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Analysis of amplitude and phase coupling in volume holography

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ABSTRACT

In this work we analyse the complex amplitude response of volume holograms. This analysis suggests a new scheme for encoding complex amplitude wavefront information onto an optical hologram which may prove useful for combining computer-generated holograms (CGH) onto volume holograms. Specifically, we analyse the amplitude and phase modulation associated with a volume phase unslanted transmission grating. Using the expressions given by the Kogelnik's coupled wave theory (KCWT) we find that there is a coupling between the amplitude and the phase modulations. This coupling can be controlled to some extent by means of the reconstruction angle: we have found that the significant magnitude is the normalized Bragg detune angle. A large variation range of the grating strength is desirable, which is enhanced by the use of shorter wavelengths, and materials exhibiting overmodulation capability and/or with a high thickness.

Keywords: Volume holography, computer-generated hologram, amplitude and phase modulation, Kogelnik's theory, photopolymer.

1. INTRODUCTION

Optical holography can generally be viewed as a process where, by means of interference with a reference wavefront, we can record both the phase and the amplitude information of a specific wavefront^{1,2}. If the hologram is volume type, then at the replay step we only obtain the diffracted beam, which is usually of interest, and the transmitted beam. There are numerous rigorous electromagnetic treatments²⁻⁴ dealing with the characteristics of the beams reconstructed by a volume hologram. However, in most cases the simplified approach given by the Kogelnik's coupled wave theory (KCWT)⁵ is accurate enough. Furthermore, the usual figure of merit when dealing with holographic recording materials is the diffraction efficiency, defined as the ratio of the intensities of the diffracted and the incident beams. Nevertheless, the amplitude and the phase magnitudes of the reconstructed beams can also be computed and they provide very useful information and enables some interesting applications⁶⁻⁹.

When analysing the modulation properties of programmable spatial light modulator devices (SLM), such as liquid crystal devices (LCD)¹⁰, we usually encounter coupled amplitude-phase modulation^{11,12}. Different strategies exist to overcome the limitation imposed by the limited codification domain available¹³⁻¹⁵. There are also mathematical models to evaluate the degradations produced on diffractive optical elements (DOE) not properly represented because of the limitations in the codification media^{16,17}. Volume holographic recording materials are not normally analysed from the point of view of the codification domain available, since optical volume holography offers the possibility of reconstructing the whole (amplitude and phase) values of the object wavefront recorded. However, alternative recording and codification schemes may ask for such available codification domain analysis. For example, various researchers have proposed alternative recording schemes in order to combine a computer-generated hologram (CGH) onto a volume hologram¹⁸⁻²⁰. Usually the aim is to take advantage of the flexibility given by CGHs in wavefront design and the high energetic efficiency and/or the wavelength selectivity given by volume holograms. Case and Dallas¹⁸ produced a hybrid CGH-volume hologram as a binary reflection absorption volume hologram. They used a binary Fraunhofer CGH as a computer-generated absorption mask in contact with the holographic film. Two plane waves incide onto the CGH-holographic film thus producing tiny reflection holograms in the areas where the CGH has a transparent cell. Bartelt and

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Case¹⁹ recorded an optical hologram onto dichromated gelatin with the object beam taken from the first order of a detour-phase CGH (Lohmann type)²¹. In this way efficiency is greatly enhanced with respect to the direct CGH reconstruction. MacQuigg²⁰ proposed a multiple-exposure method to encode a complex number onto an optical hologram. The method is based on Burkhardt's method of encoding amplitude and phase of hologram samples²². In this way they can generate any desired complex amplitude CGH onto an optical volume hologram. The method is very elegant, but it is technically very challenging. From these three methods, the one proposed by Case and Dallas would need a deeper codification domain analysis for the case when the computer-generated absorption mask is in gray level instead of binary black and white. In this communication we analyse the amplitude and the phase magnitudes provided by the KCWT and we show that this analysis suggests a new scheme for encoding complex amplitude wavefront information in an optical hologram. This scheme may prove useful for combining computer-generated holograms (CGH) onto volume holograms. Through the KCWT we find that the sinusoidal phase pattern registered in a volume phase hologram can be thought as a wave carrier. A change in the modulation of the phase oscillation generates a change in the amplitude and the phase of the transmitted and the diffracted beams. In Section 2 we introduce the expressions for volume phase unslanted transmission gratings given by the KCWT and we calculate the width of the passband of the angular response, that we will use thereafter. Simulated results are given in Section 3, where we determine which are the significant magnitudes to control the amplitude-phase codification domain available. Finally, in Section 4 the main conclusions of the paper will be given.

2. COMPLEX AMPLITUDE EXPRESSIONS AND WIDTH OF THE PASSBAND

Kogelnik's coupled wave theory (KCWT) provides an accurate description for the complex amplitude modulation performed by holographic gratings onto an incident light beam. According to Kogelnik's theory⁵, for a volume phase unslanted transmission grating the expressions for the transmitted R and the diffracted S wave amplitudes after passing through the hologram are,

$$R = \exp(-j\xi) \left(\cos \sqrt{\nu^2 + \xi^2} + j\xi \operatorname{sinc} \sqrt{\nu^2 + \xi^2} \right) \quad (1)$$

$$S = \exp(-j\xi) (-j\nu) \operatorname{sinc} \sqrt{\nu^2 + \xi^2} \quad (2)$$

where $\operatorname{sinc}(x) = \sin(x)/x$ and,

$$\nu = \frac{\pi \Delta n d}{\lambda_0 \cos \theta_r'}; \xi = \frac{\pi d}{\Lambda \cos \theta_r'} \left(|\sin \theta_r'| - \frac{\lambda_0}{2n_0 \Lambda} \right) \quad (3)$$

n_0 and Δn are respectively the average and the modulation of the refractive index, d is the thickness of the medium, Λ is the period of the grating, λ_0 is the wavelength of reconstruction in air and θ_r' is the angle of reconstruction in the recording medium related to the angle of reconstruction in air θ_r by Snell's law. Bragg angle θ'_{Bragg} inside the material is given by $\sin \theta'_{\text{Bragg}} = \lambda_0 / 2n_0 \Lambda$, thus ξ (eq. (3)) expresses deviation from the Bragg condition. The parameter ν is usually called the grating strength and expresses the amplitude of the phase modulation recorded in the volume grating. In holography, we note that usually intensity related magnitudes, such as diffraction efficiency, are sought. However, in other applications, such as the so-called Bragg processing⁶⁻⁹, we are directly interested in the complex amplitude expressions given by equations (1) and (2), which will be analysed in Section 3. The complex amplitude modulation provided by volume gratings varies with the reconstruction angle θ_r . In Fig. 1 we show the profile for the modulus (amplitude) of the angular response as a function of the reconstruction angle for the transmitted and the diffracted orders and for two different period gratings. In Fig. 1(a) and (b) we show respectively the transmitted and the diffracted orders for a grating period Λ of 1 μm (spatial frequency of 1000 lines/mm), whereas in Fig. 1(c) and (d) we show the transmitted and diffracted orders for a period Λ of 4 μm (spatial frequency of 250 l/mm). The angular responses correspond to gratings exhibiting maximum diffraction efficiency, i.e. grating strength $\nu = \pi/2$ radians. In the simulations we use some typical values for the thick layers of polyvinyl alcohol/acrylamide (PVA/AA) photopolymer that we produce in our laboratory²³⁻²⁵: $n_0 = 1.50$, $\Delta n = 0.0003$, $d = 1000 \mu\text{m}$. We consider reconstruction with at the wavelength $\lambda_0 = 633 \text{ nm}$ (He-Ne laser). The Bragg angle θ_{Bragg} varies approximately with the inverse of the period Λ of the grating. We also see that the angular responses exhibit an angular passband (or rejectband). In Ref. 26 we found that the width of the passband is inversely related with the product $Q\Lambda$, where Q is the Klein-Cook parameter defined as $Q = (2\pi\lambda_0 d) / (n_0 \Lambda^2)$. The Klein-Cook parameter expresses the degree of volume effects exhibited by the grating, with

large values ($Q > 1$) corresponding to volume gratings. In Ref. 26 we found numerically a quantitative relation between QA and the full width at half maximum ($FWHM$) for the passband of the transmitted order, in the neighborhood of the Bragg angle, for a grating strength $v = \pi/2$,

$$FWHM = \frac{3107}{QA} \quad (FWHM \text{ in lines/mm}, QA \text{ in } \mu\text{m}) \quad (4)$$

In Ref. 26 we wrote the angular responses as frequency transfer functions in the context of Bragg processing. In the present work we need to express the width of the passband in angular magnitudes instead of the spatial frequency. Both magnitudes are related through $u = \sin\theta_r / \lambda_0$, which can be approximated for paraxial angles of incidence as $u \approx \theta_r / \lambda_0$, and Eq. (4) can be rewritten as,

$$FWHM\theta_r = \lambda_0 \frac{3107 \cdot 10^3}{QA} \quad (\Delta\theta_r \text{ in radians}, \lambda_0 \text{ in } \mu\text{m}, QA \text{ in } \mu\text{m}) \quad (5)$$

The $FWHM\theta_r$ depends both on the product QA and on the wavelength used at reconstruction. For the gratings of period 1 and 4 μm in Fig. 1 we obtain that the $FWHM\theta_r$ is respectively 0.04° and 0.17°. We note that both gratings in Fig. 1 are in the volume regime with Q values of 2652 and 166 respectively for the grating periods 1 and 4 μm . The parameter $FWHM\theta_r$ will be used to normalize the Bragg detune angle in the simulated results in Section 3. To this goal we define the normalized detune angle $\Delta\theta_N$ as the ratio $\Delta\theta_N = \Delta\theta / FWHM\theta_r$, where $\Delta\theta$ is the absolute Bragg detune angle.

Fig. 1. Modulus (amplitude) for the angular responses. (a) and (b) Transmitted and diffracted orders for a grating period of 1 μm ; (c) and (d) Transmitted and diffracted orders for a grating period of 4 μm . Reconstruction wavelength at $\lambda_0 = 633 \text{ nm}$.

3. SIMULATION OF AMPLITUDE-PHASE COUPLING

Fig. 2. Modulation as a function of the grating strength v for the diffracted beam. We consider a grating with 1 μm period, reconstructed at $\lambda_0 = 633 \text{ nm}$. The normalized detune angle $\Delta\theta_N$ is respectively 0 and 1 for the first and the second row.

The complex amplitude values provided by Eq. (1) and (2) vary with the grating strength v . Let us remind that the grating strength is related with the total energy per unit area addressed onto the holographic recording material in the registering step, i.e. the exposure. In holographic recording materials, the grating strength plays a similar role to the role played by the birefringence parameter in the case of LCDs^{11,12} and the role of exposure is similar to that played by the addressed voltage in LCDs. In principle a large grating strength dynamic range would mean a larger amplitude modulation range and a larger phase modulation range. In this Section we analyse the complex amplitude modulation as a function of the grating strength v exhibited at reconstruction for the case of a volume phase sinusoidal transmission grating. We will see that the normalized detune angle $\Delta\theta_N$ plays an important role to control the coupling between the amplitude and the phase modulations. In Fig. 2 we represent the modulation as a function of the grating strength v (in degrees) for the diffracted order for a grating such as the one given in Fig. 1(a) and (b): period of 1 μm , reconstructed at $\lambda_0 = 633 \text{ nm}$, and with a

layer thickness of 1000 μm . We consider a variation for the modulation refractive index Δn from 0 to 0.00075, which produces a dynamic range for the grating strength ν from 0° to 220° . The four columns starting from the left represent respectively the intensity modulation, the amplitude (modulus) modulation, the phase-shift modulation, and the complex plane plot for the amplitude and phase modulations. In the first row we show the simulated results for incidence at Bragg angle, i.e. $\Delta\theta_N=0$. We see that at $\nu=90^\circ$ we obtain the maximum of diffraction efficiency. In the third column (phase-shift) we see a phase jump. Note that this phase-jump takes place at a zero amplitude point (second column). In the complex plane (fourth column) we see that there is actually no complex amplitude modulation discontinuity, as it should be. In the second row we consider reconstruction at a normalized detune angle of $\Delta\theta_N=1$, i.e. the absolute detune angle $\Delta\theta$ is 0.04° . We see that now we do not attain maximum diffraction efficiency equal to one. In Fig. 2, in both rows we see that the phase modulation stays constant, i.e. the diffracted order exhibits no phase modulation capability. In Fig. 3 we consider the same grating as in Fig. 2, but now we show the modulation performance for the transmitted order. Starting from the top row the normalized detune angle $\Delta\theta_N$ is respectively 0 (Bragg angle incidence), 0.5, 1, 1.5 and 2. In these plots we see (third column) that when we reconstruct out of the Bragg angle we obtain a phase modulation coupled to the amplitude modulation.

The dynamic range for this modulation in the phase-shift is larger for smaller detune angles (second row). We also see that for larger detune angles (fifth row) we obtain a phase modulation with a smaller coupled amplitude modulation range. Therefore, the coupling between the amplitude and phase modulations can be partially controlled by means of the value of the detune angle at reconstruction.

Fig. 3. Modulation as a function of the grating strength ν for the transmitted beam. We consider a grating with 1 μm period, reconstructed at $\lambda_0 = 633$ nm. The normalized detune angle $\Delta\theta_N$ for each of the rows starting from the top is 0, 0.5, 1, 1.5 and 2.

Fig. 4. Modulation as a function of the grating strength ν for the transmitted beam. We consider a grating with 4 μm period, reconstructed at $\lambda_0 = 633$ nm. The normalized detune angle $\Delta\theta_N$ is 0.5.

In Fig. 4 we plot the modulation as a function of ν (in degrees) for the transmitted order for a grating with grating period of 4 μm , such as the one represented in Fig. 1(c) and (d). The rest of the parameters are equal as the parameters for the grating in the plots in Fig. 2 and 3. We consider a normalized detune angle $\Delta\theta_N$ of 0.5. We see that the coupled amplitude-phase modulation is exactly equal as the one represented in the second row in Fig. 2, where $\Delta\theta_N$ is also 0.5. When the grating period varies, with the others parameters of the grating kept fixed, we obtain equal modulation performances for equal normalized detune angles $\Delta\theta_N$. Thus, instead of $\Delta\theta$ we find that the normalized parameter $\Delta\theta_N$ is the significant magnitude at reconstruction.

Fig. 5. Maximum grating strength ν as a function of the reconstruction wavelength used. We consider a maximum modulation refractive index of 0.00075 and a layer thickness of 1000 μm .

Looking at Eq. (3) we see that the maximum grating strength value ν depends on the wavelength used at reconstruction. In Fig. 5 we plot this dependency, where we consider, as a first approximation, that the modulation of the refractive index Δn has a constant value of 0.00075 (maximum value in Fig. 2,3 and 4) all along the visible spectrum. We see that if we use shorter wavelengths we increase notably the dynamic range for the grating strength ν . This dynamic range can also be increased if we use thick layers (as the 1000 μm layer that we use in the various simulations), and if we use materials with overmodulation capability²³⁻²⁵, which requires high values for Δn . In Fig. 6 we analyze the modulation performance for the transmitted order for a grating with a period of 4 μm . With respect to the previous figures, now we consider reconstruction with a wavelength of 458 nm (one possible line for an Ar laser), thus increasing the dynamic range for the grating strength ν to approximately 300°. We consider reconstruction at $\Delta\theta_N = 2$. We see that this plot extends the amplitude and phase modulation ranges shown in the fifth row in Fig. 3, where $\Delta\theta_N = 2$ had the same value. In particular, now we obtain a phase modulation range of 180° with not a very high amplitude modulation coupled.

Fig. 6. Modulation as a function of ν for the transmitted beam. We consider a grating with 4 μm period, reconstructed at $\lambda_0 = 458$ nm, and with Δn variation from 0 to 0.00075. The normalized $\Delta\theta_N$ is 2.

In Fig. 7 the reconstruction wavelength is 458 nm as in Fig. 6. We consider a hypothetical maximum value of 0.00225 for Δn , obtaining a very high grating strength ν range. This enables reconstructing with a large detune, thus reducing the amplitude modulation range while still maintaining a large phase modulation value. In particular we consider $\Delta\theta_N = 10$ in Fig. 7, and we see that we are able to obtain phase-mostly modulation with a phase modulation of 360°.

Fig. 7. Modulation as a function of ν for the transmitted beam. We consider a grating with 4 μm period, reconstructed at $\lambda_0 = 458$ nm, and with Δn variation from 0 to 0.00225. The normalized $\Delta\theta_N$ is 10.

The simulated results that we have analysed suggest an alternative scheme to codify information onto a holographic recording material. In particular, we have seen that the diffracted order is capable of amplitude-only modulation, and the transmitted order exhibits in general a coupled amplitude-phase modulation. In a first step we need to calibrate the grating strength as a function of the exposure, which is the parameter that we control in the lab experiments. Then we know the complex amplitude modulation achievable with the material as a function of the exposure value. Through the modulation of the exposure value at each point on the material we can codify the desired information in the codification domain available. The modulation of the exposure value can be done, for example, using some computer-generated gray level absorption mask in contact with the holographic recording material, extending the work of Case and Dallas¹⁸.

4. CONCLUSIONS

We have theoretically analysed the complex amplitude response of a volume hologram using the expressions given by the Kogelnik's coupled wave theory (KCWT) for a volume phase unslanted transmission grating. Through the KCWT

we find that the sinusoidal phase pattern registered in a volume phase hologram can be thought as a wave carrier. A change in the modulation of the phase oscillation generates a change in the amplitude and the phase of the transmitted and the diffracted beams. We have seen that the diffracted order is capable of amplitude-only modulation, and the transmitted order exhibits in general a coupled amplitude-phase modulation. This coupling can be controlled to some extent by means of the reconstruction angle with $\Delta\theta_N$, the normalized Bragg detune angle, as the significant magnitude. A large variation range of the grating strength is desirable, which is enhanced by the use of shorter wavelengths, and materials exhibiting overmodulation capability and/or with a high thickness. The analysis in this work suggests a new scheme for encoding complex amplitude wavefront information in an optical hologram which may prove useful for combining computer-generated holograms (CGH) onto volume holograms.

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