniques where they were applied to obtain apodizers for high-resolution microscopes and telescopes by spatially varying the exposure time. Later, the approach was *adapted to deposition techniques*.

Shadow masks in deposition systems can rotate relative to the substrate surface, or remain fixed on a rotating substrate, in particular undergoing a planetary rotation (where each point of a surface performs a hypotrochoidal orbit). Initially, shading techniques with *macroscopic* rotating slit masks were used for fabricating spatially variable *phase and amplitude filters*[32], gradient *spectral filters*[33] and *graded reflectance mirrors* (GRM)[34]. The capability of rotating slit masks for a miniaturization is limited because of reduced accuracy in the central part. The generation of arrays with large numbers of elements is difficult and cost-effective. Therefore, techniques with fixed masks are more appropriate for the deposition of such microstructures.

Shadow masks at fixed positions relative to a substrate were inserted in a sputtering system to fabricate waveguiding Luneburg lenses[35]. Here, the *spatial extension* of the source was a limiting factor for the realizability of layer thickness distributions. This was compensated by using thick masks with optimized depth profiles. Approximately *point-like* sources, however, can be realized in vacuum deposition systems with electron beam heating. With 2D masks fixed at certain distances, mainly Gaussian and super-Gaussian GRM for unstable laser resonators were fabricated. The reflectance profiles were optimized by designing multilayer systems layer by layer so that the vacuum chamber had to be opened between particular deposition steps. An alternative, challenging approach was to shape a *complete layer system* simultaneously with *shadow masks fixed at the substrates.* It can be shown that symmetric layer distributions are obtained for a rotation of the substrate around its own axis, a bound rotation on a circular orbit or a planetary rotation around a central axis[1]. The additional degrees of freedom of *thick masks* can be exploited in a similar way as in the case of the sputtering setup, e.g. for cutting side-lobes of radially oscillating reflectance distributions of multilayer structures.

With *arrays of miniaturized masks*, matrix arrangements of miniature GRM we referred to as graded reflectance micro-mirror arrays (GRMMA) were generated which are of interest for the coherent coupling of lasers with multiple gain sections[36]. GRMMA are hybrid reflective-refractive elements enabling for output coupling and focusing at the same time. In the border case of the deposition of only a single dielectric layer instead of a multilayer system, the array-mask technology allows to produce arrays of purely refractive microlenses[37,38]. The TFMO deposition technique is schematically shown in Fig. 2.

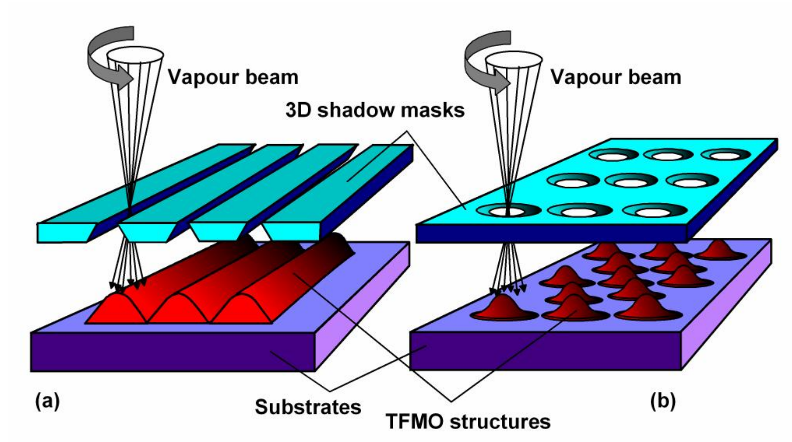

Fig. 2. Deposition of arrays of TFMO with multiple miniaturized shadow masks consisting of (a) slit-array masks, (b) hole masks enabling for the bottom-up fabrication of linear and 2D arrangements of cylindrical and circular, micro- or nanoscale single (layer or multilayer) structures, respectively (schematically, after[1]).

With additional macroscopic shadow masks placed on top of the microscopic ones, TFMO arrays with *envelope* phase and/or reflectance functions can be generated. With the help of such envelope profiles, a more complex beam shaping functionality like matching the mode volume of supermodes in Talbot resonators can be obtained[36].
Because of its proven flexibility with respect to the structure parameters as well as ease and cost-efficiency, the shadow mask deposition method has to be regarded as an enabling microoptics technology which promises further interesting progress[1].

The following advantageous features of TFMO deposition technologies are worth to be emphasized with respect to the fabrication procedure itself, to the application in high power laser beam shaping area and, in particular, in tailoring ultrashort wavepackets in space and time:

- A single step, cost-effective production of a *large number of microoptical elements* is possible (deposition of > 10^4 elements on substrates of up to 10 cm diameter was demonstrated).
- *Spectral degrees of freedom* by well-designed multilayer or metal-dielectric composite structures can be used to selectively control reflection and dispersion.
- *Continuous relief structures* of *low surface roughness* can be obtained without post-processing.
- *Ultraflat* TFMO structures can be realized without etching or reflow.
- The deposition on thin and mechanically *flexible substrates* like optical fibers or polymer foils is relatively uncomplicated.
- Compact, integrated systems can be realized by a well localized deposition of TFMO (planar optics, sensors, filters, solar cells, face of laser diodes).
- A structure *transfer into substrates* via selective etching can be used to fabricate monolithic structures of narrow angular spectrum and to exploit the specific properties of substrate materials (e.g. for VUV-capable TFMO).
- By reflective coatings on top of dielectric relief structures, *purely reflective* TFMO of *low dispersion, large spectral bandwidth* and minimized damage risk can be formed.
- *Diffractive functionality* can be integrated by combining dielectric TFMO with grating structures.
- *Non-spherical elements*, in particular conical or Gaussian-shaped *axicons*, can easily be fabricated.

4. ARRAY STRUCTURES FOR SPATIALLY SHAPING ULTRASHORT PULSES

Different types of TFMO array structures for shaping ultrashort wavepackets in space and time were designed and investigated. The main types are (a) refractive, (b) pseudo-reflective, (c) reflective, (d) refractive-diffractive, and (e) adaptive pseudo-reflective (schematic overview in Fig. 3).

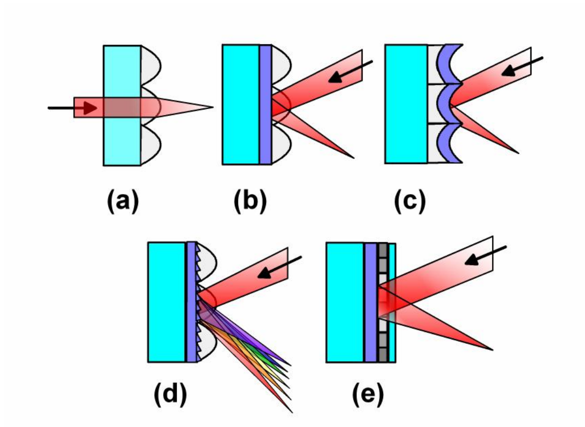

Fig. 3. Different types of TFMO structures: (a) refractive (dielectric), (b) pseudo-reflective (dielectric on metal), (c) reflective (metal on dielectric), (d), refractive-diffractive (dielectric on grating), and (e) adaptive pseudo-reflective structure (liquid-crystal layer on metal mirror with glass cover plate and segmented electrodes).

Type (c) has minimum dispersion, whereas types (d) and (e) are of increasing interest for hyperspectral and adaptive devices. Currently, the following fields of applications of TFMO components and systems are preferentially investigated: (i) spatially resolved temporal characterization of laser pulses, (ii) robust wavefront sensing, (iii) multichannel materials processing, (iv) modified Young's double slit experiments with single photons (quantum interference of "nondiffracting single photons"[39,40]).

As an example for beam shaping with ultraflat TFMO axicon arrays, Fig. 4 shows an *array of needle beams* generated from a femtosecond Ti:sapphire laser by a type-(c) reflective array component (gold coated ZnSe microstructure with concave elements, hexagonal arrangement, period 405 µm). The angle of incidence was > 25° and the angular tolerance of the system was high enough to tolerate this wavefront tilt[16,17]. The components were designed for low-dispersion Shack Hartmann wavefront sensors.

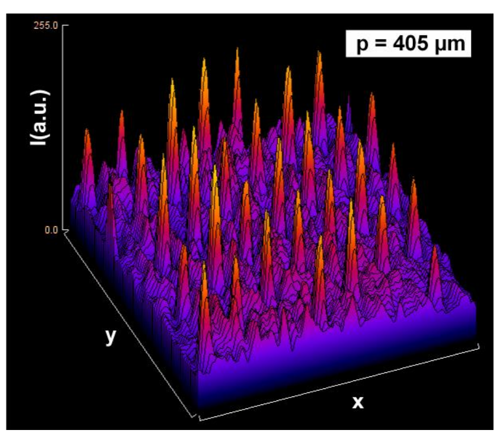

Fig. 4. Spatial intensity distribution of a hexagonal array of 10-fs needle-shaped nondiffracting beams generated with ultraflat reflective static TFMO axicons (angle of incidence > 25°).

5. PROGRAMMABLE THIN LIQUID-CRYSTAL LAYERS FOR ULTRASHORT PULSES

For many applications like spatially resolved pulse diagnostics, encoding of spectral maps, adaptive micromachining or real-time optical processing, and the manipulation of particles and cells, high-quality *adaptive microoptical array components* are required. The *demands* on such spatial light modulators (SLMs) are an excellent spectral and temporal signal transfer even at ultrashort pulse durations and ultrabroad spectral bandwidths, damage resistance, high spatial and phase resolution, and a sufficiently extended dynamic range.

Adaptive functionality of thin liquid crystal layer spatial light modulators (LC-SLMs) can be obtained by implementing grids of electrodes and steering the orientation of rod-like crystals in the electric field[41]. Temporal pulse shaping with SLMs placed in the Fourier plane of a 4f-4f-setup in a stretcher-compressor system is a well known application which recently was used to obtain sub-3-fs Ti:sapphire laser pulses[42]. A two-dimensional femtosecond pulse shaping has been demonstrated as well[43]. The spatial shaping of focal zones at pulse durations of 130 fs was applied to micromachining [44].

Concerning the orientation of the crystals relative to the substrate surface in case of zero electric field, one can differ between parallel aligned (PAN) and vertical aligned (VAN) devices. Ultrashort-pulse transfer functions of selected new types of pseudo-reflective SLMs, so-called *LCoS-SLMs* (liquid crystal on silica SLMs) have been studied[45]. The advantage of such structures mainly consists in the reflective operation mode thus eliminating the dispersion of a substrate and reducing the necessary LC-layer thickness by passing twice through the active layer.

Fig. 5 shows the temporal transfer behavior for a PAN-type LCoS-SLM with a relatively thin (3 µm) LC-layer. By measurements with an extended direct electric-field reconstruction method (SPIDER[46]) exploiting a thick nonlinear crystal (LX-SPIDER[47]), the nearly invariant shape response of a 10-fs Ti:sapphire laser oscillator pulse on a change of the gray value programmed in the SLM was proved. By determining the spectral phase as a function of the gray value, desired microoptical phase profiles like continuous reflective conical axicons and Fresnel-axicons[48] of adaptively variable parameters were written into the display.

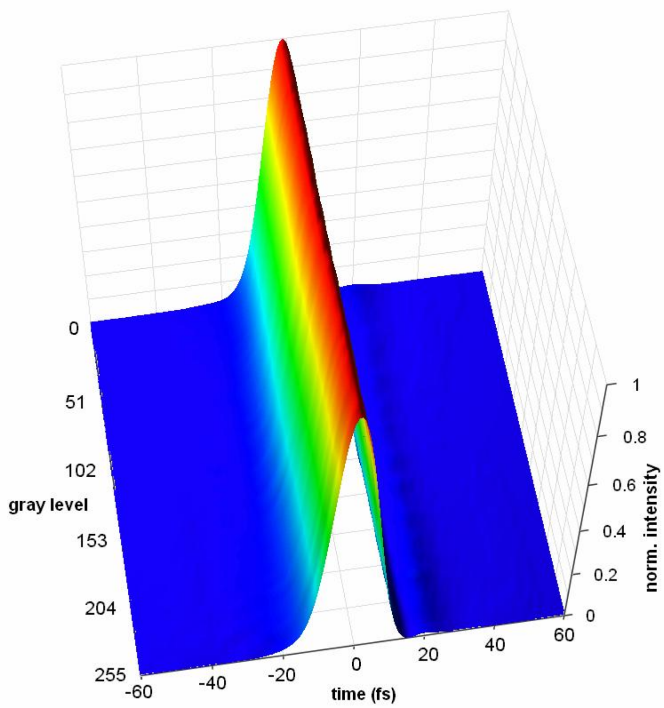

Fig. 5. High-fidelity temporal transfer function of a PAN type LCoS-SLM represented by the pulse profile as a function of the gray value. The pulse shape was measured with LX-SPIDER technique[46].

The SLMs were recently applied to the test of new types of single-shot capable spatially resolving *autocorrelators*[49] and for proof-of-principle experiments with *"flying images"* (i.e. light patterns propagating with a pseudo-nondiffracting characteristics as first proposed by Peeter Saari[50]). The setup is schematically drawn in Fig. 6. The experimentally detected (time-integrated) 3D intensity propagation of a flying image (letter "E") can be found in the plot in Fig. 7.

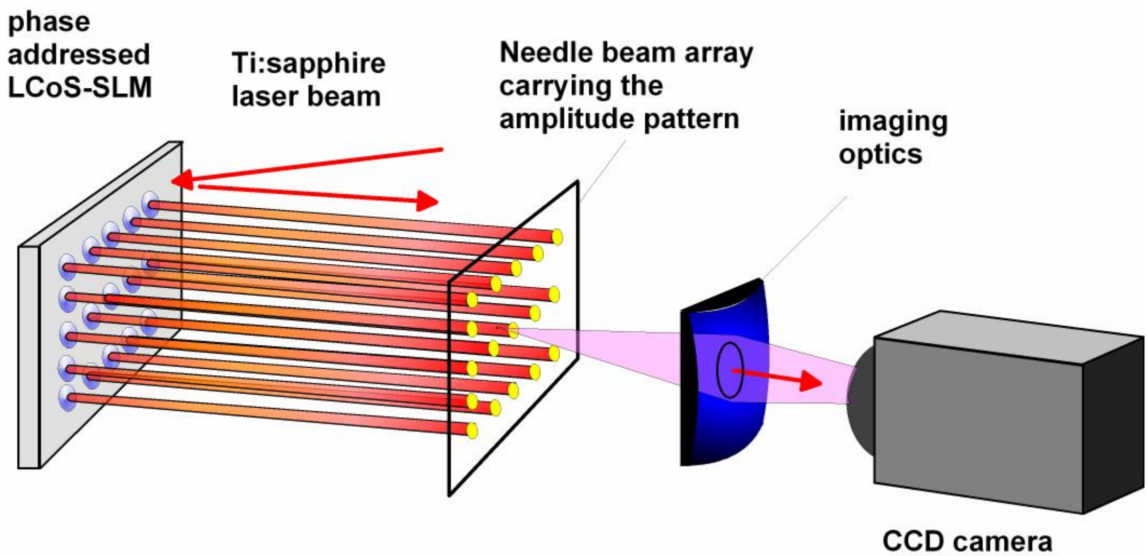

Fig. 6. Programmable needle beam arrays for the generation of "flying images". An image information is written in the spatial light distribution by addressing individual phase elements of an LCoS-SLM. The plane of interest is imaged onto a CCD-camera (schematically).

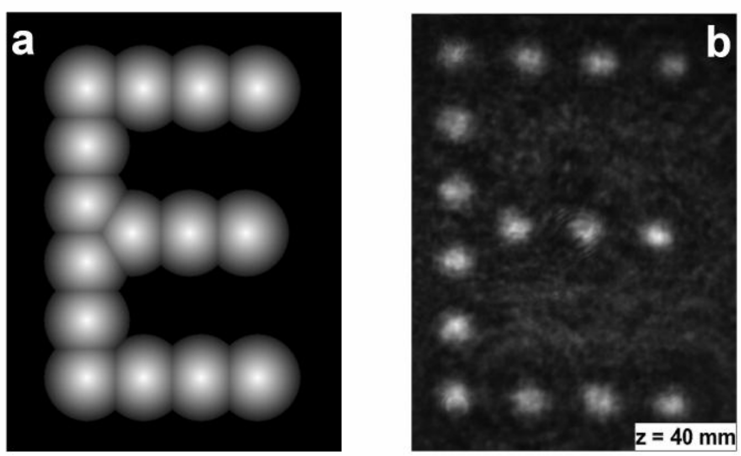

Fig. 7. Nondiffracting image generated with adaptive liquid-crystal microoptics: **(a)** programmed gray value map (horizontal period 387 µm), and (b) propagated distribution ("flying image") detected at a distance of z = 40 mm behind the LCoS-SLM (laser pulse duration < 20 fs). In the left picture, all substructures act as separately addressable reflective axicons of variable conical angle.

6. CONCLUSIONS AND OUTLOOK

An overview was given on new types of static as well as adaptive thin-film microoptical (TFMO) components which enable for a smart spatio-temporal shaping of laser fields even at extreme parameters. It was shown that with ultraflat, low-dispersion nanolayer microaxicons, extremely extended and robust Bessel-like and needle-shaped pseudo-nondiffracting beams can be generated. By using high-fidelity LCoS-SLMs, phase and/or amplitude distributions of ultrashort wavepackets become programmable. As an example, nondiffracting pixellated images ("flying images") were realized by adaptive shaping. Currently, further important tendencies are driven by ultrahigh-precision lithographical techniques, self-organization processes, biomimetic approaches and the request for superresolution. The control of the lateral, transversal or 3D structure of microoptical elements at the nanoscale promises new materials of unusual and even surprising properties (e.g. artificial refractive indices, directional spectral reflectance, tailored dispersion, all-optical nearfield probes, or cloaking). TFMO systems of much higher degree of complexity and flexibility have to be expected.

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