Phase Grating from Ordered Polymer Lattices for Optical Image Preprocessing

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Abstract. The ‘inverted’ retina of the human eye can be emulated by multilayer gratings from polymer latex particles located in the image plane of optical systems. This so called OPTO-RETINA provides v. Laue interference patterns in visible light with a trichromatic characteristic containing, simultaneously, local spatiotemporal direction and distance information, which are relevant to 3D spatial vision and 4D spatiotemporal Fourier correlator-optical preprocessing in shape and motion analysis. As a first step in the realization of OPTO-RETINA properties the formation of hexagonally ordered monolayers of polystyrene latex spheres with diameters in the μm range is reported and first results of diffraction and dispersion of white light by these layers obtained by conoscopical optical microscopy are presented.

Key words: OPTO-RETINA, 3D grating, 3D vision, 4D vision, Colour vision, Polymer, Latex, Image pre-processing, Diffraction, Conoscopic microscopy

1. OPTO-RETINA: a 4D Sensor for Trichromatic Space-Time Patchwise Fourier-Optical Image Preprocessing

The motivation to construct diffractive 3D transmission gratings arises from the desire to build an artificial imitation of the ‘inverted’ retina of the human eye. The term ‘OPTO-RETINA’ is used to describe the sensor construction shown in Figure 1, crucial component of which is a diffractive hexagonal 3D phase grating located in the image plane of a lens/pupil system in front of photoreceptors that can be interpreted as waveguides, positioned in the near field (Talbot/Fresnel region) behind the 3D grating.

Such a sensor design ensures three optical transmission steps of the image information present in the light cones that contribute to optical imaging. The first transformation step is based on the eikonal laws of geometrical optics, the second on the diffraction rules of 3D grating optics, and the third on the Talbot effect in a convergent ray path. The result of these grating-optical preprocessing steps is patchwise Fourier-optical image processing with a pixel-related local, and at the same time global, information content. Embryological and physiological studies and 3D grating-optical calculations [4–8] in human vision confirm, through their ability to explain experimentally-verified critical phenomena (Table 1), that the inverted retina of the human eye can be interpreted as a cellular multilayer phase

Table 1. Critical phenomena in human vision which are explained in grating/interference-optical terms by the inverted retina (OPTO-RETINA) model

–	optical preprocessing of the imaging light cones in 3 chromatic diffraction orders (with Gaussian band-pass transmission characteristics) [1, 4]
–	the spectral locations of the 3 wavelengths of maximum spectral sensitivity in daylight vision ($\lambda_{\max}$ 559 nm (RED)/537 nm (GREEN)/447 nm (BLUE)) [4]
–	the brightness-adaptive Purkinje shift on transition from daylight to twilight vision (shift of the RED/GREEN $\lambda_{\max}$ to 521 nm) [4]
–	two-stage quantitative (pupil adaptation to the luminosity) and qualitative (chromatic retina grating adaptation) stimulus processing [7] corresponding to the Hopfield model [3]
–	transformation of the 2 elemental physical stimuli (intensity and wavelength) into 3 psychological parameters in daylight vision (brightness, hue and saturation) [7]
–	the aperture effects or Stiles–Crawford effects I (brightness shift) and II (hue shift), as a consequence of which obliquely or perpendicularly incident ray cones have direction-dependent relative brightness and hue values [6, 7]
–	the identity of the Stiles–Crawford effect I with the Bezold–Brücke phenomenon; hue shift during intensity changes (analogous to human hearing) [7]

grating with hexagonal packing geometry of the grating elements (cell bodies or nuclei with refractive index differences from the aqueous environment), thus providing the basis for monocular trichromatic and spatial vision and space-time information processing during motion, and image analysis in photopic vision. The (always only relational) trichromatic and the space-time direction and distance information are produced in two 3D grating-optical differentiation steps of ν and λ in the phase velocity $\nu\lambda = c$ (c = speed of light). The 3D grating produces the three chromatic diffraction orders in a first differentiation step of ν and λ and generates the space-time 4D information in a second differentiation step of ν and λ , in each of the diffraction orders via combined spectral and brightness shifts, as known from the aperture effects in human vision, namely the Stiles–Crawford effects I (brightness shift) and II (hue shift) for rays incident obliquely on the pupil and retina relative to perpendicularly incident rays.

The special characteristic of the 3D grating is not just its spatial frequency filter function in the image plane, but also that, by means of its periodicity in the third spatial direction (z -direction), it transforms the Fraunhofer or Talbot diffraction patterns, known from 2D grating optics, into von Laue interference patterns, as known from X-ray crystallography with white light (Figure 2). Here, chromatic diffraction orders are separated into spatial directions fixed by the 3D grating geometry and deposited at discrete locations on concentric ring zones as point like interference maxima in a plane behind the 3D grating (Figure 1). The positions of

Figure 1. OPTO-RETINA structure (diagrammatic, not to scale): optically imaging lens/pupil system (eye) with 3D transmission grating in the focal plane and photoreceptors in the near field behind the 3D grating. The structure enables 3 transformation steps for the visual object: geometric optical imaging in the image plane, 3D-diffractive transformation of the image into 3 chromatic diffraction orders, and modulation of the space-time-relevant parameters (direction- and distance-dependent data) in the Talbot planes in the near field behind the grating. (O = visual object; LP = lens/pupil system; F = focal/image plane; G = grating with grating spacings b_1 , b_2 and d ; BO = diffraction orders 111 (RED), 123 (GREEN) and 122 (BLUE); PR = photoreceptors with locations of $\lambda_{\max}$ of the 3 diffraction orders (RED = 559 nm, GREEN = 537 nm, BLUE = 447 nm).

the maxima correspond in the hexagonal 3D grating to the points of intersection of three sets of hyperbolas crossing at 60° with concentric circles. These geometry conditions are satisfied by the arrangement of the cones in the primate retina (Figure 3). Trichromatic patchwise Fourier-optical image information deposition or transfer (already described by DeValois et al. [2] in cortical visual cell areas) of all 4D space-time signal components in the time/frequency power spectrum, to neural (retinal) networks, which provide further electrical processing takes place in the Talbot planes in the photoreceptors functioning as waveguides (Figure 1).

1.1. 3D GRATING-OPTICAL TRANSFORMATION OF LIGHT CONES INCIDENT ON THE OPTO-RETINA 3D GRATING: DUAL TRICHROMATIC AND SPACE-TIME DIFFERENTIATION OF ν AND λ IN THE PHASE VELOCITY $V_p = \nu\lambda = c = 1$

Diffractive interference effects at 3D gratings can be described by means of the von Laue equation. In order for constructive interference maxima to be produced for certain spectral components ($\lambda_{\max}$ = wavelengths with maximum spectral transmission in a diffraction order direction) in defined spatial directions $\alpha\beta\gamma$ in the 3D grating, three basic conditions must be satisfied for which, in addition to the grating spacings $b_1(x)$, $b_2(y)$ and $d(z)$ and the $h_1h_2h_3$ triplets of integers, the $\alpha_o\beta_o\gamma_o$ aperture angles of the light cones incident in the 3D grating are relevant. In white light in the visible spectral region (400–800 nm), the 3D grating, by means of

Figure 2. Fraunhofer (top left), Talbot (top right) and Laue (bottom, symmetry 6: apatite) interference patterns in white (X-ray) light.

Figure 3. Distribution pattern of photoreceptors in various retinal zones (cones and rods) [9], locations at the intersections of 3 sets of hyperbolas crossing at 60° (hexagonal pattern): fovea (left), parafovea (centre) and peripheral retina (right).

its geometry, selects the $\lambda_{\max}$ that achieve maximum transmission in the possible diffraction orders:

$$\begin{aligned} b_1(\cos \alpha - \cos \alpha_o) &= h_1 \lambda, \\ b_2(\cos \beta - \cos \beta_o) &= h_2 \lambda, \\ d(\cos \gamma - \cos \gamma_o) &= h_3 \lambda. \end{aligned}$$

1.1a. *3D grating-optical differentiation of ν and λ into three chromatic diffraction orders.* A grating spacing ratio of $b_1 = 2 \mu\text{m}$, $b_2 = 4/\sqrt{3} \mu\text{m}$ and $d = 4 \mu\text{m}$, which corresponds to a hexagonal grating geometry, gives three relevant diffraction orders $h_1 h_2 h_3 = 111, 123$ and 122 in the visible spectral region. $\lambda_{\max 111}$ determines the two other diffraction orders and will be used as an example to show how the differentiation of ν and λ takes place. Resolved to λ or $1/\lambda$ in each diffraction order, Equation (1) gives:

$$\lambda_{\max} h_1 h_2 h_3 = \frac{2 \left(\frac{h_1}{b_1} \cos \alpha_o + \frac{h_2}{b_2} \cos \beta_o + \frac{h_3}{d} \cos \gamma_o \right)}{\frac{h_1^2}{b_1^2} + \frac{h_2^2}{b_2^2} + \frac{h_3^2}{d^2}}. \quad (1)$$

The reciprocal value of Equation (1) gives ν . For $\alpha_o = \beta_o = 90^\circ$ and $\gamma_o = 0^\circ$, ν and λ result in c for 111 with 1:1, for 123 with 1.04:0.96, and for 122 with 1.25:0.8. If $\lambda_{\max 111} = 559 \text{ nm}$ (RED), then $\lambda_{\max 123} = 537 \text{ nm}$ (GREEN) and $\lambda_{\max 122} = 447 \text{ nm}$ (BLUE). This $\lambda_{\max}$ triplet corresponds to the spectral brightness sensitivity maxima of the cones, and for approximately Gaussian transmission curves centred on these three $\lambda_{\max}$ (at a spectral half intensity width of about 40–60 nm, which corresponds to around 12–20 layers in the 3D grating) and under sunlight-like illumination, they each contribute 33% of the resultant brightness values, i.e. they form standard white on which colour space is centred (33% in RED, GREEN and BLUE) and to which all other colour values are related.

For different pupillary apertures corresponding to logarithmic luminance values, the relative proportion of obliquely incident light cones changes. In 3D grating optical terms, this is evident as the shift in the sum brightness curves of the three diffraction orders (Figure 4), from which the Stiles–Crawford effects I and II (see Figure 5) for monochromatic light can be derived directly. The substantial agreement with experimentally measured data in human vision is described elsewhere [6–8].

This first differentiation of ν and λ for the perpendicular incidence of light is overlaid in a second step by a further differentiation, which itself affects all three chromatic diffraction orders to a somewhat different extent.

1.1b. *Spatial direction- and distance-specific, i.e. space-time differentiation of ν and λ in $V_p = \nu \lambda = c$ in the three chromatic diffraction orders (aperture effects).* In

Figure 4. Sum curve of the spectral brightness values for various pupillary apertures (3–6 mm diameter) relative to the sum curve for a 2 mm pupil (all curves with their maximum standardized to the value 100). The 3D grating-optical calculation was this time based on a reciprocal formulation (with respect to [5], Equation (6), $\lambda_{\max}$ shift for $\alpha_o\beta_o\gamma_o \neq 0^\circ$ toward red instead of toward blue in accordance with the nm values in Table 2). With increasing illumination intensity, i.e. smaller pupil, $\lambda_{\max}$ of the sum curve shifts from about 580 nm for a 6 mm pupil to 480 nm for a 2 mm pupil. The difference between each curve and the standard curve (2 mm) gives the Stiles–Crawford effect (SCE) I (increase and decrease in brightness) in Figure 5, typically with three intersections of the curve with the 100% line (2 mm standard value). The SCE II (hue shift) also results from the spectral brightness values, but here the energy balance in each of the three diffraction orders as a percentage change relative to white standard (33% in each of the red, green and blue colour channels) becomes relevant.

the same way as an observer of the Doppler shift of a self-luminous object moving at, for example, $0.5c$, i.e. the differentiation of the ratio between ν' or λ' and the true ν or λ in $\nu\lambda = c$ (Figure 6), can determine the direction of movement of the object in 3D space, an observer possessing an OPTO-RETINA can determine the relative position, distance and direction of movement of an object in 3D space from the ratio between ν or λ of the obliquely incident light cones ($\alpha_o \neq \beta_o \neq 90^\circ, \gamma_o \neq 0^\circ$) and ν or λ of the perpendicularly incident rays ($\gamma_o = 0^\circ$). This is due to the aperture effects, i.e. the 3D grating-optical shift in brightness and hue of light cones incident obliquely on the 3D grating, describable by means of the von Laue equation. The data in Table 2 illustrate the differentiation of ν and λ in c for angles of incidence that correspond to the usual pupillary apertures in human vision ($\gamma_o = 0 - 11^\circ$). A shift in $\lambda_{\max}$ from 559 nm in the 111 RED diffraction order ($\gamma_o = 0^\circ$) to 830 nm corresponds to a change in the angle of incidence of a light ray to $\alpha_o = \beta_o = 82.2^\circ, \gamma_o = 11^\circ$. The associated brightness shift can

Figure 5. Data calculated using 3D grating optics for the aperture effects of monochromatic test lights: Stiles–Crawford effects SCE I (increases and decreases in brightness) and SCE II (hue shift) of rays incident obliquely on the pupil and retinal 3D grating relative to rays incident perpendicularly through the centre of the pupil.

Top: 3D grating optical data on the SCE I for a pupillary diameter of 3–6 mm relative to a pupil with a diameter of 2 mm (100% line). Three intersections of each curve with the 100% line occur between 450 and 650 nm, as in the experimental data on human vision [5] (> 100% denotes increase in brightness or RED shift, < 100% denotes decrease in brightness or BLUE shift).

Bottom: 3D grating optical data on the SCE II for a pupillary diameter of 3–6 mm relative to a pupil with a diameter of 2 mm (0% line). The SCE II shifts are due to the relative change in the brightness values in the RGB diffraction orders and are evident as BLUE: (RED + GREEN) shifts relative to the percentage distribution with 33%: 66% at 2 mm (0 line). As in the experimental data on human vision [5], two intersections occur with the 0% line (+ denotes RED shift, – denotes BLUE shift in nm or %).

Figure 6. Differentiation of $\nu\lambda = c$ in the Doppler shift. Wavelength and frequency of a light source with true $\nu = 6 \times 10^{14}$ and true $\lambda = 0.5 \times 10^{-6} = 500 \text{ nm}$ ($\nu\lambda = 3 \times 10^8$) moving at $c/2$ at angle θ to the observation angle (0°). For example, if the observer sees a RED shift to $\lambda' = 700 \text{ nm} = 0.7 \times 10^{-6}$ and $\nu' = 4.3 \times 10^{14}$ ($\nu'\lambda' = 3 \times 10^8$), this means that the light source is moving away from him in the direction $\theta = 140^\circ$. For example, if the observer sees a BLUE shift to $\lambda' = 300 \text{ nm} = 0.3 \times 10^{-6}$ and $\nu' = 1 \times 10^{15}$ ($\nu'\lambda' = 3 \times 10^8$), this means that the light source is moving toward him in the direction $\theta = 20^\circ$. (■) resultant wavelength of the light (nm); (◆) resultant frequency of the light.

be calculated from the spectral brightness sum curve in Figure 4 [7]. The 111 RED diffraction order is the one that registers this aperture angle-related shift most sensitively (+271 nm shift in $\lambda_{\max}$ (559 nm) for $\gamma_o = 11^\circ$). Given mathematically strict coupling of the eikonal condition in the imaging system (in front of the 3D grating) with the diffractive von Laue conditions in the 3D grating, it is ensured that not only can every change in direction of a visual object in 3D space be registered as a hue shift (SCE II) and every change in distance as a brightness shift (SCE I), but also that all space-time changes in position relative to the focus position can be registered in effects which are mutually combined (and simultaneously with the correct sign). Each relative change in direction and/or distance can thus be derived interference-optically from the mutual balance between the two aperture effects. Depending on the type of photoreceiver used, wavelength or frequency differentiation can be processed.

Table 2. Data on the differentiation of ν and λ in $V_p = \nu\lambda = c = 1$ (V_p = phase velocity) for the 3D grating-optical calculation with the von Laue Equation (1) and its reciprocal value for $\nu = c/\lambda$ (basis for calculation of the results in Figures 4 and 5). The $\lambda_{\max}$ triplet that results for perpendicular incidence of light on the OPTO-RETINA ($\alpha_o = 90^\circ, \beta_o = 90^\circ, \gamma_o = 0^\circ$) with 559 nm (RED), 537 nm (GREEN) and 447 nm (BLUE) in the three chromatic diffraction orders shifts for oblique incidence (α_o and $\beta_o \neq 90^\circ, \gamma_o \neq 0^\circ$) toward RED in the visible spectrum (cf. sum brightness values in Figure 4), i.e., for example, to 830/659/604 nm for $\alpha_o = \beta_o = 82.2^\circ, \gamma_o = 11^\circ$. The frequency values 1/nm shift reciprocally to this. The common product of ν and λ in $V_p = \nu\lambda = \lambda/\lambda$ (final column) = c is always 1 in all three diffraction orders. All chromatic and brightness effects (SCE I and II) can consequently be derived from the grating-optical aperture conditions for the light cones incident on a hexagonal 3D grating. These are based in physical terms on the incident angle-specific space-time $\nu\lambda$ differentiation of the phase velocity.

α_o	β_o	γ_o		Blue	Green	Red	λ/λ
90	90	0	nm	447	537	559	
			1/nm	0.00224	0.00186	0.00179	1
87.9	87.9	3.0	nm	492	572	635	
			1/nm	0.00203	0.00175	0.00157	1
86.5	86.5	5.0	nm	521	595	685	
			1/nm	0.00192	0.00168	0.00146	1
84.4	84.4	8.0	nm	563	628	759	
			1/nm	0.00178	0.00159	0.00132	1
82.2	82.2	11.0	nm	604	659	830	
			1/nm	0.00166	0.00152	0.00120	1

1.1c. *Prospects.* An OPTO-RETINA with this design could represent a considerable innovative advance in optical sensory systems if full technical achievement of all transformation steps were to succeed. It could attain substantial importance for patchwise Fourier-optical image preprocessing in the reciprocal grating of the Talbot planes (multiplication in the reciprocal grating corresponds in Fourier-optical terms to a correlation, which is itself equivalent to a convolution). And it could open up the way to a ‘biological optocomputer’ with a trichromatic spatio temporal performance spectrum that calculates multiple correlations. Corrsys GmbH in Wetzlar, Germany, which has produced Correvit sensors (Correvit = trade-mark of Corrsys GmbH) based on grating-optical spatial frequency filtering since 1993 for non-contact measurements in the automotive industry and industrial strip material production lines, has set itself this goal in cooperation with the Fraunhofer Institute for Applied Polymer Research, Teltow, Germany, and in the future with other partners.

2. Model Gratings from Polymer Latex Particles

Monodisperse polymer latex particles can be used as models for creating ordered, crystalline structures in the micron and submicron range of periodicities. The crys-

talline order can be obtained in three dimensions in liquid suspensions due to electrostatic interactions [10] or hard sphere repulsion [11] of the particles as well as in two or quasi-three dimensions in deposited films after evaporation of the dispersion medium. Several techniques have been developed in recent years for the deposition of organized mono- and multilayers of latex particles on different substrates [12–15]. Potential applications of such systems extend from colloid to material science and technology including advanced nanotechnologies for electrical, optical and biological engineering [12, 15].

The optical properties of ordered latex arrays have attracted scientific attention for more than forty years [16], because of the brilliant colours they display upon illumination with white light, a phenomenon reminiscent of the examples in nature, like the opal or the surface structural colours of some insects (e.g. butterfly wings [17]). Optical applications of ordered latex structures have been discussed for microlens arrays, gratings, anti-reflecting coatings and photonic crystals [15, 18–20].

In this paper, as a first step in realizing ‘OPTO-RETINA’ properties, we study the diffraction of white light by hexagonally packed monolayers of monodisperse polystyrene (PS) latex particles ($n_D^{20} = 1.59$) in the range of particle diameters between 0.8 and 1.4 μm , by means of the conoscopical method of optical microscopy (cf. 3.2.1).

3. Experimental Part

3.1. SAMPLE PREPARATION

3.1.1. *Latex samples.* Four PS latex samples of different particle size (Table 3) were synthesized according to classical one step soapless emulsion polymerization recipes [21]. By a cautious systematic increase of ionic strength extremely narrow size distributions could be obtained up to 1.4 μm diameter. The particle size and polydispersity was estimated by transmission electron microscopy evaluating at least 800 individual particles per sample. The data were compared with particle size determination at ordered particle arrays by means of optical microscopy.

3.1.2. *Formation of ordered particle monolayers.* Different colloidal coating techniques have been tested for particle monolayer deposition by latex evaporation on glass substrates. We obtained the highest degree of order with a method described by Lasarov and coworkers [14] based on the spreading and evaporation of the aqueous latex on a thin layer of a fluorinated oil with subsequent evaporation of the oil film. The advantage of using liquid substrates (mercury, fluorinated oil) is the high lateral mobility of the polymer spheres during the self-assembling process at the substrate-latex interface [12]. Fluorinated oils are used because they are insoluble in water, have a higher density than water, and can be easily evaporated at moderate temperatures.

Table 3. Results of TEM particle size analysis of polystyrene latex samples

Latex sample-Nr.	Diameter (μm)	Standard deviation
PS 1	0.74	$\pm 3.0\%$
PS 2	1.00	$\pm 2.2\%$
PS 3	1.15	$\pm 5.2\%$
PS 4	1.41	$\pm 2.7\%$

Following Lasarov et al. [14], our experimental cell for monolayer deposition consists of a Teflon ring of 10 mm inner diameter which was pressed to a glass plate. The cell was filled with a 0.5 mm high layer of perfluoromethyldecalin (Aldrich) containing 1.25% (w/w) of a surfactant-cosurfactant mixture (1:24 weight parts) of Perfluoroalkylethanol-ethoxalate (Fluowet OTN, Hoechst, Germany) and Perfluorooctylethanol (Fluowet EA800, Hoechst) to induce better wettability. About 200 μl of the aqueous latex samples (Table 3, solid content 0.2%) were spread on the oil surface and then evaporated over several days at room temperature and humidity. Subsequently, the oil was removed by evaporation at 40 °C. As a result, polycrystalline multilayers of particles were deposited on the glass plate including islands of up to about $10^4 \mu\text{m}^2$ area of hexagonally ordered monolayers. These monolayer areas are large enough for an investigation of diffraction properties by means of microscope methods.

3.2. DIFFRACTION AT LATEX LAYERS

The investigation of diffraction of latex (monolayers and/or colloidal dispersions) is typically carried out with monochromatic laser light focused to a spot diameter of about 25 μm [22–24]. Adjusting the laser spot to an ordered region, this experimental setup enables estimation of lattice constants from the angle of the detected diffraction order at the wavelength of the incident laser beam. The observation of coloured thin films is discussed in terms of the white light diffraction [25]. The imaging of the diffraction by latex layers using a microscope will be presented here as a suitable method for the investigation of the order and the dispersion at 2D monolayers, offering the possibility of testing the 3D grating-optical transformation of light (cf. 1.1) by latex multilayers.

3.2.1. Experimental setup. The diffraction of light at the monolayers was investigated using a microscope for conoscopical investigations (Jenalab pol, Carl Zeiss, Jena, Germany) in the transmission mode. The image of the diffraction pattern at the back plane of the microscope objective was obtained by means of a Bertrand-lens placed in front of the ocular. The quality of the diffraction pattern was improved, when the Köhler's central illumination was changed to a parallel illumination

Figure 7. Image of a hexagonally packed monolayer of the sample PS 4 with an objective 100/0.9 (magnification 100, aperture 0.9).

modifying the condenser system of the microscope and by adjusting the aperture of the condenser to its minimum.

The microscope was equipped with a colour CCD-camera (0.5 inch, RGB-output) and a hard- and software package for image analysis (Soft-Imaging Software GmbH, Munich, Germany). The colour CCD-camera enables the investigation of the dispersion of white light from a mercury lamp inside the microscope.

The power of the microscope objectives was selected according to the diameter of the latex spheres in order to detect the first and the second orders of diffraction. The patterns presented here for particles with a diameter of about $1.4 \mu\text{m}$ were obtained using two objectives (magnification/aperture: 100/0.9 and 50/0.95).

3.2.2. Experimental results. The microscopic image of the sample PS 4 (Table 3) is represented in Figure 7. The latex particles are well ordered in the imaged region of $66 \times 66 \mu\text{m}^2$ and a mean distance of $1.47 \mu\text{m}$ between the particles was estimated. The bright points in the picture correspond to vacancies in the ordered structure, where no particles were placed during the formation of the layer.

The corresponding diffraction pattern of the above structure is represented in Figure 8a. The first and the second orders of diffraction were observed by using 50/0.95 objective. The regular 6-fold diffraction pattern indicates a hexagonal struc-

Figure 8. Diffraction pattern from the structure in Figure 7, obtained with white light (a) and blue light at wavelength 486 nm (b) (50/0.95 objective).

ture in the ordered layer. The elliptical shape of the light spots in the black/white figure is due to the dispersion of the white light by the lattices. In the original coloured picture, the blue light is observed at a small angle and the red light is diffracted to a larger angle. Conversely the diffraction pattern for blue light, while rejecting the other wavelengths with an interference filter at 486 nm, is of weak intensity but the diffraction spots are of circular shape (Figure 8b).

For a monolayer of PS 3 the particle distance was estimated from the microscopic image to be $1.2 \mu\text{m}$. The corresponding first diffraction orders at red (582 nm), green (552 nm) and blue (486 nm) light (RGB) were measured at distances (L_λ) of 49, 44.5 and 41 mm from the central point of the diffraction patterns. These distances were obtained by an objective $50\times$ magnification and at an identical scale to the CCD-camera image.

Using the experimentally determined particle distance $1.2 \mu\text{m}$ as the grating constant d_g , the angles of the diffracted light at different wavelengths were calculated from the formula of Born and Wolf [26]:

$$\theta_\lambda = \arcsin \lambda/d_g. \quad (2)$$

Then the distance from the sample to the image plane at the CCD-camera inside the microscope (F) was estimated from three independent measurements at different wavelengths (RGB) using the equation:

$$F = L_\lambda / \tan \theta. \quad (3)$$

The mean value of F was estimated to be 96 mm.

This value was used to calculate the grating constant d_g of the monolayers from the position of the first diffraction order using the above two equations. The distances of the first diffraction order L (central point for white light spots), the calculated values of the diffraction angle Θ , and the calculated lattice constant d_g are depicted in Table 4.

Table 4. Grating constants d_g obtained from the first diffraction order at angle θ (Equation 2), which was calculated from the distance L between the spots of the zero and first diffraction order.

Latex sample-Nr.	L (mm)	Θ (degree)	d_g (μm)
PS 1	64	23.7	0.88
PS 2	51	28.0	1.04
PS 3	43	22.1	1.20
PS 4	37	21.1	1.35

3.2.3. Discussion. The microscope represents an effective tool for investigating diffraction of prepared monolayers. The position of bright points (Figure 7, high intensity from vacancies) in strong periodicity with the points of lower intensity, indicate that the detected light from the monolayer is transmitted by the particular latex spheres, but not by the free volume between the particles in the hexagonal arrangement. This behaviour permits an investigation of diffraction by latex spheres.

The regularity of the 6-fold diffraction pattern is an integral measure of hexagonal order in the whole imaged area. The diffraction angle and therefore the grating constants of the investigated layers were calculated after calibrating the microscopic diffraction pattern for different objectives. The obtained grating constants d_g for monolayers (Table 4) from different lattices are in good agreement with particle size (Table 3), indicating a close packing of spheres in the ordered monolayers.

The dispersion of white light is directly observable by the microscopic diffraction pattern. The angular shift (Equation 2) of several wavelengths at different diffraction orders by the 2-dimensional grating of the monolayers can be detected in the spectral sensitivity range of the CCD-camera. This technique can be an effective tool in investigating the spectral effects of 3-dimensional multilayers.

References

1. Carbon, M.: Using diffraction theory of human vision for design of colour vision devices, *SPIE Proceedings, Intelligent Robots and Computer Vision* **13** (1994), 550–560.
2. DeValois, K.K., DeValois, R.L. and Yund, E.W.: Responses of striate cortex cells to grating and checkerboard patterns, *J. Physiol.* **291** (1979), 483–505.
3. Hopfield, J.J.: Pattern recognition computation using action potential timing for stimulus representation, *Nature* **376** (1995), 33–36.
4. Lauinger, N.: 3D grating optics of human vision, *Acta Ophthalmologica, Suppl.* **69** (1991), 199.
5. Lauinger, N.: The two axes of the human eye and inversion of the retinal layers: the basis for the interpretation of the retina as a phase grating optical, cellular 3D chip, *J. Biol. Physics* **19** (1994), 243–257.
6. Lauinger, N.: A new interpretation of the Stiles–Crawford effects in human vision, *J. Biol. Physics* **19** (1994), 167–188.
7. Lauinger, N.: The relationship between brightness, hue and saturation when the inverted human retina is interpreted as a cellular diffractive 3D chip, *SPIE Proceedings, Intelligent Robots and Computer Vision* **14** (1995), 208–232.
8. Lauinger, N.: The inverted retina of the human eye: a trichromatic 4D space-time optical correlator, *SPIE Proceedings, Intelligent Robots and Computer Vision* **15** (1996, in press).
9. Schultze, M.: Zur Anatomie und Physiologie der Retina, *Archiv für mikroskopische Anatomie* **2** (1866), 174–286.
10. Dosho, S., Ise, N., Ito, K., Iwai, S., Kitano, H., Matsuoka, H., Nakamura, H., Okumura, H., Ono, T., Sogami, I.S., Ueno, Y., Yoshida, H. and Yoshiyama, T.: Recent study of polymer latex dispersions, *Langmuir* **9** (1993), 394–411.
11. Pusey, P.N. and van Megen, W., Barlett, P., Ackerson, B.J., Rarity, J.G. and Underwood, S.M.: Structure of crystals of hard colloidal spheres, *Phys. Rev. Lett.* **63** (1989), 2753–2756.
12. Nagayama, K.: Two-dimensional self assembly of colloids in thin liquid films, *Colloids and Surfaces* **A109** (1996), 363–374.
13. Denkov, N.D., Velev, O.D., Kralchevsky, P.A., Ivanov, I.B., Yoshimura, H. and Nagayama, K.: Mechanism of formation of two-dimensional crystals from latex particles on substrates, *Langmuir* **8** (1992), 3181–3190.
14. Lasarov, G.S., Denkov, N.D., Velev, O.D., Kralchevsky, P.A. and Nagayama, K.: Formation of two-dimensional structures from colloidal particles on fluorinated oil substrate, *J. Chem. Soc. Faraday Trans.* **90** (1994), 2077–2083.
15. Dimitrov, A.S. and Nagayama, K.: Continuous convective assembling of fine particles into two-dimensional arrays on solid surfaces, *Langmuir* **12** (1996), 1303–1311.
16. Alfrey Jr., T., Bradford, E.B., Vanderhoff, J.W. and Oster, G.: Optical properties of uniform particle-size latexes, *J. Opt. Soc. Am.* **44** (1954), 603–609.
17. Ghirandella, H.: *Appl. Opt.* **30** (1991), 3492.
18. Hayashi, S., Kumamoto, Y., Suzuki, T. and Hirai, T.: Imaging by polystyrene latex particles, *J. Colloid Interface Sci.* **144** (1991), 538–547.
19. Wei Hu, Hongqiang Li, Bingying Cheng, Junhui Yang, Zhaolin Li, Jiren Xu and Daozhong Zhang: Planar optical lattice of TiO₂ particles, *Optics Letters* **20** (1995), 964–966.
20. Deckmann, H.W. and Dunsin, J.H.: Natural lithography, *Appl. Phys. Lett.* **41** (1982), 377–379.
21. Goodwin, J.W., Hearn, J., Ho, C.-C. and Ottewill, R.H.: Studies on the preparation and characterisation of monodisperse polystyrene latices, *Colloid Polym. Sci.* **52** (1974), 464–471.
22. Goodwin, J.W., Ottewill, R.H. and Parentich, A.: Optical examination of structured colloidal dispersions, *J. Phys. Chem.* **84** (1980), 1580–1586.

23. Van Winkle, D.H. and Murray, C.A.: Layering transitions in colloidal crystals as observed by diffraction and direct-lattice imaging, *Phys. Rev.* **A34** (1986), 562–573.
24. Burns, M.M., Fournier, J.-M. and Golovchenko, A.: Optical matter: crystallization and binding in intense optical fields, *Science* **9** (1990), 749–754.
25. Dushkin, C.D., Nagayama, K., Miwa, T. and Kralchewsky, P.A.: Coloured multilayers from transparent submicrometer spheres, *Langmuir* **9** (1993), 3695–3701.
26. Born, M. and Wolf, E.: *Principles of Optics*, Pergamon Press, Oxford, 1980.