

MICROSYSTEMS FOR OPTICAL IMAGING AND INTERCONNECTS

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Abstract

We report on our activities in the design, fabrication, characterization and system integration of planar micro-optical elements. Microfabrication technologies like photolithography, resist processing and reactive ion etching (RIE) are used to manufacture arrays of refractive and diffractive micro-optical elements. Microlens arrays, gratings, beam shapers and beam-splitters have been fabricated, tested and integrated in chemical analysis systems (μ TAS), multiple channel imaging systems for photolithography and micro-optic spectrometers.

1. Micro-optical elements

The fundamental optical functions performed by micro-optical elements are collimating, focusing, imaging, deflecting, splitting (fan-out), diffusing or beam shaping. Microfabrication technologies like photolithography, resist processing and reactive ion etching (RIE) are used to manufacture refractive and diffractive micro-optical elements. Micro-optics offers the possibility to integrate different optical functions within one element. Micro-optical elements can be assembled side-by-side on a substrate to form array optics [1, 2, 3].

1.1. REFRACTIVE AND DIFFRACTIVE MICROLENSES

Refractive microlenses are designed using the laws of geometrical optics, treating light propagation by the refraction and reflection of geometrical rays at the interfaces. In contrast, diffractive lenses are designed based on the wave nature of light, expressed by the laws of wave optics. Since diffraction effects are strongly dependent on the wavelength of light, diffractive lenses are mainly limited to monochromatic applications. The compensation of the chromatic aberrations are possible, but will here not be discussed further.

Diffractive lenses have the advantage, that nearly any optical function, including aspherics, can be generated and that wavefront and focal length can be reproduced with high absolute accuracy. Refractive lenses are often limited to plano-convex lenses with spherical surfaces. For refractive lenses, the spherical aberration depends on the way

how the lenses are used (Fig. 1a and b). This is not the case for diffractive lenses (Fig. 1c).

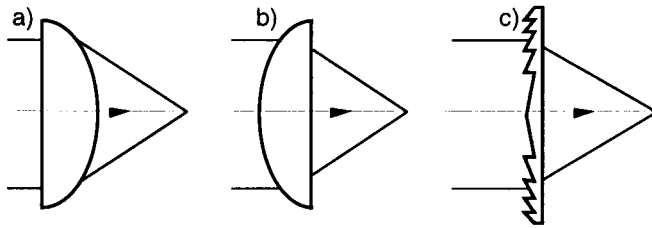


Figure 1. Refractive and diffractive lenses.

1.2. FABRICATION OF REFRACTIVE MICROLENSES

Many suitable manufacturing techniques for refractive microlens arrays have been developed. A very promising technique is the reflow or melting resist technique [4, 5, 6]. It uses solely standard semiconductor equipment and processes (resist coating, photolithography, wet processing, etching, etc.) and allows to fabricate large microlens arrays of excellent optical quality for wavelengths from the deep ultraviolet to the far infrared.

1.2.1. Reflow or melting resist technique

A thin base layer (0.5 μm to 1 μm thickness) of positive photoresist is spin-coated on a glass plate. A polymerization bake is used to harden the resist. A second layer (typically 1 μm to 100 μm thickness) of positive photoresist is coated on top of the base layer using a SUSS RC 8 spin coater [Suss KG Munich, FRG]. A uniformity on the order of $\pm 2\%$ is achieved for thick resist layers. After a pre-bake at 80 to 90°C (typically 1 hour), a chromium-on-glass mask is contact copied using a mask aligner. The exposed resist is resolved in a standard developing process. An array of photoresist cylinders is obtained. The resist cylinders are melted at a temperature of 150 to 200°C on a hot plate or in an oven.

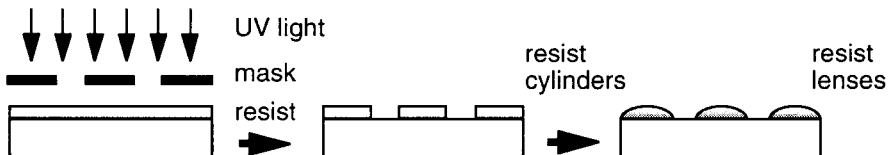


Figure 2. Fabrication of refractive microlenses by reflow or melting resist method.

a) Photolithography, b) developing and c) melting of the resist structure.

It is not trivial to fabricate microlenses with a good optical performance. The difference between a suitable lens profile and an unacceptable profile is only some parts of the

wavelength. Thus, careful optimization of all process steps is necessary. The process parameters differ significantly for different lens properties (diameter, height, array types, substrate material, etc).

1.2.2. Transfer in fused silica by reactive ion etching (RIE)

For applications in the blue and UV wavelength region the resist lenses are usually transferred into fused silica by reactive ion etching (RIE) [7, 8, 9]. RIE-transfer in silicon or GaAs is applied for microlenses used in the IR wavelength region [10]. The profile of the microlens might be slightly deformed after the RIE transfer. Usually the lenses are steeper at the rim and flatter at the vertex. Spherical aberration is severely enhanced due to the profile change and the lower refractive index of the fused silica. Profile modification is made by changing the etch rate during the RIE step. The resist is faster etched at the beginning and slower at the end. The roughness of the lens surface might be significantly increased during the RIE transfer. Figure 3 shows the deviation from a sphere for a resist lens. The profile was characterized in a Twyman-Green interferometer [Prof. J. Schwider, Univ. Erlangen, FRG] and the fabrication process was optimized to obtain spherical lens profiles. For an optimized lens, a deviation from sphere of $< \lambda/20$ (rms) and $< \lambda/4$ (p/v) was obtained for microlenses of 145 μm diameter (NA = 0.2) in resist and also in fused silica.

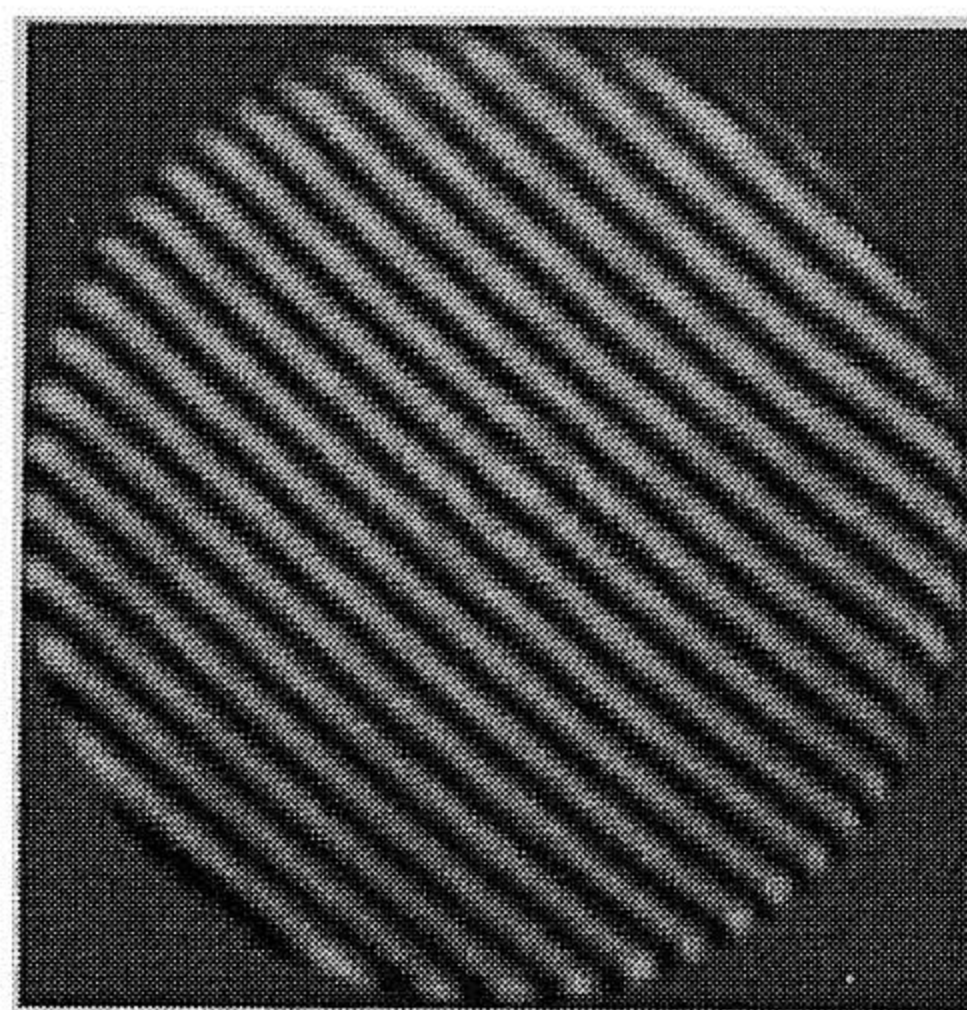


Figure 3. Deviation from a sphere for a resist lens (interferogram).

1.3 FABRICATION OF DIFFRACTIVE ELEMENTS

1.3.1. Diffractive microlens arrays

Fabrication techniques for realizing the microstructures resulting from the design of diffractive optical elements are based on a variety of high resolution lithographic and optical processes [1]. The typical procedure is to generate a mask by e-beam or by laser beam lithography. Then, to get high efficiency, the mask is transformed into surface-relief structures by dry or wet etching. Using several masks, multi-level profiles can be generated to improve the efficiency. Another technique is the direct writing of the DOE

phase relief in photoresist by e-beam or laser beam. The developed photoresist relief can be transferred into fused silica, or it can be converted into a metalized master relief by electroplating to emboss or cast low-cost replica.

1.3.2. Dammann gratings

Dammann gratings [11], which are $\{0,\pi\}$ -binary phase gratings, are commonly used as fan-out elements to generate one- or two-dimensional arrays of light spots. To achieve an even number of equally spaced, uniform intensity diffraction orders an even orders missing design is used [12, 13]. Consequently, all the even diffraction orders, except the zero order, contain almost zero intensity. The amount of intensity found in the zero order is independent of the structure and depends only on the phase depth of the grating. For a phase depth of π radians, the intensity of the zero order falls to zero. An optimum design of a 16×1 fan-out, obtained by simulated annealing, contains 1024 pixels and the smallest feature is 18 pixels wide, i.e. 1.76% of the length of the unit cell. A total efficiency of 79.5% and a uniformity error of $\pm 0.8\%$ characterize the theoretical performance of the design. The uniformity error represents the fluctuation about the mean value.

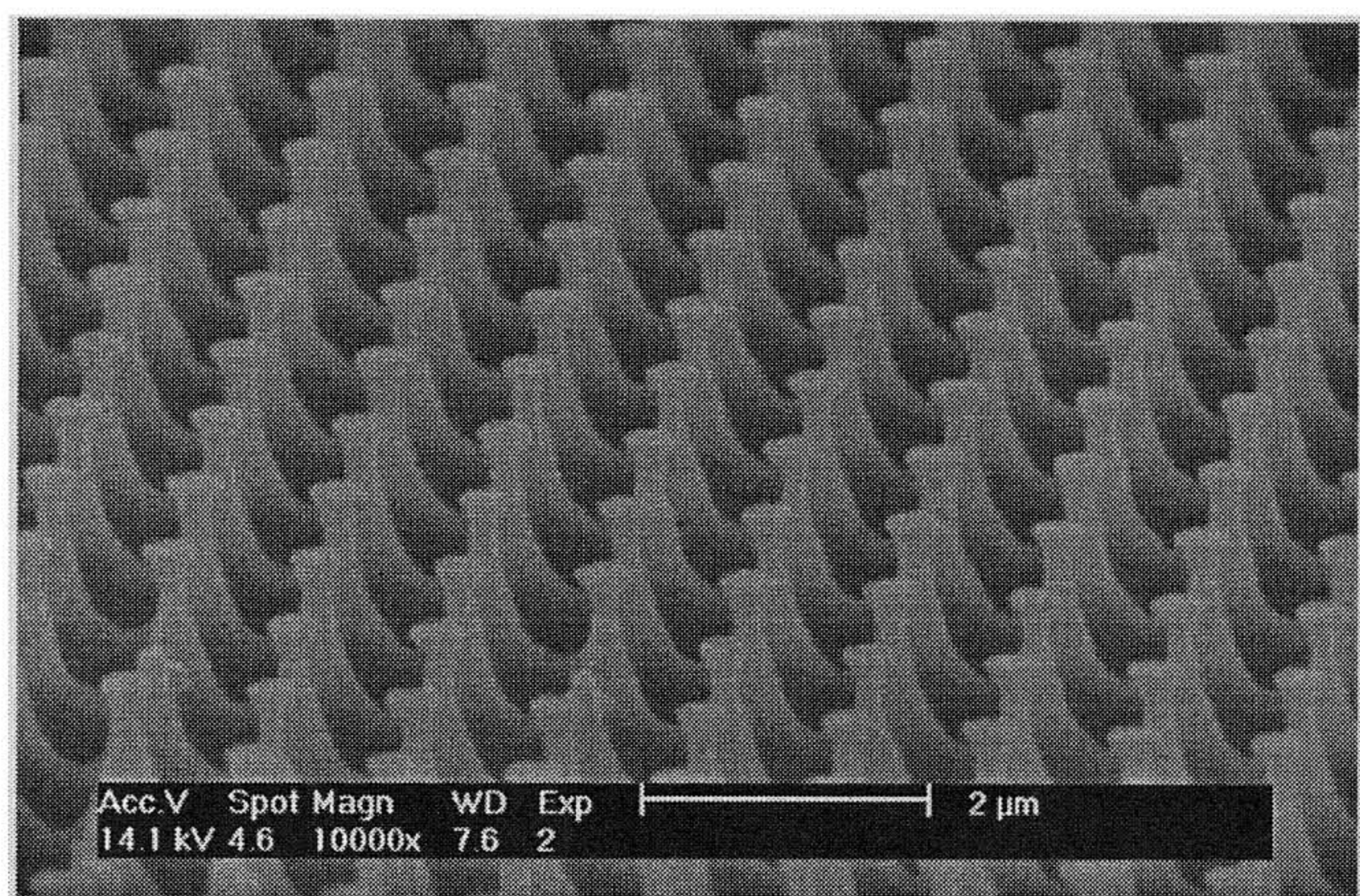


Figure 4. Interferometrically recorded crossed grating. The period Λ is $1\ \mu\text{m}$.

1.3.3. Interferometrically recorded gratings

Holography, i.e. interferometric recording, is a successful technique to store wavefields in light-sensitive materials. This technique has also been proposed to fabricate planar optical elements, such as gratings, lenses, and multiple beam splitters. Holography is ideal to fabricate off-axis elements with small feature sizes. The absolute position accuracy of the recorded grating structures is considerably higher than achievable with electron-beam writing, which suffers from stitching errors. Modulated sub-micron gratings ($\Lambda \approx 0.5\ \mu\text{m}$), which generate a 9×9 off-axis fan-out, have been fabricated [14]. Because of the high carrier frequency, these elements show Bragg diffraction behavior. First-order diffraction efficiencies of 70% have been demonstrated. Figure 4 shows a

2D grating that has been recorded by double exposure in photoresist using a Krypton laser ($\lambda = 413 \text{ nm}$).

2. Applications

Microlens arrays are used for collimation or focusing (laser arrays, detector arrays, fiber optics, sensors, optical interconnects, optical computing, etc.), for illumination (flat panel displays, TV projection systems, retro-reflectors, diffusers, etc.) and for imaging (photocopiers, 3D-photography, signal and image processing, fiber couplers, microlens lithography, shop testing, astronomy, etc.). In the following, we will present examples for the system integration.

2.1. CHEMICAL MICROCHIPS AND μ TAS

Chemical microchips and miniaturized analytical systems (μ TAS) cover a wide range of disciplines, such as analytical and organic chemistry, biochemistry, electronics, microengineering, solid state physics, laser physics, and micro-optics. Usually, a complex arrangement of lasers, detectors, filters, optics, and high precision mechanical stages is required for illumination and optical detection. Microlens arrays offer a large potential to reduce the size and to simplify the architecture of analytical systems [15]. Figure 5 shows a photograph of microlenses made in photoresist. The lenses are deposited directly onto a glass chip that contains the fluidic microchannels.

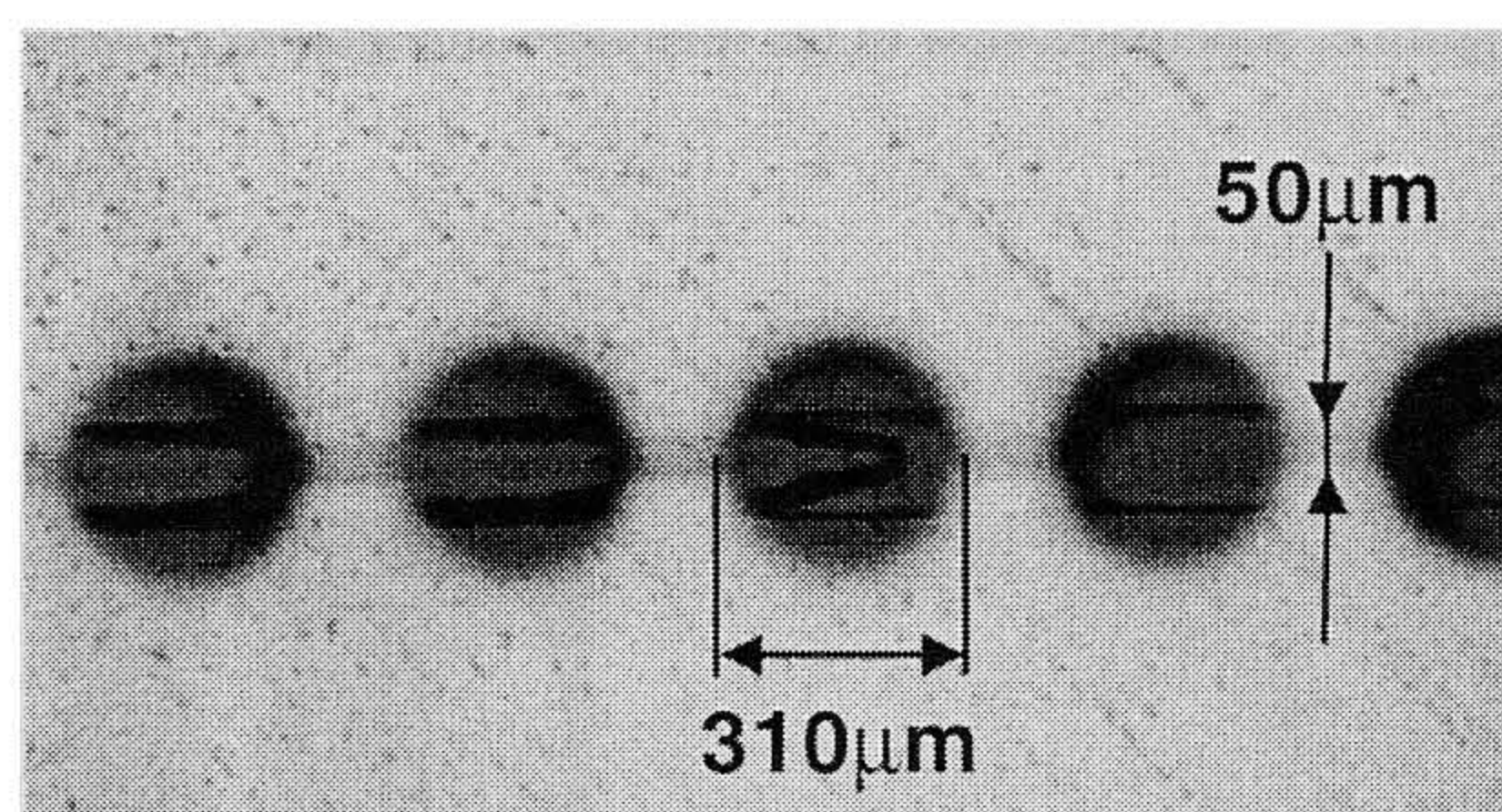


Figure 5. Photoresist microlenses deposited directly onto a chip containing microchannels which are $110 \mu\text{m}$ wide and $50 \mu\text{m}$ deep. The spherical lenses are $310 \mu\text{m}$ in diameter and $33 \mu\text{m}$ high. The third lens images the front of the liquid flow in a microchannel.

2.2. MICROLENS ARRAY IMAGING SYSTEM FOR PHOTOLITHOGRAPHY

A microlens array imaging system was developed in connection with a new contactless photolithographic technique called microlens lithography [16, 17, 18, 19]. This new lithographic imaging technique provides an increased depth of focus ($> 50 \mu\text{m}$) at a larger working distance ($> 1 \text{ mm}$) than customary proximity printing. Potential

applications are photolithography for large print areas (flat panel displays, color filters), for thick photoresist layers (micromechanics), printing on curved surfaces (or substrates with poor planarity) or in V-grooves. An array of micro-objectives is used to project a photomask onto a resist layer ($\beta = +1$ imaging). A micro-objective array is formed by a stack of microlens and aperture arrays (Fig. 6). Each objective transports a part of the mask pattern. The individual images overlap coincidentally to generate a single, complete image of the mask [20]. Micro-objective imaging systems have been assembled and integrated into a mask aligner to perform test prints in photoresist. A theoretical resolution of $3 \mu\text{m}$ was calculated by ray tracing for the whole image field [19].

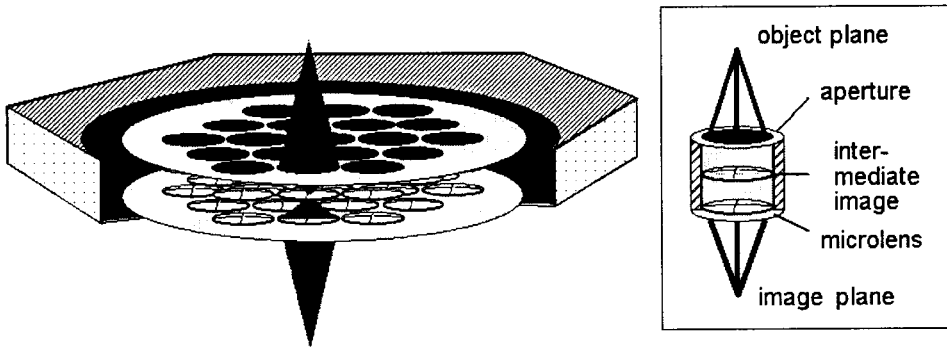


Figure 6. Schematic view of the microlens lithography system.

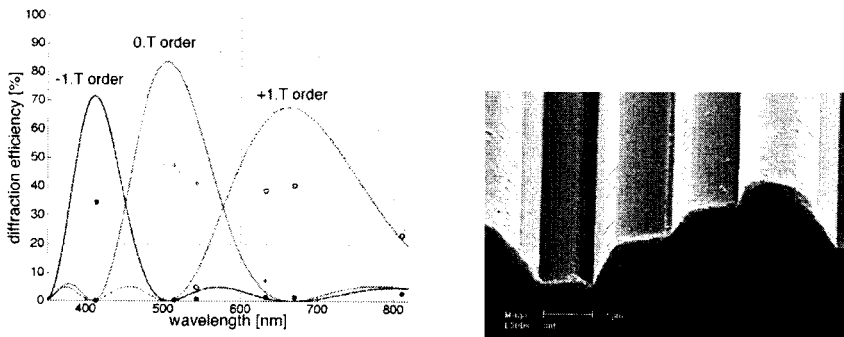


Figure 7. The left part of the figure shows rigorous theory (lines) and measurement (markers) for the color fan-out element, etched in fused silica with 4 phase levels, $16 \mu\text{m}$ grating period, and $3.3 \mu\text{m}$ profile depth. The right part displays a SEM image of a color fan-out element, etched in fused silica with $12 \mu\text{m}$ grating period and $3.3 \mu\text{m}$ profile depth.

2.3. COLOR FAN-OUT ELEMENTS

Color fan-out elements are special phase gratings which project the three color components blue, green, and red into the three central diffraction orders. This optical function is achieved by deep phase gratings. The color fan-out elements were fabricated as 4-level surface relief elements in fused silica by a 2-step photolithographic process. The grating periods are between 4 and 16 μm and the grating depth is 3.3 μm . The characterization of the elements is displayed in Fig. 7.

2.4. MICROSPECTROMETER ARRAY

The performance of refractive microlens arrays with diffractive surfaces as elements for miniaturized spectrometer systems was studied [21]. We fabricated arrays of elements, which combine the two main optical functions, namely focusing and dispersion, by mixing different manufacturing technologies. The lenses were made by melting resist technology and the gratings by interferometric recording on top of the lens array (see Fig. 8). Figure 9 shows a micrograph of the grating on a lens surface.

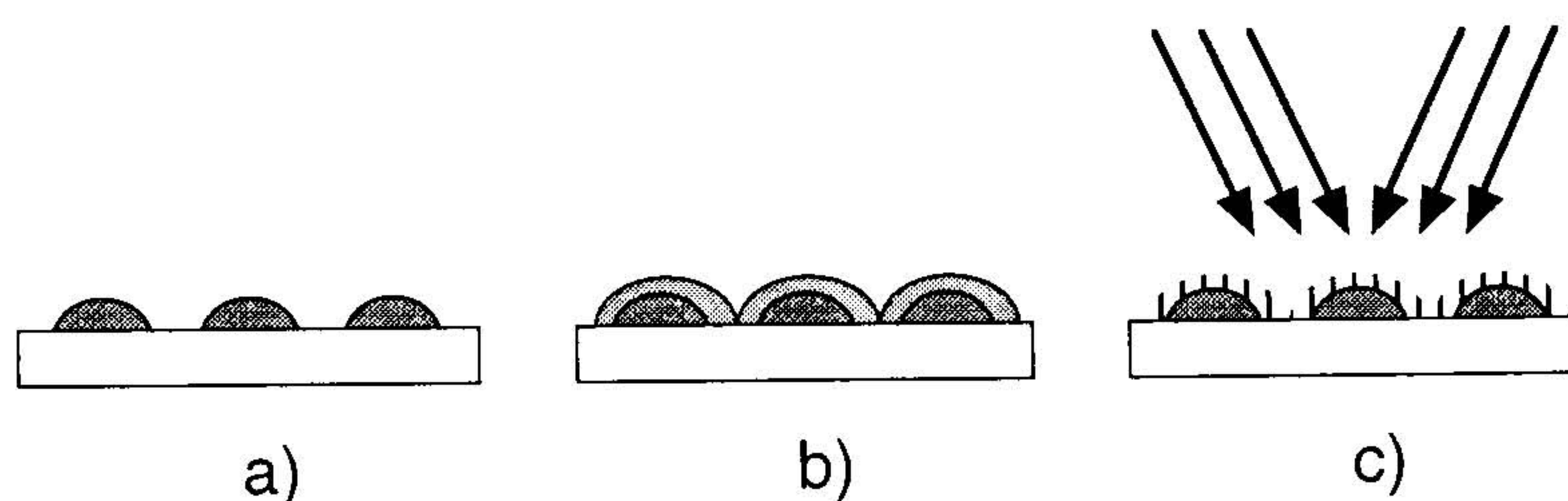


Figure 8. Fabrication of refractive microlens arrays with a diffraction grating on the curved surface: (a) microlens array fabrication, (b) photoresist coating of the array, (c) recording of the grating.

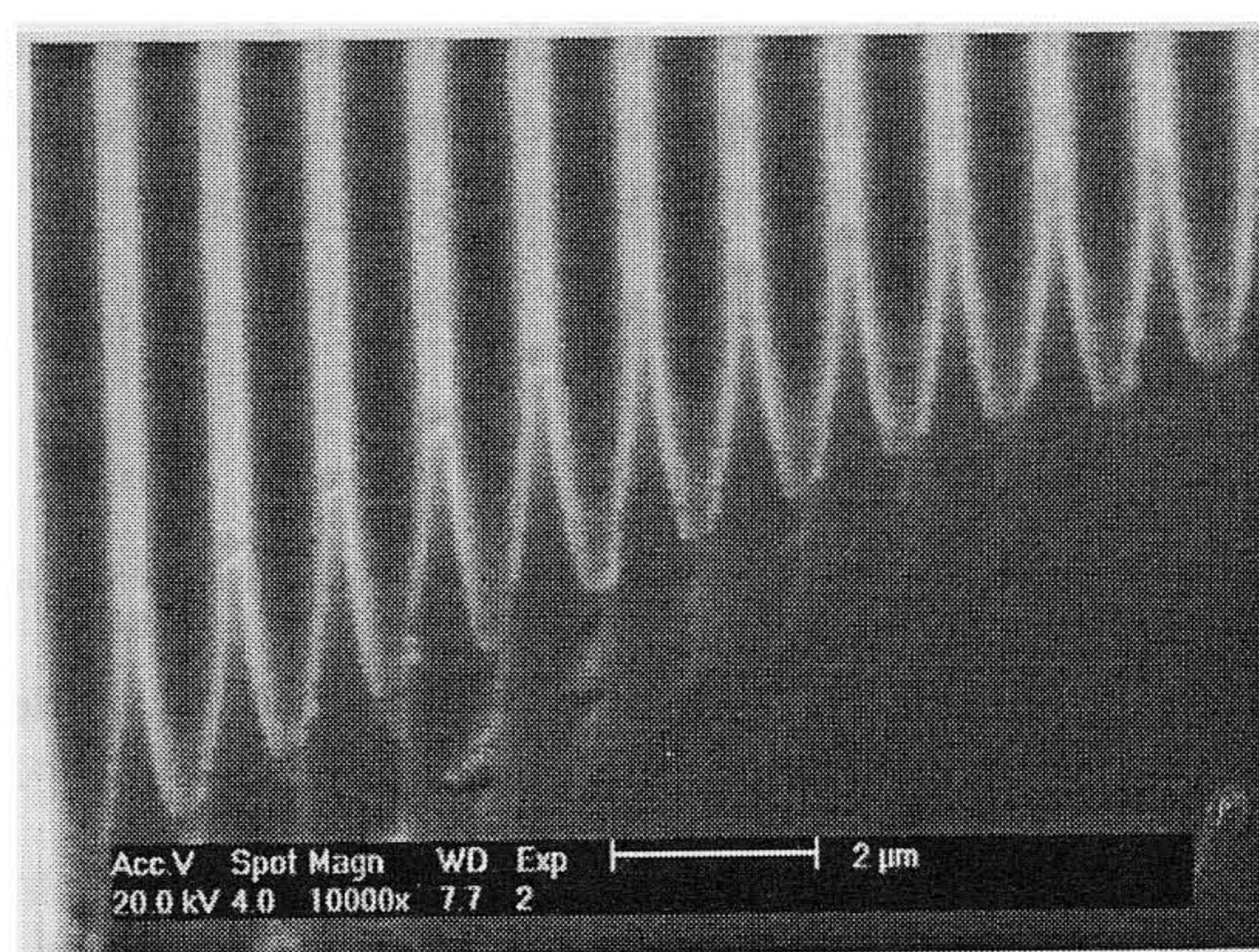


Figure 9. Cross section of a grating fabricated on a microlens array (1 μm period).

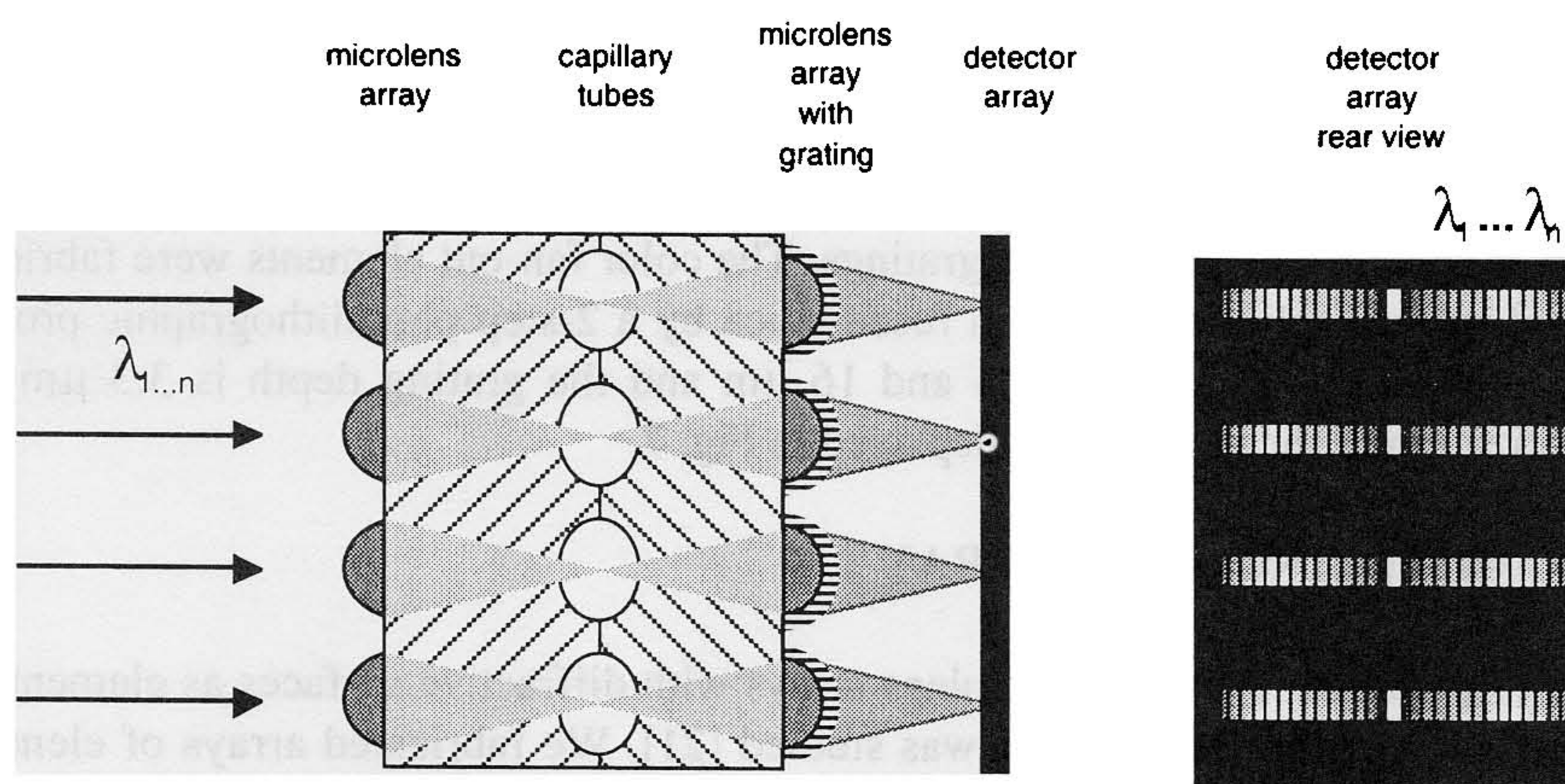


Figure 10. Proposed concept of a system for a microspectrometer array.

With respect to the application of the element in the context of a microspectrometer array, we measured the resolution and the straylight suppression. In the best case, we measured a resolution of 3 nm and a straylight suppression of 25 dB.

The advantage of the fabricated hybrid element for implementation in a spectrometer array system is obvious when looking at Fig. 10. It presents the schematic view of a possible concept for a microspectrometer array system as used for chemical analysis. The "heart" of the proposed system essentially consists of only two components. The first component implements a microlens array on one side and one half of a capillary tube on the other side. The microlens array focuses the light into the capillary tube, which contains the chemical substance to be analyzed. The second element consists of the second half of the capillary tube on one side and the microlens array with the diffraction grating on top on the other side. These two components contain the capillary tubes and all optical functions necessary. Accordingly, there are only two pieces that are critical in terms of alignment for the entire system, with the exception of the light source. With appropriate replication techniques the proposed system promises to be very attractive for low cost applications.

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