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FABRICATION OF MICROLENS ARRAYS FROM SOL-GEL COMPOSITES BY EMBOSSING TECHNIQUES.

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Organic-inorganic composite materials have been used to fabricate refractive microlenses by embossing. A processing techique to produce master microlens arrays is presented. Rheological and mechanical properties of organic-inorganic composite material are adjusted to replicate this master in the material. The patterns are stabilized after embossing by polymerization of the organic groupings using either thermal or photo initiation. Microlens arrays of 10 x 10 lenses were produced and characterized by profilometric measurements as well as optically.

1. INTRODUCTION

The development of refractive and diffractive optical elements like microlenses is of growing interest for a variety of applications such as optical interconnectors or two-dimensional focal plane arrays for fill-factor enhancement [1]. A number of techniques is described to produce microlenses like diffusion of dopands into planar substrates to build up graded index lenses [2], laser beam writing [3], photolithography [4], E-beam lithography [5] and embossing [6]. Materials used to realize such elements are silicon or GaAs for IR-applications and polymers or inorganic glasses for VIS and NIR applications [1,4].

A new material type of inorganic-organic nanocomposites shows promising properties for micropatterning since diffraction gratings with more then 2400 lines/mm have been realized by embossing or Fresnel microlenses have been obtained by holographic two wavemixing [7]. These materials are synthesized by sol-gel route where an inorganic backbone is formed by hydrolysis and subsequent condensation process followed by a polymerization of organic spezies to an organic-inorganic network.. During the sol-gel synthesis nanoparticles are produced through condensation. These nanoparticles can be generated in-situ or can be synthesized seperatly and are mixed with the organic-inorganic network before polymerization to tailor refractive index and mechanical properties. For optical applications, the process has to be controlled to keep the particle diameters below 10 nm to avoid losses by Rayleigh scattering and to guarantee high performance optical imaging properties for microlenses. By a surface treatment of these particals with polymerisable ligands, they can be chemically bond to the organic-inorganic backbone to form the nanocomposite. Whereas the inorganic component increases thermal stability and surface hardness, the organic component allows densification temperatures of less then 150 °C by thermally or photo initiated polymerization. Moreover, mechanical stresses are reduced by the organic component and layers of more than 10 μm in thickness in one step can be produced by dip or spin coating. The index of refraction can be varied by composition for an in-situ nanocompoite between 1.5 and 1.54 [7] and by adding a second inorganic nanophase (particle radius 2 nm) of titania between 1.5 and 1.7 [8] and optical losses of less then 0.5 dB/cm for HeNe laser could be measured [9]. Optical active components can be introduced like metal colloids [10], quantum dots [11] and guest-host dyes or network forming dyes [12]. Near-netshaping quality for embossed mikropatterns is possible by the low over-all shrinkage rate of less then 5 vol.% of the material. The objective of this paper was to investigate and develop a fabrication process for microlens arrays using the described nanocomposite processing route.

2. THEORETICAL CONSIDERATIONS

The paraxial focal length of a lens consisting of a single spherical surface is a function of the radius of the surface curvature and of the index of refraction of the lens material (equation 1)

$$f = \frac{R}{n-1} \tag{1}$$

The focal length is not dependent on the radius r of the lens but this radius r is a direct measure for the numerical aperture and is geometrically controlled by the radius of curvature and the height of the lens (equation 2). The numerical aperture N_A is given by equation 3.

$$r = \sqrt{h(2R-h)} \tag{2}$$

$$N_A = n \cdot \sin a \cong n \cdot \frac{r}{f} \tag{3}$$

The minimum focal spot diameter of a spherical lens for the diffraction limit (full width at half maximum) is approximatly given by equation 4

$$d_{1/2} = (0.514 \cdot \lambda) \cdot N_A = 0.514 \cdot \frac{\lambda \cdot f}{n \cdot r} \tag{4}$$

(with λ:wavelength of light) and difference of calculated and measured spot diameter is a measure for the imaging quality of the lens system. Aberrations will distort this quality and the point spread function of the optical system, which is given by the intensity distribution across the focal point, is directly correlated to these distortions.

For practicle applications, optical interconnectors need high numerical apperture > 0.1 to be able to couple in several modes in a waveguide, whereas in case of image sensors a low numerical aperture < 0.1 is required for high resolution. An idealized configuration would consist of a material with adjustable index of refraction in combination with a technique to vary the radius of curvature and the radius of the microlens in order to change focal lenth and numerical aperture over a wide range. This would allow to adjust optical properties to various application necessities.

Variation of the geometrical parameters is only possible by sophisticated processing techniques whereas variation of optical properties is only possible by material tayloring. Therefore, a combination of material development and processing techniques to fit both by simple means is necessary.

3. EXPERIMENTAL

3.1 Fabrication of master microlens arrays

To be able to produce stampers for embossing experiments with easy control of geometrical lens parameters, ball bearings of different diameters were used to press the desired patterns into a soft metal surface. By using a xy-stage, an array of master lenses can be built up. Using this technique, the geometry defining the optical properties of a lens can be varied by very simple means, e.g. the radius R by choosing adequate ball bearing diameter and radius r by an adequate impression depth. A polished aluminum block was used as soft material to produce master grating arrays. For optimizing procedures, a ball bearing of 1mm radius and high surface quality was fixed in a specially designd holder. This holder was integrated in a software controlled mechanical testing machine (ZWICK 144670) which allowed to controll force and impression depth and a special software was created to controll impression parameters very accuratly. Arrays of master lenses were fabricated by moving the aluminum block and subsequent impression of the ball bearing.

3.2 Material synthesis

For first experiments to emboss the master array in organic-inorganic composte materials, a well characterized organic-inorganic nanocomposite based on methacryloxypropyl trimethoxysilane (MPTS,I) was used as matrix material in combination with methacrylic acid (MAS,III) complexed Zirconium propoxide (II). In a first step MPTS is hydrolysed and condensated with slow addition of a catalyst (0.5 N HCL). Seperatly Zirconium propoxide is compexed with methacrylic acid. MPTS and the complexed Zr-alkoxide are mixed under stiring and water is added to complete hydrolysation and condensation. The detailed synthesis is described elsewhere [13]. By this procedure ZrO2 particles of 4 nm in diameter are produced which can be followed by photon correlation spectroscopy. Ethanol or an other alkohol is added as solvent to adjust sol viscosity for coating experiments. Formation of the organic network (organic part of the MPTS spezies and of the Zr/MAS) is initialized by a themal or photoinitiator and temperature treatment or light of appropriate wavelength transforms the intiator to radicals which activate the C=C double bonds of the methacrylate groups and polymerization starts. A composition of MPTS/Zr/MAS of 10/1/1 mol-% was choosen which results in a material with index of refraction of 1.52

3.3 Embossing of microlens arrays

Sol-viscosity was adjusted to 0.02 Pa•s and films of 20 µm were prepared by dip coating on a glass substrate. The master was pressed in the film with the same mechanical testing machine as for master preparation. Embossing pressure was choosen to be 300 N/cm^2. After pressing the master on the film, the substrate was irradiated by UV-light from the backside for 10 min to start polymerization of the methacryl groupings and to stabilize the master array as a replica in the film. The master was removed and an array of spherical lenses on the glass substrate was obtained. In a second series of experiments, a thermal process was used for curring. The film was pretreated thermally at 90°C for 10 min and the master was pressed in the film using the same parameters as for photopolymerzation. Subsequently, the substrate was heated to 130°C for 10 min to fix the replica and was cooled to room temperature slowly. When room temperature was reached, the master was removed.

3.4 Geometrical and optical characterizaton

Geometrical parameters of a single embossed microlens were measured by microscope and by three dimensional surface profiling. The focal lenght was measured using a microscope technique. The length was determined by monitoring the difference of focusing on the top of the lens and measuring vertical displacement length between the image of the aperture of the microscope.

The point spread function of lenses was measured by an optical setup, in which a laser beam of a He-Ne laser was spread by a Galileien microscope and focused by the lens array. The focal spots were imaged by a two dimensional beam profilometer and the line spread function, which represents a slit intensity scan in the point spread function, allowing to measure the diameter of focal point at full width half maximum.

4. RESULTS

A micrograph of an embossed microlens array is shown in figure 1 with a three-dimensional plot of the surface of the same sample.

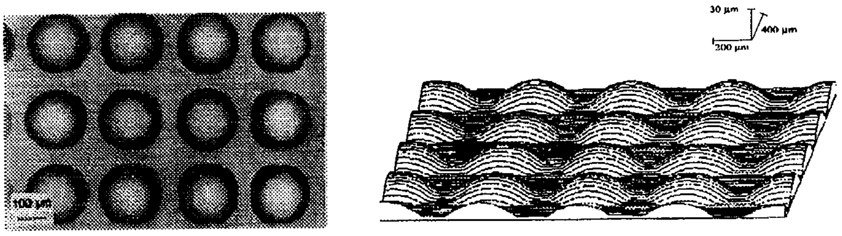

Figure 1. a) Micrograph of an embossed spherical lens array in an organic-inorganic composite material and b) three dimensional profile of a lens array of the same sample.

As can be seen, microlenses are replicated with high accuracy and high shape quality. Roughness of lens surface at present is an effect of low surface quality of the aluminum stamper which can be easily optimized. The diameter of the lens is measured to 400 ±5 µm and the height of the lenses to 20 ± 0.5 µm by profilometry. From equation 2, a diameter of the ball bearing of 2.02 mm should be expected which is in very good aggrement with the used one of 2 mm. This indicates the high replica quality of the used embossing technique. Measurement of focal lenght in the light microscope gave a value of 2 ± 0.05 mm and also agrees very well to the theoretically expected focal lenght of 2 mm. given by equation 1. From these measured values, a numerical aperture of 0.15 can be calculated by equation 3. The measured point spread and line spread functions as intensity distributions in the focal plane of the lens array are shown in figure 2.

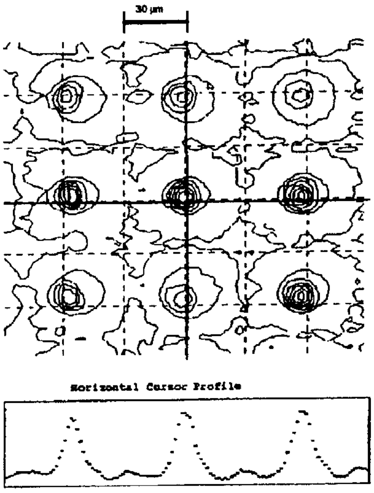

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Figure 2 Two dimensional intensity distribution in the focal plane of a 3x3 lens array (a) and corresponding line spread function of three single lenses (b)

From the line spread function, a spot diameter of about 20 µm could be measured, which is a factor of 10 higher than the expected one (equation 4) of 2.7 µm. Although the geometrical parameters of the lens and surface quality of the aluminum stamper are not at all optimized in these first experiments, the measured value emphasises the high potential of organic-inorganic resistmaterials and embossing techniques for the fabrication of microlens systems.

5. CONCLUSION

First experiments have shown, that a combination of processing techniques for master production in combination with material development allows to taylor microlens arrays in organic-inorganic composite materials. The wide variability of intrinsic material properties of this material class which reaches from dust repellent or antifogging systems up to non-linear optical properties with excellent embossing qualities will give a tool to fabricate microlens arrays of specific optical and material properties. The experiments carried out to obtain lenses with 400 nm in diameter can be adapted to obtain a wide variety of diamters.

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