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9TH INTERNATIONAL CONFERENCE
ON EDUCATION AND NEW LEARNING
TECHNOLOGIES

BARCELONA (SPAIN)
3RD - 5TH OF JULY, 2017

CONFERENCE PROCEEDINGS

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METROLOGY EXPERIMENTS TO UNDERSTAND WAVE PHASE AND DIFFRACTIVE CONCEPTS

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Abstract

The concept of phase, introduced on the study of the Diffractive Optical Elements (DOEs), presents slight understanding difficulties by the students. The phase DOEs are obtained by variations of the thickness or the refractive index of the recording medium, as opposition to the amplitude DOEs, which are obtained by the modulation of the absorption of the recording medium.

It is presented some experiences to introduce the phase concept by means of thickness and refractive index variation, using photopolymers as the phase recording media. These experiences consist in a zero-spatial frequency limit analysis based on a reflection and transmission interferometer and the recording of different types of low spatial frequency DOEs, such as sinusoidal gratings or blazed gratings, generated using a Spatial Light modulator (SLM) to modulate the recording beam. With these experiments, it is possible to measure and observe on real time the thickness and refractive index variations of the material and compare the diffraction efficiencies (DEs) of different types of grating.

The experiences proposed are suitable for the students of different subjects such as "Optical fundamental for Engineering", basic subject included in the second course for obtaining a Telecommunication Degree, for "Photonics and Optoelectronic devices", mandatory subject taught during the second year of Telecommunication master or the optative subject "Acquisition and Optical Treatment of Images" from the Master in robotics-automatic all taught at the University of Alicante. In all cases, the experiences are not only very useful to introduce the concepts to study, but also are useful also to introduce the students into the work of a research laboratory and some of the equipment and procedures that are used on it.

1 INTRODUCTION

The concepts of phase and amplitude Diffractive Optical Element (DOE) presents some difficulties at the time to be understood by the students, specially the second one. While most part of the students usually have a clearer idea about the amplitude, phase is a concept whose assimilation requires more effort. It is necessary to carefully introduce it to assure a good comprehension.

Amplitude DOE are obtained by means of the modulation of the absorption of the recording material and phase DOE can be produced by variations of the thickness or the refractive index of the recording medium. This work presents some experiences centred on the study of these two parameters, directly related with the phase DOEs. As the recording medium for these experiences, we have chosen to use photopolymers [1] due to their low price, easy fabrication, good optical properties and versatility [2-4]. In this particular case, the selected photopolymer is Biophotopol [5], a green non-toxic photopolymer with similar characteristics to those of the most common materials such as the Polyvinyl Alcohol/Acrylamide (PVA/AA) based photopolymers [6-8] but without the toxic components that conforms this kind of compositions [9,10] to avoid any kind of risk working with the students.

Photopolymers are phase materials, the illumination with light of the wavelength at which they are sensitive, which is given by the dye used in the composition, will produce thickness and/or refractive index changes in the illuminated areas. This is due to the monomer polymerization, which increases the compaction of the material causing an initial shrinkage of the illuminated zones and a spatial gradient of the concentrations of the different components. Governed by Fick's law [11,12], this gradient produces a diffusion of the components from the non-illuminated areas, where the concentration is higher, to the illuminated ones, where there is less concentration of the different components. This causes the changes in the thickness and/or refractive index.

2 EXPERIENCES

Two different experiences are proposed, based in two different set-ups. The first one, shown in Figure 1 is a zero-spatial frequency limit analysis using a transmission (Figure 1 a)) and a reflection (Figure 1 b)) interferometer [13, 14].

Figure 1. Zero frequency limit analysis set-up using a transmission (a) and reflection (b) interferometers. P is polarizer, WP is Wave Plate and MO is Microscope Objective.

In the zero-spatial frequency limit, no diffusion processes are produced and the data obtained is directly related to the physical properties of the material. These set-ups permit to measure on real time the phase shift between the unexposed and exposed areas of the material as a function of exposure, analysing the phase changes. In the case of the transmission interferometer, the measured changes are due to two different effects, monomer polymerization and thickness variations. To analyse separately the thickness variations, the reflection interferometer can be used. Both set-ups have two arms, one used to expose the material and the other one to measure in real time the phase shift. The exposure beam is provided by a solid-state Nd-YVO₄ Verdi laser with a wavelength of 532nm, at which the dye presents the maximum absorption. A half-opened diaphragm is used to leave an unexposed area in the photopolymer layer. Since the photopolymer does not present any absorption at 633 nm, we use a He-Ne laser to generate an interference pattern. The grating used in both cases has a spatial frequency of 4 lines/mm to generate a series of diffracted orders from the unexpanded He-Ne beam; we block all the orders except +1 and -1. One of the two orders impinges on the exposed zone (illuminated by the Nd-YVO₄ laser) and the other one impinges on the non-exposed zone. In both set-ups, the distance between the two orders is about 1 cm, enough to eliminate the influence of the monomer diffusion in the polymerization process. Once the two orders have propagated throughout the photopolymer or have been reflected depending on the set-up, a lens is used to make them interfere. A microscope objective is used to amplify the interference pattern onto a CCD camera, model pco.1600 from pco.imaging. This camera has a resolution of 1600 x 1200 and a pixel size of 7.4 μm x 7.4 μm . The recording intensity used is 0.25 mW/cm². The Figure 2 shows an example of the fringe pattern captured by the CCD for different exposure times.

Figure 2. Fringe pattern captured by the CCD camera for different exposure times.

Once the interference pattern has been stored, it is possible to measure the shift with respect to the initial pattern obtained for the unexposed layer. To increase the accuracy in this calculation, it is interesting to cross correlate the different interference patterns with respect to the unexposed areas and this process is strongly related with another subjects such as digital imaging processing or signal processing. This cross correlation produces a clear peak whose location for each exposure time with respect to the centre of the image is equal to the shift in the fringe pattern. A full fringe shift is equal to a 2π rad variation in the phase shift. In the transmission experiment, the phase shift is directly related to the index modulation of the material, in the reflection experiment the data obtained is directly related to the thickness variation of the material. It is possible to determine if the material is shrinking or swelling depending on the sense of the movement of the fringes.

The other experience proposed is based on the recording of low frequency DOEs such as sinusoidal gratings, binary gratings or blazed gratings [15-17]. The set-up used is represented in Figure 3. This set-up is based on a new generation spatial light modulator (SLM) which uses a liquid crystal on silicon display (LCoS) [18] to introduce the periodic pattern. In the setup, we can distinguish two beams, the recording beam and the analysing beam. The modulator is placed along the recording arm and sandwiched between two polarizers (P) oriented to produce amplitude-modulation. Then, with a 4f system the intensity distribution generated by the LCoS is imaged onto the recording material. The recording intensity is the same used for the other set-ups, 0.25 mW/cm^2 .

As in the interferometric set-ups, the analysing arm is made up of a He-Ne laser at a wavelength of 633 nm, at which the material exhibits no absorption, used to analyse in real time the elements formed on the material. This arm is designed to collimate the light incident on the recording material and a diaphragm (D1) was used to limit the aperture of this collimated beam of light. A non-polarizing beam splitter (BS) was used to make the two beams follow the same path up to the red filter (RF) placed behind the recording material to ensure that only the analysing beam is incident on the CCD placed at the end of the setup. To separate the different diffraction orders, we placed a lens behind the material, obtaining the Fraunhofer diffraction pattern on the camera.

Figure 3. Experimental setup used to register and analyse in real-time the DOEs (blazed gratings): D, diaphragm; L, lens; BS, beam splitter; SF, spatial filter; LP, lineal polarizer; RF, red filter; M, mirror.

Using this set-up, the students will record different kind of phase elements, such as sinusoidal or blazed gratings to analyse the differences between them and their diffraction efficiencies (DE), analysing on real time the phase depth modulation and comparing it with the theoretical one. The students will work with periods about $672 \mu\text{m}$ to maximize the observability of the changes in the material. These changes will be given by both the thickness changes and refractive index changes. To study and compare its effects, the students will also analyse materials with sealant and

coverplating [19]. The use of a sealant with a refractive index similar to the one of the photopolymer as an index matching system avoids the effects of the thickness change in the measurements in order to achieve a DOE in which the phase modulation is only due to the refractive index changes.

3 RESULTS AND DISCUSSION

With the first set-ups, the students will measure and represent the phase shift of the fringe patterns and evaluate if the material is able to reach the $360^\circ, 2\pi$ radians, phase modulation, a full fringe shift, required to store some kind of DOEs [20]. They will can also determine if the material is shrinking or swelling depending on the movement of these fringes, as has been said in the previous section. Figure 4 (a) shows the phase shift as a function of the exposure time for an $80\text{ }\mu\text{m}$ layer and (b) shows the phase shift as a function of the exposure time for a $100\text{ }\mu\text{m}$ layer. Both figures are represented with the error bars to evaluate the repeatability of the experiment, near the same for the two thicknesses evaluated.

Figure 4: Phase shift as a function of exposure time for a (a) $80\text{ }\mu\text{m}$ layer (b) $100\text{ }\mu\text{m}$ layer.

The students could analyse the effects of the thickness of the layer and determine the optimum thickness to reach the 2π phase modulation. They can also use the reflective interferometric set-up to calculate the shrinkage or swelling suffered by the material and represent it as it is shown in Figure 5. In this case, the thickness variations of the material (Δd) can be expressed following this equation [14]:

$$\Delta d = \frac{\Delta\Phi\lambda\cos\alpha}{4\pi} \quad (1)$$

where $\Delta\Phi$ is the phase shift (in radians) between the exposed and nonexposed zones along the whole round-trip forward reflected paths, and λ and α are the wavelength and the incident angle of the reading beam, respectively. This is an easy experiment to measure the shrinkage of the material with a high resolution, of the order of the wavelength.

Figure 5: Shrinkage as a function of exposure time of a 90 μm thickness layer

The second set-up can be used by the students to measure the evolution of the different diffracted orders on the Fraunhofer region during the DOEs recording, using the CCD camera. For the students, it is interesting to compare the DE as a function of time for different types of gratings with the theoretical one, given by the Bessel equations [21]. The students could observe the phase depth modulation due to the changes on the refractive index of a real grating and compare it with the theoretical one to analyse the maximum phase depth achieved by each kind of diffraction grating. Figure 6 shows the comparison between the theoretical phase depth modulation of a sinusoidal grating as a function of the phase depth (a) and sinusoidal grating recorded experimentally onto a photopolymer (b). In this case, after 200 s of exposure time, a phase depth of 2π is achieved, needed to store complex DOEs as has been said at the beginning of this section.

Figure 6: a) DE of the first four orders for a sinusoidal grating as a function of the phase depth b) experimental DE as a function of time of a sinusoidal grating.

With this set-up, the students could also analyse the differences between using or not the sealant liquid and experimentally analyse the effects of it. Figure 7 shows the comparison of a grating recorded on a photopolymer without any sealant (a) and using a sealant liquid (paraffin) with a refractive index near to the average refractive index of the photopolymer together with a coverplating as index matching system. The grating recorded in the non index matched material takes more time to reach the maximum DE due to the shrinkage produced in the illuminated zones. This shrinkage produces a decrease in the phase modulation, quickly corrected at longer exposure time by the diffusion processes. This is very interesting to show the effects of the thickness changes in the phase DOEs.

Figure 7: a) DE as a function of time for a sinusoidal grating (a) without using the index matching system, (b) using sealant and coverplating as index matching system.

As has been said before, this set-up it also interesting to study different kind of gratings. The comparison of the DE curves of different kind of gratings could help the students to understand the possible uses of these DOEs and also to observe the different evolution of the orders exhibited by the different kind of diffraction gratings. Figure 8 a) shows the theoretical DE as a function of time of a blazed grating. In this type of complex gratings, with many potential applications in optical communications, all the energy of the zero order is concentrated in the first one, reaching the 100 % of DE, while in the sinusoidal grating the intensity is distributed between the different orders. It depends on each particular application the type of DOE selected and this importance can be shown to the students as a complement of the phase concept study at the time they are studying the phase profile of different types of gratings. Figure 8 b) shows the experimental DE as a function of time of a blazed grating recorded onto a photopolymer. In this case, the maximum DE reached is around the 60 %. This is due to the low pass filtering introduced by the experimental set-up, specially by the last diaphragm used to eliminate the pixilation of the SLM LcOs.

Figure 8: a) Theoretical DE as a function of time of a blazed grating , b) Experimental DE as a function of time of a blazed grating.

4 CONCLUSIONS

This work has presented two different experiences to make easier the understanding of phase, introduced during the study of the DOEs. Along the different experiments, the students could study what a phase DOEs is and the effects of the thickness and refractive index in the final DOE. To record these DOEs, a green non-toxic and non-expensive photopolymer with good optical properties, the Biophotopol, developed at the University of Alicante, is proposed. This phase material is easy to fabricate and permits the students to work without any risk and to observe in real time how is the recording process of a photopolymer is and the influence of some characteristics of the material, working in a real research group environment.

These experiences are suitable for the students of different subjects such as "Optical fundamental for Engineering", basic subject included in the second course for obtaining a Telecommunication Bachelor, for "Photonics and Optoelectronic devices", mandatory subject taught during the second year of Telecommunication master or the optative subject "Acquisition and Optical Treatment of Images" from the Master in robotics-automatic, all taught at the University of Alicante [22-24].

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