Photopolymer for Optical Holography and Holographic Interferometry

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Summary: In our laboratory, we have continued in experimental study of acrylamide-based photopolymer recording material. Our exposition and detection setup was used for real-time measurements of a diffraction grating formation process. Based on the results of our measurements, the chemical composition of the material was modified to increase sensitivity, value of refractive index modulation and stability of the formed structure. Recently, the material has been successfully applied to holographic interferometry.

Keywords: holographic interferometry; holography; photopolymerization; recording material; refractive index

Introduction

Photopolymers are attractive recording media for different holographic applications such as diffractive optical elements, holographic memories, or holographic interferometry.[1,2] They enable complex wave fields recording without an additional wet chemical developing process, because a hologram is formed already during exposition due to a light induced polymerization. In our laboratory, we have been preparing and testing acrylamide-based photopolymer recording material for several years.[3,4] Our early photopolymers, which were based on composition presented in paper,[5] are very good for measurements in holographic research. Applications such as holographic interferometry require photopolymers with higher sensitivity, higher refractive index modulation, and better stability of the formed hologram. Therefore, we decided to optimize the original chemical composition. The role of each component in the recording system was studied with our exposition and detection setup. Based on the results of our measurements, the composition has been modified. We than started to apply the acrylamide-based material to holographic interferometry[6] and the first results are presented.

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Holographic Recording in Photopolymers

Hologram is a microstructure where material characteristics such as absorption, refractive index, relief, etc. are spatially modulated. If the hologram is illuminated, incident light is transformed into a useful signal due to an effect called diffraction of light. An example of a hologram recording and reconstruction is given in Figure 1. Signal and reference waves overlap and produce an interference field which is recorded in a light sensitive medium. It changes its properties according to the intensity of illumination of the interference field (some materials require also a developing process).

In photopolymers, the refractive index is changed already during exposition. The

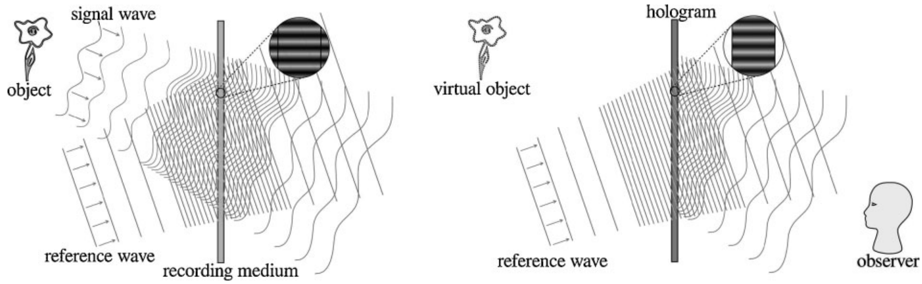

Figure 1.
A hologram record (on the left) and reconstruction (on the right).

main components of a photopolymer recording medium are molecules of monomer and light sensitive initiator. Typically, these components are incorporated in a polymer binder which forms a thin layer on a glass plate. Light, in the form of an interference field, initiates a radical polymerization process. In bright places, the polymer density increases as the polymerization proceeds. The refractive index is proportional to the polymer density in the first approximation and so the refractive index modulation is formed in the recording medium. The process of a hologram formation is illustrated in Figure 2.

Characterization Method and Setup

Harmonic interference field creates in real-time a simple volume phase grating. The grating is usually characterized with its diffraction efficiency. However, the main quantity of the volume phase medium, which can be calculated from the efficiency measurement, is its refractive index modulation. The refractive index is more easily interpreted by parameters (concentration, molar refraction) of the recording material.

For characterization of a photopolymer recording material, we have built up a special setup. It is composed of an exposition and detection part (see Figure 3). The beam of the recording laser is expanded and collimated. One half of it comes through the material directly and the second half is reflected by the mirror. Both then overlap at the recording material and form the harmonic interference field which is recorded. The diffraction efficiency of the forming grating is continuously measured with a narrow beam of a collimated laser diode which is adjusted at the Bragg angle. When the detection beam passes through the transmission grating, a new diffracted beam is formed. Both beams (diffracted and passing) are then detected with PIN photo-diodes connected to digital oscilloscope. The real-time measurement must not influence the recording process and therefore the wavelength of the detection laser is chosen from the non-absorption band of the material (laser diode @656nm). In contradiction, the recording laser is tuned to the maximum of the absorption band (Nd:YAG laser @532nm).

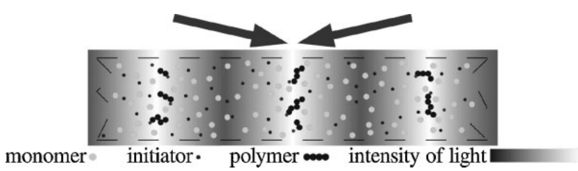

Figure 2.
Scheme of polymer recording.

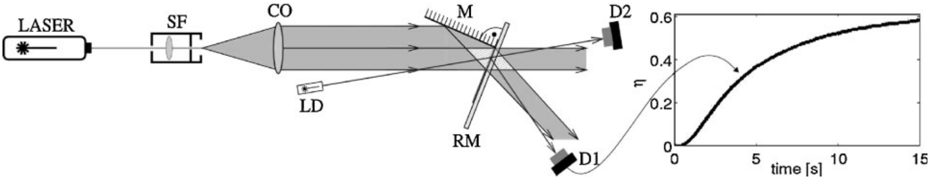

Figure 3.
Exposition and detection setup: SF – spatial filter, CO – collimating lens, M – mirror, RM – recording medium, LD – laser diode, D1, D2 – photo-detectors.

The diffraction efficiency η is defined as the ratio of the diffracted intensity (measured with detector D1) and the incident intensity of the probe beam from the laser diode. The efficiency η, and the first harmonic amplitude $n\mathrm{B}_{1\mathrm{B}}$, of the refractive index are connected through Eq. (1) which was derived in the coupled wave theory[7]

$$\eta = \sin^2 \frac{\pi n_1 d}{\lambda \cos\theta}. \qquad (1)$$

In Equation (1), d is the thickness of the material, λ is the wavelength of the probe light, and θ is the Bragg angle of the volume phase grating. The refractive index modulation $n\mathrm{B}_{1\mathrm{B}}$ is evaluated as an inverse function to Equation (1). The time dependence of $n\mathrm{B}_{1\mathrm{B}}$ is called grow-curve. We use the grow-curve for experimental and theoretical material characterization as $n\mathrm{B}_{1\mathrm{B}}$ does not depend on thickness, wavelength, and angle.[8] Selected grow-curves are presented further (see Figure 4 and 5).

Recording Material Optimization

The acrylamide-based photopolymer is used as an experimental holographic recording material for more than 20 years.[9,10] It is composed of acrylamide monomer, triethanolamine initiator, sensitizing dye (erythrosine B, eosin Y, methylene blue, etc.), and polyvinyl alcohol binder. All components are commercially available and relatively inexpensive. They are dissolved in water and the solution is spread on a glass plate and dried. The dry layer deposited on a glass substrate is easy to handle and toxic acrylamide incorporated in the binder is

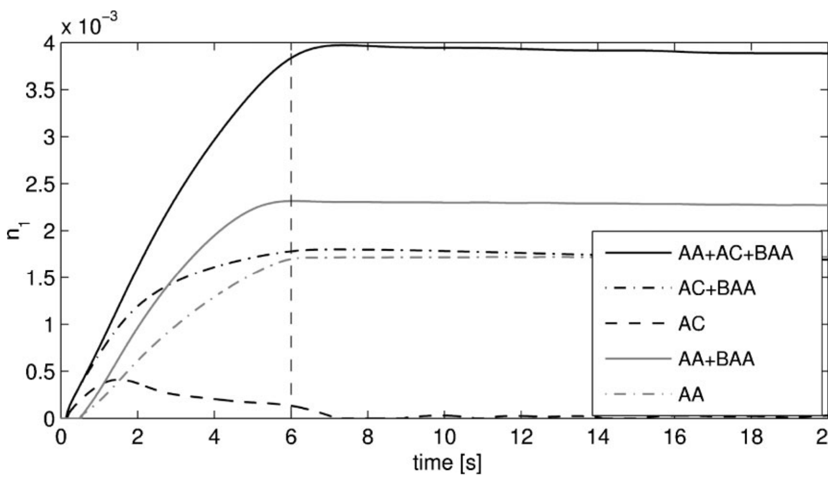

Figure 4.
Grow-curves of materials with different content of monomers. Overall intensity was 6 mW/cm^2, spatial period was 700 nm and exposition time was 6 s.

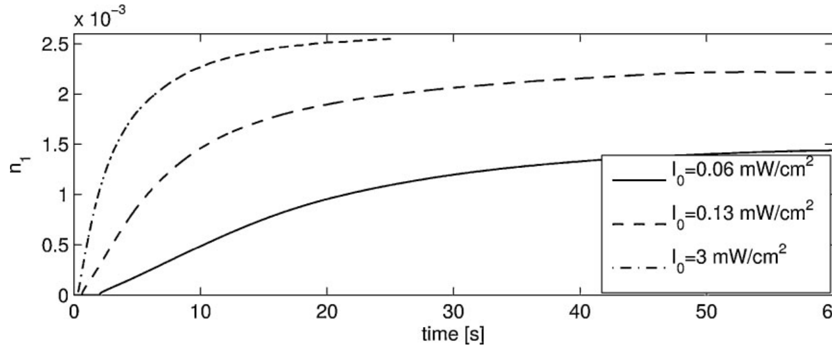

Figure 5.
Comparison of grow-curves with different overall exposition intensities. The spatial period of the interference field was 700 nm.

relatively safe for usage in the holographic research. However, there are several disadvantages of the original composition which limit its practical usage such as low sensitivity, low maximum value of the refractive index change, poor stability of the formed grating, or lower resolution power.

With a view of a better recording material, we have studied the influence of monomers on the recording process. Samples of the material with different monomer composition were prepared, as monomers have fundamental influence on the process of a grating formation. In each sample layer, the concentration of active C=C double bonds was the same (see Table 1 for relative amount of monomers). Concentrations of remaining components were similar as in the case given further in Table 2.

The results of measurements are presented in Figure 4. If only AA (grey dash-dot line) is present in the layer, the grating forms slowly and a low value of refractive index modulation nB_1 $_B$is reached. Addition of the cross-linker BAA (grey solid line) increases the rate of grating growth. A higher value of nB_1 is obtained but the refractive index modulation slightly decreases after the exposition proceeds. If only AAC (black dashed line) is added, the grating starts to form early but the rate of grating formation is low. The maximum value of nB_1 is low and a decrease of nB_1 can be observed already during the exposition. When the exposition is interrupted, the modulation decreases very quickly to zero and the grating is completely erased. If a small amount of the cross-linker BAA is added (black dash-dot line) the rate of the grating formation increases and also the stability of the formed grating. The grating which is formed in the recording material with both monomers and cross-linker (black solid line) starts to grow very early after the beginning of exposition. Its grow rate is high and large and relatively constant

Table 2.
Composition of the optimized dry layer (thickness 60 μm).

Componet	Concentration in % (w/w)
polyvinyl alcohol (M_w = 89000-98000)	31.6
Acrylamide	15
N,N'-methylene-bis-acrylamide	3.8
acrylic acid	7
Triethanolamine	42.5
erythrosine B	0.06

Table 1.
Relative concentrations of acrylamide (AA), methylene-bis-acrylamide (BAA), and acrylic acid (AAC) in different samples.

Monomers	AA	AA + BAA	AAC	AAC + BAA	AA + AAC + BAA
Ratio AA:AAC:BAA	100:0:0	95:0:5	0:100:0	0:95:5	47.5:47.5:5

value of nB_1 is reached. Consequently, BAA has positive effect on the stability of the formed grating and AAC increases the grow-rate of the grating.

In a very similar way, the influence of remaining components on the recording process was also examined. Based on the results of our measurements, recording material with modified composition was prepared (see Table 2 for details). In comparison with other acrylamide-based materials,[5,11,12] higher values of refractive index modulation are obtained for exposures in the range 10–30 mJ/cm^2 (see grow-curves in Figure 5). Transmission gratings recorded in a 60 μm thick layer reach diffraction efficiency up to 0.5 and they degrade minimally with time after exposition.

Holographic Interferometry

The Holographic interferometry (HI) is an application where the improved recording material has been successfully used. A group of Technical University of Liberec, which we cooperate closely with, deals with this measuring technique. Before the results of HI measurements on our photopolymer will be shown, the basic principles are introduced.

The HI is a technique, where displacements of an object or optical path deviations can be measured. Measurements can be applied to stress, strain, and vibration analysis. The advantage of the method is that the information about the whole measured area is acquired at once without the necessity of its scanning. There are several different techniques in HI. One of them is a double exposure holographic interferometry which is based on two holographic expositions of the same object being in the two different states. For example, the method can be used for deformation measurements of a solid body. The first exposition is taken, when the object is unloaded and the second exposition is taken after loading of the object. Both states are recorded in the photopolymer medium with precision much higher than the wavelength of used light. After illumination of the hologram with the reference wave, two waves are produced. One corresponds to the first state of the object and the other belongs to the second state of the object. If the phase difference (the deformation is not large) of both waves is in reasonable limits, a visible interference pattern is created. The interference pattern (interferogram) is carrying the information about the change the object undergoes between two expositions. Here, the application of a photopolymer material is very convenient, as the recording plate need not be removed from the setup for wet chemical developing process.

Our acrylamide-based material has been used in the method of time-average holographic interferometry[13] which could be viewed as a generalized double exposure method. Vibration modes of a piezoelectric element have been measured. In Figure 6, the experimental setup is schematically illustrated. There is only one holographic exposure of the vibrating surface necessary, but the exposure time has to be much longer than the period of vibration. The condition mentioned above is fulfilled easily in the case of our photopolymer as its sensitivity is around 15 mJ/cm^2 and the recording intensity are always less than 1 mW/cm^2. So necessary exposition times are much longer compared with the period of vibrations, but also short enough to prevent a hologram movement during long expositions.

The method compares only the maxima to minima of the vibration amplitudes when the exposure time is long enough. Observed fringes in the reconstructed image are the contours of equal vibration modes amplitudes. The fringe with maximal intensity usually corresponds with the zero amplitude vibration and those are the nodal points. In Figure 7, captured interferograms of vibrating piezoelectric bimorph clamped in the two points are shown for several different frequencies and amplitudes of the drive voltage. We can see that higher order of the mode structure is arising with higher frequency.

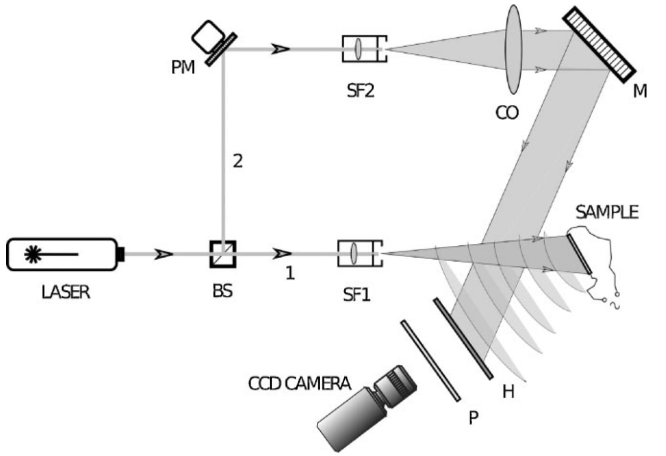

Figure 6.
Experimental setup for piezoelectric bimorph measurement, BS - beam splitter, PM - phase modulator, SF - spatial filter, CO - collimating objective, M - mirror, H - hologram (photopolymer recording structure), P - polarizing filter.

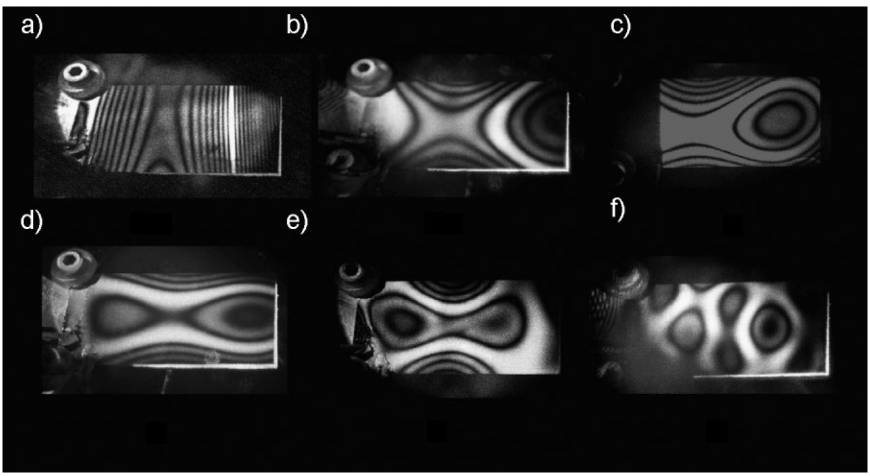

Figure 7.
Vibration modes of piezoelectric bimorph, sinusoidal drive current: a) 1 KHz, 1 V, b) 2 KHz, 2 V, c) 3 KHz, 2 V, d) 4 KHz, 3 V, e) 8 KHz, 3 V, f) 16 KHz, 8 V.

Conclusion

Acrylamide-based photopolymer recording material has been prepared and its composition has been modified to better adjust its characteristics for practical applications. For characterization, we have used our experimental setup which enables real-time measurement of the recording process in photopolymers. The recording material with optimized composition has been applied to holographic interferometry. Interferograms produced on prepared samples of the photopolymer are formed in situ and without need of wet chemical developing process that is the great advantage of the method. With our optimized material, we have successfully acquired time average interferograms of vibrating piezoelectric elements with various vibration modes.

Photopolymer recording material reduces the experimental effort and makes the method more user friendly. Due to their very low inherit material noise, photopolymers could help to reduce the minimal measured amplitude in another holographic method.

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