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Holographic optical elements for Bragg image processing

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ABSTRACT

In this work we analyse the very specific properties offered by volume holography when applied to image processing with no Fourier plane. Bragg diffraction, exhibited by holographic optical elements (HOEs), modifies the impulse response of an imaging system, facilitating spatial filtering operations with no need for a physical Fourier plane (Bragg processing). We show both experimental and simulated results with holographic phase gratings and with holographic lenses generated on a polyvinyl alcohol/acrylamide (PVA/AA) photopolymer. We determine which are the significant parameters to model the performance of the HOEs for Bragg filtering: orientation and bandwidth of the passband of the filter. We relate these spatial filtering parameters with their corresponding counterparts in volume holography. We also show how the local variation of these parameters is responsible for space-variance properties of the HOE when applied in Bragg processing. We have also analysed the impulse response characteristics of the Bragg filter together with the effects of the limited aperture of the imaging system.

Keywords: Optical image processing, holographic optical elements, space-variant imaging, Bragg diffraction, photopolymer.

1. INTRODUCTION

In the application of volume holography to optical information processing most of the work has been dedicated to Vander Lugt kind of filters, and in general to filters to be used in the Fourier plane of an optical processor¹. A different strategy was proposed at the end of the 70s, dedicated to modify the impulse response of the optical system with no need for a Fourier plane²⁻⁴. The system is simple and compact: we simply need an imaging setup. This image processing strategy takes advantage of the characteristics of the angular response of the volume hologram that modifies the plane wave spectrum of the object. Following this strategy, image edge enhancement and image restoration were demonstrated. In recent years, the interest in this Bragg processing based operations has attracted the attention of researchers working with acousto-optic light modulators (AOLMs)⁵⁻¹⁰. In AOLMs, Bragg diffraction effects have been described using the frequency transfer function formalism. Using this formalism in combination with Kogelnik's expressions we showed the application of polyvinyl alcohol/acrylamide (PVA/AA) photopolymers to edge enhancement by Bragg processing^{11,12}.

Holographic optical elements^{13,14} (HOEs) can be thought as generalized holographic grating structures. In the case of holographic lenses (or hololenses) the important parameters are the diffraction efficiency together with the generic parameters associated with the imaging capabilities of lenses, such as the compensation of aberrations. As we demonstrated in a previous work¹⁵ hololenses can be applied as Bragg filters. Actually, they can be considered as space-variant Bragg filters. In general when the local structure of a HOE varies across its surface we can expect a space-variant image processing capability. In principle, in the hololens two properties of the filter vary across the surface: the bandwidth of the passband and the shift in the position of the passband.

In this work we continue with the analysis of Bragg filtering capabilities started in previous works^{11,12,15}. In Section 2 we give a general background to the subject. Mostly the analysis of Bragg filters is carried out in the frequency domain. Even though the frequency transfer function formalism gives a direct insight to Bragg filters, in Section 3 we find it interesting to show the analysis from the impulse response point of view. According to this analysis we show how the limited aperture of the imaging system is modified by the Bragg filter. In Section 4 we study two of the important parameters which define the space-variance properties of HOEs: the local Bragg angle variation and the bandwidth of the

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passband of the Bragg filter. We determine the relation between the bandwidth and some parameters related with the volume character of the HOE. Finally, in Section 5 the main conclusions of this work are summarised.

2. IMAGING SYSTEM WITH A BRAGG FILTER

2.1 Kogelnik's coupled wave theory

In previous works¹¹ we have shown that Kogelnik's theory provide an accurate description for the spatial filtering operations performed by holographic gratings. According to Kogelnik's theory¹⁶, 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 Bragg processing we are actually interested in the complex amplitude expressions given by equations (1) and (2).

2.2 Imaging system and plane wave spectrum decomposition

We can express the angular responses R and S , which depend on the angle θ_r of the incident beam with respect to the normal of the hologram, as frequency transfer functions. According to Figure 1, let us consider θ_o and ψ respectively as the angles of the plane wave spectrum of an input object and the orientation of the grating with respect to the optical axis in a certain optical system. Thus the angle θ_r is given by $\theta_r = \theta_o - \psi$, and the angular responses R and S of the grating modify the spectrum of plane waves propagating from the object. Similarly, equations (1) and (2) can be expressed as a function of the spatial frequency u (cycles/meter) as $p = \sin \theta_o / \lambda_0$, or as a function of the angular frequency p (rad/meter), given by $p = 2\pi u$, to obtain the angular frequency transfer functions $H_0(p)$ and $H_1(p)$ for the zero and the first diffracted orders.

Figure 1. Imaging system with a volume grating. We show the deviation of the transmitted and the diffracted images by the grating.

Let us analyze the effect of the holographic grating inserted in an imaging setup as in Figure 1. We develop the expressions in one dimension. Extension to two dimensions is straightforward. The holographic grating is at distances z_{1A} and z_{1B} respectively from the object $f(x)$ and the lens, and z_2 is the image distance. When no grating is inserted the image amplitude $g(x')$ is given as the convolution ($\otimes$) of the object by the impulse response of the optical system $h_s(x')$,

$$g(x') = (f \otimes h_s)(x') \quad (4)$$

Using the convolution theorem we can rewrite equation (3) as,

$$G(p) = F(p)H_s(p) \quad (5)$$

where capitals represent the Fourier transform functions. When we introduce the holographic grating in the setup the angular frequency spectra of the object $F(p)$ is filtered respectively by the transfer functions $H_0(p)$ and $H_1(p)$ of the grating, thus we obtain two different filtered images,

$$G_0(p) = F(p)H_0(p)H_s(p); \quad G_1(p) = F(p)H_1(p)H_s(p) \quad (6)$$

being $G_0(p)$ and $G_1(p)$ respectively the angular frequency contents for the transmitted and the diffracted images. We see that spatial filtering is performed with no physical Fourier plane.

3. IMPULSE RESPONSE OF THE BRAGG FILTER

3.1 Transfer function and impulse response

In general, the filtering capabilities of Bragg filters are analysed according to the frequency transfer function formalism as given in previous Section. However, the analysis of the impulse response (or point-spread function) for the filter can provide another useful insight into Bragg filters. We will consider the important case when the grating is oriented at $\psi = \theta_{\text{Bragg}}$, where θ_{Bragg} is the Bragg angle in air. We know that in this case we can make the transmitted order behave as a high-pass filter, with the diffracted order acting as a low-pass filter⁸. In Ref. [11] we showed asymmetric edge enhancement using volume gratings recorded on PVA/AA photopolymer. This result has been previously discussed by Davis et al.⁸ using AOLMs.

To simulate the volume grating we consider typical values for a PVA/AA photopolymer grating with maximum diffraction efficiency: $n_0 = 1.50$, $\Delta n = 0.003$, $d = 100 \mu\text{m}$, $\Lambda = 0.9 \mu\text{m}$ (1125 l/mm). For these values, at $\lambda_0 = 633 \text{ nm}$, we obtain: $\theta_{\text{Bragg}}(\text{in air}) = \pm 20.8^\circ$. In Figure 2 we show the profile corresponding to the transfer functions for the transmitted (plots (a) and (b)) and the diffracted (plots (c) and (d)) orders. Plots (a) and (c) show the amplitude (modulus) and plots (b) and (d) show the phase. We consider the grating oriented at Bragg angle $\psi = \theta_{\text{Bragg}}$ and the frequency content is plotted as a function of the angle θ_o (in degrees) with respect to the optical axis of the imaging system (Figure 1).

Figure 2. (a) Transfer function (modulus) and (b) phase for the transmitted order. (c) Transfer function (modulus) and (d) phase for the diffracted order. The X axis is given as a function of the angle θ_o (scaled with $\lambda_0 = 633 \text{ nm}$). Grating thickness is 0.1 mm.

If we look at the amplitudes in Figure 2(a) and (b), we see that $H_0(p)$ shapes a high-pass filter and $H_1(p)$ behaves like a low-pass filter respectively. In the vicinity of the origin the phase for the transmitted order (fig. 2 (b)) has the step profile typical of a derivative filter, changing from -90° to 90° . In the approximation to small angles we actually can see that the transfer function for the transmitted order becomes a derivative filter when the parameter ν is close to $\pi/2$ radians. We remind that when $\nu = \pi/2$ rad (at $\theta_r = \theta_{Bragg}$) a phase volume grating exhibits 100% diffraction efficiency¹⁷.

Next we show in Figure 3 the impulse response corresponding to the transfer functions $H_0(p)$ and $H_1(p)$ shown in Figure 2. The impulse response is given as the Fourier transform of the transfer function. In Figure 3(a) we consider the original impulse function located at coordinate $-25 \mu\text{m}$. In Figure 3(b) and 3(c) the modulus of the impulse responses of $H_0(p)$ and $H_1(p)$ are plotted respectively. Note that the Y-axis in Figure 3 (b) and (c) is magnified in order to show the details of the impulse responses. We observe that the responses for the transmitted and for the diffracted order are totally different with an evident widening in the case of the diffracted impulse response, thus producing a smoothing effect when convolved with an extended object.

Figure 3. (a) Original impulse function; (b) Transmitted and (c) diffracted impulse response. Grating thickness is 0.1 mm.

In Figure 4 we consider a transmission grating with a thickness of 0.3 mm and with grating strength $\nu = \pi/2$. In Figure 4 (a) and (c) we show respectively the transfer functions for the transmitted and the diffracted order. In Figure 4 (b) and (d) we show the impulse responses for the two orders. We see that the shrinking in the passband for the transmitted order produces a widening in the basement of its impulse response. The same effect appears in the impulse response for the diffracted order.

Figure 4. Transmitted order: (a) Transfer function (modulus) and (b) impulse response. Diffracted order: (a) Transfer function (modulus) and (b) impulse response. Grating thickness is 0.3 mm. The angle θ_0 is scaled with $\lambda_0 = 633 \text{ nm}$.

3.2 Influence of the cutoff frequency of the imaging system

The impulse responses shown in Figure 3 and 4 would correspond to the image obtained from a point object using the imaging system in Figure 1 and considering unlimited extent for the exit pupil. Actually, the exit pupil has a finite radius R . This finite radius R determines the cutoff frequency u_{max} for the transfer function of the optical system $H_s(p)$, which is given by¹,

$$u_{max} = \frac{R}{\lambda_0 z_2} \quad (7)$$

where u_{max} is the spatial frequency cutoff in cycles/mm (the maximum angular frequency is $p_{max} = 2\pi u_{max}$). Let us consider typical values for our imaging setup in Figure 1 to get an order of magnitude of the cutoff frequency: $z_2 = 59$ cm and $R = 3.25$ cm. The numerical aperture of the imaging system is very low and we obtain that the cutoff frequency is about 100 cycles/mm, i.e. the plane wave spectra with an angle over 3.4° is blocked. In Figure 5 (a) we show the impulse response of the system for this cutoff frequency and with no Bragg filter. We observe the typical sidelobes given by diffraction limited imaging. In Figure 5 (b) and (c) we show the impulse responses for the transmitted and the diffracted orders respectively. These figures should be compared with the previous Figures 3 (b) and (c). Now that the limited aperture of the system is considered we see that the impulse responses are widened, especially the impulse response for the transmitted order. We see that the optical system is clearly modifying the original response given by the filter. Actually, plots in Figure 5 (b) and (c) are respectively the convolution of the plots in Figure 3(b) and (c) by the impulse response of the system, given in Figure 5 (a).

Figure 5. Impulse response for an imaging system with a cutoff frequency of 100 cycles/mm: (a) with no Bragg filter, (b) considering the transmitted order and (c) considering the diffracted order. We consider a grating thickness of 0.1 mm.

4. ORIENTATION AND BANDWIDTH OF THE PASSBAND

4.1 Orientation of the Bragg angle and space-variant processing

A generic holographic optical element can be partly viewed as a holographic grating with a variable local structure across the surface. According to this point of view different properties may vary locally: the grating strength $v(x,y)$, the Bragg angle orientation $\theta_{Bragg}(x,y)$, and the bandwidth of the passband of the Bragg filter. The variation of any of these properties will be responsible for the introduction of a space-variance capability when the HOE is analysed as a Bragg diffraction filter. In a previous paper we analysed the properties exhibited by holographic lenses (hololenses). We showed that hololenses were able to produce space-variant edge-enhancement¹⁵.

Note that in the case of space-variant systems the output of the system can not be calculated as a convolution by a unique impulse response^{18,19}. The equations (4)-(6) are valid for space-invariant systems. In the more general case of space-variant systems the impulse response varies along the object coordinate x , i.e. $h_s(x'; x)$, and we replace the convolution integral in equation (4) for a superposition integral,

$$g(x') = \int_{-\infty}^{+\infty} h_s(x'; x) f(x) dx \quad (8)$$

The convolution theorem is no longer valid and in principle the transfer function formalism can not be used. However, we can still consider that the space-invariance remains for small vicinities in the object plane. Following this approach the frequency transfer formalism can be used at the expense of using a different transfer function for each vicinity.

Next we show the calculations for the orientation of the Bragg angle at reconstruction for hololenses. The orientation of the Bragg angle varies across the surface, i.e. the orientation of the passband of the Bragg filter varies locally. For simulations we consider the parameters corresponding to hololenses that we have produced on PVA/AA photopolymer. In the registering step we use illumination with $\lambda_R = 514$ nm (Argon laser) with a collimated reference beam at an angle of incidence of 16.8° with respect to the normal of the hologram. The object beam is a diverging spherical beam with a radius of curvature of 10 cm, whose principal ray incides at an angle of -16.8° with respect to the normal of the hologram. The diameter of the interference region on the material is 2 cm. Thus, we generate an off-axis hololens with a 10 cm focal length for the 514 nm wavelength and with a 2 cm diameter. In the reconstruction step we use a beam with a wavelength $\lambda_C = 633$ nm (He-Ne laser). We call positive Bragg angle when at reconstruction the ray incides from the direction of the reference beam used at the registering step. Negative Bragg angle corresponds to reconstruction from the direction of the object beam at the registering step.

In Figures 6(a) and (b) we show a contour plot respectively for the positive and the negative Bragg angle in air along the X - Y plane of the hologram. In the gray level legend of the figures we can see that the range of variation for the positive Bragg angle is between 22° and 19° approximately. In the case of the negative Bragg angle the variation is larger, ranging from -11° to -30° . At the center, coordinate $(0, 0)$, the Bragg angle is respectively $+20.8^\circ$ and -20.8° . The angle variation is much smaller in the case of the positive Bragg angle due to fact that in this case the reconstruction beam tries to replay the reference beam, which had a collimated wavefront. We can expect that when we use the hololens as a Bragg filter the extent of the neighborhood where a certain impulse response $h_s(x'; x)$ is valid is narrower if we incide along the negative Bragg angle direction.

Figure 6. (a) Positive and (b) negative Bragg angles across the aperture of the hololens.

4.2 Bandwidth of the passband

The bandwidth of the passband of the Bragg filter determines the scale of the object that can be properly filtered. In principle, the larger the bandwidth the smaller the object that is appropriately filtered¹⁵. We want to obtain a quantitative relation for the bandwidth of the passband as a function of typical parameters used in the design of volume holograms. Let us define which are the starting conditions for this analysis. We consider the profile for the zero order transfer function $H_0(p)$ when the grating exhibits maximum diffraction efficiency, i.e. grating strength $\nu = \pi/2$. We calculate the bandwidth of the passband as the full width at half maximum ($FWHM$) in the neighborhood of the Bragg angle. By numerical evaluation we have found that the $FWHM$ is directly related with the product QA , where A is the period of the grating and Q is the Klein-Cook parameter defined as,

$$Q = \frac{2\pi\lambda_0 d}{n_0 \Lambda^2} \quad (9)$$

where the magnitudes in equation (9) have already been introduced in the text. The Klein-Cook parameter expresses the degree of volume effects¹⁷ exhibited by the grating. In general, small values of Q ($Q < 1$) correspond to thin gratings, while large values ($Q > 1$) correspond to volume gratings. We have found that the following expression provides quantitative relation between the volume hologram magnitude QA and the spatial filtering property $FWHM$,

$$FWHM = \frac{3107}{Q\Lambda} \quad (FWHM \text{ in cycles/mm}, Q\Lambda \text{ in } \mu\text{m}) \quad (10)$$

In Figure 7 we show the relation between the $FWHM$ and the product $Q\Lambda$. The circles correspond to the values of $FWHM$ calculated for a set of Bragg filters with a different product $Q\Lambda$. The continuous line corresponds to the fitting curve for the circles previously evaluated. The expression for the fitting curve was given in Eq. (10). We see that the bandwidth diminishes with the increase in the product $Q\Lambda$. The relation in Eq. (10) is a very important result as it is the connection between holographic parameters and spatial filtering parameters. Depending on the scale of the object that we want to filter we need a Bragg filter with a certain $FWHM$. From the value of the $FWHM$ we calculate the product $Q\Lambda$ that should be exhibited by HOE. According to this product $Q\Lambda$ we modify the registering setup to record the appropriate HOE.

Figure 7. Relation between the bandwidth of the passband of the Bragg filter and the product $Q\Lambda$.

Now we can apply Eq. (10) to calculate the local $FWHM$ for the hololens reported in the previous Section 4.1. In Figure 8 (a) we show the value of the product $Q\Lambda$ across the hololens, and in Figure 8(b) we show the corresponding local $FWHM$. We consider that the hologram has a thickness of 0.1 mm. We see that the product $Q\Lambda$ varies approximately between 200 and 400 μm , while the $FWHM$ varies between 8 and 14 cycles/mm. In Figure 9 (a) and (b) we show respectively the product $Q\Lambda$ and the $FWHM$ for a hologram thickness of 1 mm. We see, Eq. (10), that a ten-fold increase in the product $Q\Lambda$ produces a ten-fold decrease in the values for the $FWHM$. Thus, depending on the scale of the object to be filtered we should consider the thinner hololens (narrower object, i.e. with a high frequency bandwidth) or the thicker hololens (wider object, i.e. with a low frequency bandwidth).

Figure 8. (a) Product $Q\Lambda$ and (b) bandwidth ($FWHM$), across the aperture of the hololens for a hologram thickness of 0.1 mm.

Figure 9. (a) Product QA and (b) bandwidth ($FWHM$), across the aperture of the hololens for a hologram thickness of 1 mm.

4.3 Extended object

Let us simulate the effect of the Bragg filters on extended objects. In Figure 10 we show an example of the resultant images produced by the filters given in Figure 2. We consider an amplitude object. Results using a phase object have also been done¹². Our input object is composed of two slits with different widths of $7\ \mu\text{m}$ and $70\ \mu\text{m}$ as can be seen in Fig. 10(a). In Figure 10(b) and (c) we plot the transmitted and the diffracted images processed respectively by the filters $H_0(p)$ and $H_1(p)$. We see that the result is different for the two slits. In the case of the wider slit ($70\ \mu\text{m}$) the transmitted image (Fig. 10(b)) is an edge enhanced version of the input object, and the diffracted image (Fig. 10(c)) is a low-pass version where the edges have been smoothed. For the thinner slit ($7\ \mu\text{m}$) we do not obtain any useful image processing operation: the transmitted image is a distorted version of the original slit, and in the diffracted order we just obtain a background noise along the X -axis. The different performance of the filter for the two slits is due to the relative width of the passband of the filter with respect to the width of the frequency spectrum for each slit. The frequency spectrum of the thinner slit is much larger than the passband of the filter (product $QA \sim 300\ \mu\text{m}$, $FWHM \sim 10$ cycles/mm), thus the filter is not discriminating between low and high frequencies.

Figure 10. (a) Input object: two slits with a different width ($7\ \mu\text{m}$ and $70\ \mu\text{m}$); (b) Transmitted image; (c) Diffracted image. Grating thickness is 0.1 mm.

In Figure 11(a) and (b) we plot respectively the transmitted and the diffracted images processed respectively by the filters $H_0(p)$ and $H_1(p)$ for a holographic grating with maximum diffraction efficiency and with a thickness of 1 mm. The rest of the parameters are the same as for the simulation in Figure 10. Now the bandwidth of the filter has reduced in a factor of ten with respect to the hologram with a 0.1 mm of thickness. Now none of the two slits is enhanced as their frequency bandwidth is much larger than the bandwidth of the passband of the filter.

In Figure 12 we plot the filtered images when we consider the filter shown in Figure 2 together with the limited resolution of the imaging system, described in Figure 5. In Figure 12(a) we show the low pass version of the object obtained when no Bragg filter is inserted in the imaging system. We observe the attenuation at the edges of the slits and the existence of a ripple, especially in the wider slit. In Figure 12(b) we show the transmitted image processed by the filter $H_0(p)$. In comparison with the result given in Fig. 10(b) we can see that the edge enhancement is smoothed by the limited resolution of the imaging system, and a certain degree of ripple is apparent in the result. Thus, if we want to

obtain an accurate result for the Bragg filtered result we should also take into account the limited bandwidth of the imaging system. This is more important when the numerical aperture is lower.

Figure 11. (a) Transmitted image; (b) Diffracted image. Grating thickness is 1 mm.

Figure 12. Effect of the limited resolution of the imaging system. (a) Transmitted image with no Bragg filter and (b) with the Bragg filter. Grating thickness is 0.1 mm.

Finally, in Figure 13 and 14 we give some experimental results obtained using the setup described in Figure 1. In Figure 13 we show respectively the image transmitted by the imaging system with no filter (Fig. 13(a)) and with a filter (Fig. 13(b)), which corresponds to Figure 12(b). We note that the width of the columns of the number 4 is about $70 \mu\text{m}$. In Figure 13(a) we note the ripple effect that was predicted in Figure 12(a) due to the limited aperture of the imaging system. Some extra interference effects may also arise by reflections in the optical surfaces. In Figure 13(b) the vertical edges are clearly enhanced while some ripple is also existent.

Figure 13. Experimental images. (a) Direct image with no grating; (b) Zero order filtered image. The columns of the number 4 have a width of about $70 \mu\text{m}$.

In the Figure 14 we show some experimental images obtained using the hololens as a Bragg filter for a thickness of 0.1 mm. The images correspond to an area of approx. $9 \times 7 \text{ mm}$ in the object (USAF 1951 resolution target). We consider the transmitted image, i.e. the zero diffraction order. As commented in Section 4.1, we distinguish two different situations for the orientation of the hololens: the direction of the optical axis of the imaging setup is in the range of the positive Bragg angle of incidence, or is in the range of the negative Bragg angle. Images 14(a) and (b) correspond respectively to a positive Bragg angle orientation and to negative Bragg angle orientation. The object is fixed and the

hololens is rotated about the $x = 0$ axis. We see that about a third part of image (a) is edge enhanced, whereas the rest of the image has been transmitted without any filtering. We remark the rotating the hololens we select a different region of the object to be edge enhanced. In image (b) we appreciate a narrow dark fringe crossing the image in the vertical direction. We saturated the illumination to increase the contrast of the fringe. The dark fringe is due to the removing of frequencies in the selected area of the object. This energy is sent to the diffracted order. It is interesting to note that the width of the selected area of the object in the case of the negative Bragg angle orientation is clearly smaller than for the positive Bragg angle orientation. This is consistent with the fact that the Bragg angle varies more rapidly in the case of the negative Bragg orientation (as given in Fig. (6)).

Figure 14. Zero order (transmitted) images obtained with the 0.1 mm thick hololens. (a) corresponds to incidence at *positive* Bragg angle and (b) at *negative* Bragg angle.

5. CONCLUSIONS

We have shown both experimental and simulated results with holographic phase gratings and with holographic lenses generated on a polyvinyl alcohol/acrylamide (PVA/AA) photopolymer. We have analysed the impulse response characteristics of the Bragg filter together with the effects of the limited aperture of the imaging system. We have seen that when the numerical aperture of the imaging system is low, then there can be an important low pass filtering effect especially on the impulse responses for the zero order of the Bragg filter. We have determined the relation between the bandwidth of the passband of the filter and the corresponding parameters in volume holography. We have also shown how the local variation of the orientation and the bandwidth of the passband is responsible for the space-variance properties of the HOE when applied in Bragg processing.

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