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Mechanism of multiple grating formation in high-energy recording of holographic sensors

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We report numerical analyses of Bragg diffraction by Denisyuk reflection holograms recorded by a high-energy pulsed laser. An intensity threshold must be passed to pattern a multilayer reflection and transmission hologram, which exhibits a nonlinear fringe structure. Numerical evaluations are provided for the laser light intensity, readout diffraction offset angle, transmission of the layer, and thickness of the polymer matrix during hologram recording. A non-sinusoidal surface pattern is formed at the top of the multilayer structure, and its effect on the diffraction properties of the structure becomes significant when the recording tilt angle is increased. Experimental results show that the angle of the diffracted light increases nonlinearly according to the tilt geometry in grating formation. © 2014 AIP Publishing LLC. [http://dx.doi.org/10.1063/1.4905352]

Holography is a well-established 3D imaging technique that has applications in displays,1–4 data storage,5 metamaterials,6 fabrication sensors because photosensitizing dyes are toxic for enzymatic assays, cause undesired light absorbance, and require time-consuming chemical processing steps.22 Recently, high-energy pulsed laser recording has been proposed for the production of holographic sensors in hydrogel matrices.23 The mechanism of grating formation in pulsed laser recording has been attributed to change in nanoparticle (NP) size, displacement by means of thermal energy, and metal oxide shell formation.24–26 The physical parameters such as incoming wavelength, power, pulse duration, nanoparticle size, and surface plasmon resonance influence the optical characteristics of photochemical patterning.26–28 When holograms are produced in Denisysuk reflection mode, in addition to the desired multilayer grating running parallel with the plane of the polymer film, a transmission grating running almost perpendicular to the plane of the film tends to form due to the reflection from the lower surface boundary of the emulsion and air.16,23,29 For optimal operation of a holographic sensor comprising the multilayered structure, it is important to minimize the formation of transmission grating while maximizing the monochromatic Denisysuk grating. The analytical solution for image recording through silver halide chemistry has been described by Kogelnik theory.30 The coupled wave theory allowed understanding of diffraction in sinusoidal volume gratings and provided analytical formulas for the computation of diffraction efficiency. Another approach to Kogelnik’s theory is parallel stacked mirrors model, which is based on the differential formulation of the Fresnel reflection within the grating.31 However, no systematic approach has been developed to understand the fundamentals of the pulsed laser induced

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of the field, the interference profile was computed by adding the waves. Furthermore, the exponential decay produced by the absorption of the recording medium creates a variation along the direction of propagation of the beam. Figure 2(a) illustrates a typical normalized intensity field distribution obtained from a recording medium with varying tilt angles from 0° to 20° while the transmission (20%) and thickness (10 μm) were kept constant. The incident beam was propagated from the top in Denisyuk reflection mode, as evident from the intensity of the wave, which exponentially decayed as it propagated through the recording media. Although Fig. 2(a) shows the intensity distribution, the holographic structure formation occurs at a threshold. Therefore, only the waves with above certain intensities lead to patterning. When the threshold was applied to the simulations shown in Fig. 2(a), multilayer patterns were obtained (Fig. 2(b)). The threshold was 0.5, which implied the average between the minimum and maximum intensities of the field distribution. In the simulated pattern, black regions correspond to the non-patterned material, while white regions represent the patterned material. Along with the vertical standing wave (~193 nm), larger period waves of ~3.1, 1.5, and 0.8 μm were obtained in the horizontal direction for 5°, 10°, and 20°, respectively. The spacing of the surface (horizontal) grating decreased as the tilt angle approaches 0°. This was expected since the angle between the two interfering beams decreased. As the mirror tilt angle increased, the multilayer pattern diminished. Figure 2(c) illustrates the interference pattern arising from the superposition of the reflected waves as the transmission was varied from 0% to 40% with 10% increments, while constants were tilt angle (5°), thickness (10 μm), and intensity (0.5). As the transmission increased, the amount of intensity required increased to pattern the matrix. This represents a compromise between the absorption and the intensity. Figure 2(d) shows the interference pattern arising from the superposition of the reflected waves as the threshold intensity was varied from 0.5 to 0.8 with 0.1 increments, while constants were tilt angle (5°), transmission (20%), and thickness (10 μm). Figure 2(e) shows the interference pattern arising from the superposition of the reflected waves as the matrix thickness was varied from 2.0 to 10.0 μm with 2.0 μm increments, while constants were transmission (20%), tilt angle (5°), and intensity threshold (0.5). As the thickness of the matrix increased, the number of fringes in the multilayer structure also increased. At least, 5 μm thick hydrogel was required to obtain ~10 stacks (Fig. 2(e)). Supplementary Figures S1–S5 show detailed simulation results. Thus, using simulation, we can predict the optical characteristics such as the periodicity of the transmission grating, the regions that will be patterned at a given absorption value, and the number of multilayer gratings that will be formed.

We have evaluated the optical properties of the gratings shown in Fig. 2(b). A finite element time domain allowed simulating the readout of the holograms. Figures 3(a)–3(c) show the simulations that describe normally propagated electric field of the incoming 1 and refracted 2 waves in transversal electric mode. The first order diffracted waves 3 were observed at ~25°, ~35°, and ~65° from the normal, 4 shows the second order of the diffraction. Enhanced online
multimedia movies 1–3 show the interaction of the electromagnetic waves with the photonic structures.\textsuperscript{32}

The fabrication of holographic sensors consisted of the preparation of a polymer film, \textit{in situ} nanoparticle growth, and formation of a hologram in the polymer matrix. The holograms were recorded in Denisyuk reflection mode (Fig. 4(a)). The hologram was probed by reflection spectrophotometer (Fig. 4(b)). Supplementary material describes recording and probing of the holograms.\textsuperscript{32} Upon illumination at normal incidence using a supercontinuum white light laser, the photonic structure showed a narrow-band Bragg peak at \(~530\text{ nm}\) produced by the reflection grating.
same time, a surface transmission grating creates higher orders of diffraction (Fig. 4(c)). The Bragg peak can be modulated from UV to near-infrared in sensing applications. As the target molecules bind to receptors in the hologram, the changes in Donnan osmotic pressure lead to structural or refractive index changes that alter the photonic band gap, the changes in Donnan osmotic pressure lead to structural or refractive index changes that alter the photonic band gap, the changes in Donnan osmotic pressure lead to structural or refractive index changes that alter the photonic band gap, the changes in Donnan osmotic pressure lead to structural or refractive index changes that alter the photonic band gap, the changes in Donnan osmotic pressure lead to structural or refractive index changes that alter the photonic band gap, the changes in Donnan osmotic pressure lead to structural or refractive index changes that alter the photonic band gap, the changes in Donnan osmotic pressure lead to structural or refractive index changes that alter the photonic band gap, the changes in Donnan osmotic pressure lead to structural or refractive index changes that alter the photonic band gap, the changes in Donnan osmotic pressure lead to structural or refractive index changes that alter the photonic band gap, the changes in Donnan osmotic pressure lead to structural or refractive index changes that alter the photonic band gap, the changes in Donnan osmotic pressure lead to structural or refractive index changes that alter the photonic band gap, the changes in Donnan osmotic pressure lead to structural or refractive index changes that alter the photonic band gap, the changes in Donnan osmotic pressure lead to structural or refractive index changes that alter the photonic band gap, the changes in Donnan osmotic pressure lead to structural or refractive index changes that alter the photonic band gap, the changes in Donnan osmotic pressure lead to structural or refractive index changes that alter the photonic band gap, the changes in Donnan osmotic pressure lead to structural or refractive index changes that alter the photonic band gap, the changes in Donnan osmotic pressure lead to structural or refractive index changes that alter the photonic band gap.

Kogelnik’s coupled wave theory has explained the sinusoidal diffraction.\textsuperscript{30} Additionally, parallel stacked mirrors model showed a differential formulation of the Fresnel reflection within the grating.\textsuperscript{31} In the present work, light-matter interaction by high-energy pulsed laser recording does not follow the same principles.\textsuperscript{24,28} The reason is that the photochemical patterning described by the previous models implies that the change in the refractive index is proportional to the intensity of the recording beams producing a sinusoidal profile. However, the patterning of NPs is not linear with respect to the intensity of the recording beam in the present work. In contrast to the previous models, we consider that patterning of silver NPs occurs at a given threshold. This threshold in addition to the absorption required by the NPs limits the patterned regions within the recording medium.

We have studied hologram recording using a high-energy pulsed laser to evaluate the parameters that affect grating formation. A threshold should be passed to form a diffraction grating, hence rendering this image recording technique fundamentally different than photochemistry. Additionally, the grating should be produced at the lowest tilt angle to reduce the effect of the transmission grating in the readouts. We have also fabricated holograms with predictive optical properties at various diffraction angles using a pulsed laser, which produced multilayer Bragg and transmission gratings within pHEMA matrixes. However, a limitation of the high-energy pulsed laser recording is that it produces holograms with diffraction efficiencies less than 5%, which needs to be improved for practical applications. The model and the fabrication technique can be applied to other holograms that are formed using complex objects such as concave and convex mirrors, prisms, and retroreflectors. Rationally designing diffraction gratings via high-energy pulsed laser recording will allow fabricating holographic patterns with predictive optical characteristics.